JPhys Photonics

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To cite this article: Tie Jun Cui *et al* 2024 *J. Phys. Photonics* **6** 032502

Journal of Physics: Photonics

CrossMark

OPEN ACCESS

RECEIVED
10 October 2022

REVISED
8 May 2023

ACCEPTED FOR PUBLICATION
2 January 2024

PUBLISHED
31 July 2024

ROADMAP

Roadmap on electromagnetic metamaterials and metasurfaces

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Keywords: metasurfaces, metamaterials, programmables, space-time, optics

Contents

1. Introduction 4
2. Effective medium metamaterials 7
2.2. Negative refraction 10
2.3. Perfect lens and superlens 13
2.4. Transformation optics (TO) 16
2.5. 3D metamaterials 19
2.6. Metamaterials with extreme parameters 22
2.7. Chiral and bianisotropic metamaterials (BAMMs) 25
2.8. Photonic topological metamaterials 28
2.9. Metamaterial antennas 31
3. Metasurfaces: physics and applications 35
3.2. Metasurface fabrication and devices 38
3.3. Metasurfaces with simultaneous amplitude and phase modulations 42
3.4. Metasurfaces for polarization control 45
3.5. Metalenses: forging ahead towards applications 49
3.6. Metasurfaces for multi-functional edge imaging 52
3.7. Metasurfaces for holographic imaging 55
3.8. Active metasurfaces 59
3.9. Optical metasurface sensors 61
3.10. Geometric phase and nonlinear photonic metasurfaces 64
3.11. Resonant dielectric metasurfaces for nonlinear photonics 66
3.12. Nonlinear optical holography 69
3.13. Metasurfaces go to quantum 72
3.14. Ultrafast plasmonics 75
3.15. THz generation with metasurfaces 78
3.16. Broadband metasurfaces and applications 82
4. Spoof surface plasmonic systems 85
4.2. Spoof SPP transmission lines (TLs) 87
4.3. Passive spoof SPP devices and antennas 91
4.4. Active spoof surface plasmon (SP) devices 94
4.5. Spoof localized surface plasmons (SLSPs) 97
4.6. Spoof SPP circuit and system 100
5. Information metamaterials and metasurfaces 103
5.2. Field programmable metamaterials and metasurfaces 107
5.3. Information metasurfaces and Shannon entropy 109
5.4. Digital signal processing on information metasurfaces 112
5.5. Light-controlled programmable metasurfaces (PMSs) 115
5.6. Adaptive and smart metasurfaces 119
5.7. Programmable and smart wireless power transfer (WPT) 122
5.8. Metasurface-enabled intelligent electromagnetic (EM) sensing 125
6. Space-time modulated (STM) metamaterials and metasurfaces 127
6.2. Universal space-time modulated (STM) metamaterials for manipulating light 131
6.3. Time-modulated metamaterials 134
6.4. Time-domain digital coding metasurfaces 138
6.5. Space-time-coding (STC) digital metasurfaces 140
6.6. Programmable nonreciprocity via space-time metasurfaces 143
6.7. New-architecture wireless communication systems 147
6.8. Reconfigurable intelligent surfaces (RISs) and holographic massive MIMO transceivers for wireless communications and radar sensing 150
References 152

1. Introduction

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History and background

The flourishing area of electromagnetic (EM) metamaterials and metasurfaces has attracted significant interests for several decades. Early work can be traced back to 1968 when Victor G Veselago firstly presented the theory of negative refraction with negative permittivity and negative permeability [1]. Then in late 1990s, Sir John B Pendry proposed a methodology to realize the negative permittivity [2] and negative permeability [3] using periodically-arranged metallic wires and split-ring resonators in subwavelength scale, establishing the fundamental theory and experimental research of metamaterials [4, 5]. In the early-stage researches, the effective medium theories (EMTs) play an important role in describing the macroscopic properties of three-dimensional (3D) EM metamaterials, and diversely novel physical phenomena have been demonstrated, including the negative refraction, perfect lens and superlens, and invisibility cloaking. Therefore, the metamaterials characterized by EMTs are also called as effective medium metamaterials. Although there is a long history of the effective medium metamaterials, there are still ongoing scientific breakthroughs and emerging engineering applications nowadays.

Metasurface is an ultrathin version of the metamaterial consisting of a single or few layers of meta-atoms, which have been demonstrated with unprecedented capabilities in manipulating the EM waves and lights. By now, numerous functionalities have been realized, such as beam engineering, waveplates, polarizers, and holograms [6, 7]. Digital coding and programmable metamaterials and metasurfaces have been proposed to simplify the design process of metamaterials and metasurfaces, and to reach dynamic manipulations of EM waves in real time [8]. Most importantly, the digital coding representation bridges the physical science and information science, evolving the metamaterial/metasurface into a new platform that can be viewed as an information processor or system on the physical layer, namely as the information metamaterial or metasurface [9]. Space-time modulated (STM) metamaterials and metasurfaces are artificial structures with varied EM parameters in both space and time domains [10, 11]. Compared with the traditional designs that are spatially modulated only, the STM metamaterials and metasurfaces possess another degree of freedom (DOF) that empower various applications in manipulating the EM waves and fields, representing one of the most promising avenues towards the novel science and technology. These flexible and intelligent metamaterials and metasurfaces pave novel technical routes and promote revolutionary developments in imaging, sensing, communications, and even artificial intelligence (AI).

The area of plasmonics is always tightly related to the EM metamaterials, as they share similar EM concepts and methods [12]. These two fields merged into each other more deeply since the proposal of spoof surface plasmons (SPs) by Sir John Pendry in 2004 [13], which mimic the modal profiles and physical properties of the optical SPs in the microwave and terahertz frequencies using subwavelength artificial structures to construct the negative permittivity. The spoof SPs also benefit from the realization in ultrathin corrugated metallic strips [14], as they are compatible with the printed circuit boards (PCBs) and integrated circuit (IC) technologies. Since the propagating and localized spoof SPs were experimentally realized in PCBs in 2013 and 2014 [14, 15], this area flourishes with prospective applications emerging in microwave circuits, sensing, and wireless communications [16].

Roadmap organization and aim

In this Roadmap, leading experts from various significant branches of metamaterials and metasurfaces present comprehensive overviews of these branches and anticipate their prospective trends. The key areas of research and technology addressed in this roadmap include:

(1) **Effective medium metamaterials:** In section 2, Luo and Lai firstly introduce the EMTs for non-Hermitian metamaterials in 2.1. Wang, Lin, and Chen review the negative refraction in 2.2; while Chen and Wu discuss the perfect lens and superlens based on metamaterials in 2.3. Then in 2.4, Yin, Zhao, and Chen investigate the advances of transformation optics (TO), which provides precise control of the EM fields in an engineered physical space. In 2.5, Wegener introduces the challenges and recent advances of 3D metamaterials. In 2.6, Li, Zhou, and Engheta review the metamaterials with extreme parameters, especially the epsilon-near-zero (ENZ) metamaterials that have exhibited various potential

applications. In 2.7, Asadchy, Simovski, and Tretyakov review the roadmap of the chiral and bianisotropic metamaterials (BAMMs). In 2.8, Yang and Zhang introduce photonic topological metamaterials.

(2) **Metasurfaces—physics and applications:** In section 3, Sun and Zhou introduce the light-bending metasurfaces in both transmission and reflection configurations based on the generalized Snell's law in 3.1. In 3.2, Xu and Sun discuss the impact of advanced fabrication technologies on the realization of high-performance metasurfaces. Then in 3.3, Sun and Zhou review the complex-amplitude metasurfaces, which have been widely investigated for beam forming, Airy Beam generation, and meta-holograms. In 3.4, Zhou *et al* introduce the metasurface-assisted polarization optics, which provides a new platform to develop advanced optical devices with micrometer-scale footprint and unusual functionality. The real application advantages of the metalens technology are reviewed by Li and Zhu in 3.5. Zhou *et al* describe the metasurfaces for multi-functional edge imaging in 3.6. In 3.7, Zhang *et al* investigate the metasurfaces for holographic imaging, which offer an excellent tool to realize the holographic applications. In 3.8, Xiao discusses the active metasurfaces with tuning functions after fabrication, which are highly desirable and promising new platforms for sixth generation (6G) wireless communications, remote sensing, and radar applications. In 3.9, Liu and Zhang focus on introducing the metasurface biosensors. In 3.10, geometric phase-controlled nonlinear photonic metasurfaces are reviewed by Tang *et al*, exhibiting great flexibilities in controlling the phase, polarization, and amplitude of the generated nonlinear optical waves. In 3.11, Koshelev and Kivshar provide a brief summary of some of the observed effects in nonlinear optical metasurfaces. In 3.12, Li *et al* review the nonlinear metasurfaces, which can act as a novel platform to demonstrate marvelous nonlinear optical effects. In 3.13, Wang, Tsai, and Zhu overview the metasurfaces applied in photonic quantum technologies, which have provided a wide variety of advanced optical quantum devices in quantum source generation, quantum state manipulation, quantum information processing, and quantum detection and imaging. Bykov *et al* review the ultrafast plasmonic in 3.14, which has provided numerous unique functionalities and advantages for the designs and applications of metasurfaces and metamaterials. In 3.15, McDonnell and Ellenbogen introduce some demonstrations, which show great promise in achieving the sought-after functional controls required for wide variety of THz applications. Two metasurface structures with broadband properties are introduced by Luo *et al* in 3.16.

(3) **Spoof surface plasmonic systems:** In section 4, the basic physical principle and development of spoof surface plasmons (SSPs) are introduced and reviewed by Garcia-Vidal in 4.1. Then in 4.2, Liu and Li present the spoof SSP transmission lines (TLs) based on the ultrathin corrugated metallic strips. In 4.3, Tang and Ma review the passive SSP devices and SSP antennas in the microwave frequencies; while in 4.4, Zhang and Luo investigate active SSPs which allow dynamic tuning of the device functions or multi-frequency operations. In 4.5, Zhang and Cui discuss the field of spoof localized surface plasmons (SLSPs), emphasizing their applications in sensing and envisioning the future trends. In 4.6, Zhang, He and Zhang discussed the SSP applications in microwave circuits and wireless communication systems.

(4) **Information metamaterials and metasurfaces:** In section 5, the basic concept and mechanism of digital coding metamaterials and metasurfaces are presented by Cui in 5.1. Then Wan brings the introduction of field-programmable metamaterials and metasurfaces in 5.2. In 5.3, Wu investigates the working principle of information metasurfaces, especially from the perspective of Shannon entropy to characterize their capabilities in information processing. In 5.4, Liu and Cui further review the iconic theories of digital signal processing on information metasurfaces, including the convolution theorem, information entropy, and mathematical operations. In 5.5, Jiang *et al* explore light-controlled programmable metasurfaces (PMSs) that enable non-contact remote control by the driven light. In 5.6, Ma and Liu introduce the adaptive and smart metasurfaces, which integrate external sensors and embed intelligent algorithms to build feedback channels to realize smart control of EM waves. In 5.7, Li and Han discuss the application of metasurfaces in wireless power transfer (WPT), emphasizing the low-cost and high-efficiency property to facilitate the development of WPT. In 5.8, Li demonstrates the great potential of intelligent metasurfaces in EM sensing, which synergize metasurfaces and AI for wave and data manipulations respectively to obtain a better cost-performance index.

(5) **STM metamaterials and metasurfaces:** In section 6, Cotrufo and Alù review the nonlinearity-induced nonreciprocal metamaterials with bias-free designs and simplified fabrications in 6.1. Caloz *et al* investigate the STM metamaterials for light manipulations in 6.2, which is believed to be able to simultaneously manipulate the spatial and temporal spectra of lights in unprecedented fashions. In 6.3, Galiffi *et al* focus on the introduction of time-modulated metamaterials from both theoretical and experimental perspectives. In 6.4, Cheng *et al* provide the basic concept and working principles of time-domain digital coding metasurfaces, which opens up a novel branch of digital metasurface by applying the coding strategy in the time domain. Based on this, Zhang, Galdi, and Cui further elaborate

on the space-time-coding (STC) digital metasurfaces in 6.5, which enables spatial and spectral controls of EM waves by simple coding matrices. In 6.6, Galdi and Cui discuss the implementation of programmable nonreciprocity via the space-time metasurfaces. In 6.7, Dai, Cheng, and Cui demonstrate several prototypes of the new-architecture wireless communication systems based on the STC digital metasurfaces. In 6.8, Renzo discusses two promising application forms of the metasurface, i.e. reconfigurable intelligent surfaces (RISs) and holographic massive multiple-input multiple-output (MIMO) transceivers, in the fields of wireless communications and radar sensing.

Concluding remarks

From this roadmap, we are glad to see that big progresses have been achieved in the EM metamaterials and metasurfaces ranging from optics to microwaves. After decades of fast developments, the EM metamaterials and metasurfaces not only provide excellent platforms for EM-wave manipulations, but also bring out new disciplines for information sciences and communication technologies. The future for the EM metamaterials and metasurfaces looks bright, and there are exciting challenges and opportunities ahead from both fundamental sciences and engineering applications.

Acknowledgments

T J C acknowledges the supports from the Basic Scientific Center of Information Metamaterials of the National Natural Science Foundation of China (62288101), the National Key Research and Development Program of China (2017YFA0700201, 2017YFA0700202, and 2017YFA0700203), the Major Project of Natural Science Foundation of Jiangsu Province (BK20212002), and the National Natural Science Foundation of China for Basic Science Center of Information Metamaterials. A A acknowledges support from the Department of Defense, the National Science Foundation and the Simons Foundation.

2. Effective medium metamaterials

2.1. Effective medium theories (EMTs) for non-Hermitian metamaterials

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Status

EMTs are the cornerstone of the materials science. EMTs provide a simple and neat way to describe the macroscopic properties of a composite material by homogenizing it as an effective medium with a set of constitutive parameters such as effective permittivity and permeability. In the rising field of metamaterials and metasurfaces, the EMT plays the critical role from the beginning. Most of the novel wave phenomena bestowed by metamaterials and metasurfaces, such as negative refraction, super-lensing, cloaking, and generalized laws of refraction and reflection, can be characterized by the effective medium description. Generally, the criterion for the EMTs to be applicable is that the microstructures of metamaterials and metasurfaces are in the subwavelength scale, thereby minimizing the unwanted effects such as the diffraction, the Bragg scattering and the multipoles of higher orders, which could ruin the simple picture of an effective medium. So far, the EMTs have been successful in wide applications under this limit. However, with forthcoming revolutions in metamaterials involving spatial dispersions and non-Hermitian effects, there is urgent need to develop new forms of EMTs that can deal with such changes.

Current and future challenges

The EMTs for metamaterials were originally developed in the deep subwavelength limit. At this limit, the spatial dispersion is weak, and the description of effective medium is usually accurate even for complicated structures. When the frequency gets higher, the Bragg scattering leads to strong spatial dispersions, which would usually destroy the effective medium picture. Nevertheless, there are also some interesting exceptions. One exception is the zero-index materials whose wave vector is located at the Brillouin zone center at a certain frequency. The degeneracy of two different multipoles could lead to the formation of Dirac-like linear dispersions, which can be perfectly explained as the effective permittivity and permeability accidentally crossing zero at the same frequency. This physics has been recently exploited in a wide spectrum from microwaves [17] to optical frequencies [18, 19], and from two dimensions [17–19] to three dimensions [20, 21]. Another interesting exception is the metamaterial with 'shifted' dispersions. In such cases, the equal frequency contours at the working frequency are 'shifted' to the Brillouin zone edge. This shift in the k-space does not destroy the effective medium description, but only makes the effective parameters nonlocal. Remarkably, the impedance of such metamaterials with pure dielectric components can be omnidirectionally matched to that of free space [22], which is extremely challenging in traditional approaches.

When metamaterials become non-Hermitian, the previous EMTs may fail and a substantial extension is required. For instance, the rich physics of exceptional points (EPs) in general non-Hermitian systems has not been explored in the EMT previously. This indicates that the current EMT is limited and unsuitable for non-Hermitian systems. For another instance, the famous Maxwell–Garnett (MG) theory [23] could fail in the quasi-static limit when loss/gain constituents are included [24]. This breakdown of the MG theory is attributed to the existence of deep sub-wavelength evanescent fields induced by the inhomogeneity in the quasi-static limit. For transverse-magnetic (TM, out-of-plane magnetic fields) polarization, the MG theory gives the effective permittivity a d-dimensional model [25] as,

$$\frac{\varepsilon_{eff}-\varepsilon_h}{\varepsilon_{eff}+(d-1)\,\varepsilon_h}=\sum_i f_i\frac{\varepsilon_i-\varepsilon_h}{\varepsilon_i+(d-1)\,\varepsilon_h}, \tag{1}$$

where ε_i and f_i are the relative permittivity and filling ratio of the ith inclusion. ε_h is the relative permittivity of the dielectric host.

Equation (1) breaks down when tiny absorptive constituents are introduced. Due to the continuity of the displacement field, energy flux is redistributed when propagating waves (black arrows) encounter the inhomogeneities, as illustrated in figure 1(a). Such a flux redistribution is achieved by evanescent waves (red wavy arrows) in the deep subwavelength scale, which significantly change the local electric field distribution.

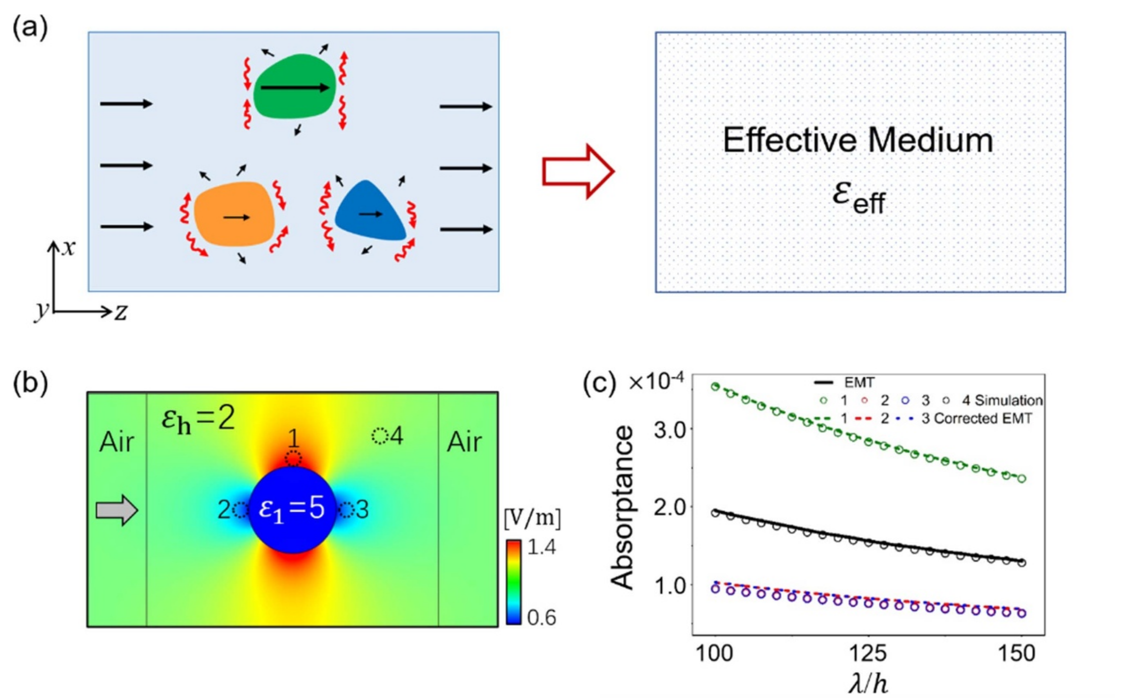

Figure 1. (a) Schematic of the evanescent waves induced by inhomogeneities at the deep subwavelength scale, which play a vital role in the effective medium description (right). (b) Simulated electric-field distribution in an example. The dashed circles denote the four positions of tiny absorptive components. (c) Absorptance as a function of wavelength obtained from simulation (dots), traditional MG theory (solid lines) and corrected MG theory (dashed lines), for a tiny absorptive component successively placed at the positions 1–4.

Consequently, dissipative component would experience drastically different local fields at different positions, leading to position-dependent absorption. The MG theory, which averages out the local evanescent fields, obviously fails to predict this position-dependent characteristic.

Advances in science and technology to meet challenges

To describe the position-dependent absorption, a corrected MG theory was developed [24]. For a metamaterial containing M large inclusions and M' tiny inclusions, the effective permittivity can be calculated based on the corrected formula as,

$$\frac{\varepsilon_{eff}-\varepsilon_h}{\varepsilon_{eff}+(d-1)\,\varepsilon_h}=\sum_i^M f_i\frac{\varepsilon_i-\varepsilon_h}{\varepsilon_i+(d-1)\,\varepsilon_h}+\sum_j^{M'} f_{aj}\frac{\beta_j^2\left(\varepsilon_{aj}-\varepsilon_h\right)}{d\varepsilon_h+\beta_j\left(\varepsilon_{aj}-\varepsilon_h\right)},\tag{2}$$

where β_j denotes the correction factor for the j-th additional tiny inclusion (relative permittivity ε_{aj}, filling ratio f_{aj}). Here, β_j is the ratio between the local and averaged fields that is evaluated through numerical simulation or analysis. Figure 1(c) shows that the results obtained from the corrected EMT (equation (2)) match well with the simulation results. In this way, the corrected EMT has managed to describe the position-dependent absorption which is clearly beyond the traditional MG theory.

Next, we demonstrate how to develop an EMT to describe the emergence of EPs in non-Hermitian metamaterials. Without loss of generality, we investigate the case of a ring of EPs arising near the Dirac-like point in the band diagram of a metamaterial with simultaneous zero effective permittivity and permeability, when loss/gain is introduced to the system [17]. This ring of EPs cannot be described by the traditional EMTs.

To describe this unique feature, a unique non-Hermitian EMT was proposed based on an extension to the complex frequency space [26]. Here, the effective permittivity and permittivity are both complex functions of the complex frequency, i.e. $\varepsilon(\omega)=\varepsilon_R(\omega)+i\varepsilon_I(\omega)$ and $\mu(\omega)=\mu_R(\omega)+i\mu_I(\omega)$ with $\omega=\omega_R+i\omega_I$. Considering a small frequency regime near the Dirac-like point, a linear relation between the effective parameters and frequency is assumed as:

$$\begin{cases}\varepsilon_R\left(\omega_R\right)=A_{\varepsilon_R}\times\left(\omega_R-\omega_{\varepsilon_R}\right),\\ \mu_R\left(\omega_R\right)=A_{\mu_R}\times\left(\omega_R-\omega_{\mu_R}\right),\\ \varepsilon_I\left(\omega_I\right)=A_{\varepsilon_I}\times\left(\omega_I-\omega_{\varepsilon_I}\right),\\ \mu_I\left(\omega_I\right)=A_{\mu_I}\times\left(\omega_I-\omega_{\mu_I}\right),\end{cases}\tag{3}$$

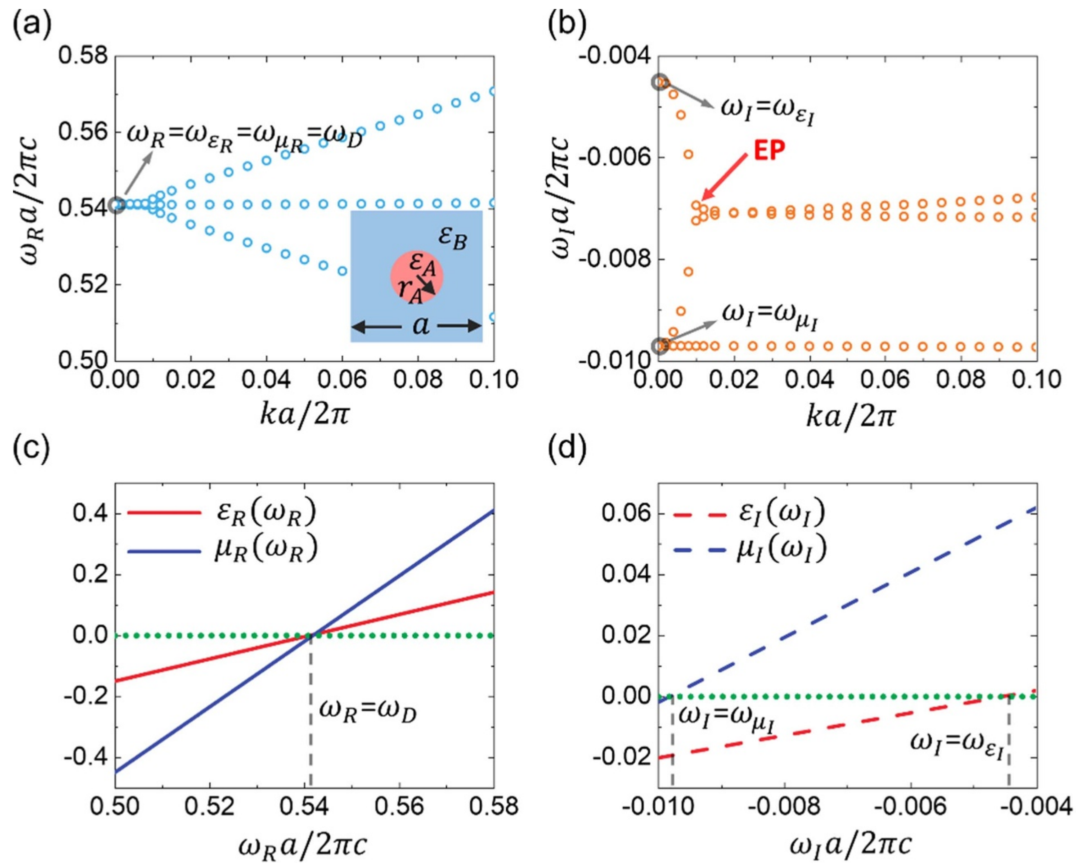

Figure 2. (a) Real and (b) imaginary parts of eigen-frequencies for given real Bloch wave vectors. The inset illustrates the unit cell of a metamaterial composed of a square array of cylindrical rods. (c) Real and (d) imaginary parts of the effective parameters.

where the coefficients A_{ε_R}, A_{μ_R}, A_{ε_I}, A_{μ_I}, ω_{ε_R}, ω_{μ_R}, ω_{ε_I} and ω_{μ_I} are constants. Interestingly, by setting $\omega_{\varepsilon_R} = \omega_{\mu_R} = \omega_D$ and $\omega_{\varepsilon_I} \neq \omega_{\mu_I}$, the ring of EPs can be immediately obtained from the dispersion relation. ω_D is the Dirac point frequency in absence of loss/gain.

Here, we show an example of such non-Hermitian metamaterials, which consists of a square array of dielectric cylindrical rods (relative permittivity $12.5 + 0.5i$, radius $0.2a$, a is the lattice constant). Figures 2(a) and (b) show the band structures in terms of ω_R and ω_I along the k_x direction for transverse-electric (TE, electric field along the rods) modes. A ring of EPs occurs at ω_D [27], inside which the ω_R has degenerate flat dispersions, while the ω_I splits into two branches. Outside the ring of EPs, the situations are just the opposite.

The effective parameters $\varepsilon(\omega)$ and $\mu(\omega)$ are calculated and plotted in figures 2(c) and (d) as functions of ω_R and ω_I, respectively. Clearly, we have $\omega_{\varepsilon_R} = \omega_{\mu_R} = \omega_D$ and $\omega_{\varepsilon_I} \neq \omega_{\mu_I}$, which are consistent with the non-Hermitian EMT. By further investigating the EMT, we find that complex Dirac-like cones occur for the case of $\omega_{\varepsilon_R} = \omega_{\mu_R} = \omega_D$ and $\omega_{\varepsilon_I} = \omega_{\mu_I}$. While a point of quadratic degeneracy occurs in the ω_I spectrum. This EMT also perfectly explains the existence of flat longitudinal bands in the band diagrams where $\mu(\omega) = 0$. In this way, the non-Hermitian metamaterial involving EPs can be well described by the EMT.

Concluding remarks

Through the above two examples, we have shown that despite the triumph of traditional EMTs in composites and metamaterials, they could fail when the system turns non-Hermitian, i.e. loss/gain is introduced. In order to describe the emerging new physics in non-Hermitian metamaterials such as position-dependent absorption and the EPs, the EMT must be corrected to take the local field distribution into consideration, or extended to the complex frequency domain. We note there are still unexplored and exciting possibilities to further interpret the interesting physics in non-Hermitian metamaterials via the EMTs, e.g. the coalescence of EPs [28] and the singularities like coherent perfect absorption and lasing [29].

Acknowledgments

National Key R&D Program of China (Grant Nos. 2020YFA0211300, 2017YFA0303702) National Natural Science Foundation of China (Grant Nos. 11 974176, 12174188), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

2.2. Negative refraction

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Status

In 1968, Vesalago predicted in his pioneering paper an exotic phenomenon of negative refraction (figure 3(a)) at the interface between free space and the so-called negative refractive index medium [30]. Remarkably, this negative-index medium is found applicable to build the perfect lens [31]. Distinct from conventional lens whose imaging resolution is always limited by the wavelength of light, the perfect lens is capable to focus all Fourier components of a point source, including evanescent waves. Therefore, the negative-index materials are of paramount importance for advanced imaging technologies with a resolution in the deep-subwavelength scale.

However, the construction of negative-index materials remains a long-standing challenge. The situation began to change only after the concept of metamaterials was proposed [4]. The metamaterial is typically composed of deep-subwavelength unit cells, which can be, for example, a combination of split ring resonators and metallic rods. The negative permeability occurs at the frequency above the resonant frequency of split-ring resonators, while the negative permittivity can be induced by inserting metallic rods into the unit cell [3]. This way, it is feasible to create a frequency band with a negative refractive index—the related permeability and permittivity are both negative—through the structural optimization.

In addition to negative-index materials, people found the negative refraction of light can be realized by exploiting, for example, the anisotropy in hyperbolic materials [32] (figure 3(b)), the chirality in chiral materials [33] (figure 3(c)), the nonlocality in photonic crystals, the phase gradient in metasurfaces [6] (figure 4), and moving media [34]. Remarkably, the negative refraction in hyperbolic metamaterials can be exploited for the design of hyper-lens with an enhanced imaging resolution. Meanwhile, the anomalous negative refraction from metasurfaces is promising for the design of planar metalens, critical to the integrated optics.

Moreover, negative refraction can also happen for surface waves [35], such as metal plasmons, spoof SPs, and graphene plasmons. Due to their highly squeezed wavelength down to the order of 1/100 wavelength of light in free space, surface waves can offer a disruptive way to control the flow of light information at the extreme nanoscale.

Perhaps even more important is that the analogous phenomenon of negative refraction exists in many other wave systems, such as acoustic, mechanical, elastic, and water waves. The topological negative refraction was recently reported in a Weyl phononic crystal; as a hallmark feature, all reflection is suppressed during this counterintutive refraction process [36].

Current and future challenges

Although metamaterials have demonstrated fascinating functionalities, there are still challenges in the design of negative-index metamaterials, as fundamentally restricted by fundamental laws of passivity and causality. To be specific, the dispersion of permittivity in lossless regions must follow the inequalities of $\partial\,\mathrm{Re}\left[\varepsilon\left(\omega\right)\right]/\,\partial\omega>0$ and $\partial\left(\omega\,\mathrm{Re}\left[\varepsilon\left(\omega\right)\right]\right)/\,\partial\omega>\varepsilon_0$. These inequalities indicate that materials with negative permittivity have a large positive dispersion. The same rule holds for the negative permeability. This fact fundamentally limits the bandwidth over which a negative refractive index can be obtained. Specifically, the creation of negative permeability in the visible range is still challenging mainly due to a finite electron density and hence a finite plasma frequency in metals. Mie resonances using displacement currents could be a potential route to realize the artificial magnetism. But the fabrication of high-permittivity materials in the visible regime remains challenging.

Energy efficiency is another key issue in the negative refraction. According to the Kramers–Kronig relation, the intrinsic loss of a material is inevitable, especially around the resonant frequency. Radiation loss significantly increases when the impedance of a metamaterial mismatches to that of the surrounding medium. A typical example is the low coupling efficiency between propagating waves in air and high-k states in hyperbolic metamaterials.

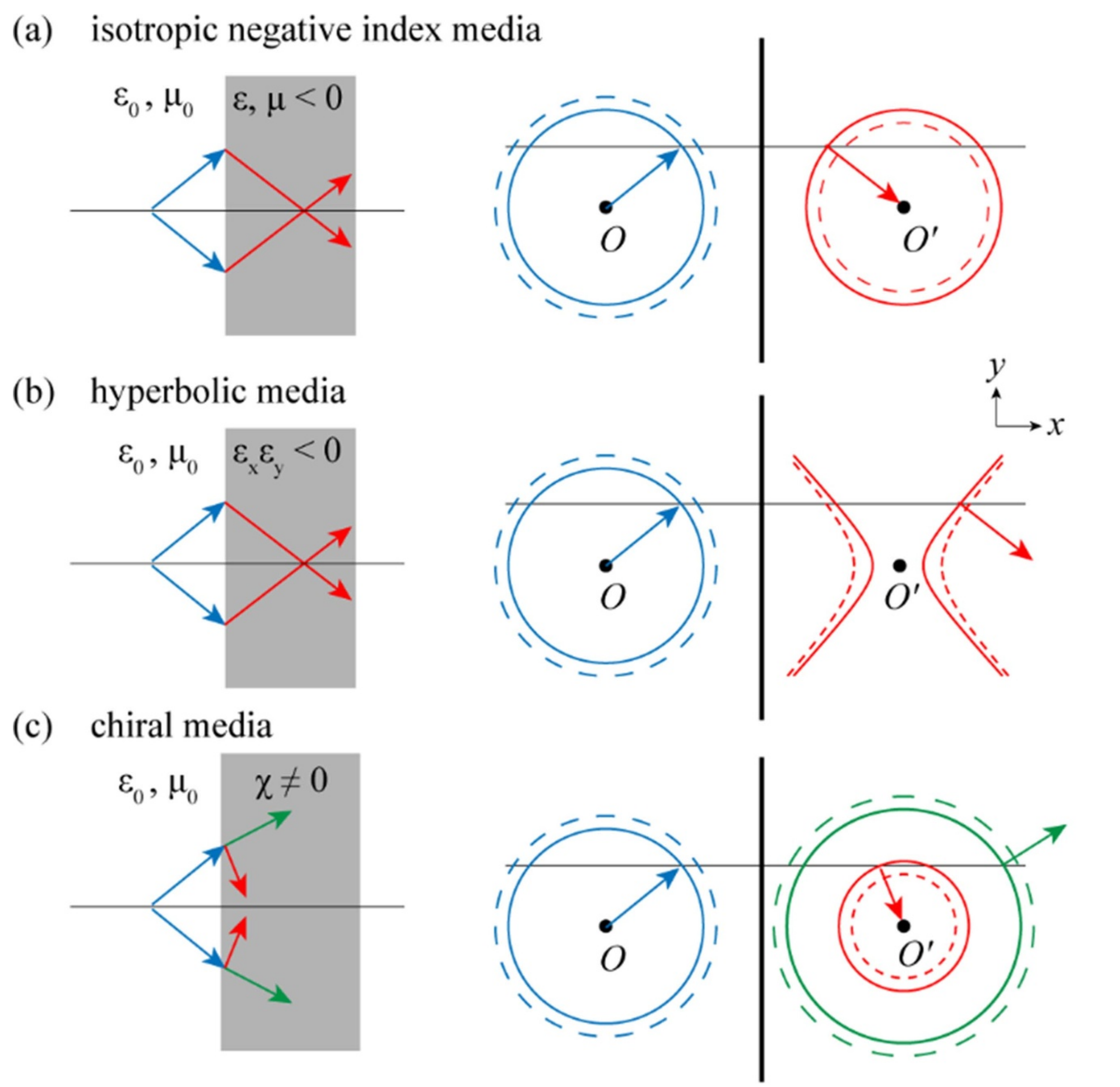

Figure 3. Conceptual representation of negative refraction in homogeneous media. (a) Isotropic negative-index media. (b) Hyperbolic media. (c) Chiral media. Solid and dashed isofrequency contours refer to smaller and larger frequencies, respectively.

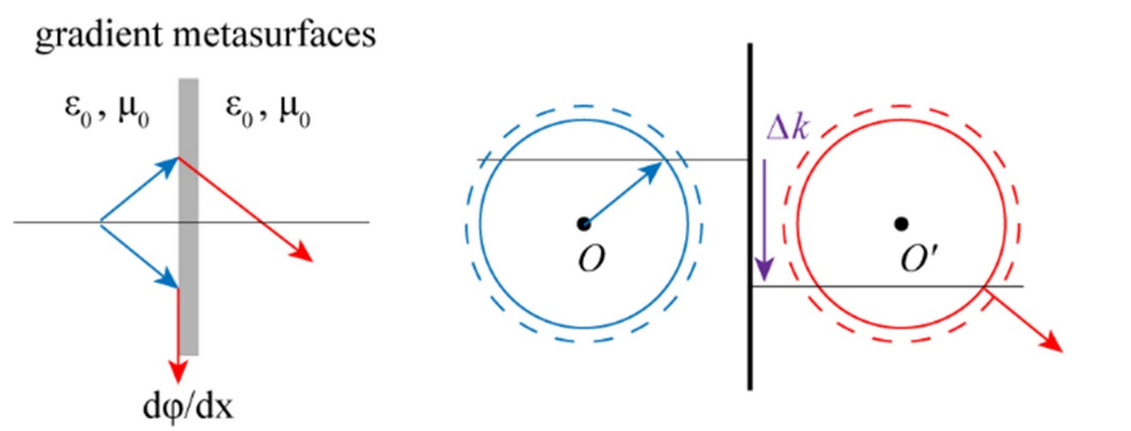

Figure 4. Negative refraction by gradient metasurfaces. Inhomogeneous metasurfaces introduce an transverse wave vector $\Delta k \propto d\varphi/dx$ to deflect the refraction angle at the interface.

Isotropic materials that exhibit the negative refractive index remain challenging due to the fabrication difficulties associated with combining electric and magnetic resonators into a single medium. A dilemma is that the isotropy requires bulk structures occupied with more resonators to realize negative refraction in all directions, whereas more resonators in each unit usually bring additional losses. Especially for high-frequency scenarios, the surface roughness can further increase the scattering loss in 3D nanostructures.

Different from natural materials, the nonlocality can be flexibly engineered in metamaterials, bringing a material response related to the wavenumber, i.e. $\vec{D}(\vec{k}) = \varepsilon(\vec{k})\vec{E}(\vec{k})$. Versatile control over the spatial dispersion, whether it is eliminated or enhanced, is still in its infancy and worthy of in-depth study. Some successful attempts have demonstrated improved efficiencies in light refraction assisted by bianisotropy or nonlocal effects. Since the first appearance, negative-index metamaterials have been at a center of lively debate. A big challenge is the application of metamaterials, and in particular, how to use the unique properties of negative refraction and avoid their shortcomings.

Advances in science and technology to meet challenges

New mechanism to create the negative refraction can be found in artificial structures with nontrivial band topology. The boundaries of Weyl metamaterials host one-way gapless surface waves and forbid the interfacial reflection due to the open nature of equifrequency contours [36]. Veselago's lensing has recently been observed in Weyl metacrystals at a point below the Weyl frequency, and demonstrated robust to disorders and intrinsic losses. However, negative refraction of evanescent waves is restricted by the lattice constant, and elaborately designed structures with deep subwavelength needs further exploitation. Introduction of active materials, time-varying modulation and nonlinear process is a notable route that can break the fundamental physical limits in ordinary materials.

Improved fabrication techniques are urgently needed to overcome the drawbacks of current negative index metamaterials. The 3D structures with less materials yet larger volumes can significantly reduce the intrinsic loss. Development of 3D printing techniques is promising to tackle some of the challenges associated with isotropic metamaterials. Structural mechanics should be taken into consideration when the filling ratio of vacuum approaches the limit of unity. Fabrication methods for multi-layered and multi-material structures would be of great importance to take the advantages of different materials, leading to improved performance in bandwidth and loss.

Despite the recent advancement in nanotechnology and the fabrication of layered van der Waals heterostructures, the experimental observation of negative refraction for highly squeezed graphene plasmons remains elusive. On the other hand, the scattering of surface waves into the propagating waves is oftentimes significant during the refraction process of surface waves. Actually, the scattering-free plasmonic optics has not been experimentally demonstrated yet, not to mention the creation of scattering-free negative refraction for surface waves, a phenomenon that is highly sought after in the context of plasmonic circuitry.

Concluding remarks

The past decades have witnessed a rapid development of negative refraction in metamaterials and metasurfaces. We have briefly reviewed the history and status of negative refraction, discussed the remaining limitations in bandwidth and loss, and future possibilities to meet challenges. Despite considerable challenges still exist, we expect that advances in fabrication techniques and remarkable properties in new materials can promote negative refraction into practical applications.

Acknowledgments

This work at Zhejiang University was partly sponsored by the National Natural Science Foundation of China (NSFC) under Grant Nos. 61625502, 11961141010, 61975176, 62175212 and 62171407, the Top-Notch Young Talents Program of China, the Fundamental Research Funds for the Central Universities (2021FZZX001-19), and Zhejiang University Global Partnership Fund.

2.3. Perfect lens and superlens

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Status

The conventional optical imaging system suffers the diffraction limitation because evanescent waves, which carry detailed sub-wavelength spatial information of an object, will exponentially decay in space and cannot be collected at the image plane. As a consequence, the spatial resolution of a microscope cannot be smaller than $0.61\lambda/\mathrm{NA}$, where λ is the wavelength of light and NA is the numerical aperture of the microscope [37]. Due to promising applications such as in real-time bimolecular imaging and nanolithography, breaking the diffraction limitation is persistently desired for the super-resolution optical imaging systems.

The first milestone was the theoretical work by Pendry in 2000 [31]. He shows the left-handed material, first proposed by Vesolago in 1968, can amplify the evanescent waves and cancels the decay of evanescent waves in the space outside of the material. The lens implemented by such material can catch both propagating and evanescent without missing any sub-wavelength spatial information of objects. Therefore, the image of an object can be perfectly reconstructed by the lens, the perfect lens. Later, super-resolution imaging was experimentally demonstrated by a silver film lens [38]. The experimental work indicates that the imaging quality of the lens is affected by the loss of negative index materials, but still achieves a sub-wavelength spatial resolution, so the lens is called superlens.

Superlens can be near-field or far-field. The superlens proposed by Pendry is a near-field one, which just enhances evanescent waves but does not convert them to propagating waves (figure 5(a)). Zhang *et al* realized a far-field superlens by deploying a coupling element with the periodic structure to convert evanescent waves to propagating waves after they leave the lens [39] (figure 5(b)). Furthermore, Zhang's group utilized a multi-layered Al/Al2O3 structure to demonstrate hyperbolic superlens for far-field sub-diffraction-limited imaging. In such hyperbolic superlens, evanescent waves can be converted to propagating waves in the multi-layered structure [32] (figure 5(c)).

Though the superlens has a two-decade long story, it is continuing to be studied driven by the various possible applications to improve the focusing performances by means of lowering loss, expanding working band, and by materials other than negative index material. Not limited to EM waves, the study has been extended to other classical wave imaging, for example, acoustic waves and elastic waves [40].

Current and future challenges

Negative index materials-based superlenses have been proven to overcome the diffraction limitation and many prototypes of superlenses have been proposed from radio frequency (RF) to x-ray in the past two decades [37]. Nonetheless, there remain several practical challenges that hold engineering applications of superlenses.

The main challenge is the material loss of the superlens, which will significantly limit both the resolution and the imaging quality of objects. The narrow working frequency band is another challenge of the superlens. Due to the negative index usually resulting from the resonance of meta-atoms, the low loss negative index is inevitable to be a very narrow frequency band. The complex fabrication process is also a big challenge to superlenses. Defects engendered by the complex fabrication will further aggravate the imaging performances. Meanwhile, the fancy fabrication process for a complex nanostructure usually requires a high cost.

Advances in science and technology to meet challenges

Replacing plasmonic materials with dielectrics is a feasible approach to eliminate the negative effects of loss to the superlens. A breakthrough is the work of Luo *et al*, in which they demonstrated the sub-wavelength imaging effect in photonic crystals made of the dielectric slab with a 2D periodic array of air holes [41] (figure 6(a)). Inspired by their work, superlenses based on photonic crystal slabs have been experimentally demonstrated from microwave to visible light bands.

Introducing multiple resonances can regulate the dispersion properties of metamaterials and achieve a broad bandwidth with specific responses. Gao *et al* deployed a multiple resonant structure to implement a superlens at the microwave band, which can achieve certain bandwidth for sub-wavelength imaging [42] (figure 6(b)).

Some new mechanisms or specific configurations have been introduced into the superlens. One of the important advances is the microsphere-based superlens. The dielectric microsphere works as a 'photonic nanojet' which enhances the near-field illumination as well as converts evanescent waves to magnified propagating waves [43] (figure 6(c)). The microsphere fricated by high-index materials is improved as a

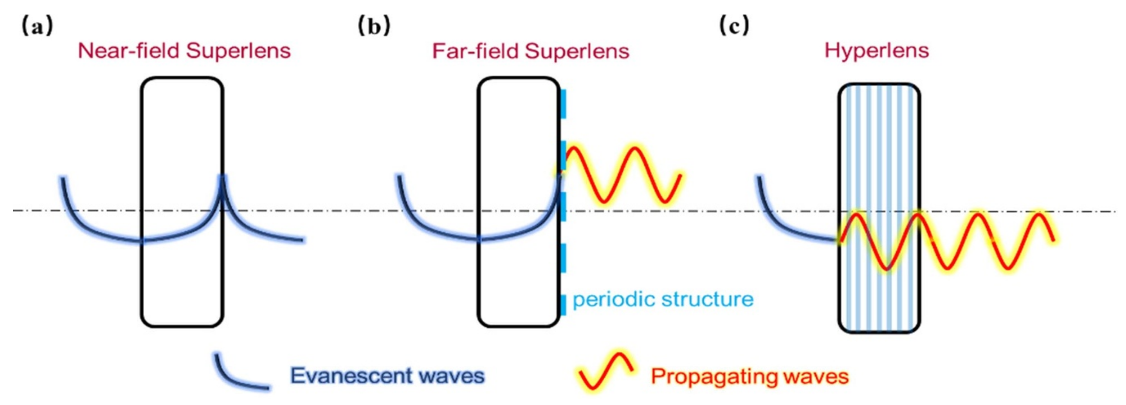

Figure 5. Schematic diagram of the impacts on the evanescent waves by various superlenses. (a) Near-field superlens. (b) Far-field superlens. (c) Hyperlens.

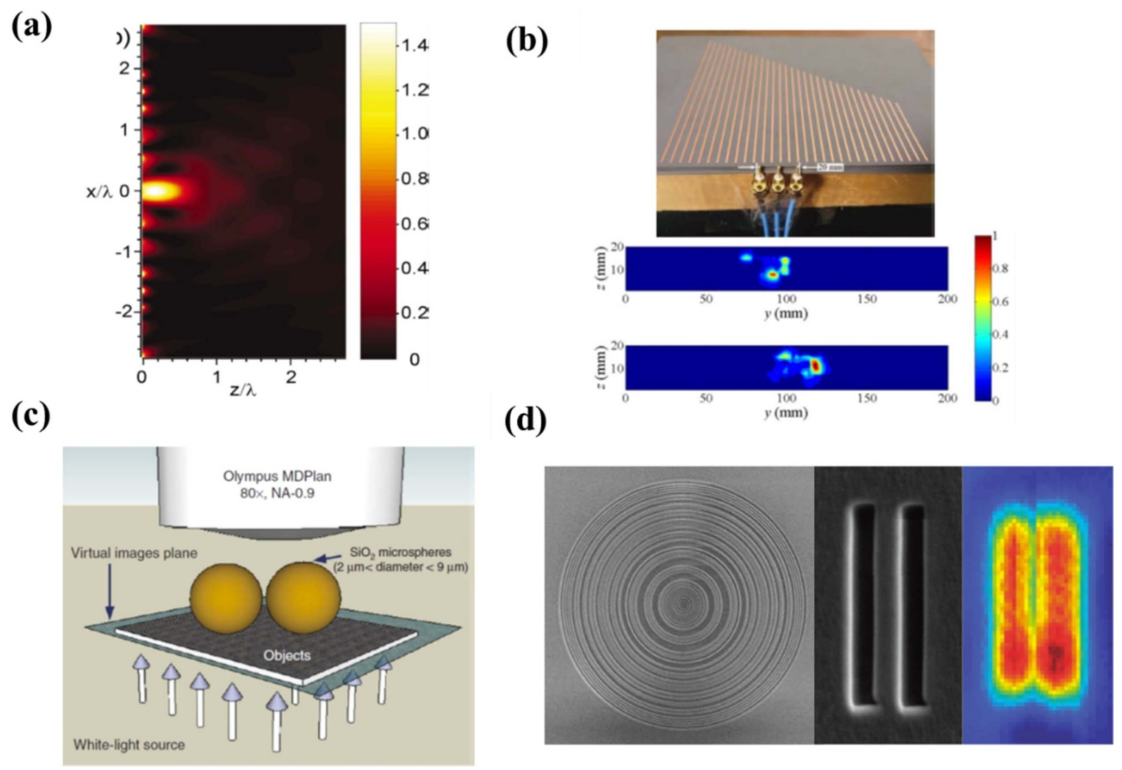

Figure 6. (a) The sub-wavelength imaging in a dielectric photonic crystal [41]. Reprinted with permission from [41], Copyright (2003) by the American Physical Society. (b) Multi-frequency far-field superlens and sub-wavelength imaging results at different frequencies (1.23 GHz at above and 1.43 GHz at below) [42]. © [2015] IEEE. Reprinted, with permission, from [42]. (c) Experimental configuration of white-light microsphere nanoscope with $\lambda/8$–$\lambda/14$ imaging resolution [43]. Reproduced from [43], with permission from Springer Nature. (d) SEM image of the super-oscillatory lens (SOLs), a 112 nm slit and its SOL image at $\lambda = 640$ nm [44]. Reproduced from [44], with permission from Springer Nature.

simple yet effective way to achieve super-resolution imaging. Another important advance was proposed by Rogers *et al*, in which they demonstrated far-field metamaterial superlens based on the super-oscillatory phenomenon [44] (figure 6(d)).

More recent works about improving superlens performances can be found in journals, and they are not cited here due to space limitations in this paper.

Concluding remarks

The evanescent wave amplification of negative index metamaterial provides light imaging a revolutionary opportunity to overcome the diffraction limitation. In the past two decades, we witness a fast and stirring development of the perfect and superlens, which are still active and have been extended to other classical waves. Superlens is continually improving its performance and tends to cooperate with other imaging technologies. While there still exist some practical challenges to be overcome, we expect that the steady progress in mechanism, material, configuration scheme, and fabrication technology, leads to a promising prospect for the future of superlenses.

Acknowledgments

This work is supported by National Natural Science Foundation of China (NSFC) (61771237) and partially by the Fundamental Research Funds for the Central Universities and Jiangsu Key Laboratory of Advanced Technique for Manipulating Electromagnetic Waves.

2.4. Transformation optics (TO)

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Status

TO [5, 45] is similar to general relativity (GR). In TO, the equivalence between properties of materials and metric properties of space is set up, while in GR, mass-energy tensors and metric properties of space are equivalent to each other. The rise of TO gives us a new paradigm for science of light, where we can design arbitrary flow of light in space based on the form invariance of Maxwell's equations under coordinate transformations, and to precisely control the EM field in an engineered physical space, as illustrated in figures 7(a)–(d). Furthermore, this new paradigm is not limited to optics and EMs, and has been extended to other wave dynamic systems, such as acoustic or sound waves, elastic waves, water waves, and thermodynamics [46]. Besides, TO has also shown extraordinary abilities in talking with GR and astronomy, such as mimicking the fascinating phenomenon in universe that are challenging to observe, and helps to investigate complex celestial behaviors. The intersection of them may give more possibilities for the development of both two fields, forming a new direction, such as transformation astronomy or transformation cosmology.

Under the guidance of TO methods, researchers have designed many novel devices, and realized them by engineered metamaterials in a wide range of physical systems. However, most of them are only proof-of-principle demonstrations, except for TO antennas [47] in communication systems. The designed TO antennas show excellent performance than traditional ones, such as high gain and large radiation angles, which is important in 5G and the forthcoming 6G wireless communication systems. Besides, TO devices have shown many potential applications in other fields, such as calming water waves in ports. With the continuous development in these fields, TO is coming to have a wider range of applications in future.

Current and future challenges

Most TO devices are proposed theoretically in the beginning due to the lengthy process of discovering and acquiring the necessary materials. For the well-known anomalous optical phenomenon, negative refraction, it has taken several decades before realizing it experimentally. Besides, the realization of the invisible gateway [48], one kind of TO devices from the scientific fiction, also spends more than a decade, as shown in figure 7(e). Such devices require negative EM parameters and specific design methods as well, thus hindering the development of TO experimental realization.

On the other hand, most TO devices are implemented at low frequencies by utilizing metamaterials. When it comes to optical frequency regime, it will be very challenging to fabricate macroscope devices with nano-scale unit structures. However, we have several attempts to overcome these difficulties. For example, with the aid of conformal mapping, an optical TO device can be realized by a gradient-index waveguide [49], as shown in figure 7(f). Self-focusing property for geometry optics and Talbot effect for wave optics are both demonstrated experimentally. Such a one-dimensional device is easy to fabricate and shows extraordinary ability in photon controlling applications. Besides, TO devices have also shown potential abilities in on-chip applications, such as on-chip multimode routing and communication systems. These devices have better performance than traditional ones due to the aberration-free imaging properties of Maxwell's fish-eye lens and special design based on conformal mapping. However, further efforts from the aspects of science and technology are both needed to push forward the applications of TO.

Advances in science and technology to meet challenges

TO devices usually require extreme material parameters that go beyond natural materials, and most of them are implemented by metamaterials. In recent years, with the continuous development of two-dimensional (2D) materials, some landmark phenomena have also been discovered, such as the discovery of magic angles in bilayer graphene, which may realize topological superconductivity. Inspired by this, some novel natural materials, such as α phase molybdenum trioxide (α-MoO_3), were utilized to realize bilayer twisted photonic system [50], as shown in figure 8(a), and the tuneable topological transitions from hyperbolic dispersion to elliptical dispersion was observed around the photonic magic twist angle. Moreover, such topological transition was also observed in bulk calcite by controlling angle of the optic axis, and another exotic phenomenon, ghost phonon polaritons, which exhibit bi-state nature, being both propagating and evanescent within the crystal, was observed at the same time [51], as shown in figure 8(b) (this phenomenon was actually also theoretically proposed with the help of TO years ago, called conjugate metamaterials and the related non-Hermitian optical interfaces). These devices based on natural material properties exhibit

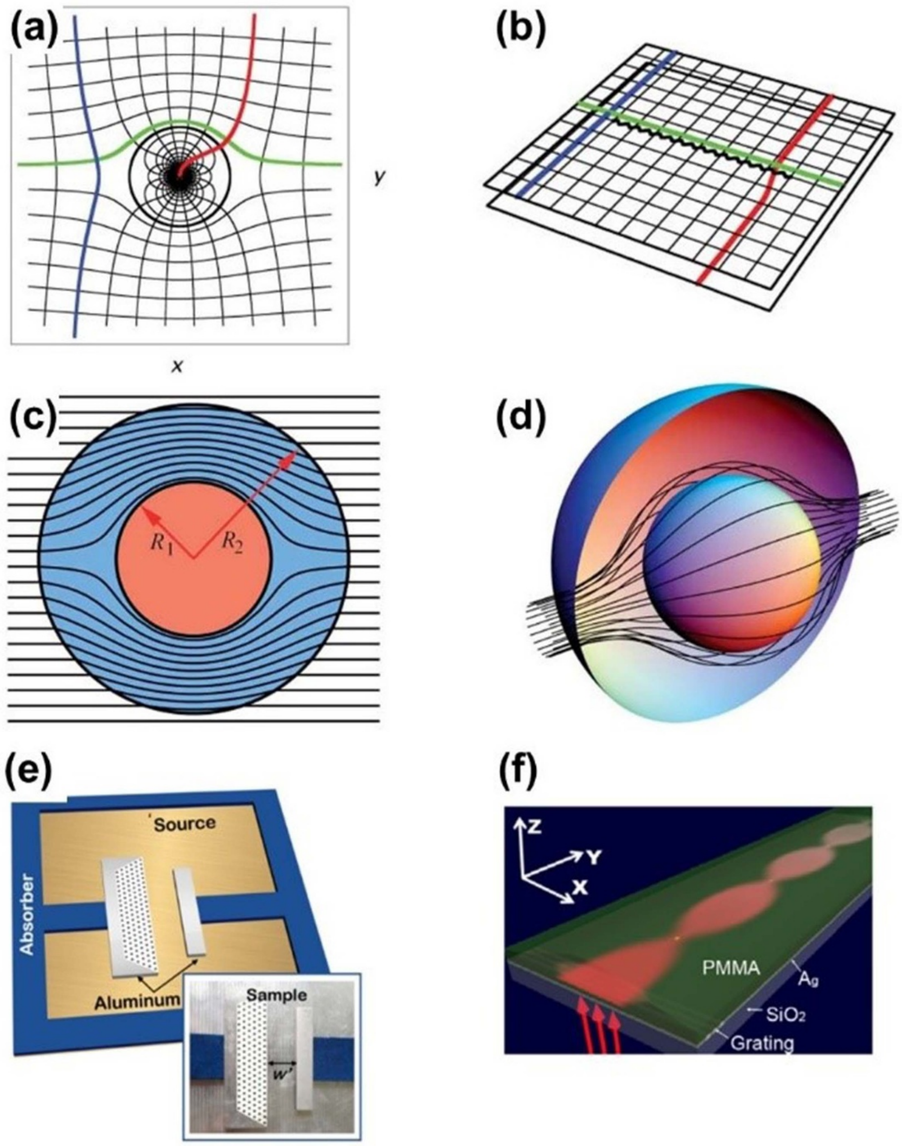

Figure 7. (a), (b) Schematics of optical conformal mapping. From [45]. Reprinted with permission from AAAS. (c) Ray-tracing of a two-dimensional cloak and (d) a three-dimensional cloak. From [5]. Reprinted with permission from AAAS. (e) The invisible gateway formed by the superscatterer and a metal block. Reprinted with permission from [48], Copyright (2021) by the American Physical Society. (f) A self-focusing TO device. Reprinted with permission from [49], Copyright (2017) by the American Physical Society.

many intriguing phenomena, which is beyond metamaterials and the intersection of novel materials and TO may induce new discoveries in the coming future.

Most traditional TO devices are passive. Once the device is designed, it cannot be changed. Therefore, the performance of the device is significantly limited in applications. An effective approach is to incorporate adjustable units to replace conventional fixed units, thereby enabling the realization of active devices. In this way, when combined with AI technology, various TO devices can be more powerful after training. For example, figure 8(c) shows a self-adaptive cloak, which can realize real time cloaking in a bumpy background without human intervention [52]. This makes TO has potential applications in radar systems. Besides, creatures in nature have amazing abilities far beyond our imagination, such as toothed whales, which can easily manipulate directional beams by deforming their foreheads. Inspired by this, we can build an efficient acoustic steering device based on conformal mapping [53]. This shows potential applications in underwater acoustics. Many other bioinspired TO devices, such as from cats' eyes or bats' noses, are highly anticipated.

Finally, diffraction limit has always been a huge obstacle for subwavelength imaging. It is also one of the most challenging scientific questions nowadays. Some imaging devices based on TO approaches, such as perfect lens, hyper lens, have shown latent abilities to overcome the difficulties but performed badly when loss is considered. Besides, perfect imaging in Maxwell's fish-eye lens (MFEL) with a drain assistance has also

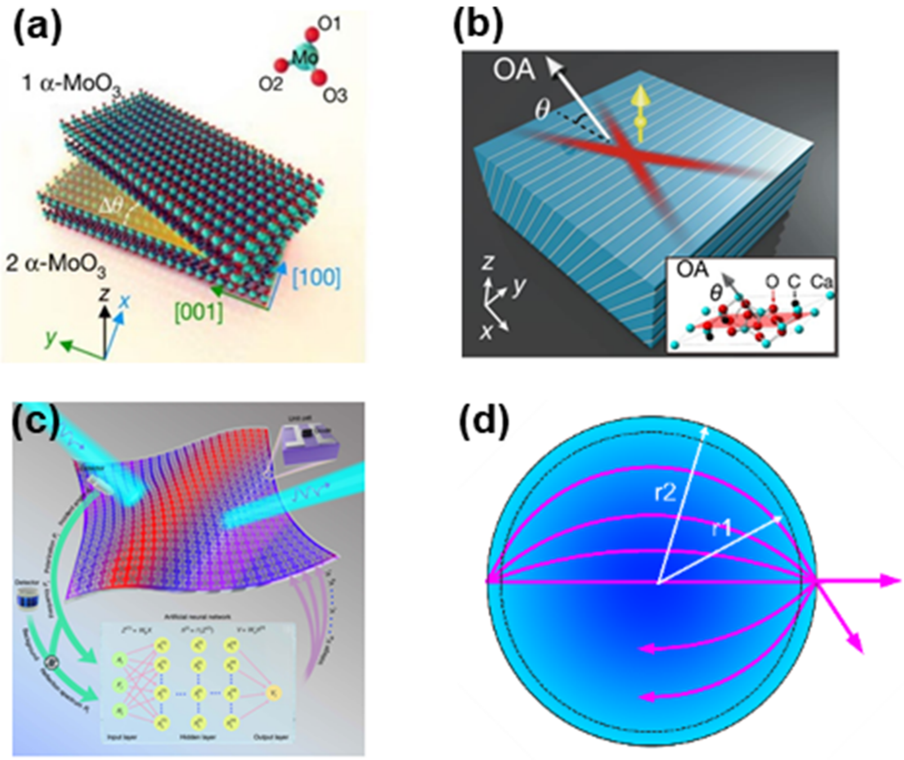

Figure 8. (a) Twisted α-MoO_3 bilayers. Reproduced from [50], with permission from Springer Nature. (b) Ghost hyperbolic polaritons in a bulk crystal of calcite. Reproduced from [51], with permission from Springer Nature. (c) Schematic of a self-adaptive metasurface cloak. Reproduced from [52], with permission from Springer Nature. (d) A solid immersion MFEL. Reprinted with permission from [54], Copyright (2022) by the American Physical Society.

been proposed as a potential candidate, although it has been subject to intense debate. Interestingly, when introducing additional boundary into a truncated MFEL inspired by the solid immersion lens, as shown in figure 8(d), the super-resolution imaging will be achieved without a drain. The images are formed in the air background due to the perfect focusing and total reflection at the outer interface. It might be more surprising to replace such a boundary with structured metasurfaces or 2D materials. This may open a new approach for the fields of TO and metasurfaces, where the interaction between them will lead to a good development for perfect lens.

Concluding remarks

The development of TO has slowed down over the years, but it still has great importance on theoretical design, material science, and fabrication technology. The powerful theoretical methods of TO make it applicable to most wave systems, and can also be combined with other advanced technologies, such as AI and bioinspired technologies. Besides, some natural materials in combination with TO may open a new field for researchers. So far, the biggest technical challenges of TO rely on two aspects: one is to further extend TO to other multi-physics systems; the other is to perfectly realize theoretical designs in experiments, which require the development of material fabrication technology. When these become possible, TO, as an approach, will leave its unique mark on physics and mathematics, and applications based on it like sensing, computing, and imaging will have a disruptive impact on traditional devices. For sure, these need constant efforts for all of us.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (Grant No. 2020YFA0710100), the National Science Foundation of China (Grant No. 92050102), and the Fundamental Research Funds for the Central Universities (Grant No. 20720220033).

2.5. 3D metamaterials

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Status

About two decades ago, the field of metamaterials took off with the idea of rationally designing and making artificial materials with effective EM, optical, elastic, acoustic, or thermodynamic properties that go beyond those of their ingredients, qualitatively and/or quantitatively [55, 56]. In the broader field of materials science as well as for laypersons, the notion 'material' is connected to 3D structures. In this sense, metamaterials are 3D micro- or nanostructures, the design as well as the making of which poses severe challenges up to date. This is especially true for 3D optical metamaterials operating at visible frequencies, where the wavelength is as small as some hundreds of nanometers [56, 57].

On this basis, starting about a decade ago, the idea of optical metasurfaces emerged. Metasurfaces are 2D or quasi-2D structures. It has been argued that metasurfaces are easier to manufacture using technologies established in microelectronics, bringing real-world applications in reach on a much shorter timescale compared to 3D metamaterials. While this reasoning makes sense, one should be clear that 2D structures conceptually offer only a subset of the possibilities that 3D structures do. In fact, at many points in the field of metasurfaces, the design freedom of strictly 2D structures is not sufficient. Hence, researchers start considering non-planar architectures, thereby making the transition from metasurfaces to metamaterials.

Progress in the field of 3D metamaterials has been closely linked to progress in 3D manufacturing of micro- and nanostructures, especially to 3D additive manufacturing. The connection between 3D metamaterials and 3D additive manufacturing is bidirectional. The first and obvious connection is that 3D additive manufacturing provides a versatile tool to realize complex 3D metamaterials. Second, 3D metamaterials might become the 'meta-inks' of future 3D printers. Let us illustrate this statement by the analogy to 2D graphical printers, e.g. ink-jet printers. Here, three different ink cartridges (cyan, yellow, magenta) allow for thousands of effective colors. This flexibility is achieved by printing rather complex microstructured dot patterns, a process sometimes referred to as 'dithering'. The human eye averages over these microstructured dot patterns and perceives a homogeneous effective color. By analogy, a small number of material cartridges in 3D printing might allow for realizing many different effective EM, optical, elastic, acoustic, or thermodynamic properties [56, 58]. Therefore, we here assume a broader viewpoint, not limited to just EM and optical 3D metamaterials. Figure 9 illustrates an example.

Current and future challenges

Let us divide the current and future challenges into three parts.

First, novel interesting and relevant effective 3D metamaterial behaviors need to be identified. Here, human creativity is needed. Concerning EM and optical behaviors, I should like to refer the reader to the other sections in this roadmap that emphasize this aspect. However, as pointed out above, it is also interesting to think beyond ('meta') electromagnetism. For example, the idea of bi-anisotropic optical metamaterials, which generally includes chiral effects as well as non-reciprocal effects, has been carried over to elasticity [56, 59, 60], where Eringen micropolar elasticity serves as a suitable effective-medium description.

Second, the so-called inverse problem remains challenging: Today, for most EM, elastic, and other 3D metamaterial structures, it is possible to compute the metamaterial behavior on the basis of a given microstructure with reasonable numerical effort, often by using commercially available software packages. However, the inverse of this forward problem is far more demanding. Here, a user defines a set of wanted effective material properties. The task of the inverse problem is to find the 3D micro- or nanostructure that provides these target properties. While topology optimization (see references in [56]) has solved the inverse problem for a variety of particular cases, it is often still numerically demanding for 3D problems. Moreover, topology optimization needs considerable numerical effort in each case. Machine-learning approaches, which are conceptually distinct, are currently emerging in materials science [62]. While a huge computational overhead may be needed for training neuronal networks for a certain class of metamaterial problems, each particular problem can thereafter be solved by the user in essentially zero time. Progress in this field is rapid. However, not even the general inverse problem for 3D Cauchy elasticity (the counterpart of dielectrics in electromagnetism) has been solved to date.

