Focusing light with a single subwavelength aperture flanked by surface corrugations

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In this letter, we show theoretically how a single subwavelength aperture surrounded by a finite array of grooves made on a metallic film can act as a "lens" for electromagnetic radiation within a certain frequency range. The dependence of this resonant focusing ability with the geometrical parameters defining the structure is extensively analyzed. Universal curves for the depth, length and width of the focus as a function of the number of grooves are also given. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1631384]

Since the discovery of extraordinary optical transmission (EOT) phenomena observed in two-dimensional arrays of subwavelength holes perforated in metal films,[1] there has been a renewed interest in the optical properties of subwavelength apertures (holes or slits) from both the fundamental and applied points of view.[2–9] It is now well established[10] that this phenomenon is related to the resonant excitation by the incident light of surface electromagnetic (EM) modes of the corrugated metal surfaces. This mechanism suggested that EOT could be present in a single aperture surrounded by surface corrugations. This hypothesis has been recently verified.[11,12] More surprisingly, it has been also shown how, by patterning the exit plane of the aperture, the angular distribution of the transmitted light in the far-field region can be "shaped," producing highly collimated beams at resonant wavelengths.[12] These two combined abilities make this type of structure a good candidate to play a major role in many optoelectronic applications.

Recently, we have analyzed the common physical origin of both beaming[13] and enhanced transmission[14] observed in single subwavelength slits flanked by a finite array of grooves. We have shown that these two effects (which only appear for p-polarized light) are due to the formation of surface EM resonances, which can be tailored through the geometrical shape of the indentations. In this letter, we show how this type of devices can be also used as a **lens**, focusing the electromagnetic field in the output region in a frequency range that coincides with the one in which beaming of light appears.

In Fig. 1, we represent schematically the structure under study: a single slit surrounded by $2M$ grooves in the input surface (at which the incident light is impinging on) and by $2N$ in the output surface. Grooves are periodically distributed and symmetrically located with respect the central slit. It can be shown that, in the subwavelength regime (slit width much smaller than the wavelength (λ), total transmittance $[T(\lambda)]$ is controlled basically by the input corrugation and metal thickness, whereas the normalized-to-transmittance Poynting vector at point $\mathbf{r}$ located in the transmitted region $[\mathbf{S}^{\mathrm{nor}}(\lambda,\mathbf{r})=\mathbf{S}(\lambda,\mathbf{r})/T(\lambda)]$ only depends on the geometrical parameters defining the output surface: N, a (width of the slit and grooves), h (depth of the grooves), and d (period of the array). This quantity $[\mathbf{S}^{\mathrm{nor}}(\lambda,\mathbf{r})]$ is then independent of metal thickness and of the details of the input surface. All

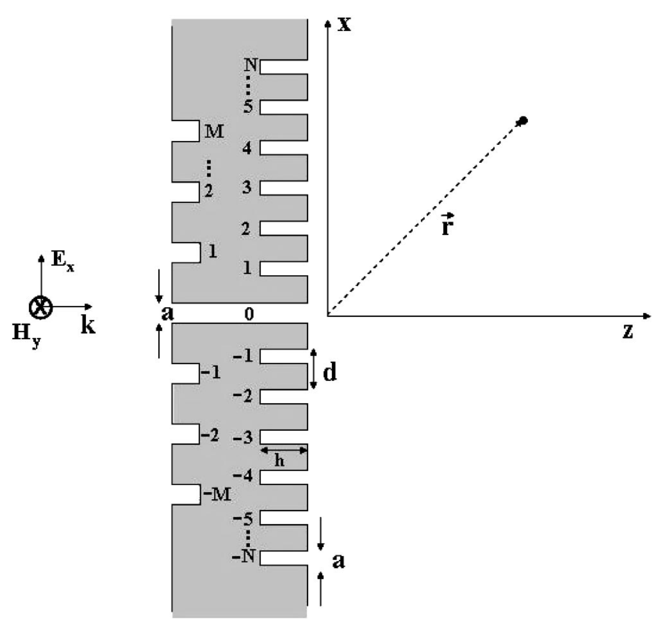

FIG. 1. Schematic picture of the system under study: a single subwavelength slit surrounded symmetrically by $2M$ grooves on the input surface and $2N$ grooves on the output surface. A p-polarized EM plane wave is impinging from the left. Geometrical parameters of the output corrugation are: d period of the array, all indentations widths are a and all groove depths are h. The x axis runs along the output surface, whereas the z axis is perpendicular to it.

