WDM, and modulation at only 2 Gb s^{-1}, this could provide a throughput of up to $10^6 \times 2$ Gb s^{-1} = 2 Pb s^{-1}. This approach relies on a waveguide-based interposer that maps between the optical inputs and outputs, shown in Fig. 2b, and detectors and modulators (or emitters) located near data registers on the chip[13].

Optical communications must support the continued growth of information technology in the coming decade by providing orders of magnitude higher throughput, while achieving unprecedented density, energy and cost per bit. Emerging integration technologies will help achieve these goals. Spatial multiplexing will also play an indispensable role. ❐

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Unrelenting plasmons

Antonio I. Fernández-Domínguez, Francisco J. García-Vidal and Luis Martín-Moreno

Worldwide research efforts on plasmonics and metamaterials have been growing exponentially for the past ten years. Will this course hold true over the next decade?

Following a brief historic introduction to plasmons, their useful properties and early applications, we highlight some of the key advances in the field over the past decade. We then discuss new directions for the future, such as the use of 2D materials and strong coupling phenomena, which are likely to shape the field over the next ten years.

For centuries, metals were employed in optical applications only as mirrors and gratings. New vistas opened up in the late 1970s and early 1980s with the discovery of surface-enhanced Raman scattering and the use of surface plasmon (SP) resonances for sensing. However, it was not until the 1990s, with the appearance of accurate and reliable nanofabrication techniques, that plasmonics blossomed[1]. Initially, the attention focused on the exploitation of SPs (collective electronic oscillations at the surface of metals) for sensing, subwavelength waveguiding and extraordinary optical transmission[2]. Since then, the scientific and technological interest in SPs has expanded. Correspondingly, as illustrated in Fig. 1, the number of publications in the field has increased in a steady exponential fashion for more than two decades, and the momentum driving plasmonics research looks set to continue.

In a simplified picture, there are five distinctive characteristics that make SPs attractive: their ability to concentrate light beyond the diffraction limit; their ability to modify the local density of photonic states; their ultrafast response; their environmental sensitivity; and their flexibility in design. The main factor limiting their use is the high optical absorption inherent to metals. Therefore, the quest for minimizing dissipative damping has been a crucial driving force for plasmonics.

Beyond noble metals

The endeavour of improving plasmonic performance, most notably by reduced optical loss, has been accompanied by the pursuit of materials that outperform noble metals in specific optical functionalities. Different options, such as aluminium, metallic alloys and heavily doped semiconductors, have all been investigated and have advanced our understanding and broadened the catalogue of available plasmonic platforms. However, noble metals may still have more to offer. Recently, it has been shown that their plasmonic characteristics can be significantly improved using standard surface science fabrication protocols[3].

The advent of graphene has inspired research into 2D materials defined by their atomic thickness, some of which are very promising for applications in both the terahertz and mid-infrared regimes. Doped graphene supports SPs in these frequency ranges, featuring out-of-plane decay lengths and in-plane wavelengths that can be three orders of magnitude smaller than free-space radiation. This fact, together with their large electrical tunability, makes graphene plasmons excellent candidates for resonators and sensors. Despite the inherent absorptive character of graphene, there are reasons for being optimistic about the prospects of reducing damping in graphene-based plasmonics. For instance, the encapsulation of graphene within boron nitride (BN) films has increased SP propagation lengths by one order of magnitude[4]. Moreover, graphene is not the only member of the set of 2D plasmonic materials. Apart from BN, the interest in other media, such as semiconducting MoS_2 or black phosphorus, has been mounting over the past year or so. We envisage that plasmonic materials of atomic thickness will be a very active and fruitful research area over the next ten years.