Third, once a 3D metamaterial structure has been designed, it still needs to be manufactured, e.g. by 3D additive manufacturing. The challenges are to achieve finer features (i.e. better spatial resolution) in 3D printing [63], make 3D printing faster and scalable [61], allow for more dissimilar ingredient materials [64], and to 'democratize' 3D printing by making 3D printers more affordable. An up-to-date overview on various

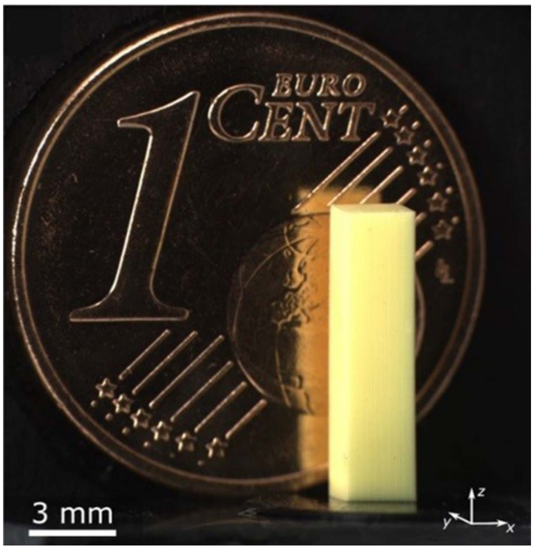

Figure 9. Photograph of a 3D chiral elastic metamaterial containing more than 105 3D unit cells and more than 3 × 109 voxels. A Euro cent coin serves for reference. [61] John Wiley & Sons. © 2020 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

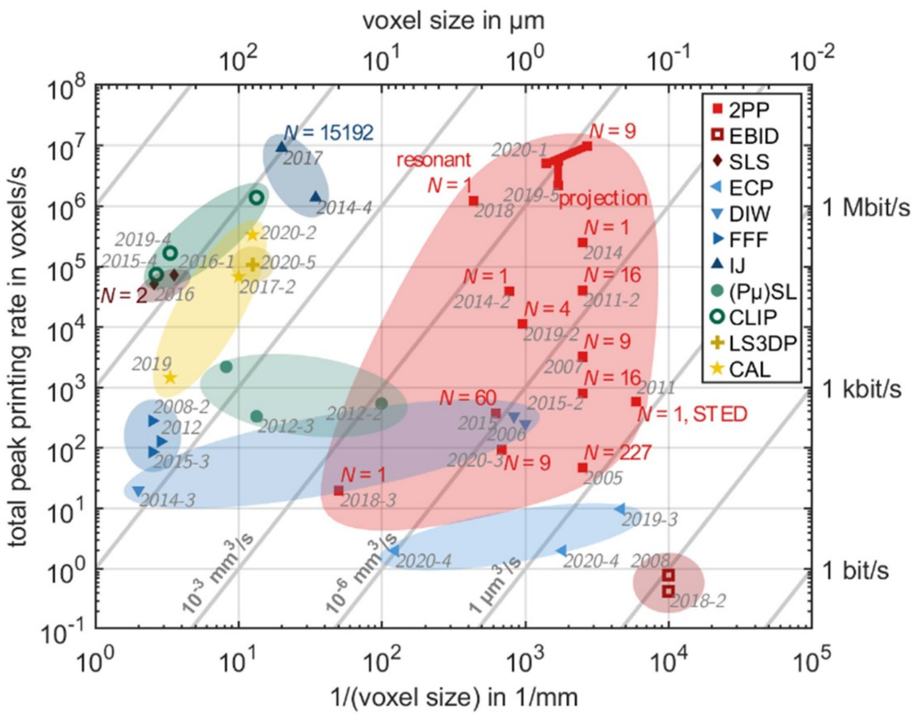

Figure 10. Comparison of 3D additive manufacturing approaches suitable for making 3D metamaterials in terms of 3D printing rate and voxel size. [61] John Wiley & Sons. © 2020 The Authors. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

3D printing technologies in terms of printing rate and voxel size is given in figure 10 (also see https://3dprintingspeed.com/#top). Obviously, two-photon based 3D laser printing (2PP) approaches are very attractive.

Advances in science and technology to meet challenges

In the future, all three parts of the previous section need to be addressed to advance the science and technology of 3D metamaterials. Being an experimentalist, I should like to emphasize the third part, the technology for making 3D metamaterials, in what follows.

I believe it is fair to say that multi-photon based 3D additive manufacturing approaches (cf. figure 10) are currently leading in regard to realizing complex micro- or nanostructured 3D metamaterials [56–61, 63, 64].

However, to make the step from prototype fabrication for academia to mass manufacturing for commercial applications, any 3D additive manufacturing approach faces the issue of manufacturing speed. To allow for comparing between technologies that may have vastly different voxel sizes and hence vastly different voxel volumes, the printing speed needs to be expressed in terms of the number of voxels printed per unit time. Current best values are in the range of 107 voxels s^{-1} [61] (see figure 10). For comparison, standard 2D graphical ink-jet printers operate around 107 pixels s^{-1}. Nevertheless, the making of a single 3D metamaterial containing more than hundred thousand complex 3D unit cells or several hundreds of billions of voxels may still take more than one day [61]—which is not likely to be acceptable for mass manufacturing. Using either a yet larger number of laser foci that are scanned in parallel [61] or using parallelized light-sheet 3D laser printing [58] appear as attractive future avenues. Finally, replacing two-photon absorption by two-step absorption (unpublished) allows for replacing expensive and bulky femtosecond lasers, that are required for making two-photon absorption efficient, by inexpensive (few Euro) and extremely compact (few mm^3) continuous-wave semiconductor laser diodes. The 3D laser nanoprinters based thereupon may become as small and ubiquitous as graphical ink-jet printers are today.

Concluding remarks

The field of 3D structures and 3D metamaterials contains 2D structures and 2D metamaterials (metasurfaces) as special cases. However, design and manufacturing are more demanding in 3D compared to 2D. In recent years, laser-based 3D additive manufacturing has made dramatic progress [56, 58, 64]. In my view, 3D manufacturing will eventually make the difference and decide whether 3D metamaterials will enter our every-day life or not. Applications may go beyond ('meta') electromagnetism and optics. For example, major sports shoe manufacturers are already selling shoes with 3D printed shoe soles that comprise rationally designed 3D elastic metamaterial lattices.

Acknowledgments

The research of M W has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy via the Excellence Cluster '3D Matter Made to Order' (EXC-2082/1-390761711), which has also been supported by the Carl Zeiss Foundation through the 'Carl-Zeiss-Foundation-Focus@HEiKA', by the State of Baden-Württemberg, by the Helmholtz Association, and by the Karlsruhe Institute of Technology (KIT). It has been further funded by the Helmholtz program 'Materials Systems Engineering', by the Max Planck School of Photonics, by the Karlsruhe School of Optics & Photonics (KSOP), by the Alexander von Humboldt foundation, and by the Hector Fellow Academy.

2.6. Metamaterials with extreme parameters

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Status

EM constitutive parameters of materials, such as permittivity ε and permeability μ, determine their electric and magnetic macroscopic responses. Extreme values of ε and μ may provide counterintuitive EM properties in light–matter interaction with such media, leading to novel theories and potential applications. The ENZ metamaterials, as a key representative of extreme-parameter metamaterials, have emerged as one of the extensively investigated cases of extreme metamaterials, exhibiting various potential applications.

The essence of the ENZ metamaterials lies in suppression of the spatial variation of phase at non-zero frequencies due to stretched wavelength caused by a near-zero refractive index, and therefore offers a unique wave dynamic with temporally oscillating yet spatially static property. One of the most exciting near-zero-index effects is the anomalous tunneling of wave, known as supercoupling, found in an arbitrarily bent narrow channel filled with ENZ media [65], as conceptually illustrated in figure 11(a). The supercoupling effect is accompanied with notable electric field enhancement and squeezing. The possible high field strength, together with near-zero linear dielectric response in ENZ metamaterials, may result in enhancement of the optical nonlinearity. As reported in [66] and schematically shown in figure 11(b), an ENZ material layer demonstrates large nonlinear refractive index compared with a vanishing linear part. The enhanced Kerr nonlinearity was also observed in ENZ media [69]. Another interesting wave property in ENZ metamaterials is the effective decoupling of temporal and spatial variations of EM waves. In conventional cavity resonators filled with ordinary dielectrics, the resonance frequency is generally determined by the cavity's shape and dimensions. A direct consequence of the space-time decoupling of dynamic waves in ENZ materials is the geometry-independent cavities whose resonance frequencies are independent of the external shapes [67], as shown in figure 11(c). Another feature with far-reaching impact is the notion of 'photonic doping' of ENZ media, where one or several arbitrarily located macroscopic dielectric impurity 'dopants' are inserted in an ENZ host in order to engineer at will the effective permeability of the whole structure [68], as illustrated in figure 11(d).

Current and future challenges

ENZ metamaterials have open up new horizons for controlling EM waves and manipulating wave–matter interaction. However, as in any new field of science and engineering, there are technological challenges. One such challenge is the material loss in naturally available ENZ materials, which may impede the progress toward some of the real-world applications [70]. Although to mitigate the material loss several schemes, such as lowering the photonic density of states for receiving scattered electrons, or even introducing optical gain to compensate the loss in the ENZ metamaterials [70] have been conceived, they can be intricate in implementation. Another solution to emulate near-zero-index behavior is via constructing artificial metallic resonant elements at lower frequency regions. However, EM resonances with high-quality-factor can lead to strong currents over the surface of metallic resonators, which inevitably makes ENZ response sensitive to the ohmic loss and fabrication imperfection. The presence of excessively high loss can indeed limit the scope of some of the potential applications of ENZ materials. Consequently, it has been important to explore and search alternative platforms for ENZ metamaterials with lower loss from microwave to optical frequencies. One such platform, as briefly described in the next section, is to use the structural dispersion instead of material dispersion, as exemplified in the waveguide-based structures operating at their cut-off frequencies.

Advances in science and technology to meet challenges

Recent advance in waveguide-based ENZ metamaterials suggests a promising route to overcoming the challenging problem of plasmonic-based ENZ loss. Consider the fundamental TE10 mode in a conventional rectangular metallic waveguide. EM waves propagate at frequencies above the cut-off frequency fc of the waveguide, while it decays exponentially at frequencies below fc. This implies that a rectangular waveguide behaves effectively as an epsilon-positive and an epsilon-negative metamaterial, in the frequency ranges above and below fc, respectively. Importantly, at the transitional point of fc, the waveguide functions with an effective permittivity crossing zero, exactly corresponding to an ENZ metamaterial. Essentially, the

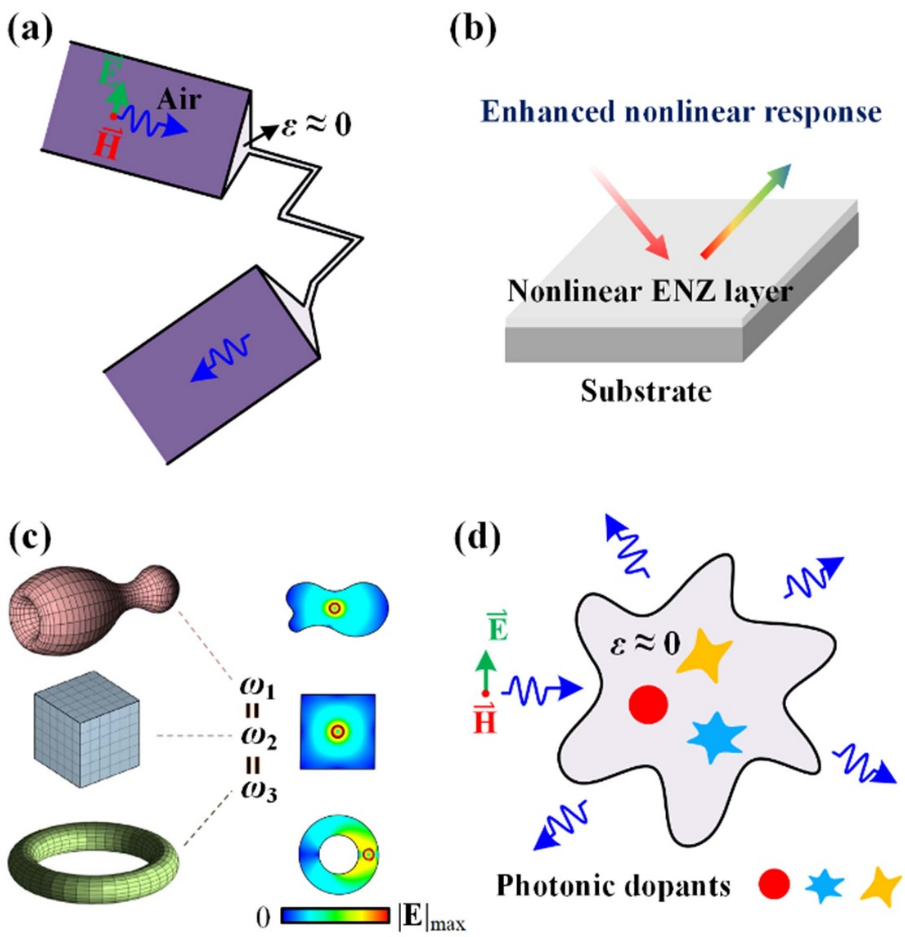

Figure 11. Sevral wave-based properties in ENZ metamaterials. (a) Supercoupling of electromangetic wave through a irregularly bent narrow channel filled with ENZ material [65]. (b) Enhancement of optical nonlinearity via ENZ materials [66]. (c) Geometry-independent ENZ resonant cavities [67]. Reproduced from [67]. CC BY 4.0. (d) Photonic doping of ENZ materials [68]. The photos are reproduced from [65–69], used with permission.

waveguide-based ENZ metamaterials exploits structural dispersion, instead of material dispersion, for emulating the ENZ response, and thus circumvent some of the challenging issues of plasmonic-based ENZ loss, since the waveguide platform provides low ohmic dissipation. Furthermore, as opposed to strongly resonant modes in metallic resonators, waveguide modes may avoid enhanced fields, hence ensuring lower loss and high efficiency for ENZ devices.

Facilitated by the platform of waveguides, a whole host of interesting ENZ devices have been proposed recently. As shown in figure 12(a), a microwave antenna with ENZ response is constructed by a substrate-integrated waveguide fabricated on a flexible substrate [71]. This flexibly bendable antenna can offer various radiation patterns while its operating frequency remains unchanged. A flexible TL is proposed based on photonic doping of a waveguide-emulated ENZ metamaterial [72], as illustrated in figure 12(b). EM waves can tunnel through this irregularly-curved TL with high efficiency. Inspired by the uniform phase distribution in the ENZ medium, a multi-port in-phase power divider is investigated [73], whose photograph is shown in figure 12(c). This metamaterial divider can be designed by a center hub with arbitrary cross-sectional shapes, and provides more degrees of freedom for power allocation. Recently, the optical metamaterial-inspired lumped circuits, named as optical metatronics, have drawn substantial interests. The waveguide-based ENZ metamaterials offer a promising platform to implement the idea of metatronics free from plasmonic loss, proposing a new subject of waveguide-based metatronics [74], which is conceptually illustrated in figure 12(d). By engineering the waveguide dispersion, waveguide metatronics can be designed at arbitrary frequencies where metallic materials can be utilized.

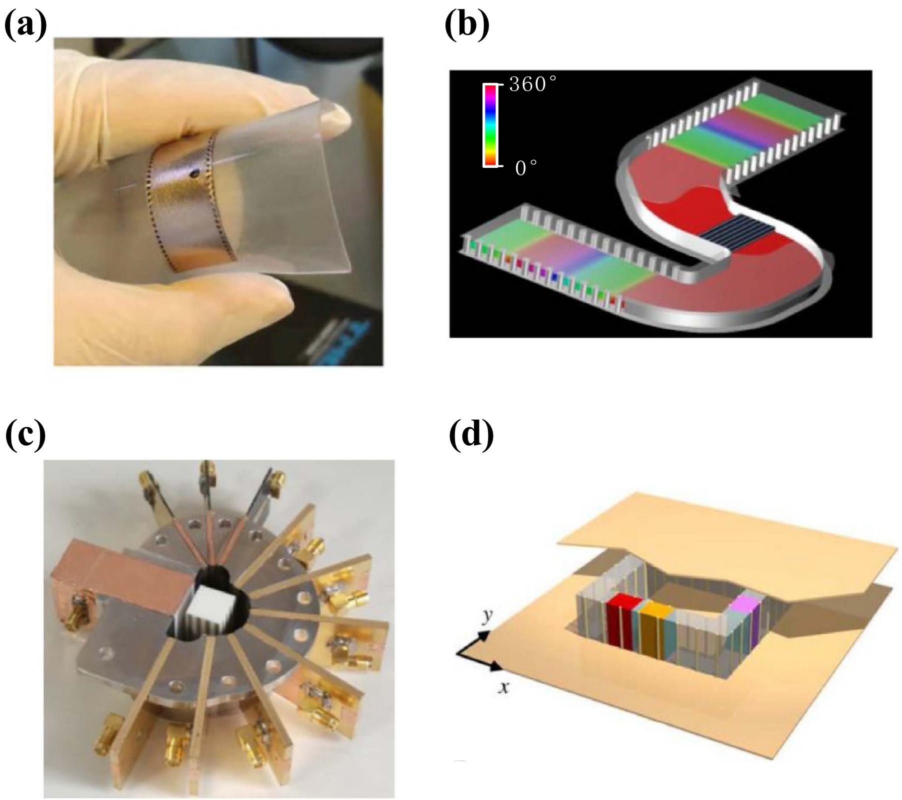

Figure 12. Applications of waveguide-based ENZ metamaterials. (a) Bendable ENZ antennas with fixed frequency [71]. © [2020] IEEE. Reprinted, with permission, from [71]. (b) Geometry-independent waveguide transmission lines [72]. Reproduced from [72]. CC BY 4.0. © [2021] IEEE. (c) Multiport power divider with designable power division ratios [73]. Reprinted, with permission, from [73]. (d) Waveguide metatronics [74]. Reproduced from [74]. CC BY 4.0.

Concluding remarks

ENZ metamaterials and near-zero-index metastructures are a member of the extreme-parameter media. Utilizing the structural dispersion to achieve low-loss ENZ-like behaviors, recent advances in waveguide-based engineered structures suggest a promising route to exploit ENZ responses and effects while avoiding the detrimental effect of material loss. With high efficiency and flexibility, waveguide-based ENZ metamaterials can span a wide range of applications in various technological fields such as microwave engineering, photonics, material science, etc.

Acknowledgments

Y L acknowledges partial support from National Natural Science Foundation of China (NSFC) under Grant 62022045. Z Z acknowledges partial support from NSFC under Grant 62301162.

2.7. Chiral and bianisotropic metamaterials (BAMMs)

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Status

The most general linear homogeneous bianisotropic medium (BAM) is described by the following material equations:

$$\mathbf{D}(r) = \overline{\overline{\varepsilon}} \cdot \mathbf{E}(\mathbf{r}) + \overline{\overline{\gamma}} \cdot \mathbf{H}(\mathbf{r}), \tag{1a}$$

$$\mathbf{B}(\mathbf{r}) = \overline{\overline{\mu}} \cdot \mathbf{H}(\mathbf{r}) + \overline{\overline{\tau}} \cdot \mathbf{E}(\mathbf{r}). \tag{1b}$$

Here, dyadics $\overline{\overline{\gamma}}$ and $\overline{\overline{\tau}}$, responsible for excitation of electric polarization by magnetic field and magnetic polarization by electric field, respectively, are often represented as $\overline{\overline{\gamma}} = \overline{\overline{\xi}} + j\overline{\overline{\kappa}}, \overline{\overline{\tau}} = \overline{\overline{\xi}} - j\overline{\overline{\kappa}}$, where $\overline{\overline{\xi}}$ is called the non-reciprocal magnetoelectric dyadic and $\overline{\overline{\kappa}}$ is the reciprocal magnetoelectric dyadic. In the special case of bi-isotropic medium, i.e. when all constitutive tensors degenerate to scalars or pseudoscalars, ξ is called the Tellegen parameter and κ is the chirality parameter. In natural bianisotropic metasurfaces (BAMSs) non-reciprocal magnetoelectric coupling is very rare and very weak. The most common bianisotropic response observed in natural BAMs is chirality which is manifested in form of optical activity and dichroism. Discovered in XIX century, these effects were sufficiently understood only in 1970s (see e.g. in [75]). The general classification of BAMs—natural and composite ones—also can be found in [75]. The format of this Roadmap does not allow us to refer to original papers, concerning basic properties and effects, and we refer only to books and overview papers where the reader may find more references.

Metamaterials are usually prepared so that the desired magnetoelectric coupling effects are resonant at the operational frequencies. Since this resonant property is unusual in natural materials and useful for many applications (from polarization transforming to sensing single molecules), BAMMs are actively studied. BAMMs with nonreciprocal magnetoelectric coupling were experimentally demonstrated (see the references in work [76]), but this nonreciprocity was not yet applied in devices. Most important BAMMs nowadays are reciprocal composites—artificial chiral and omega media [75, 76]. They were extensively studied due to their unique properties: high and controllable chiral (optical activity and dichroism) and omega (asymmetric reflection/absorption) responses.

Chiral metamaterials are characterized by symmetric tensors $\overline{\overline{\kappa}}$ which can be diagonalized by a proper choice of the coordinates. Metamaterials modeled by symmetric but traceless tensors $\overline{\overline{\kappa}}$ are called pseudochiral materials. They exhibit chiral effects for wave propagating along specific directions, although the microstructure is mirror-symmetric. Omega composites have anti-symmetric, traceless $\overline{\overline{\kappa}}$. Canonical particles exhibiting chiral and omega coupling effects are shown in the top panels of figure 13 [75, 76]. Whatever possible magnetoelectric coupling phenomenon can be viewed as a combination of canonical coupling effects in four canonical particles shown in figure 13 [77]. Magnetoelectric coupling in reciprocal particles is a phenomenon resulting from spatial dispersion. However, this is weak (small-scale) spatial dispersion which is compatible with the concept of continuum. As a rule, the mean size of the array unit cell in the operational band of BAMMs does not exceed l/4. This allows BAMMs to be considered as effectively continuous media and makes (1) useful for studying many wave phenomena.

For applications, the most important BAMMs are BAMSs. Metasurface is an optically thin metamaterial layer—usually, a monolayer or a double layer of particles modeled as an effective sheet of electric and magnetic surface currents Je, Jm, or, equivalently, as a sheet of surface electric and magnetic polarizations P and M. The constitutive equations of a BAMS can be written as follows [76]:

$$\mathbf{P}(r) = \overline{\overline{\alpha}}_{\mathrm{ee}} \cdot \mathbf{E}(\mathbf{r}) + \overline{\overline{\alpha}}_{\mathrm{em}} \cdot \mathbf{H}(\mathbf{r}), \tag{2a}$$

$$\mathbf{M}(r) = \overline{\overline{\alpha}}_{\mathrm{mm}} \cdot \mathbf{H}(\mathbf{r}) + \overline{\overline{\alpha}}_{\mathrm{me}} \cdot \mathbf{E}(\mathbf{r}). \tag{2b}$$

The main advantage of a metasurface compared to a bulk metamaterial is lower dissipation loss. Also, optical BAMSs are cheaper in fabrication because most of advantageous properties of a reciprocal BAMM can be achieved with a monolayer BAMS (see in [76]). Planar arrays of anisotropic plasmonic particles, especially on highly refractive substrates grant resonant chiral response, whereas arrays of simple plasmonic nanoparticles (spheres, disks, etc) on such substrates manifest resonant omega response (see in [76]). During the last decade, it was demonstrated that BAMSs provide unique ways for designing reciprocal and one-way polarization transformers, photonic Weyl semimetals, and 100%-efficient anomalous reflection and refraction control [76, 78].

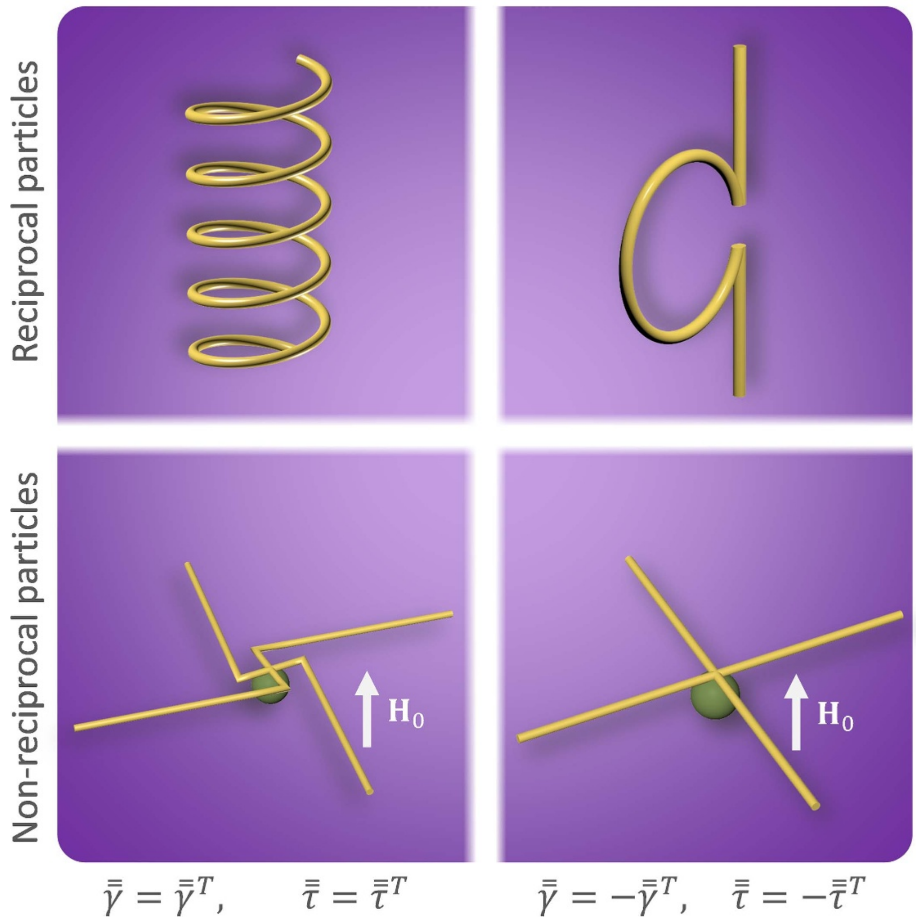

Figure 13. Four fundamental classes of bianisotropic meta-atoms.

Current and future challenges

One of the current challenges for BAMSs is proper design and realization of constitutive particles in novel operational bands (mm waves, THz range, mid-IR, and near-IR range), where the polarizabilities may have multipole components whose resonances may overlap with those of the dipole magneto-electric polarizability. Challenges common for all metasurfaces hold also for BAMSs, for example, low angular stability of the EM response and/or its very high polarization sensitivity. These problems restrict the angular spectrum and polarizations of the incident waves properly transformed by metasurfaces [79]. Multifunctionality is also a common challenge for metasurfaces. It is often desired that BAMS should grant simultaneous control of amplitudes and phases of the reflected or transmitted beams within the required beamwidth, or simultaneous control of the beam intensity and polarization, etc. As a rule, these requirements are contradictory [79]. The common challenge related with granularity and finite sizes of metasurface unit cells is a high level of scattering loss and parasitic sidelobes [79]. Realization of nonreciprocal bianisotropic response is challenging since external magnetization is usually needed. For optical BAMSs technological challenges arise—submicron bianisotropic particles are expensive to fabricate even if they are planar. Meanwhile, the chiral response of planar BAMSs may be insufficient for some applications.

Nowadays, BAMSs are basically flat sheets whose curvature has little impact on operation. However, in prospective applications this issue can become essential. For example, the orbital angular moment (OAM) of photons in vortex light beams promises a breakthrough in the information capacity of telecommunication systems. Huge volume of digital information can be recorded in OAMs quantized from 0 to 104 [80]. However, the wave beam should propagate to very large distances along a helical spiral (whose pitch is determined by OAM). We expect that transfer of the optical information in the near IR range may be enabled in a cladded fiber whose cladding will be a novel BAMS.

Advances in science and technology to meet challenges

Many of the aforementioned challenges can be overcome with the advent of BAMSs whose EM properties are varied not only in spatial, but also in the temporal dimension. Such time-modulated BAMSs can possibly provide unique opportunities for designing active and nonreciprocal bianisotropic devices both in the microwave and optical ranges [81]. Moreover, time-modulated BAMSs are inherently tunable and multifunctional, which will facilitate their use as RISs in future wireless communication networks [82]. The bianisotropic nature of these metasurfaces can provide additional degrees of freedom for the control and conversion of OAM states in wireless signals.

Large reduction in fabrication costs of some types of BAMMs and BAMSs can be achieved with the use of self-assembly techniques, such as DNA-origami [83]. This advance would allow creation of macroscopic devices for applications in nonlinear optics, stereochemistry, and pharmaceutical engineering.

While both reciprocal and nonreciprocal bianisotropic responses are typically weak in BAMMs and BAMSs at optical frequencies, they can be greatly enhanced using the concept of bounds states in the continuum [84]. Based on specific symmetry properties, these states can support resonances with extremely high quality factors (limited only by fabrication tolerance and dissipation loss in exploited materials) and, therefore, boost bianisotropy by several orders of magnitude. Resulting structures can find important applications for enantiomeric sensing in chemical engineering of molecules.

Finally, proper design of bianisotropic constitutive particles for high-frequency operation bands can be addressed by using novel techniques, such as numerical optimizations (the adjoint method, automatic differentiation method, etc) and machine learning. Together with previously developed T-matrix and modular synthesis approaches [77], these tools would enable smart and efficient optimization of bianisotropic particles and systems for simultaneously several independent directions or polarizations of incident waves.

Concluding remarks

As broad generalizations of anisotropic media, BAMMs and BAMSs provide a sheer abundance of EM phenomena and application potentials. Although analytical models of these systems are well developed, effective and inexpensive implementation in various frequency regimes is yet to come. We expect that BAMMs and BAMSs will find connections to other disciplines, including emergent 2D and topological materials, bioengineering, 6G telecommunications, and advanced nanophotonics.

2.8. Photonic topological metamaterials

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Status

Since the 1980s, the discovery of the integer quantum Hall effect and the subsequent topological interpretation ushered in a new era for condensed matter physics. To date, the notion of topological phases has gone far and beyond the original realm of condensed matter physics, and has made a profound impact in areas including the photonics [85], acoustics and mechanics. The underlying principle of topological physics is that the bulk property of materials can be exhaustively classified by Abelian [86] or non-Abelian groups, which can be viewed as topological charges. Furthermore, the bulk topological invariant also determines the number of edge states through the celebrated 'bulk-edge correspondence'. Until now, nontrivial topological phases and the interesting phenomena associated with them have stimulated a variety of applications such as dissipation-less transportations, one-way propagation and single-mode lasing.

Metamaterials, comprising a periodic array of artificially designed sub-wavelength structures [56] (see figure 14), provides an ideal platform for generating and investigating the topological properties of light. Based on metamaterials, various topological phases have been theoretically proposed and experimentally demonstrated, such as photonic Weyl points [78], Weyl surfaces [87], Dirac points [88], nodal lines [89] and nodal links [90], etc. With the design flexibility and tunability, metamaterials also offer a powerful platform to observe those non-periodic topological effects. It is convenient to introduce various inhomogeneities in the metamaterials, as one could adjust separately the size and direction of each unit cell composing the metamaterial. Without the constraints of high dielectric constant and strict periodicity as required in photonic crystals, metamaterials are also more feasible to be fabricated and assembled. Furthermore, benefitting from deep sub-wavelength unit cells of metamaterials, the topological properties can be readily modeled using EMT, and the surface modes are more confined to the interface of metamaterials than photonic crystals. Due to the strong confinement of the EM waves, near-field scanning greatly facilitates the measurements and discoveries of novel phenomena in various topological photonic metamaterials.

Despite the rapid progress in topological metamaterials, many fundamental observables and topological features have not yet been experimentally demonstrated, such as the concepts of quantum oscillation and wormhole effect, non-Abelian gauge field, disorder or defect photonic systems, etc. Topological photonic metamaterials provide an ideal platform for the investigation of those intriguing effects arising from the interplay among artificial gauge fields, topological bands, spatial symmetries and photonics.

Current and future challenges

The notion of gauge fields is of great importance in modern physics. Starting from the famous Aharonov–Bohm effect, exploring the physical consequences of gauge fields has attracted extensive attention both in theories and experiments. Very recently, the interplay between artificial gauge fields and topological physics has facilitated the discovery of many novel topological phenomena, such as the zeroth chiral Landau level, where the pseudo magnetic field is applied onto Weyl/Dirac semimetals via introducing external strains into the material's lattice [91]. However, in 3D bulk crystals, directly imposing a significant strain is very challenging because these systems are not flexible. Artificial gauge fields or pseudo magnetic fields cannot be easily generated. As yet geometries only with films or wires are extensively studied to explore the relevant effects. Therefore, it is important to realize arbitrarily controllable artificial gauge fields in the 3D crystals. Based on 3D Weyl/Dirac photonic systems, some novel physics phenomena, such as chiral anomaly, gravitation and torsion related effects, will be experimentally demonstrated.

Very recently, crystalline topological photonics has also attracted much attention. Various symmetry protected topological phases have been classified, their experimental realizations need a flexible platform. In addition, high-order topological phases are rarely realized in 3D photonic systems, although they have been well developed for scalar acoustics fields. Meta-crystals with symmetry-compatible metallic resonators are the most promising candidates for this purpose.

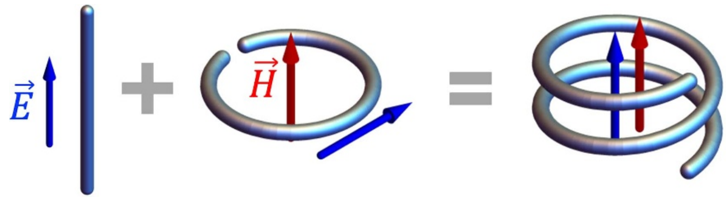

Figure 14. Three basic metallic elements (rod, splitting ring and helix) are used in constructing electromagnetic metamaterials.

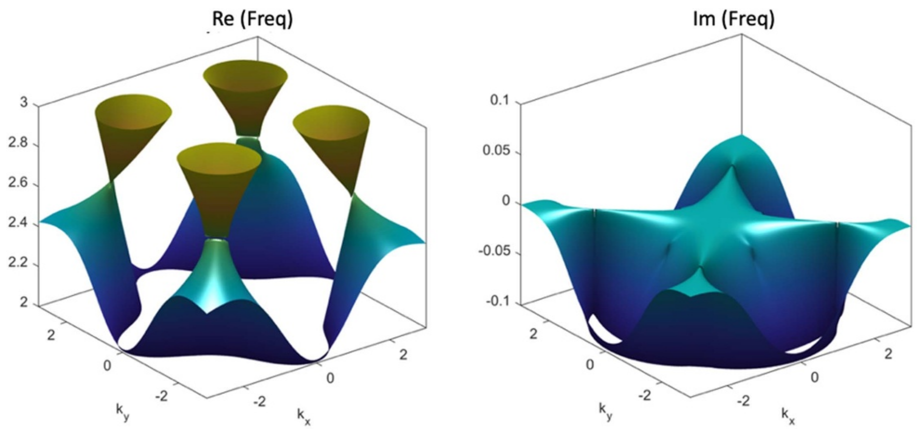

Figure 15. Real and imaginary parts of frequency of a non-Hermitian ideal Weyl system.

With the rapid developments of twisted bilayer graphene, the concept has been transferred to photonic systems, leading to the emerging of a new research field—Moiré photonics. The twisted photonic lattices may introduce flat bands and thus localized modes for lasing and sensing. In this regard, metamaterials show many advantages with more degrees of freedom.

Non-Hermitian topological photonics host some interesting physics that go beyond the conventional systems with PT-symmetry. Introducing loss or gain to topological photonics may lead to more exotic topological phenomena, such a bulk Fermi arcs and skin effects. In an ideal Weyl system, the inclusion of ohmic loss induces exceptional arcs (see figure 15). However, the sample fabrications may be challenging.

High-dimensional topological phases with extra exotic topological states were mostly studied theoretically. Recently, it was shown that certain intrinsic EM properties such as bi-anisotropic terms, can serve as the synthetic dimensions for carefully engineered topological photonic metamaterials. This has led to the experimental observation of higher-dimensional topological phenomena, such as linked Weyl surfaces and Yang monopoles [87].

Advances in science and technology to meet challenges

Metamaterials operating in the microwave bands can be precisely fabricated with PCB technology. The distributions of the density of states could be mapped out experimentally with the near-field scanning setups. The extension of topological metamaterials design to a higher frequency regime requires well-developed fabrications and phase-resolved near-field scanning systems. Although in optical bands the metallic loss will hinder the observation of those topological properties, in terahertz regimes metallic resonance structures are still very promising due to the low ohmic loss of metals. However, with current fabrication technologies, it is still challenging to construct complicated micro-scale metallic structures. Hence, more advanced techniques are needed.

Non-Hermitian topological metamaterials require the precise inclusion of loss and gain components. While loss can be realized via resistance, the gain media is not easy to implement. However, the well-developed topological electric circuits may represent a powerful platform, where voltage followers (op-amp buffers) have been widely applied. Furthermore, topological electric circuits can be designed to possess reconfigurable and programmable features, which may infuse new energy in topological photonic metamaterials. Incorporation of other features including nonlinearity, nonreciprocity, time-varying and even moving media, will potentially contribute to the development of topological photonic metamaterials.

Twisted meta-crystals can introduce both commensurate and incommensurate lattices, which may exhibit fruitful physics, e.g. novel topological surface states and localizations in quasi-lattices. The mechanisms are usually hard to grasp with tight-binding models as in EM waves multiple coherent scattering plays a dominant role. While the full-wave simulations are not only time-consuming but also conceal the underlying physics, some effective theoretical methods that take into account non-local effects are needed for dealing with the problems.

Concluding remarks

In summary, photonic topological metamaterials offer a platform for designing various exotic topological phenomena, such as artificial gauge fields in 3D topological systems, crystalline symmetry protected topological phases and newly arising non-Abelian topological charges. In particular, artificial gauge fields and pseudo magnetic fields can be introduced to control the charge-neutral particles or wave-packets, leading to potential applications in photonic wave manipulation and communication.

Acknowledgments

This work was supported in part by Horizon 2020 Action Projects 648783 (TOPOLOGICAL), 734578 (D-SPA), and 777714 (NOCTORNO); the Research Grants Council of Hong Kong (AoE/P-502/20).

2.9. Metamaterial antennas

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Status

Metasurfaces, the 2D counterpart to volumetric metamaterials, are realized through the intelligent patterning of subwavelength unit cells (i.e. meta-atoms, nano-antennas) which provide a desired spatially varying complex surface impedance. Metasurfaces have imbued engineers with the capacity to tailor EM wave propagation in unprecedented ways using electrically thin structured surfaces. Due to their ability to be realized with conventional PCB and additive manufacturing techniques, metasurface-based antennas have the potential to realize systems with significant size, weight, power, and cost (SWaP-C) reduction by replacing large and heavy conventional antenna components with lightweight and low-cost alternatives that have the same or sometimes even superior performance.

In the RF regime, the transformative properties of metasurfaces have been exploited to develop a variety of innovative antenna systems including transmit- and reflect-arrays [92], binary and multi-bit coding surfaces, cloaking radomes [93, 94], focusing lenses, low-profile and conformal antennas, multifunctional wearable antennas [95], etc. Such metasurface-enabled devices have demonstrated agile beam forming, EM absorption, radar cross section (RCS) reduction, enhanced bandwidth and gain, polarization diversity, and miniaturization, among other desirable phenomena. Metasurface-lined horn antennas (i.e. metahorns) which improved sidelobe, bandwidth, and cross-polarization performance over traditional horn antennas were one of the first real-world practical demonstrations of how metasurface-enabled antennas could outperform conventional systems [96].

Meanwhile, metasurface-based lenses (i.e. metalenses) comprised of aperiodic arrangements of nanoantennas are a burgeoning technology that have the potential to disrupt conventional optical system design through the realization of dispersion-engineered optics with performances unachievable by conventional components [97]. Moreover, reconfigurable metasurfaces have been demonstrated in both the RF and optical regimes with tunable and multifunctional behaviors through the use of active circuit components and phase change materials (PCMs) [98], respectively. Figure 16 shows several metasurface-enabled designs including an advanced short backfire antenna [99], a flexible wearable antenna with a highly-truncated metasurface ground plane [100], and a broadband achromatic metalens comprised of 2.5D dielectric nanoantennas.

The volumetric form of metamaterial antennas is also progressing well, thanks to the rapid development of additive manufacturing technologies [101]. It is also enabled by early theoretical studies on TO, the concept behind the design of invisibility cloaks. Antennas with complex spatial material profiles, which are purposely designed, can now be manufactured with various 3D printing techniques. Much of the technological progress has also led to commercial success, in the design of new SATCOM antennas [102] and has been predicted for a sustained growth for applications in wireless communications such as 5G and beyond [103]. Figure 17 demonstrates some 3D printed metalens antennas developed by Queen Mary University of London for millimeter wave (mmWave) communications.

Almost all the metamaterial antennas are currently based on periodically ordered distributions of meta-atoms mainly due to their mathematical simplicity. Such designs, however, suffer from fundamental limits that have been studied according to causality, related to dispersion relations, and theoretical limits of general physical systems. The root of these limits is associated with the well-known diffraction limit, in both the spatial and angular domains [104]. Disordered many-particle hyperuniform systems have now been found to have several applications in the fields of metamaterials. For example, hyperuniform disordered plasmonic gold surfaces have been proposed with highly directive far-field diffraction patterns; as for metamaterial antennas, hyperuniform disordered Luneburg lenses that possess peculiar properties have been theoretically and experimentally studied [105]. Finally, when applied to the design of metasurfaces, hyperuniform disordered distributions can be used as a generalized design tool for RCS reduction, which has the advantage of avoiding lengthy computational optimization approaches [106].

Current and future challenges

While metasurfaces have seen a number of successful demonstrations in recent years, certain challenges must be overcome before they can be ubiquitous in antenna system design. In particular, the dispersive (i.e. resonant) behaviors of their electrically small meta-atom building blocks often limits metasurface-based

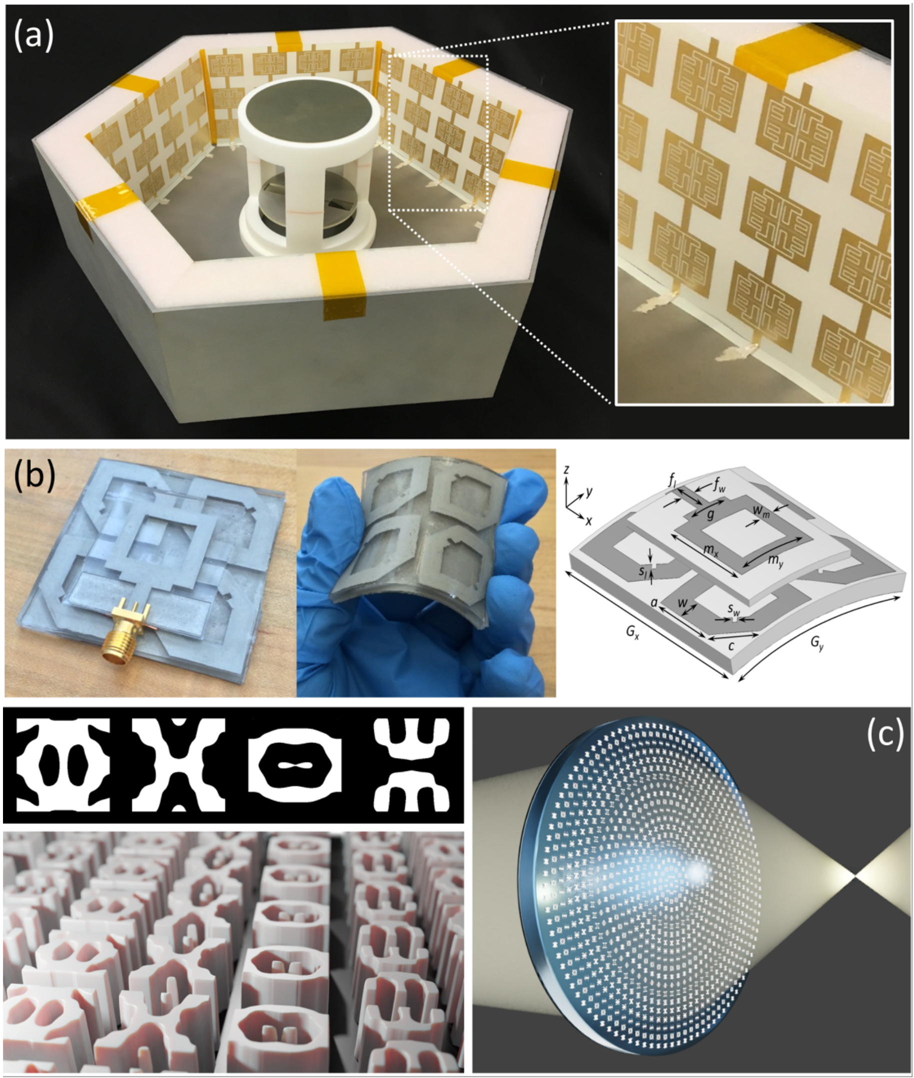

Figure 16. (a) Metamaterial short backfire antenna with its optimized anisotropic metasurface liner (inset) [99]. Reproduced from [99]. CC BY 4.0. (b) A flexible circularly polarized antenna with a highly-truncated metasurface ground plane for wearable applications [100]. © [2014] IEEE. Reprinted, with permission, from [100]. (c) A 2D binary meta-atom supercell representation (top left) is realized in 3D after nanofabrication (bottom left) and patterned to create a broadband achromatic focusing metalens (bottom right).

antenna system bandwidth. Additionally, realizing metasurfaces for high-power microwave applications is often challenging due to the high local field enhancement produced by their resonant meta-atom building blocks which limits their potential power-handling, especially in electrically reconfigurable systems.

In the optical regime, realizing cost-effective ways to mass produce large diameter, high efficiency metalenses is needed before metasurface-based solutions will be adopted by traditional optical engineers. The narrow field-of-view (i.e. angular) and polarization-dependent performances of current generation metalenses also need to be overcome in order to compete with conventional solutions. Moreover, due to their extreme multiscale nature (up to seven orders of magnitude) optical metalenses present a significant computational challenge to accurately model their EM behavior, especially when accounting for mutual coupling between a collection of their geometrically diverse unit cell building blocks.

In addition, despite the many successful applications claimed by metamaterial antennas, overcoming the classic fundamental limit of small antennas and phased arrays remains a challenge. While focusing on significant SWaP-C reduction is one way forward, engineers and researchers will have to evaluate the benefit of metamaterial antennas from the viewpoint of multi-functional systems.

On active metamaterials including coding metasurfaces, there are also challenges around the use of active components and associated control circuits. Moreover, frequency scaling-up and manufacturability of large intelligent reflecting surfaces (IRSs) can be very challenging. Finding 'killer' applications of metamaterials and antennas have always been an ongoing topic of discussion. While negative refraction, perfect lens and

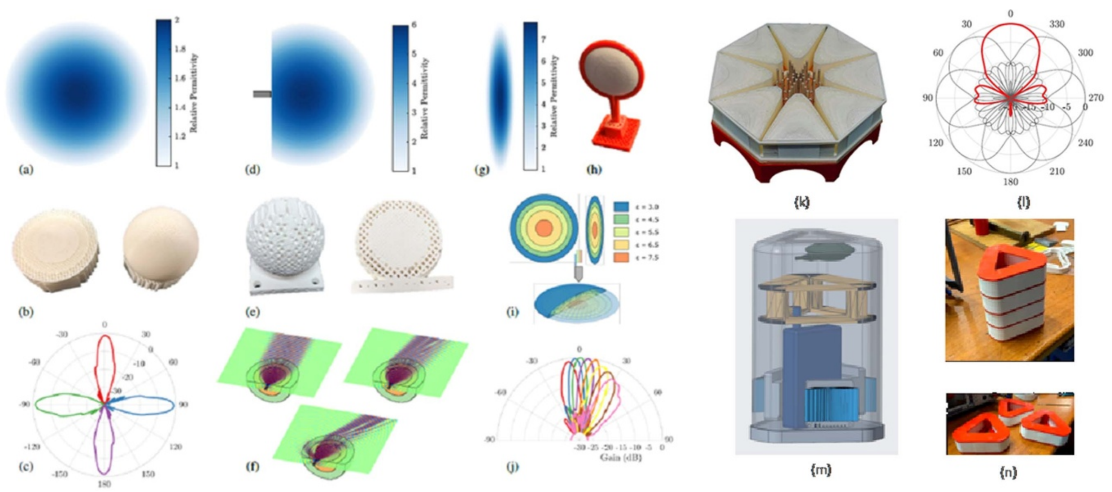

Figure 17. 3D printed metalens antennas developed by Queen Mary University of London for millimeter wave communications. (a) Permittivity distribution of a classic Luneburg lens antenna. (b) Photograph of a 3D printed Luneburg Lens antenna using effective medium theory. (c) Measured radiation patterns at 28 GHz with feed position at 0°, 90°, −90°, and 180°. (d) Permittivity distribution of the Gutman lens with the focal point moved to a position of 0.45 R. (e) Photograph of the 3D printed Gutman lens at 60 GHz. (f) Simulated electric field patterns showing beam steering as the feed position is moved along the flat face of the lens. (g) Permittivity distribution of a compressed Luneburg lens. (h) Photograph of the 3D printed compressed Luneburg lens at 84 GHz. (i) Setup for multi-material 3D printing of the compressed lens with five different filaments. (j) Measured radiation patterns of the compressed lens at 84 GHz. (k) 3D-printed eight-beam dielectric lens antenna with radiation pattern multi-functionality. (l) Optimized 45° radiation pattern corresponding to the 3D-printed 8-beam dielectric lens antenna. (m) & (n) 3D printed antennas for tactical communications with permission by Plextek.

invisibility cloaks have been proven theoretically viable, challenges remain to demonstrate new unprecedented applications, their practicality and engineering realization.

Advances in science and technology to meet challenges

While the resonant nature of passive metasurface elements may limit antenna bandwidth, current research into time-varying metasurfaces has the potential to overcome such restrictions and realize unique functionalities that cannot be achieved with linear time-invariant systems. In [11], STC digital metasurfaces realized harmonic beam steering through a time-modulated PMS. Concepts from such time-varying metasurfaces may help to realize electrically small antennas that meet or perhaps even beat the classical Chu limit governing antenna bandwidth. Still, in [99] an optimized passive metasurface was used to improve the aperture efficiency of a hexagonally arranged short-backfire antenna for operation at the L1 and L2 GPS bands by introducing a dispersion-engineered anisotropic surface impedance on the cavity walls.

Metasurfaces have also led to breakthroughs in on-body and wearable antenna applications where the desire to reduce antenna size as much as possible while simultaneously maintaining high efficiency is severely impacted by dielectric loading of the human body. Recently, however, it has been shown in [100] that highly-truncated metasurfaces can be utilized, as a replacement for conventional metallic ground planes, to achieve these goals.

In the optical regime, new nanofabrication processes are being developed to widen the range of dispersion-engineered nano-antennas (meta-atoms) in order to realize broadband large-diameter metalenses. Furthermore, deep learning techniques have recently been developed to accelerate metasurface inverse-design, predict unit cell coupling in aperiodic metalenses, and improve as-fabricated device performance by enabling optimization of robust designs impervious to common nanofabrication uncertainties [107].

In recent years, a number of exciting new materials with active properties have emerged from research into ferroelectrics, ferromagnetics, piezoelectrics, and the discovery of graphene and 2D nanomaterials (e.g. carbon nanotubes). These materials offer the prospect of engineered media (metamaterials) that have tunable properties, which can be used to dynamically control EM fields and waves [108].

Machine learning algorithms have now tightly coupled to almost all subjects of science and engineering. Data driven materials discovery will accelerate the development of active metamaterials, as high frequency material performance, especially for ferroelectrics, may be manipulated according to multiple, multiscale unknowns including oxygen vacancy densities, grain sizes and domain boundaries existing in the system. For example, a human–machine interactive learning framework has been developed with a scalable semi-empirical model to accurately predict material properties enabled by deep learning [109]. Applications of machine learning in wireless communications [110], sensing and radar systems will also add new opportunities for metamaterial antennas, where additional EM requirements may emerge so that multiple functionalities such as computing, communication and sensing will converge.

Concluding remarks

Metasurfaces provide RF and optical engineers with new tools with which to control the propagation of EM waves. Metasurface-based antennas have the potential to disrupt conventional systems, provided sufficient bandwidths, polarization diversity, power-handling capacity, efficiency, tunability, and mechanical robustness can be realized by their meta-atom building blocks. Meanwhile, optical metalenses that realize improvements in broadband, wide field-of-view, and polarization-insensitive performances while being fabricatable at mm and cm scales could revolutionize optical system design as functionalities currently realized by bulky and heavy multi-lens element groups are replaced with a single planar dispersion-engineered metasurface that performs multiple optical functionalities. To this end, advances in additive-manufacturing and nanofabrication techniques combined with emerging computational and machine learning methods could pave the way for metasurface antennas to see applications in a wide range of areas in coming years.

Acknowledgments

S D C and D H W were supported in part by Defense Advanced Research Projects Agency (DARPA) under Award Numbers HR00111720032 and HR00112110016. D H W also gratefully acknowledges support from the John L and Genevieve H McCain endowed chair professorship at the Pennsylvania State University. Y H would like to thank IET AF Harvey Research Prize and UK EPSRC for funding 'Software defined materials for dynamic control of electromagnetic waves (ANIMATE)' research (EP/R035393/1).

3. Metasurfaces: physics and applications

3.1. Metasurfaces and generalized Snell's law

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Status

Freely controlling the propagation of light plays important roles in both sciences and applications. Reflection/refraction of light at an interface between two different media is widely utilized to control light propagation, which is described by Snell's law established in the 17th century. Recently, two different groups [6, 7] independently discovered that light reflection/refraction at certain specifically designed metasurfaces do not obey the conventional Snell's law, but rather than a generalized Snell's law with a new term contributed by the metasurfaces. These metasurfaces are composed by planar microstructures with different geometries, such that the whole devices exhibit transmission/reflection phases linearly changing in space. Phase gradients in these systems provide additional tangential wave-vectors to the reflected/transmitted light beams, leading to the anomalous light lending (see figure 18(a)). Furthermore, as the phase gradient is larger than the free-space wave-vector of light, a normally incident light beam can be perfectly converted to surface waves bounded on the metasurfaces (see figure 18(b)) [7]. The generalized Snell's law, derived from the interfacial phase discontinuities at designer metasurfaces, enables arbitrary controls on reflection/refraction of light, overcoming the limitations imposed by the conventional Snell's law.

While the reflection-type metasurfaces proposed in [7] can realize high-efficiency anomalous reflections, early proposed transmission-type metasurfaces [6] exhibit low efficiencies for anomalous refractions due to multiple-mode generations. To solve this issue, Grbic's group proposed a new type of transmissive metasurface to manipulate the wavefronts of EM waves in microwave regime with very high efficiencies (see figure 19(a)) [111]. Different from previous systems exhibiting only electric responses, such a metasurface consists of meta-atoms possessing both electric and magnetic responses making their impedance matched with air. As a result, it can efficiently engineer the transmission wavefront with reflection loss significantly suppressed. In addition, Chen's group proposed a tri-layer meta-device composed by carefully designed anisotropic resonators sandwiched by two orthogonal metallic gratings (MGs), which can simultaneously achieve anomalous refraction and polarization rotation for incident THz wave, with efficiency boosted by multiple scattering processes inside the device [112].

Realizing plasmonic metasurfaces at high frequencies (e.g. THz and optical frequencies) face grand challenges due to structural complexities and enhanced Ohmic losses. Alternatively, Staude *et al* proposed a low-loss dielectric metasurface composed by disk-like resonators that exhibit both electric and magnetic resonances and thus an impedance matched with air [113]. Such dielectric metasurfaces, in either transmission or reflection configuration, can modulate local phases of light within the whole range of $[0, 2\pi]$, being ideal candidates to efficiently engineer the wavefront of light at optical frequencies.

Going beyond the diffraction-optics concept based upon phase accumulations inside bulk optical devices, metasurfaces stimulate a brand-new direction of 'flat optics' based on tailored interfacial phases. Following this idea, many intriguing wave-manipulation effects were successfully demonstrated with flat meta-devices, such as focusing, holograms, cloaking, special beam generations, and so on.

Current and future challenges

As the basis of nearly all wavefront engineering, realizing arbitrary beam steering is highly important but still faces challenges, of which one is how to maintain high efficiencies for all bending angles. While metasurfaces realized in early years work well in most cases, they all encounter the low-efficiency issue for large bending angles. Revisiting the commonly adopted design strategy based on Huygen's principle [6, 7], we note that the meta-atoms in a metasurface were usually determined by the conditions that they yield desired transmission or reflection phases as they are arranged in a periodic lattice. However, local field experienced by a meta-atom contains out-going waves generated by other meta-atoms inside an inhomogeneous metasurface, which is obviously different from that in a periodic metasurface. Neglecting such local-field corrections is only justified for small-angle deflections, but can cause serious efficiency reduction for large bending angles.

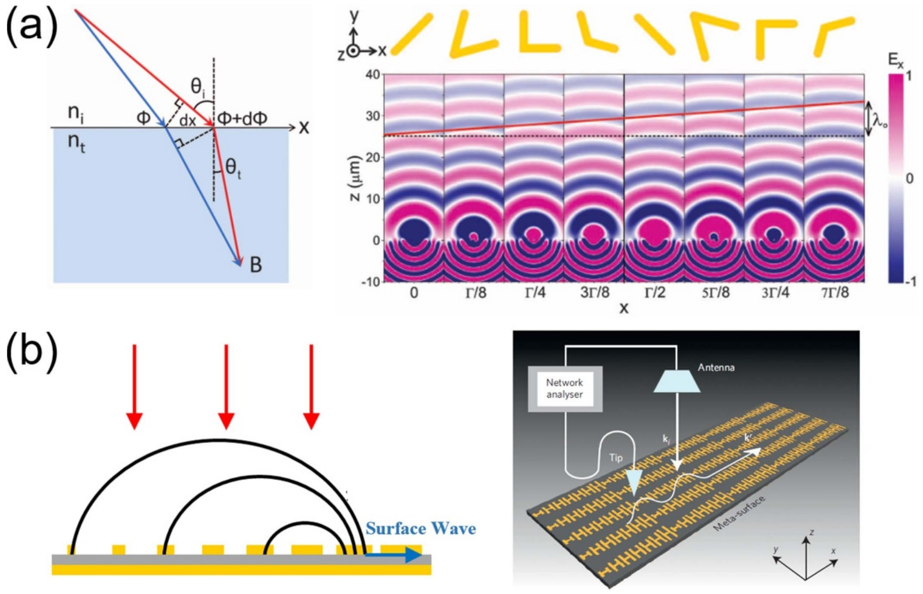

Figure 18. Anomalous deflection [6] and surface wave excitation [7] determined by the generalized Snell's law. From [6]. Reprinted with permission from AAAS. Reproduced from [7], with permission from Springer Nature.

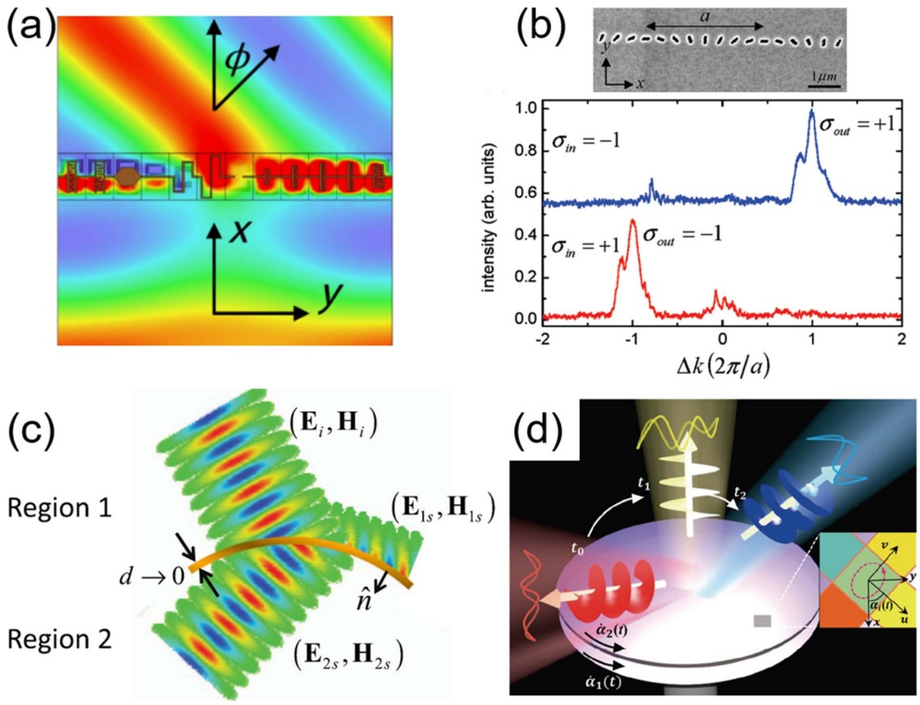

Figure 19. Anomalous beam steering achieved respectively by (a) resonant metasurface [111]. Reprinted with permission from [111], Copyright 2013 by the American Physical Society. (b) PB metasurface [114]. Reprinted with permission from [114]. Copyright (2011) American Chemical Society. (c) Loss-gain metasurface [115]. Reproduced from [115]. CC BY 3.0. (d) Tunable metasurface [116]. Reproduced from [116]. CC BY 4.0.

Another key issue is how to expand the working bandwidth of the beam-deflection meta-devices. Since a metasurface is typically constructed by a series of different meta-atoms exhibiting desired phases at a single frequency, the metasurface cannot maintain an ideal linear phase distribution at other frequencies, due to distinct frequency dispersions possessed by different meta-atoms. Such an issue intrinsically limits the working bandwidths of light-bending meta-surfaces. Although Pancharatnam–Berry (PB) metasurfaces (see figure 19(b)) [114] can preserve desired phase profiles for anomalously scattered waves at all frequencies thanks to the dispersionless properties of geometric phases, the efficiencies of these devices are still frequency-dependent which again limit their working bandwidths.

Finally, most passive metasurfaces can only deflect light to certain pre-determined angles, being unfavorable for many applications requiring dynamic beam-steering. To redirect impinging waves to arbitrary directions actively, we need to construct meta-surfaces exhibiting phase profiles that can change with respect to time. A commonly adopted approach is to connect each meta-atom with an external knob, which can control the phase retardation of the very meta-atom covering a full range of 2π. However, while such local-tuning mechanism works well in microwave regime where PIN and varactor diodes are available, it is hard to work in high-frequency regimes, due to lacking suitable active elements and enhanced Ohmic losses. New schemes are desired to achieve this goal.

Advances in science and technology to meet challenges

Designing metasurfaces that can perfectly bend light to extremely large angles attracted intense interests recently. In 2016, Mohammadi Estakhri and Alù proposed to determine the impedance profile of a metasurface based on the total EM fields at different local positions including both incident and out-going waves, rather than considering only the incident wave as in the conventional design strategy (see figure 19(c)) [115]. Theoretical analyses based on this strategy revealed that a perfect-efficiency metasurface should contain not only passive materials with appropriate losses but also active materials with certain gains. However, such gain–loss metasurfaces are difficult to realize in practice. Later, researchers found that perfect-efficiency beam-bending metasurfaces can also be formed by passive materials exhibiting non-local responses, which is realizable in practice. However, designing these non-local metasurfaces usually rely on large-scale parameter optimizations. Many practically more applicable design schemes were then proposed until recently.

Many efforts were also devoted to expanding the working bandwidth of the meta-devices. A practical way is to adopt low-quality (Q) factor meta-atoms to form the meta-devices, so that the desired linear phase profiles can be maintained within relatively broad frequency band. For PB metasurfaces, the key issue is to expand the frequency band inside which the constitutional meta-atom possesses a high polarization conversion ratio, which is usually achieved via reducing the Q factors of two resonances for two orthogonal polarizations. Dielectric metasurfaces typically exhibit broad band, due to the low-Q nature of the dielectric resonances. However, the requirement of full 2π phase coverage calls for dielectric structures with high aspect-ratios, which are challenging in practical fabrications.

New-concept metasurfaces were proposed for dynamically controlling EM waves at high frequencies. For instance, combining a graphene layer with a carefully designed metasurface, researchers can dynamically control the wavefront of a THz beam reflected by the meta-device with the graphene layer gated uniformly [117]. To realize a continuous beam steering, a mechanically reconfigurable metasurface was proposed with its microstructures fabricated on a stretchable substrate. However, refraction angle can be only adjusted from 11.4° to 14.9° by stretching the substrate by $\sim$30% [118]. Alternatively, a cascaded meta-device consisting of two transmissive metasurfaces was recently proposed, which can dynamically steer a THz beam through it over a large solid angle, as two constitutional metasurfaces are rotated at different speeds (see figure 19(d)) [116].

Concluding remarks

Based on the generalized Snell's law, light-bending metasurfaces in both transmission and reflection configurations were recently reported, aiming to achieve high-efficiency, broadband, full-space, wide-angle and tunable steering on EM waves at frequencies ranging from microwave to visible. Many new design strategies were proposed, based on local or nonlocal responses of meta-atoms with different types facing different requirements. In the future, considerations on time, momentum and material spaces can provide more degrees of freedom to design metasurfaces for controlling light.

Acknowledgments

The authors acknowledge the financial support from National Key Research and Development Program of China (2020YFA0710100, 2017YFA0303504), National Natural Science Foundation of China (Nos. 11874118, 91850101, 11734007, 62192771), and Shanghai Science and Technology Committee (Grant No. 20JC1414601).

3.2. Metasurface fabrication and devices

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Status

Metasurface, a novel platform to manipulate propagating properties of EM waves, has been widely used to achieve unconventional photonic behavior on a 2D surface. This magical photonic manipulation is based on the generalized Snell's law proposed by Yu *et al* in 2011, where defines the general principle of light propagation on an inhomogeneous surface [6]. The boundaries with phase discontinuities can be realized by a number of subwavelength meta-atoms with various or gradually changing magnitude/phase-frequency response (see figure 20(b)). In the early stage, the basic elements of metasurfaces are usually designed to compensate the phase shift in the optical path. This is a significant advance to break the geometrical limitation in broadband achromatic imaging [119] (figure 20(c)). Later, metasurfaces are extended to ultrahigh-resolution displays [120] (figure 20(a)), on-chip mode conversion for integrated photonic circuitries [121] (figure 20(d)), beyond-5G wireless communication [11] (figure 20(e)), and intelligent wave-front manipulation [52] (figure 20(f)).

The high-performance realization of metasurface does not only relies on clever structural design, but also depends on the reliable fabrication technologies. This is because that the EM responses of meta-atoms are highly related to the fabrication resolution of their subwavelength geometries. For example, conventional PCB technology is usually chosen to fabricate metasurfaces at low frequencies, e.g. microwaves and mmWaves. However, most of current commercial PCB techniques cannot match the fabrication requirement for metasurfaces at terahertz and higher frequencies due to the fabrication resolution. Therefore, photon/electron-related lithography processes and laser direct writing, have been selectively adopted in the optical metasurface realization. Among them, laser direct writing, which can modify almost all the materials including diamond, sapphire and lithium nitrate, has exhibited its potential on realizing 3D meta-atoms with high-index, non-linear or ultrahard features. All these advanced fabrication technologies triggers metasurfaces developed rapidly from theory to devices in the past decade.

Current and future challenges

Metasurface devices have exhibited significant potential in practical applications over almost all the EM spectrum. However, there are still several fabrication challenges that limit metasurface devices from the industrially mass production and application.

- **Large-scale heterostructure integration.** For beyond-5G wireless communications, low loss, high-DOF beam adaptivity, large apertures are required properties of metasurface devices. Currently, to meet this beam adaptivity, thousands of tunable elements, such as diodes and varactors, have to be welded manually onto the metasurface devices after plasmonic structures are fabricated through PCB technology. This unintegrated manufacturing process will rise material and labor costs, and therefore, does not match the requirement on mass industrial production. It is necessary to develop a heterostructure-integrated fabrication procedure that merges the boundary between semi-conductor elements and plasmonic circuitries for meter-scale metasurfaces.
- **3D fabrication for special application.** By extending 2D or quasi-3D meta-atoms to true-3D structures, the additional out-plane structural DOF may bring more exotic photonic properties into the metasurfaces. Further merging true-3D structures with the exotic material properties of high index, nonlinear effect or high-temperature resistance, metasurface will find their applications in specialized scenarios. However, massive ture-3D meta-atoms with specialized materials will cost a long fabrication time by laser direct writing. This is because the aforementioned materials usually need high volumetric power density in serial laser fabrication process. The rapid fabrication of massive true-3D subwavelength meta-atoms is the main challenge to realize optical metasurface for special application.
- **Multi-spectrum functional integration.** Current metasurface devices mainly focus on the function realization within a single spectral regime. However, there are still growing requirement on multi-spectrum integrated metasurfaces. To achieve this multi-spectrum functional integration, the meta-atoms of the metasurface should have high-order structural DOF regarding the wavelengths of interest. Therefore, the geometrical and material requirement of all the spectral regimes should be taken into consideration in the metasurface fabrication.

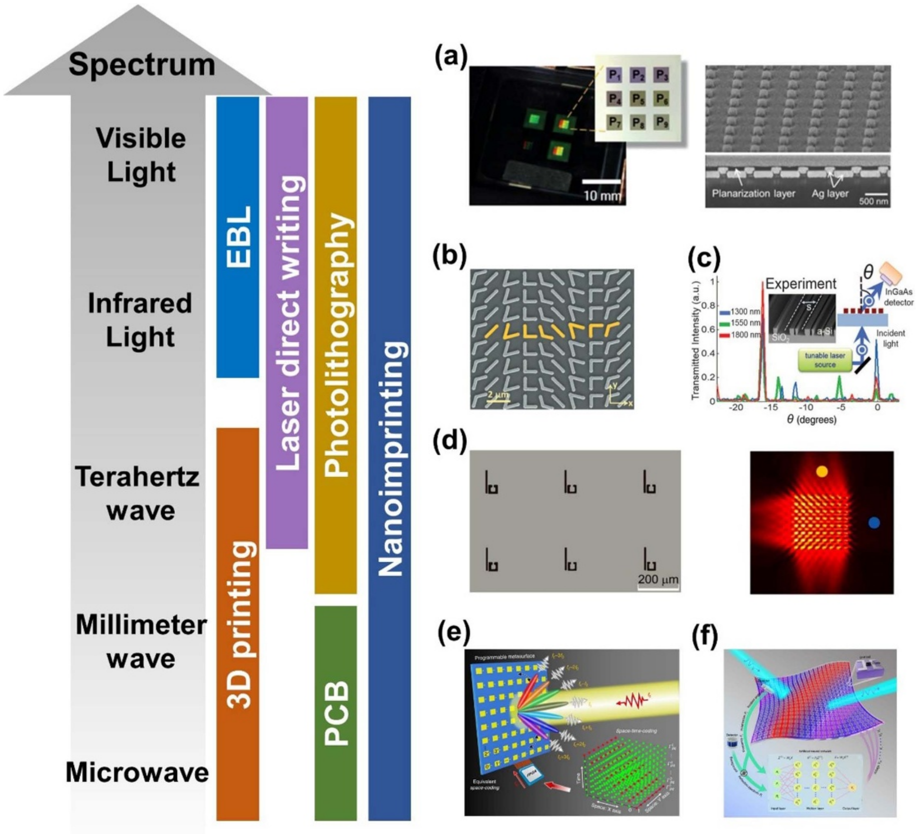

Figure 20. Metasurface devices fabricated with various fabrication technologies. (a) Metasurface-driven displays with ultrahigh resolution [120]. From [120]. Reprinted with permission from AAAS. (b), (c) Infrared metasurface for phase compensation [6, 119]. From [6]. Reprinted with permission from AAAS. From [119]. Reprinted with permission from AAAS. (d) Terahertz metasurface-based surface plasmon excitation [121]. Reproduced from [121]. CC BY 4.0. (e) Programmable metasurface for beamforming and wireless communication [11]. Reproduced from [11]. CC BY 4.0. (f) Deep-learning metasurface-based camouflage technology [52]. Reproduced from [52], with permission from Springer Nature.

Advances in science and technology to meet challenges

To meet the aforementioned challenges, several advanced fabrication technologies are worth of attention here, accompanied with currently used PCB, lithography, etching and lift-off processes.

- **High-resolution 3D printing.** The 3D printing technologies have become mature for commercial use recently. In contrast to conventional 2D fabrication technologies, commercial 3D printer can be used to convert photo/thermal-sensitive polymers and metals into complex 3D shapes that produce orbital-angular momentum and chirality of light over a relatively large area (see figure 21(a)) [122]. With ten-micrometer fabrication resolution, it is enough to achieve metasurface at sub-terahertz regimes. Additionally, it is very convenient to realize the metasurface with mechanical tunability for intelligent EM application.
- **Nanoimprinting.** The nanoimprinting technology (see figure 21(b)) is a class of fabrication process flow with master plate lithography, mechanical stamp, deposition and etching [120]. The lithography-fabricated mask, which can be repeatably used in nanoimprinting, ensures that the nanoimprinting-based metasurface own the advantage of low cost and high geometrical resolution in mass production. Additionally, nanoimprinting with micrometer-scale resolution is also feasible for large-area fabrication. Therefore, it is possible to integrate cross-wavelength functions within a single large-size metasurface through nanoimprinting technology.
- **Ultrafast laser nanomachining.** Ultrafast laser nanomachining has attracted much attention for its non-contact 2D surface ablation and 3D modification in the transparent dielectric materials under the environment of air. By utilizing an O-FIB technology (optical far-field-induced nearfield breakdown [123], see figure 21(c)), the fabrication resolution has been significantly improved to <20 nm, which provides a minimum birefringent modification as high as 9 nm. Moreover, femtosecond laser-induced plasmonic nanoimprinting enables high-efficient fabrication of uniform micro/nanostructures on the hard materials [124]. These works greatly broaden the application scenario of ultrafast laser fabrications and providing powerful tools to obtain metasurfaces working under harsh environments.

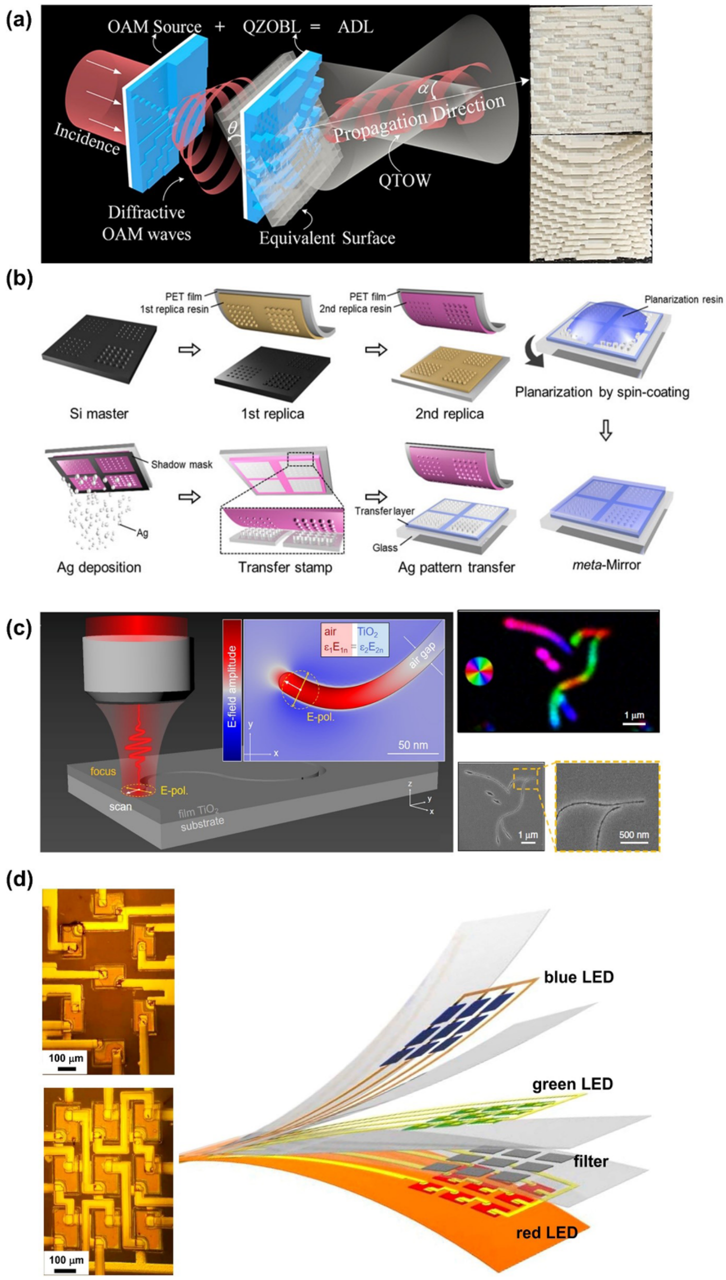

Figure 21. Selected methods to meet metasurface fabrication challenges. (a) Commercial 3D printing: an example to produce orbital-angular momentum with sub-terahertz metasurface [122]. Reprinted with permission from [122]. Copyright (2021) American Chemical Society. (b) Nanoimprinting lithography process [120]. From [120]. Reprinted with permission from AAAS. (c) O-FIB: a new type of laser direct writing under the environment of air [123]. Reproduced from [123]. CC BY 4.0. (d) Micro-LED array process: the candidate for large-scale heterostructure integration [125]. Reproduced with permission from [125].

- **Micro-LED array process.** Micro-LED (light-emitting diodes) process could Integrate organic/plasmonic elements and their semiconductor-based driving circuitry in a compact form for high-performance displays in several inches (see figure 21(d)) [125]. This unique property provides a potential fabrication routine for high-performance tunable metasurfaces for wireless communications and optical applications in automatic production.

Concluding remarks

Advanced fabrication technologies enable the metasurfaces developed rapidly from theory to reality in the past decade. Nowadays, metasurface devices have attracted great attention from various communities due to their novel applications in beyond-5G wireless communications, optical imaging/holography and high-resolution displays. Further developing high-resolution, low-cost, large-area and heterostructure-applicable fabrication technologies, will pave the way to new metasurface devices for industrial applications and promote metasurfaces as a powerful platform for scientific study, from microwaves to visible light.

Acknowledgments

This work at Jilin University was sponsored by the National Natural Science Foundation of China (NSFC) Grant Nos. 61805097, 61935015 and 62175083. S X acknowledges the Support from Fundamental Research Funds for the Central Universities.

3.3. Metasurfaces with simultaneous amplitude and phase modulations

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Status

Light is believed as alternative carrier of information other than electron, which receives intensive attention in science and applications. Amplitude, phase and polarization are fundamental characteristics of light fields. However, owing to the weak interactions between light and natural molecules/atoms, naturally existing materials only exhibit limited abilities to control light waves. Metasurfaces, constructed by planar meta-atoms with predefined optical responses arranged in specific global orders, are recently proposed to efficiently manipulate light fields in subwavelength scale [126]. Relying on resonances of different natures (e.g. electric resonance, magnetic resonance, Mie resonance, etc), metasurfaces can induce dramatic changes on amplitudes and/or phases for impinging light. Meanwhile, anisotropic responses of metasurfaces on light waves polarized along orthogonal directions offer numerous opportunities to tailor the polarization state of light. Early efforts are mainly devoted to designing periodic metasurfaces consisting of functional meta-atoms exhibiting different properties, which can manipulate these fundamental properties of light in the desired manner.

Recently, scientists gradually realized the important role played by global order on which the meta-atoms are arranged inside a metasurface. A diversified set of fascinating wave-manipulation effects were realized by inhomogeneous metasurfaces composed by different resonators exhibiting tailored EM properties. According to Huygens' principle, interference among waves scattered by different meta-atoms can form a new wavefront for scattered light beam, depending on the amplitudes and phases of locally scattered waves. A wide range of wavefront-engineering effects has been achieved with such planar meta-devices, such as anomalous reflection/refraction, surface wave excitations, meta-lens, special beam generation, holograms, and so on [126]. These unique features offer metasurfaces powerful wave-manipulation capabilities, making them particularly suitable for future on-chip photonic applications.

However, most early reported metasurfaces were designed to exhibit desired phase profiles only, where the amplitude distributions of scattered waves were usually not considered. In fact, simultaneous controls on amplitudes and phases of locally scattered light fields are highly desired in many important applications, such as beam shaping, complex optical-field generations, holograms, and so on. For example, conventional holography techniques replying on either amplitude- or phase- modulation inevitably suffer from the issues of low quality, speckle noise and/or twin images, due to losing certain information of target object. In 2013, Ni *et al* experimentally demonstrated a high-resolution low-noise hologram based on a metasurface (see figure 22(a)) that can modulate both amplitude and phase of light wave locally in the visible range [127]. Following similar concept, complex-amplitude metasurfaces are widely investigated for beam forming, multiple diffractions, vectorial beams, etc.

Current and future challenges

Finding appropriate meta-atoms to independently manipulate both amplitudes and phases of locally scattered waves is also highly challenging in practical designs. Taking the widely adopted V-shape nano-antenna as an example [127], we find that the amplitude and phase of wave scattered by it are strongly correlated with each other as we tune its geometric parameters (i.e. the arm length and opening angle). Therefore, people have to adopt time-consuming calculations within a huge parameter space to search for meta-atoms that can yield the desired complex amplitudes of scattered fields. Certain approximations need to be taken in practical designs, in cases that desired amplitude and phase are difficult to meet precisely. In addition, transmission amplitudes enabled by different meta-atoms inside such single-layer metasurface are usually far away from 100%. All these limitations significantly degrade the performances of realized meta-devices.

Ohmic loss is another DOF that can be used to manipulate the amplitudes of light waves, but how to control losses in desired manner is challenging. For instance, Bao *et al* proposed an Ohmic-loss-assisted coding metasurface exhibiting a specific complex-amplitude profile for light fields [128]. Via individually designing the widths of lossy ITO patterns, four digital elements are obtained that can modulate the

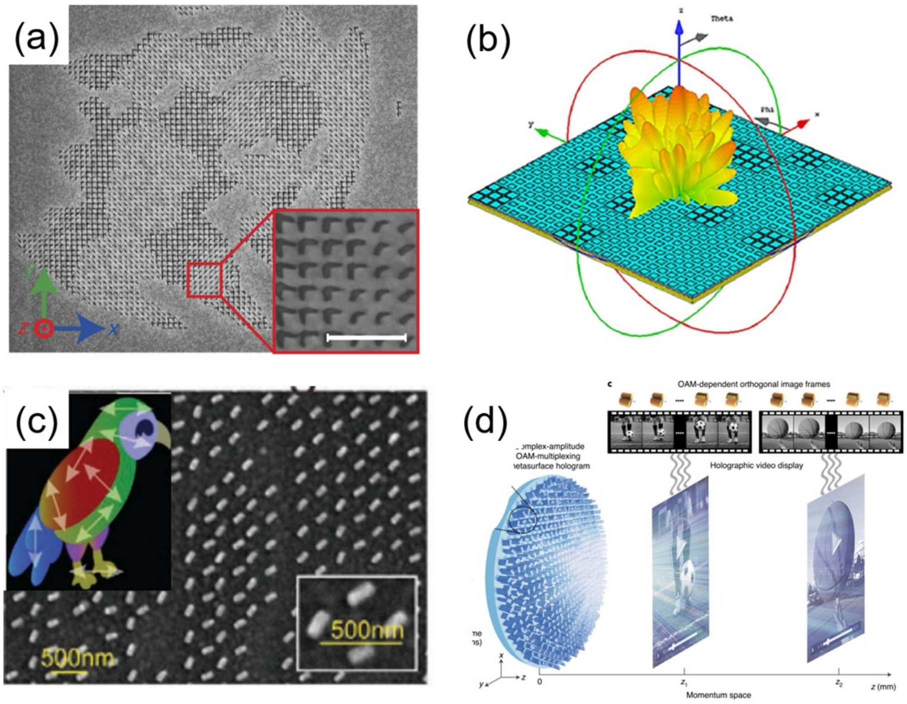

Figure 22. Complex-amplitude metasurfaces working for (a), (b) linear polarization and (c), (d) circular polarization light. Reproduced from [127], with permission from Springer Nature. Reprinted from [128], with the permission of AIP Publishing. [129] John Wiley & Sons. © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced from [130], with permission from Springer Nature.

amplitude and phase of light field in the ranges of [0.3, 0.7] and [0, 2π], respectively. Such a complex-amplitude metasurface is demonstrated to work for beam steering and scattering reduction (see figure 22(b)). To achieve full-range amplitude and phase modulations, a complex-amplitude meta-hologram is demonstrated in microwave regime [131]. The amplitude is manipulated within [0, 1] by changing the dimension of an ohmic sheet inside the Fabry–Pérot-based tri-layered meta-atoms. Meanwhile, phase of light transmitted through them can vary within [0, 2π] as the geometries and orientations of meta-atoms change. This strategy provides an alternative approach to achieve high-quality microwave holography. However, extending such a local-tuning mechanism to frequencies higher than GHz remains a challenge, due to lacking suitable active elements.

Finally, early reported complex-amplitude metasurfaces usually suffer from limited functionalities and narrow working bands, owing to complexities in designing the practical structures. In addition, to meet certain application requirements (e.g. vectorial optical fields generations), nearly all relevant characteristics of light waves (including amplitude, phase and polarization) should be individually manipulated in subwavelength scale. Therefore, new-concept metasurfaces exhibiting more controllable parameters are needed to achieve such complicated optical fields manipulations, which, however, inevitably increase the challenges in both designs and fabrications.

Advances in science and technology to meet challenges

Various new-concept metasurfaces are proposed to solve the issues mentioned in last section. For instance, Farmahini-Farahani *et al* proposed a microwave metasurface to independently control both amplitude and phase of an incident wave locally in the desired manner. The unit cell consists of two cascaded microstructures with distinct geometries, which can tune the amplitudes and phases of locally transmitted waves [132]. However, such multi-layered metasurface is difficult to realize at optical frequencies. Liu *et al* proposed a broadband single-layer C-shape metasurface for simultaneously controlling the amplitudes and phases of light waves [133]. Illuminated with linearly polarized (LP) light, such meta-atoms can scatter cross-polarized light exhibiting tailored amplitude and phase as we change the sizes and orientations of meta-atoms correspondingly. Arbitrary controls on the intensity of each diffraction mode are experimentally demonstrated based on such a metasurface. In addition to controlling the LP waves, researchers also proposed to individually manipulate the amplitude and phase of circular polarized light based on PB metasurfaces [134]. Through tuning the geometry anisotropies (and in turn the polarization-conversion capabilities) of the PB meta-atoms, amplitudes of the cross-polarized scattered light can be flexibly varied.

Meanwhile, a dispersionless phase profile can be realized in such a PB metasurface. It should be noted that, however, all metasurfaces working for cross-polarized modes [133, 134] will inevitably suffer from the influences from the undesired co-polarized waves.

More degrees of freedom are explored to expand the functionalities of complex-amplitude metasurfaces. In 2013, Lin *et al* reported a metahologram in a detour phase scheme that can generate complicated optical fields within a broad wavelength range. Such a cascaded device is formed by a radial polarizer and detour phase hologram that can cooperatively generate the radially polarized vortex beam [135]. However, such a diffraction-based device suffers from the problems of low-efficiency and large-scale pixel (greater than wavelength). Deng *et al* proposed a multi-freedom metasurface than can independently modulate the amplitude, phase and polarization of impinging lights. With two kinds of dispersionless phases combined together (PB phase and detour phase), such meta-atoms have multiple freedoms (including the orientation, separation and displacement) for wave manipulations. Owing to these advantages, full-color vectorial holograms at visible wavelengths were experimentally demonstrated with such a meta-device [129] (see figure 22(c)). Ren *et al* proposed a holography technique that can be used to encode 200 pieces of information with different orthogonal OAM. Such functionality is realized by a full-range-controllable complex-amplitude metasurface designed at visible wavelengths. Based on Fourier transformations, the carried images can be reconstructed on two separate planes, as the meta-device is illuminated by light exhibiting different OAM [130] (see figure 22(d)).

Concluding remarks

Complex-amplitude metasurfaces have been widely explored in the past few years for diverse applications, including beam forming, Airy Beam generation, metaholograms, and so on. Equipped with more tuning degrees of freedom, new-concept metasurfaces are continuously proposed to exhibit expanded functionalities for controlling light, including frequency-multiplexed, polarization-modulated, full-space wave manipulations. In the future, active/tunable metasurfaces, that can achieve full-range and independent controls on amplitudes and phases of light waves in deep-subwavelength scale, are highly desired.

Acknowledgments

The authors acknowledge the financial support from National Key Research and Development Program of China (2020YFA0710100 and 2017YFA0303504), National Natural Science Foundation of China (Nos. 11874118, 91850101, 11734007 and 62192771), and Shanghai Science and Technology Committee (Grant No. 20JC1414601).

3.4. Metasurfaces for polarization control

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Status

As a fundamental property of light, polarization describes the vector property of optical field. In comparison with its scalar counterparts (e.g. amplitude and phase), polarization related optical phenomena are more complicated due to the involvement of light–matter interaction. Understanding and controlling the polarization of light are beneficial to fundamental research such as material science and quantum physics. Meanwhile, the on-demand polarization control can facilitate many practical applications, including optical communications, advanced imaging and sensing.

Polarization control in traditional optics relies on natural crystals such as quartz and calcite. Due to the relatively small difference between the ordinary and extraordinary refractive indices of these crystals, it is difficult to develop crystal based ultrathin polarization related optical elements due to the system complexity, large volume and high cost. Driven by system integration and device miniaturization, there is huge interest in developing ultrathin and lightweight planar optical devices for polarization control. Benefiting from the unusual properties, the emergent optical metasurfaces have provided a compact platform for polarization control at the subwavelength scale, leading to a paradigm shift in the design of polarization optics.

Optical fields with spatially-variant polarization distributions have received great attention owing to the promising practical applications such as super-resolution imaging and lithography. Metasurfaces have been used for polarization control at the interfaces [136–140]. Combined with phase manipulation, the desired vectorial fields can be further generated in the diffraction space, with either 2D polarization profiles or 3D distributions [129, 141–148]. Polarization multiplexing is another important topic of the emerging metasurface-assisted polarization optics [149–160]. The rich DOFs in metasurface design allows one to develop all-in-one meta-devices with multiple functionalities, by taking full advantage of the different responses of multi-tasked metasurfaces to multiple polarization incidences.

Current and future challenges

Despite the rapid progress in metasurfaces for polarization control, some challenges remain to be overcome. Vector fields can be generated not only at the interfaces of metasurfaces by controlling their geometric shape, dimensions and spatial configurations, but also in the diffraction space, where the complex amplitudes (i.e. amplitude and phase) of output light would also affect the polarization distribution in the far-field. The mapping between the light field on the metasurface plane and that in the far-field needs to be carefully considered. Besides, in order to generate the desired 2D polarization profiles/3D polarization distributions in the far-field, the meta-atoms on the metasurface may need to be capable of manipulating not only polarization, but also the amplitude and phase of the incident light simultaneously.

Apart from the above challenges in generating specific vector fields, there are also some challenges in metasurface-assisted polarization multiplexing. On one hand, numerous efforts have been made to increase the number of polarization-multiplexed information channel. For instance, configuring more than two nanostructures to form a super-cell and stacking different nanostructures along the optical axis can provide more DOFs, enabling multi-channel metasurfaces with engineered responses to more polarization states. However, it is still not clear about the upper-limit of the information channels enabled by metasurface-assisted polarization multiplexing. Another issue is the performance limitations of polarization-multiplexed multifunctional devices, e.g. design difficulty, low efficiency, crosstalk and function degradation, which are caused by the coupling between the polarization control in different channels. Attempts have been made to alleviate the coupling to some extent, whereas it is still challenging to achieve complete decoupling of the functionalities in different channels.

Advances in science and technology to meet challenges

The recent advances in metasurfaces for polarization control are summarized in figure 23. Under the illumination of incident light with different polarization states, e.g. unpolarized, LP, circularly-polarized (CP) and elliptically-polarized light, metasurfaces can generate vector fields not only on their surfaces, but also in the far-field. With metasurfaces, many basic polarization optical elements can be readily developed through generating homogeneous polarization distributions on their surfaces. By taking full advantage of the resonant effect in the meta-atoms, high contrast of refractive index along different principal axes can be

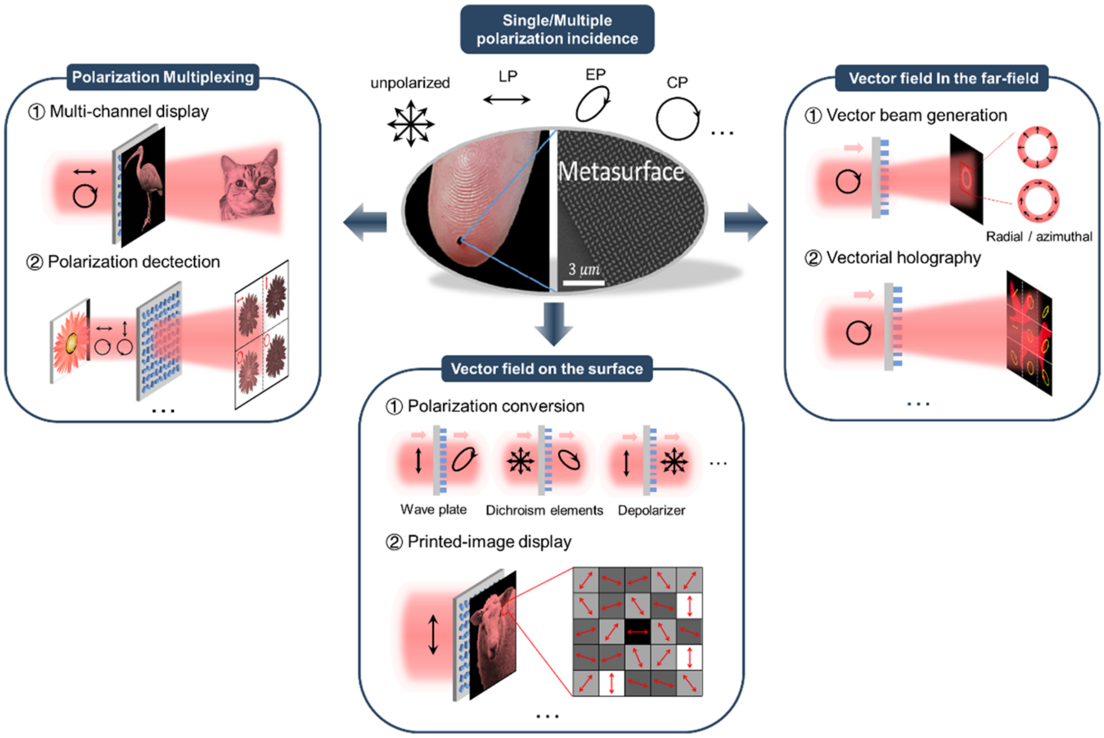

Figure 23. Schematic of advances in metasurfaces for polarization control. Reprinted with permission from [161]. Copyright (2018) American Chemical Society.

achieved, making it easy for developing ultrathin polarization conversion optical elements such as wave plates [136]. Besides, a single metasurface can perform relatively complex polarization conversion which requires the combination of multiple polarization optical elements in traditional optics. For instance, Wang *et al* proposed a metasurface for arbitrary polarization conversion dichroism, which can generate the same customized polarization output regardless of the incident polarization [137]. The meta-atom is composed of two nanobricks working as linear birefringent waveplates. By tailoring the orientation angles of the two nanobricks and the dimensions of one nanobrick, the metasurface can act as a linear polarizer, circular polarizer or elliptical polarizer. If the anisotropy of each meta-atom in a metasurface is tailored cell-by-cell, inhomogeneous vector field can be formed on the surface, which can be transformed into intensity distribution by using a bulky optic analyzer [138–140]. Yue *et al* encoded an image with pixel sizes of 300 nm $\times$ 300 nm into a metasurface, which can be observed by placing the metasurface between a bulky polarizer and analyzer [138]. This research team further demonstrated a color printed-image display by introducing structural-colors into their previous work [139]. The color image is composed of two sets of intensity distribution for the red and green components, each corresponding to a polarization profile generated by nanostructures on the metasurface. Generally, the metasurface-based printed-image displays feature a high resolution on the order of $\sim$10 000 (84 667 in [140]) dots per inch, which paves a new avenue for metasurfaces in various applications including ultra-compact displays, high-density data storage, high-end anti-counterfeiting and so on.

By combining the polarization control with phase manipulation of incident light, metasurfaces can be used to generate desired vector field in the diffraction space. Bao *et al* proposed a metasurface for the generation of perfect vector vortex beams [141]. By the inverse vector Rayleigh–Sommerfeld formula, the desired amplitude, phase and polarization modulations of the metasurface are calculated, and realized by meta-atom consists of two identical nanobricks with varied positions and orientations. Similarly, for vectorial holography, the far-field polarization distribution should be mapped to vector field on the surface which can be physically implemented by using metasurface. One solution is segmenting different functional zones on the metasurface, and each zone generates one part of the holographic image with pre-designed polarization [129, 142–145]. The main challenge of this approach lies in designing meta-atoms for simultaneous phase and polarization control, among which diatomic and supercell configuration are widely employed for vectorial meta-holography. Diatomic metasurfaces performed phase and polarization modulations with displacements and orientations of identical nanostructures [129, 142]. For super-cell configuration, two groups of nanostructures were used to modulate the left-handed circularly polarized

(LCP) and right-handed circularly polarized (RCP) light respectively, and polarization control were implemented by adjusting the phase difference and amplitude ratio of LCP and RCP components [143–145]. Together with k-space ptychography, full-color vectorial meta-holography were realized based on the approach mentioned above [129, 145]. To generate holograms whose far-field has designer-specified polarization response, Rubin *et al* linked the vector field on the metasurface plane and that in the far-field by the Fourier transform, and a matrix-valued phase retrieval algorithm was proposed to obtain a Jones matrix profile of the meta-atoms on the metasurface [146]. Meanwhile, there is much progress in generating 3D polarization distributions by metasurfaces. Chen and his colleagues demonstrated a metalens that can focus light into an arbitrarily shaped focal curve in 3D space, with controlled local polarization distribution [147]. Inspired by the idea of spatial harmonic beating, Dorrah *et al* demonstrated a meta-device with customized polarization response along the propagation direction, i.e. the polarizations in different planes along the propagation direction were variable and controllable [148].

Significant progress has also been made on metasurface-assisted polarization multiplexing, which have developed from the primary orthogonal polarization multiplexing, to polarization multiplexing of two arbitrary states, and to current triple polarization multiplexing. As a result, a variety of multifunctional meta-devices with functions unattainable by using traditional optics are reported. Multi-channel displays, in the form of multiplexing nanoprinting [149, 150], holography multiplexing [151], and integration of nanoprinting and holography [152–155] were extensively studied and reported. Deng *et al* proposed multiplexing meta-image displays for anticounterfeiting [149]. The displaying of a continuous grayscale image and a pseudo-binary anticounterfeiting pattern can be readily switched by placing the metasurface in different polarization optical setups. Li and his colleagues introduced a meta-atom composed of two nanostructures, which enables the displaying of two independent grayscale images with arbitrary non-orthogonal polarization multiplexing [150]. Zhao *et al* proposed multi-channel meta-holography based on nanostructures with varied orientation and dimensions [151]. The holographic image reconstructed in the far-field is readily switched by changing the incident and detected polarizations. By using an interleaving design scheme, Zhang *et al* proposed a multichannel metasurface [152]. This device can display a holographic image in the far-field, and an encoded image in the polarization profiles of output light can be revealed by a polarizer. Zheng and his research team found that the orientation degeneracy implied in Malus law can provide a new design DOF for geometric phase manipulation, and different kinds of polarization-multiplexed displays merging the functionality of nanoprinting and holography were demonstrated [153–155]. Recently, Bao *et al* proposed a single-layer metasurface with multiplexed information channel up to six [156]. The 2D planar Jones matrix with six DOFs was physically implemented by a meta-atom composed of four nanostructures with varied positions and orientations, which enables advanced functionalities such as triple sets of printing-hologram integrations. The implementation of other polarization-multiplexed devices such as multifunctional metalens and multi-channel spatial frequency filters also attract attention of the metasurface community. Li *et al* demonstrated the combination of nanoprint and metalens by a single-celled metasurface [157]. The near- and far-field functionalities are completely decoupled by exploiting polarization multiplexing. Huo *et al* placed a helicity-multiplexed metasurface working as spatial frequency filters in a Fourier transform system, to realize the switching of either bright-field or phase contrast imaging by changing the helicity of incident CP light [158]. With engineered polarization responses, metasuface can be designed to perform polarization detection, which can also be regarded as a kind of multi-channel device. Khorasaninejad *et al* proposed a metalens capable of chiral imaging by interleaving two groups of off-axis sub-lens [159]. The LCP and RCP components can be focused on different regions of the detection plane. Rubin *et al* demonstrated a full-Stokes camera enabled by a metasurface, which can characterize the Stokes vector of each point of the incident light [160]. Four polarization components in the incident light were designed to be diffracted to different orders and separated.

Concluding remarks

Over the past decade, metasurfaces have revolutionized design concepts in polarization optics, benefitting from the rich DOFs for polarization control in nanostructured metasurface design. Metasurface-assisted polarization optics provides a new platform to develop not only counterparts of many conventional polarization optical elements (e.g. wave plates and polarizers), but also advanced optical devices with micrometer-scale footprint and unusual functionality, such as ultra-compact image displays, vectorial holograms and miniaturized polarization cameras. So far, significant progress and advances have been achieved with metasurfaces for advanced polarization control. Metasurface approaches have been demonstrated to generate 2D polarization profiles near the surface of metasurfaces, and 2D/3D polarization distributions in the far-field. Besides, enabled by polarization multiplexing, the meta-devices have been developed from single functionality with response to only one specific polarization state, to multifunctionality with multiple polarization responses. Nevertheless, some issues worth further exploration and studying to enrich and promote the researches on metasurfaces for polarization control, including but not limited to the abovementioned challenges in generating user-defined 3D polarization distributions in the far-field and expanding the number of multiplexing information channels. We envision that metasurface-assisted polarization optics would promote the exploitation of light's polarization, and can be applied in a wide range of areas such as optical communications, smart sensing, and data storage.

3.5. Metalenses: forging ahead towards applications

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Status

Metasurface is an ultrathin version of metamaterial constituted of a single or few layers of meta-atoms, which have demonstrated unprecedented capabilities in manipulating light. It was initially proposed by subwavelength resonators showing controllable light reflection and refraction with a generalized Snell law [6], and its design principle was further enriched by non-resonant geometric (PB) phase and dynamic propagation phase. The constituent material was extended from the metal to dielectric to further reduce the loss, and make the high efficiency devices more applicable. By now, numerous functionalities have been realized, such as beam engineering, waveplates, polarizers, holograms, and so on. Among them, metalens for imaging has captured significant attention in recent years due to extremely wide applications in optical systems [162]. Great efforts and progresses have been made towards imaging applications, such as efficiency improvement, chromatic and image-aberration corrections [163], etc. However, recent studies have shown that the imaging performances of metalenses in efficiency, working bandwidth, image aberrations, field-of-view (FOV), etc are mutually constrained [164]. Therefore, the comprehensive performance of today's metalenses is still inferior to the traditional refraction lenses and compound lenses. Thus, it is necessary to carefully examine the real application advantages of metalens technology.

Generally speaking, the major advantage of metalens for imaging lies in two aspects. One is the ultrathin, ultralight, and flat architecture, which very much favors minimized, compact and portable devices. The other is the designable multi-functionality with extremely flexible wavefront shaping, polarization control, spectrum tailoring, and function multiplexing. It is also in favor of compact integration by using singlet metalens to replace multiple elements to construct optical systems. Therefore, the device miniaturization and function expansion would be the core of metalens technology, which is very promising in nowadays portable devices like smart phone, augmented reality, pan-tilt camera, and so on. While in the real applications the sacrifices in its comprehensive imaging performance like the efficiency, FOV, bandwidth, etc with respect to its traditional refractive counterparts should be carefully considered and balanced.

Current and future challenges

Although tremendous efforts have been carried out to correct the chromatic and imaging aberrations, it remains big challenges to achieve comprehensively high performance for a macroscopic metalens comparable to the state-of-art of refractive lens groups. Generally speaking, one can hardly design and fabricate a large-scale metalens with simultaneously high efficiency, broadband achromatism, and wide-field imaging. In principle, the reason lies in the fact that the ultrasmall nano-atoms could hardly offer sufficient phase accumulation to compensate the spectral dispersion for a large aperture lens, even if the resonance and geometric phase are exploited. In comparison, propagation phase that heavily relies on the height or aspect ratio of the nano-posts (meta-atoms) would provide larger space for improvement. Therefore, a possible solution lies in enlarging the height of nano-posts, which need to have very large aspect ratio and will undoubtedly add great challenges to nanofabrication. In fact, there have been several papers concerning on the issue [164]. This principle is also valid for another kind of flat lens—multilevel diffractive lens (MDLs), which can be regarded as a paralleled strategy for achromatic flat-lens [165]. Different from metalens, the MDL stemmed from the diffractive optics with optimized complex ring heights, where sufficient phase compensation against the material and diffractive dispersion can be properly achieved. There have been a number of achromatic MDL literatures reporting relatively larger lens diameters compared with metalens thanks to its larger thickness, though it may have some weaknesses in angular dispersion and efficiency. The difficulty of large aspect ratio in polymer structures remains challenge especially for large NA lenses that need small feature size of diffractive rings.

Another important issue is the FOV that severely constrained by the large image aberration (i.e. coma) of metalens. The fundamental limit lies that an ideal large FOV lens should always be of the focusing phase profile for different incident angles no matter what kind of lenses. It is very stringent requirement that needs the lens to have an angular-dependent phase profile, which is extremely difficult. The fact is that most singlet lens only has limited FOV under paraxial approximation condition, beyond which the phase profile will be distorted severely. Compared with refractive lens the diffractive lens and metalens are even worse due to large coma and lower efficiency that lead to even smaller FOV. Although some angular dispersions have manipulated by coupling effect or tilting units, it is still very challenging to reach an overall control in a wide-angle range. To circumvent this problem, great efforts have been made by employing doublet

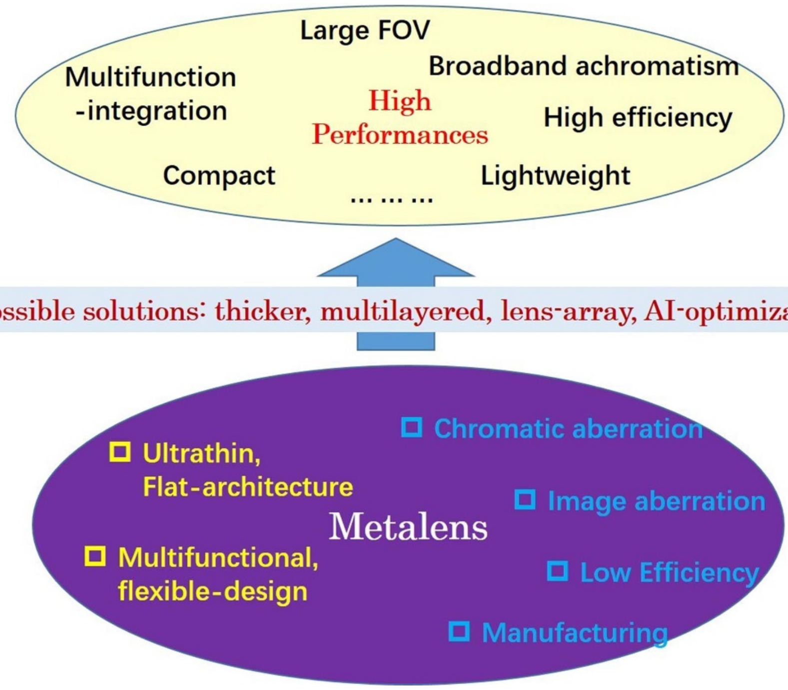

Figure 24. Schematics of metalens roadmap towards high-quality imaging applications.

meta-lenses or imposing quadratic phase profiles to enlarge the FOV [166]. Nevertheless, the overall performance is still not good enough, because one has to sacrifice in either the size of clear aperture or image quality. More possibilities would refer to multi-layered meta-design with complex topological optimization [166], which indeed still has big challenges in time-consuming structural optimization, multilayer fabrication, and efficiency improvement.

Advances in science and technology to meet challenges

Towards the ultimate goal of high-quality imaging performance of metalens, versatile shapes of nano-inclusions with respect to the geometric phase, integrated resonances and propagation phases have been extensively exploited to achieve the broadband achromatic metalenses. But the limited height of nanoposts prohibits its overall performances. A recent considerable high efficiency (near to 90%) was reported in TiO_2 metalens with a record-high aspect ratio (37.5) of the nanopillars [167]. Its relatively high height of 1.5 μm ensures this good performance, while its diameter is still very small (25 μm) indicating the insufficiency to achieve a macroscopic achromatic lens. Nevertheless, it show possibility of high aspect ratio and height nanopost as the advances in nanofabrication, and promises feasible application in high efficient imaging. Of course, the MDL is another possible solution according to the development of gray-scale lithography and transferring technique accompanied with advanced algorithm in structure designs. As for the wide-field imaging lenses, people have proposed adjoint method and Catenary design that efficiently alleviate the coupling problem among unit cells, and demonstrated preliminary wide-angle metalens imaging. Further improvements are undergoing.

Besides the great efforts in developing high-quality metalens from the optical principle, another exciting solution is the assistances of advanced algorithms and powerful computing capability, such as deep learning, topological optimization, inverse design, etc [168]. Many progresses have been made varying from the meta-atom design to performance improvement. As a typical example, neural nano-optics was proposed very recently for high-quality thin lens imaging, which is based on a fully differentiable learning framework [169]. It is undoubted that with the deep involvement of AI technology, high performance metalens is promising.

Apart from these improvement in metalens imaging, another noteworthy issue is the application scenario. Since the major advantage of ultrathin and flat metalens is integration, which is expected to revolutionize the conventional optical devices to more compact form. However, pervious approaches mostly took metalenses as substitutions of conventional refractive lens, which did not change the framework of optical settings. In this regard, the overwhelming impact of metalens was not totally shown. Fortunately, there have been some approaches to implement metalens imaging devices in very compact form, like endoscope imaging, polarization camera, wide-field microscope [170], and so on, showing potential revolutionized applications.

Concluding remarks

In summary, metalens as a brand-new imaging technology have been stressed much more towards practical applications. As such, its chromatism, FOV, working efficiency have been intensively studied and improved. Although the current overall performance of single-chip metalens is still inferior to the traditional refraction compound lenses, there are improvement spaces remain. Figure 24 schematically shows the roadmap of metalens towards high-quality imaging applications. To my personal opinion, there are some clues for further upgrading metalenses to application level. First, thicker metalens (or MDL) with higher aspect ratio of inclusions will effectively expand the phase space to thoroughly improve the imaging performance. Second, multi-layered metalens with/without inter-layer couplings would be an extendable optimization dimension to handle the spectrum and angular dispersions. Third, metalens array stands for a unique framework of the flat architecture, and will provide more designable space to reach high-quality imaging. Last but not least, advanced computation technology empowered by AI will play more and more important role in meta-design and performance improvement. Besides, new opportunities have appeared in application scenarios where the compact integration is much more important, such as, endoscope, augmented reality, compact microscopes, etc. Being endowed with unique advantage of compact integration both in device size and functions, metalenses would revolutionize optical technologies with more information-accessible, stable and portable devices.

Acknowledgments

The authors acknowledge the financial support from The National Key R&D Program of China (2022YFA1404301), National Natural Science Foundation of China (Nos. 12174186, 92250304 and 62288101). Tao Li thanks the support from Dengfeng Project B of Nanjing University.

3.6. Metasurfaces for multi-functional edge imaging

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Status

Optical imaging has been an irreplaceable tool with applications in a variety of fields ranging from biology and chemistry to physics and engineering. Edge detection is of fundamental importance in optical imaging analysis since it preserves important geometric boundaries and significantly reduces the amount of data to be processed. To detect the edges of an object, optical analog computation of the object information is preferred over digital processing due to its advantages in real-time parallelism, high-speed and power-efficiency in specialized computational tasks. Recently, metasurfaces consisting of engineered nano-structures have shown exceptional abilities in light manipulation [6], enabling many applications such as light field imaging [171], polarization imaging [160] and hologram [172]. Thanks to their compactness and flexibility in wavefront design, optical metasurface devices have been also demonstrated for various functionalities in optical analog signal processing. Our goal is to describe the current state of the art in the field of edge imaging by using metasurfaces, outline the challenges and offer directions for future works.

Recently, there have been some experimental demonstrations of edge detection with metasurfaces [173–176]. As shown in figure 25, when the LP light incidents onto the metasurface, the LCP and RCP components experience opposite angular shift due to the opposite OAM from interacting with the metasurface. When the metasurface placed at the Fourier plane of a standard 4f system as demonstrated in figure 25(b), it leads spatially shifted images with an out of phase center linear component. The resulting image contains only the spatially shifted edges of the object with the overlapping region being blocked by an analyzer. Figure 25(c) presents a dielectric metasurface embedded in glass substrate and the formed edge image. The designed dielectric metasuface works at transmission mode and provides advantages of high efficiency, and broadband imaging. Similar edge detection scheme has been extended to the 2D spatial differentiation by using a metasurface with a symmetric phase gradient along the radial direction, which radially splits the incident LP beam into LCP and RCP components as shown in figure 25(d) [174].

Furthermore, quantum switchable optical edge detection, which has high signal-to-noise ratio (SNR) at the same photon flux level with using classical light sources, is enabled by formulating polarization-entangled photon source and the designed metasurface. The entangled photon source with quantum state described by $\frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$ provides the $|H\rangle$ or $|V\rangle$ polarization controlled by the polarization state in the heralding arm as shown in figure 26. An edge image is formed with $|V\rangle$ polarized illumination due to the $|H\rangle$ polarization of the analyzer, while the full image formed with $|H\rangle$ polarized illumination. It can be regarded as an entanglement assisted remote switch for edge detection. A synchronized detector triggered by the heralding signal only accumulate the incident light within a very short time window when the switch is turned ON, which prevents almost all noise photons from being detected.

Current and future challenges

Multifunction. Multifunctional optical systems have garnered great interest in past decade because they are capable of integrating components and reducing system size. In addition to existing superiorities, multifunctional metasurfaces are highly desired to provide tunable functionalities using minimal number of optical components. For example, many optical microscopy techniques have been developed for various biological studies, each with different advantages in resolution, contrast, imaging speed, etc. However, biological system commonly involves many different types of dynamics often require different microscopy techniques to visualize. Simultaneously achieving multiple microscopy modalities typically requires very complex system and is not practical in many applications.

Nonlinearity. Optical nonlinearities have seen increasing demand in all optical computations, especially in optical artificial neural networks. An analog computing metasurface capable of nonlinear operations enables nontrivial calculations by using a small amount of calculation elements. However, due to the negligible nonlinearity of the current material system, the nonlinearity is absence in the existing metasurface design. New material system with giant nonlinearity is in urgent demand. Furthermore, nonlinearity provides an additional DOF to tune metasuface allowing more complex functionalities.

Compact. A single device performing imaging and analog processing simultaneously will greatly miniaturize the whole system and provide a higher degree of integration capability for portable and wearable platforms. Traditionally, optical analog computing including edge detection need the frequency domain

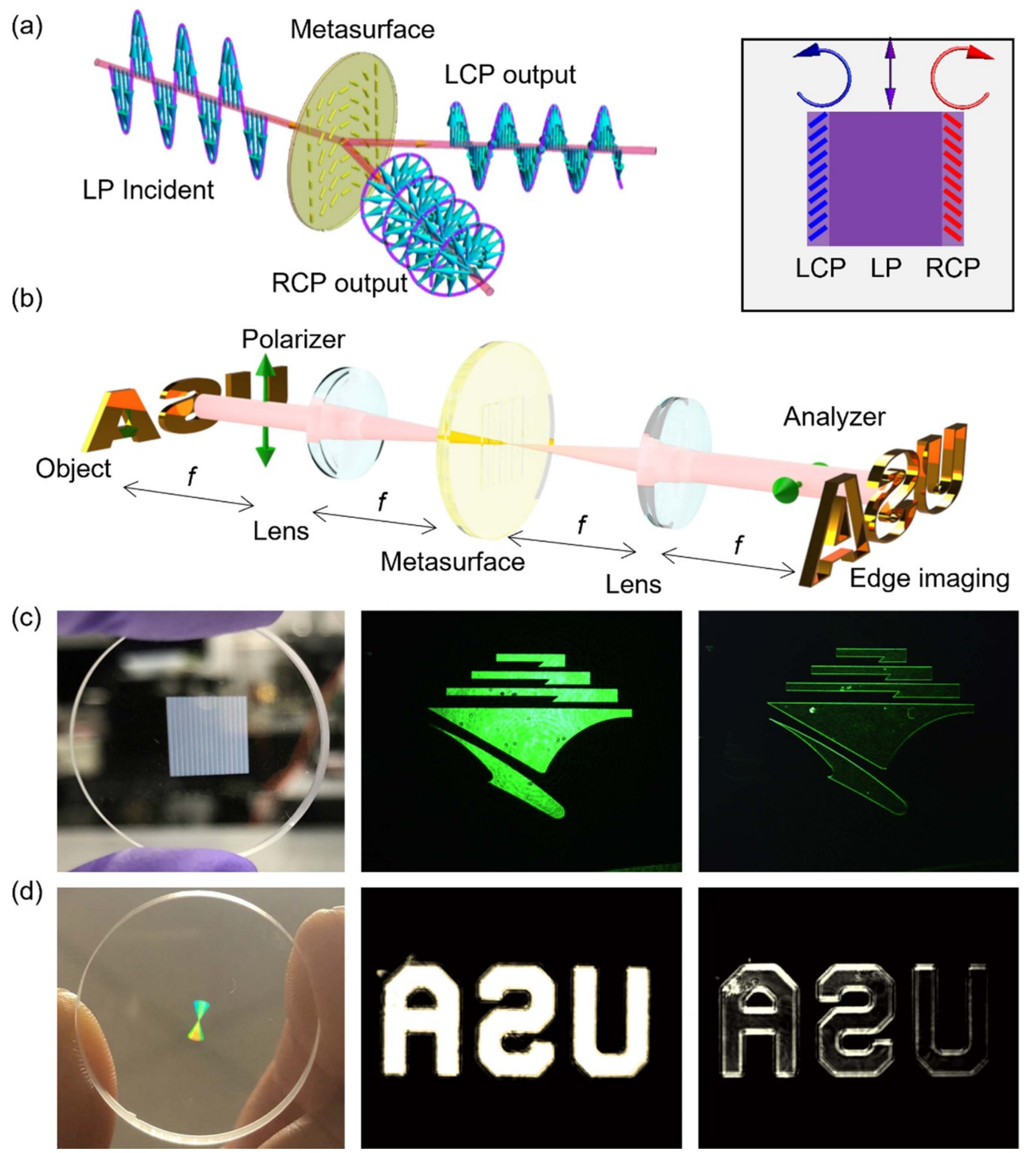

Figure 25. The metasurface enabled one- and two-dimensional edge imaging. (a) The schematic illustration of one-dimensional edge detection based on spin-Hall effect. Reproduced with permission from [173]. (b) A 4f system, consisting of two identical lenses with 2f apart from each other, is used to implement the experiment. The metasurface is placed at one focal length behind the first lens and one focal length in front of the second lens. (c) From left to right, the photo of a metasurface for one-dimensional edge detection, the full image, and the edge image. (d) The 2D edge detection metasurface and resulting images. Reproduced from [174]. CC BY 4.0.

modulation at the Fourier plane in a 4f optical system. However, the spatially separated conjugate planes and the Fourier planes makes the combination of the optical elements difficult.

Super resolution. Super-resolution microscopy techniques emerged in the past two decades circumvented the long-believed Abbe diffraction resolution limit. Illuminations with large spatial frequency components allow for fine sampling of the object, resulting in a super-resolution reconstructed image. To further enhance the resolution capability of existing super-resolution microscopes, metasurfaces provide a way to manipulate light with larger wavevector than that supported by classical materials. A metasurface enabled super-resolution microscope may be integrated with additional functionalities to achieve, for example, super-resolution edge imaging or phase contrast imaging.

Advances in science and technology to meet challenges

Intelligent design. In principle, a metasurface can achieve arbitrary wavefront modulation as long as the amplitude, phase and polarization of the desired light field is known. Existing metasurface designs focus on

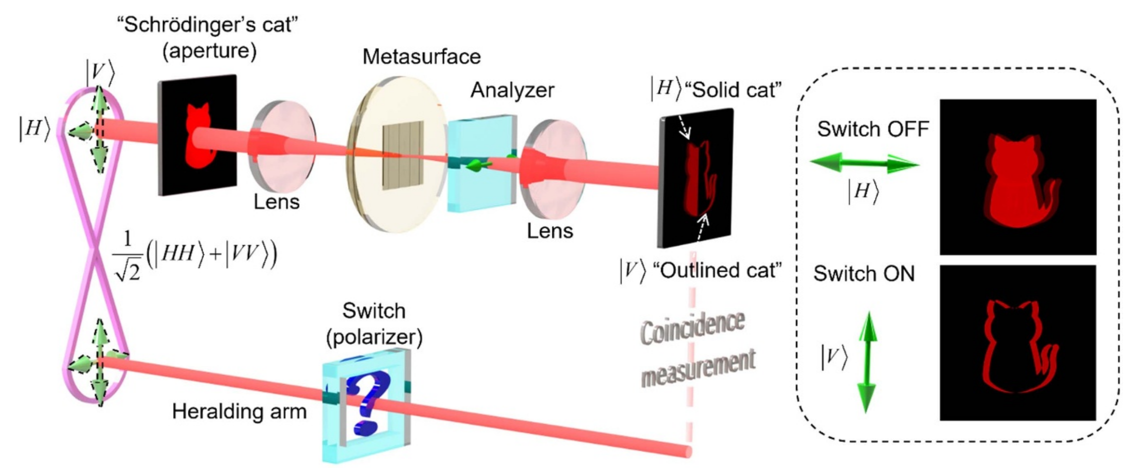

Figure 26. The schematics of a metasurface enabled quantum edge detection. The metasurface is designed to perform edge detection for a preferred linear polarization. $|V\rangle$, i.e. polarization state orthogonal to the analyzer. The dashed light-red line stands for the switch-to-detector synchronization path. The question mark means polarization selection of idler photons of the heralding arm is unknown. If the Schrödinger's cat is illuminated by unknown linear polarization photons from polarization entangled source, the image would be a superposition of a regular 'solid cat' and an edge enhanced 'outlined cat'. When the idler photons of the heralding arm are projected to $|H\rangle$, it indicates the switch OFF state and leads to a 'solid cat' captured. While the heralded photons are projected to $|V\rangle$, an edge enhanced 'outlined cat' is obtained with the switch ON state. Reproduced from [175]. CC BY 4.0.

these three parameters and provide a single function per metasurface. To achieve multifunctional device, other degrees of freedom are to be explored. For example, it would be interesting to investigate a spatially dependent slow varying phase delay design, which provides a spatially varying imaging modality for optical microscopes. Furthermore, by analyzing the total effective response of multiple elements in an optical system and integrating onto a metasurface, a compact system with only the metasurface and few other components can be realized.

Advanced material development. The nonlinearity in natural materials is very weak and is impractical for realizing nonlinear modulation of metasurface in practical applications. Artificial material systems processing large nonlinearity is essential to achieving a metasurface with nonlinear processing capabilities. In fact, all plasmonic materials could be utilized to obtain strong nonlinear response due to the quantum size effect. Recently, it has been shown that ultrathin metallic quantum well possesses exceptionally large nonlinearity at visible to near-IR frequency range. A nonlinear metasurface based on such material system will revolutionize the field of tunable computational metasurface, laying the cornerstone for nonlinear optical computations [177–179].

High resolution. Manipulating light with spatial frequencies beyond the diffraction limit is the key to improving the resolution of existing super-resolution imaging techniques. Compared to natural material, hyperbolic metamaterials support in theory arbitrarily large lateral wavevectors and has seen applications in super-resolution imaging [180]. Based on such material system, a metasurface enabled super-resolution microscope could bring various imaging methods such as label-free super-resolution dark-field microscopy down to deep-subwavelength level.

Concluding remarks

Multifunctional edge imaging based on metasurface has played an important role for a lot of imaging applications. We believe their roles could be equally important, both for fundamental science and for applications in microscopy. There are active efforts in this area, with new techniques being developed for edge detection with various electrical/optical/thermal tunabilities. The multifunctional edge imaging is an exciting and challenging research field with many open questions.

Acknowledgment

This work is supported by the Gordon and Betty Moore Foundation.

3.7. Metasurfaces for holographic imaging

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Status

With the capability in recording the information of phase, amplitude and 3D profiles of optical fields, holography offers a valuable method in various applications including display, wavefront shaping, data storage, and optical neural networks [181]. However, conventional holography suffers from low resolutions, poor image quality, limited color appearance, and so on, which limits the performance in many practical applications. Metasurfaces consisting of subwavelength-scale meta-atoms arranged in a surface, provide a way to realize holograms with ultra-high resolution, large field-of-view (FOV) and ultra-thin film structures. In addition, with the advantage of manipulation of light properties in a wide DOF, including amplitude, phase, polarization, and wavelength, metasurfaces offer an excellent tool to realize holographic applications [182].

There are many approaches to generate phase and amplitude modulation for metasurface holograms, which are shown in figure 27. The earlier phase modulation relies on the resonance of the meta-atoms with respect to incident optical fields, and the scattered light undergoes a phase modulation by varying the geometric shape and orientation of the V-shaped meta-atoms, as shown in figure 27(a) [97]. Then, the C-shaped split-ring resonators are proposed to achieve both amplitude and phase modulation [133]. Next, the geometric PB phase is employed to construct metasurface holograms based on the interaction between circularly polarized light and anisotropic meta-atoms, which the induced PB phase is $\pm 2\theta$ with θ being the orientation angle of the meta-atoms [172]. A common geometric PB metasurface modulates only the phase of the output light, and a complete control of both the amplitude and phase is demonstrated based on the X-shaped meta-atoms, which are consisted by two arms with the independently induced PB phase $\exp(j2\sigma\theta_1)$ and $\exp(j2\sigma\theta_2)$, so the cross-polarized output light has the complex field distribution represented by $\cos(\theta_2-\theta_1)\exp[j\sigma(\theta_1+\theta_2)]$, as shown in figure 27(b) [183]. Then, to overcome the intrinsic optical losses of metals, the Huygens metasurfaces are proposed in terms of high-index dielectric nanoparticles with overlapped electric and magnetic resonances, and the phase modulation is realized by tuning the diameter of the silicon nanoparticles, as shown in figure 27(c) [113]. Moreover, the transmissive metasurface based on the propagation phase is also demonstrated to achieve a high transmission efficiency. As shown in figure 27(d), the metasurface is constructed by elliptical silicon posts arranged on a hexagonal lattice, and the propagation phase is generated by propagation of the waveguide modes along the nanoposts [184].

The metasurfaces are commonly fabricated by the methods of electron-beam lithography, focused ion beam milling and so on. However, these methods suffer from low fabrication speed which is not suitable to fabricate large-area patterns, and it is also hard to realize full-color and polarization-dependent holograms due to the resonance nature of metallic/dielectric structures. Recently, the laser reduced graphene-oxide (rGO)-based devices offer a new solution for nanostructured holograms [185]. The rGO-based holograms are demonstrated based on the refractive index modulation through the athermal photoreduction induced by femtosecond (fs) pulse (figure 27(e)). The phase modulation is controlled by the fs pulse fluence, and the pixel size is decided by the diffraction-limited focal spot size, and the full-color holograms are constructed based on the spectrally flat refractive-index within the visible range of rGO. Next, the topological insulator Sb_2Te_3 thin film cavity is employed to construct ultrathin holograms (figure 27(f)) [186]. The cavity structure is composed of a bulk of Sb_2Te_3 thin film sandwiched between two metallic surface layers on a Si substrate, and the phase shift is generated through multi-reflections of light between two surface layers in the resonant cavity. Based on this mechanism, a 60 nm thick binary hologram is realized using fast direct laser writing methods with total size 3 mm $\times$ 3 mm.

The applications of metasurface holograms are shown in figure 28, and one of major applications is the multiplexing of polarization, wavelength, spin angular momentum (SAM), OAM and so on. For the polarization multiplexing, Arbabi *et al* [184] demonstrated linear polarization multiplexing by using the anisotropic elliptical posts whose short axis and long axis could be independently tailored to modulate different phase profiles, and different holograms are readout for vertical and horizontal polarized incident beams. For the SAM or circular polarization multiplexing, the PB phase can be employed to realize interchange of off-axis images based on the flipped sign of induced PB phase between right circular polarization and left circular polarization [192]. Furthermore, by combing the geometric PB phase with the propagation phase, polarization multiplexing hologram can be realized with two arbitrarily orthogonal polarization states, as shown in figure 28(a) [187]. For the wavelength multiplexing, Wei *et al* [188] constructed two types of meta-atoms with wavelength selective resonance (figure 28(b)), and the shape of

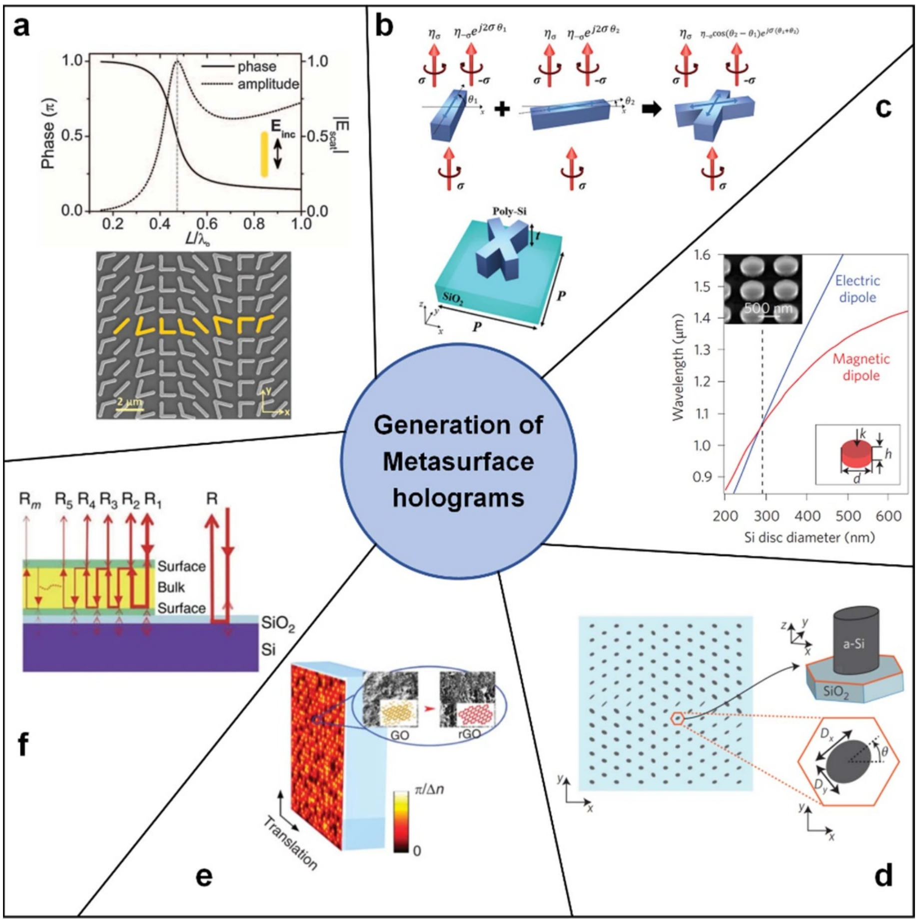

Figure 27. Generation of metasurface holograms with different methods. (a) Phase modulation based on the resonance of the plasmonic V-shaped meta-atoms [97]. Reproduced from [97], with permission from Springer Nature. (b) Amplitude and phase modulation based on geometric PB phase [183]. Reproduced from [183] with permission from the Royal Society of Chemistry. (c) Dielectric Huygens metasurface generated by silicon nanoparticles with overlapped electric and magnetic resonances [113]. Reprinted with permission from [113]. Copyright (2013) American Chemical Society. (d) Phase modulation generated from the propagation of the waveguide modes along nanoposts [184]. Reproduced from [184], with permission from Springer Nature. (e) Hologram generated by laser reduced graphene-oxide [185]. Reproduced from [185]. CC BY 4.0. (f) Binary hologram generated by topological insulator Sb_2Te_3 thin film cavity [186]. Reproduced from [186]. CC BY 4.0.

the meta-atoms determines the resonant frequencies, while the phase modulation is controlled by the orientation of meta-atoms with geometric PB phase calculated by a modified parallel GS algorithm. For the OAM multiplexing, different from previous multiplexed metasurface holograms constructed by special designed meta-atoms, the OAM multiplexing is based on the discrete spatial frequency distributions of meta-atoms (figure 28(c)) [189]. To construct the OAM multiplexed holograms, first, the desired image of the hologram is sampled with a 2D Dirac comb function in the spatial frequency domain, and second, the corresponding phase profile in the input metasurface plane is obtained by using the iterative phase retrieval method, and third, the spiral phase of OAM is added to the phase profile obtained in the second step. After these steps, an OAM-selective hologram is obtained, and OAM-multiplexing is realized by superposing several different OAM-selective holograms into together, so different images are readout when different OAM beams incident onto the metasurface.

Current and future challenges

There are mainly two challenges for metasurface holography. The first one is the fabrication of large-area metasurfaces with nanostructured units, and the second is tunable and reconfigurable metasurfaces with high modulation speed. For the first challenge, the common serial fabrication techniques, such as e-beam lithography (EBL) and focused-ion beam (FIB) milling, usually take a long time to fabricate a large-area pattern. Besides, the fabrication cost is expensive, and the sample preparation and lifting off processes are complicated. For the second challenge, many methods are employed to realize dynamic meta-holography, such as thermal stimulation, mechanical stretch, chemical reactions, liquid crystals, semiconductors and graphene-like 2D materials. In the microwave regime, Li *et al* proposed a tunable 1-bit coding metasurfaces by incorporating a PIN diode into the meta-atoms, and the state of meta-atoms can be switched between '1'

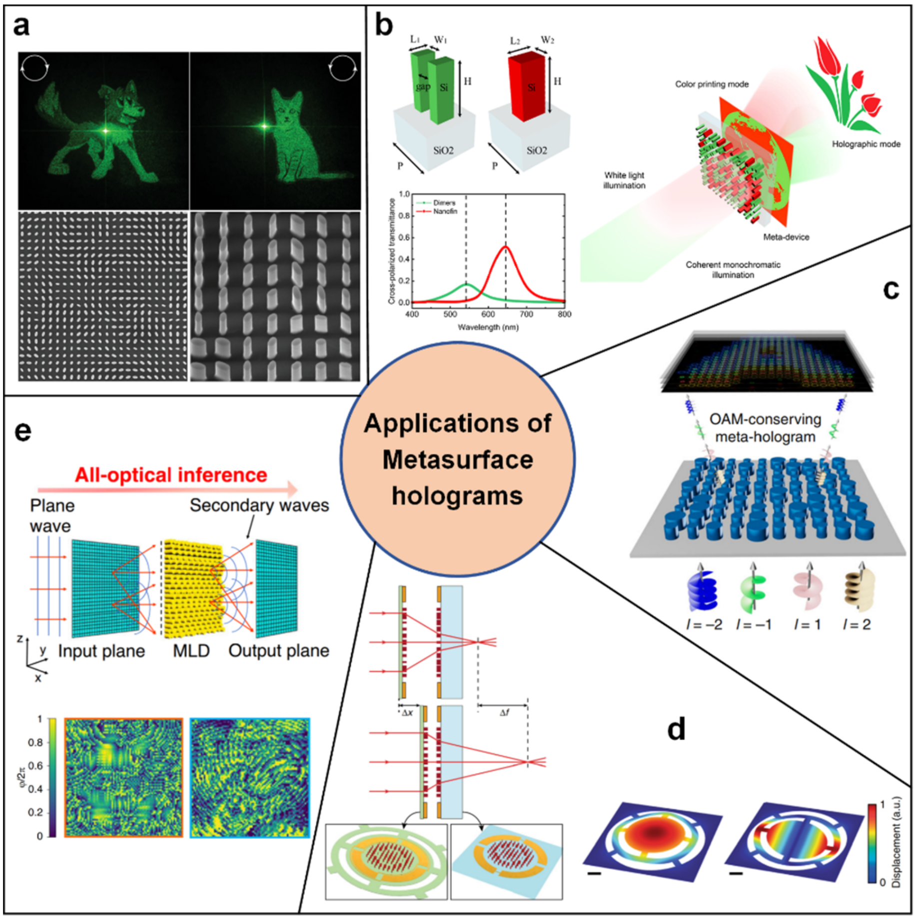

Figure 28. Applications of metasurface holograms. (a) Polarization multiplexed hologram realized with two arbitrarily orthogonal polarization states [187]. Reprinted with permission from [187], Copyright (2017) by the American Physical Society. (b) Wavelength multiplexed hologram realized with two types of meta-atoms, which the shape controls the resonant frequencies and the orientation controls the induced PB phase [188]. Reproduced with permission from [188]. CC BY-NC 4.0. (c) OAM-multiplexed holography based on the discrete spatial frequency distributions of meta-atoms [189]. Reproduced from [189]. CC BY 4.0. (d) A MEMS tunable dielectric metasurface lens with tuning speed around 4 kHz [190]. Reproduced from [190]. CC BY 4.0. (e) Optical machine learning decryptor (MLD) consisted by holograms fabricated by 2PP laser writing method [191]. Reproduced from [191]. CC BY 4.0.

and '0' by controlling the voltages across the diode, and the tuning speed has reached more than 30 MHz [193]. However, in the visible regime, to realize high tuning speed remains a difficult task, and the methods based on microelectromechanical systems (MEMS) offers a high tuning speed (∼kHz) comparing to other methods. A doublet with two metasurface lenses has been demonstrated by placing a moving metasurface on a MEMS membrane and a stationary metasurface fixed on the substrate, as shown in figure 28(d) [190]. The distance between two metasurfaces could be tuned by applying a voltage between the membrane and the substrate, and the tuning speed could reach to around 4 kHz. Another approach to the high-speed tunability is realized based on space channel multiplexing meta-hologram [194], where different holograms are encoded into different space channels and each space channel has different spatial locations, and the dynamic holographic display is realized based on a time sequence beam with high frame rate (9523 frames per second) selectively illuminating different space channels during each frame.