Sensing

The efficiency of SP-based phenomena in metallic platforms has been pushed to unprecedented limits, opening the way for a myriad of applications. For example, through the implementation of nanoscale plasmonic tips, spectroscopic techniques are approaching the level of chemical recognition and spatial resolution required to identify single molecules[5]. It is likely that the combination of advances in nanometrology and a deeper understanding of Raman enhancement mechanisms will establish single-molecule spectroscopy as a widespread tool. Similarly, the large field enhancement and acute environmental sensitivity of SPs are being exploited in prototypes for microfluidic sensors. These are versatile and label-free instruments able to detect extremely low sample volumes and concentrations. Furthermore, SPs are key ingredients for optical nanotweezers, which take advantage of the complex force fields that originate from plasmonic light confinement to trap and accurately manipulate individual nano-objects in real time. This SP-assisted miniaturization of equipment (spectroscopes, biosensors and tweezers, among many others) has made possible lab-on-a-chip devices integrating all the functionalities of a conventional laboratory, and is currently close to industrial production.

Optical antennas

For many purposes, the excitation of SPs by an external light source is a requisite. Owing to their large momentum mismatch, this cannot be done in a straightforward manner. One option is to use nanoantennas[6], which operate with visible and infrared light in a similar way to conventional antennas with radio and telecom waves. By means of the strong field amplification and small modal volume of SPs, nanoantennas can improve the radiative properties of light emitters (such as fluorophores or dye molecules). Such plasmonic-enhanced microscopic light sources are expected to have a strong impact on areas such as super-resolution imaging or solid-state lighting[7]. Large distributions of nanoantennas can also act as macroscopic light receivers. This ability is appealing for solar energy conversion, as SPs can boost solar cell absorption efficiency[8], but the added costs are currently hindering the widespread implementation of plasmonic-enhanced photovoltaic technology. Nanoantennas can also function as frequency-selective and non-fading light reflectors. This makes them excellent candidates for the next generation of colour printing technology pixels[9]. The development of polarization-dependent, 3D and stereoscopic microprints based on these plasmonic pixels is likely to benefit areas including lithography, holography and anti-counterfeiting.

Nanolasers

The small modal volume of SPs can be used to enhance light–matter interactions in optical nanocavities. Perhaps one of the most interesting applications of SP cavities occurs when they are filled with optically active media to yield nanolasers[10]. These can be open systems, composed of single or periodic arrays of metallodielectric nanostructures, designed to amplify SP-assisted stimulated emission. Both the reduced dimensions and the ultrafast operation of nanolasers represent an important advance towards the on-chip integration of optical and electronic technologies. The development of plasmonic nanolasers is not without hurdles and even some controversies, and the challenge towards real-world applications will require considerable efforts in the next few years. One of the main goals over the next decade will be to realize efficient and practical nanolaser devices operating under electrical, instead of optical, pumping.

Enhanced nonlinear optics

Macroscopic optical nonlinearities are extensively used in standard photonics technology. They originate from small anharmonicities in the electromagnetic response of matter, which makes them inherently weak and — crucially — highly dependent on the amplitude of the electric excitation. Plasmonic field enhancement represents an exceptional way to boost nonlinear effects on the subwavelength scale. Proof-of-concept experiments have recently shown orders-of-magnitude enhancement of nonlinear phenomena such as frequency conversion, switching and modulation of optical signals[11] using plasmons. Moreover, SP-amplified optical nonlinearities also provide a feedback mechanism for plasmonic signals themselves, with optical gain used to compensate for plasmon decay, giving rise to self-sustained or soliton-like SPs. In this context, plasmonics in ultrasmooth metal surfaces offers new strategies to miniaturize current (inherently bulky) nonlinear optics technology.