Advances in science and technology to meet challenges

The sub-diffraction optical writing method provides an alternative method to fabricate large-area nanoscale metasurface hologram. The laser direct writing techniques based on two-photon polymerization (2PP) pave the way toward fabrication of nanoscale feature size and 3D structures. By combing photoinitiation process with a femtosecond (fs) Gaussian beam at wavelength 800 nm and photoinhibition process with a doughnut-shaped beam at wavelength 375 nm, the fabricated smallest feature size has reached to 9 nm based on a special designed photoresin with high mechanical strength, which is comparable to the resolution of EBL [195]. Furthermore, Elena *et al* demonstrated a 3D-printed holographic perceptrons to realize optical machine learning decryptor (MLD), as shown in figure 28(f) [191]. The MLD is consisted by holograms with phase profile derived from machine learning algorithms, which could diffract input images into specific output formats. The holograms fabricated by 2PP laser writing method have a pixel diameter 419 nm and pixel density of >500 million per square centimeter, which shows a good accuracy for optical decryption.

Concluding remarks

Metasurface holography has demonstrated its superior advantage in realization of holograms with high resolution, large FOV, full-color appearance, and multiplexing of polarization, wavelength and OAM. Nowadays, the nanofabrication of metasurface holograms is still a challenge, and with the development of the novel optical materials, including rGO and topological insulator Sb_2Te_3, the laser direct writing methods provide a promising candidate for fabrication of holograms with high resolution and efficiency, which pave the way for realization of low-cost and large-area metasuface holograms.

Acknowledgments

This work was sponsored by Shanghai Pujiang Program (No. 21PJ1411200), National Natural Science Foundation of China (No. 61975123), Zhangjiang National Innovation Demonstration Zone (No. ZJ2019-ZD-005), Shanghai Frontiers Science Center Program 2021–2025 (No. 20), and Pilot Project from Shanghai Commission for Science and Technology (No. 21DZ1100500).

3.8. Active metasurfaces

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Status

Metasurface is a rapidly developing research field due to series of promising potential applications for integrated ultrathin planar devices. Among them, metasurfaces working in the optical wavelength range have attracted considerable attention, due to the possibility to replace the bulky and heavy conventional refractive optical elements such as lenses. Recent progress in realization of highly efficient optical metasurfaces based on theoretical understanding of light interaction with metasurfaces and in targeted developed fabrication processes enables industrialization possibility. However, the resonant nature of metasurfaces results in principle strictly passive and static drawbacks. To extend the functionalities of dielectric metasurfaces to real-world optical applications, active metasurfaces with tuning of the functions after fabrication are highly desirable and will provide new platforms for display, optical computing and radar applications [196].

Current and future challenges

The most straightforward method is to tune the resonance of metasurfaces by structural reconfiguration. The tiny variation in the arrangement, shape and orientation of the single nanostrcture can bring corresponding huge changes in the EM response of the entire system. Such structural reconfiguration can be achieved through mechanical deformation, using highly deformable materials based on flexible or shape memory effect and MEMS. The difficulties in synthesis of proper polymer, limited modulation speed, and high driving voltage are the significant problems that need to be solved.

Another method bringing about a striking effect is to change the refractive index of the materials around the elements of metasurfaces using microflow with different solvents or liquid crystals. Among them, the use of external stimuli to surrounding liquid crystals is a particularly promising method of tuning the optical response of metasurfaces because of liquid crystals' large and broadband optical anisotropy, as well as high transparency [198]. The key challenges of LCs embedded metasurfaces are well-developed alignment and orientation control methods. The strong surface interactions between LC molecules and nanostructures requires special chemical surface treatments in order to reconfigure the functions in real time with sufficient freedom and low power consumption.

The functions of metasurfaces can be more effectively controlled by changing the refractive index of constructing materials since light is highly located inside or near the nanostrctures. By tuning the dielectric constant, metasurfaces with active materials such as phase-change material can be modulated under external stimuli including thermal, electrical, magnetic, optical, chemical, or electrochemical methods. Figure 29 shows an exciting progress of a chip-scale dynamic metasurfaces with reprogrammable functions with electrically driven phase-change metadevices through the incorporation of a heterostructure microheater integrated with a hybrid plasmonic-PCM metasurface [197]. The potential operation speed of a few kHz and lower peak voltages enables fully integrable dynamic metasurfaces. Another modulating method is to tune the carrier density of conductive materials (such as graphene, semiconductors, and transparent conducting oxides) through electrostatic gating or optical excitation. Furthermore, chemical reactions and thermo/magneto/electro-optic effects also provide approaches to alter the optical properties of active materials such as yttrium iron garnet.

No matter what method is used, the modulation speed, modulation depth (effect), cycle stability, reversibility, and process complexity are all essential factors for active metasurface. The practical applications also have urgent requirements for small pixel size, low power consumption and solid-state integration. The above solutions all suffer from some form of tradeoff, the final optical devices with specific functions determine the optimal technical solution.

Advances in science and technology to meet challenges

The major challenge in active metasurfaces resides in how to seek efficient tunable ability without decaying the wavefront control functions. New advances in technology can mitigate some of the limitations described above. For example, innovative design methods together with AI empowered metasurfaces may further expand the modulation speed and depth. Machine learning methods coupled to optimization algorithms have been proposed to program the metasurfaces for tunable complex functionalities, pushing metasurfaces toward unprecedented levels of functionality. Novel physical mechanisms, such as newly developed topology-protected BIC metasurface and other related structures may be incorporated into future metasurfaces to provide a way to exceed the modulation depth limitations. Finally, new emerging materials

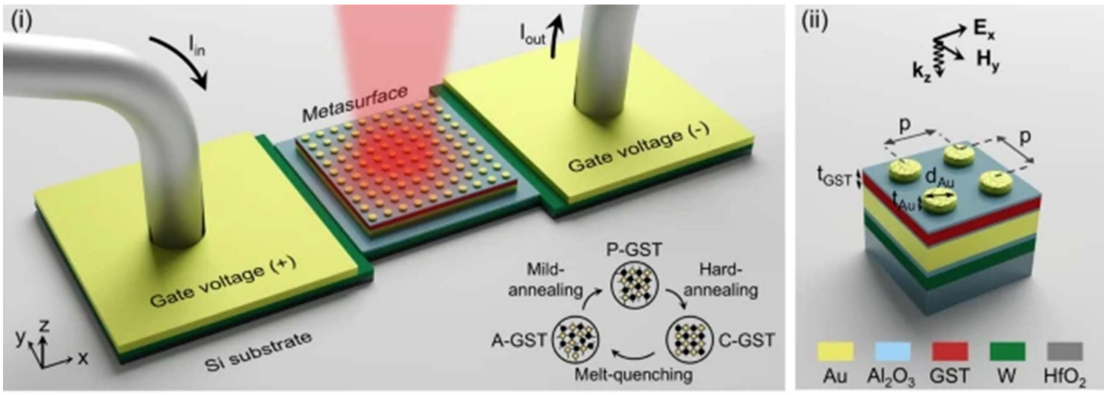

Figure 29. The heterostructure consisting a resistive microheater integrated with a phase-change metasurface [197]. Reproduced from [197].

such as transition metal nitrides and transparent conductive oxides may provide new platforms beyond those described above. Development of advanced liquid crystals also have similar benefits.

Concluding remarks

Active metasurfaces provide a way to do what is not possible with passive devices, and providing unique modulation capabilities of light. Currently, they are limited by the materials that are used for tuning, or by the fundamental limitations of metasurface design. Much more work is needed to improve the modulation speed/depth and cycle stability of active metasurfaces, as well as reduce pixel size, energy consumption and losses. New devices under development such as time-domain-control of metasurfaces may provide a solution to power limitations, while new concepts in topology-protected BIC metasurface may enable advancements beyond the limits or the emergence of new capabilities. Intelligent coding metasurface system can manipulate light using small pixels and associate digital information simultaneously in a smart way. Multidisciplinary research involving material science, physics, chemistry, optics, as well as computer science, are the critical trends in this field and may solve all the challenges mentions above in the future.

Acknowledgments

I would like to thank my past and present group members and collaborators for their work on the topic of active metasurfaces.

3.9. Optical metasurface sensors

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Optical sensors play a crucial role in monitoring, detecting and quantifying target objects based on various forms of light–matter interactions. Metasurfaces provide a unique platform for optical sensing applications, because metasurfaces can fully control the characteristics of light in an almost arbitrary manner. In particular, significant progress has been achieved in the field of metasurface-based biosensors over the past years. As illustrated in figure 30, through the rational design of metallic and dielectric building blocks of metasurfaces, so-called meta-atoms, we can tailor and enhance the interactions between light and analytes including molecules, viruses, and proteins, so that the optical signals can be greatly amplified.

It is known that metallic nanostructures support localized surface plasmons (LSPs) to confine light to the dimension below the diffraction limit. Compared to the intensity of incident light, the local field can be enhanced by orders of magnitude, which has been widely used in surface enhanced Raman spectroscopy for sensing down to the single-molecule level [199]. Using metasurfaces composed of an array of well-defined metallic structures, we can achieve good spatial homogeneity as well as desired spectral responses for biochemical/biomedical detection. Nevertheless, the intrinsic Ohmic loss of metals causes certain limitations, such as strong absorption and photo-thermal effect, motivating researchers to investigate metasurfaces using low-loss, high-refractive-index dielectric materials. According to Mie theory, individual dielectric meta-atoms can show rich and pronounced resonances in response to both electric and magnetic components of light, in sharp contrast to metallic nanostructures that primarily respond to electric fields [200]. Such a feature is very helpful to design novel metasurfaces to shape the spectral resonances and beam profiles. Consequently, dielectric metasurfaces have attracted intensive interest in recent years for optical biosensing.

Current and future challenges

There are two major challenges when developing metasurface biosensors. First, we need to consider some key parameters, such as the working wavelength, spectral tunability, local field enhancement, and quality factor (Q) of optical resonances, which may also cause trade-offs among themselves, to address the sensitivity and specificity requirements. The sensing mechanisms vary from case to case. For instance, we can detect infrared absorption, Raman, or circular dichroism signals for different targets, while they work in different wavelength regions. Furthermore, high-Q metasurfaces can produce strong local fields to enhance light-analyte interactions and hence sensitivity, but at the same time, the narrow linewidth implies limited sensing bandwidth that is not desirable for biochemical specific detection. All these factors impose difficulties to realize simultaneous tracking of multiple analytes by a single metasurface. The second challenge is wafer-scale, cost-effective, and high-throughput fabrication of metasurfaces with critical dimensions below 100 nm, ideally by conventional semiconductor manufacturing tools, which is crucial to transform the technology into practical applications. However, most metals used in metasurfaces, including gold and silver, are not compatible with complementary metal-oxide-semiconductor (CMOS) manufacturing techniques. To further develop integrated, practical meta-systems for rapid, accurate and personalized sensing and diagnosis, we also need to leverage the breakthroughs of microfluidics, flexible electronics, internet of things (IoT), artificial intelligence (AI), and other research disciplines in the aspects of hardware implementation and data acquisition, analysis and sharing.

Advances in science and technology to meet challenges

Recognizing the above challenges, people have devoted significant efforts to advance the design, material platform, and fabrication for metasurface biosensors. For instance, Wu *et al* reported a plasmonic metasurface showing a sharp Fano-resonance, which arises from the interference between subradiant and superradiant plasmonic modes [201]. The resonant frequency of the metasurface can be readily tuned to match the vibrational fingerprints of molecules in the mid-infrared region. The authors demonstrated

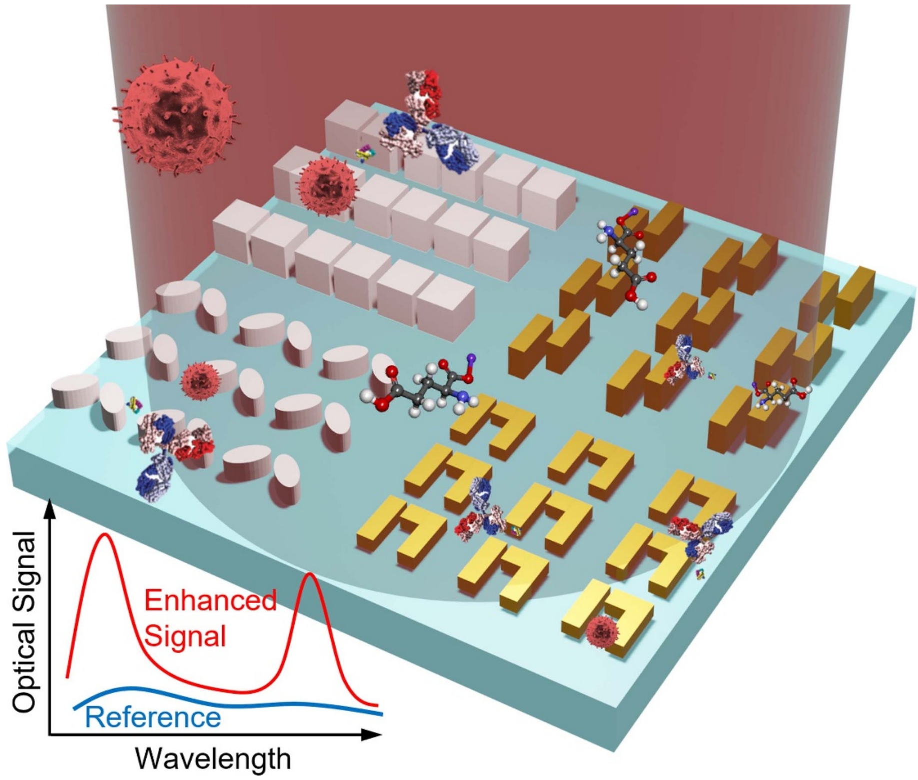

Figure 30. Schematic of biosensors based on optical metasurfaces, which consists of metallic (gold color) and dielectric (gray color) meta-atoms with rationally designed geometries.

multispectral biosensing of the recognition protein (protein A/G) and antibody (anti-mouse IgG) monolayers with nanometer thickness (figure 31(a)). They also determined the spatial orientation of the proteins with respect to the metal surface normal. Another method to achieve high-Q resonances is utilizing quasi bound states in the continuum (BICs), which have been extensively studied in the context of all-dielectric metasurfaces. One example is shown in the left panel of figure 31(b), in which the unit cell of the metasurface consists of one pair of tilted silicon nanobars to break the in-plane mirror symmetry and produce a Q-factor as high as 144 [202]. Combining this BIC-type dielectric metasurface with hyperspectral imaging, Yesilkoy and co-workers reported ultrasensitive biomolecule detection. The right panel of figure 31(b) present the spatially resolved maps of resonance wavelength shift caused by the binding of IgG molecules on the metasurfaces sensors, showing the sensitivity as low as 3 molecules per μm^2.

In addition to spectral engineering, we can also design metasurfaces to control the local field profile through mode engineering for sensing applications. Yao and Liu proposed achiral silicon nanocube dimers to create strong and uniform chiral hotspots (figure 31(c)), which originate from the simultaneous enhancement of magnetic and electric fields and their proper spatial overlap in the dimer gap [203]. Up to 15-fold enhancement of the global optical chirality is obtained, which can be used for enantioselective sensing and sorting of chiral molecules. Very recently, García-Guirado *et al* experimentally demonstrated chiral sensing by using silicon nanocylinders [204]. It is shown that the dielectric platform exhibits a larger circular dichroism enhancement than the plasmonic counterpart. It is worth pointing out that wafer-scale dielectric metasurfaces have been reported [205, 206]. Furthermore, AI could facilitate complicated photonic and sensor designs via a data-driven approach [207, 208], which are otherwise impossible by the traditional methods.

Concluding remarks

The past decade has witnessed remarkable progress of optical metasurfaces in both fundamental technological aspects, among which metasurface sensors just represent one example. Although we focus on

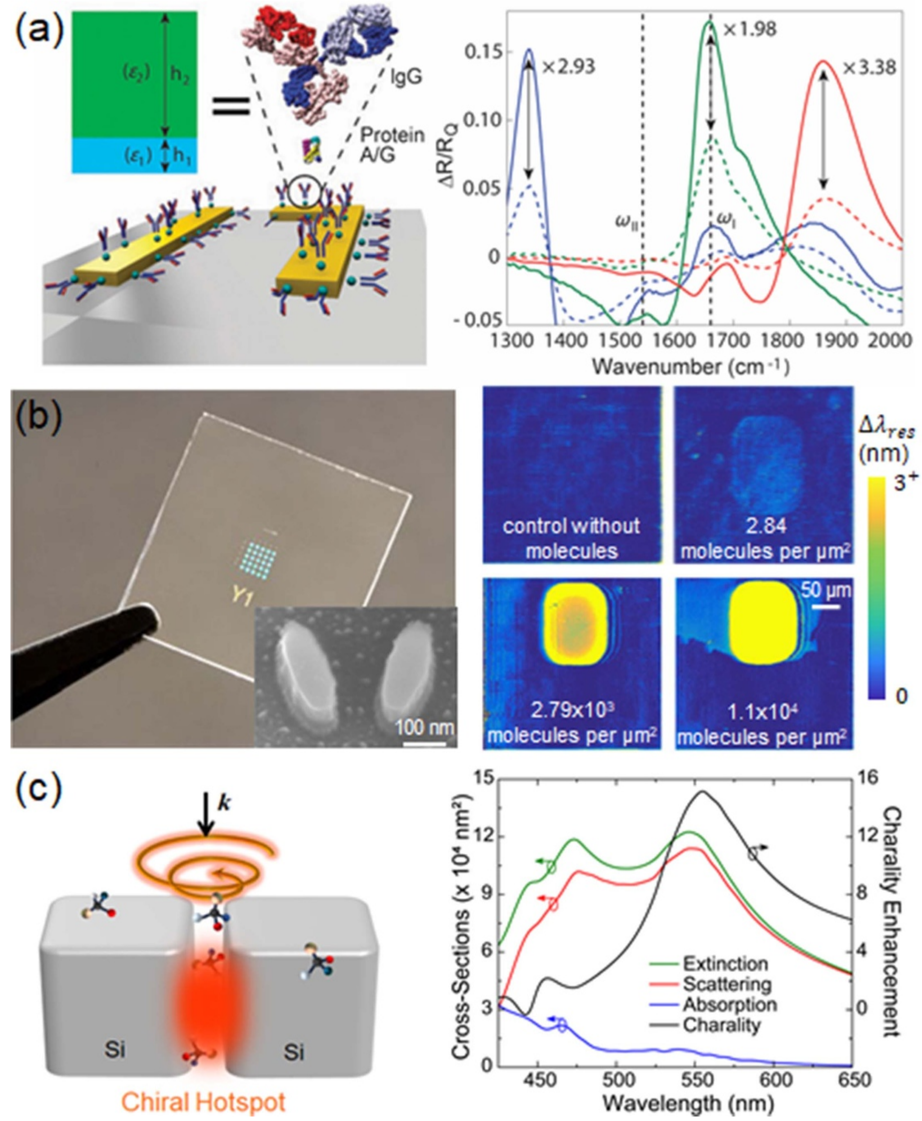

Figure 31. (a) Schematic of an infrared Fano-metasurface (left), and experimental spectra before (dashed lines) and after (solid lines) binding of IgG antibodies to three different Fano-metasurfaces immobilized by protein A/G (right). Reproduced from [201], with permission from Springer Nature. (b) Photograph and scanning electron micrograph of dielectric metasurface sensors that support quasi-BIC modes (left), and resonance shift maps for detection of IgG molecules with different concentrations. Reproduced from [202], with permission from Springer Nature. (c) Schematic of a pair of silicon nanocubes to create chiral hotspot (left), and simulated cross-section spectra and superchiral field enhancement (right). Reproduced from [203] with permission from the Royal Society of Chemistry.

metasurface biosensors in this paper, metasurfaces have been explored in other scenarios, such as temperature, humidity, polarization, and depth sensing. With the continual, cross-disciplinary effort to address the major challenges in the areas of physics, design, materials, and manufacturing, we expect that metasurfaces will open new horizons in a variety of sensing applications.

Acknowledgments

The authors acknowledge the financial support from the National Science Foundation (CBET-1931777, ECCS-2136168 and DMR-1654192).

3.10. Geometric phase and nonlinear photonic metasurfaces

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Status

The geometric phase is an important concept in both quantum and classical systems [209]. The main idea underpins the geometric phase is that the state that undergoes an adiabatic evolution along a closed path in a specified parametric space will gain an additional phase factor that depends on the encircled area of the path loop. In linear optics, the geometric phase, also named as PB phase, plays an important role in designing multifunctional photonic metasurfaces, enabled by the interaction of circularly polarized light with anisotropic plasmonic or dielectric meta-atoms [97]. Specifically, when circularly polarized light is incident onto anisotropic meta-atoms, the light scattered in the forward and backward direction with opposite circular polarization experiences a geometric phase that depends on the in-plane orientation angle of the meta-atom. This geometric phase is dispersionless and can be further used to manipulate the polarization and amplitude of light. One can realize a continuous 0–2π phase control of light by simply varying the in-plane orientation angles of the meta-atoms. In addition, by combining geometric phase with other phase manipulation mechanisms in a metasurface, such as the propagation phase, resonant phase and topological phase, the complex amplitude control over light waves has been extensively used to design various metasurface devices [210].

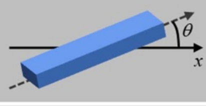
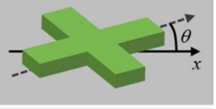
In 2015, the concept of geometric phase was successfully extended to nonlinear optics, implemented by using plasmonic metasurfaces [211]. Similar to its linear optical counterpart, the nonlinear geometric phase in harmonic generations is determined by the symmetry and orientation angles of the meta-atoms (table 1). For harmonic generation and wave mixing processes, the nonlinear optical processes obey certain symmetry selection rules. Of particular interest is the case of a circularly polarized fundamental wave (FW). When it interacts with the meta-atom with m-fold rotational symmetry, the allowed harmonic orders are $n = lm \pm 1$, where l is an integer, $\pm$ means that the harmonic waves have the same or opposite circular polarization state to that of the FW [212]. The nonlinear geometric phases in harmonic generations on the metasurfaces are then introduced by rotating the orientation angles of the meta-atoms [211, 212]. For example, under the pumping of a circularly polarized FW, a gold plasmonic meta-atom with three-fold rotational symmetry (C3) radiates a second harmonic (SH) wave of the opposite circular polarization state to that of the FW. The SH wave experiences a geometric phase factor of $3\sigma\theta$, where $\sigma = \pm 1$ represents the left- or right- circular polarization state of the FW, and θ is the in-plane orientation angle of the C3 meta-atom. It is found that the phase of the generated SH wave can be continuously tuned from 0 to 2π by varying θ. The nonlinear geometric phase was also applied to other nonlinear optical processes such as third harmonic generation, four-wave mixing, and difference frequency generation.

One of the advantages of nonlinear photonic metasurfaces over their linear counterparts is that the FWs can be easily filtered out, resulting in nonlinear signals with high SNRs. Various nonlinear optical functionalities, such as imaging [213], image encoding [214, 215], vortex beam generations [216, 217], optical holography [218, 219] at the SH frequency, have been successfully demonstrated with the geometric phase controlled metasurfaces. Recently, based on the optical rectification effect in plasmonic-ITO hybrid metasurface, geometric phase controlled plasmonic metasurfaces were also developed to control the phase of the THz waves generated from the metasurface source [220].

Current and future challenges

Due to the quasi-2D characteristics of the nonlinear photonic metasurfaces, the phase-matching conditions of nonlinear optical processes on nonlinear metasurfaces can be greatly relaxed. However, the other side of the coin is that the light–matter interaction length is short, leading to relatively low nonlinear conversion efficiencies compared to that in conventional crystals. In general, increasing the pumping power can improve the nonlinear conversion efficiency, however, the pumping density should not exceed the damage threshold of the metasurface device.

Table 1. Relationships between the symmetry, polarization states, harmonic orders, and the nonlinear geometric phase. n, order of harmonic generation; '+' and '–' mean the harmonic waves are of the same and opposite circular polarization states to that of the fundamental wave, respectively; C_2–C_4, two- to four-fold rotational symmetry of the meta-atom; θ, relative orientation angle of the meta-atom with respect to the laboratory frame; σ, circular polarization state of the fundamental wave. Empty areas in the table mean the corresponding nonlinear optical processes are forbidden by the symmetry selection rules.

Harmonic order	Sign of σ	C_2 	C_3 	C_4 
$n = 2$	+			
	−		$3\sigma\theta$	
$n = 3$	+	$2\sigma\theta$		
	−	$4\sigma\theta$		$4\sigma\theta$
$n = 4$	+		$3\sigma\theta$	
	−			
$n = 5$	+	$4\sigma\theta$		$4\sigma\theta$
	−	$6\sigma\theta$	$6\sigma\theta$	

Advances in science and technology to meet challenges

There may be several solutions to circumvent the above challenge. The first one is to fabricate large area metasurface devices. This is because, under the same pumping intensity, metasurfaces with larger area sizes can endure higher pumping power and therefore have higher nonlinear optical efficiency. With the rapid development of advanced nano-fabrication techniques, this solution is highly feasible. For example, the manufacturing of optical metasurfaces with wafer-scale size has been demonstrated by many research groups and companies. The second solution is to choose the constituent materials with high nonlinear optical susceptibilities and damage thresholds. Compared to metals, some dielectric (including semiconductors) materials have both higher optical nonlinearity and higher damage threshold, therefore the dielectric metasurface may provide an excellent platform for developing ultra-compact nonlinear optical sources. In addition, one may incorporate materials with very large nonlinearity to the metasurface design, exploiting the strong field enhancement and phase control of the metasurface and the large nonlinearity of the nonlinear material.

Concluding remarks

Compared to conventional nonlinear optical devices, geometric phase controlled nonlinear photonic metasurfaces exhibit great flexibilities in controlling the phase, polarization, and amplitude of the generated nonlinear optical waves. By further improving the nonlinear conversion efficiency on the plasmonic, dielectric or metal-dielectric hybrid metasurfaces, the chip-type nonlinear optical devices with wavefront engineering functionalities can be developed to meet the challenges in high capacity optical information processing, optical integration, optical computing, and so on.

Acknowledgments

G L would like to acknowledge the financial supports from the National Natural Science Foundation of China (91950114).

3.11. Resonant dielectric metasurfaces for nonlinear photonics

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Status

Nonlinear optics underpins many areas of applied research including integrated photonics, lasers, frequency conversion, optical modulation, yet nonlinear response of many natural optical materials is weak. For macroscopic nonlinear materials, the phase matching requirements limit the efficiency of nonlinear processes, complicating their use as practical devices. Artificial metastructures developed in the recent decades can help to overcome these limitations owing to the subwavelength size and specific arrangement of constituent meta-atoms, which allow to relax the phase-matching constraints.

Metasurfaces represent a special group of metamaterial structures that combine a strong local field enhancement with ultrathin CMOS-compatible geometry. Metasurfaces have the advantage over 3D metamaterials in their lower optical losses and technical feasibility of fabrication [221]. Historically, metallic metasurfaces were first exploited to enhance optical nonlinearities via excitation of surface-plasmon-polariton resonances. Yet, the reported conversion efficiencies for plasmonic metasurfaces were low because of material absorption and low damage threshold [222]. Very recently, high-index dielectric metasurfaces were suggested as a promising alternative to plasmonics complementing and even outperforming metallic structures in nonlinear applications because of low material losses and sufficient confinement of local EM fields [184, 223]. Due to the rich mode structure of dielectric nanostructured arrays, their resonant response can be used to shape light in unusual ways, e.g. to achieve magnetic response at the optical frequencies [224], offering advanced ways for the subwavelength control of nonlinear interactions.

Beyond phase-matching, the nonlinear response is governed by resonant properties of metasurfaces. Recently, it was shown that mutual interferences of Mie-resonant modes in dielectric metasurfaces can lead to a variety of novel effects in the near- and far-field regimes, including Fano resonances, anapole states, and BICs [225]. More specifically, it was shown that dielectric metasurfaces with symmetry-broken meta-atoms can be employed to engineer sharp resonant response in both reflection and transmission at the normal incidence associated with the physics of optical BICs [226]. The concept of BIC unified earlier works on asymmetric dielectric metasurfaces with high-quality modes associated with Fano resonances, dark states, and electromagnetically-induced transparency. Design and main spectral characteristics of an asymmetric dielectric metasurface supporting BICs are shown in figures 32(a)–(d). When the metasurface symmetry is broken, BIC transforms into quasi-BIC with a finite yet large quality factor (Q factor). The sharpness of the peak in reflection and transmission, or equivalently, the mode Q factor can be tuned gradually by changing the asymmetry of the unit cell. Novel capabilities of controlled radiation losses and field enhancement lead to new potential applications in nonlinear optics and nanophotonics.

Current and future challenges

Discovery of broken-symmetry resonant metasurfaces with sharp resonances not subjected to the phase matching principles have challenged us to reexamine some of the fundamental constraints associated with enhancement of their nonlinear response, and to develop new capabilities to remove some of these constraints. In the example of harmonic generation, we highlight seven mechanisms that drive the resonant response of dielectric metastructures. They include (i) consistency between resonant wavelengths of fundamental frequency (FF) and harmonic frequency (HF) modes; (ii) spatial and spectral overlap between pump pulse and the FF mode; (iii) efficiency of nonlinear conversion between FF and HF modes; (iv) Q factor values for FF and HF modes; (v) efficiency of outcoupling for the HF mode; (vi) consistency between the directivity pattern of harmonic signal and the collection objective aperture; (vii) excitonic resonant structure of the nonlinear susceptibility. All mentioned mechanisms need to be properly balanced and controlled by material and structural engineering in order to achieve giant nonlinear response.

Sub-micron characteristic dimensions of metasurfaces operating in the visible and near-IR imply strong requirements to the quality of nanofabrication. One of the major challenges for high-Q nonlinear metasurfaces is reduction of the fabrication errors which includes elimination of surface roughness, spatial disorder, inclination of walls and rounding of sharp corners. Just recently it was shown that for practical metasurfaces with some structural imperfections the harmonic signal depends strongly on the ratio between the radiative and non-radiative mode losses and is maximized only in the critical coupling regime [227]. As shown with an orange shaded area in figure 32(c), the critical coupling is achieved when radiative loss becomes balanced with the non-radiative loss which requires engineering of either one or both mechanisms

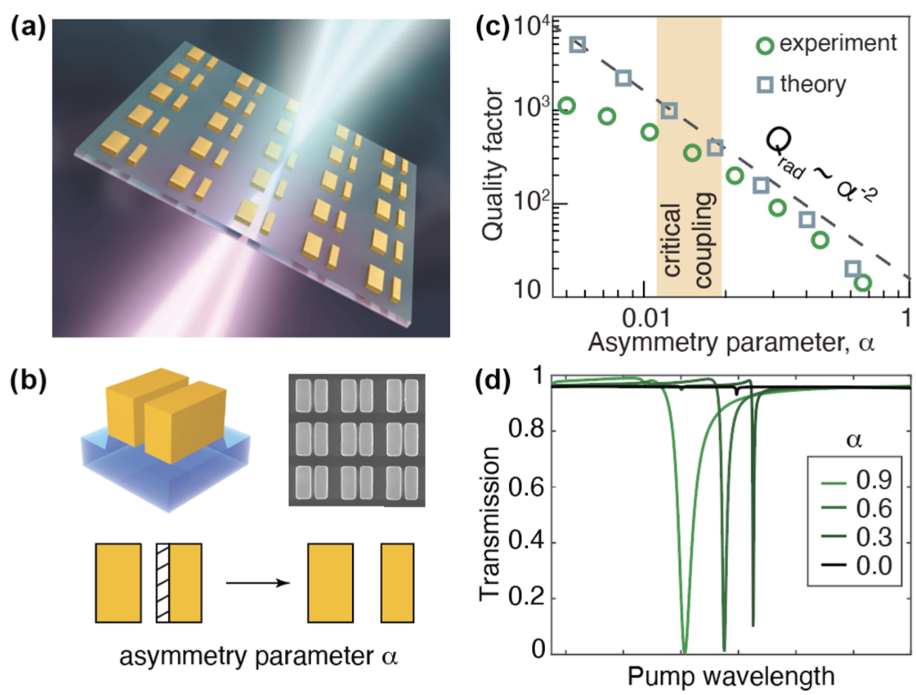

Figure 32. Asymmetric dielectric metasurfaces supporting quasi-BIC resonances. (a) An artist impression, (b) meta-atom design, (c) experimental and theoretical dependences for the Q factor on asymmetry and (d) spectral characteristics for different values of the asymmetry parameter. (c), (d) Reprinted with permission from [225]. Copyright (2021) American Chemical Society.

of losses and limits the optimal Q factor of the FF mode. Necessity of proper match between the pump bandwidth and FF mode linewidth adds additional constraints on the operating mode Q factor. For example, for ps pulses in the visible and near-IR range the optimal mode Q factor lies between few hundreds and few thousands. Last but not least, strong narrow-band field enhancement in quasi-BIC metasurfaces leads to an extreme sensitivity to a change of the refractive index that may limit nonlinear functionalities for the pump intensities beyond the perturbative regime.

Advances in science and technology to meet challenges

Recent progress in metasurface engineering suggests that many of the mentioned limitations can be overcome using BIC resonances. In particular, it was shown that high Q factor of quasi-BICs in broken symmetry metasurfaces boosts the harmonic generation efficiency dramatically. Figure 33(a) shows the measured third-harmonic signal for various asymmetry parameters from Si metasurface with a design from figure 32 supporting a quasi-BIC in the near-IR [227]. The measured signal exceeds the value achieved for non-BIC modes by a few orders of magnitude. The dependence of the mode linewidth on the asymmetry parameter allows to achieve the critical coupling condition easily (shown with an orange shaded area in figure 33(a)) and adjust the temporal match between the mode and pump. This means that structural imperfections are effectively eliminated by the BIC tunability without the need to change the fabrication setup.

For metasurfaces with a better fabrication quality, the field enhancement inside the meta-atom is even higher and the pulse self-action effects can be observed. Figure 33(b) shows the third-harmonic signal spectra for a Si metasurface with improved structural quality that reveal a broad peak coming from the probe pulse and an additional sharp feature induced by the quasi-BIC resonance [228]. As the pump power increases, the peak associated with the resonant mode demonstrates a gradual spectral blueshift and broadening. Blueshift of the quasi-BIC in the multiphoton absorption regime drives the transition from the subcubic to supercubic regimes for the generated third-harmonic power.

For asymmetric dielectric metasurfaces with quasi-BICs operating in the mid-IR observation of high-harmonic generation becomes possible. Figure 33(c) shows the harmonic intensity spectrum and power-to-power dependence observed in a broken-symmetry Si metasurface with a quasi-BIC at the wavelength of 4 μm [229]. The spectrum reveals that 5th to 11th harmonics are observed for sub-ps pulse excitation and their power dependence on the pump intensity is clearly non-perturbative with a similar slope independent of the harmonic number.

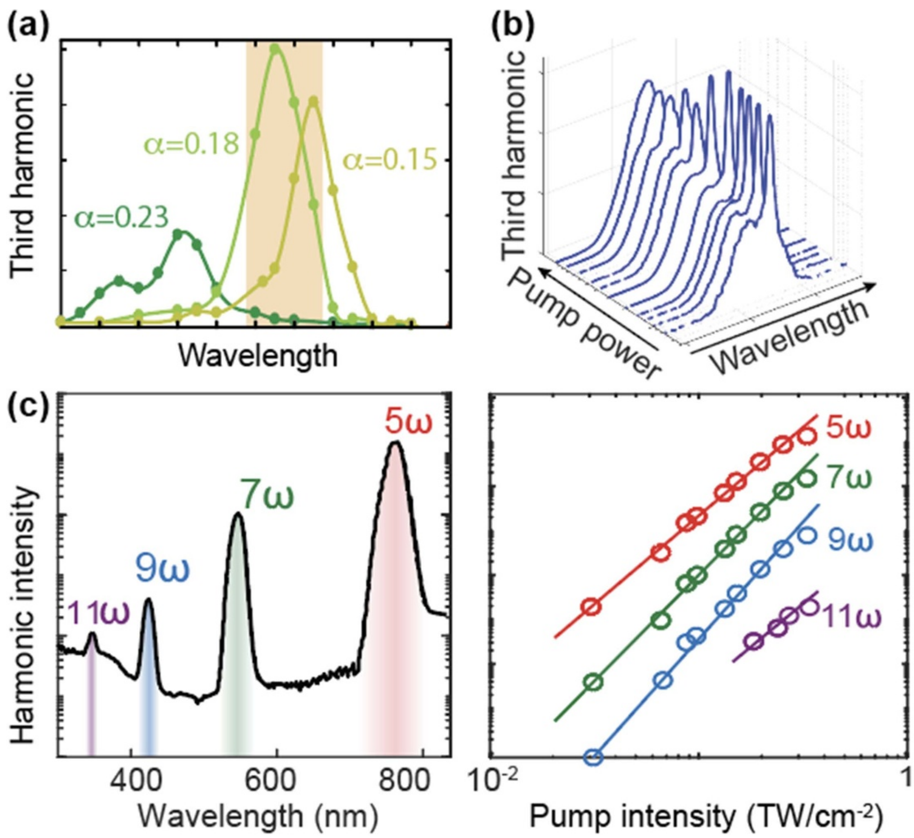

Figure 33. Nonlinear harmonic generation. (a), (b) Third and (c) high harmonic generation with broken-symmetry metasurfaces from figure 32 supporting quasi-BICs. (a) Reprinted with permission from [227]. Copyright (2019) American Chemical Society. (b) Reprinted with permission from [228]. Copyright (2021) American Chemical Society. (c)–(d) Reprinted with permission from [229]. Copyright (2022) American Chemical Society.

Concluding remarks

Although the field of nonlinear optics is a well-established discipline, for many years it explored macroscopic media and required propagation distances much longer than a wavelength of light. Recent progress in metamaterials and metasurfaces expanded this field into new directions. Nonlinear effects in metasurfaces have attracted a lot of attention in recent years. They do not rely on phase-matching conditions and symmetry-related selection rules of natural materials, but in structured media nonlinear responses can be enhanced substantially by local and collective resonances. Consequently, nonlinear processes may extend beyond simple harmonic generation and spectral broadening due to electronic nonlinearities. We have provided a brief summary of some of the recently observed effects in nonlinear optical metasurfaces, but this field experiences a rapid growth with many discoveries and surprises yet to come.

Acknowledgments

This work was supported by the Australian Research Council (Grants DP200101168 and DP210101292).

3.12. Nonlinear optical holography

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Status

Holography was invented by Dennis Gabor to record and reconstruct wavefronts, and became one of the most significant branches of optics. Optical holographic elements provide huge flexibility to manipulate the amplitude, phase, and other properties of light, which brings various functions. Such complex wavefront engineering has been widely applied into displays, data storage, encryption, tweezers, beam generation, and other fields.

Nonlinear optics describes the nonlinear interactions between light and matter, such as nonlinear harmonic generation, spontaneous parametric down-conversion, sum- and difference-frequency generation, four-wave mixing, and so on. Such phenomena are excited by high-intensity electric fields. Due to the simultaneous phase modulation that accompanies such nonlinear interactions, nonlinear holography has been introduced. One and two-dimensional (1D and 2D) modulation based on (quasi) phase matching in patterned nonlinear crystals has been shown to generate harmonic high order Gaussian beams [230].

Metasurfaces composed of subwavelength structures, known as meta-atoms, can modulate the complex amplitude, polarization state and even the spectral features of light fields at will. Based on surface plasmonic resonances or high permittivity dielectric Mie resonances, nonlinear metasurfaces have been applied for the enhancement of optical nonlinearity. Meanwhile, anapole modes, Fano resonances, BICs, topological edge states and other optical local effects can lead to remarkable nonlinear optical phenomena.

Nonlinear metasurface holograms (metaholograms) offer various physical channels for light manipulation. The schematic of nonlinear metasurface holography is shown in figure 34. The methods to modulate harmonic generation are as flexible as in linear metasurfaces, but are, however, much more complex. Nevertheless, phase modulation, including the helicity-dependent PB phase, and resonance phase are common approaches to achieve nonlinear optical metaholograms. PB phase, which relies on the polarization conversion caused by geometric rotation of nanostructures, can facilitate the phase manipulation in nonlinear processes, and also exhibit broadband properties and high order harmonic generation for displaying specific images [218]. Resonance phase is generated by the interaction between the incident electric field and nanostructure, whose geometric size and shape determine the nonlinear phase modulation. Resonance phase excited by multilayer metal nanoantenna has been shown to produce polarization sensitive 3D holographic reconstruction [231]. Furthermore, there have been numerous reports on nonlinear metaholography using different materials and functions.

Current and future challenges

Although metasurfaces exhibit impressive optical properties, the basic mechanisms of optical modulation still require further investigation. Nonlinear optical metaholograms is also facing issues including boosting efficiency, increasing the number of channels through multiplexing, application of higher orders, and so on. It indicates that there is a sea of opportunity for both principle and technical research.

For metallic nonlinear metaholography, experiments have verified the feasibility of PB phase and resonance phase, and that the harmonic generation is determined by the symmetry of the structures. The nonlinear phenomena can be more complex when the metasurfaces possess both resonance and geometric modes. The same issues exist for dielectric nonlinear metasurfaces [232], where the influence on phase modulation by various resonant modes should be considered.

Reconfigurable metasurfaces have attracted great attention for active spatiotemporal modulation. Phase change materials, chemical reactions, and electrical tuning are main methods to achieve active metaholography [233]. However, mechanisms of nonlinear metasurface light modulation still requires exploration for materials in different states and under locally high-intensity fields.

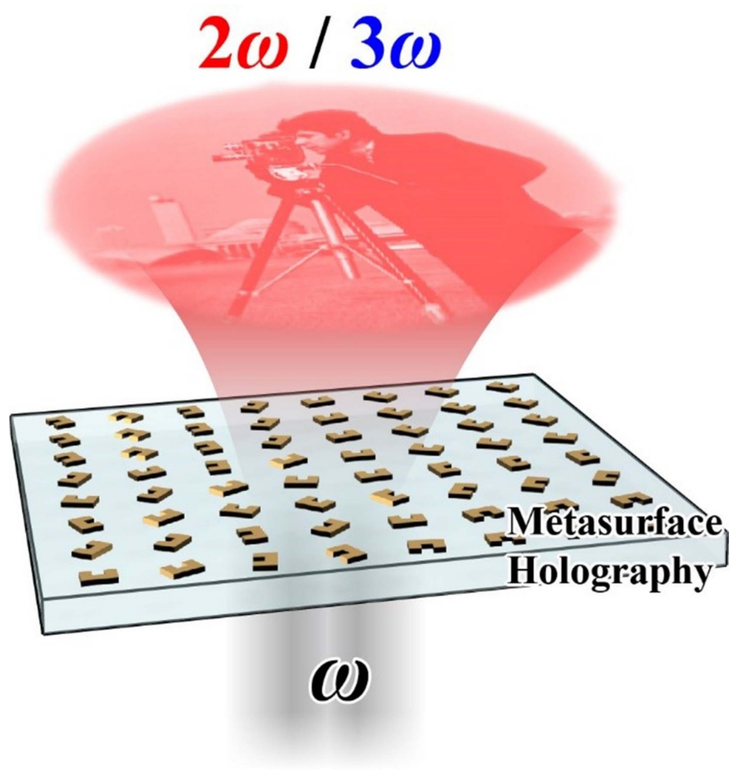

Figure 34. The schematic of nonlinear metasurface holography.

Limited by low efficiency and single functionality, it is hard to introduce nonlinear metaholography into practical applications at current stage. Increasing the efficiency is an essential topic in nonlinear optics, and it is one of the most crucial challenges for a nonlinear metaholography. Consequently, there is little research on higher order harmonic generation holography. Because of the huge efficiency difference resulting from the different susceptibilities between each harmonic generation, it is usually too difficult to realize the reconstruction of the generation of two different harmonics at the same time.

Functionally, most nonlinear holographic metasurfaces are polarization sensitive, but there are a few reports about vectorial nonlinear metaholography. Multiplexing methods of linear metaholography has been widely studied and developed, while interest in nonlinear multiplexing metaholography could be an interesting direction in the near future to provide more degrees of freedom and options of metaholography modulation.

Advances in science and technology to meet challenges

The design of the meta-atoms determines the optical performance of nonlinear metaholography. Local resonance enhancement through the correct selection of constituent materials with high susceptibilities and elaborate meta-atom design could be effective approaches leading to higher nonlinear efficiencies. Meanwhile, some novel mechanisms of light–matter interactions will offer effective ways to significantly enhance nonlinearity (figure 35). Frese *et al* demonstrated a plasmonic metahologram consisting of C_2 and C_3 symmetric gold nanoantennae, where the intensities of the second and third harmonic generations were comparable [234], allowing a demonstration of bi-color holography.

Active nonlinear modulation is an attractive and realistic goal. Wu *et al* reported the SH generation of dynamic 3D holography [235]. Two FF waves were incident on a nonlinear crystal, one carrying holographic information acting as the object wave and the other as the pump wave, while phase matching should be satisfied. There have already been some attempts to produce reconfigurable nonlinear metasurfaces. Pogna *et al* realized a switchable SH metasurface with photoinjection using a laser pulse in a semiconductor nanopillar array [236] to successfully realize an all-optical control frequency converter. Yue *et al* studied nonlinear metasurfaces using phase-change materials. In the crystalline state, the meta-atom presents a large third-order susceptibility [237] which is duly switched off over the phase change to the amorphous state.

Furthermore, nonlinear metaholography can achieve multiple functionalities. The similarities of polarization modulation between linear and nonlinear metasurface have been proven, and precise meta-atom design may supply a harmonic holographic reconstruction where the polarization states are

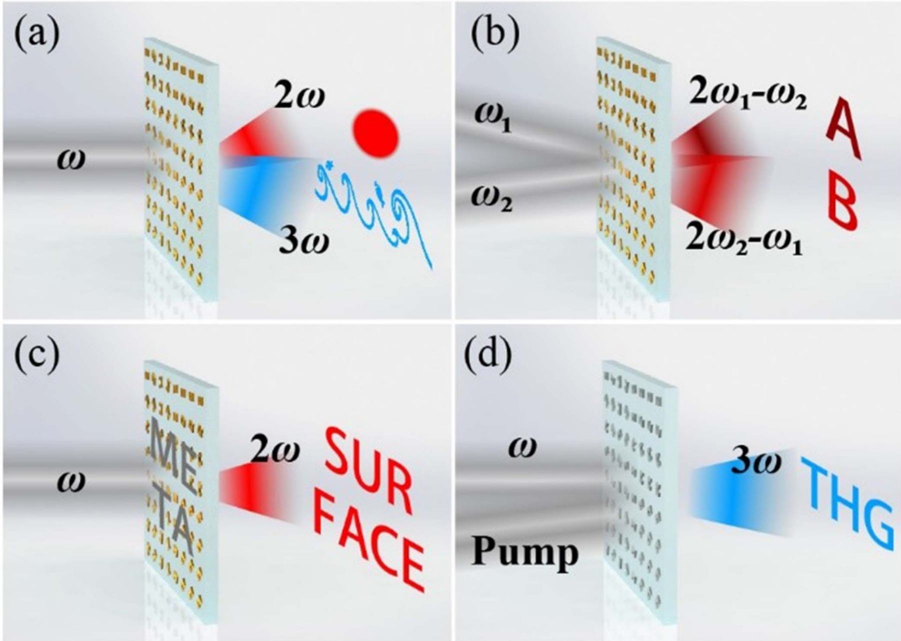

Figure 35. Advances of nonlinear metasurface holography. (a) Bi-color nonlinear metasurface holography. (b) Four wave mixing holographic multiplexing. (c) Nonlinear metasurface for real and Fourier space imaging encoding. (d) Expectation of switchable nonlinear metasurface holography.

artificially manipulated. Nevertheless, the symmetry of the meta-atoms underlines the fundamental physics which is much more complex than the linear case. For example, multiplexing metaholography encoding was introduced into a nonlinear diatomic metasurface [219] consisting of C_3 gold nanostructures to display two separate images in the real and Fourier space respectively.

Various developments in linear metasurfaces could be promoted to the nonlinear regime. For instance, the fields of ultrafast optics and quantum optics have been extremely active recently. Pulse shaping and local field enhancement may cause remarkable optical effects in nonlinear metasurfaces. They have already been utilized for enhanced generation of entangled photon pairs and quantum edge detection. Because of such flexible manipulations, more techniques can be brought into nonlinear metaholography, including quantum holography, ghost imaging, optical measurement, and bio detection, to name a few.

Concluding remarks

Nonlinear metasurfaces can act as a novel platform to demonstrate marvelous nonlinear optical effects. Great efforts have been devoted to realizing harmonic generation, multiplexing, and even tunable phenomena. Although the basic physical mechanisms require further investigation, and practical applications of nonlinear optical metaholography need to be improved drastically, the intriguing physical phenomena and incredible potential for light modulation indicates that there is a promising bright future for this field.

Acknowledgments

L H acknowledges the funding provided by Beijing Outstanding Young Scientist Program (BJJWZYJH01201910007022), National Natural Science Foundation of China (Nos. 61775019 and 92050117) program, and Fok Ying-Tong Education Foundation of China (No. 161009). J R acknowledges the POSCO-POSTECH-RIST Convergence Research Center program funded by POSCO, and the National Research Foundation (NRF) grant (NRF-2022M3C1A3081312) funded by the Ministry of Science and ICT (MSIT) of the Korean government. X L acknowledges the support from Beijing Institute of Technology Research Fund Program for Young Scholars (XSQD-201904005). T B acknowledges the Institute of Information & Communications Technology Planning & Evaluation (IITP) grant (No. 2019-0-01906, the POSTECH Artificial Intelligence Graduate School program) funded by the MSIT of the Korean government.

3.13. Metasurfaces go to quantum

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Status

Optical metamaterials, especially metasurfaces (2D metamaterials), have recently shown powerful functionalities and broad application foregrounds in classical optical fields [6, 238]. Metasurfaces and metamaterials have also presented good prospects in the non-classical fields [239, 240], such as quantum source generation, quantum state manipulation, atom trapping, quantum information processing, quantum detection and imaging, as shown in figure 36.

In terms of quantum source generation, the common method to generate non-classical light is to employ the spontaneous parametric down conversion (SPDC) process of nonlinear crystal or the spontaneous emission of quantum emitters, both of which can produce entangled photon pairs and single photon states. The most straightforward application of the metasurface is using its abilities of light field manipulation to operate the pump light or down-converted light in the SPDC process, in order to obtain novelty effects that bulk quantum optics cannot achieve. By combining the phase-encoded metalens array and the nonlinear crystal, the high-dimensional entanglement can be acquired as well as the multi-photon state generation [241]. The metasurface is able to split the different spins of single-photon emissions from quantum dots through arbitrary propagation control and high collimation [242]. On the other hand, the special light field produced by the metasurface enables various coupling regimes between the light field and quantum emitters, which can realize enhanced emission rates or reduced fluorescence lifetimes [243–246], and simultaneous manipulation of spontaneous emission and far field radiation [247]. Based on Mie resonances in the metasurface, the photoluminescence enhancement [248] and generation of two-photon quantum states [249] have been demonstrated. In fact, simply using the nonlinearity of the materials, such as metal or perovskite, metasurfaces present the generation and modulation of photonic entanglement and the significant enhancement of both linear and nonlinear photoluminescence [250, 251]. The most integrated metasurfaces-based quantum source system should simultaneously carry out the generation of quantum states and the manipulation of quantum light field. The room-temperature generation of SAM-encoded single photons has been experimentally demonstrated from the dielectric protected silver metasurface coupled with the nano-diamonds containing nitrogen-vacancy centers [252].

Metasurface is also a new platform for special quantum state manipulation, by harnessing the extraordinary light-molding capabilities of metasurfaces [253, 254]. The quantum entanglement between two qubits trapped on a chip and separated by macroscopic distances, has been achieved and manipulated, through engineering their coherent and dissipative interactions via the metasurface [255]. The long-lifetime coherence and the switchable local density of optical states can also be obtained by a metasurface combined with quantum emitters [256, 257]. By using the metasurface to split a single incident laser beam into multiple beams with desired polarization states, a cold atomic ensemble can be easily acquired in a much simple and compact system [258].

The principal manifestations of quantum properties of light are associated with quantum interference and quantum entanglement, which enables the manipulation of quantum states in a variety of applications. By employing the polarization splitting capability of the specially designed all-dielectric metasurfaces, the non-classical multiphoton interferences can be realized, which simultaneously images multiple projections of quantum states, enabling a robust reconstruction of amplitude, phase, coherence, and entanglement of multiphoton polarization-encoded states [259]. The dielectric metasurface can also demonstrate the generation of entanglement between the spin and orbital angular momentum (OAM) of photons, as well as the four Bell states showing non-local correlations between two photons that interacted with the metasurface [161]. Due to the unique anisotropic phase response that creates two extreme eigen-operations, the continuous control over two-photon interference shows bosonic bunching, fermionic antibunching or arbitrarily intermediate behavior, beyond their intrinsic bosonic nature [260].

Since metasurfaces show extraordinary abilities to manipulate the phase, polarization, field distribution of light, their applications can be extended to the quantum optics, including quantum imaging, quantum sensing, quantum detection, weak measurements, and even hypersensitive biomolecule detection [261–263]. Based on the polarization dependent metasurfaces, the polarization-entangled photon source can be used to realize optical edge detection [175], ghost imaging for nonlocal discrimination between a set of polarization objects [264], and entanglement dependent quantum imaging [265]. A hybrid integrated quantum photonic

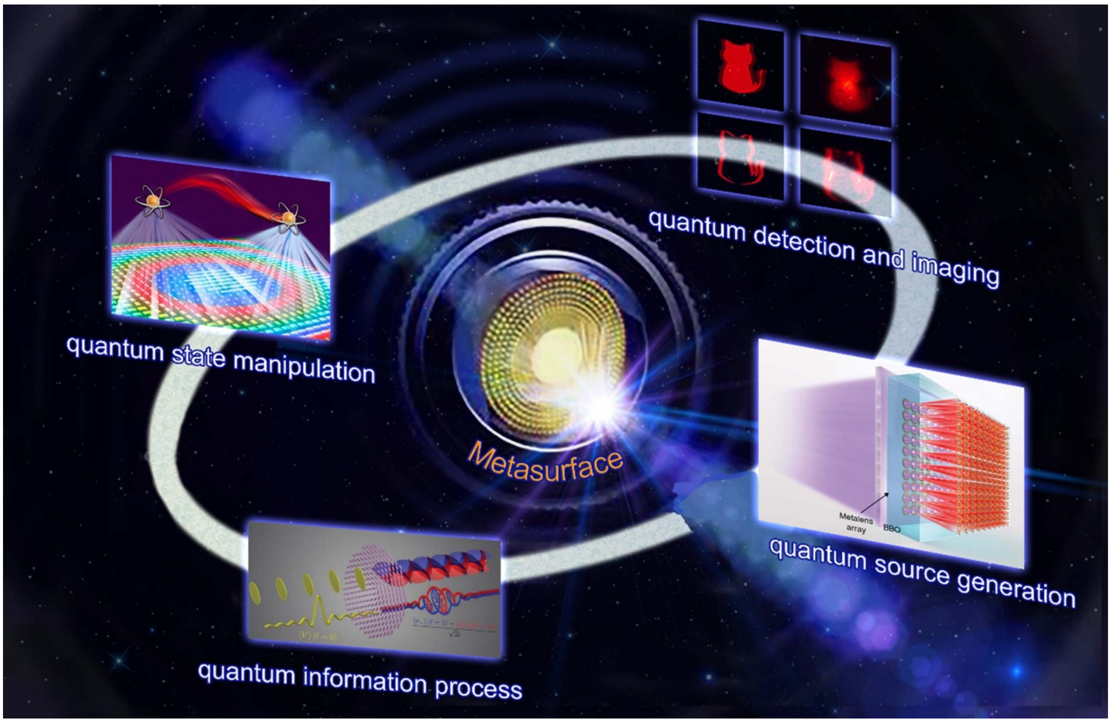

Figure 36. Applications of metasurfaces in photonic quantum technologies. Reproduced from [175]. CC BY 4.0. Reprinted with permission from [255]. Copyright (2018) American Chemical Society. From [161]. Reprinted with permission from AAAS. From [241]. Reprinted with permission from AAAS.

system is possible that is capable of entangling and disentangling two-photon spin states at a dielectric metasurface. Through the interference of single-photon pairs at a nanostructured dielectric metasurface, a path-entangled two-photon NOON state with circular polarization exhibits a quantum HOM interference visibility of 86 ± 4% [266]. Finally, the metasurface can also be used in quantum weak measurement. The dielectric metasurface works as a weak effective magnetic field introducing a tiny momentum shift for spins of photons, so that any desired weak coupling strength between the device and the system can be obtained, which provides potential applications in precise measurements of phase, polarization, and frequency of light [267].

Current and future challenges

Recently, there appears several trends of photonic quantum technologies. With the introduction of integrated photonic technology, the optical quantum chips have enabled the quantum source generation, quantum information processing and detection of quantum states of light at a decreasing scale and increasing level of complexity. The quantum circuitry composes of integrated generation of multiphoton states and programmable devices approaching thousands of components only occupying centimeter-scale footprints [268]. Employing the high-dimensional low-loss interferometer, the photonic quantum computer, generates up to 76 output photon clicks, which yields an output state space dimension of 1030 and a sampling rate that is faster than the state-of-the-art simulation strategy and supercomputers by a factor of ∼1014 [269]. More recently, the phase-programmable Gaussian boson sampling, which produces up to 113 photon detection events out of a 144-mode photonic circuit, with improved quantum source. Such quantum computer yields a Hilbert space dimension up to ∼1043, and a sampling rate ∼1024 faster than brute-force simulation on classical supercomputers. Such parallel computation system might inspire the new tendency of future quantum metasurfaces system [270]. On the other hand, the new material component has been introduced to photonic quantum technologies. Lithium niobate ($LiNbO_3$) on insulator (LNOI) is a promising material platform for integrated photonics due to single crystal $LiNbO_3$ film's wide transparent window, high refractive index, and high second-order nonlinearity. Based on LNOI ridge waveguide, almost all integrated devices can be realized [271].

Advances in science and technology to meet challenges

To meet the above-mentioned challenges, several solutions have been raised. With the growing maturity of nanofabrication and the improved design methods, such as physical intuition-based design methods and computer algorithms-based inverse design methods, the integration of subwavelength-structured metasurfaces and optical waveguides is gradually reshaping the landscape of photonic ICs, giving rise to numerous meta-waveguides with unprecedented strength in controlling guided EM waves [272]. As for the parallel computation system, the metalens array-based high-dimensional quantum entanglement generation has opened a door to this issue, and parallel information processing and detection devices will emerge in the near future [241]. By combining LN's high second-order nonlinearity and flexibility in achieving various on-chip structures, we can achieve many quantum optical applications via nonlinear processes, such as generating entangled photon pairs via SPDC. In addition to the quantum optical applications oriented towards nonlinear optics, LN has also been used to demonstrate heralded single-photon sources, quantum interfaces, and quantum memories [273].

Concluding remarks

Metasurfaces have been applied in photonic quantum technologies for several years, providing a wide variety of advanced optical quantum devices in quantum source generation, quantum state manipulation, quantum information processing, and quantum detection and imaging. In the future, the development direction of quantum metasurfaces field should follow the development rules of photonic quantum technologies, and effectively demonstrate the necessity of adopting metasurfaces and the superiority of metasurfaces.

3.14. Ultrafast plasmonics

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Status

Metamaterials and metasurfaces provide a flexible platform for manipulating intensity, phase and polarization of EM fields. The requirements for strong light-matter interaction with meta-materials necessitate the use of resonant dielectric and/or plasmonic nanostructures as the building blocks. Plasmonic nanostructures harness the properties of free-electron oscillations in metals and highly doped semiconductors in order to provide strong EM field confinement and enhancement near the interfaces [274]. This enhancement is in turn results in driving the electron gas out of equilibrium and enables a number of transient optical phenomena occurring on various timescales [275] (figure 37). The dynamics of the highly non-equilibrium free-electron gas is responsible for strong and ultrafast optical Kerr-type nonlinearity resulting in the changes of the refractive index of the material with the intensity of the incident light [276]. The empirical constraint on the reduction of the switching time of the nonlinearity can be improved by more than five orders of magnitude with plasmonic meta-atoms (figure 38). The nonlinear response can be further enhanced by exploiting hyperbolic dispersion in anisotropic media, exhibiting plasmonic or dielectric behavior for different polarizations, and ENZ properties of natural materials as well as metamaterials, related to the onset of the plasmonic behavior [277, 278]. Ultrafast phenomena in metamaterials are driven by the coupling between electronic, acoustic and structural degrees of freedom, upon the optical excitation. Overall plasmonic metamaterials and metasurfaces can be reconfigured in an ultrafast manner and used to control amplitude, phase and polarization of the transmitted, reflected or guided light all-optically, paving the way to active and switchable functionalities.

On picosecond timescales, the nonlinear response of plasmonic meta-atoms is defined by optically-induced heating and subsequent cooling of the free-electron gas. The speed of the latter process and the resulting Kerr-type nonlinearity, is defined by the relaxation of the electron temperature and limited by the electron–phonon scattering. On a sub-picosecond timescale after the excitation, the electron distribution is non-thermal and relaxes much faster via electron–electron scattering. This opens a pathway to largely unexplored ultrafast non-equilibrium plasmonics, with applications in all-optical control of optical signals and plasmonic photochemistry among others [279]. Manipulation of phase and efficiency of parametric (coherent) nonlinear optical processes with plasmonic nanostructures and metamaterials remains an active field of study.

In femtosecond and sub-femtosecond domains, short electron bursts produced by ultrafast photoemission from plasmonic nano- and meta-structures can be used as electronic gates for ultrafast electronics [280]. Further bridging the gap between attosecond physics and plasmonics, localized high-harmonic generation in gases assisted by plasmonic field localization was considered.

Current and future challenges

Ultrafast plasmonic metamaterials and metasurfaces can be envisaged in both the implementation of tuneable/switchable EM fields for particular applications and using the metamaterials as a tool for studying new effects in molecular, atom and material physics.

A persistent challenge for the implementation of ultrafast plasmonic nonlinearities in various metamaterial and metasurface designs still evolves around enhancing the nonlinear response in order to reduce the required light intensities and control (reduction) of the switching times. Both tasks can be addressed at the material level and nanostructuring as well exploitating subtle properties of nanostructured media and their hybridization with molecular or atomic species. In the former case, the role of nonlocal spatial dispersion is not fully explored and may provide an opportunity for tailoring the nonlinear response, especially in the ENZ regime. The ENZ spectral range can be engineered by designing the metamaterials, using natural plasmonic metals or by doping semiconductors. The slow light propagation in the ENZ media is also beneficial for nonlinear effects. On the other hand, exploitation of strong coupling of plasmonic meta-atoms to, for example, molecular or TMDC excitons, also gives an opportunity to influence the strength of the ultrafast nonlinear response by driving the system between weak and strong coupling regimes. A search for new plasmonic materials with a tailored free-carrier concentration and/or non-parabolicity of the conduction band is essential for enhancing the nonlinearity. Modification of electron–electron and electron–phonon scattering rates provides access to tailored dynamics of hot-electrons, therefore offering control of the nonlinearity response time. Even for the same material, nanostructures with anisotropic electron diffusion can be used to reduce the signal switching time [281]. Hetero-nanostructures providing additional channels for electron relaxation in adjacent materials are also efficient in controlling the

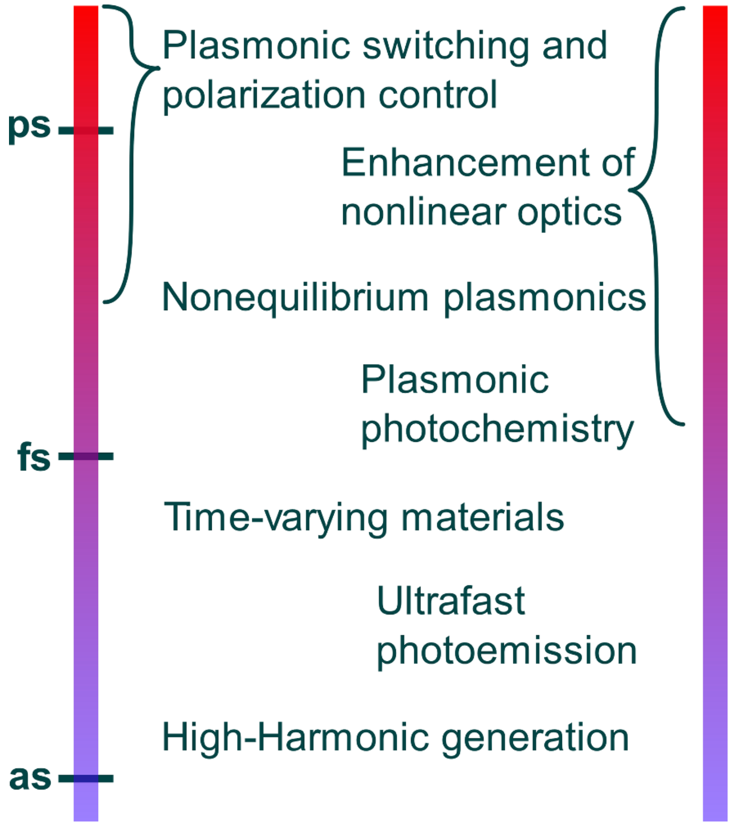

Figure 37. Processes and timescales in ultrafast.

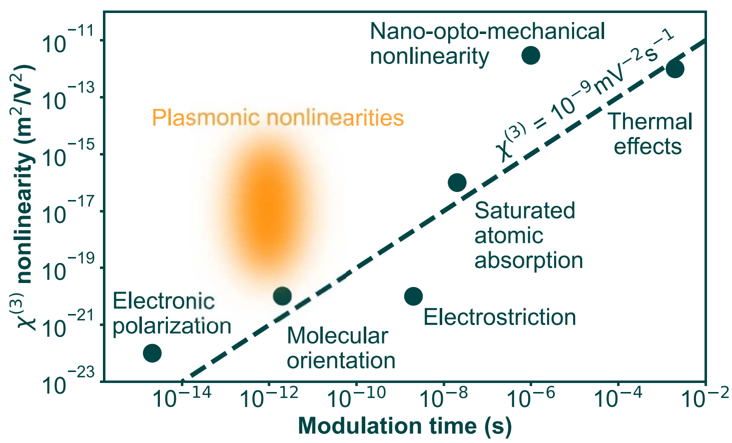

Figure 38. Empirical relation between the value of the third-order nonlinearity and its relaxation time (dashed line). Experimentally observed behavior of plasmonic nano- and metastructures lies in the shaded yellow region and deviates from this universal trend.

nonlinearity temporal response. Similarly, an appropriately chosen environment which provides a channel for hot-carrier energy sink can be exploited.