Exploiting dissipation and hot electrons

As discussed above, the dissipation experienced by conduction electrons undergoing plasmon oscillations was

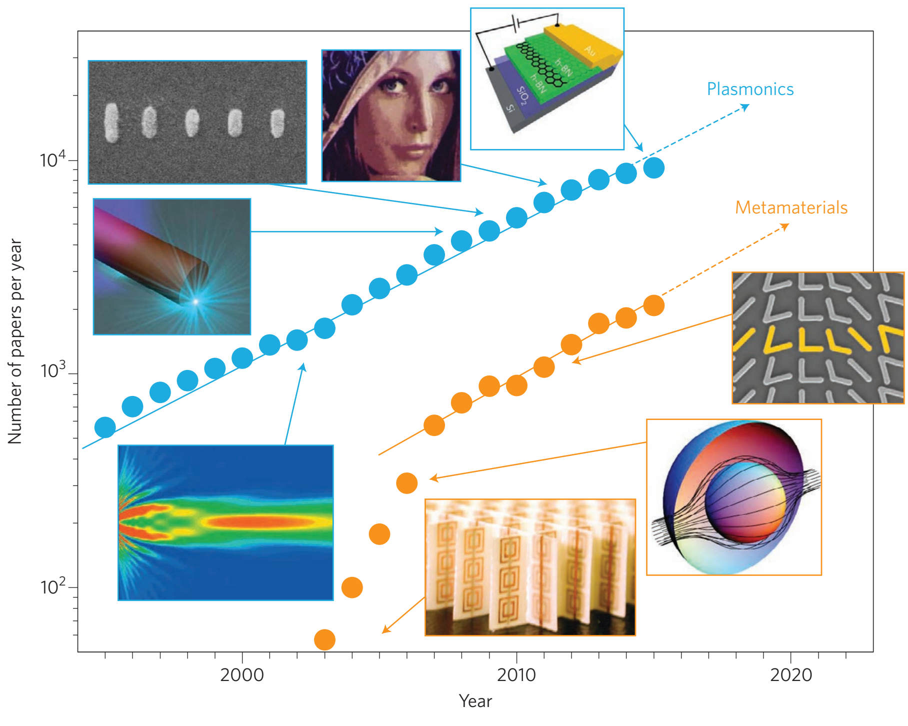

Figure 1 | Number of papers published per year in the fields of plasmonics (blue circles) and metamaterials (orange circles) between 1995 and 2015 (data taken from ISI Web of Knowledge, 2016). Solid lines are a guide for the eye illustrating the exponential growth experienced by the volume of the literature in both areas. Dashed lines are speculative projections of this trend into the near future. The insets show some of the most relevant milestones in the evolution of both research fields. Inset images from bottom left (clockwise): SP-assisted beaming[2], nanolasing[10], optical antennas[6], colour printing[9], graphene plasmons[4] (plasmonics), metasurfaces[15] (metamaterials), cloaking[18] and negative refraction[17]. Figure insets reproduced with permission from (bottom left, clockwise): ref. 2, APS; ref. 10, Nature Publishing Group; ref. 6, Nature Publishing Group; ref. 9, Nature Publishing Group; ref. 4, Nature Publishing Group; ref. 15, AAAS; ref. 18, AAAS; ref. 17, AAAS.

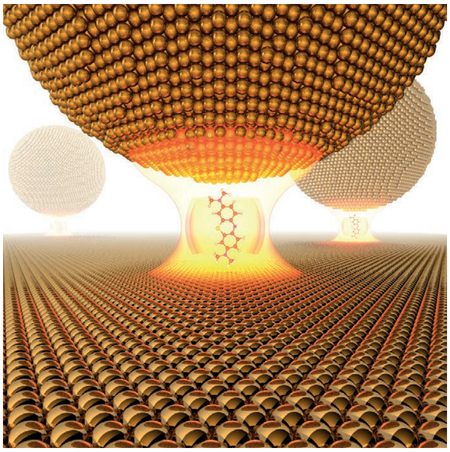

Figure 2 | Illustration of a particle-on-mirror plasmonic cavity strongly coupled to a single molecule placed within its (sub-) nanometric gap. Figure reproduced from ref. 20, Nature Publishing Group.