In terms of new potential applications beyond simple switching/modulation of the meta-structures, several new concepts heavily rely on the ultrafast plasmonics, in particular in the ENZ regime. They are related to the development of nonlinear topological nanophotonics where topological properties of metasurfaces, including Berry phase and transverse photon spin, can be controlled and the implementation of time-varying materials in the optical domain. While the latter are yet to be fully realized experimentally, optical nonlinearities in plasmonic and/or ENZ materials are widely accepted as one of the routes to time-varying media [282]. Here the challenge is in the requirement for non-adiabatic, strong and fast modulation of optical parameters on the timescale of the optical field oscillation. While such requirements can be achieved through parametric third-order nonlinearity, and essentially be described within the framework of an optical four-wave-mixing process, this approach suffers from low susceptibility of conventional materials. Spatial and temporal control of ultrashort pulses and topological quasiparticles of EM fields is another emerging area for ultrafast plasmonics, which combines several advantages of metasurfaces in phase and polarization manipulation enabled by nonlinear dynamics of plasmonic meta-atoms. Ultrafast magneto-plasmonics, nano-photochemistry, and ultrafast quantum optics are also important strands of applications.

Advances in science and technology to meet challenges

Nonlinear plasmonics generally requires high light intensities and the quest continues for new materials and meta-designs to reduce these intensities, increase bandwidth of the nonlinear response and achieve a higher damage threshold for materials and nanostructures. For established plasmonic materials, such as gold, the progress in fabrication and development of high quality single crystalline and ultrathin films is essential for reducing absorption losses. The availability of single crystalline ultrathin films (impossible with traditional sputtering), their nanostructuring and integration in metasurfaces and/or 3D metamaterials with atomically smooth interfaces will also provide an enhanced nonlinear response due to electron gas confinement and may influence the temporal response [283]. Ultrasmooth plasmonic surfaces will also allow exploitation of full potential of hybridization with 2D materials, such as TMDCs. Using 2D electron gas and associated graphene plasmons may allow reduction of the all-optical switching speeds and energies in the IR spectral range.

Related to the improved quality of materials and the trend toward hetero-nanostructures and complex shapes of meta-atoms calls for improved theoretical treatment of the non-equilibrium processes and computational nonlinear photonic material design. Even though non-equilibrium hot-electron relaxation in metals has been theoretically described with various degrees of accuracy down to the *ab initio* level, the theoretical description gets much more complicated for complex nanostructured geometries due to an increase in computational complexity. This is especially important in the case of hybrid molecular-plasmonic metastructures, where treatment of realistic processes at the interfaces is required, including non-equilibrium electron gas, the enhanced EM field and electron transfer between the molecular and plasmonic components.

Ultrafast plasmonics in femtosecond and sub-femtosecond domains relies on the development and availability of carrier-envelope phase stabilized laser systems, extreme ultraviolet light sources and pulse measurement techniques. Photoemission studies in this domain allow to image the free-electron oscillations in the time domain and with a nanometer spatial resolution [280]. Further studies of ultrafast photoemission in plasmonic structures will open a way for the generation of cost-effective and/or highly sensitive means of direct measurement of optical waveforms, creation of tailorable short electron pulses for ultrafast electron imaging and observing optical nonlinearities in the time domain. Development of new characterization techniques of the non-equilibrium electron gas spanning the range of the timescale of interest to ultrafast plasmonics will be important to fully understand ultrafast response and develop new applications.

Concluding remarks

Ultrafast plasmonics has provided numerous unique functionalities and advantages for the design and application of metasurfaces and metamaterials. Initially conceived as a mean to achieve fast reconfigurability and active functionalities, with the development of new applications of metasurfaces and metamaterials its role has shifted towards providing new opportunities in ultrafast gating and imaging, Kerr mode-locking, optical frequency combs, optical parametric generators and oscillators, polarization control, phase conjugation, adiabatic frequency shifts, anywhere where strong nonlinearity, ultrafast response and engineered amplitude, phase and polarization of light is required. Non-equilibrium plasmonics has also opened new application areas for metasurfaces to be exploited in photochemistry and photocatalysis where EM mode engineering provided by metasurfaces and hot-electrons provided by plasmonics are a powerful tool to influence the chemical reactivity. Combination of plasmonic and magnetic materials enabling ultrafast all-optical magnetization switching and electron spin control is another emerging application area for novel data storage media. Combination of abilities for LDOS manipulation in plasmonic metamaterials and its ultrafast modulation is important for designing controllable single photon sources for quantum technologies. Addressing the challanges described above will further facilitate adoption of the ultrafast plasmonic meta-devices in these applications and will be a basis for development of new ones.

Acknowledgments

This work was supported by the European Research Council project iCOMM (789340) and UK EPSRC (EP/W017075/1).

3.15. THz generation with metasurfaces

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Status

Nonlinear broadband THz generation from plasmonic metasurfaces was observed already in 2011 [284] (see figures 39(a) and (b)). These deeply sub-THz wavelength (1 THz = 300 μm) nano-structured particle assemblies emit broadband EM fields in the THz spectrum after illumination with ultrashort laser pulses. Various mechanisms have been considered for the THz emission, including ponderomotive acceleration of photo-ejected elections [284] and quadratic optical rectification [285] (see figures 39(c)–(e)), which was also discussed in the case of flat metal films [286]. The emitted THz field from these metasurfaces was found to be comparable to that of much thicker nonlinear crystals, for example ZnTe [285]. This remarkable feature marks their potential contribution to the growing field of THz science and technology.

The THz region of the EM spectrum (0.1–10 THz) has recently seen widespread adaptation to numerous fields in both fundamental and industrial areas such as fast wireless communications, stand-off detection, non-destructive testing and biomedical imaging [287]. The unique THz sensing capabilities are enabled by molecular spectroscopic fingerprints in the THz spectrum, combined with a relatively low photon energy (1 THz = 4 meV), which is both non-ionizing and can penetrate through many optically opaque materials. Great progress has been achieved in the areas of THz generation and detection. However, developing broadband functional THz optics and sources has proven difficult due to absorption in traditional optical elements and requirements for large operation bandwidths. To overcome some of the challenges in the field, nonlinear metasurfaces emerge as a promising pathway for progress.

The first demonstration of nonlinear functional THz beam shaping used metasurfaces consisting of regions of inverted split-ring-resonators (SRRs). The inversions exerted π phase shifts on the local emission which was leveraged to demonstrate the generation of spatiotemporal quadropoles and dispersed THz beam steering [288], in addition to THz Fresnel zone plate emitters [289]. More recently, functional PB phase metasurface THz emitters were demonstrated [220] (see figure 40). The geometric phase concept allowed progress beyond binary phase manipulation and demonstrated full gradient phase metasurface emitters. This advancement opened the door to demonstrate multiple new concepts for THz sources including THz circular spin-state separation, continuous all-optical control over the linear polarization state of the emission, tailored emission of THz vector beams, time-domain polarization dispersion, and beam steering [220]. These recent demonstrations show great promise in achieving the sought after functional control required for the wide variety of THz applications.

Current and future challenges

A number of key challenges and areas of research for THz nonlinear metasurfaces are still open to investigation and improvement. Firstly, the more mature field of linear metasurfaces and also harmonic generation from nonlinear metasurfaces have resulted in numerous diverse applications such as advanced beam shaping, imaging, holography, and optical encryption [212]. The initial recent results utilizing geometric phase nonlinear metasurfaces for THz generation show the promise of extending these applications into THz sources for the first time. This functionality and unmatched level of control over the emitted THz field, which stem from the mapping of local meta-atom position and orientation directly to the desired far field properties, is the key advantage of using the nonlinear metasurface platform. Therefore, an immediate challenge is to demonstrate THz metasurface emitters with more advanced functionalities.

In addition, in order to make the THz metasurface emitters more attractive for a wide variety of applications, the optical to THz conversion efficiency should be maximized. To date, the absolute power conversion efficiency of such metasurfaces has so far been limited to the order of 10^{-7}–10^{-8}. While impressive for their ultra-thin thickness, this performance still lags behind some of the conventional THz sources, and as a result may impede the adaption of metasurface THz emitters to certain applications which require a high SNR, or penetration through thick layers of material. One limitation on the demonstrated conversion efficiency comes from the relatively low damage threshold of the plasmonic meta-atoms that were used. Therefore, finding solutions to this problem in the form of more complex designs or usage of new materials, may allow to enhance the conversion efficiency.

Lastly, the onset of different THz emission mechanisms and their interplay is not yet fully understood. These different mechanisms may interact destructively and lead sometimes to saturation of the emitted THz field or modifications on the temporal dynamics and spectrum of the emitted radiation. Through better understanding of the generation mechanisms, more informed choices can be made on the design of the meta-atom, metasurface, and also the optimal material characteristics required for THz generation.

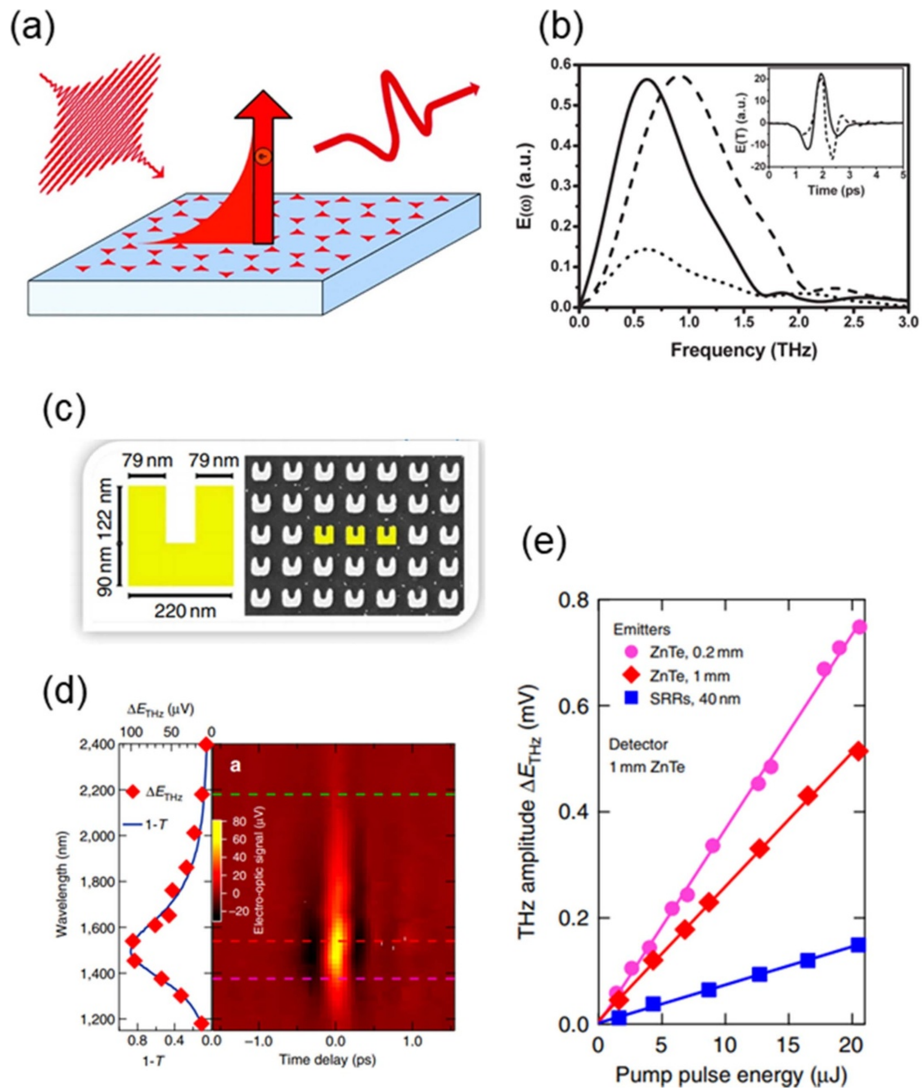

Figure 39. THz generation from nonlinear metasurfaces. (a) Illustration of THz generation from a plasmonic metasurface after ultrashort pulse illumination. The emitted THz pulse in this work is theorized to be generated from the nearfield ponderomotive acceleration of photoejected electrons. (b) Time and frequency domain plots of the generated THz electric field, showing a broadband THz generation extending up to approximately 2 THz. The solid line and dashed line are for particle dimensions of 390 nm and 780 nm respectively. The dotted line represents the emission from a ZnTe nonlinear crystal, scaled down by a factor of 100. Reprinted with permission from [284]. Copyright (2011) American Chemical Society. (c) Gold SRR array for the generation of broadband THz electromagnetic fields. (d) THz electric field magnitude as a function of laser wavelength and temporal delay. The maximum THz signal is observed when pumping at the SRR magnetic dipole resonance. (e) THz electric field amplitude versus pump pulse energy for a 40 nm thick SRR array and for two ZnTe nonlinear crystals with thicknesses of 0.2 mm and 1 mm. The THz amplitude from the metasurface is appreciable relative to much thicker nonlinear crystals. Reproduced from [285], with permission from Springer Nature.

Advances in science and technology to meet challenges

The challenges associated with increasing the efficiency of nonlinear THz metasurfaces can be undertaken in a number of ways. Recently, large enhancements of the conversion efficiency of nonlinear metasurfaces (typically for second harmonic generation) have been shown through mode matching, where the meta-atom array spacing is engineered in order to generate a collective resonance. This mode results in a spectrally sharp high-Q absorption resonance which can significantly enhance the interaction with the pumping beam, and in turn results in enhanced harmonic emission [290]. A second mode can also be designed for the generated harmonic, resulting in even further enhancement. Such enhancements have only been applied so far to second and third harmonics, or additional four wave mixing schemes. Applying single or doubly resonant mode enhancement to the THz regime may potentially result in a drastic increase in the achievable optical to THz conversion efficiency. Moreover, the second resonant mode of the THz could potentially be used to obtain further spectral control over the emitted radiation.

Another promising advancement that should be made is in the exploration of new metasurface material systems for THz generation, considering the limitations posed by using plasmonic materials. Recently,

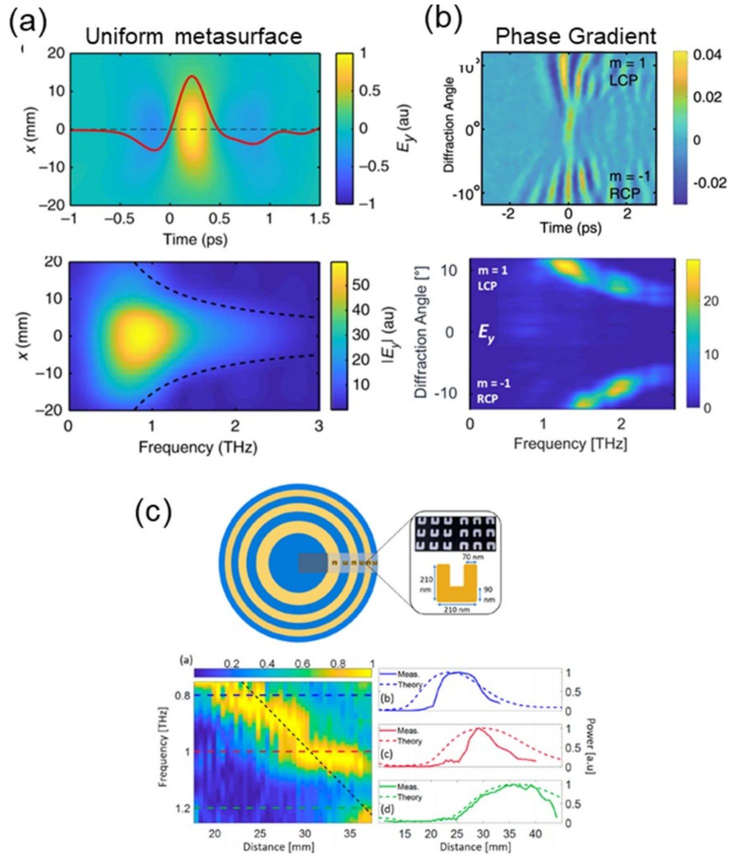

Figure 40. Functional THz emitters based on nonlinear metasurfaces. (a) Uniform plasmonic metasurface using SRRs resulting in the nonlinear emission of single cycle sub ps THz pulses. The frequencies generated range is up to ∼2.5 THz [288]. Reproduced from [288]. CC BY 4.0. (b) Phase gradient metasurface utilizing C3 meta-atoms resulting in the nonlinear emission of broadband THz left hand circular and right hand circular polarized pulses to the ±1 diffraction orders [220]. Reproduced from [220]. CC BY 4.0. (c) Illustration and section of a THz Fresnel zone plate constructed using SRRs [289]. Reproduced with permission from [289]. The metasurface generates broadband THz fields and exhibits focusing of the same fields.

significant research has been undertaken on all dielectric nonlinear metasurfaces. In contrast to plasmonic metasurfaces, nonlinear dielectric metasurfaces utilizing resonant high index meta-atoms (GaAs, lithium niobate amongst others) show a high damage threshold, high peak power saturation point and much better conversion efficiency [232]. In order to apply dielectric metasurfaces to nonlinear THz generation, a suitable material such as GaAs could be used, which has a large second order nonlinear susceptibility (200 pm V^{-1}). Furthermore, the possibility to combine both enhanced EM fields via collective modes with dielectric metasurfaces, may provide another means to enhance the THz emission.

Further capabilities of nonlinear metasurfaces can be gained by extending the typically used single layer of meta-atoms into more complex systems. Recent works have shown the integration of metasurfaces into photoconductive antenna devices for field enhancement, multi-layer metasurfaces for enhanced second harmonic generation, and meta-systems consisting of multiple metasurfaces for beam manipulation. These complex meta-systems can provide enhanced generation efficiency and beam control in an extremely compact form. Significant fabrication, material engineering as well as theoretical challenges need to be overcome in order to realize such complex systems.

Concluding remarks

Nonlinear metasurface THz emitters have emerged as a new and promising platform for the generation of controlled THz waves. Their demonstrated functionality and ability to control the local phase and polarization of the generated THz waves is already surpassing most of the state of the art THz sources. However, there is still significant room for progress. Many more ideas that were already examined for controlling light by linear and nonlinear metasurfaces can be studied within the realm of THz metasurface emitters. In particular, new and clever ways to boost their conversion efficiencies will make them highly attractive for an abundance of THz applications. For example, through further studies and optimization of the metasurface fabrication, composition of materials, and careful engineering of the metasurface modes, significant improvements in the conversion efficiency are expected. Further research and improvement of the metasurface platform will provide a highly functional THz source which can be used to fully exploit the range of diverse applications utilizing THz waves.

Acknowledgments

The authors should like to acknowledge the European Research Council (ERC) for the funding received under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 715362).

3.16. Broadband metasurfaces and applications

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Status

Metasurfaces have found widespread applications in various EM and optical problems. However, there are great challenges to extend the operational bandwidth. Taking the radar absorbing metasurface as an example, it seems impossible to realize complete absorption of very low-frequency radar wave within a given thickness (such as 1 mm). Meanwhile, in the design of flat lens (metalens) based on metasurfaces, the simultaneous increase of bandwidth and aperture is a challenging scientific question remaining unsolved.

Over the recent two decades, many methods have been proposed to increase the operational bandwidth, which is determined by the frequency response of both the constituting materials and their geometric structures. In principle, it is possible to control the frequency response, i.e. dispersion, of metasurfaces by elaborately choosing the materials and optimizing their geometric structures. To highlight the intrinsic relationship between the structures and functions, both metamaterials and metasurfaces could be termed as 'structured functional materials'.

Figure 41 shows some representative EM metasurfaces with broadband characteristics. The left and right columns depict the metallic and dielectric structures, respectively. In general, owing to its flexible electric current modulation ability and relatively thin profile, metallic structures show superior performance in microwave, mmWave, and terahertz bands. However, at infrared, visible and ultraviolet band, the metallic loss become significant, thus dielectric materials are preferred, except for applications associated with SPs and related phenomena. In many functional optical metasurfaces, adoption of dielectric alternatives has become the current standard. In the flat optical lensing problem, while the energy efficiency of dielectric metalens can be larger than 80%, a single layer of metallic metasurface only show an efficiency typically below 20%.

As shown in figures 41(a)–(c), the metallic catenary and V-shaped structures represent two typical ultrathin structures used for arbitrary phase modulation and generalized Snell's law [291, 292]. Since the phase shift is not accumulated through the propagation length, the bandwidth is only limited by the polarization conversion efficiency. By using dielectric materials, broadband and high-efficiency catenary metasurfaces have been demonstrated [293]. To realize polarization-independent and achromatic phase modulation, square or circular shaped structures with dispersive dielectric materials could be harnessed (figure 41(d)) [294].

Another broadband structure is the chiral metasurface made of metallic or dielectric helix, which could enable broadband circular dichroism (figures 41(e) and (f)). By changing the orientation angle of each helix, broadband geometric phase may be realized. Finally, it should be noted that reflective configuration is a general strategy to guarantee the energy efficiency (figures 41(g) and (h)). Since no transmission occurs, the overall reflectivity could be very high up to 100%, if the absorption loss is also suppressed.

Current and future challenges

In the design of broadband metasurfaces, dispersion engineering plays a key role. For a given effective medium, any physically realizable frequency dispersion can be decomposed into a series of Lorentz resonances. Consequently, one can use a set of isolated resonators to tune the dispersion property and increase the working bandwidth. In general, there are three distinctive approaches widely used in the community:

First of all, a complex subwavelength structure may exhibit many different resonances at separated frequencies, if different EM modes can be supported. For instance, a split ring resonator could exhibit at least three resonances for two orthogonal polarizations, which is the key to realize broadband polarization conversion [295].

Secondly, structures with different shapes, sizes, and resonant frequencies may be placed side by side in the same layer, or layer by layer to enhance the operation bandwidth. Although a layer-by-layer approach would increase the thickness of the device, it is much more flexible and scalable than the side-by-side configuration.

Thirdly, one can combine positive and negative dispersion properly to realize a much broader bandwidth. This strategy is applicable in the design of full spectrum camouflage, polarization conversion, phase modulation, and achromatic flat lenses [296]. In hybrid optical systems based on refractive and diffractive elements, the chromatic aberration can also be significantly suppressed.

Although great success has been achieved, however, the dispersion engineering techniques reported so far are far from perfect. There are great challenges to further increase the bandwidth of EM metasurfaces with larger size and more functionalities. As shown in figure 42, there are some fundamental limitations on the

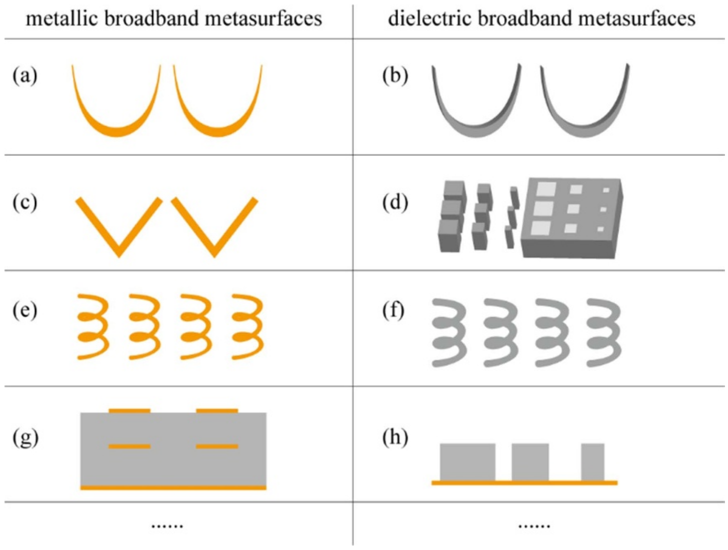

Figure 41. Representative broadband metasurfaces. The left (right) column shows metallic (dielectric) structures.

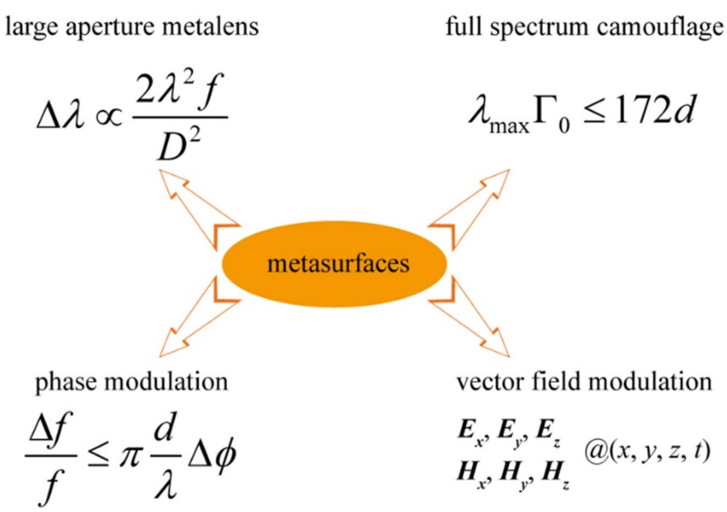

Figure 42. Typical applications of broadband metasurfaces. The formulas describe the relation between the bandwidth and geometric size. For vector field modulation, no simple formulas can be given.

relationship between the bandwidth and geometric sizes [297, 298]. For instance, for a metalens with $f = 1.0$ m, $D = 0.1$ m, and $\lambda = 532.1$ nm, the operational bandwidth is only about 0.06 nm, which is not suitable for broadband imaging. Thus far, it is still not known how to increase the bandwidth to more than 100 nm without introducing additional refractive or reflective optical elements. For full spectrum camouflage, the extension of low-frequency absorption is often accompanied with an increase of the material thickness. It is a great challenge to beat this restriction without resorting to magnetic materials such as ferrites. Furthermore, the compatibility of microwave, terahertz, infrared and optical responses is also an open question.

Advances in science and technology to meet challenges

Since the current bandwidth of functional metasurfaces are fundamentally limited and recent efforts have shown limited bandwidth enhancement ability, interdisciplinary innovations at multiple levels must be pursued to meet the technical challenges raised by practical engineering applications.

First of all, further dispersion engineering of structured functional materials is required. By introducing new constituting materials and free-form metasurface optimization based on adjoint simulation, the frequency response of metasurfaces can be tuned to be closer to the ideal cases. As a first step, a more generalized theory for dispersion engineering is desired.

Secondly, the geometry of metasurface may go beyond flat surfaces to the combination of flat and curved surfaces. Taking the metalens as an example, one may combine flat metalens and traditional free-form refractive element to eliminate the chromatic aberration and monochromatic aberration simultaneously. Since metalens and diffractive elements show opposite dispersion, their combination is helpful for the cancellation of chromatic aberration.

Thirdly, with active and reconfigurable materials and devices, the operation bandwidth may be extended to break the classic limit. On the one hand, one can tune the operation frequency band dynamically such that the bandwidth is varying with time. Consequently, the overall bandwidth may be increased significantly. On the other hand, with the help of non-Foster active device, one may break the Rozanov's thickness-bandwidth limit in real time [299]. However, it is still a grand challenge to realize miniaturized and high-performance non-Foster device.

Finally, innovation in the operation principle is needed to overcome the bandwidth limit completely. For instance, by introducing the interference of a coherent beam, coherent perfect absorption could be realized for an unprecedented bandwidth covering the microwave, terahertz, and optical bands [300]. Moreover, owing to the natural similarities in wave mechanics, the operation principle may be extended to all kinds of waves such as EM waves, acoustic waves and even matter waves.

Concluding remarks

To summary, the operation bandwidth is a key index for metasurfaces, which is of particular importance for many applications such as EM camouflage, optical imaging, display and communications. Owing to the resonant nature of effective medium and some fundamental limitations such as causality and Kramers–Kronig relation, many metasurfaces are suffering from the narrow bandwidth. Over the past decade, following the dispersion engineering principle, many novel methods have been proposed to increase the bandwidth of metasurfaces. In general, novel constituting materials and geometric shapes would be helpful for the further increase of bandwidth. However, to realize revolutionary improvement of the performance (e.g. increase the bandwidth of large-aperture metalenses and broadband absorbers by several orders), more fundamental innovations are required. We believe active and reconfigurable materials/devices may be the next breakthrough in the following years.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 61975210 and U20A20217).

4. Spoof surface plasmonic systems

4.1. Metal metasurfaces supporting spoof surface plasmons (SPs)

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In undergraduate Classical Electromagnetism courses, it is commonly taught that a perfect electrical conductor (PEC) completely expels EM fields, making it unable to support the propagation of bound EM waves on its surface. Although metals act as PECs at the microwave, terahertz, and mid-infrared frequencies, in 2004, a ground-breaking discovery revealed [13] that when the surface of a PEC is structured on a much smaller length scale than the operating wavelength, the structure effectively behaves as a metamaterial in which surface EM modes can be supported. These modes, referred to as spoof SPs, exhibit properties like those of standard SPs in the optical and near-infrared frequency regions. Since then, the concept of spoof SPs has opened new research avenues in Plasmonics, aiming to transfer the potential of SPs at optical frequencies to lower frequencies. This concept has been extended from planar surfaces to waveguides and resonators, as discussed below, encompassing the entire range of structures studied in conventional Plasmonics.

The concept of spoof SPs was firstly proposed for structured 2D metallic surfaces [13, 301]. The simple model in figure 43(a) shows the main principle of spoof SPs. It consists of a metallic surface (relatively permittivity of ε_m) pierced by a 1D periodic array of grooves of depth h, width a, and period d, these three geometrical parameters being much smaller than the free-space wavelength. The EM fields confined at adjacent grooves couple through diffraction and can store EM energy at the surface to mimic the behavior of natural SPs. The periodicity of the groove array prevents the out-coupling into free space radiation and thus provides the condition to support a bound EM mode. Assuming that only the TM mode with lowest order is excited inside the groove, and taking the PEC limit for the metal permittivity ($\varepsilon_m \to -\infty$) the dispersion relation of the spoof SPs can be expressed as:

$$k_x = k_0\sqrt{1 + \frac{a}{d}\tan^2(k_0 h)},$$

where $k_0 = \omega/c$ and k_x is the wave vector in the propagation direction. The dispersion relation of the spoof SPs obtained from the equation above is shown in figure 43(b) for various h/d values. Note that it resembles of the dispersion of natural SPs supported on a flat metallic surface. At low frequencies the spoof SP bands are close to the light line ($k_x = k_0$, grazing plane-wave), indicating poor confinement. As the frequency increases the dispersion curve of spoof SPs shifts away from the light line and the modes acquire a subwavelength confinement in the vertical direction. Finally, the dispersion curves of spoof SPs approaches $\omega = \pi c/(2h)$ at $k_x = \pi/d$, at the border of the first Brillouin zone.

Spoof SPs can be supported by a PEC surface pierced by a 2D array of holes as well. Here, we suppose that the holes are squares with width a and are arranged periodically with a period d. Different from the 1D arrays of grooves, where the waveguide mode is always propagating, the lowest-order waveguide mode in the square holes is evanescent for $\lambda_0 > 2a$, which leads to a cut-off frequency given by $\omega = \pi c/a$. It can be demonstrated [13] that the EM response of a 2D array of holes perforated on the surface can be mapped into that of a non-structured, homogeneous surface described by parallel ($\|$) and perpendicular ($\perp$) components of the dielectric (ϵ) and magnetic (μ) response functions which can be expressed as:

$$\epsilon_{\|}(\omega) = \frac{\pi^2 d^2}{8a^2}\left(1 - \frac{\pi^2 c^2}{a^2\omega^2}\right)$$

$$\mu_{\|} = \frac{8a^2}{\pi^2 d^2}$$

$$\epsilon_{\perp} = \mu_{\perp} = \infty.$$

The parallel dielectric function of the corrugated metal surface given above is analogous to that of a lossless Drude metal, with the cut-off frequency of the hole waveguide replacing the plasma frequency. This result reveals the purely geometric origin of spoof SP modes, and demonstrates how the EM response of corrugated metal surfaces can be adjusted through their geometry. The initial work on planar surfaces described in [13, 301] was followed by subsequent experimental verifications of spoof SPs in the microwave [302] and terahertz regions [303].

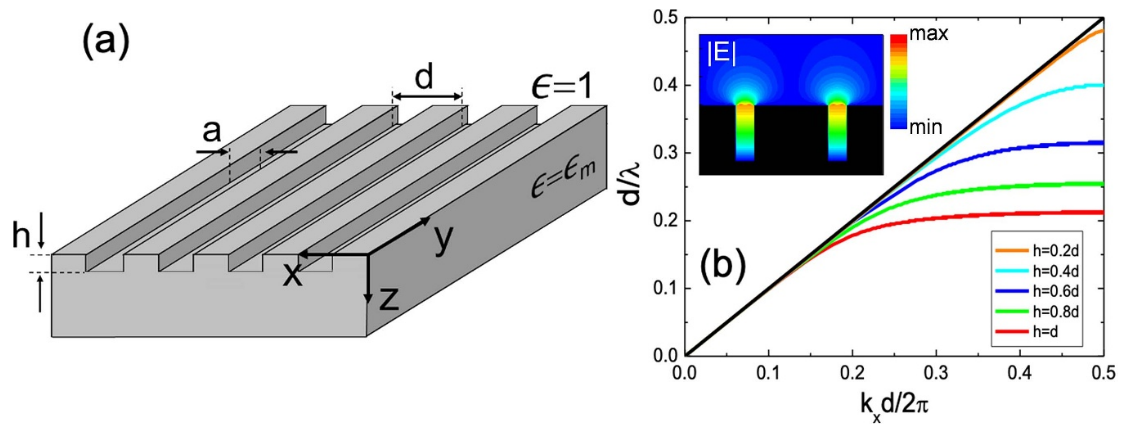

Figure 43. (a) Sketch of a 1D periodically corrugated geometry. (b) Dispersion relation (inverse of the wavelength versus wavevector) of the spoof SP modes supported by a 1D array of grooves for different values of the ratio h/d. Black line depicts the corresponding light line ($k_x = k_0 = 2\pi/\lambda$). The inset shows the electric field amplitude of the spoof SP mode at $k_x = \pi/d$ for $h = 0.6d$.

The concept of spoof SP was subsequently extended to 1D structures, where the lateral confinement makes it possible to design waveguides. Theoretical investigations along this line include periodically corrugated wires [304], wedges [305], channels [306], periodic chains of dominoes [307] and metal–insulator–metal waveguides [308]. In the microwave and terahertz bands, where most experimental research works have focused, spoof SPs in waveguides display not only deep subwavelength confinement but also large propagation lengths. Moreover, the concept of spoof SPs in waveguides has also enabled an efficient propagation of EM field along curved surfaces. Shen *et al* [14] demonstrated theoretically and experimentally that the so-called conformal surface plasmons (CSPs) supported by ultra-thin films can achieve low-loss propagation along arbitrarily curved surfaces.

The localized version of spoof SPs has been found to be supported by textured PEC particles of closed surfaces, exhibiting similar properties to those of LSPs in the optical regime [309]. An EM response equivalent to that of a cylinder made of a Drude metal was demonstrated for an infinitely long PEC cylinder corrugated with a periodic array of grooves. Subwavelength particles sustaining natural LSPs exhibit a dipolar response dominated by the electrical dipole mode whose resonant frequency is given by the material permittivity. On the contrary, the resonant frequency of spoof LSPs scales with size, requiring a different approach to reach the subwavelength regime in textured metamaterial particles. In [309], this was achieved by using a dielectric material with a large refractive index within the grooves, resulting in a dipolar response. Additionally, a novel magnetic spoof-LSP structure was devised in [310], displaying a magnetic response unlike the purely electrical dipole character of conventional LSPs.

Applications of spoof SP structures and devices still face several challenges, including impedance matching and losses. Achieving impedance matching over a wide frequency range is difficult, as the impedance of spoof SP structures can vary significantly with frequency, which makes the design of devices operating efficiently over a broad bandwidth challenging. Losses are also a significant issue in spoof SP structures, specially at high frequencies. These include metallic, substrate and radiation losses, which can limit the performance of spoof SP devices. Therefore, there is still much research work to be done in this field to take advantage of the full potential of spoof SPs in the applied front.

Despite the obstacles above, the rapid evolution from basic studies on 2D hole and 1D groove arrays to the development of different waveguiding schemes and resonators based on spoof SPs has led to the feasible implementation of both passive and active devices in less than 20 years. These devices have already been incorporated into wireless telecommunication systems [311] and body sensor technology [312]. We expect that future research in this area will focus on exploring new functionalities for spoof SPs in different areas, indicating the direction of research for the coming years. Garcia-Vidal *et al* [16] offers a comprehensive review combining both a fundamental and applied perspective on the topic.

4.2. Spoof SPP transmission lines (TLs)

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Status

Since most metals exhibit the properties of perfect electric conductors at lower frequencies, optical surface plasmon polaritons (SPPs) cannot be excited at the interface between the metal and dielectric in the microwave and terahertz (THz) bands. However, thanks to the idea of drilling corrugated holes and cutting periodic grooves on a metallic surface, an exciting concept of spoof SPPs has been theoretically proposed by Pendry *et al* [13, 301] and experimentally verified using microwave reflectivity measurements by Hibbins *et al* [302]. Spoof SPPs inherit most of the exotic features of natural SPPs, such as field confinement, localized resonance, and subwavelength resolution. The most important advantage of spoof SPPs is that it allows controlling its dispersion properties at will by simply changing the geometric parameters. Thus, it is also recognized as a geometry-induced SPPs and is highly expected to offer an inspiring route for low-frequency applications.

In the early studies, the subwavelength corrugated metal surface was in the form of a TL to support the propagation of spoof SPPs, resulting in the birth of various corrugated configurations, for example, a metallic surface decorating a periodic groove, metallic cylindrical with corrugated grooves and helically periodic metallic wires, as well as some specially corrugated metal array including channel, wedge, domino block *et al* [313]. Such MGs induced spoof SPP TL is the most original, however, their inherent 3D geometries limit their applications in advanced functional devices and integration systems. Because the surface EM waves can be confined in the subwavelength range and propagate on curved flexible surfaces is critical for the miniaturization and planarization of components and devices. Shen *et al* [14] proposed an interesting concept of CSPs. It has been shown that the spoof SPPs can propagate on an ultrathin corrugated metallic film with a long propagation distance in broadband, and the metallic film with near-zero thickness can be folded, bent, twisted, and wrapped to arbitrary surfaces. With the in-depth study of spoof SPPs, two other promising spoof SPP TLs have appeared. One is the high-index contrast gratings (HCGs) induced spoof SPP TL, which was proposed by Liu and Li *et al* to support the ultralow loss propagation of spoof SPPs [314]. Such is recognized as a potential candidate to address the issues of large metallic loss and short propagation length. The other one is the waveguide structural dispersion-induced SPP TL, which is realized by exploiting the well-known structural dispersion waveguide modes only with two positive-ε dielectric materials [315]. Such a confined surface wave is considered to be a perfect low-frequency analog of optical SPPs.

In the real microwave and THz applications, most advanced circuits mainly consist of two-conductor TLs and relevant components and devices. Therefore, it is significant to efficiently excite the aforementioned spoof SPP TLs using the traditional two-conductor TL, such as co-planar waveguide (CPW), microstrip line (MS), *et al.* For this purpose, Ma *et al* [316] proposed a bridge structure consisting of a gradient Goubau ground and a gradient metallic strip with gradient grooves. In such a manner, traditionally guided quasi-TEM waves in CPW can be efficiently converted into SPP waves in a metallic strip decorating double-sided corrugated grooves and then efficiently converted back to quasi-TEM waves in CPW in broadband. Subsequently, many other transition schemes have also been reported for efficiently bridging spoof SPP TLs and other single or double-conductor TLs, including MS [317], slot line [318], dual-strip MS [319], substrate integrated waveguide (SIW) [320], coaxial waveguide [321], and rectangular waveguide [322], as shown in figure 44. Thanks to the unique features of low crosstalk, low propagation loss, and strong field confinement for spoof SPP TLs, various efficient and wide-band spoof SPP-based functional devices and components have been designed [323] including low-/high-/band-pass filters, frequency splitters/combiners, crosstalk suppression lines, and multichannel demultiplexers *et al.* Additionally, active components (e.g. diodes) or chips have been employed and directly loaded on the spoof SPP TLs for some active and nonlinear applications [324], such as amplifier circuits [325], phase-matched SH generators [326], multi-scheme digital modulators [327], and integrated spoof SPP circuits and wireless communication systems [311], as shown in figure 45. In general, the high-efficiency and broadband excitation of spoof SPP TLs make it a solid step in practical applications and also provides a positive route for its potential applications in advanced large-scale ICs and systems, wireless communications, and other fields.

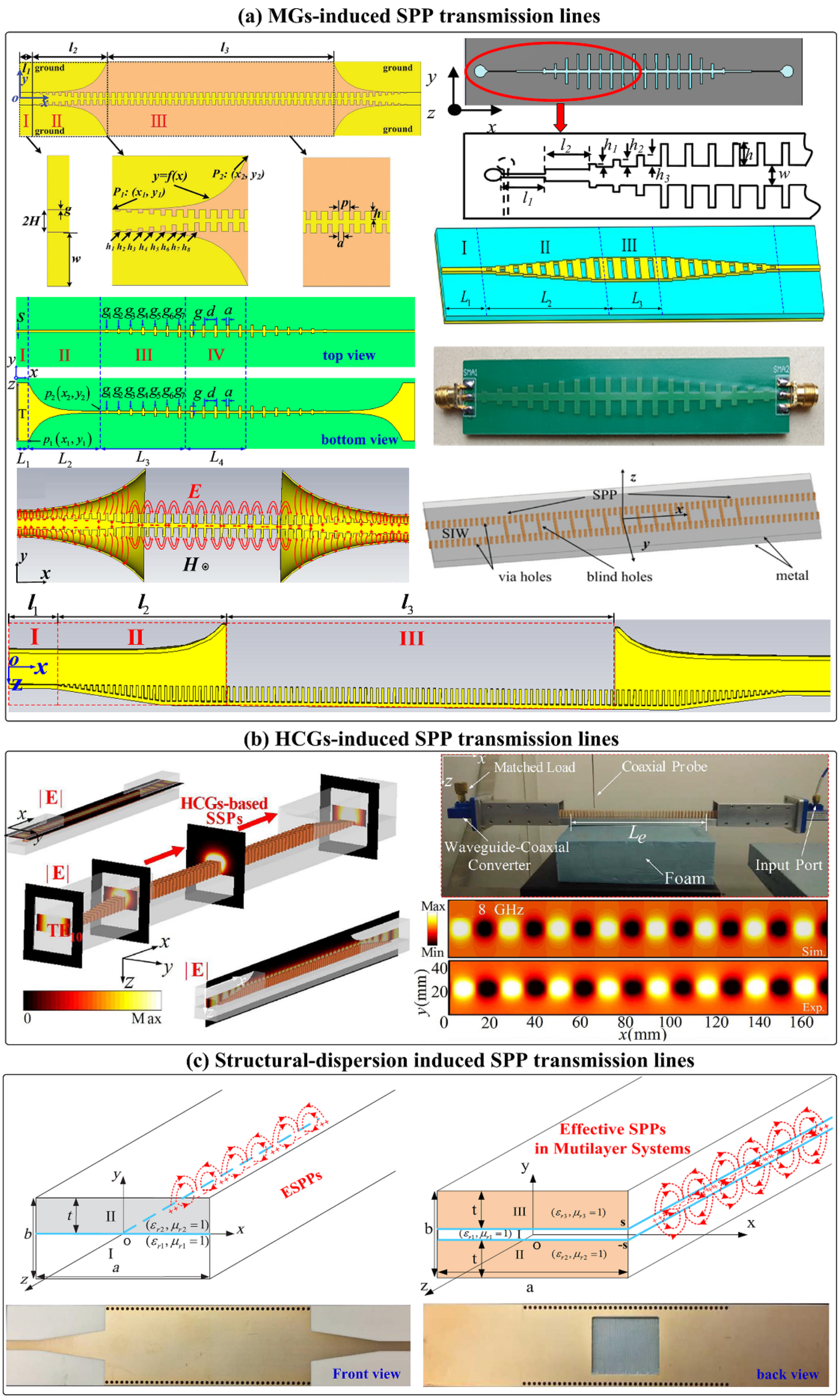

Figure 44. Broadband and high-efficiency excitation of spoof SPPs. (a) MGs-induced spoof SPP transmission lines excited by CPW [316], microstrip line [317], slot line [318], dual-strip line [319], substrate integrated waveguide [320], coaxial waveguide [321], and rectangular waveguide [322]. [316] John Wiley & Sons. © 2013 by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Reprinted from [317], with the permission of AIP Publishing. Reproduced from [318], with permission from Springer Nature. © [2017] IEEE. Reprinted, with permission, from [319]. Reprinted from [320], with the permission of AIP Publishing. Reproduced with permission from [321]. Reprinted from [322], with the permission of AIP Publishing. (b) HCGs-induced spoof SPP transmission lines excited by rectangular waveguide [314]. © [2015] IEEE. Reprinted, with permission, from [322]. (c) Structural-dispersion-induced spoof SPP transmission lines excited by substrate-integrated waveguide [315, 323]. Reprinted with permission from [315], Copyright (2017) by the American Physical Society. Reproduced with permission from [323].

Current and future challenges

Spoof SPPs have demonstrated significant advantages in designing efficient low-loss TLs, however, some challenges remain in fundamental theory and practical applications. First, although the efficient conversion

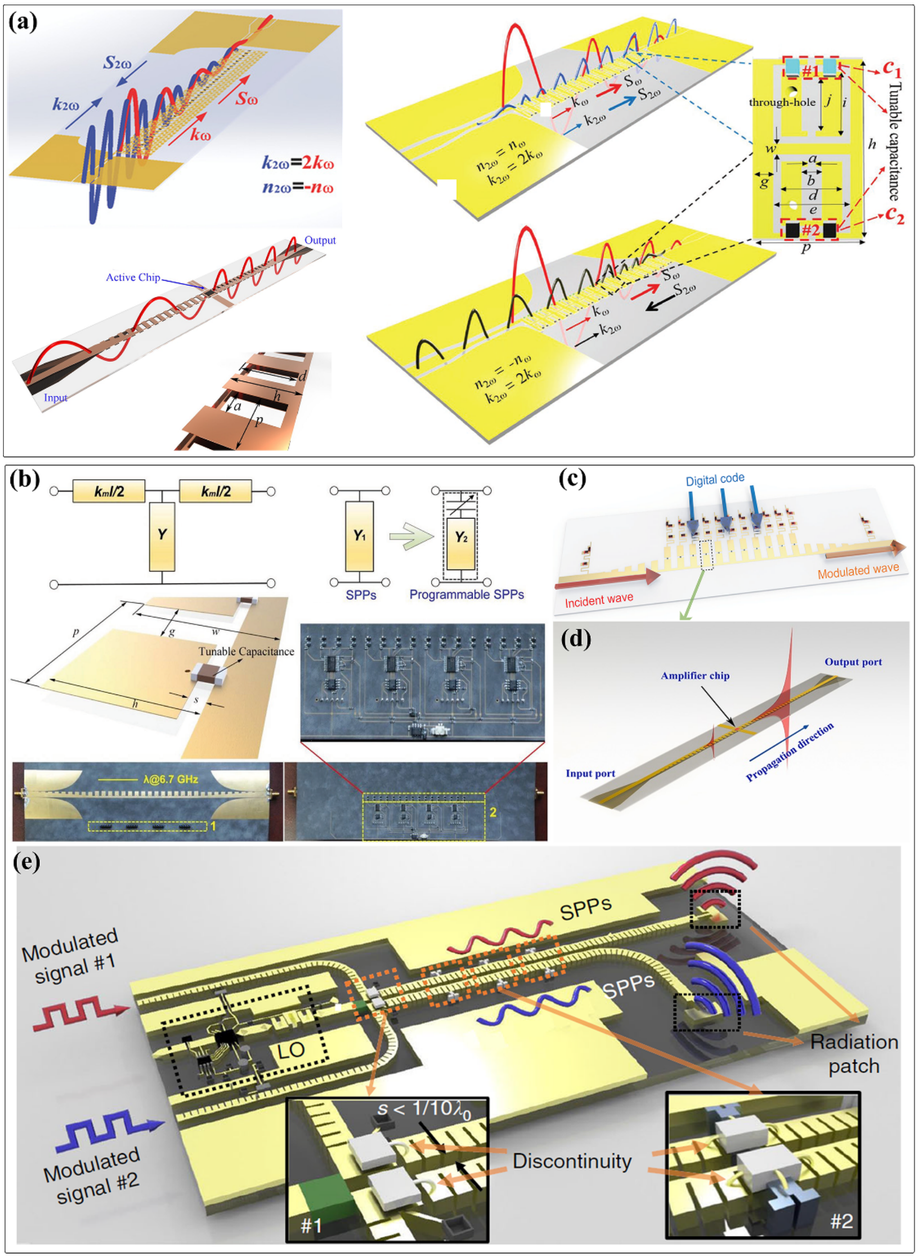

Figure 45. Active nonlinear spoof SPP transmission lines. (a) Second harmonic generator [326]. Reproduced from [326]. CC BY 4.0. (b) and (c) Programmable and digital spoof SPP transmission lines [324, 327]. Reproduced from [324]. © IOP Publishing Ltd. All rights reserved. Reproduced from [327], with permission from Springer Nature. (d) Active amplification of spoof SPPs [325]. [325] John Wiley & Sons. © 2014 by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (e) Spoof SPPs based communication system [311]. Reproduced from [311]. CC BY 4.0.

between spoof SPP TLs and traditional double-conductor TLs has been realized by a smooth transition bridge, the extra bridge part is an obstacle to the miniaturization and integration of the spoof SPP TLs in real integration circuits and systems. Consequently, the theory and technique for efficiently exciting spoof SPPs with a sufficiently short bridge length or without extra transition part need to be further studied and developed, including modes and impedance matching mechanisms, efficient excitation method, *et al.* Second, HCGs-induced SPP TLs have exhibited ultralow loss transmission characteristics, however, their 3D geometry and hybrid transmission modes limit their real applications. Therefore, their advantages need to be further studied, especially in the THz and near-infrared regions, where the inherent metallic loss cannot be ignored. Third, structural dispersion-induced SPPs only can be excited in a waveguide that supports TE_{10} mode, thereby limiting its applications in integration with other TLs, especially in the field of active nonlinear spoof SPP TLs. Finally, enough new physics and fairly great performance of spoof SPP TLs have been demonstrated, and the fundamental physical properties of three spoof SPP TLs have been thoroughly excavated and researched. How to take advantage of strong field confinement and subwavelength resolution to further develop wider novel physics and applications (e.g. quantum spin Hall effect, compacted dimensions on singular plasmonic surfaces, generalized Kerker effect, THz sensing, and non-Hamiltonian topological thermal insulators [323]) shortly soon is a challenge.

Advances in science and technology to meet challenges

There may be some solutions to address the challenges of the above-described spoof SPP TLs. Combining advanced mode coupling theory with TL theory the fundamental physics of matching transitions for these three spoof SPP TLs can be further studied, including the effective impedance, wave momentum, and mode matching, *et al.* Potential transition scenarios, for example, the mode matching and bridge transition in the direction perpendicular to the SPPs transmission can be exploited to meet different application needs with the current printing circuit board technology. With the advancement of integrated optoelectronics, benefit from the characteristics of modern complementary metal oxide semiconductor technology and the non-metallization form of HCGs, HCGs-induced SPP TLs can find significant potential applications in numerous advanced optoelectronic devices and systems, such as ultra-low loss hollow-core waveguides, photodetectors, integrated interconnects and slow-wave delay lines, as well as vertical cavity surface emitting lasers. For structural dispersion-induced SPP TLs, waveguide metatronic, an analog of optical metatronics, uses structural dispersion in waveguides to get the materials and structures needed to build the lumped circuitry and is a potential pioneer for assisting the design of the epsilon-negative TLs, ENZ TLs, or the TLs where both exist using all positive-ε dielectric materials [74] for active nonlinear applications. In addition, spoof SPP TLs exhibit significant advantages in the aspect of crosstalk reduction and loss suppression, and hence they can be utilized to realize the planarization and miniaturization of mmWave and THz components and devices to meet signal integrity requirements of large-scale highly ICs and systems.

Concluding remarks

Since the concept of spoof SPPs was proposed by Pendry *et al*, spoof SPP TLs have been developed to be a research branch with great promise in the field of surface plasmonics. Significant advantages of spoof SPPs such as strong field enhancement, subwavelength confinement, and dispersion tunable have been exploited to help design various passive and active plasmonic TLs. Benefiting from the efficient mode conversion scheme between spoof SPPs and traditional guided waves, as well as their significant properties of low crosstalk, low propagation loss, and low radiation loss in the bending region, spoof SPP TLs are considered promising information carriers for future subwavelength microwave and THz devices and systems. Given the current trends in research for passive and active applications, we expect that in the near future spoof SPP TLs can play a key role in the design and analysis of signal integrity in ICs and systems, 6G wireless communication, and information security.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Nos. 61771238, 61871215 and 61701246); the Fund of Prospective Layout of Scientific Research for NUAA (Nanjing University of Aeronautics and Astronautics); the Fund of Qing Lan Project of Jiangsu Province.

4.3. Passive spoof SPP devices and antennas

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Status

On the interface between a good plasmonic metal and a dielectric, there exist the SPPs. They are aroused by the strong light–matter interactions, as indicated in figure 46(a), and propagate on the surface as a specific type of surface wave with extremely localized EM fields. The SPPs have been explored to merge electronics and photonics at nanoscale and developed for biosensing, microscopy, extraordinary optical transmissions, etc in the optical regime [328]. Below the far-infrared, e.g. at terahertz and microwave frequencies, metals behave close to PECs rather than plasmas, and therefore the SPPs are no longer supported on them. In 2004, the 'spoof' surface plasmon polaritons (spoof SPPs, or SSPPs), which is also termed as the 'designer' SPPs, were conceived on decorated metals at lower frequencies [13]. Figure 46(b) depicts the first theoretic model that supports the spoof SPP mode. The EM wave is trapped by the periodic sub-wavelength structures in the metal and the energy is bounded to the surface, resulting in localized EM field which is similar to that for natural SPPs. Since then, different types of textured surfaces have been proposed as spoof SPP waveguides, such as the domino structure sketched in figure 46(c) [307]. Field localization, as well as SPP-like dispersion curves as plotted in figure 46(d), has been theoretically and experimentally demonstrated. To be noted, due to the fact that the spoof SPP waveguides are composed of designable sub-wavelength units, they are also considered as the plasmonic metamaterials.

The spoof SPPs inherit SPP-like merits such as field confinement, field enhancement and sub-wavelength resolution, which reveal great potentials in ICs and compact systems. Currently, planar waveguides (e.g. the strip line, the MS, the CPW and the SIW) are widely used in advanced microwave circuits and systems. In order to adopt the spoof SPPs in planar integrated systems, research on the thickness of the spoof SPP waveguide was carried out [14, 329]. It has been proved that the dispersion characteristics, as well as the EM properties, are not sensitive to the change of thickness (see figure 46(d)). Therefore, the ultra-thin spoof SPP TL is achieved in figure 46(e), in which the propagating spoof SPP wave is localized to the TL and 70% of the flowing energy is confined in the sub-wavelength scale, as given in figure 46(f). In addition, different types of spoof SPP TLs, including the single-strip TL, the grounded single-strip TL, the dual-strip TL, have been developed to adapt to different application environments [330, 331]. Correspondent excitations have also been realized for efficient conversion between the spoof SPP mode and the guided-wave modes [316].

Owing to the unique EM properties of spoof SPPs, passive circuits and devices with attractive performance have been developed. First of all, due to the strong field confinement, the spoof SPP circuit may break the physical limit of signal integrity because mutual couplings between components are significantly depressed [331]. Compact spoof SPP TL array, feeding networks and devices such as couplers have been delivered [329, 332, 333]. Secondly, as is given in figure 46(d), the dispersion curve of spoof SPPs presents a cutoff frequency, which has been utilized for filtering purposes. Different types of filters, including low-pass, band-pass and band-stop ones, have been developed [334, 335]. Thirdly, since the dispersion characteristics can be designed through tailoring geometric parameters (e.g. the parameters given in the inset of figure 46(d)), novel functional devices have been created, such as the frequency splitter, the spoof SPP rejection, and the spoof SPP logical gates [336].

Aside from the passive devices, antennas are also key to wireless communication systems. Although the spoof SPPs are essentially slow waves that cannot radiate, different methodologies have been presented to create antennas of spoof SPPs. Among them there are three main categories. Firstly, modulation to the spoof SPP TL, as is shown in figure 47(a), is involved so as to generate space harmonics that travels fast enough to radiate [337]. Another way to generate space harmonics is to apply periodically aligned radiators fed with the spoof SPP TL, as depicted in figure 47(b) [338]. Frequency-dependent leaky-wave antennas have been created and demonstrated in this way. Secondly, the structures of spoof SP are used as emitters that obtains EM energy through coupling and radiates it to the free space. For example, the ring resonator of spoof SPP in figure 47(c) is designed to generate vortex beams [339], and the resonator based on spoof LSP in figure 47(d) is used as an end-fire radiator [340]. Thirdly, due to the increased effective length and depressed mutual coupling, the spoof SPP schemes are especially powerful in the design of minimized antennas (see figure 47(e)) and compact feeding networks for antenna arrays [341].

Current and future challenges

Although the spoof SPPs have exhibited sufficient advantages in designing passive devices and antennas, there are still some challenges in fundamental theory and practical applications. First, although the conformal

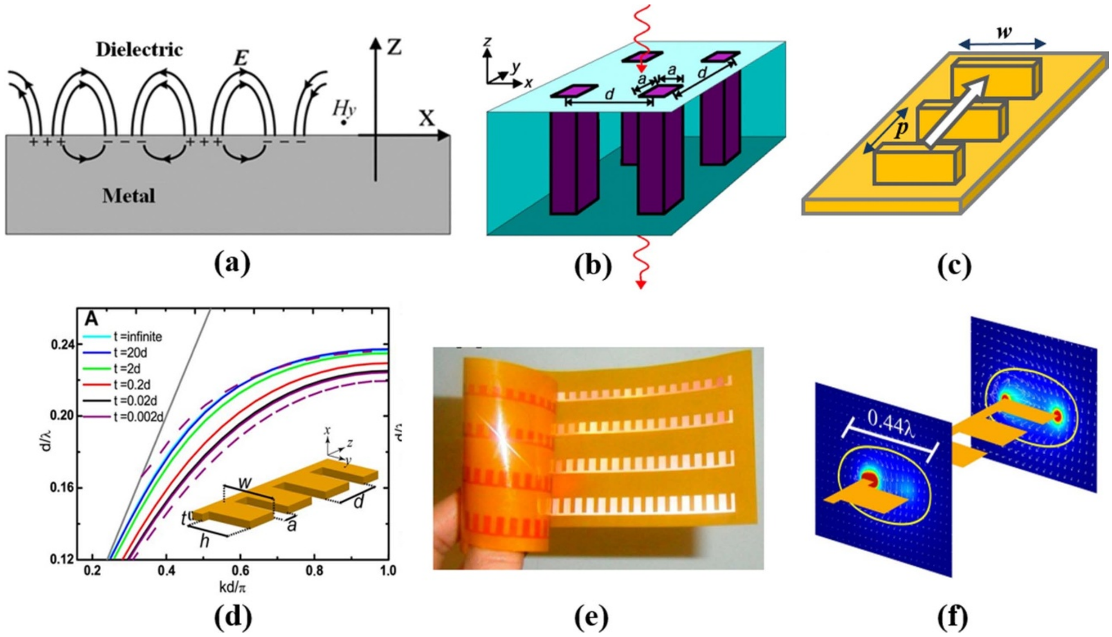

Figure 46. Evolution from SPPs to the ultra-thin spoof SPP TL. (a) The EM field on a metal-dielectric interface where SPPs exist. (b) The first theoretic model that predicts the spoof SPP modes induced by the structure [13]. From [13]. Reprinted with permission from AAAS. (c) Schematic diagram of a 1D array of grooves that supports the propagation of spoof SPPs. Reproduced from [307]. CC BY 4.0. (d) Normalized dispersion relations for the fundamental spoof SPP mode as a function of thickness t [14]. (e) Photograph of the nearly zero-thickness spoof SPP TL on a flexible and ultrathin dielectric film [14]. (f) Power flow on the ultra-thin spoof SPP TL. The orange line denotes the modal size of the spoof SPP mode, which represents 70% of the integrated energy flow [14]. Reproduced with permission from [14].

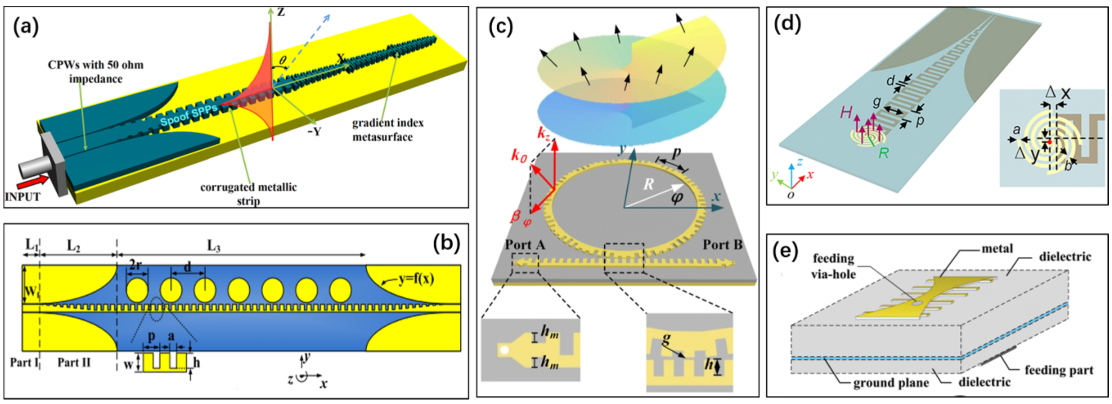

Figure 47. Some spoof SPP antennas presented in literatures. (a) A spoof SPP antenna based on the phase-gradient modulation [337]. Reprinted from [337], with the permission of AIP Publishing. (b) A beam scanning patch array fed by the spoof SPP TL [338]. © [2016] IEEE. Reprinted, with permission, from [338]. (c) The spoof SPP ring resonator that is coupled to an access waveguide for wave input [339]. Reprinted with permission from [339], Copyright (2020) by the American Physical Society. (d) An end-fire antenna based on the spoof LSP resonator [340]. Reproduced from [340]. CC BY 4.0. (e) A minimized patch antenna [341]. © [2020] IEEE. Reprinted, with permission, from [341].

spoof SPPs was first proposed based on the ultrathin ungrounded single-conductor corrugated metallic strip line, which have the advantages of flexibility, low loss and easy fabrication, some grounded spoof SPP devices and antennas are also well developed in later. Therefore, the theory and technique of both ungrounded and grounded spoof SPPs need to be further studied and discussed, including the mode analysis, impedance analysis, efficient excitation, and so on. In addition, the application scenarios of above two kinds of spoof SPP devices and antennas also need to be defined and clarified according to respective characteristics. Second, the mode of spoof SPPs is usually different from that of traditional TLs such as MS, CPW, etc. And, therefore, the spoof SPP devices and antennas cannot be directly integrated into the traditional microwave and mmWave circuits due to mode mismatch. Third, many spoof SPP devices and antennas have been reported in the microwave region in recent years, and shown enough new physics and fairly great performance, but most of them are only individual devices or antennas. Hence, we should first explore the advantages of the spoof SPP devices and antennas compared to the traditional technique, and further integrated them with the traditional circuit system or develop the new spoof SPP-based system. Meanwhile, the appropriate working frequency that can give full play to advantages of spoof SPPs should also be further considered.

Advances in science and technology to meet challenges

There are maybe some solutions to meet the challenges of passive spoof SPP devices and antennas. The advanced EM theory combined with TL knowledge can be applied to investigate the fundamental characteristics of grounded and ungrounded types of spoof SPPs, such as the modes, effective impedance, momentum, and so on. Under these theoretical instruction, the spoof SPP devices and antennas can be designed more accurately. Different compact matching transitions can be further developed to meet different requirements based on the existing technologies, such as the PCB technology, the CMOS technology, and so on. In this way, the spoof SPP devices and antennas can be smoothly and efficiently integrated with the conventional ICs. As the development of flexible electronics, spoof SPP devices and antennas have great potentials in the applications of wearable systems, because they can efficiently propagate along ultrathin and conformal film, which is difficult to achieve with most traditional TLs. In addition, spoof SPPs may have unique advantages in mmWave and terahertz circuits in terms of loss reduction and crosstalk suppression, and they also can be used to realize the miniaturization of devices and antennas so as to satisfy the requirement of highly ICs.

Concluding remarks

The spoof SPPs inherit the unique EM characteristics with natural SPPs at optical frequencies, and possess great potentials in microwave technology. Due to the flexible dispersion characteristics, extraordinary field confinement and subwavelength resolution, they are able to offer new solutions to the design of ICs and systems. A large variety of passive devices and antennas have been already delivered, opening up a new promising direction within the microwave research. We expect their fast development and wide applications in wireless communication, security, nursing and daily care, and so on.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (61971134, 61631007, 62071117 and 61831006), the Fundamental Research Funds for the Central Universities (2242021R41078), and the 111 Project (111-2-05).

4.4. Active spoof surface plasmon (SP) devices

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Status

SPPs can confine EM fields in a deep subwavelength volume, resulting in numerous applications at optical frequencies. Transplanting the concept of SPPs from optical to microwave/THz frequencies using the metamaterial technology [13] enables new applications in inter-chip communications. Such designer (or spoof) plasmonic interconnects embrace the advantages of both electrical and optical ones as they can be made ultra-small and at the same time operate at an ultra-fast speed [14]. The dispersion property of SSPPs can be freely engineered by the geometrical parameters of the structure. This unique feature offers great flexibility in the device design and hence, triggered intense research interest into SSPP devices and platforms over the past decade, where a variety of components have been demonstrated, including TLs [14], filters [319, 342], sensors [343, 344], antennas [345, 346], etc. Despite the remarkable development in the passive SSPP devices, active devices which allow dynamic tuning of the device functions or multi-frequency operations are still not fully explored. Further applications of the spoof plasmonic concept to circuit applications requires the design of active, reconfigurable, and nonlinear devices for the efficient generation and guidance, dynamic modulation, and amplification of spoof surface plasmonic signals in an ultra-compact platform.

By incorporating active elements or materials in the spoof plasmonic structure, such as varactor diodes, active chips, graphene, etc, the dispersion properties of the structure can be dynamically manipulated, giving rise to various peculiar properties. For example, the transmission property of a SSPP TL can be continuously modulated by tuning the bias voltages applied on the varactor diodes or graphene layer loaded to the SSPP structure, enabling the continuous modulation of the amplitude of SSPP signals [347, 348]. On the other hand, loading the SSPP unit structure with PIN diodes allows the dynamic switching between two discrete dispersion states corresponding to the on state and off state of the diode, providing a logic approach to realize digital modulations of amplitude, phase, and frequency [327, 349] of SSPPs (see figures 48(a) and (b)). Active chips, such as low-noise amplifier chips can be integrated with SSPP structures to compensate the loss of the device, or to provide high gain for the signals [325, 347], as shown in figure 48(c).

Current and future challenges

In communication systems, the large path losses may limit the transmitting distance of the signals. Therefore, critical to further development of the spoof plasmonic concept to circuit application is the ability to amplify the SSPP signals in an ultra-compact platform. However, the traditional MOS-based nonlinear amplifier chip may lead to signal distortion, which would be even more severe when applied to the SSPP amplification [350]. The efficient amplification of signals without introducing undesired distortion is of great importance to the enhancement of the signal integrity in SSPP ICs. Another challenge is to realize integratable non-reciprocal components for asymmetric signal transmission and modulation. The active transistor may provide unidirectional gain due to its intrinsic non-reciprocal natures, but will suffer from poor noise performance and low power capacity. Spatiotemporal modulation and breaking the linearity are two promising approaches to break the reciprocity without introducing bulky magnets, where the former requires very complex setup. The third problem to be considered is improving the nonlinear conversion efficiency for the frequency conversion and modulation of SSPP signals, where the fulfillment of a critical phase-matching condition is required. To address the above challenges a general theoretical model that can guide the design of nonlinear SSPP devices is desired, and novel devices that can fully exploit the unique characteristics of SSPPs should be explored.

Advances in science and technology to meet challenges

The nonlinearity of SSPP structures can be achieved by incorporating nonlinear elements (e.g. varactor diode) or materials (e.g. graphene) which have high nonlinear susceptibility into the unit cell. By tailoring the geometries with loaded elements or materials, the dispersion behaviors of SSPPs can be manipulated directly, allowing for rigorous phase matching and large tunability range. Distinct tunability even from the forward to backward phase matching has been demonstrated experimentally, giving rise to switchable forward and backward high harmonic generations in the same frequency band with high conversion efficiencies [351].

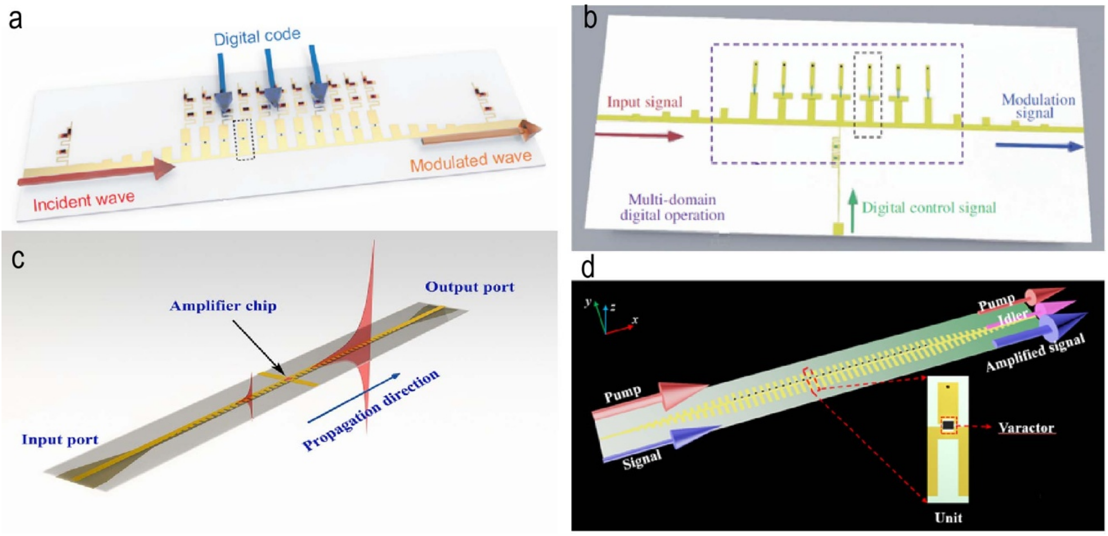

Figure 48. (a) Digital SSPP waveguide. Reproduced from [349]. CC BY 4.0. (b) SSPP waveguide for multi-scheme-modulation. Reproduced from [327], with permission from Springer Nature. (c) Broadband SSPP amplifier based on the active chip. [325] John Wiley & Sons. © 2014 by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (d) SSPP parametric amplifier. Reproduced from [350]. CC BY 4.0.

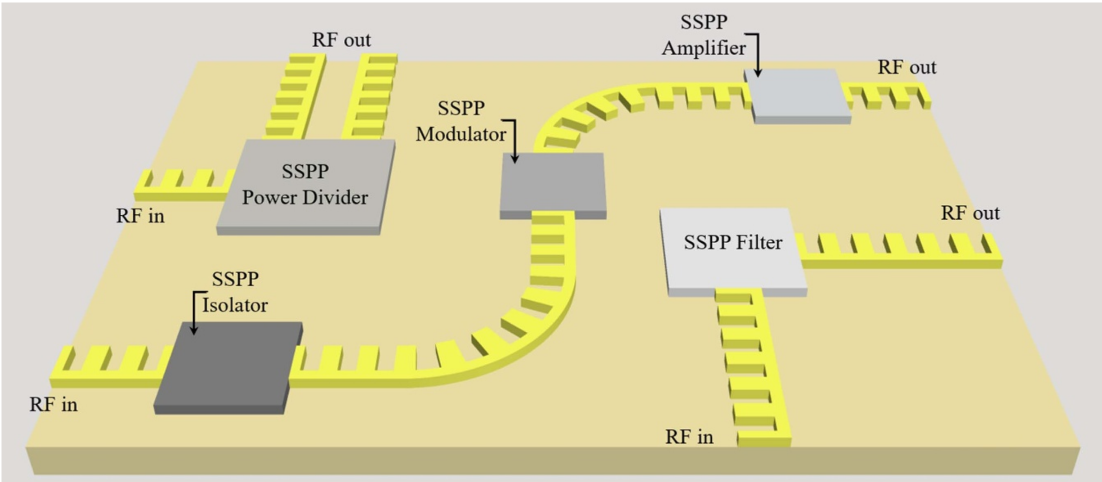

Figure 49. Schematic of an SSPP integrated circuit for communications.

Recently, a theoretical model considering how the interplay between the Kerr susceptibility and transmission loss affects the signal gain is proposed [350]. This model reveals that the parametric amplification approach, which has already been widely used at optical frequencies, may be extended to tackle of challenge of SSPP signal amplification. Under the phase matching condition, efficient energy transfer from the pump wave to the signal wave is enabled, leading to the amplification of the SSPP signals, as shown in figure 48(d). As predicted by the theoretical model, sufficient gain can be achieved within only a few number of SSPP propagating wavelengths, making this technique suitable for on-chip integrations. More importantly, the experiment confirms that the SSPP parametric amplifier has a stable phase response and negligible distortion of the amplified SSPP signals. Based on the parametric amplification technique, a magnetic-free spoof surface plasmonic isolator is further demonstrated, which not only inherits the advantages of conformal SSPPs including compactness, integratability, and low cost, but also has remarkable isolating performance in suppressing the transmission of backward-propagating noises [352].

Concluding remarks

Thus far, most active SSPP devices have been fabricated with PCB technique and demonstrated at microwave frequencies. The future development of high data rate communication systems require the realization of ICs in mmWave and even THz frequency region on a chip, including coherent signal generation, transmission, amplification, modulation, and detection of signals (see figure 49). To push SSPPs towards applications in high speed communications, the realization of active SSPP components and devices with CMOS process or MEMS technique with improved performance compared with conventional devices is a central problem to be considered for future research. With the already demonstrated advantages such as phase stability, high gain, and large modulation depth, we anticipate the revolutionization of interconnect systems with further advancement of the active SSPP technique.

Acknowledgments

The authors would like to thank Yi Ren for preparing the figures.

We acknowledge funding support from National Natural Science Foundation of China (62271139, U21A20459, 61871127), Singapore Ministry of Education (MOE2018-T2-2-189(S)), A*Star AME IRG Grant (A20E5c0095) and Programmatic Funds (A18A7b0058), National Research Foundation Singapore Competitive Research Program (NRF220 CRP22-2019-0006 and NRF-CRP23-2019-0007).

4.5. Spoof localized surface plasmons (SLSPs)

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Status

SLSPs mimic the modal profiles and physical properties of optical LSPs in microwave and terahertz frequencies, by constructing effective negative permittivity in subwavelength metal corrugations, as shown in figure 50(a). The SLSP concept was theoretically proposed by Pors *et al* in 2012 [309]. In 2014, Cui *et al* proved that SLSPs can be sustained by ultrathin metal layers on PCBs, and envisioned SLSPs' applications in planar circuits as shown in figures 50(b) and (c) [15, 310].

Unique properties of SLSPs. Besides resembling optical LSPs' enhancement effects for resonances, electric fields, and sensitivities, SLSPs in microwave and terahertz frequencies exhibit their unique properties. First, the SLSPs are flexibly tunable by geometric patterns, originating from the plasmonic metamaterial concept. Second, amounts of multipole higher-order resonant modes can be sustained in one single SLSP resonator. Third, the quality factors (Q-factors) of SLSPs are much higher than optical LSPs. The multipole resonances and high Q-factors originate from low loss in metals at lower frequencies. We remark that compatibility to planar circuit processes endows SLSPs with significant application values in both PCBs and ICs. Being superior to conventional planar resonators such as microstrip ring resonators, the electrical sizes and Q-factors of SLSPs are outstanding. The resonant modes can be strongly confined with low radiative loss even when the circumferential standing waves are bent into the deep-subwavelength scale [353].

Sensing applications. SLSPs combine the enhancement effects of standing-wave ring resonators and surface evanescent waves, therefore exhibit promising potentials in sensing [343]. The SLSP sensing tracks the resonance frequency shift which varies with local permittivity changes. The target signal may come from liquid concentration changes, transducer materials that react to hazardous gas, or effective permittivity changes originated from stretching or pressing. Many efforts have been devoted to EM designing to improve the sensitivity and Q-factors of SLSPs. Applications in liquid concentration sensing (figure 51(a)), monitoring of the engineering structures (figure 51(b)) have been demonstrated [15, 354]. The subfield of SLSP sensing have been comprehensively reviewed with prospective discussions in [343].

Applications in microwave engineering and physics explorations. SLSPs have also been applied in microwave engineering as bandpass filters (figure 51(c)) and omnidirectional antennas (figure 51(d)) [340, 355], using their superiorities over other planar resonators. Flexible geometries and abundant multipole modes also make SLSPs a good platform for physics explorations. Electric and magnetic coupling (figure 51(e)) [340], mode splitting, Fano resonances, EM induced transparency, and novel topological phenomena have been investigated in SLSPs. Recently, OAM modes in SLSPs have been proposed and become an attractive topic (figure 51(f)) [356].

Current and future challenges

SLSPs exhibit promising properties and application potentials as a newly proposed concept. The crucial challenge now is to land on practical applications, which will promote SLSPs into a prosperous engineering field instead of interesting physical phenomena.

It is good timing for the development of microwave SLSP sensing in the trend of the IoT [343]. The intrinsic high sensitivity and Q-factors endow SLSP sensors with outstanding sensing performance. SLSPs' deeply-subwavelength sizes lead to ultra-compacted footprint; the strong modal confinement leads to high immunity to electromagnetic interference (EMI); and the compatibility to planar circuits makes SLSPs integratable with signal processing and wireless communication circuits. Combining with different transducer materials, SLSP sensors can be versatile for hazard gas sensing, pulse and breath monitoring, sweat monitoring, *et al.* Challenges move from EM resonance designing to systematic designing. Detection circuits which track the frequency shifts on a compacted and portable chip or circuit board will be the key technique. To land onto practical engineering, specific problems such as thermal drift effects, noise cancellation algorithms, calibration of sensing signals, etc, should be taken into considerations.

Terahertz SLSPs have been experimentally realized and applied for liquid concentration sensing [343], while there is still vast developing space in SLSPs' applications in terahertz biomedical sciences and

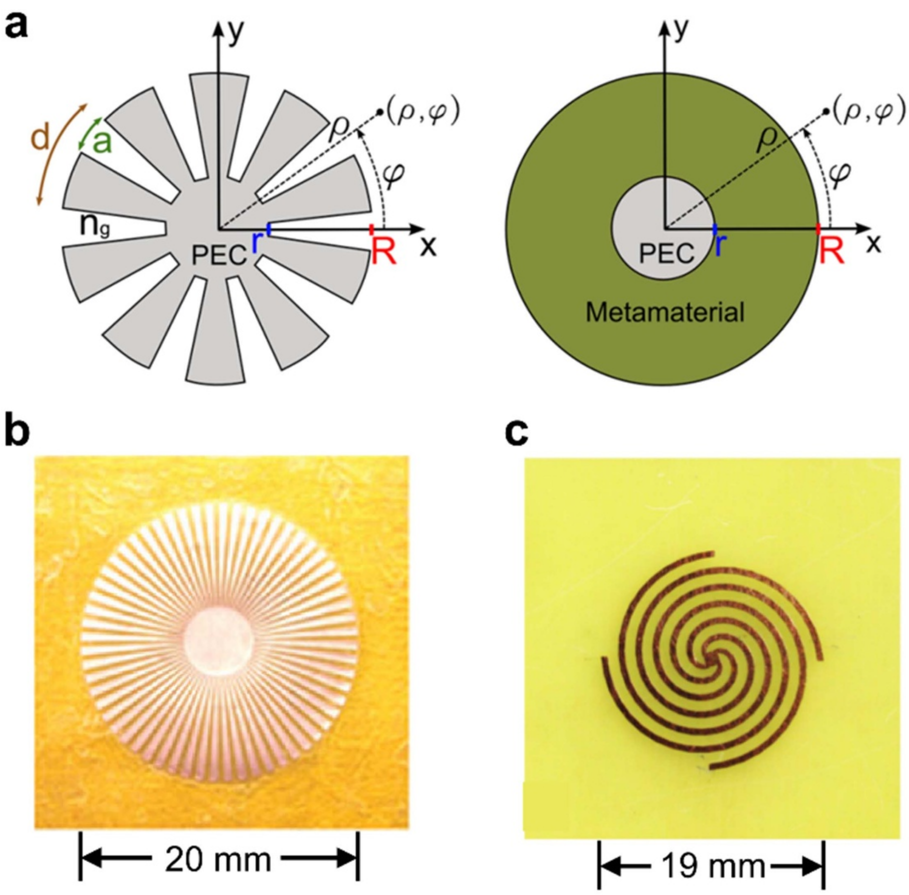

Figure 50. (a) Conceptual schematics of SLSPs. Reprinted with permission from [309], Copyright (2012) by the American Physical Society. (b), (c) Photographs of ultrathin SLSPs on PCBs, with straight (b) and spiral (c) arms. (b) [15] John Wiley & Sons. © 2013 by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) Reproduced from [310]. CC BY 3.0.

technologies. The plasmonic hot spots can enhance the EM wave–matter interactions and amplify the faint signals from vibrational and rotational energy levels of biomolecules. Challenges reside in high aqueous absorption in terahertz frequencies, which may seriously decrease the Q-factor and even destroy the resonance peaks. Microfluidic channels can be employed to limit the volume of the solution, and to control the inlet and outlet of the solution and the drying nitrogen gas. Deeply subwavelength sizes of SLSPs can break down the diffraction limit and enhance the local sensitivity in a tiny volume, therefore may be more promising in terahertz sensing with microfluidics.

Inheriting from optical LSPs, SLSPs are generally believed to be promising in sensing applications, while their potentials in microwave engineering have been ignored to some extent. The flexible geometric tunability and abundant multipole resonances endow SLSPs with powerful abilities in bandwidth controlling, which has been preliminarily revealed in bandpass filters as shown in figure 51(c) [355]. Better rectangle coefficients can be expected with elaborately designing of the SLSP unit. Intralayer and interlayer coupling can also be explored to improve the bandwidth tuning capability. The applications can be extended from circuit filters to radomes using SLSP arrays. Challenges arise in the simultaneous control of all multipole modes to realize desirable bandwidth properties.

Advances in science and technology to meet challenges

While there are grand challenges to drive SLSPs into mainstream applications, there are quite solid supports from associated techniques. For microwave sensing, the mature techniques of amplitude and phase measurement in Radars can be borrowed to construct the detection circuits. The SLSP sensors can be also integrated with communication modules to accomplish IoT sensors. ICs also host as good platforms for SLSPs, including CMOS, III–V semiconductor processes, etc. Integrated sensors can be more robust to environmental noises. The deeply subwavelength sizes of SLSPs will also be attractive in ICs as passive resonators or antennas.

Besides technical supports, deeper scientific explorations also promote SLSPs' development. As briefly exhibited in figures 51(e) and (f), various novel mechanisms keep pushing the sensitivity and Q-factors to

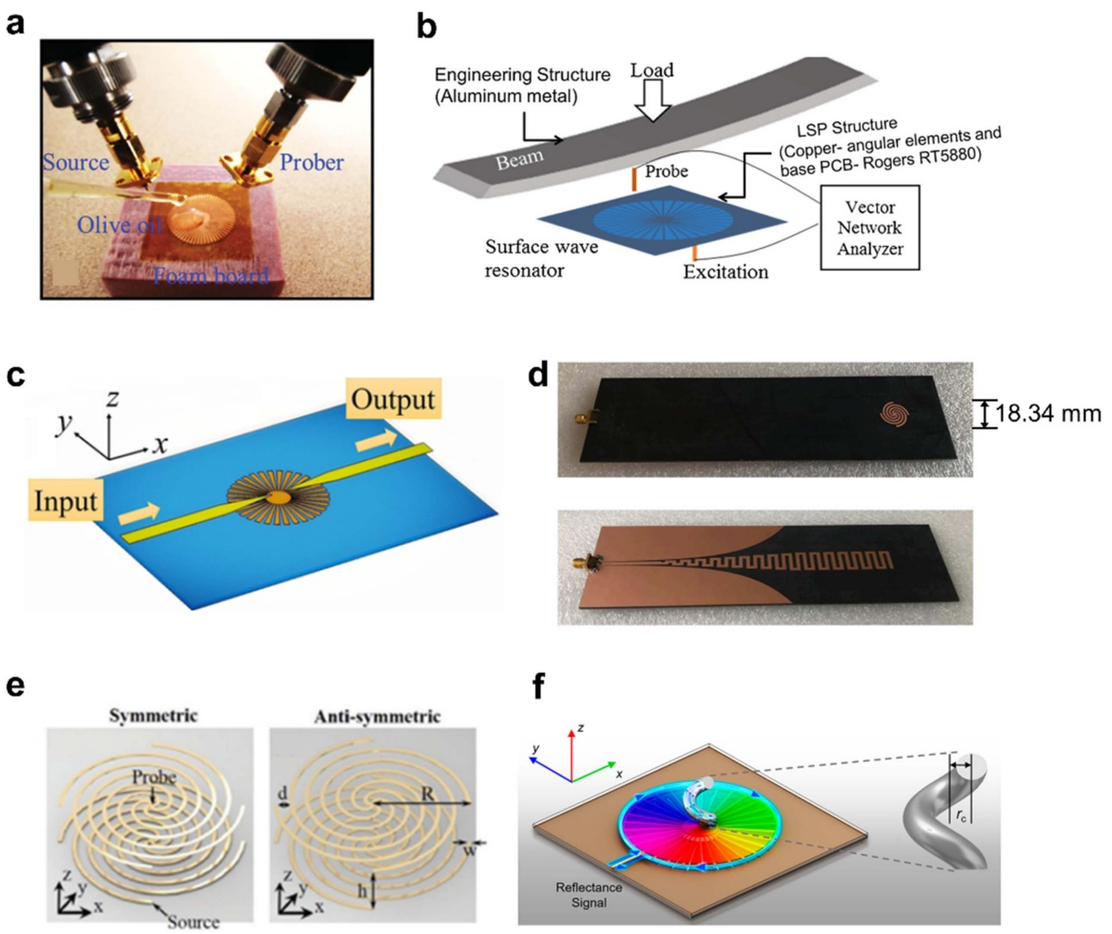

Figure 51. Applications of SLSPs. (a) SLSPs for liquid permittivity sensing. [15] John Wiley & Sons. © 2013 by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) SLSPs for monitoring of engineering structures. Reprinted from [354], Copyright (2016), with permission from Elsevier. (c) SLSPs as wide-bandpass filters. [355] John Wiley & Sons. © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (d) SLSPs as omnidirectional antennas. Reproduced from [340]. CC BY 4.0. (e) Coupling between SLSPs. Reprinted with permission from [356], Copyright (2016) by the American Physical Society. (f) OAM in SLSPs. Reprinted with permission from [357]. Copyright (2020) American Chemical Society.

higher limits, including mode coupling, Fano resonances, BICs, etc [343, 353, 356]. OAM in SLSPs supply a novel scheme for dichroism detection, the detection limit of which can be leveraged via sharp resonances [357]. Recent investigations of topological photonics in SLSP structures also envisions brand new application possibilities. Principle innovations will lay a solid basis for novel systematic schemes and outstanding engineering performance.

Concluding remarks

The last decade has witnessed the emergence and fast development of SLSPs. Now is good timing to land this concept onto practical engineering, with solid supports from associated techniques and principal innovations. We expect SLSPs as a prospective field, which will hopefully promote innovations in microwave and terahertz sensing, microwave engineering, and ICs.

Acknowledgments

The authors acknowledge the financial support from the National Natural Science Foundation of China under Grants 61701108 and 62288101, the National Key Research and Development Program of China under Grants 2017YFA0700201, 2017YFA0700202 and 2017YFA0700203, and the Fundamental Research Funds for the Central Universities under Grant 2242021k30047.

4.6. Spoof SPP circuit and system

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Status

In recent years, SSPPs have developed rapidly and become one of the hot topics in academic and engineering communities. The development of spoof SPP metamaterials have shown a trend from isolated device to IC and system, making a lot of progress towards industrial application (see figure 52). Originally SPPs exist in the optical regime and the concept of spoof SPPs was firstly proposed by Pendry *et al* in 2004 [13]. For integrated and practical demand, in 2013, Shen *et al* proposed the concept of CSPs that can propagate on ultrathin and flexible films from microwave to mid-infrared frequencies [14]. Since then, various planar spoof SPP devices have been proposed at microwave and THz frequencies, including resonators and sensors [310, 344, 358–360], filters [361–364], splitters and couplers [335, 365–367], and antennas [338, 345, 368–370]. The unique physical properties of spoof SPPs, such as field confinement, field enhancement and adjustable wave-vector, enrich and develop the design scheme of microwave devices.

Another trend in the development of spoof SPPs is to combine it with IC technology, thus the concept of spoof SPP-based chip has been born. This field is still in the early stages of development and relevant research focuses on TLs, I/O interconnects, passive and active devices. In 2015, Yu, and coworkers, first proposed an on-chip spoof SPP TL in the microwave band [371]. Then a low loss, high integration on-chip CMOS sub-terahertz SPP waveguide converter has been designed and manufactured in a standard 65 nm CMOS process [372]. In addition, owing to the extreme field confinement of SPP, a series of studies of spoof SPP-based interconnects have been carried out [373–376].

In summary, systematization and integration are two important trends in the development of spoof SPP technology. However, there are still many problems waiting to be solved and scientists are also continuing to carry out further research.

Current and future challenge

With the advent of CSPs, merits of spoof SPPs have been widely used in constructing high-performance microwave devices. However, there are still several challenges which limit the application and development of spoof SPP circuits and systems, as shown in figure 53.

The first challenge (challenge #1) is the effective realization and application of spoof SPPs in chip technology. Micro–nano scale and multi-layer architecture of chip technology provide both much more functional freedom and designing difficulty for spoof SPP circuits and systems. The problems of efficient excitation, transmission loss and integration with complex systems hinder the realization and application of on-chip spoof SPPs. The second one (challenge #2) is the inadequate combination of digital and analog technologies in systematical level, which leads to certain restrictions in realizing simplified, multi-functional and reconfigurable spoof SPPs systems. The last one (challenge #3) is that research basis of system integration of spoof SPP circuits and devices is still insufficient. Essential issues including layout, signal integrity analysis and integrated packaging of spoof SPP systems are supposed to be studied further.

Advances in science and technology to meet challenges

A possible route to meet the challenges of spoof SPP circuits and systems is the cross fusion of multi-technologies. For challenge #1, physical feature of spoof SPPs and chip technology can promote each other mutually. On one hand, physical feature of spoof SPPs brings novel advantages to current chips. On the other hand, flexible material parameters and geometrical configuration of new chip technology can be utilized to tap the potential physical features of spoof SPPs. Recently, many works have been proposed to break the challenge of realization and application of spoof SPPs, including achieve efficient excitation using the characteristic impedance extraction method [377], reduce transmission loss using dispersion design [378] or loading parallel varactors in reconfigurable units [379], and replace fundamental channels in complex systems [311, 312].

For challenge #2, two steps are essential to realize the deep digital-analog combination. One is that appropriate mapping between analog spoof SPPs and discrete digital space has been established. Then general modulation and demodulation methods oriented towards various application scenes. It is worth mention that the two steps may belong to a cyclic process, which means that the mapping step is supposed to be performed iteratively to ensure the effective and high-quality modulation and demodulation of spoof SPPs. In recent years, reconfigurable spoof SPPs [336, 349, 379] possessing dispersion tenability have attracted a lot

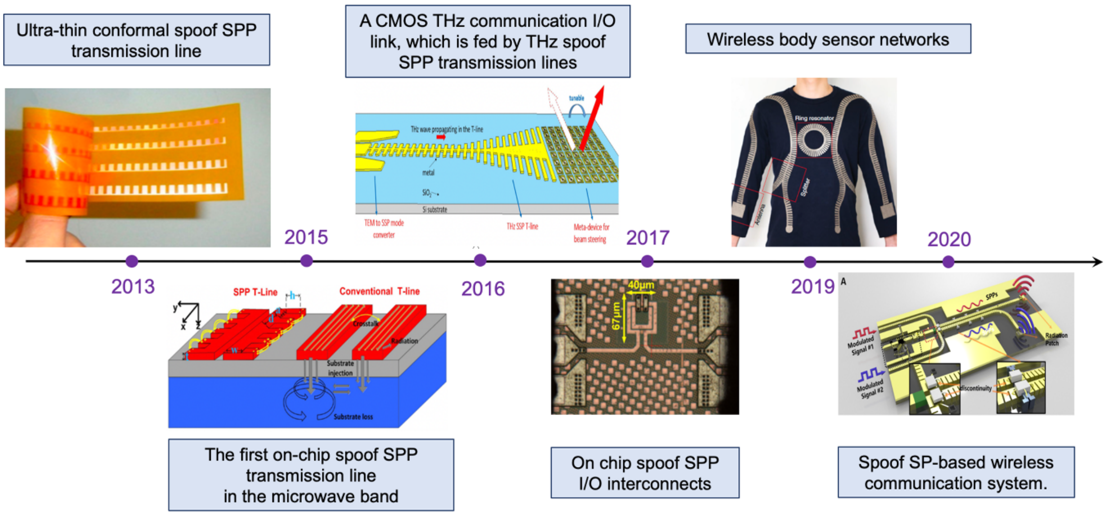

Figure 52. Schematic diagram of development of spoof SPP [14, 311, 312, 371, 372, 376]. Reproduced from [14]. CC BY 4.0. Reproduced from [371]. CC BY 4.0. Reproduced from [372]. CC BY 4.0. © [2019] IEEE. Reprinted, with permission, from [376]. Reproduced from [312], with permission from Springer Nature. Reproduced from [311]. CC BY 4.0.

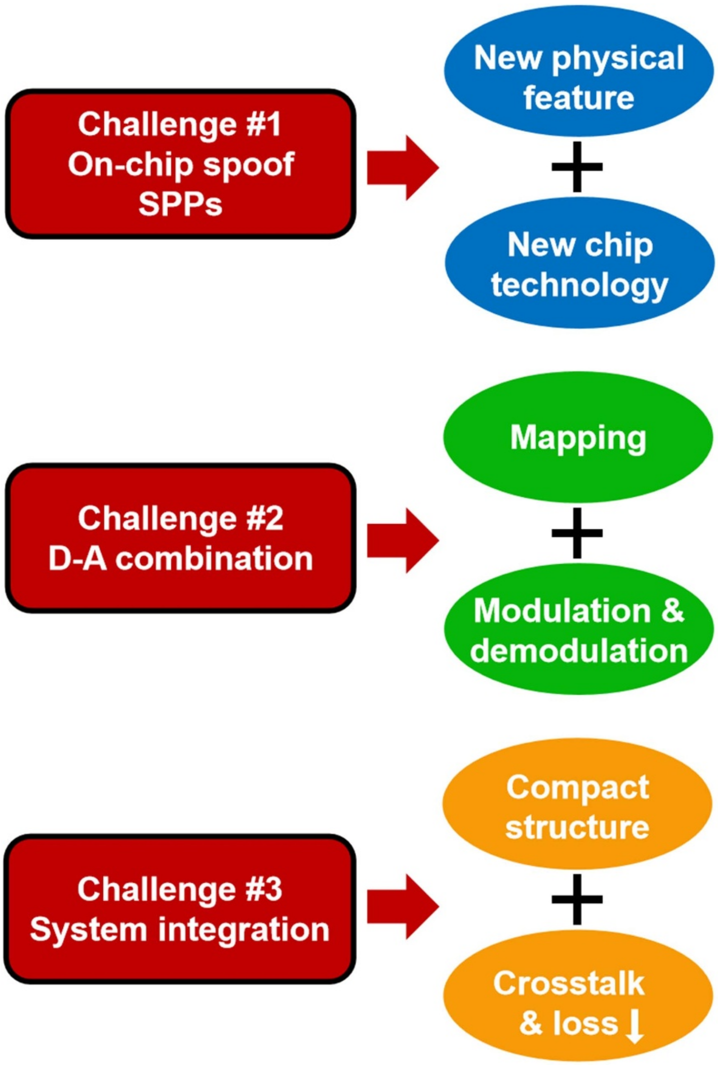

Figure 53. (a) Challenges and corresponding advances of spoof SPP circuits and systems.

of attentions. Reconfiguration of spoof SPPs can be achieved by loading tunable elements into the spoof SPP structures, which provides a appropriate path to realize the deep digital-analog combination in active circuits.

For challenge #3, not only miniaturization of spoof SPP circuits but also the improvement of performance of system has to be achieved. According to the previous research, there is a roughly positive correlation between the field confinement and geometrical size of spoof SPP structures. In other words, smaller spoof SPP structures usually possess weaker field confinement. Although the weakened field confinement is helpful to reduce the loss of systems, it is more difficult to suppress the crosstalk between channels. To solve the contradiction in spoof SPP system integration, new compact meta-unit has to be investigated to achieve loss reduction and crosstalk suppression simultaneously.

Concluding remarks

Although systematization and integration are the difficulties and pain points of the development of spoof SPP, they are also the most valuable parts to study and explore. Developing the systematization and integration of spoof SPP aim at the urgent demand for functional diversification and miniaturization of the new generation information system. However, it is still in the early stages, and although some achievements have been made, there are still many problems to be solved. We believe that combined with its excellent physical properties, spoof SPP is expected to improve the existing information system in the future as envisioned in this roadmap. Continuing research and development have become more critical than ever to navigate and develop the diverse possibilities.

5. Information metamaterials and metasurfaces

5.1. Digital coding metamaterials and metasurfaces

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Status

Metamaterials have long been characterized by effective medium parameters (such as permittivity permeability, and refractive index) with engineered values, which have shown powerful abilities in manipulating EM fields and waves [1, 2, 4, 5, 380]. If we consider the metamaterials from the viewpoint of electric circuits, the above mentioned effective-medium metamaterials can be seen as analog metamaterials since their medium parameters are continuously determined (see figure 54(a)) by controlling the EM responses of varied meta-atoms [380]. Associated with digital electronic circuits, digital metamaterials were presented by introducing two *metamaterial bits* in 2014 [381]. In a digital metamaterial, the desired medium parameter (such as the permittivity) was synthesized by only two meta-atoms with distinct permittivity values (such as positive permittivity and negative permittivity), which were called as the metamaterial bits. It was shown that the proper spatial mixture of the metamaterial bits will result in *metamaterial bytes*, which can be regarded as meta-molecules [381]. Using this methodology, several meta-devices were designed with numerical simulations, including digital hyperlens, gradient-index flat lens, and ENZ supercoupler [381]. The proposal of the digital metamaterial makes it possible to describe the medium parameters in digital way (see figure 54(b)), and hence could simplify the design process of meta-devices. However, such digital metamaterials still belong to the scheme of effective media.

In 2014, another concept of *digital coding metamaterial* was also proposed independently [8], in which the metamaterial was represented by digital codes (see figure 54(c)) instead of effective medium parameters, which is different from the concept in [381]. The digital coding metamaterials are classified into 1-bit coding and multi-bit (m-bit) coding with 2 and 2^m digital states of the meta-atom. For the 1-bit phase coding metamaterial, each meta-atom has two digital states (0 and 1) with 180° phase difference; for the 2-bit phase coding metamaterial, the meta-atom has four digital states (00, 01, 10, and 11) with 90° phase difference; and so on [8]. There are four main features of the digital coding metamaterial.

(1) The digital meta-atoms contain active devices to switch the digital states in real time. The EM functions of a metamaterial are controlled by its spatial coding sequences (or coding patterns) of digital states, hence it is easy to design the metamaterial and its functions by using optimization methods or machine-learning algorithms [382].
(2) All possible coding sequences (or patterns) and their EM functions could be precalculated and stored in a field programmable gate array (FPGA). Hence different functions will be switched in real time with FPGA by choosing the appropriate coding sequences on the same metamaterial platform, which makes the appearance of programmable metamaterial [8].
(3) The digital coding characterization of the metamaterial makes a tight connection between the digital world and EM physical world. As illustrated in figure 55, the coding sequences are both controlling commands to the EM functions and the digital information streams. Hence this kind of metamaterial could modulate the EM waves and digital information simultaneously, which sets up the basis of information metamaterial [9, 383].
(4) In the frame of information metamaterial, the metamaterial is no longer an effective material but an information and EM-wave processing system [384].

Current and future challenges

As stated in above discussions, the digital coding metamaterials have great advantages in controlling the EM fields and waves in real time and processing the digital information directly. However, there are still big challenges in the physical level and information level in this area.

In the physical level, the first challenge comes from the coding strategy: how to extend the phase coding to amplitude coding, polarization coding, and others? How to extend 1-bit coding to multi-bit coding? How to extend the isotropic coding to anisotropic coding? How to extend the space-domain coding to time-domain coding and frequency-domain coding? The second challenge in the physical level is the active device integrated in the digital meta-atom. Besides the PIN diodes and varactors that are usually employed in the current information metamaterials, how to choose other kinds of active devices, semiconductor materials, and 2D materials to reach faster modulation speeds to switch the digital states of meta-atoms? How to realize high-performance FPGAs to improve the information processing speeds of meta-arrays? The third challenge

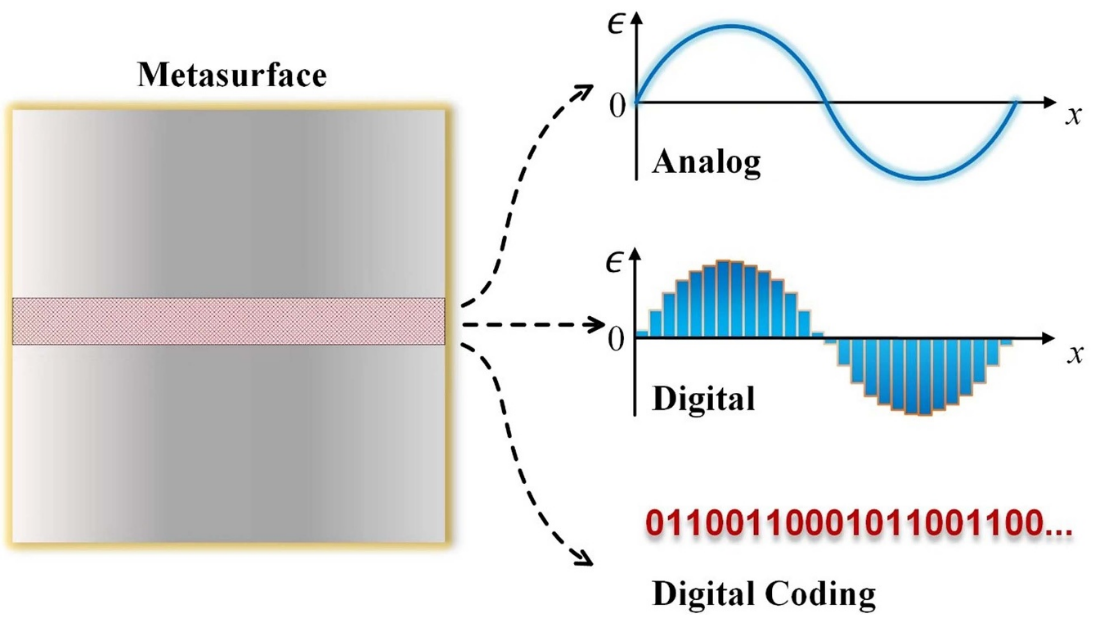

Figure 54. Schematic diagrams of analog metamaterial, digital metamaterial, and digital coding metamaterial.

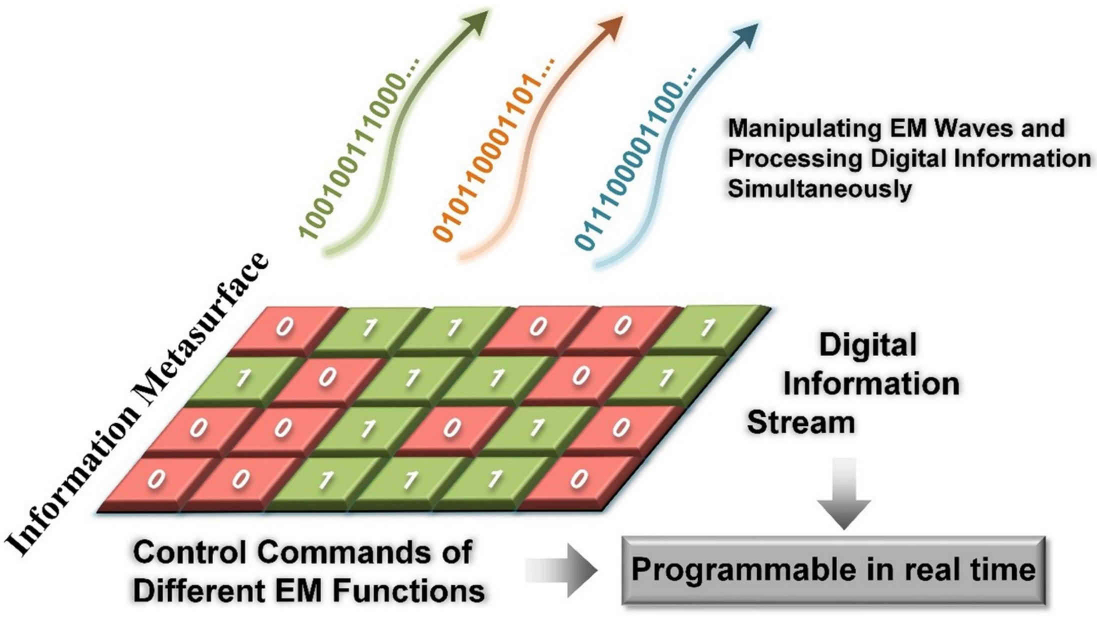

Figure 55. The digital coding metamaterial could manipulate the EM waves in real time and process the digital information simultaneously.

is to extend the digital coding information metamaterials from the microwave to mmWave, terahertz, and optical frequencies; and extend the reflection-type information metamaterials to the transmission-type.

In the information level, there are many challenges to modulate the digital information directly on the metasurface platform, which include how to perform signal processing in the physical level? How to present information modulations on the metasurface to develop EM information theory? How to integrate the AI with the information metamaterials to perform intelligent operations? And how to integrate the EM physics and digital baseband in the same platform to realize new-architecture information systems and push the wireless communications forward.

Advances in science and technology to meet challenges

Since the concept of digital coding metamaterials was proposed in 2014, significant progress has been achieved in both science and technology aspects to meet the challenges mentioned in the earlier section. On the coding strategy, phase coding is the most commonly used coding since it can make significant manipulations to the EM fields and waves. In the phase coding, there is a balance to choose 1-bit coding and multi-bit coding. Multi-bit coding has more powerful capabilities to control the EM waves and process the digital information, but its physical realization becomes more difficult. It was demonstrated that 2-bit coding may be a good choice to balance the function ability and hardware cost [385]. Besides the phase coding, amplitude coding and polarization coding are also important to realize more functions [128, 386], and should be further investigated in the future. On the other hand, the coding space is extended from space domain to frequency and time domains [387, 388], and the space-time coding digital metamaterials have shown much more degrees of freedom in manipulating the EM waves and modulating the digital information [11]. The isotropic coding strategy was also extended to anisotropic coding to increase the capability [389].

On the active devices integrated in the digital meta-atoms, the PIN diodes, varactors, and transistors are usually employed in the information metamaterials, since they are commercially matured and have low costs in the microwave frequencies. Recently, the information metamaterials have been extended to the mmWave frequencies and shown excellent performance in the wireless communications [390]. In the future, the information metamaterials in the terahertz frequency should be investigated if the challenges from the active devices and materials are resolved [391]. Though a few transmission-type digital coding metamaterials have been realized [392], more efforts are needed to reduce the insertion loss and blockage of EM waves. It is also important to develop new methodologies and algorithms for the digital coding metamaterials to control the EM fields and waves via the coding sequences, beyond the current array theory. Specifically, for the space-time coding digital metamaterials, the spatial beams, waveforms, polarizations, and spectra of EM waves can be controlled independently and simultaneously by designing the STC matrices using a new methodology [391].

Since the information metamaterial is represented by digital coding sequences, it is possible to directly modulate the digital information on the physical platform. In the current stage, two simple signal processing algorithms are performed on the metasurface platform: digital convolution operations to manipulate the steering and scanning of EM beams [393], and addition operations to control multiple beams independently [394]. In the future, more signal processing (e.g. correlation, filtering, and wavelet transform) should be investigated on the physical layer to enlarge the capabilities. Besides the signal processing algorithms, information modulation on the metasurface is also important. Information entropy has been defined on the physical layer to measure the information capacity of the digital coding metasurface [383], from which a simplified version of EM information theory was presented by studying two kinds of information: digital bit-stream information and EM information [395, 396]. It is expected that the complete EM information theory will be explored by both EM and communication communities. The information metamaterial is also easy to collaborate with AI to achieve intelligent operations. The convolutional neural network (CNN) was firstly used in the programmable metamaterial to realize real-time microwave imaging with simplified hardware architecture [385], which was further extended for automatic target recognition and even microwave camera [397, 398]. Deeper integration of information metasurfaces with CNN was conducted recently to reach programmable AI machine [399], which had light speed for AI calculations and fulfilled programmable functions of picture recognition, target detection, and wireless communications.

In fact, the information metamaterials have found big impacts in the communication community. The programmable information metasurfaces are just the physical platforms of RISs to control the wireless channels and enhance the communication capacity, which have been intensively studied in recent years [400]. More importantly, the time-coding information metasurfaces have been successfully employed to simplify the system architectures and reduce the costs of wireless communications [388, 390], due to the fact that the EM physics and digital baseband share the same hardware platform. With the STC information metasurfaces, a new-architecture wireless communication system was realized by taking advantages of both space multiplexing and frequency multiplexing [401]. When light-controlled varactors are used in the meta-atoms, light-controlled digital coding metasurface was presented [402], resulting in a combined light-microwave wireless communication system [403].

Concluding remarks

Digital coding not only provides a new representation of metamaterials to simplify the design process, but also sets up a bridge between the EM physics and digital information, resulting in programmable metamaterials and information metamaterials. The programmable metamaterials can manipulate the EM fields and waves in real time; while the information metamaterials can control the EM waves and process the digital information simultaneously. The digital coding, programmable, and information metamaterials have brought us many new concepts, EM modulation methodologies, functional devices, and information systems. As a new direction of metamaterials, there are a lot of challenges to be explored in the future for engineering applications, such as the commercial applications in the sixth-generation wireless communications.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (62288101), National Key Research and Development Program of China (2017YFA0700201, 2017YFA0700202 and 2017YFA0700203), and Major Project of Natural Science Foundation of Jiangsu Province (BK20212002).

5.2. Field programmable metamaterials and metasurfaces

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Status

With massive transistors, the integrated chips can process behaviors of electrons to realize different electronic devices, therefore, they have been an important foundation for modern information science and technology. Similar to the digital concept of integrated chips, digital programmable metamaterials or metasurfaces (DPMs) are consisted of massive reconfigurable units, and they can dynamically process behaviors of EM waves on the apertures (figure 56). In this sense, the DPMs serve as integrated chips for EM waves.

After the DPMs were proposed [8], world-wide attentions were attracted due to their great potential in information science and technology, especially in the fields of radar and communication. By designing different aperture codes of the DPMs, variational radiation patterns can be produced, thus leading to DPM-based computational imaging [193]. Besides spatial modulations, DPMs can also perform temporal modulations of EM waves. Several wireless communication systems that can directly modulate signals on the apertures of DPMs have been proposed [388, 404, 405]. Also, the DPMs can be treated as a part of programmable communication channels which can enhance the signals and suppress the interferences [82, 406].

Since the DPMs can modulate EM waves in space, time and frequency domains on the aperture, they have actually possessed the nature of informatization [384]. This informatization makes DPMs a perfect bridge that links metamaterials to the information world, and makes DPMs a perfect universal platform that breaks the bounds between radar and communication. Considering the innovative effects brought by the DPMs in so far, it is believed that the DPMs are of great use in the future intelligent world.

Current and future challenges

The DPMs are consisted of massive units, and the macroscopic responses of the DPMs are supposition of the response of each unit. This logic architecture forms the basis for any functional DPMs. Usually, each unit of the DPMs is abstracted as a digit symbol representing a discrete state. However, this abstraction is always accompanied with some approximations due to modeling errors, frequency dispersion or unit couplings. As a result, the realized DPMs are not perfectly consistent with the abstracted models. Hence, the most fundamental issue for researching and applying the DPMs is to accurately depict this logic architecture, namely that to accurately characterize each unit and the DPMs themselves.

Practical informatization is another issue of the DPMs. Because of their informatization nature, the DPMs can be conveniently integrated with the existed electronic systems, and it is this integration that endows the DPMs with great potential in the information world. To make full use of the DPMs, innovative system architectures and algorisms are needed in the hardware and software integrations. Therefore, it is expected that researching DPMs in the frame of information systems will be a major focus in the future.

Researching the DPMs in practical scenarios is also an important issue. Basically, the DPMs can be used to realize variational functions such as detection, imaging, communication and sensing. Nevertheless, knowing who will use and where to use these functions is extremely important for the development of DPMs. Taking the 6G mobile communication as an example, the DPMs are used in this scenario as a potential standard technology to improve the quality of communication. The practical scenarios will promote the further development of the DPMs.

Advances in science and technology to meet challenges

The realization of the DPMs is strongly dependent on the controllable substances that are used to design programmable units, such as positive-intrinsic-negative (PIN) diodes, varactor diodes and liquid crystal. From the perspective of realization, it is meaningful to explore more kinds of controllable substances and elevate integration technologies for the DPMs, especially in the circumstance that the modern information technology is continually updating. Accordingly, the theoretical researches of the DPMs need to be more targeted and effective. Advanced realization technologies and complete theories are necessary bases for accurately designing and implementing the DPMs.

AI is an important constituent of modern information technology, and it has been researched and used in various areas. Naturally, AI has a great impetus to both the theoretical and practical researches of the DPMs. It is anticipated that the AI will promote the evolution of the DPMs to intelligent metamaterials or metasurfaces.

Apart from exploring the DPMs themselves, combination of different scientific areas is an efficient way to expand the researches of the DPMs. Radar and communication systems are immediate application scenarios

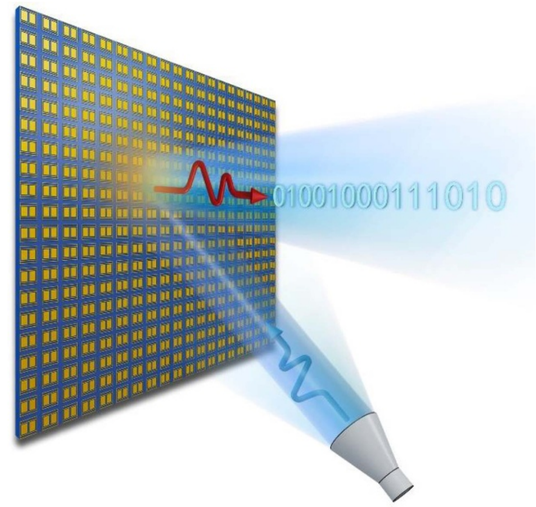

Figure 56. Schematic diagram of a DPM. Reproduced from [8]. CC BY 3.0.

for the DPMs. Many important researches have been conducted on these scenarios. Furthermore, the DPMs can also contribute to most of the science and technologies that have important development prospect, such as semiconductor, topology, quantum information, and bioelectronics. More application scenarios of the DPMs are expected with the development of the modern science and technologies.

Concluding remarks

After several years of researches and applications, both the scientific and the engineering communities have realized the tremendous potential of the DPMs. From theoretical concepts to practical mechanisms, the DPMs have brought innovations to many fields. Although a lot of work remains, the DPMs are believed to be an important constituent of future information science and technologies.

5.3. Information metasurfaces and Shannon entropy

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Status

Metamaterials and metasurfaces can manipulate EM waves flexibly by engineering the responses and the distribution of the meta-particles. Digital coding and programmable metamaterials have been recently proposed to reach dynamic manipulations of EM waves by introducing active circuit components to the digital unit cell and controlling them in a programmable manner through external digital devices. Most importantly, the digital coding representation helps bridge the material science and information science via the metamaterial platform, and thus allowing us to view metamaterial as an information processor on the physical hardware layer. Accordingly, several metamaterial-based information processing systems have been built, such as the wireless communication systems and the computational imaging systems [385, 401, 407]. In recent years, a few theoretical frameworks have been established to characterize the information processing capability of the information metamaterial systems [383, 395, 396].

The concept of entropy was initially introduced to describe the macroscopic behavior of a thermodynamic system that consists of a huge number of atoms, and was later extended to the field of information science as a measure of information uncertainty. Shannon entropy, one of the famous information entropy, was firstly proposed by Claude Shannon in 1948 to measure the average level of information inherent in the variable's possible outcomes. A larger information entropy implies more uncertainty of the information source, and thus the larger capacity of information it can carry.

A PMS can dynamically manipulate the scattering features of the incident EM wave, and thus can be considered as an information modulation device where the information to be sent is modulated in the far-field region, as is shown in figure 57. The ever-changing radiation patterns enabled by the PMS can be exploited for information transmission and processing, such as wireless communication [401, 407], computational imaging [385], and cloaking [408]. To guide the analysis and design of metasurface for information-oriented technologies and applications, several different approaches have been proposed to synthesis coding patterns for reach desired radiation patterns [393, 394]. In recent years, more research interests are focused on the characterization of information processing ability of metasurfaces from different perspectives [383, 395, 396].

Current and future challenges

To characterize the information processing capabilities of the coding and PMSs, the relation for the entropy and the amount of information between the coding pattern of the metasurface and the generated far-field pattern should be investigated. As is previously discussed, the information encoded in a metasurface can be modulated in the far-field region, such that the radiation pattern can be used as a medium for information transmission and processing, facilitating applications such as wireless communication, computational imaging and cloaking.

In the metasurface-assisted communication model, the transmitted signals generated by the PMS can be received by multiple receivers deployed at different positions in the far-field region. For instance, a metasurface modulated with random phase can diffuse the incident plane wave to multiple directions, and thus inheriting potentially large entropy, as is shown in figure 57(d). Therefore, it is essential to develop a suitable approach to estimate the amount of information carried by the coding pattern and the generated radiation pattern.

The diffused radiation patterns can also be used for computational imaging. For example, it is reported that orthogonal radiation patterns are particularly suitable for computational imaging [409]. Thus, the property of the orthogonal radiation patterns generated by the metasurfaces should be explored to assist the analysis and design of metasurface-based computational imaging systems.

The random-phase modulated metasurface can be used for RCS reduction as well, and have shown great potential for modern stealth technologies. Thus, it is important to characterize the property of the diffused far-field radiation pattern generated by the random-phase metasurface, and establish a mapping relation for the information entropy between the metasurface and its far-field pattern, which might help find the optimized cloaking approach for RCS reduction.

More recently, it has been established that the coding and PMSs can be extended to spatiotemporal metasurfaces when the meta-atoms are modulated in both the space and time domains. Facilitated by ultrafast dynamic modulations, spatiotemporal metasurfaces can achieve much powerful controls of the EM waves, and can realize novel physical effects such as engineered angular dispersion, breaking of the Lorentz

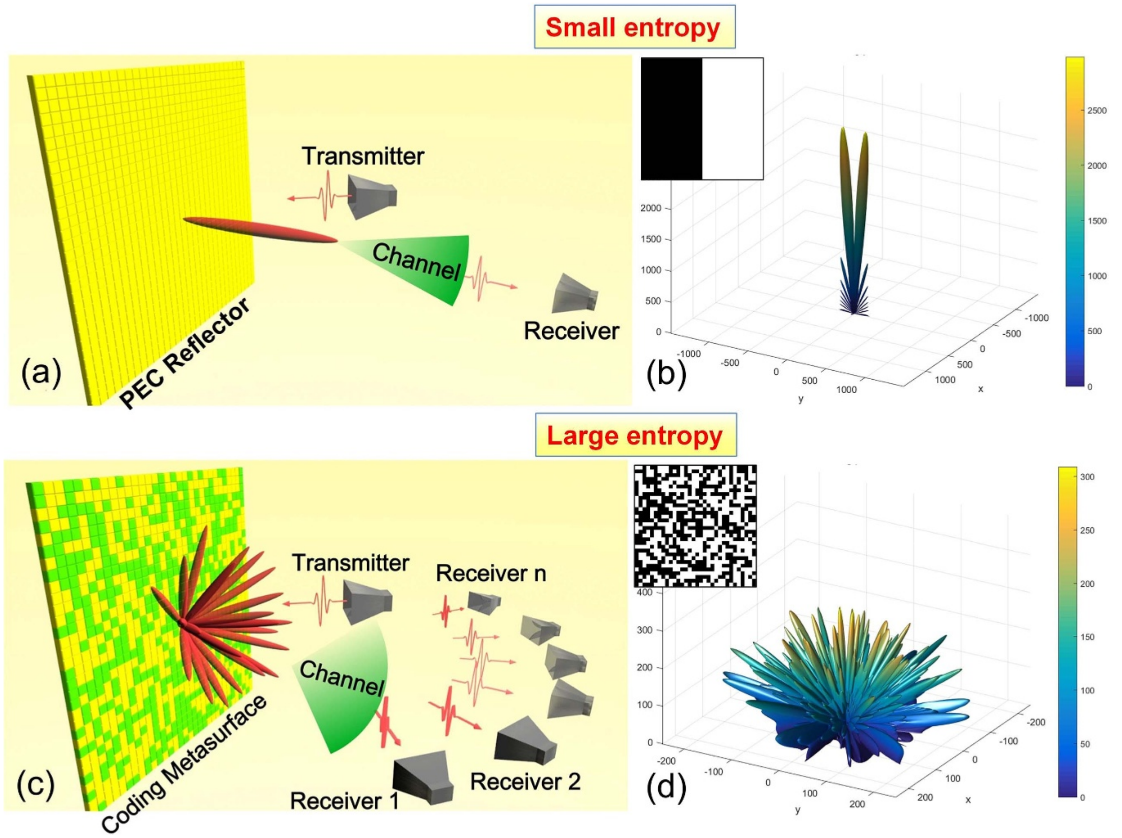

Figure 57. A reflection-type information system showing the relationship between information entropy and radiation pattern. (a) A reflection-type information system composed of a PEC reflector. (b) A reflection-type information system composed of a coding metasurface. (c) Coding pattern and far-field radiation pattern of the half 0 and half 1 coding scheme. (d) Coding pattern and far-field radiation pattern of the random coding scheme. Reproduced with permission from [383]. CC BY-NC 4.0.

reciprocity, and Doppler shift. Therefore, the information processing ability of the spatiotemporal metasurface should be investigated as well.

Advances in science and technology to meet challenges

To guide the analysis of metasurfaces from the information perspective, several metasurface-based information and entropy theories have been developed in the past few years [383, 396]. In 2016, Prof. Tie Jun Cui's group proposed a theoretical framework to measure the information entropy of the coding pattern of metasurface and the generated radiation pattern [383]. In this work, the information entropy of the coding pattern and the far-field pattern are characterized by geometrical entropy and physical entropy, respectively. They showed that the entropy of the radiation pattern generally increases with the increasing of the entropy of the coding pattern. These theoretical findings are expected to help establish novel metasurface-based information systems for communication, radar and imaging applications.

In 2020, Prof. Tie Jun Cui's group proposed to characterize the information of the metasurface and its radiation pattern from a different perspective [395]. Specifically, differential entropy is adopted to characterize the EM energy distribution at the metasurface and the far-field region, in which the decrease of entropy is defined as information. Due to the generalized uncertainty principle between a Fourier transform pair, it was further revealed that the total information of the metasurface and the radiation pattern has an upper bound of $\ln\left(4\pi S/e^2\lambda^2\right)$, as is shown in figure 58(a). As a result, the maximum number of orthogonal radiation states generated by a given-sized metasurface can be derived as $4\pi S/e^2\lambda^2$, where S is the size of the metasurface. The obtained result of the maximum number of orthogonal radiation states is expected to guide the analysis of metasurface-assisted computation imaging system. In addition, this work showed that the far-field information generated by a random-phase modulated metasurface is a constant, which is irrelevant to the modulated phase pattern, as is shown in figures 58(b)–(d). In the future, it is expected to adopt this theory to find the optimized coding pattern for metasurface-based cloaking system.

More recently, Prof. Tie Jun Cui's group proposed to characterize the information transitions of the spatiotemporal metasurface [396]. In this work, the researchers showed that the number of output states of the meta-atom can be extended when periodic temporal modulation is adopted. This work also showed that

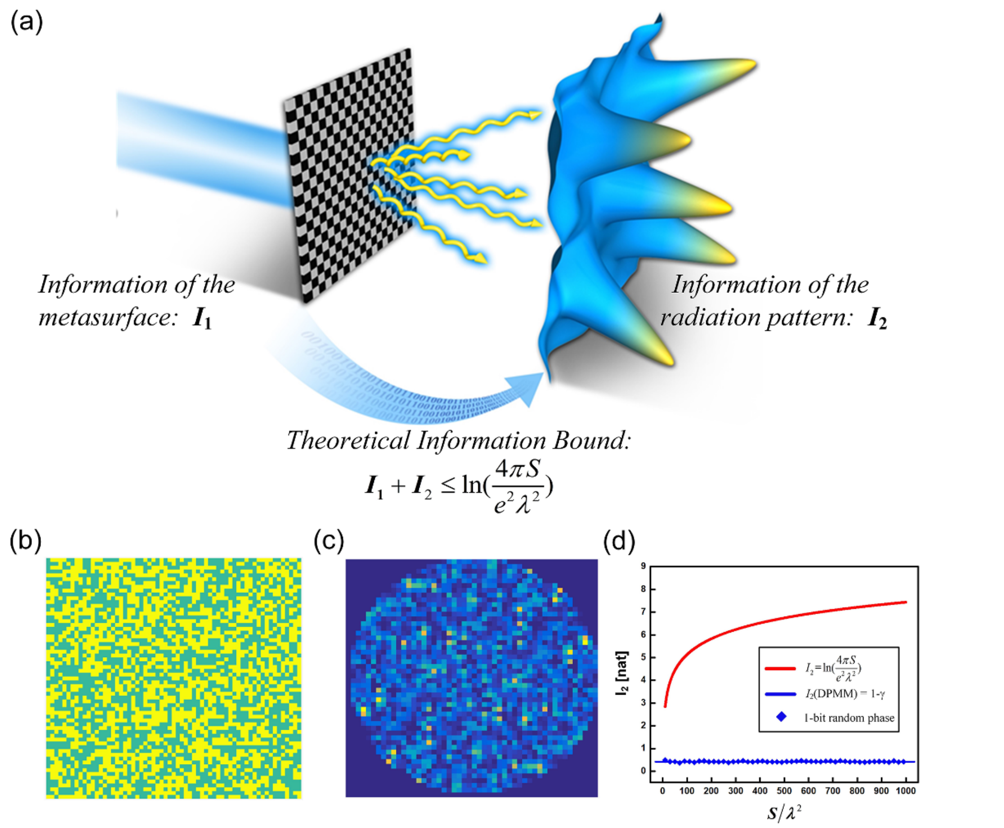

Figure 58. (a) Schematic of information relation between the metasurface and its radiation pattern. (b), (c) A sample of 1 bit disordered-phase pattern of the metasurface and the generated far-field intensity distribution. (d) Theoretical and calculated results of the far-field information of the radiation pattern with respect to different sizes and phase patterns of the metasurfaces. Reproduced from [395]. CC BY 4.0.

the responses of the spatiotemporal metasurfaces can be independently controlled at multiple harmonics, facilitating the realization of frequency-gapped multi-channel information processing applications.

Concluding remarks

In summary, during the past few years, several theoretical frameworks have been established to characterize the information processing capabilities of the coding and PMSs. The presented theories and the obtained results provide deeper physical insights into understanding metasurfaces, and are expected to offer new approaches to facilitate the analysis and design of metasurfaces from the information perspective. The findings of these researches are generally applicable in a wide range of spectra, which would be helpful to lay the groundwork for future researches into the regime of information metasurfaces. In the next stage, it is expected to adopt the theoretical findings of these investigations to help establish novel metasurface-assisted information systems.

5.4. Digital signal processing on information metasurfaces

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Status

Information metasurfaces have been explored to efficiently manipulate the wave front of the impinging wave, opening a successful route towards dynamic beamforming with deeply-subwavelength-thicknesses devices. The digital representation of information metasurfaces allows us to directly apply many signal processing algorithms to the analysis and design of information metasurfaces, which had led to many intriguing physical phenomena and engineering applications. One of the achievements is the application of convolution theorem on the information metasurface [393], which breaks the angle resolution limit of beam scanning enabled by solely gradient coding patterns. The convolution-based coding approach enables the formation of multiple beams in arbitrary directions, and beam scanning with continuous angle, which may find wide applications in radar detection and imaging systems, particularly those requiring high scanning resolutions at low costs.

Another pioneering work is the estimation of the amount of information possessed by an information metasurface using information entropy [383]. As information metasurfaces can dynamically generate arbitrarily different radiation patterns, it can be considered as an information source, in which the information is modulated through the ever-changing radiation patterns in the far field. Statistical analysis reveals the proportional relation between the entropy of coding pattern and radiation pattern.

In another context, optical analog computing has recently gained renewed interest as an alternative approach for digital signal processing, which is conventionally performed in the digital domain via ICs. As computer technology are reaching its physical limitations, there is a demand on the calculation of differential/integral equations, particularly for specialized tasks such as object classification and edge detection. These computational devices can operate at ultra-fast speed, limited by the speed of light, and more importantly, are capable of performing a large number of operations in parallel. Recent progress in information metasurfaces provides the opportunity to implement various mathematical operations, such as spatial differentiators. Bao *et al* [410] proposed to perform differentiation and integration operations using C-shaped coding particles with amplitude and phase engineering capabilities (figure 59), providing great flexibility to realize complex field controls that may find applications in imaging and wireless communications [410].

Current and future challenges

The size of the information-metasurface-based digital signal processing devices can be reduced by increasing the working frequency, for example, to terahertz and optical waves. The small wavelength of terahertz/optical waves enables miniaturization and integration, but also poses great challenges in manufacturing. The active components (e.g. pin-diodes, varactor diodes) become very expensive at millimeter and terahertz wave frequencies, and is even not commercially available at optical wavelength. The bias layout should also be careful designed to minimize the influence on the radiation performance.

In addition to the fabrication challenges, the algorithm for achieving a specific digital signal processing operation is also of most importance. The future advancement of information-metasurface-based digital signal processing devices should focus on developing an algorithm that allows the user to 'design by specification', whereby the algorithm can automatically find an optimized amplitude and phase profile to realize a given mathematical operation. Some potential approaches include the Fourier optics and Green's function methods. The general mechanism of Fourier optics is to firstly convert a signal to the Fourier space, perform the signal processing operation in the frequency domain and then transform the frequency spectrum back to the real space; while Green's function approach operates directly in the real space, avoid transforming back-and-force between the real and the Fourier space.

Advances in science and technology to meet challenges

Recent advances in space-time information metamaterials, in which the phase and amplitude profiles are controlled independently in both space and time domains, has enabled a wide variety of applications (figure 60), including the programmable wave-based analog computation [411]. Rajabalipanah *et al* [411] proposed to perform 1st- and 2nd order spatial differentiation, 1st-order spatial integration, and integral-differential equation solving using a space-time information metamaterial. More mathematical operations can be instantly implemented with different space-time coding patterns, and most importantly, these operations can be switched in real time. Another work reported a general method for realizing continuous controls of the propagation of harmonics, giving us full programmable capability in engineering harmonic component in desired directions [412].

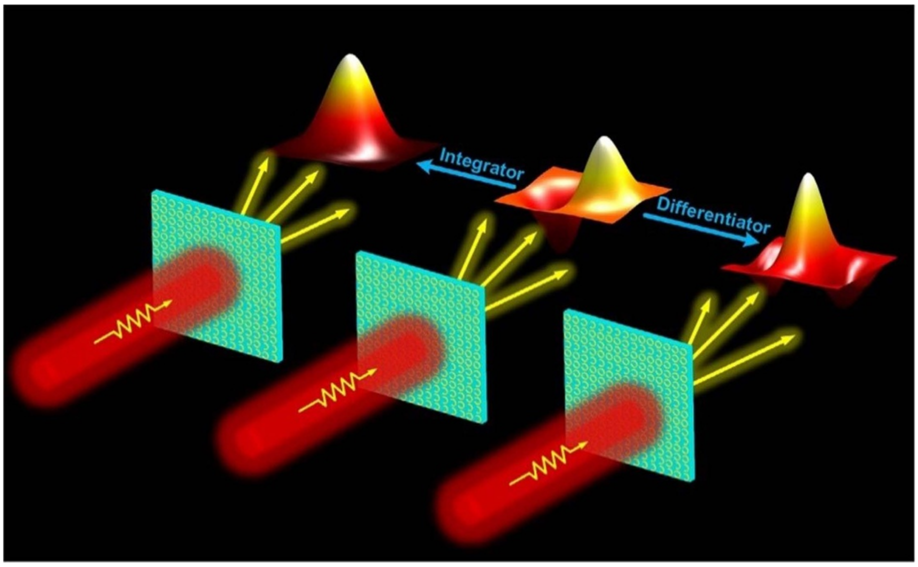

Figure 59. Mathematical operations of transmissive near fields controlled by metasurface with phase and amplitude modulations. [410] John Wiley & Sons. © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

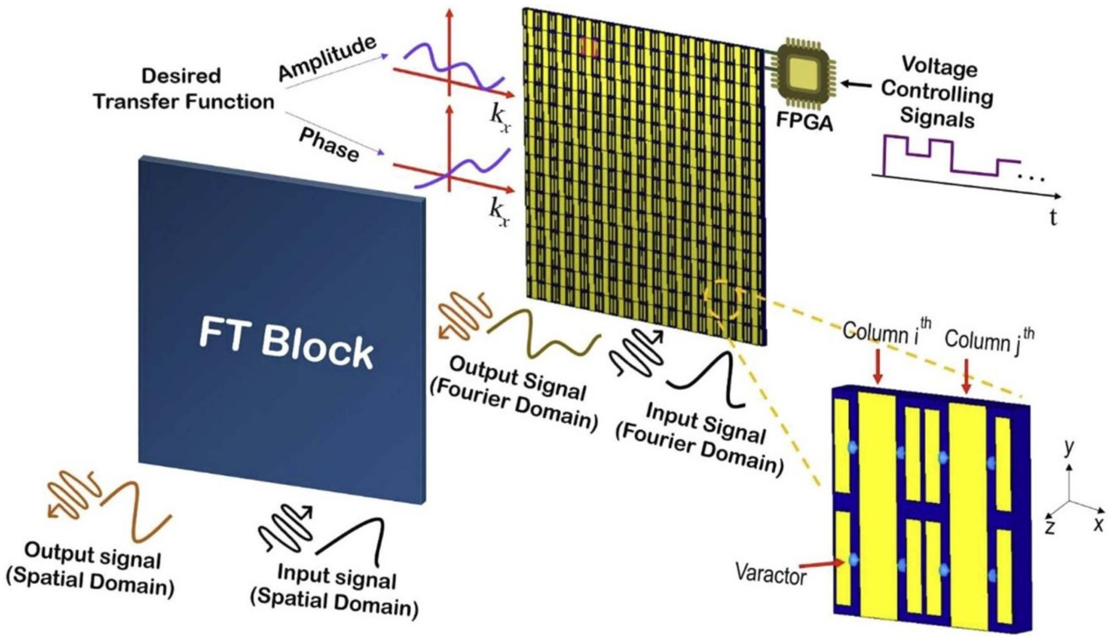

Figure 60. Analog signal processing through space-time digital metasurfaces. Reproduced from [411]. CC BY 4.0.