initially thought to be detrimental for nano-optics. However, in some contexts the previous hindrance has been converted into a potential benefit. On extremely short (few femtosecond) timescales, SP decay generates hot electrons (and holes), which occupy short-lifetime states above the Fermi energy. The quasi-bound character of these plasmon-induced carriers serves as an efficient channel for optical-to-electrical energy transduction[12]. Recent experiments demonstrate that hot-carrier generation in plasmonic nanostructures can yield efficient photodetectors and photocatalysts. On much longer timescales, thermalization takes place and SP absorption gives rise to nanometric-sized heat sources and sinks. This allows the creation of temperature gradients on the nanoscale, a prospect that is under investigation for magnetic recording and bioimaging. Furthermore, thermoplasmonic prototypes are currently undergoing clinical trials for medical therapy (cancer treatment) applications[13].

Hand-in-hand with metamaterials

Despite being initially established as an independent research area, metamaterials science has evolved hand-in-hand with plasmonics for the past decade. Figure 1 shows that after an initial surge in metamaterials literature, prior to maturity, the exponential evolution of the number of papers per year in both fields run parallel in time. SP modes and antenna arrays acquired a pivotal role in metamaterials as the quest took place for demonstrating effects such as negative index at frequencies approaching the visible regime. This pushed the field into the challenge of SP damping too, which found solutions in particular cases through loss compensation and optical gain[14].

Fabricating devices larger than a handful of unit cells thick has been a constant challenge hampering metamaterials technology. However, structures based on single metamaterial layers, that is, 2D metamaterials or metasurfaces[15], have been exploited recently. These are much thinner than the operating wavelength, which, in principle, makes them easier to fabricate and less sensitive to absorption losses. By increasing the complexity of the internal composition and the collective coupling of 'meta-atoms', metasurfaces yield efficiencies comparable to bulk metamaterials. Moreover, by combining metals with 2D materials such as graphene[16], electrically and/or optically tunable metasurfaces can be realized. Functionalities such as negative refraction[17] and cloaking[18] have been accomplished through metasurfaces. With such progress we can anticipate the key part that they will play in photonics technology, for example, by providing tunable planar transfer functions for superlenses, beam steerers and beam shapers.

Strong coupling

By shrinking their modal volume, the interaction between SPs and an ensemble of quantum emitters (quantum dots and organic molecules) can be pushed into the so-called collective strong coupling regime. This phenomenon takes place when light and matter states exchange energy faster than their respective decay channels, giving rise to new quasiparticles usually termed plasmon–exciton–polaritons. The properties of these hybrid states can be adjusted through their light and matter content, which means a new, and qualitatively different, degree of light manipulation. A different research route consists of taking advantage of the phenomenon of collective strong coupling to take chemistry and materials science into new directions, that is, modifying chemical and material properties through vacuum fluctuations[19]. We envisage that plasmonic cavities will find applications as catalysts, inhibitors of chemical reactions, and enhancers of energy and charge transport, prospects that are now attracting much fundamental research.

Strong coupling of plasmons and quantum emitters can also appear at the single-emitter level, as has been demonstrated experimentally very recently[20]. In this regime, the hybrid nature of quantum light sources is expected to have a strong impact on the optical properties of the compound system. Contrary to semiconductor microcavities, the large coupling strengths attainable in metallic nanocavities, such as the particle-on-mirror geometry sketched in Fig. 2, make them robust to thermal fluctuations. Therefore, emitter–plasmon devices represent a promising basis for nonlinear nanophotonic components at the single-photon level, able to operate at room temperature.

Quantum plasmonics

Among the latest generation of nano-optical devices, some are designed to support SP modes localized within subnanometric dimensions, and others are devised to operate at the level of a few plasmon quanta. The need for theoretical tools able to describe all these systems has pushed plasmonics into the domains of condensed-matter physics and macroscopic quantum electrodynamics. The interplay between these two fields has led to significant advances in our understanding of plasmonic phenomena involving a few electronic or photonic quanta. However, crucial aspects, such as establishing the limits of plasmonic enhancement on the atomic scale, or the robustness of quantum coherence and correlations achievable in SP platforms, still need to be addressed. ❒

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