The current information-metasurface-based signal processing devices are designed for only linear functionalities. The recent advances of gain-type information metasurface [413, 414], realized by the use of amplifiers, can enable nonlinear functionalities such as complex non-linear equation solving.

With the great advances in surface acoustic, the information information-metasurface-based signal processing devices designed for EM waves can be extended to acoustic wave, offering great possibilities for the miniaturization of analog acoustic signal processors. Such analog acoustic signal processors operate at the speed of sound, and may potentially lead to ultrasound imaging and detection at the hardware level.

Owing to the rapid growing CMOS technique, the fabrication of large-scale information metasurface is becoming feasible, which may help realize large scale analog image processing.

Concluding remarks

In an information-metasurface-based digital signal processing system, the signal gets processed as the EM wave interacts with the information metasurface. They require no analog-to-digital conversion, and may potentially lead to direct, ultrafast, wave-based analog computation within subwavelength thicknesses. One of the advantages of performing signal processing directly on information metasurface is the ability to process information in parallel, which is of particular usage in the case of, for example, large matrix multiplications. By developing inverse design algorithm for optimizing the amplitude and phase profiles, we anticipate the realization of more complex mathematical operations, for example, the second derivative for ultrafast edge detection. The system can also be developed to tackle multi-channel signals by, for example, designing anisotropic structures that responds differently to orthogonal polarizations. Future development of information-metasurface-based digital signal processing systems may advance toward the realization of wave-based neural network at the hardware level, which support non-linear operations far beyond the Fourier optics approach.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (62288101), and the National Key Research and Development Program of China (2017YFA0700201, 2017YFA0700202 and 2017YFA0700203).

5.5. Light-controlled programmable metasurfaces (PMSs)

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Status

Metasurfaces are ultrathin array structures consisting of patterned subwavelength elements arranged in specific sequences, which have shown great capabilities to manipulate multiple features of EM waves. Recently, developing of active metasurfaces with dynamic responses is a hot topic within the metasurface research community. Tunable and reconfigurable dynamic metasurfaces are typically constructed by integrating static elements with semiconductor components or sensitive materials, which can realize functional tunability under external stimuli. To achieve real-time control ability and more significantly different functions on single metasurface, PMSs were proposed and implemented by further introducing the programmable devices into the metasurface designs [8]. PMSs have offered remarkable solutions to control EM waves in real time, enabling wide application fields of cloaking, radars, imaging and communications [384]. Because of fast switching capability, PMS is very suitable for realizing time-modulated metasurfaces that can tailor EM waves in time domain. Very recently, many attempts have been made to move PMSs into a higher-level stage: intelligent metasurfaces, whose functionality can be changed by themselves according to external environment.

Overall, recent developments in PMSs have opened new opportunities in EM manipulation. Usually, the PMSs operating at microwave and mmWave band are realized by adopting an electrical control method, in which the control signals are directly applied on the metasurfaces through electrical wires. Different from the wired electrical control approach, the wireless optical control method can be used to control metasurfaces in a noncontact remote way, leading to a kind of light-controlled PMSs that can be driven optically to implement EM functions. In 2018, two photodiode-based light-controlled PMSs working in reflective and transmissive modes were designed and realized [415, 416], as shown in figures 61(a) and (b), respectively. In both the designs, an array of photodiodes is integrated into the metasurface for providing the light-controllable bias for metasurface elements. The experimental results verify that under different illumination intensities, the two fabricated metasurface samples can be used to control dynamically the reflection beam and transmission amplitude of EM waves, respectively. Besides the light-controlled microwave devices, the optically controllable direct-current (DC) illusion device based on photoresistor network has been also realized [417]. On the light-controlled programmable platforms, the physical connection to the DC power supply is no longer required, which enriches the control mode of PMSs and is helpful for designing remote-control metasurfaces and hybrid photoelectric metasurfaces.

Current and future challenges

Despite light-controlled PMSs show great promise for developing remotely-tuning and multi-physics field metasurfaces, several limitations are still needed to be solved. The most notable one is how to use light signals for achieving local programmability at the unit-cell level on metasurface platforms. In other words, it is challenging to realize the case where each constitutive element of the metasurface can be controlled independently by visible light. For electrically-controlled PMSs, local programmability can be well achieved through the multi-output control circuit that is able to provide independent driving signals for each unit by a series of wires. However, for the wireless light-controlled PMSs, the required multiple independent control signals are hard to be provided by spatial illumination light in practice, due to the propagation divergence and mutual interference of light beams. In the previously reported two light-controlled PMSs [415, 416], the metasurfaces can only be controlled at the global level or in one direction, thus leading to poor reconfigurability. Another major concern is the distance of remote control of light-controlled PMSs. For the photodiode-based optical control scheme, the control signal is generated by the light intensity dependent photodiode array. To provide the enough and the precise control signal, the light control distance is usually limited to the centimeter level. Therefore, new approaches should be developed to increase significantly the distance of remote control.

The third challenge is how to construct advanced optical-sensing smart PMSs with self-adaptive capability. In the current demonstrated light-controlled PMSs, human interventions are needed to change or switch the light signals for controlling the functions of metasurfaces. The reason is that these light-controlled PMSs lack the optical-sensing-feedback mechanism and the corresponding closed-loop control circuits. Indeed, light is naturally suitable for smart sensing application by detecting automatically its intensity, color

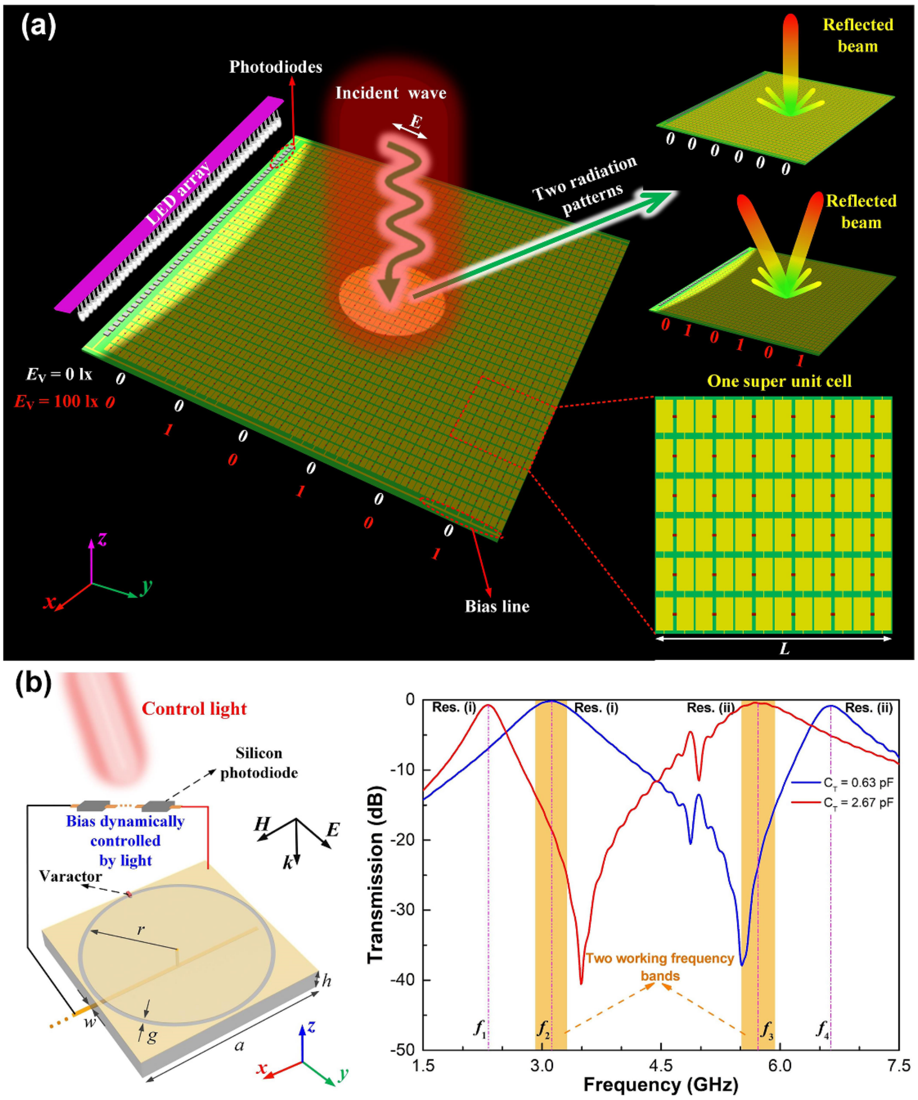

Figure 61. Two photodiode-based light-controlled programmable metasurfaces that are used for controlling (a) the reflection beams and (b) the transmission amplitude of EM waves in a real time. Reproduced from [415]. CC BY 4.0. Reprinted from [416], with the permission of AIP Publishing.

and other characteristics using optical sensing components and necessary closed-loop control circuits, but this is at the cost of system complexity. In the above-mentioned designs of light-controlled PMS, the external light signals are quasi-static, which are adopted to control the microwave wavefronts in the spatial domain. Developing of time-domain or even spatio-temporal light-controlled PMS poses further challenges. To realize the light-controlled time-varying metasurfaces, the light signal should be changed rapidly with time. This requires the designs of more advanced light sources and high-speed photoelectric detection circuits, which will involve more technical issues.

Advances in science and technology to meet challenges

Recent advances in technology can mitigate some of the limitations discussed above. In 2020, a highly integrated broadband light-controlled PMS with strong programmability was constructed by integrating multiple independent optical interrogation networks on the back of the dynamic metasurface [418], as shown in figure 62(a). To achieve 2D tuning ability, the metasurface platform is divided into multiple subarrays, each of which contains 4 × 4 elements and an optical interrogation network based on an ingeniously arranged series photodiode array. In such a case, each subarray can be controlled by light beam remotely and independently, thus achieving local programmability in wavelength scale. The interrogation network is able to convert light intensities to voltages and then applies the biases to the metasurface elements for changing their reflection phase. Therefore, under different light illumination patterns, the distributions of microwave reflection phase on the metasurface aperture can be tuned wirelessly and then generate different EM functions in real time. As examples, three interesting functions of external cloaking, EM illusion

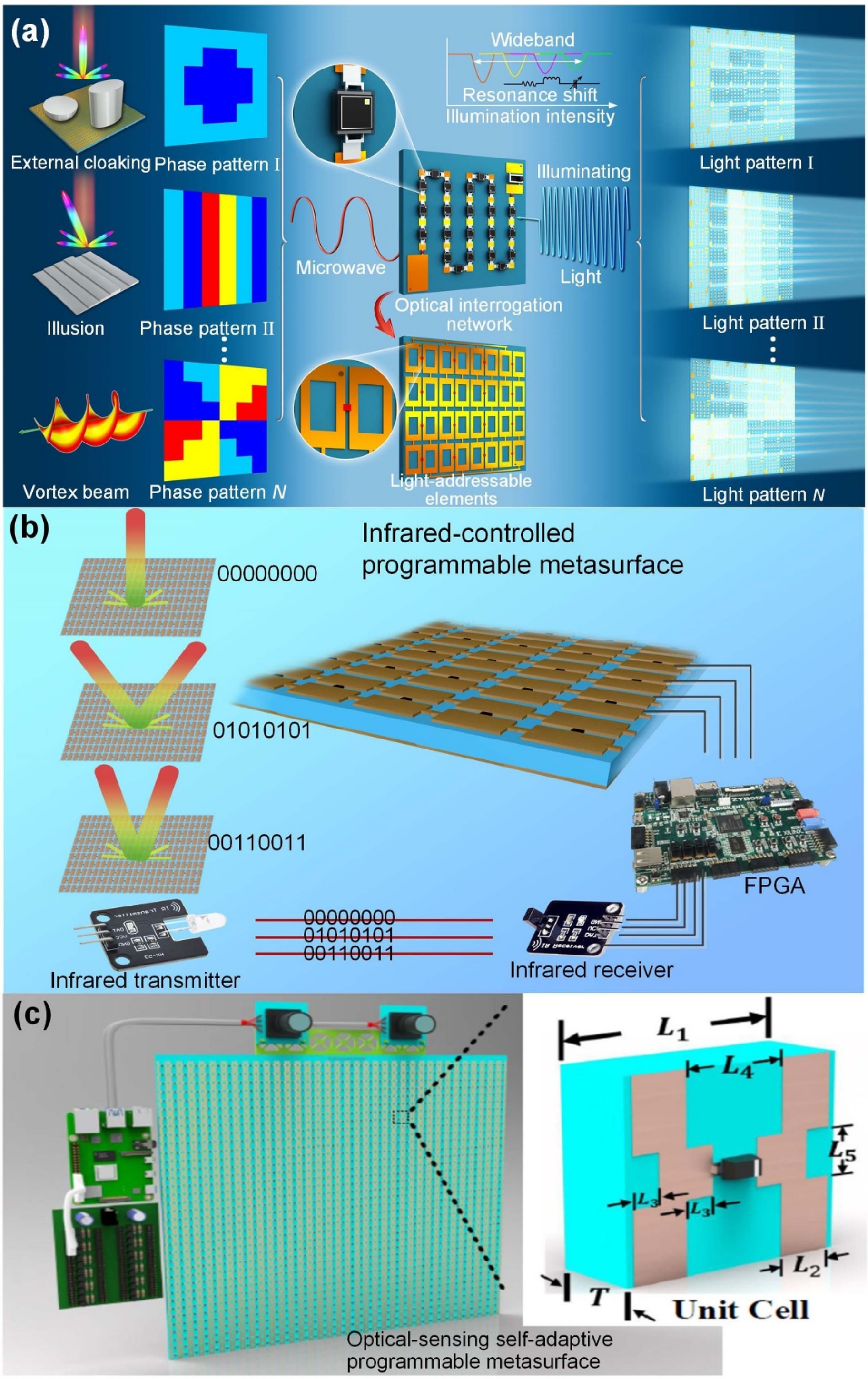

Figure 62. (a) Architecture of the broadband light-controlled programmable metasurface that can achieve local programmability in wavelength scale, thus realizing a lot of different EM functions. (b) Illustration of an infrared-controlled programmable metasurface for wirelessly controlling the reflection beams at a long distance. (c) Illustration of the optical-sensing self-adaptive programmable metasurface based on two cameras, which can realize the automatic beam tracking without any human participation. Reproduced from [418], with permission from Springer Nature. Reprinted from [419], Copyright (2020), with permission from Elsevier. Reproduced with permission from [420].

and dynamic vortex beam generation were verified in the experiment and the measured results are in good agreement with the simulation ones.

To improve greatly the optical control distance, an infrared-controlled PMS, another type of light-controlled PMS based on infrared technology was proposed and realized (see figure 62(b)) [419]. Such the infrared-controlled PMS contains a metasurface, a FPGA controller and an infrared transceiver. The coding sequences are firstly stored in FPGA and are then switched wirelessly using infrared ray to tune the reflection phase of the elements, thus controlling the reflection beams of the metasurface in real time.

Experimental results show that the metasurface can be programmed at a long distance of about 10 m for realizing beam splitting and beam scanning functions. To achieve smart ability, very recently, an optical-sensing self-adaptive PMS was constructed by integrating two cameras and a Raspberry Pi into the metasurface (see figure 62(c)) [420]. The two independent cameras are used to detect the position of the objects and then sent the information to the Raspberry Pi for generating the required coding sequences. In this manner, the reflection beams of the metasurface are always pointed to the objects without any human intervention, realizing the automatic beam tracking. Moreover, dual-polarization decoupled metasurface [421] and full-polarization PMS [422] have been demonstrated, which can be adopted in further designs of advanced light-controlled PMS for realizing more attractive functions.

Concluding remarks

Light-controlled PMSs allow real-time control of EM waves in a noncontact remote fashion, which can not only be used to realize wirelessly PMSs, but also offer an actual route to build the bridge linking the optical signal and microwave signal and hold promise for the development of multi-physics field metasurfaces and multifunctional microwave optical integrated devices. We have presented here several different optical control mechanisms, such as by using photoresistors, photodiodes, infrared transceiver and cameras for realizing light-controlled PMSs, and have also shown the challenges in their implementations. The current researches are mainly focused on how to use optical signal to control dynamically EM functions. In the near future, the light-controlled PMS will be further investigated from the perspective of information processing for developing multi-domain integrated hybrid platform that can process optical and RF signals simultaneously, which may find many important applications in 6G wireless communications.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2017YFA0700201 and 2017YFA0700203), the National Natural Science Foundation of China (61890544, 61731010 and 11874142), the National Postdoctoral Program for Innovative Talents (BX2021063), the Fundamental Research Funds for the Central Universities (2242021k30040), and the 111 Project (111-2-05).

5.6. Adaptive and smart metasurfaces

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Status

In past two decades, metamaterials and metasurfaces have attracted the worldwide attention due to their unparallel capabilities on tailoring EM fields. Among various sub-directions, one important branch is the digital coding and PMSs proposed by Cui *et al* in 2014 [8], which bridges the physical world and digital world within metasurface platforms. Such digital design and control method naturally provides an incubator for adaptive and smart metasurface designs, which highly depends on the flexibly programmable specialty and integratable architectures. Therefore, the self-adaptively metasurfaces with programmable EM functions are presented in 2019 [196], as shown in figure 63(a). By integrating the sensors like gyroscope, the metasurface can detect the change of the environment and itself states for its decision-making based on the intelligent algorithm, like self-adaptive beam-staring when the metasurface is moving or rotating. But, these sensed targets such as motion state of metasurface, environment light or temperature cannot be dominated by the PMS. More recently, to further focus on sensing the controllable objects, Ma *et al* proposed a smart sensing metasurface to sense the incident microwave and meanwhile manipulate the coding patterns for diverse scattering fields such as dual-beam and RCS reduction [423], as shown in figure 63(b).

The above-mentioned smart metasurface can be classified as the hardware-driven intelligence, which contains feedback channels in the metasurface structures compared to conventional metasurfaces. Correspondingly, some smart designs based on general PMS and embedded with intelligent algorithms can be regarded as a software-driven intelligence, also showing great potentials in both communication and imaging fields. For example, in order to break through the conventional microwave imagers which usually require either time-consuming data acquisition or complicated reconstruction algorithms, Li and co-workers introduced metasurfaces to build an *in-situ* sensing and monitoring system [385], as shown in figure 63(c), where the reprogrammable metasurface acts as a real time massive microwave radiator to detect the object fast. The image of the object was reconstructed *in-situ* by a machine-learning algorithm from the echo microwave data. Before long, Li and co-workers further designed a more intelligent metasurface imager and recognizer system [397], using deep learning methods to transform measured microwave data into profile images of the whole human body and recognize human hand signs instantly, brought the smart metasurfaces into the region of smart homes and health monitoring.

Current and future challenges

For hardware-driven smart metasurfaces, the main challenge is the further highly integrated multi-dimensional EM sensing and control within metasurface structure. Like the presented smart metasurfaces, the sensors, which aims at the environment detection, are the relatively independent modules embedded with metasurface, requiring relatively low degree of complexity. But, when the sensing target is EM parameters like amplitude, phase and polarization, the complexity of element structure will significantly increase. The balance between EM sensing structure and EM manipulating structure, as well as their control design will become very difficult to grasp, even in the microwave band. Therefore, we can naturally think that the frequency band limitation is another challenge of the current smart metasurfaces. Higher frequency band means higher data transmission, processing speed, and greater data throughput, which will be an unprecedented improvement for intelligent information processing especially like optical band.

For software-driven smart metasurfaces, like aforementioned metasurface imager, the PMS acts as a real-time microwave detector and the continuously varying radiation pattern of the metasurface is pre-designed by the features extracted from the optical images of target objects using principal component analysis (PCA). A total of 53 different radiation patterns are needed to obtain high-quality images of human bodies. It is a fact that the fewer the number of radiation patterns need, the faster of imaging speed will be. However, the data acquisition by the metasurface and the data processing by PC is two relatively independent process, makes it hard to optimize the radiation patterns of metasurface. Another challenge in metasurface imager is that although using the deep learning algorithm for imaging can improve the quality and speed of imaging process, a large number of training data need to be gained in advance to train the imaging neural network, which raise the time and manpower cost. In fact, the huge price of making training data always become a large hurdle for the usage of deep learning methods, which is currently the biggest obstacle of combining deep learning and smart metasurface.

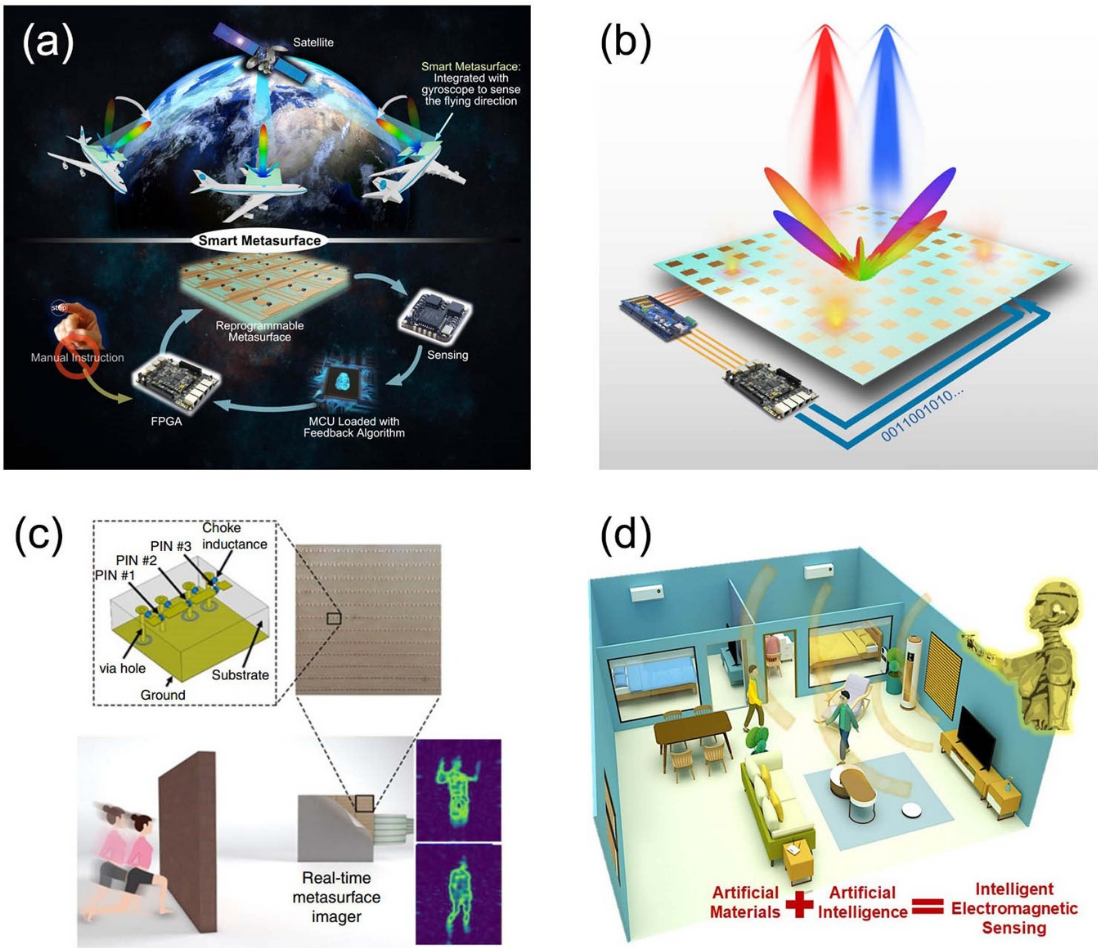

Figure 63. (a) The self-adaptively smart metasurface. (b) The smart sensing metasurface. (c) The *in-situ* sensing and monitoring system. (d) The intelligent EM sensing based on metasurface. Reproduced from [196]. CC BY 4.0. Reproduced from [423]. CC BY 4.0. Reproduced from [385]. CC BY 4.0. Reproduced from [397]. CC BY 4.0.

Advances in science and technology to meet challenges

As we have mentioned, the PMS can act as a fast microwave radiation to detect the surroundings and the subsequent signal processing algorithm could using the echo data realizing various functions. The efficiency of the whole procedure would be increased if the measurement process driven by metasurface could be accelerated. Recently, researchers reduced the radiation patterns needed for metasurface to obtain a high-quality image of human body by integrating the measurement process directly into the data-processing deep-learning pipeline, and jointly optimize the radiation patterns and the signal processing modules [424], making the data acquisition learnable and thus increasing the intelligence level of metasurface, as shown in figure 63(d).

To reduce the amount of training data for deep learning algorithm, unsupervised learning has gained more and more attention. As an example, in a case of computer-generated hologram, researchers have put the physical mechanism of wave propagation into the structure of a neural network responsible for generating holograms, which forms an unsupervised variational auto-encoder structure and as a result getting rid of making coupled training samples [425]. More importantly, the PMSs are possible to establish a physical neural network which has been verified in optical systems [426, 427] with passive and fixed structure. Based on the natural diffraction of EM wave, the light-transmission process in a multi-layer substrate system is regarded as a network weight calculation process. By appropriately arranging the transmissive phase and amplitude distribution, a multi-layer metasurface system is equivalent to a well-trained neural network to perform the functionalities like pattern recognition. Furthermore, when such multi-layer system is based on PMSs, the sensing, learning and signal-processing capacity will become much more powerful and imaginative [428].

Concluding remarks

In summary, both hardware- and software-driven smart metasurfaces show great potentials but also facing the relatively challenges in structure or algorithm levels. More AI methods should be explored to enhance the intelligence of smart metasurface and increase its interaction ability with environment and human. Meanwhile, the unsupervised learning algorithm could be further developed to reduce the use cost of AI methods. Besides, the physical neural network architecture based on metasurfaces also provides a hopeful direction to solve the bottleneck on software and hardware of smart metasurfaces.

Acknowledgments

This work was supported in part from the National Key Research and Development Program of China under Grant Nos. 2017YFA0700201, 2017YFA0700202 and 2017YFA0700203, the National Natural Science Foundation of China under Grant Nos. 61871127, 61735010, 61731010, 61890544, 61801117, 61722106, 61701107, 61701108, 61701246 and 61631007, the State Key Laboratory of Millimeter Waves, Southeast University, China (K201924), the Fundamental Research Funds for the Central Universities under Grant No. 2242018R30001, the 111 Project under Grant No. 111-2-05, and the Fund for International Cooperation and Exchange of the National Natural Science Foundation of China under Grant No. 61761136007.

5.7. Programmable and smart wireless power transfer (WPT)

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Status

A century ago, WPT was pioneered by Tesla, which was achieved through the well-known resonant loops. The magic of radically dropping wires for conveying energy attracts many researchers, leading to the emergence of the WPT community. Later research on this topic systematically examined various near-field and far-field techniques [429].

Within the near-field region, which is about several meters, two-coil systems, four-coil systems with relay resonators, and principle resonators were adopted [430]. We note that existing works on near-field WPT by capacitive or inductive coupling can achieve over 70% system energy efficiency from several watts to kilowatts. The carrier frequencies of resonance technique for near-field WPT ranges from several kilohertz to a few megahertz. Although the power transmission efficiency of these methods is relatively high, the operating frequencies are not coincident with current wireless communication bands, leading to different antennas for WPT and communication in a wireless device. Large aperture antennas generate high-gain narrow beams for the far-field WPT [431].

From the above reviews on the reported WPT status, we can conclude that an adaptively smart WPT system is urgent to satisfy the complicated EM space, which can hardly be implemented by the conventional WPT techniques. Metasurface, consisting of artificially structural unit-cells, is a promising solution to enhance the WPT system performance [433–435]. When electronically tunable components meet metasurface, Cui *et al* proposed the digital coding and PMSs by integrating with a FPGA [8]. The digitally controlled phase-shift of each unit-cell makes the PMS a low-cost and high-efficiency beam-forming platform for adaptively WPT, which is a critical factor for wireless power focusing and delivering in the near-field condition [436]. By integrating adaptive algorithms on FPGA for managing WPT and wireless energy harvesting, an intelligent WPT system can be achieved, forming a brand-new methodology for the WPT community [432].

A scheme of adaptively smart WPT for dynamic charging based on a 2-bit PMS is illustrated in figure 64. When portable devices within the smart WPT coverage area request charging, the PMS will constantly track and focus wireless power to targets even they are moving. We mention that positioning sensors such as cameras and magnetic coils are integrated with the PMS platform to assist the dynamic tracking. A general theory of STM digital coding metasurface was further proposed to obtain simultaneous manipulations of EM waves in both space and frequency domains, as shown in figure 65, which can flexibly control the propagation direction and harmonic power distribution simultaneously [11]. We emphasize that the programmable regulation capability of high-efficiency spots is fundamental to realizing smart WPT. Therefore, smart WPT applications such as automatic charging, intelligent monitoring, and simultaneous wireless information and power transfer (SWIPT) system could be developed based on the adaptively PMS control platform.

Current and future challenges

Even though a 2-bit PMS prototype demonstrates the feasibility of programmable and smart WPT, the main challenges are twofold, including hardware aspect and software aspects. There exists a trade-off between realizable and performance on both aspects for the reported smart WPT system. However, for a practical application requirement, these issues should be detailed.

In the hardware aspect, higher digital bit resolutions (2-bit, 3-bit, etc) with low loss for PMS are challenging. Higher digital bit resolution offers higher accurate manipulations of EM waves. Nevertheless, more lumped components are needed for higher digital bit resolution, increasing loss for microwave signals. Meanwhile, the complicated biasing would cause more power consumption. When a large aperture for high-power and high-efficiency transmission is required, thousands of control signals also challenge the application scenario of PMS. On the other hand, the current feed for the PMS is a horn antenna that should be installed over the PMS, resulting in an additional deployment space.

Turning now to the software aspect, various adaptive algorithms integrated into the FPGA should be considered comprehensively. Focal pattern synthesis by beam-forming for different WPT targets is required, including single point, multiple points, and shaped regions. To realize smart WPT, adaptive power delivery policies for various application scenarios are still unavailable. Furthermore, for a smart WPT system, the safety issue of human exposure to EM fields and electromagnetic compatibility (EMC) should also give full consideration to the power delivery algorithm. We mention that the PMS could serve as a versatile platform

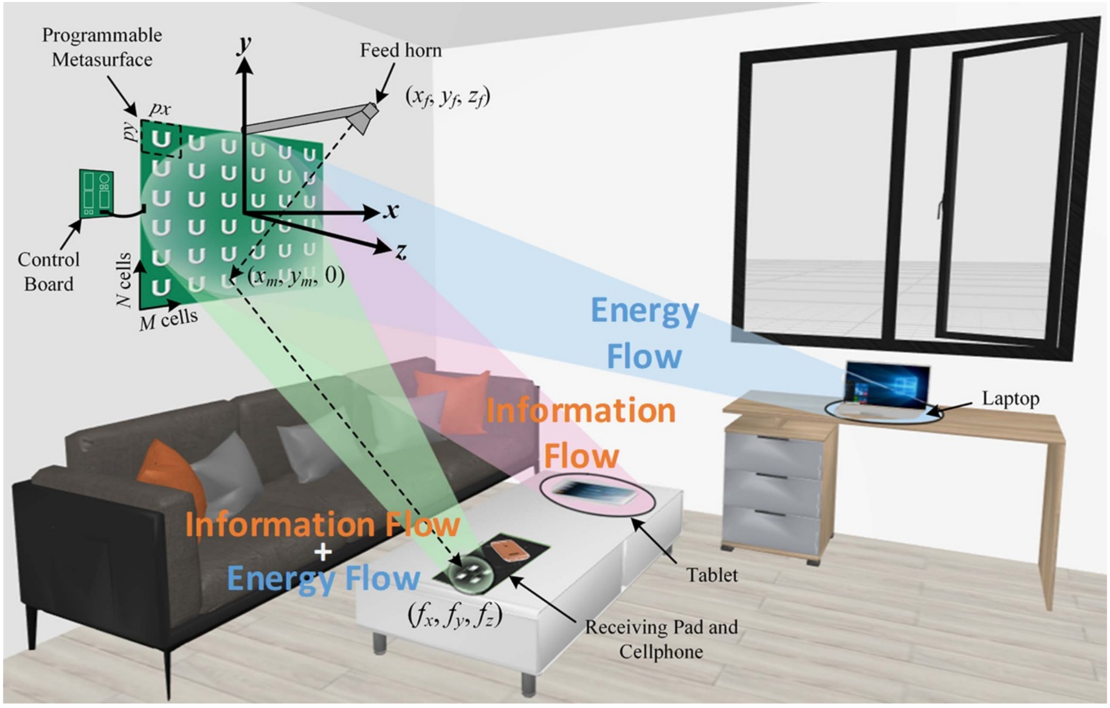

Figure 64. Programmable and smart wireless power transfer technology based on programmable metasurface in smart home applications. © [2022] IEEE. Reprinted, with permission, from [432].

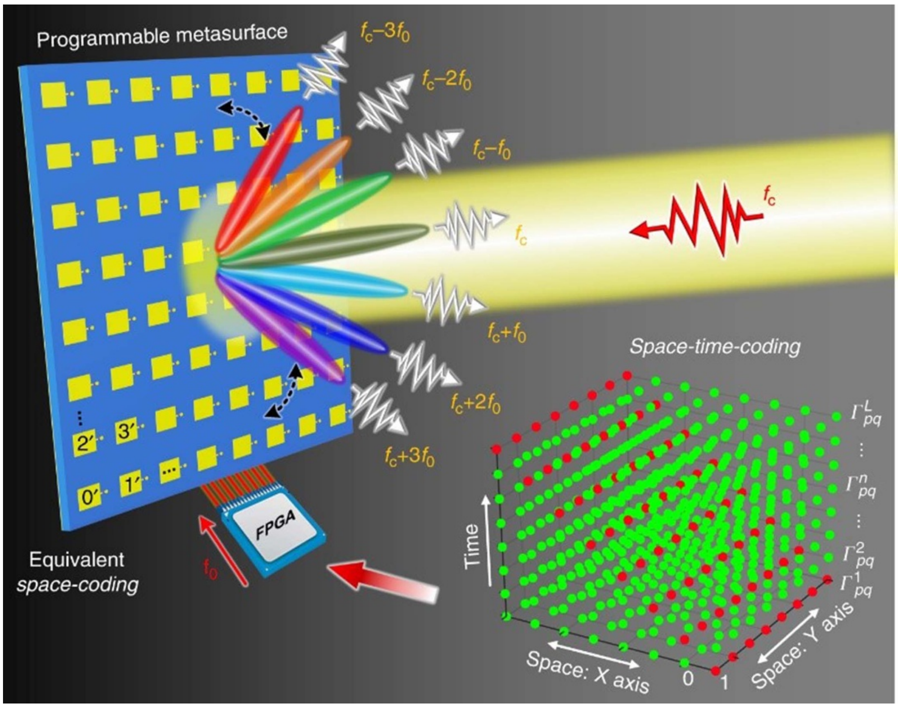

Figure 65. Conceptual illustration of a space-time-coding digital metasurface that can simultaneously manipulate EM waves in both space and frequency domains, i.e. control the propagation direction and harmonic power distribution simultaneously. Reproduced from [11]. CC BY 4.0.

to integrate various sensors and actuators, enabling extra sensing and recognizing abilities for intelligent decisions.

With the rapid development of WPT, the concept of SWIPT is envisioned, aiming to combine WPT into the modern communication network. Under such an architecture, PMS, which could modulate information directly and transmit wireless power, is a noteworthy scheme. The existing SWIPT scheme employs mature wireless technologies from distinct communities, leading to complex collaboration. By contrast, the PMS for SWIPT shows a highly integrated solution that is established from a brand-new perspective. Future challenges on PMS for SWIPT include high-power coverage with the arbitrary area, high-power harmonics carrying information, and information security and EMC safety.

Advances in science and technology to meet challenges

The thorny issues of increasing bit resolution of PMS unit-cell and aperture scale may be solved by the advanced semiconductor technology that packages lumped components and metamaterial unit-cells to form a new PMS chip. In other words, we could treat this chip as a conventional high-speed circuit component to realize the smart WPT system. The main difference of this chip is that it directly regulates EM waves with a standard digital interface through metamaterials, which is the bridge between digital space and EM space. On the other hand, numerous novel applications based on PMS prove that a general-purpose PMS chip with multiple functionalities is urgent, especially for the smart WPT that operates under high-power conditions.

Reducing the existing spatial feed PMS profile could be achieved by assigning the feed point onto the radiating surface. The radiation mechanism is distinct from the current one in this form, which manipulates surface waves instead of scattered waves. This type of metasurface is termed impedance modulated metasurface or holographic metasurface. However, a reliable programmable modulated metasurface is still unavailable. One possible solution for such a low-profile programmable platform is to adopt the idea of digitization which starts from figuring out opposite EM response states. For the software aspect challenges, the machine learning and AI-driven framework is a clear direction for training adaptively intelligent WPT algorithms. Through theoretical analysis, numeric modeling, and microwave measurement, tons of data of wireless power distribution, human safety region, and power consumption networks can be obtained to feed the training models. A bidirectional cycle for the power transmission side and reception side is required in the AI model, serving a realistic, innovative WPT system. The programmable space-time coding and intelligent metamaterial technologies will play significant roles in future SWIPT systems.

Advances in EM theory, circuit theory, and data science direct the development of WPT to a programmable and intelligent paradigm. The presented works also indicate that a platform based on PMS can meet the current WPT needs and embed a power transmission network into the wireless communication network, giving rise to a ubiquitous internet of everything.

Concluding remarks

We review the status of the current WPT and depict the programmable and smart WPT. An adaptively smart WPT prototype system based on a 2-bit PMS is described. The STC digital PMS is also revisited, which shows great potential to integrate wireless information and power with harmonic operations. The novelty and feasibility of this topic are presented. Some existing issues are elaborated to face the increasingly complicated EM space. Opportunities in both hardware and software aspects of programmable intelligent STC information metasurface are also revealed. Future possible improvements and development directions are discussed. The smart WPT system can be evolved into the SWIPT system, when it is integrated with wireless sensor networks, communication modules, and advanced algorithms.

Acknowledgments

The authors acknowledge the National Key Research and Development Program of China under Grant Nos. 2017YFA0700201, 2017YFA0700202, 2017YFA0700203 and 2021YFA1401001, and the 111 Project under Grant No. 111-2-05, National Natural Science Foundation of China (No. 62001342), Key Research and Development Program of Shaanxi (No. 2021TD-07), Outstanding Youth Science Foundation of Shaanxi Province (No. 2019JC-15).

5.8. Metasurface-enabled intelligent electromagnetic (EM) sensing

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EM sensing as a powerful non-contact examination tool is of great importance in various areas, such as, medical diagnose, nondestructive testing, safety screen, resource exploration, and so on. Generally, three types of EM sensing schemes, (i.e. real-aperture, synthetic-aperture, and coding-aperture) have been widely employed to date [437]. Typically, these schemes usually trade off the sensing performance with cost (either hardware or computation) mainly due to the lack of intelligence, especially in the era of big data. As a consequence, it is highly demanded to develop the sensing strategies with the intelligence for acquiring and processing the high-dimensional data stream. Here, we refer the intelligence as that the EM sensor can adaptively organize the task-oriented sensing pipeline (data acquisition plus processing) without any human intervene. In the past decade, intelligent metasurface [438], synergizing engineered ultrathin materials for flexible wavefront manipulation [193, 409, 439] and machine learning techniques for efficient data processing [440, 441], emerges as a versatile wave-information-matter platform for the intelligent sensing. Three representative proof-of-concept demonstrations in this emerging area are highlighted as follows.

Machine-learning-based metasurface imager. As pointed out above, one of the fundamental but challenging issues for the EM sensing is to handle the high-dimensional data stream. To address this issue, Li *et al* introduced the concept of machine-learning metasurface imager [385]. In the metasurface imager, the metasurface is firstly trained with the linear embedding techniques (e.g. PCA, random projection), and then serves as a wave-based computing device for retrieving the compressive information and recognizing the features. Particularly, the object reconstruction and recognition can be achieved from the trained compressive measurements in an almost digital-computation-free way, as illustrated in figure 66(a). It is worth pointing out that, due to the reprogrammability, such imager can be adopted for different sensing functionalities by the control software without modifying the costly hardware.

Deep-learning-driven metasurface imager and recognizer. The mechanism behind the above machine-learning-based metasurface is that the high-dimensional scene data can be well represented with the remarkably reduced features in a linear way. However, the object features of interest are usually nonlinearly related to the measurements for most practical object reconstructions and recognitions, thus, the above linear-machine-learning-based metasurface imager is limited to handle the relatively simple sensing tasks. In order to tackle this issue, the concept of deep-learning-driven metasurface imager and recognizer has been introduced in [397], by integrating a large-aperture reprogrammable metasurface for physical compressive measurements and the deep learning techniques for efficient digital data processing, as sketched in figure 66(b). We designed an intelligent EM sensor working at around the frequency of commodity Wi-Fi signals, i.e. 2.4 GHz, and demonstrated that it could be utilized to accomplish a series of high-quality sensing tasks including real-time imaging, body gesture identification, and human vital-sign monitoring in real-world settings. More importantly, we found that the intelligent EM system works very well for realizing the above complicated sensing tasks even when it is excited by the ambient wireless signals in our daily lives.

Intelligent metasurface camera with learnable data acquisition and processing. Yet, it should be noticed that the above sensing strategies remain not intelligence as we anticipate, in the sense that they indiscriminately acquire and process data and most of them are non-relevant to the object of interest. In order to approach to the intelligence, Li *et al* and Wang *et al*, proposed two integrated intelligent sensing schemes in the frameworks of variational autoencoder [424] and free-energy minimization [398], respectively. Here, we denote the integrated sensing that the optimal settings of data acquisition and postprocessing can be simultaneously learned subject to the undergoing task, given hardware and scene, as shown in figure 66(c). They experimentally showed that these strategies could drastically improve many performance-critical metrics including sensing quality, system complexity, computational efficiency, power consumption, and so on.

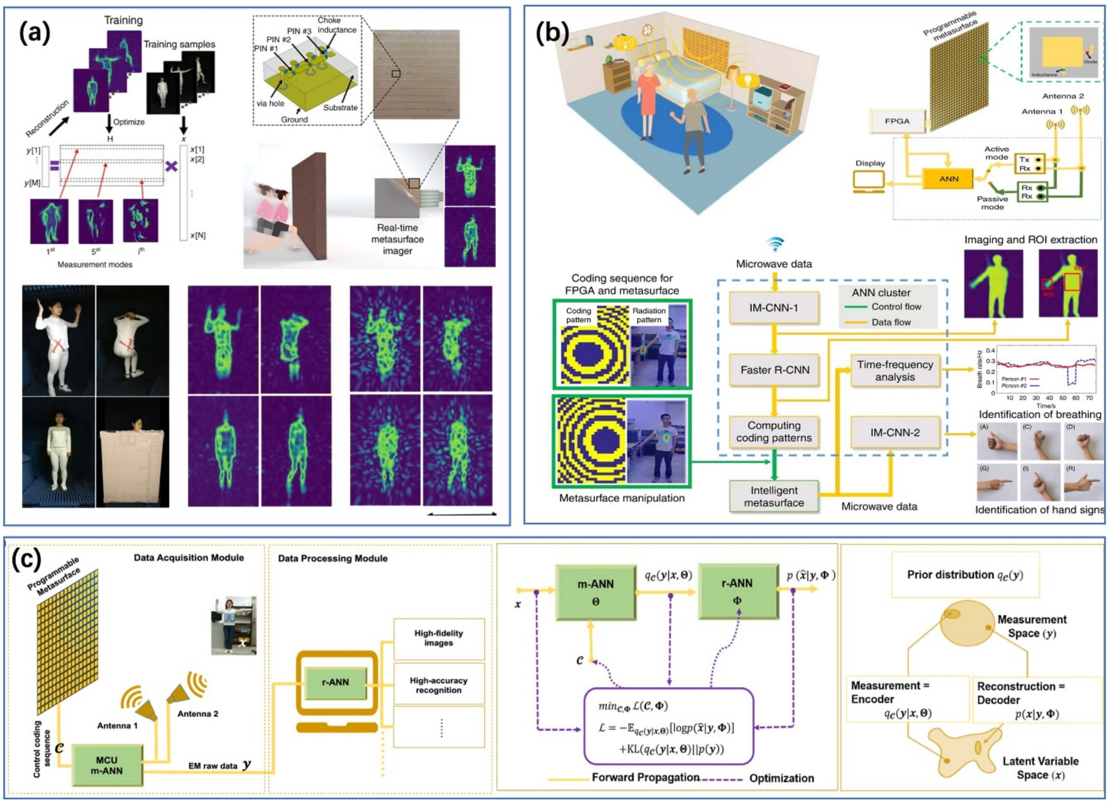

Figure 66. Three representative metasurface-enabled intelligent sensing schemes. (a) Machine-learning metasurface imager trained with PCA method [385]. Reproduced from [385]. CC BY 4.0. (b) Intelligent metasurface imager and recognizer for a successive of sensing tasks of imaging, body sign recognition and respiration identification [397]. Reproduced from [397]. CC BY 4.0. (c) Intelligent integrated metasurface camera in the context of variational autoencoder [424]. Reproduced from [424]. CC BY 4.0.

Concluding remarks

To summarize, we discuss the emerging research of the metasurface-enabled intelligent EM sensing, where the reprogrammable metasurfaces for the flexible wavefront manipulation and AI techniques for the efficient digital data postprocessing are synergized to achieve the goals of intelligent sensing. The research still in its infancy, and many important issues need to be tackled in future. Here, we highlight three potential directions for the further developments. The first one is about the theoretical mechanisms behind the AI-empowered intelligent metasurface sensor, for instance, the ultimate sensing resolution and accuracy it can achieve. Secondly, it is appealing to design more specialized dynamic metasurfaces with lower cost and lower power consumption. Thirdly, it is of great interest to extend the aforementioned hybrid-computing-based sensing systems to all-wave 'green' systems to lift up the barrier of the Moore's law. In a word, we anticipate that the metasurface-enabled intelligent sensing could be exploited to achieve the sensing goals that the conventional sensors are difficult to achieve, and that the developed methodologies could be readily generalized for other frequencies and beyond.

6. Space-time modulated (STM) metamaterials and metasurfaces

6.1. Nonlinearity-induced nonreciprocal metamaterials

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Status

Nonreciprocal devices—in which light waves propagate asymmetrically along opposite directions—are essential components for optical communications, radar and light detection and ranging technology, nonlinear signal processing, and integrated photonic circuits. Yet, EM nonreciprocity is challenging to obtain in practical scenarios: any system that is linear, time-invariant, and with symmetric constitutive tensors, is bound by Lorentz reciprocity to support a symmetric transmission matrix, even in the presence of loss and of arbitrarily asymmetric geometries and anisotropic media. Metamaterials have been a focus of recent effort to break reciprocity in recent years, based on magnetically biased unit elements, spatio-temporal modulation patterns, and more recently nonlinearity-based approaches [442]. In particular, nonlinearity-induced nonreciprocity has recently attracted considerable attention due to its simplicity in design and fabrication, and most importantly that does not require any form of external bias. The basic concept is sketched in figure 67(a): a compact resonator, which may consist of the unit element of a metamaterial, is coupled asymmetrically to (at least) two ports, such that waves injected from different ports induce different intracavity field intensities $|\mathbf{E}|^2$. In linear settings this asymmetry is not sufficient to induce nonreciprocity, and the port-to-port transmission remains symmetric. However, the situation changes if the resonator contains a nonlinearity, such as the Kerr optical effect based on which the permittivity profile locally depends on the electric field intensity, $\Delta\varepsilon \propto |\mathbf{E}|^2$: different internal intensities will now induce different dielectric environments, and the system is no longer constrained by reciprocity. In particular, the device can be tailored such that the linear transmission spectra (gray line in figure 67(b)) undergo different frequency shifts (red and orange lines in figure 67(b)) when the same input intensity is injected from different ports, leading to largely different transmission levels in the two directions for same input power and impinging frequency. Due to its simplicity and generality, this approach has been recently explored to create passive, bias-free nonreciprocal metamaterial devices in vastly different EM platforms and geometries, such as silicon racetrack resonators [443] (figure 67(c)), silicon metasurfaces [444, 445] (figure 67(d)), radiofrequency circuits [446] (figure 67(e)), photonic crystal cavities [447] (figure 67(f)), and atomic systems supporting quantum nonlinearities [448]. Besides proof-of-principle experiments of nonreciprocal transmission, researchers have also shown the potential of these devices to obtain bias-free on-chip routing for lidar applications (figure 68(a)), whereby the signal reflected from one side is redirected to a different port for temporal detection. Arrays of these nonlinear elements can form nonreciprocal metamaterials with broader bandwidths and even topologically robust features [449]. Generally, these nonreciprocal devices rely on simple material requirements and fabrication processes, and they can be easily integrated into miniaturized photonic circuits. The simplicity in design and fabrication and their bias-free operation are, however, counterbalanced by constraints and tradeoffs, as discussed in the following.

Current and future challenges

Nonlinearity-based nonreciprocity currently faces relevant challenges that hinder its mainstream application in modern technologies. First, the operation is fundamentally rooted on nonlinear responses, which typically require relatively large operational powers, mainly dictated by the intrinsic nonlinearity strength and resonator features. For example, for silicon-like Kerr resonators operating in the 1550 nm spectral window the power required to obtain relevant nonreciprocity is in the order $P \approx 10^4\,\mathrm{W} \times \left(V\left[\mu\mathrm{m}^3\right]/Q^2\right)$ [442] where V is the resonator volume (measured in $\mu\mathrm{m}^3$) and Q is total quality factor. For typical values of $Q \approx 10^3 \div 10^5$ and $V = 0.1 \div 100\ \mu\mathrm{m}^3$ (where smaller mode volumes normally lead to smaller Qs), the required powers are in the $1 \div 10\,\mathrm{mW}$ range, corresponding to intracavity stored energies in the range of $10 \div 100\,\mathrm{fJ}$. While increasing the quality factor can largely reduce the operating power, it comes at the cost of reduced spectral bandwidth, which also limits the maximum modulation speed at which the devices can be operated. A second major drawback is that the superposition principle in these nonlinear devices is not applicable. Thus, while these devices can be designed to behave nonreciprocally when excited from only one

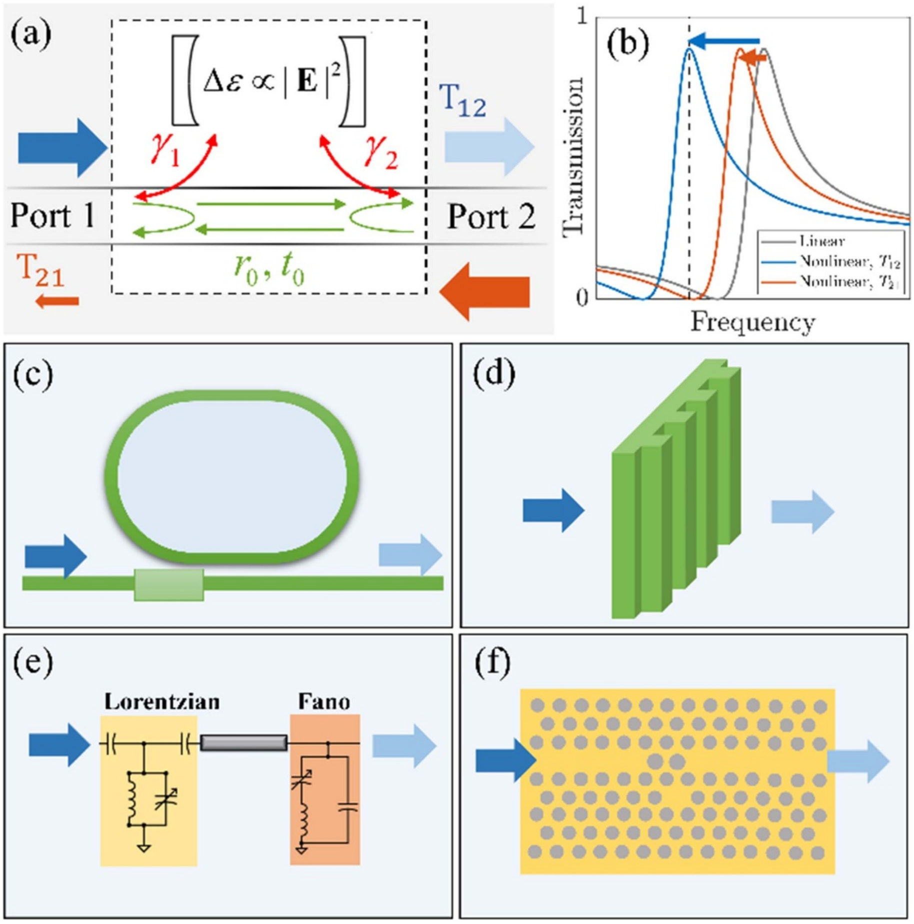

Figure 67. (a) Schematic of a two-port nonlinear asymmetric resonator. (b) A nonlinearity-induced shift of the transmission spectra can lead to largely different transmission levels in the two directions for same input power and impinging frequency. (c)–(e) Examples of different devices to achieve nonreciprocity via nonlinearity. © [2021] IEEE. Reprinted, with permission, from [442].

port, the behavior under simultaneous two-port excitation does not generally lead to a well-defined nonreciprocal transmission. As a practical consequence, this implies that these devices cannot isolate a system from external pulses whenever simultaneous excitation from both ports is expected, limiting their application to pulsed operation [450].

Finally, in contrast to conventional nonreciprocal technologies, these devices obey time-reversal symmetry if the underlying nonlinearities can be assumed to be instantaneous, which leads to constraints on the overall performance. In particular, time-reversal symmetry dictates that in a single resonant device the power range over which nonreciprocity occurs ('NRIRs' in figure 68(b)) and the maximum forward transmission ('Max T' in figure 68(b)) are not fully independent, and increasing one affects the other (figure 68(c)) [444].

Advances in science and technology to meet challenges

These outstanding challenges are being addressed by exploiting recent advances and discoveries in the fields of metamaterials, nanophotonics and light–matter interaction. The intrinsically weak nonlinearities available in natural materials can be replaced by much larger responses available in metamaterials, such as intersubband transitions in multi-quantum-well semiconductor heterostructures, potentially combined with dielectric or metallic metasurfaces to increase coupling efficiency. Strong nonlinearities, however, are often accompanied by large material loss, leading to trade-offs in the structure design. Two-dimensional (2D) semiconductors such as graphene and transition metal dichalcogenides offer interesting prospects in this direction, providing a route to low-loss large nonlinearities.

While simultaneous multi-port excitation of these devices is generally detrimental for isolation purposes, it also opens interesting avenues for other applications, since excitation from one port can be used as an additional external DOF to dynamically and coherently control the system. In particular, simple

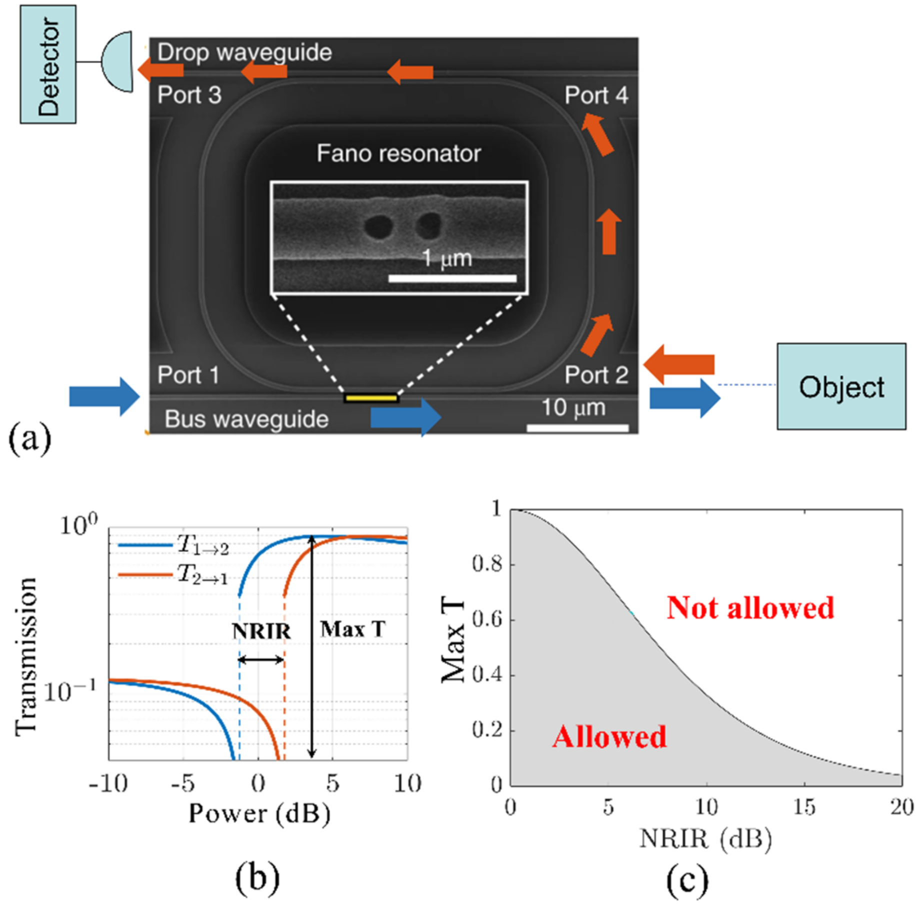

Figure 68. (a) Nonlinearity-based nonreciprocal device used as a passive router for, e.g. lidar applications, by adding a drop waveguide to pick up the reflected signal. Reproduced from [443], with permission from Springer Nature. (b) Calculated transmission of a single-resonator device under one-port excitation, showing a finite nonreciprocal intensity range (NRIR) and maximum forward transmission smaller than one. (c) Trade-off between NRIR and maximum forward transmission, which affect any single-resonator nonreciprocal device based on nonlinearity and time-reversal symmetry. © [2021] IEEE. Reprinted, with permission, from [442].

time-reversal symmetry considerations show that a weak signal from one port can largely modify the transmission features of a large signal coming from the opposite one, which can be used to realize a nonreciprocal switch where small changes in the phase of a control signal largely affect the probe transmission (see part II of [442]). Further investigation of these opportunities, involving multi-port devices, may lead to sophisticated full-optical control of light routing and nonreciprocity.

The fundamental bound between nonreciprocal power range and insertion loss (figure 68(c)) is closely tied to the assumptions of single-mode operation and time-reversal symmetry, which suggests that the bound can be surpassed by breaking these assumptions. It has been recently shown [443, 446] that a system of two cascaded nonlinear resonators can overcome the bound in figure 68(c), providing unitary transmission over a finite range of powers, albeit at the expense of spectral bandwidth. Moreover, time-reversal symmetry can be broken with delayed nonlinearities [451], which can lead to more advanced functionalities (forbidden in the instantaneous regime), such as high-contrast nonreciprocal pulse compression and reshaping. We envision that expanding these mechanisms to metamaterials composed of a large number of resonators and tailored interactions will lead to largely improved metrics, paving the way for bias-free, broadband and low-insertion-loss nonreciprocity. Recent demonstrations of intensity-dependent topological phenomena, e.g. [449], leveraging these phenomena in tailored metamaterials, are a demonstration of the powerful opportunities enabled by these concepts.

Concluding remarks

Nonlinearity-based nonreciprocity has recently matured from a theoretical curiosity to a practical platform to create nonreciprocal devices in vastly different areas of the EM spectrum. These devices, which combine nonlinear response with structural asymmetry to break Lorentz reciprocity, are particularly attractive because of their simple implementation and bias-free operation, which make their fabrication and system integration particularly easy. By exploring metamaterials made of tailored nonlinear asymmetric resonators, we expect that this technology will overcome the current challenges and lead to novel opportunities for fundamental and applied research.

Acknowledgments

Our research on these topics has been supported by the Air Force Office of Scientific Research MURI program and the Simons Foundation.

6.2. Universal space-time modulated (STM) metamaterials for manipulating light

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Status

STM metamaterials are media whose structure is formed by the variation of an EM parameter in both space and time from an external drive. They represent one of the most promising avenues for manipulating light towards novel science and technology [452]. Figure 69 shows an example of an STM metamaterial that has been recently introduced by some of the authors [453]. The modulated parameter may be the refractive index, the permittivity and permeability, or any of the bianisotropic and higher-order spatial-dispersion constitutive parameters and combination thereof, the drive may be of different natures, including acoustic, electronic, and optical, and the combined spatial and temporal natures of the modulation allows to simultaneously manipulate the spatial and temporal spectra of light in unprecedented fashions. STM metamaterials may be seen as a multi-dimensional (2 + 1D and 3 + 1D) and 'new-physics' (mostly still to be discovered) extension of conventional STM structures, such as traveling-wave parametric amplifiers [454] and electro/acousto-optic modulators [455]. Alternatively, STM metamaterials may be considered as a new area of special and GR, where the motion of objects is replaced by the (more practical) propagation of perturbations, without any net transfer of matter, and where novel related effects that have been so far restricted to cosmological systems can be implemented in real devices.

Current and future challenges

Being still in an embryonic state, the field of STM metamaterials is currently facing challenges of all orders: physical, computational, implementational, and applicational. The major *physical* challenges pertain to explaining the differences in the space-time phenomena (e.g. Doppler shift, Bradley aberration, Fresnel–Fizeau drag, Roentgen coupling) due to perturbation motion rather than matter motion, to understanding the virtually unlimited combinations of possible spacetime modulation configurations (uniform/nonuniform, 2/3 + 1D, rectilinear/spherical/anisotropic, unbounded/bounded with various spacetime boundaries), and to identifying the novel opportunities resulting from the relaxation of the time invariance constraint in the fundamental bounds of EM systems. The *computational* challenges include the extension of time-invariant schemes to general time-variant systems, particularly the resolution of the issue of 'numerical traps' caused by the space-time discretization of smooth dynamic interfaces, and the development of efficient convolutional frequency/time-domain algorithms. The *implementation* challenges are mostly related to the difficulty of fabricating structures with addressable, subwavelength modulation units, and with sufficiently high modulation speed to produce the most interesting STM effects, particularly at optical frequencies. Finally, the *application* challenges consist in turning the novel properties of STM metamaterials into novel functionalities to realize devices that will displace or complement state-of-the-art EM technologies.

Advances in science and technology to meet challenges

Several research groups are working on STM metamaterials and have already started to address some of the challenges mentioned in the previous section. An extensive list of references pertaining to the years prior to 2020 are given in [452]. On the front of the *physical* challenges, matter space-time crystals have been extended to STM crystals [456] and the matter STM Fresnel–Fizeau drag has been shown to translate into an EM density averaging effect [456], where light in the homogeneity regime is deflected in the opposite direction to that of the perturbation propagation [10]. Figure 70 extends the concept of opposite matter and perturbation Fresnel–Fizeau drags (left panel) to the case of a nonuniform-velocity (or accelerated) modulation (right panel), where light is not only deflected along a straight line, but also curved [453], as around a black or a white hole (figure 69). Another advance has been the extension of the time reversal concept to space-time reversal, whereby the image of the source is formed away from the latter, at a position that can be controlled by the modulation velocity [457]. The diversity of 3 + 1D STM combinations has been touched upon in works on gravitational analogs using the tools of GR [458] and this approach is currently transposed to electrodynamics and metamaterials by our group [453]. The topic of breaking fundamental bounds of time-invariant systems has been initiated in [459] for pulsed-wave excitations and extensions to continuous-wave excitations and to new bounds are currently being investigated. On the *computational* front, little work has been dedicated to the simulation of STM metamaterials. The resort to Bloch–Floquet expansions is restricted to unbounded periodic structures. Moreover, the inapplicability of efficient

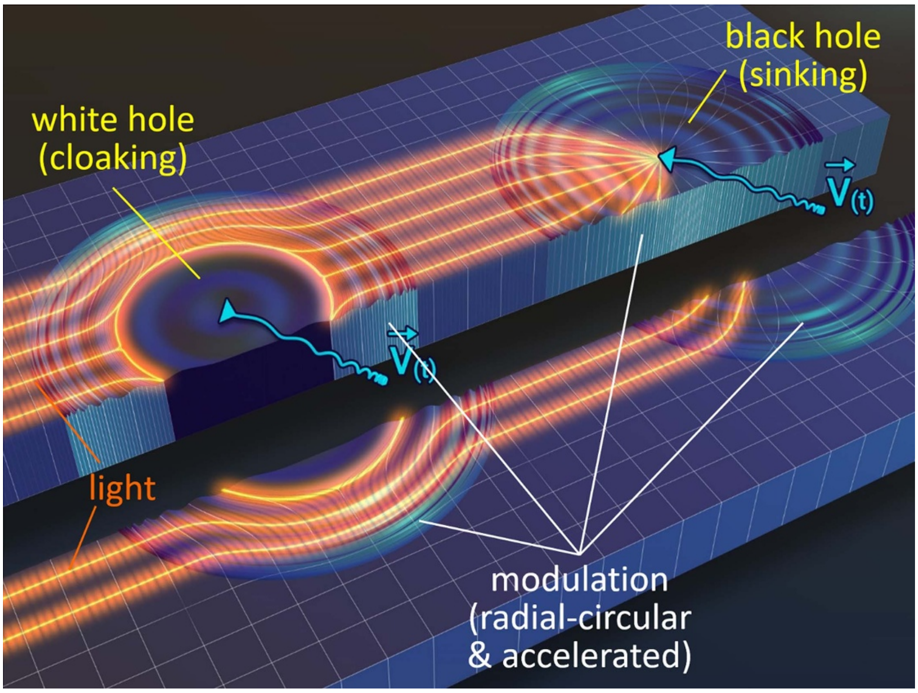

Figure 69. Space-time modulated (STM) metamaterial with two electromagnetic holes curving light.

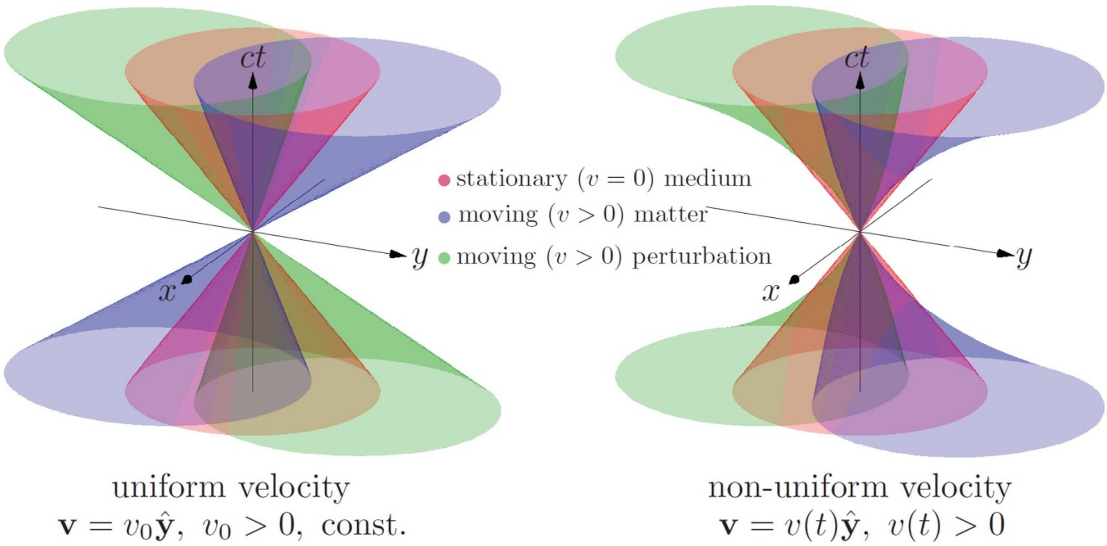

Figure 70. Propagation of light in uniform-velocity and accelerated moving matter and moving perturbation (STM metamaterial).

semi-analytical schemes that split the medium polarizations into fields and constitutive parameters constitutes a real challenge. However, some gravitational physics schemes, such as the 3 + 1D splitting method, might be transposed to STM electrodynamics. *Implementations* have been so far mostly restricted to basic transformations, such as harmonic generation and spatial nonreciprocity, in microwave metasurface platforms, using diodes and varactors for modulation, but more sophisticated STM metasurfaces [460] are under development and optical STM systems with oblique laser fronts modulating dielectric slabs have already been demonstrated. Given the diversity of possible STM metamaterial configurations, the *applications* constitute a smaller challenge than the implementation. Many potential ones have been discussed in [452] and many more will be certainly devised in forthcoming years.

Concluding remarks

STM metamaterials constitute a very rich emerging field of EM science and technology. They include many theoretical and practical challenges, but several research groups are working on them, and their efforts will likely prove rewarding in terms of sustainable scientific and technological advances in electrodynamics. This paper has focused on classical aspects of STM metamaterials, but there is little doubt that STM metamaterials will also contribute to the development of quantum systems and ultra-fast/atto-second physics. In the realm of current metamaterial research, STM metamaterials probably represent the most advanced and promising investigation area.

6.3. Time-modulated metamaterials

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Status

Time-varying media have witnessed a surge of interest in the last decade amidst the quest for magnet-free nonreciprocity, as detailed in another section of this Roadmap. These opportunities have come in conjunction with the rise of interest in highly nonlinear materials and metamaterials, such as 2D materials and multiple quantum wells, opening an unprecedented range of opportunities to extend the metamaterial concepts from the spatial to the temporal and spatio-temporal domains.

Time-varying systems feature different symmetries than static ones, enabling efficient frequency mixing and transformations, as well as energy exchanges between the signal and the modulation network. Many fundamental scattering problems for time-varying media, such as the effect of abrupt switching on frequency conversion, amplification and time-reversal, have been attracting recent investigations. For instance, recent studies analyzed the problem of non-Hermitian switching [461], whereby the resistive properties of a medium are abruptly changed in time, leading to a distinct scattering response compared to their Hermitian counterpart. Another avenue is temporal switching in media featuring an underlying material dispersion, which introduces nontrivial effects on time-scattering processes [462].

Systems featuring periodic modulations of their parameters, termed photonic time-crystals, have also attracted increasing interest. One direction explored within these systems is the one of topological physics. The conventional energy gaps hosting topologically protected edge modes are replaced in photonic time crystals by unstable regimes of parametric amplification (k-gaps), which nevertheless can host temporally localized (transient) states [463]. In addition, the engineering of synthetic frequency dimensions offers a path towards higher-dimensional topological physics [464]. Finally, the metamaterial concept is intertwined with the idea of homogenization, i.e. an effective description of the emergent properties of a material, which accounts for its underlying structure: homogenization studies have recently been carried out for STM metamaterials, which indicate promising avenues for the engineering of giant bianisotropic responses, among many others [10].

Rapid progress was also accomplished on the experimental side, with recent demonstrations of time-reversal and temporal disorder-induced instabilities in water wave systems [465], while in acoustics, the development of digitally controlled meta-atoms promises temporal control for frequency generation and dispersion engineering [466]. In near-infrared optics, time-refraction was recently reported experimentally in indium tin oxide [467], whereas a terahertz experiment demonstrated efficient frequency conversion via ultrafast photocarrier excitation of a GaAs waveguide (figure 71). Here, optical pumping effectively switched the waveguide system from a single-metalized to a double-metalized waveguide, altering its structural dispersion, and producing efficient frequency conversion [468].

Current and future challenges

The many opportunities ahead for time-varying systems are matched by several challenges, both at the level of fundamental and phenomenological aspects, theoretical and numerical techniques, and most notably experimental capabilities.

From the theory side, a comprehensive understanding of wave scattering in complex time-varying structures is still under development. The interplay of temporal modulation with material dispersion, structural dispersion, and their combinations becomes even more challenging when the additional timescale of a finite switching time needs to be accounted for. All these features are generally present in any realistic scenario, since the strong wave–matter interactions required to achieve efficient pumping generally occur near resonances.

In addition, the interplay between transient modulations and periodic ones places rather formidable challenges: the Fourier methods for periodic structures which the metamaterials community inherited from solid state physics are often insufficient to model realistic systems such as ENZ materials in the presence of a

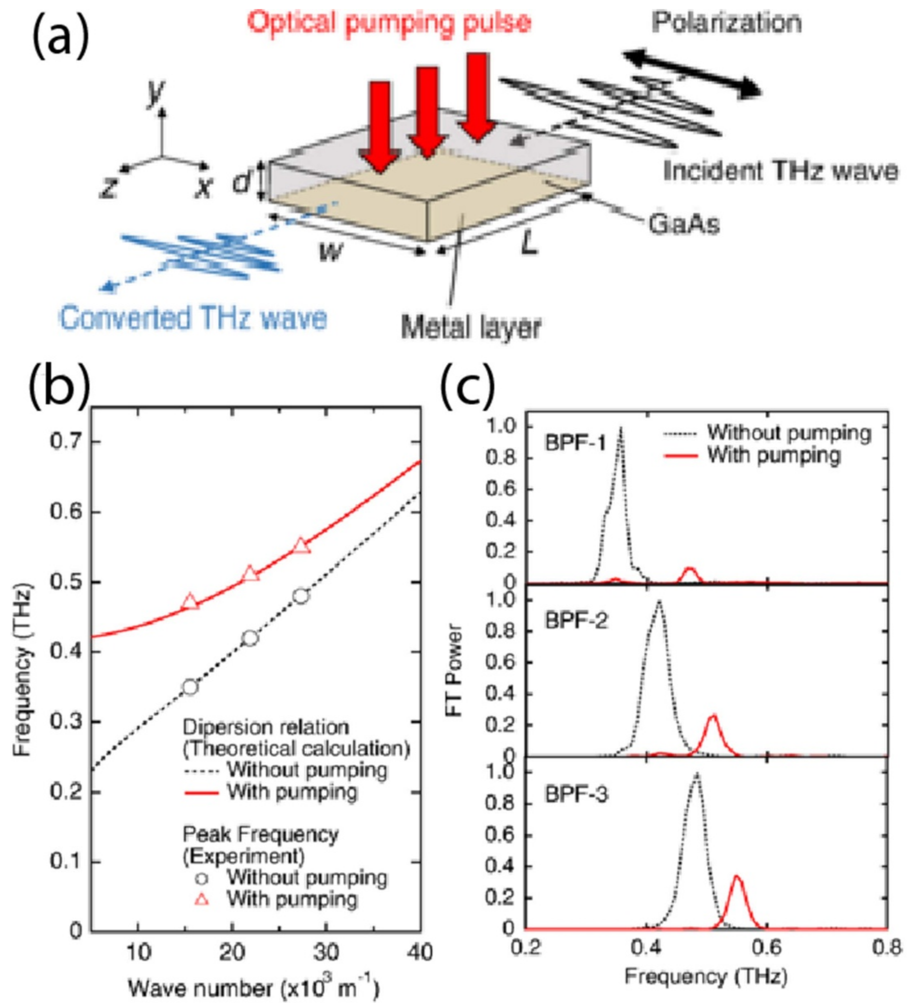

Figure 71. (a) Frequency conversion induced by photocarrier excitation at the surface of a GaAs slab. The photoexcitation effectively produces an additional metallic layer at subpicosecond timescales, thereby switching the dispersion of the mode ((b), from the black line to the red line), which results in a frequency shift (c) Reprinted with permission from [468], Copyright (2021) by the American Physical Society.

strong pump, where transient modulations are typically stronger than periodic ones, and can have sizable spectral effects on a probe beam. On the other hand, adiabatic methods have very limited accuracy when significant spectral shifts are involved. Adding to the challenge, the development of effective descriptions for the pumping mechanisms responsible for temporal modulations of typical highly nonlinear materials such as indium tin oxide, lithium niobate and aluminum zinc oxide will be crucial in the coming years, as off-the-shelf material models will be needed to match theoretical predictions based on macroscopic electrodynamics with experimental results.

Experimentally, ENZ materials have undeniably opened unprecedented opportunities for ultrafast switching and frequency conversion due to their strong nonlinearities. However, the key challenge remains the trade-off between modulation speed and modulation strength. Whilst the speed of material modulation does not, per se, affect the extent of frequency conversion, a wave needs to be propagating through the modulated medium in order to experience such a shift. Therefore, a slow modulation would have to be applied to a bulk medium, in order to observe sizable spectral effects. Even in acoustics and RF, effective material response speeds can pose serious challenges: even if optical pulses may be used for acoustic modulation in certain optomechanical setups, or varactors may be deployed in RF, the introduction of external pumps and nonlinear elements conspires to yield highly dispersive effects, as well as potential instabilities which may pose limitations on the speed at which a sizable modulation may be imparted. These limitations are important, as they generally prevent time-reversal and non-trivial temporal scattering between discrete modes in a structure.

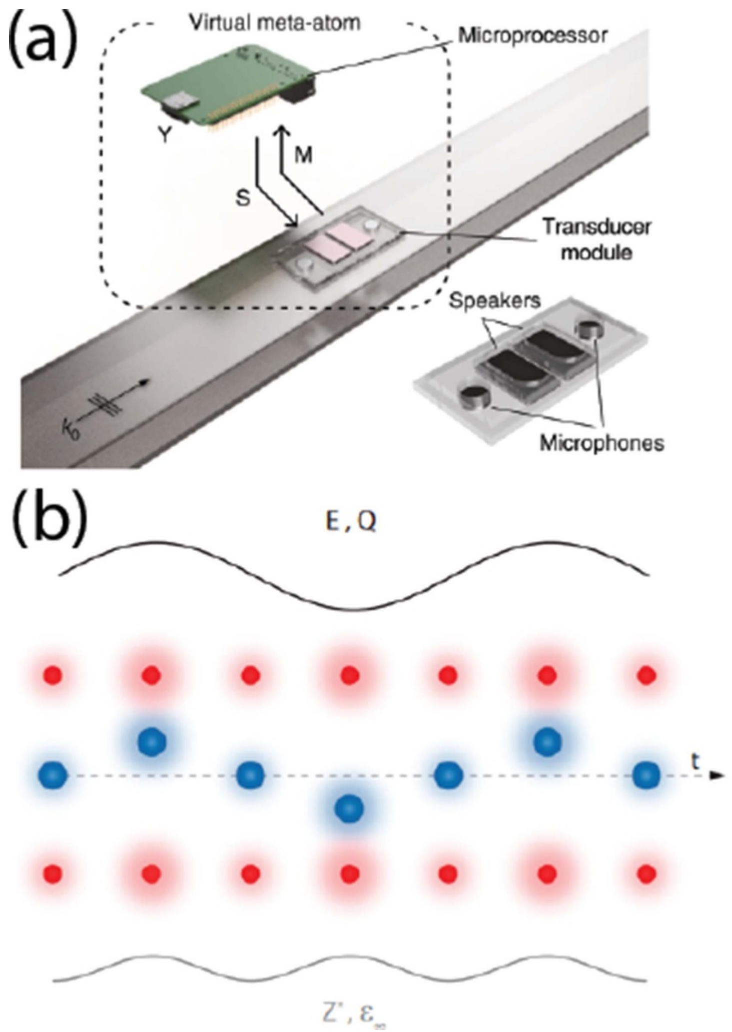

Figure 72. (a) Illustration of a digitally virtualized acoustic meta-atom comprising microphones and speakers connected to a microprocessor to design its active response. The meta-atoms were fitted into an acoustic waveguide to tailor its dispersion profile. Reproduced from [466]. CC BY 4.0. (b) Concept of phonon-mediated parametric amplification of light: the pump field E produces oscillations Q in a diatomic lattice at the same pumping frequency (top black line). However, the quadratic dependence of the induced charges produces an oscillation of the material permittivity in time at twice the pumping frequency (bottom black line). This can couple forward and backward optical waves of the same frequency, which produces parametric gain. Reproduced from [469]. CC BY 4.0. Nondegenerate versions of such an experiment could lead to a vast range of time-varying effects.

Advances in science and technology to meet challenges

From the theory side, novel analytic, semi-analytic and numerical methods are needed to incorporate the relevant time-varying physics into commonly studied metamaterial geometries such as waveguides, slabs and resonators. Ideally, one might want to first solve a structure in space, and then incorporate the effects resulting from temporal variations into the scattering parameters of the structure, while capturing any resulting frequency shifts. However, it is still to be determined whether such a two-step strategy would capture all of the physics involved, and what the limitations of such a model would be. Furthermore, multi-scale analysis might be necessary, in order to account for both the fast modulation responsible for effects such as four-wave mixing and the slower, larger transient phenomena associated with electron heating.

Multi-scale modeling will also play a key role in incorporating the effects of underlying material dynamics in pump-probe scenarios into a set of effective time-dependent parameters that describe the macroscopic electrodynamics of a time-modulated material. In this context new bridges may need to be established between non-equilibrium condensed matter physics and metamaterial science, forming a potential furnace for completely novel ideas and directions.

From the experimental side, recent progress has been made in acoustics to achieve complete control of material parameters by introducing digitally virtualized meta-atoms comprising microphones, speakers and an internal processor, which can be programmed to produce effectively any desired material response in time, at kHz frequencies (figure 72(a)) [467].

On the other hand, optics implementations still present formidable challenges (and equally great opportunities): firstly, rigorous experimental studies on the fundamental speed limits for nonlinear pumping in ENZ materials are still in the making, and probing them might require pumping at extremely high intensities. A promising route to achieve strong modulation efficiencies is offered by polaritonic media, with phonon and exciton polaritons having recently gained a spotlight in the nanophotonics scene thanks to their longer lifetimes compared to SPs. Recent results in silicon carbide have highlighted (even without any structurally enhanced resonances) the potential of exploiting such material resonances for parametric amplification (figures 72(b) and (c)) [469]. In order to extend the interaction times to enable efficient frequency conversion, while allowing for efficient pumping strategies, it is undoubtable that metasurfaces will play a key role in the future and might open new horizons to achieve more efficient nonlinear wave–matter coupling. Finally, the implementation of many ideas in time-varying media generally requires the use of non-degenerate pump-probe setups, which poses a few technological and implementation challenges.

Concluding remarks

Time-modulation embodies a new paradigm for metamaterials, introducing a new DOF for wave control. This paradigm effectively brings together ideas from plasma physics, non-equilibrium systems and nonlinear optics, much like the very field of metamaterials stemmed from a convergence between optics, solid state physics and microwave engineering. From this angle, we expect this rising field to play a dominant role in the next decade of wave science and metamaterials.

New theoretical challenges must be met in order to efficiently and accurately model the multiple temporal and spatial scales involved in the temporal material response exhibited by highly nonlinear media and even tunable RF and acoustic components, with much of the related phenomenology still under development.

It is also undeniable that the full blossoming of this area, particularly in optics and EMs, will be highly contingent on the further development of current experimental capabilities, as well as the discovery of new material platforms and techniques. In the next stage, a clear way forward appears to be indicated by polaritonics, and its deployment for next-generation nonlinear optics will likely form a cornerstone of future progress in photonic time-varying metamaterials.

Acknowledgments

E G acknowledges funding from the Simons Foundation (855344, E G). P A H acknowledges funding from Fundação para a Ciencia e a Tecnologia and Instituto de Telecomunicações under Project UIDB/50008/2020 as well as from the Spanish Ministry of Science and Innovation through the Ramón y Cajal program (Grant No. RYC2021-031568-I), through Project No. PID2022-141036NA-I00 financed by MCIN/AEI/10.13039/501100011033 and FSE+) and from the María de Maeztu Programme for Units of Excellence in R&D (Grant No. CEX2018-000805-M). A A's work on these topics is supported by the Department of Defense and the Simons Foundation. J B P acknowledges funding from the Gordon and Betty Moore Foundation.

6.4. Time-domain digital coding metasurfaces

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Status

The digital coding metasurface is an important branch of the metasurface family, whose EM properties can be programmed and reconfigured in real time by controlling the amplitude or phase states of the internal subwavelength meta-atoms [8, 470]. With the aid of the tunable devices or materials incorporated within the meta-atoms such as the diodes, MEMS switches, graphenes or liquid crystals, it is feasible to achieve finite amplitude/phase states as we change the biasing voltages, and represent them in custom codes [471–473]. As a result, the whole metasurface can be described with a dynamic coding sequence to indicate all the working status of the meta-atoms. Extensive studies suggest that, despite the tiny amplitude or phase quantization error, the digital coding metasurface have manifested itself as a powerful and efficient tool to engineer the wavefront during the wave–matter interactions. The design complexity of the metasurface is significantly reduced owing to the new architecture, since the puzzle of entire performance optimization where millions of element dimensions should be considered simultaneously, evolves into a simple code optimization problem. In addition, the consise architecture also leads to the dramatic simplification of the feeding and controlling network, making it easy to be integrated to the external digital signal processors [388, 474–476]. Since the amplitude/phase state varies according to the meta-atom position for this metasurface, it is actually a type of space domain digital coding metasurface (SDDCM).

Although the SDDCM have demonstrated outstanding capability of the amplitude, phase or even polarization modulation upon the incident EM field, the spectral modulation remains a significant challenge due to the weak nonlinear properties from the meta-atoms. This is due to the fact that the average dwell time of each working state corresponding to specific coding sequence of the metasurface, is much longer than the switching time between adjacent states. Consequently, the transient effects originating from the state switching can be neglected in this case, which hinders the nonlinear applications such as second-harmonic generation, third-harmonic generation and four-wave mixing [477]. One possible route to enhance the material nonlinearity lies in the optimization of the element symmetry, orientation and the coupling among neighboring meta-atoms, but the conversion efficiency from the fundamental harmonic to high order harmonics still need to be further improved [211, 478].

To circumvent this problem, it is important to reexamine the transient behaviors if the dwell time and the switching time are kept in the same order. Specifically, when the reflection/transmission coefficients of the metasurface are varied rapidly and periodically, it is revealed that, the material nonlinearity is greatly enhanced [388, 474–476]. This can be understood from the Fourier series expansion of the reflection/transmission function. Consequently, a bunch of high order harmonics will be generated. The coding strategy of the time domain digital coding metasurface (TDDCM) is distinct from that of the traditional SDDCM, in which the two working states ('0' state and '1' state) are changed quickly and alternatively for the digital metasurface in a periodic manner, as shown in figure 73(a). Under the excitation of monochromatic wave (fundamental harmonic in figure 73(b)), several high order harmonics will be produced for the echo wave from the time-varying metasurface, and the fundamental harmonic can be perfectly cancelled out (figure 73(c)) [476]. Such excellent property can greatly benefit the applications such as the wireless communication, velocity illusion and frequency cloaking (figure 74(a)). Figure 74(b) shows the design of a microwave TDDCM. The effective capacitance of varactor diode embedded within the meta-atom can be tuned continuously by the biasing voltage, leading to the required time-varying phase response for the whole metasurface.

Current and future challenges

Although the nonlinear spectral modulation can be implemented by the TDDCM, the conversion efficiency from the fundamental harmonic to the desired order harmonic is a critical issue to confront. In addition, in some application scenarios such as wireless communication and radar detection, a plenty of harmonics need to be employed simultaneously. But the independent amplitude and phase control for the multiple harmonics are very difficult at present. At last, the frequency interval between neighboring harmonics is usually below 100 MHz due to the limit of the control circuit, which should be further improved in the future.

Advances in science and technology to meet challenges

A possible route to enhance the nonlinear conversion efficiency is to optimize the periodic phase modulation waveform of the metasurface. Actually in order to get the *n*th order harmonic at f_n, the slope of the phase curve should be linear according to the integral relationship between phase and frequency. Considering the

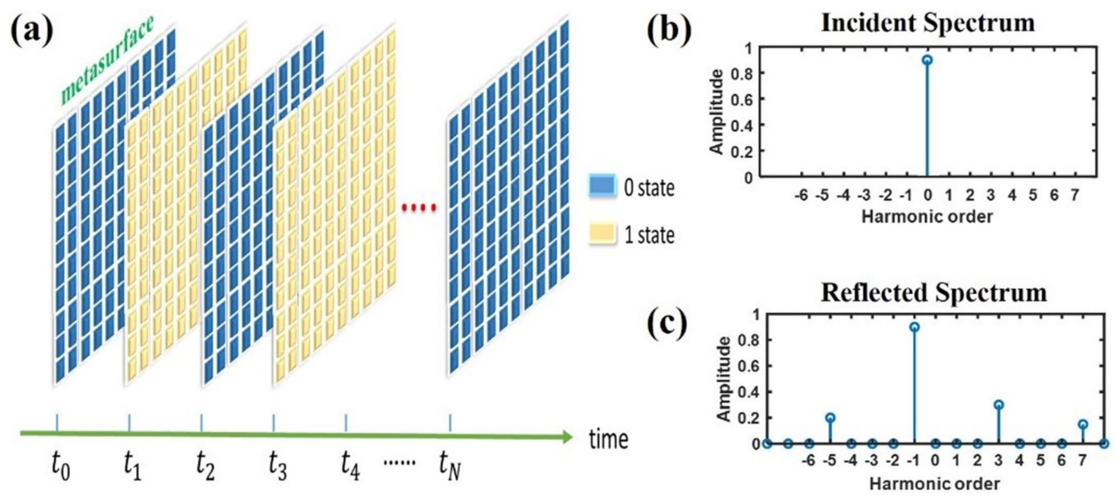

Figure 73. (a) Periodic coding strategy of the digital metasurface in time domain to enhance the material nonlinearity and enable spectral modulation. The working states of the meta-atoms are changed quickly and alternatively in a periodic manner between the '0' state and '1' state. (b), (c) Incident and reflected spectrum of the plane wave during the wave–matter interaction.

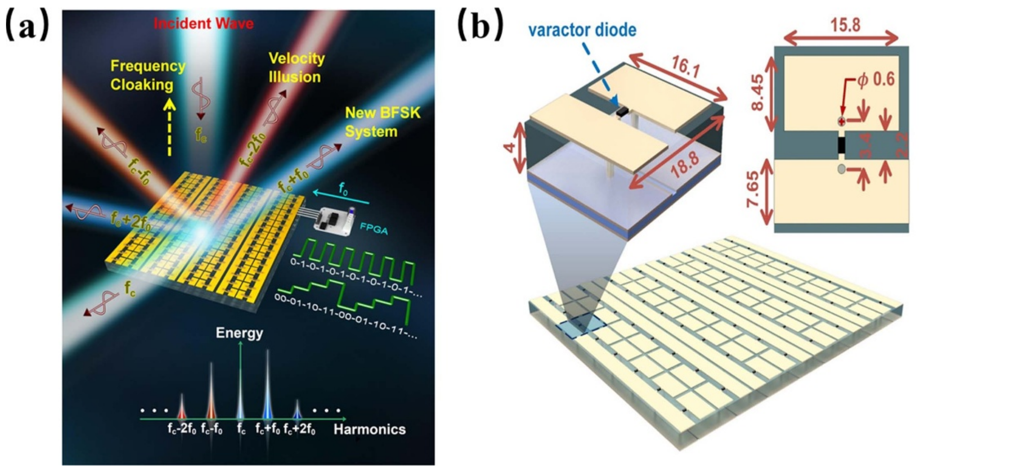

Figure 74. (a) Schematic of the TDDCM for harmonic generation for nonlinear applications. (b) Structure of the met-atom and the TDDCM. Reproduced from [388]. CC BY 4.0.

phase quantization for the digital coding metasurface, it is more suitable to employ multi-bit metasurface to suppress the undesired harmonics. The independent control of the multiple harmonics can be obtained by carefully devising the coding strategy in time domain, which is helpful to remove the constraint relation between the amplitude and phase of each harmonic, and implement wavefront manipulations separately. The control circuit that is used to provide necessary biasing voltages on the tunable devices in the meta-atoms, is an important factor to determine the frequency offset between the incident and reflected waves, because the biasing waveforms are usually rectangular pulses, and the rising and falling edges are inversely proportional to the frequency offset. Therefore, it is essential to improve the circuit performance with faster speed and larger voltage range.

Concluding remarks

In summary, the time domain metasurface offers a new approach for harmonic generation, which no longer rely on the nonlinearity of natural materials. The nonlinear manipulation can be programmed with various coding schemes, which enables accurate control of multiple harmonics simultaneously.

Acknowledgments

This work is supported by the National Key Research and Development Program of China (2018YFA0701904, 2017YFA0700201, 2017YFA0700202 and 2017YFA0700203), the National Natural Science Foundation of China (61731010 and 62288101).

6.5. Space-time-coding (STC) digital metasurfaces

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Status

Space-time and time-varying metamaterials have gained a growing attention in the last few years, and have become one of the most fascinating research directions in the fields of EMs and physics. Time-varying metamaterials are characterized by time-modulated constitutive parameters, which can be combined with spatial modulations within the emerging paradigm of space-time metamaterials. The constitutive parameters of these structures, such as permittivity, impedance, and conductivity, are spatially and temporally variant. In recent years, space-time and time-varying metamaterials have been intensively studied to realize many novel physical phenomena and applications [479, 480]. However, since most of these structures rely on continuous parametric modulation, which can be considered as the 'analog modulation', it is difficult to implement at the hardware level. Therefore, current works on analog-type space-time metamaterials are mostly based on theoretical or numerical research, which hinders practical applications to a certain extent.

As an important branch of metamaterials, digital coding and PMSs have been extensively studied to manipulate EM waves by simply changing the coding sequences in a discretized manner [480]. Digital metasurfaces rely on relatively simple hardware architectures to realize a 'digital modulation', and are very suitable for the implementation of spatiotemporal modulations and for overcoming the application limitations of traditional space-time metamaterials. In the early studies of digital metasurfaces, their coding schemes were only implemented in the spatial dimension, resulting in space-domain-coding digital metasurfaces, which could control the spatial characteristic of EM waves. Afterwards, time-domain-coding (TDC) digital metasurfaces were proposed to control the spectral properties of EM waves by extending the coding method to the temporal dimension.

In 2018, Zhang *et al* originally proposed the concept of STC digital metasurfaces by jointly encoding the constitutive parameters (e.g. amplitudes and/or phases) in both the space and time domains [11]. STC digital metasurfaces can simultaneously control the spatial and spectral characteristic of EM waves, i.e. they can manipulate the propagation directions in the space domain and the spectral distributions in the frequency domain, which can be further applied to beam steering and shaping [11, 391], scattering-signature control [11], multi-bit programmable phases [481], nonreciprocity [482], harmonic manipulations [476, 483], analog computation [411] and wireless communications [401], etc.

Current and future challenges

STC digital metasurfaces provide a versatile and powerful platform to perform spatiotemporal modulation, which allows precise control of EM waves in multiple dimensions of time, space and frequency with a simple hardware architecture. Figure 75(a) shows a conceptual illustration of a STC digital metasurface [11], where each programmable element is integrated with PIN diodes and is temporally switched with a periodic time-coding sequence according to a 3D STC matrix. By applying different control signals via a FPGA, time-coding sequences and the spatial coding distribution of the STC digital metasurface can be suitably designed to attain a specific functionality.

For instance, a representative application enabled by STC digital metasurfaces is 'harmonic beam steering', i.e. the steering of given harmonic orders toward desired directions. Figure 75(b) displays an optimized STC matrix for 1D steering, whereas figure 75(c) shows the corresponding scattering patterns, from which one can see that the main beams at different frequencies point to different directions with uniform power levels.

Although STC digital metasurfaces have been investigated in depth for many applications, there are some challenges and limitations on this field [480]. The design of the STC matrix to achieve different functionalities is a key aspect of a STC digital metasurface, and a crucial challenge is how to efficiently address this synthesis in real-world scenarios. Another critical challenge is to increase the modulation speed, especially for applications to wireless communications, imaging and radar.

Advances in science and technology to meet challenges

STC digital metasurfaces enable powerful control capabilities of wave manipulation and information processing. One of their most exciting and promising applications is the construction of new-architecture wireless communication systems [480]. Some simplified-architecture transmitters and systems based on TDC digital metasurfaces have been proposed to realize modulation schemes such as BFSK, QPSK and

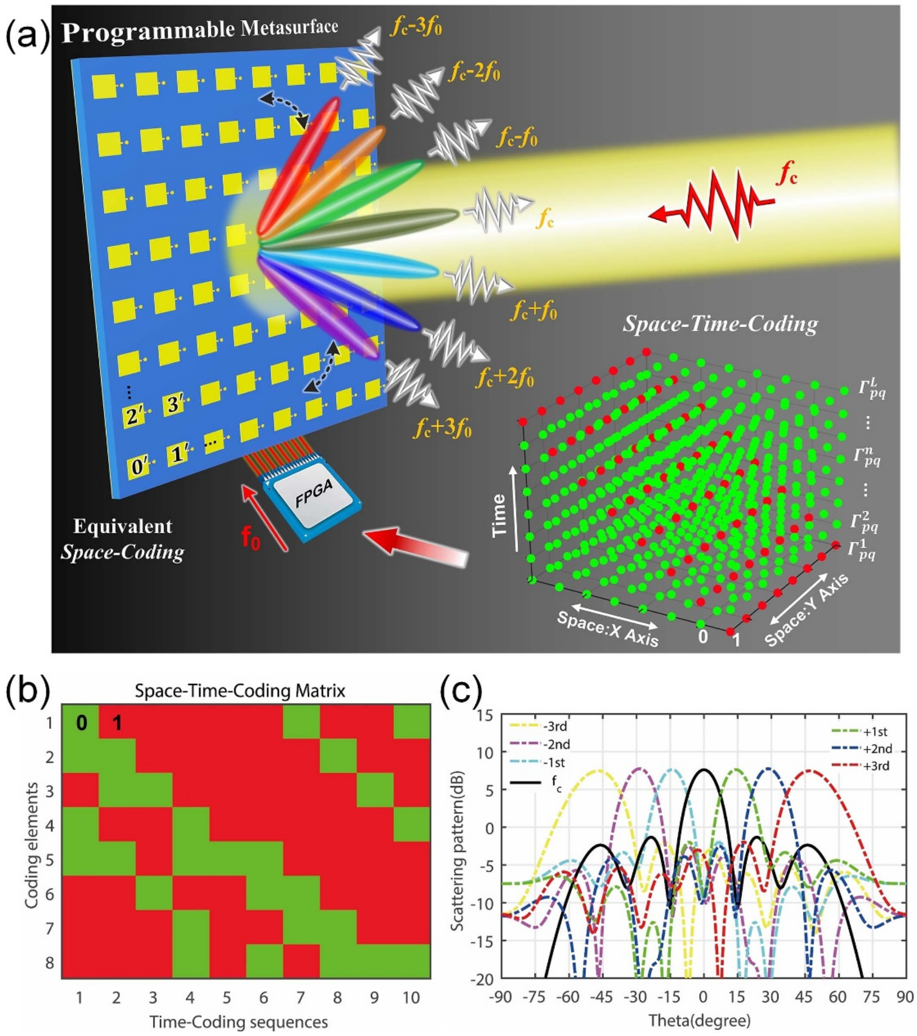

Figure 75. (a) Conceptual illustration of a STC digital metasurface. (b) An optimized space-time-coding matrix. (c) Corresponding scattering patterns of harmonic beam steering. Reproduced from [11]. CC BY 4.0.

quadrature amplitude modulation (16QAM), but these systems can only transmit the same information to users located at different spatial directions due to the lack of space modulation.

By judiciously designing the STC matrix through optimization algorithms, digital information can be encoded and processed in the multi-dimensional domain simultaneously. As previously mentioned, STC digital metasurfaces have the capability of controlling EM waves in both space and frequency dimensions [11], hence they are especially suited to perform space- and frequency division multiplexing, which are widely used in wireless communications to improve the channel capacity. Figure 76(a) shows the conceptual illustration of space- and frequency-division multiplexing wireless communication based on a STC digital metasurface [401], in which different information can be directly transmitted to target users independently and simultaneously. With the aid of a binary particle-swarm optimization algorithm, a new information encoding scheme was proposed to realize this multiplexing technique [401]. Each user has a specific frequency assigned to establish its independent channel, and the mutual interference among different users is rather low. For experimental verification, a dual-channel wireless communication system with space- and frequency-division multiplexing was built to transmit two different color photos to two users, as shown in figure 76(b). To further realize multi-user wireless communications, machine learning algorithms can also be exploited to design the STC matrix.

Playing the role of both energy radiator and information modulator, STC digital metasurfaces provide a low-cost, simple-structured solution for realizing multiplexed wireless communications, enabling direct data transmission without the requirement for antenna arrays and traditional radio-frequency modules. This application of multiplexed wireless communication demonstrates the power of STC digital metasurfaces very well, which has important applications in the future 6G wireless communication and novel radar, imaging systems.

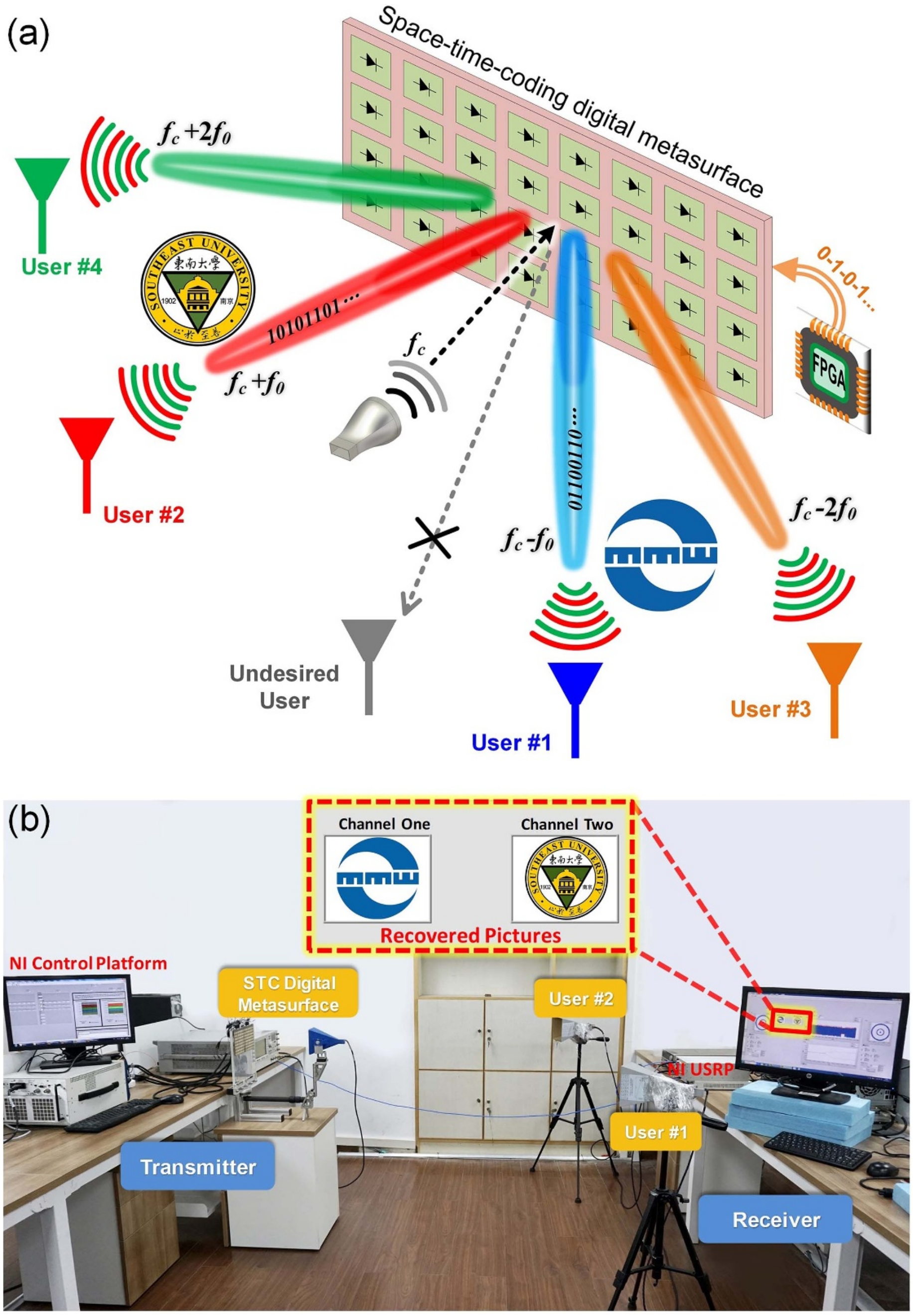

Figure 76. (a) Conceptual illustration of space- and frequency-division multiplexing wireless communication based on a STC digital metasurface. (b) Photograph of a dual-channel wireless communication system. Reproduced from [401], with permission from Springer Nature.

Concluding remarks

STC digital metasurfaces significantly extend the application range of conventional metasurfaces, paving the way for advanced wave manipulations in the multi-dimensional domain and promising new advances in physics, EM and information science. Although some great challenges and limitations still exist in this field, we expect these challenges to be the driving force for rapid developments in this direction, ultimately making STC digital metasurfaces powerful hardware platforms for next-generation intelligent and cognitive information systems.

Acknowledgments

This work was supported by the National Postdoctoral Program for Innovative Talents (BX2021062), the National Natural Science Foundation of China (62101123 and 62288101), the China Postdoctoral Science Foundation (2020M680062) and the Jiangsu Planned Projects for Postdoctoral Research Funds (2021K058A).

6.6. Programmable nonreciprocity via space-time metasurfaces

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Status

Reciprocity is a pervasive property in many branches of physics, ranging from EMs to thermodynamics, which, loosely speaking, implies the possibility to exchange the source(s) and detector(s) in a system without altering the received-transmitted field ratios. With reference to EM scenarios, of specific interest here, the reader is referred to [484] for a comprehensive overview.

In a reciprocal EM scenario, a wave and its time-reversed version experience the same (reflection, refraction, absorption) responses, which implies fundamental limitations in many engineering applications. For instance, in wireless communication systems, a reciprocal antenna that radiates a highly directive beam is bound to receiving its reflected echo. Likewise, strong absorbers are bound to be very good emitters within the same frequency range, thereby curtailing the efficiency of energy-harvesting and thermal-management systems [485].

To lift these limitations, the quest to *break* reciprocity has been of longstanding interest in EM engineering. At microwave frequencies, nonreciprocal effects can be attained by breaking the time-reversal symmetry via biased magnetic materials such as ferrites. However, these devices tend to be bulky, expensive, and difficult to integrate and scale up at higher frequencies. Alternative *magnetless* approaches typically rely on *nonlinear* materials, transistor-based devices or moving media, which also exhibit limitations in terms of power-dependence, signal intensity, and operating frequency. Thanks to the recent advances in dynamically tunable metasurfaces, approaches based on spatio-temporal modulation are becoming an attractive in terms of size, cost, and integrability.

The basic physical principle is illustrated in figure 77 [486]. The metasurface ideally imparts on the impinging wavefront a space-time phase gradient which induces an anomalous reflection exhibiting both an angular-frequency ($\Delta\omega$) and wavenumber (Δk) shift (figure 77(a)). Accordingly, by considering the time-reversal channel (figure 77(b)), the reflected beam will not follow the original forward-incidence channel, but it will instead exhibit an angular-frequency ($2\Delta\omega$) and wavenumber ($2\Delta k$) shift, thereby realizing frequency and angular isolation. Figure 77(c) illustrates a possible implementation based on the concept of 'digital-coding metasurfaces' [482], where the required space-time phase gradient is realized in a quantized, *programmable* form by means of reconfigurable 'meta-atoms' featuring PIN diodes controlled by a FPGA. Figure 78 illustrates the experimental results obtained with a prototype working at X-band microwave frequencies.

Conceptually similar approaches have been demonstrated at C-band microwave frequencies [487, 488], and implementations at optical frequencies have been realized via travelling-wave modulation of nonlinear Kerr building blocks [489].

Current and future challenges

Among the most promising applications of the above-described nonreciprocal platforms, it is worth mentioning the field of 'reconfigurable intelligent surfaces' (RISs), which is emerging as a viable paradigm for the transition of mobile-network technologies from 5th to 6th generation. In the envisaged scenario, RIS platforms are to be integrated in a wireless propagation environment (e.g. on walls, windows, furniture) so as to transform it into a *smart* space that can be reconfigured 'on the fly' in order to optimize suitable communication metrics (see, e.g. [490], for a recent roadmap).

Within this broad framework, space-time metasurfaces could provide advanced, programmable field-manipulation capabilities without the need of excessive decoding, encoding, and radio-frequency processing blocks, also enabling software-defined, self-adaptive, and cognitive functionalities. In particular, nonreciprocal operations could be attained 'on demand', so as to synthesize different beam patterns for the transmitting and receiving states, thereby enabling *full-duplex* operations.

However, space-time metasurface platforms are still in their infancy, and a series of challenges must be addressed to fully unlock their potentials. From the modeling side, while simple semi-analytical, time-domain 'adiabatic' approaches [482] can capture the basic physical effects, more accurate predictions are needed for successful integration in complex communication environments. In this context, especially critical is the modeling of the switching elements, biasing lines, and inter-element coupling effects. Moreover, while proof-of-principle nonreciprocal effects can be intuitively designed via simple space-time phase gradients [482], significantly more sophisticated design approaches need to be developed for high-efficiency,

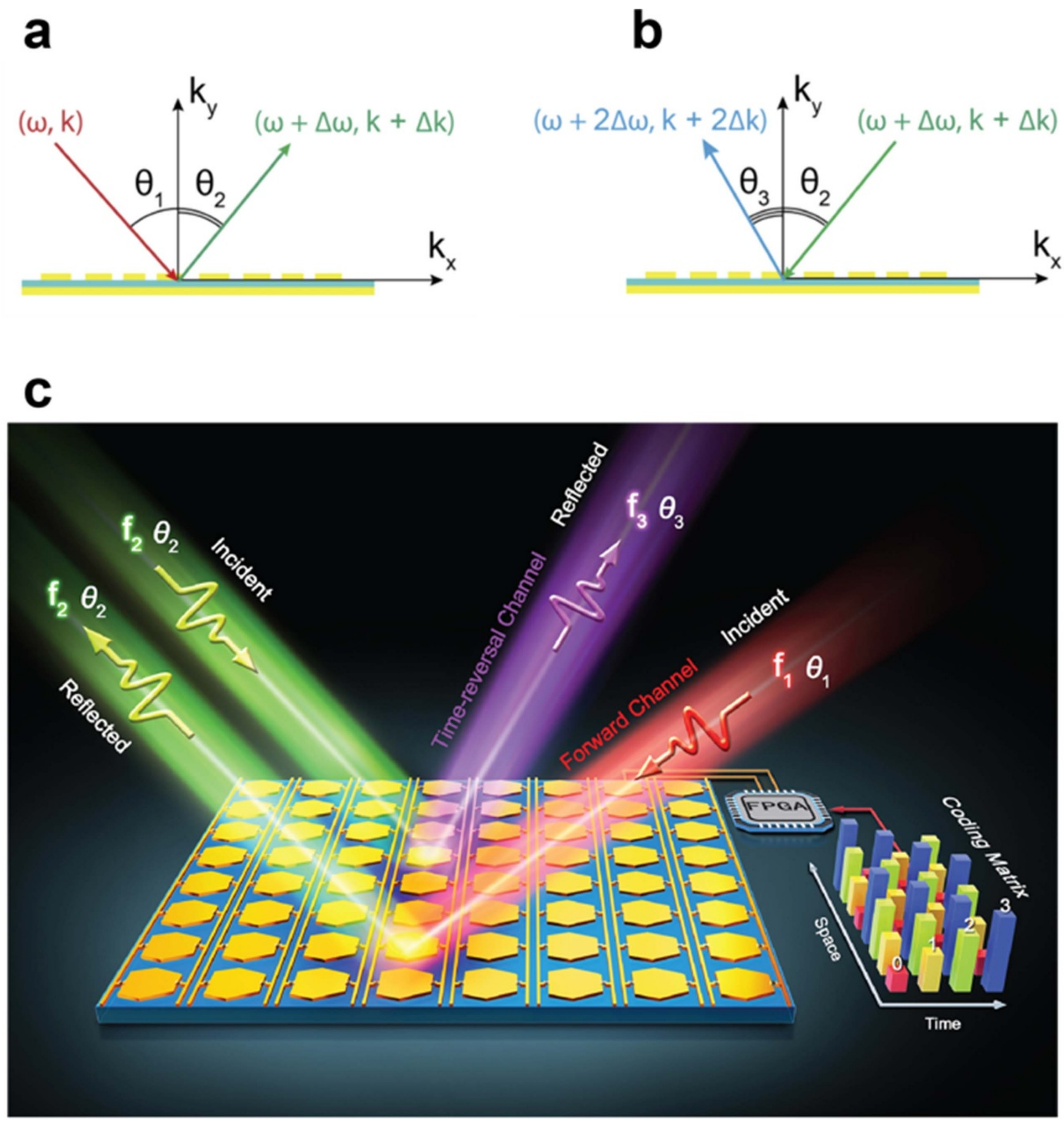

Figure 77. (a), (b) Conceptual illustration of a nonreciprocal reflection (forward and time-reversed channels, respectively) implemented via an ideal space-time gradient metasurface. Reproduced from [486]. CC BY 4.0. (c) Schematic of a programmable implementation based on a space-time coding digital metasurface. [482] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

full-duplex operations in realistic scenarios. From the implementation viewpoint, it should also be mentioned that implementing the actual independent control of the individual metasurface elements is quite challenging, and has been simplified via common (e.g. column) biasing in experimental prototypes [482]. From the technological viewpoint, perhaps the most crucial challenge is the implementation of *faster* switching schemes, so as to enable higher modulation frequencies. While the reliance on PIN diodes allowed a relatively simple proof-of-principle implementation [482], it also implied some strong limitations in the angular separation between the forward-incidence and time-reversal channels (see figure 78). Overall, PIN diodes are inherently limited to switching rates of hundreds of MHz, which are clearly insufficient for operating at mmWave/subTHz frequencies of interest for 6th generation communication systems [490].

Further developments and improvements (e.g. in terms of efficiency and programmability) are also expected for optical-frequency implementations which, besides the communications scenario, may also find important applications to energy harvesting and heat management.

Advances in science and technology to meet challenges

As previously mentioned, more accurate EM modeling approaches need to be pursued. While a full-wave time-domain modeling of the entire platform is likely to become computationally unaffordable in realistic scenarios of interest, more viable approaches could rely on clever blends of full-wave (unit-cell), circuit-type

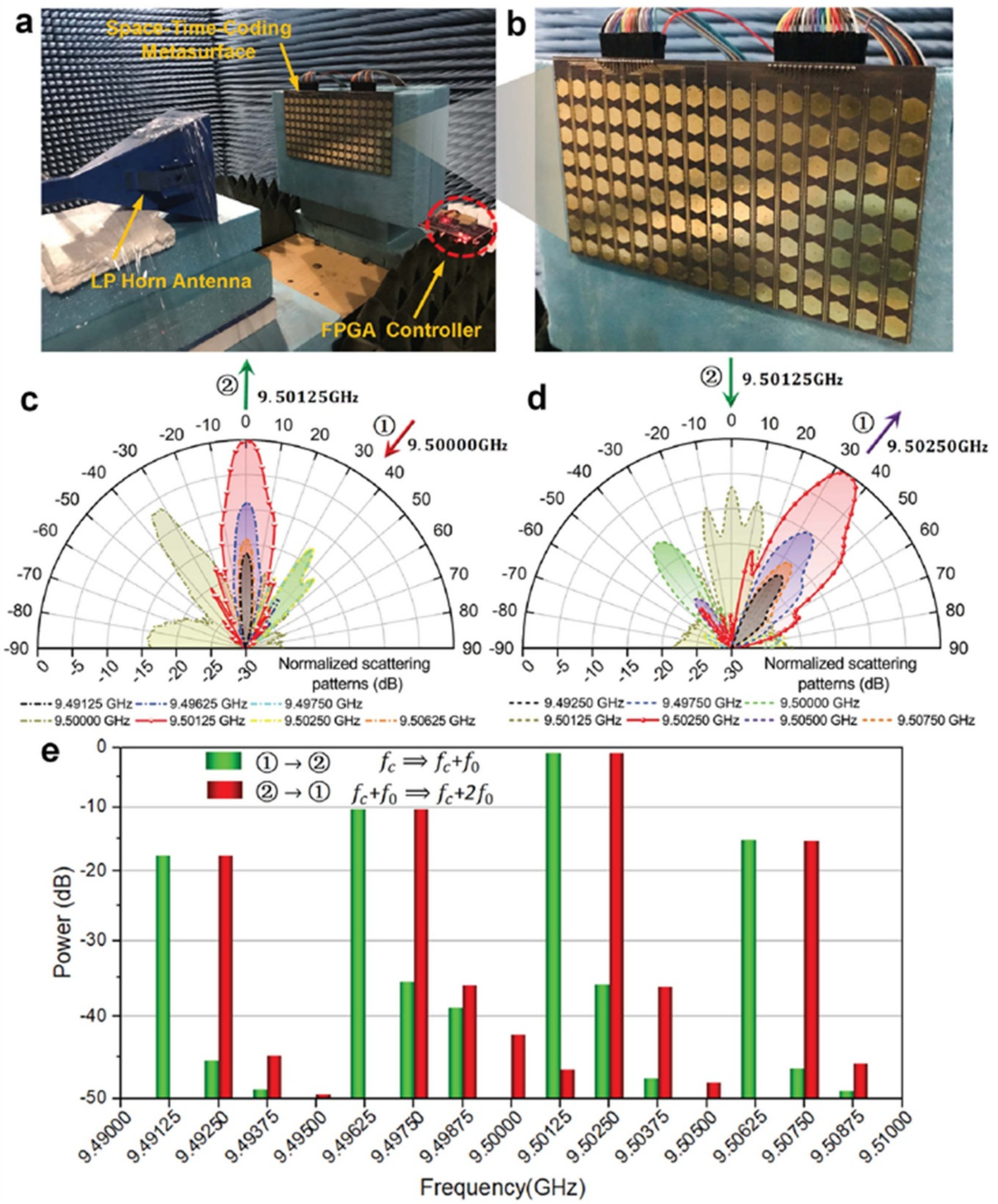

Figure 78. Experimental results pertaining to the implementation in figure 77(c). [482] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (a), (b) Photographs of the measurement setup and fabricated prototype, respectively. (c), (d) Measured scattering patterns at different harmonic frequencies, for the forward and time-reversal scenarios, respectively. (e) Comparison between measured spectral power distributions pertaining to the forward (green bars) and time-reversal (red bars) scenarios. f_c and f_0 denote the center and modulation frequency, respectively.

(e.g. PSpice), and semi-analytical (e.g. ray-based) models, to account for inter-element coupling, biasing lines and loading effects of the active elements.

From the design viewpoint, the application of AI- and machine-learning-powered approaches is becoming increasingly popular in the RIS research community for the channel optimization [490], but it remains largely unexplored for nonreciprocal platforms based on space-time metasurfaces. For instance, via more sophisticated space-time modulations (rather simple gradients), it should be possible to synthesize desired (different) beam-shaping effects (rather than simple steering) for the transmitting and receiving states. Ideally, these optimization approaches should not only be restricted to the conceptual (i.e. phase-distribution/coding) design, but they should be extended to the physical-layer design (via suitable integration with the above EM models) in order to consistently account upfront for the inherent physical limitations.

In connection with the need for faster modulation schemes, there are several potential developments foreseeable in the technology of dynamic tunable metasurfaces capable of operating up to subTHz frequencies (see, e.g. [491], for a recent review). Conventional schemes rely on the integration of semiconductors (Schottky junctions, GaAs, InAs) with either electrical or photo-induced control, and can reach switch-on times of 20 ps. Alternative schemes, based on high-electron-mobility transistors have been proven to reach modulation speeds of few GHz. Finally, 2D materials (such as graphene, hexagonal boron nitride, transition metal dichalcogenides, and black phosphorus) and phase-change materials (such as vanadium dioxide) are also very promising candidates that can potentially reach very fast modulation speeds. Within this framework, while proof-of-concept demonstrations are available, further experimental evidence is needed on realistic, PMS platforms of practical interest.

For applications to optical frequencies, alternative nonlinear materials (such as indium tin oxide) could be utilized to increase the dynamic phase modulation depth. Recently, this concept was theoretically explored to design arrays of time-modulated nanoantennas operating in the near-infrared frequency range by means of gate biasing with radio-frequency signals [492]. While experimental evidence is needed, this represents a promising candidate platform for full-duplex optical communications.

Concluding remarks

To sum up, we have attempted a compact overview of recent advances, challenges and perspectives in the field of space-time metasurfaces for programmable nonreciprocity, with special emphasis on implementations based on digital coding metasurfaces. Overall, these platforms look very promising for advanced wavefront manipulations enabling full-duplex communications, and are expected to play a key role in RIS-type application scenarios for next-generation wireless networks. Moreover, they may also open up new perspectives in energy-harvesting and thermal-management scenarios. Within this framework, we have also highlighted some critical limitations (in terms of modeling, design, and technological aspects) that are expected to be overcome by near-future developments.

6.7. New-architecture wireless communication systems

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Status

Owing to the superiorities of low loss, ultrathin thickness, and easy fabrication, metasurfaces have undergone fast developments in EM wave control over the past decade, leading to a variety of interesting phenomena, novel devices, and promising applications [493]. As one of the emerging concepts in recent years, researchers have been working on developing practical implementations of metasurface to demonstrate its potential in related areas. Especially in recent years, metasurface has attracted much attention in the field of wireless communication from both academy and industry. Some notions have been proposed to descript its unique capability of EM wave manipulations, such as RIS [494] and IRS [495], which are considered to play an important role in the next-generation mobile communication technologies. One of the most attractive features of metasurface for wireless communications lies in the dynamic controllability of EM waves. It opens up a new way for manual control of the wireless channels and even direct modulation of the information, thereby constructing a new architecture of wireless communication system [388]. This kind of new-architecture system enables information modulations and transmissions without using the traditional RF components, which is believed to be low-cost, power-saving, and high-integrated.

Figure 79(a) displays the block diagram of this system, in which the incident wave and control signal of the metasurface can be regarded as the local oscillator and baseband signals in traditional wireless communication systems, respectively. In this way, as long as the mapping relationship between the bit stream and the control signal is established properly, the digital information can be modulated on the carrier wave and propagated in free space. Based on this framework, several proof-of-concept prototypes have been successfully realized to demonstrate the feasibility, reliability, and robustness of the system [388, 390, 401, 406, 496, 497]. These prototypes have implemented different modulation schemes, such as frequency shift keying modulation [388], phase shift keying modulation [496], and QAM [390, 497], as respectively shown in figures 79(b)–(d). In addition, figure 79(e) further demonstrates that this architecture can also introduce the MIMO technology to realize simultaneous transmissions of multiple data streams [406]. All the systems, working from microwave to mmWave band, have fully exhibited their excellent capability for information modulation and energy radiation, indicating the huge application potential of the new-architecture wireless communication system.

Current and future challenges

Although this new concept has shown great promises, several challenges still exist that need to be addressed. One of them is the limited modulation mode of metasurface, namely phase modulation, in the current system implementations. This is mainly because most of the reconfigurable metasurfaces focus on achieving the controllability of the EM wave phase [498]. While all parameters of EM waves can participate in the information modulation. Therefore, the metasurface with only phase reconfigurability will constrain the available modulation scheme, as well as the spectrum efficiency of the new-architecture system. Another issue comes to the switching speed of the element, which is dominated by the tunable components integrated into the element, and the most common devices are PIN diodes and varactor diodes. In general, it will determine the symbol rate to a large extent, which is highly related with the transmission rate of the system. The upper limit of the switching speed in varactor diode-based systems can only reach a few MHz due to the wide variation range of the reverse biasing voltage, while hundreds of MHz can be expected in the PIN diode-based systems. In addition, since these diodes are originally used in the microwave and mmWave circuits, they also restrict the operating frequency band of the system. Owing to the ease in obtaining high-amplitude response and convenience in designing the feeding networks, most of the prototypes choose reflective metasurface for proof-of-concept demonstrations. Such an implementation always requires a feeding antenna located in the upper space of the metasurface to provide the carrier wave. As a consequence, it usually encounters the issue of high profile as well as blockage effect, which hinders the practical application progress of the new-architecture system. Furthermore, as most metasurfaces are regarded as 'lossy' devices since they only consume EM energy by dielectric losses, ohmic losses, structural resonances, etc, it usually requires additional power compensation from the carrier source to obtain proper SNR performance.

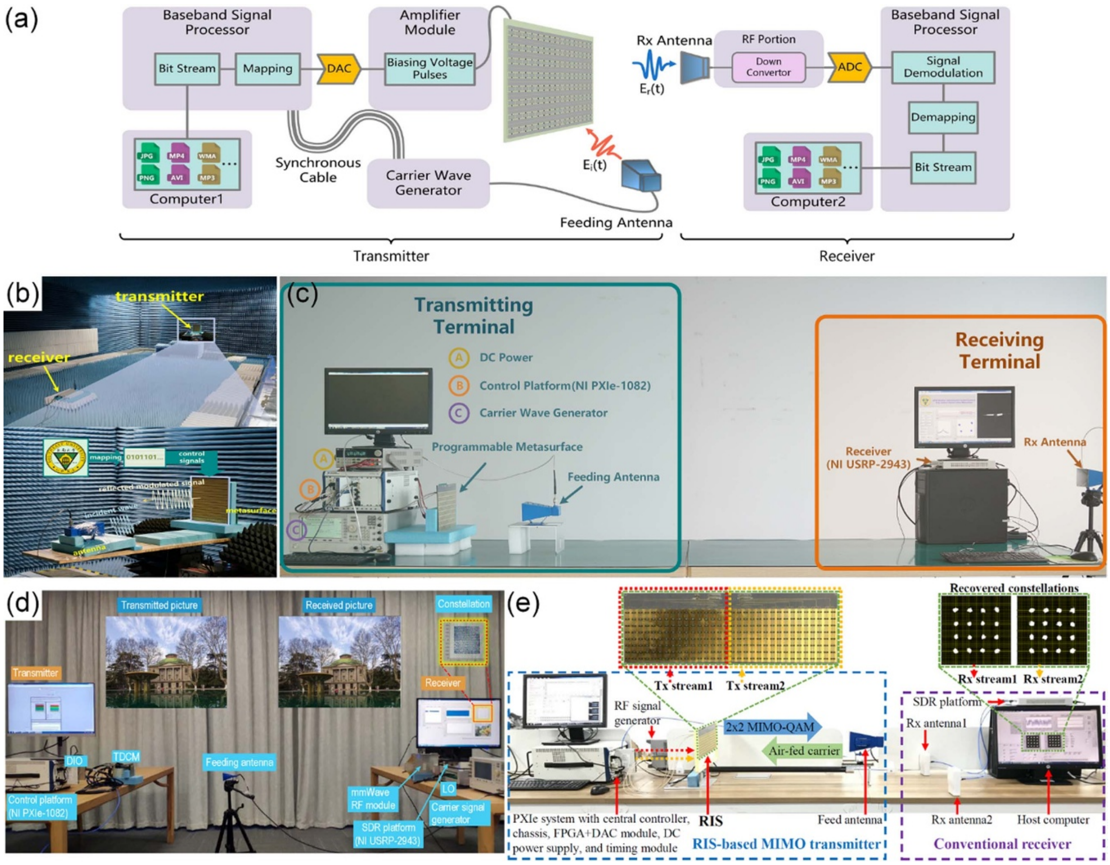

Figure 79. (a) Block diagram of the new-architecture wireless communication system. Experimental environments and results of the proof-of-concept prototypes of (b) BFSK system. (c) QPSK system. (d) 256QAM system. (e) 2 × 2 MIMO-16QAM system. [496] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced from [388]. CC BY 4.0. [496] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Reproduced from [390]. CC BY 4.0. © [2020] IEEE. Reprinted, with permission, from [406].

Advances in science and technology to meet challenges

With those challenges aforementioned above, several solutions may be considered as follows. Firstly, more types of metasurface can be involved into the system building to increase the number of controllable EM parameters, thereby enriching the systematic functions and performance. For example, amplitude reconfigurable metasurface can be utilized to implement amplitude shift keying modulation scheme, frequency reconfigurable metasurface is able to realize multi-band system, and polarization reconfigurable metasurface can provide another wireless channel. In particular, the complex-amplitude (amplitude and phase) reconfigurability is considered to be the most promising technology, not only because it provides the possibility of high-order modulation scheme like QAM modulation, but also due to its excellent capability in arbitrary spectrum synthesizing to improve the spectrum efficiency. In terms of increasing the communication rate of the system, since the current systems are diode-based and the design methods of element are relatively mature, more advanced diodes are indeed convenient and efficient candidates. In addition, some emerging technologies are also worth exploring to design metasurface with faster switching speed or higher working frequency, such as graphene, semiconductors, liquid crystal, and vanadium dioxide. As for the high profile and blockage effect caused by reflective metasurface, the transmissive, radiative, or waveguide-fed metasurfaces can be considered as the potential solutions to reduce the profile and separate the incident and modulated fields, extending the application scenarios of the system. Finally, if some IC chips are embedded into the element, such as transistors and amplifiers, metasurfaces capable of EM amplifications can be expected accordingly. Besides the improvement of wireless communication with such amplifiable metasurfaces, it is also reasonable to envision more promising applications including the wireless relay and signal repeater.

Concluding remarks

In conclusion, metasurface-based new-architecture system have paved a new way to wireless communication. Such a direct modulation architecture enables information modulation and EM wave propagation simultaneously with outstanding characteristics including cost reduction, simplified assembly, and reduced power consumption. However, there is still a long way to go to realize the broad applications of this new-architecture system. Both academic research and engineering exploration matter the same to facilitate its development. The system performance and application potential can be further enhanced with more advanced designs, devices, and strategies. We believe that the new-architecture wireless communication system will become one of the milestones in the field of metasurfaces, pushing this physical concept into practical applications.

Acknowledgments

The authors would like to acknowledge the National Key Research and Development Program of China under Grant Nos. 2017YFA0700201, 2017YFA0700202, 2017YFA0700203 and 2018YFA0701904; the National Natural Science Foundation of China under Grant Nos. 61731010 and 62288101, the 111 Project under Grant No. 111-2-05, the Jiangsu Province Frontier Leading Technology Basic Research Project under Grant No. BK20212002, and the Fundamental Research Funds for the Central Universities under Grant No. 2242022k30004.

6.8. Reconfigurable intelligent surfaces (RISs) and holographic massive MIMO transceivers for wireless communications and radar sensing

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State-of-the-art

It is frequently argued that current fifth-generation physical layer technologies, such as massive MIMO systems, mmWave communications, and ultra-dense heterogeneous networks, are unable to achieve the key performance indicators of sixth-generation communication networks [499]. For large MIMO to attain a high spectral efficiency, several antennas with active RF chains are required, which results in a significant energy consumption and hardware expense. Additionally, shifting to the sub-THz frequency band to make use of the wide spectrum makes EM waves more vulnerable to obstructions by objects like furniture and walls in indoor settings. Sub-THz communications also require more expensive RF chains and complex hybrid precoding techniques. The dense deployment of tiny base stations results in high hardware costs, network energy usage, and maintenance costs. Additionally, ultra-dense networks require sophisticated interference management strategies. To face these fundamental challenges, two breakthrough concepts have recently been put forth: (1) **programming the EM environment through reconfigurable surfaces** and (2) **designing dynamic holographic massive MIMO transceivers**.

Programming the environment through reconfigurable surfaces—The controllability of the wireless environment is a concept that leverages recent advances in the field of dynamic metasurfaces. The core technology to enable this function is known as RIS [110, 498]. An RIS is a planar surface made of many quasi passive and low-cost digitally-controllable scattering elements, each of which can impose a phase shift/amplitude on the impinging EM waves. These surfaces can turn a wireless environment into a transmission medium with desirable characteristics. Specifically, this is possible without utilizing active power amplifiers, digital signal processing unit, and multiple RF chains. These appealing advantages of an RIS have resulted in extensive research activities focused on fundamental performance limits, channel modeling, signal processing algorithms, and prototypes design. An industry specification group was established within the ETSI (see www.etsi.org/committee/ris).

Designing dynamic holographic massive MIMO transceivers—Building transceivers with hundreds or thousands of antenna elements, which can simultaneously serve multiple users, is challenged by practical difficulties in the conventional sub-6 GHz band and, especially, in the mmWave and sub-THz frequency bands. This includes the high fabrication cost, increased power consumption, constrained physical size and shape, and deployment limitations. A promising technology to realize massive arrays at a reduced cost and power consumption utilizes large surfaces of radiating metamaterial elements. These surfaces are known as dynamic metasurface antennas or holographic MIMO. They enable the implementation of a new generation of wireless transceivers with several controllable radiating elements and just a few RF chains [500, 501]. This emerging technology is fundamentally different with respect to massive MIMO arrays [501]. First, the number of independent data streams is smaller than the number of metamaterial-based antenna elements. This is a desirable feature in massive MIMO transceivers for application to sub-THz communications, since the number of RF chains is reduced while guaranteeing the desired beamforming gain [501]. Research on dynamic holographic surface-type transceivers has received much less attention than RIS to date, but the research works available in the literature have shown the potential performance benefits of this technology. One promising application of this technology consists of realizing high-rank transmission channels even in line-of-sight conditions, which may result in a dramatic increase of the spatial capacity density especially in the sub-THz frequency range [502].

Beyond state-of-the-art

The current research on the ***reconfigurable surfaces*** and ***holographic massive MIMO transceivers*** is insufficient to assess the benefits of these two technologies, especially in the sub-THz band. While these two technologies are both built upon breakthroughs in the field of dynamic metasurfaces, they are usually treated in isolation, without truly leveraging their joint potential for realizing the Internet of Surfaces paradigm [503]. Important open research directions include the following.

Physically-consistent models: Current communication models for RIS are oversimplified, are not physically consistent, and are often not used correctly. In [504] e.g. the authors show that a reconfigurable surface may generate unwanted beams towards several directions. This is due to the inherent limitations in implementing reconfigurable elements. The unwanted beams increase the level of interference and reduce the amount of power towards the direction of interest, which cannot be accepted for transmission in the sub-THz frequency band. A unified approach for modeling surfaces that can be used for reconfigurable surfaces and dynamic holographic transceivers by departing from first principles and its integration into wireless network design frameworks is an open research direction.

Physically-consistent and robust signal processing algorithms and resource management protocols: The need of physically consistent methods for reconfigurable surfaces and dynamic holographic transceivers has a dramatic impact on the optimization algorithms for their optimization. A physically consistent design criterion for dynamic surfaces lead to new optimization constraints [504]. These new constraints lead to complex optimization problems to solve that need to be tackled in a scalable manner. A unified optimization framework that accounts for EM constraints, signal processing methods that are robust by design to hardware non-idealities and to the EMI, and scalable resource management schemes that take account by design the channel estimation overhead are needed [505].

Holographic massive MIMO transceivers with integrated sensing and communications: The fundamental performance limits of holographic massive MIMO transceivers are not understood, especially if these surfaces are large and are deployed in channels dominated by line-of-sight propagation, as sub-THz channels are. In [502, 506], e.g. it is shown that large-size surfaces enable the creation of orthogonal transmission modes even in line-of-sight channels. This may fundamentally boost the transmission rate. How to exploit these transmission modes in practice is, however, not understood. Also, these results consider only communication modes, while the fundamental performance limits and how to achieve them in practice when holographic massive MIMO transceivers are realized for radio sensing and communication simultaneously are unknown [507]. Unveiling the fundamental performance limits of dynamic surfaces transceivers in the near-field and far-field regimes with integrated sensing and communication, e.g. in terms of communication modes, radar sensing accuracy, and their tradeoff through multi-objective optimization, is a challenging research issue.

Plug&Play autonomous reconfigurable surfaces with low deployment and optimization overhead: Three features of reconfigurable surfaces that reduce their cost and power consumption are the absence of digital signal processing units, power amplifiers, and RF chains. These features ease the implementation of the surface but pose major challenges for their operation and optimization. For example, channel estimation is negatively affected by these features. The development of a new generation of plug&play surfaces that can automatically identify the devices in the network and can optimally configure their operation for serving them at low channel overhead and no control channel is a promising research direction [503].

System-level performance assessment and evaluation in large-scale networks: The analysis of the potential gains of deploying reconfigurable surfaces and holographic MIMO transceivers in wireless networks is limited to simple network topologies, while no system-level assessments have been reported to date. The only exception to this status quo is [508], where, however, only reconfigurable surfaces are considered. Also, the network interference is ignored and very simple models for the reconfigurable surfaces are utilized [508]. Understanding the network-level performance offered by jointly deploying reconfigurable surfaces and holographic MIMO transceivers and endowing them with communication and sensing capabilities is a major open research issue [509].

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