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calculations we present in this short letter are for p-polarized light. Let us outline the main points of our theoretical formalism; details of the calculations can be found in.[13,14] We perform a a modal expansion of the EM fields in the different regions and, as we are interested in the subwavelength regime, we only consider the fundamental propagating eigenmode in grooves and central slit. We also assume perfect metal boundary conditions, so that no absorption is present in the system. Although, in principle, it is expected that this approximation should fail in addressing real metals in the optical regime we have previously shown[13,14] that this approach is accurate enough to describe in semiquantitative terms the underlying physics displayed by nanostructured good metals like silver and gold at optical wavelengths. Within this formalism, the y component of the magnetic field in the output region can be written in a Huyghen's-principle form as

$$H_y(\mathbf{r}) = \frac{1}{\mu_0 c} \sum_\alpha E_\alpha G(\alpha,\mathbf{r}), \tag{1}$$

and all other components of the EM field can be obtained from $H_y(\mathbf{r})$ for the polarization considered. Here, α runs over all indentations of the output surface (from $-N$ to N, with $\alpha=0$ labeling the central slit). E_α is related to the x component of the electric field at the opening α at $z=0$ and $G(\alpha,\mathbf{r})$ is a Green's function providing the EM field at point $\mathbf{r}$ radiated by indentation α (see Ref. 13 for the precise mathematical expression of these quantities). From Eq. (1), it is clear that, in order to have a nonisotropic radiation pattern, E_α must be large at several indentations. In Ref. 13, we studied the conditions leading to large E_α: excitation of single groove cavity modes (controlled by a and h) plus in-phase coupling between indentations (which is stronger at $\lambda \approx d$). Therefore, for fixed d, a, and N, there is an optimum value of h for which E_α are large, and hence the beaming effect could be observed at a resonant wavelength λ_R. For example, for $d=500$ nm, $a=40$ nm, and $N=10$ (typical values used in previous experiments), the optimum depth is $h_{\rm opt}=83.5$ nm, and beaming effect appears for $\lambda_R=532$ nm. In Fig. 2(a), we show the corresponding electric-field intensity profile for this particular case. By looking at the far-field region, a highly collimated beam with a very low divergence (around 3°) is observed, but also it is worth commenting on the appearance of a very elongated focus (note the different scale units in x and z axes) at around $z=46.3$ μm, in the intermediate region (between near- and far-field regions). Clearly, there is a focusing effect associated with the beaming phenomenon. Let us now concentrate on the properties of this focus for the wavelength at which beaming is maximum. At the end of the letter, we will consider focusing for wavelengths close to this resonant condition. In Figs. 2(b) and 2(c) (black line), we give more details of the focus by cutting panel (a) at the line $x=0$ in panel (b) and by the line of maximum e-field intensity ($z=46.3$ μm) in panel (c). These curves also help us to further characterize the focus by defining the focal length (f, distance to the surface of maximum of e-field intensity), focal depth (Δ, full width at half-maximum of e-field intensity along the z direction), and focal width (δ, as before, but this time along the x direction).

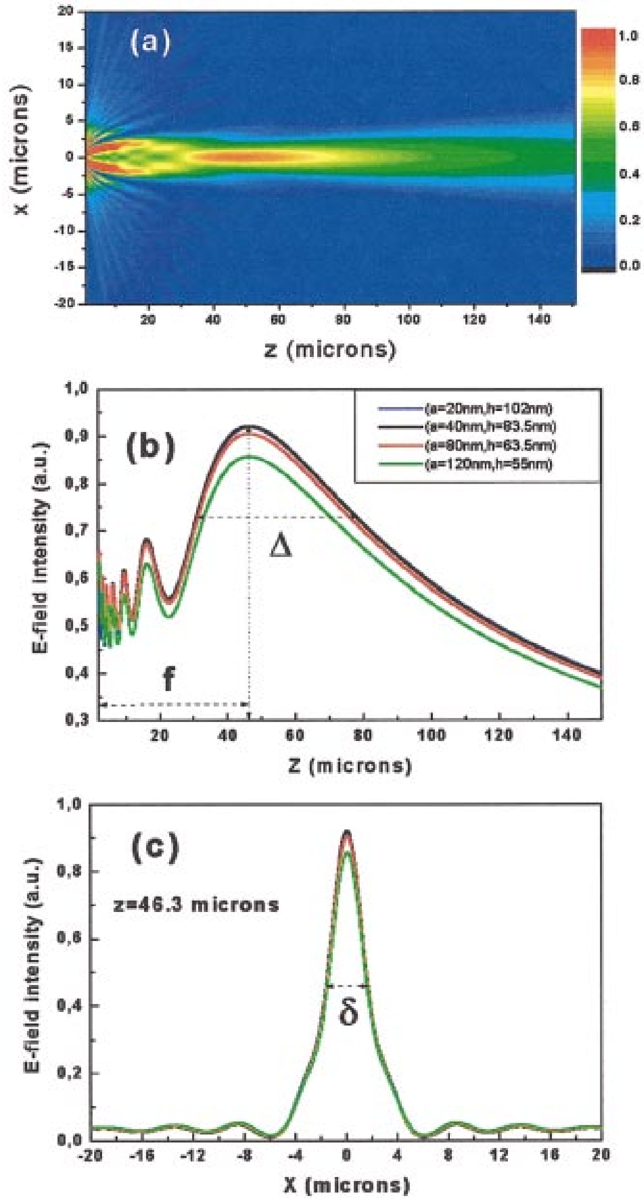

FIG. 2. (Color) (a) E-field intensity profile (arbitrary units) as a function of x and z (in microns) for the case $N=10$, $d=500$ nm, $a=40$ nm and $h=83.5$ nm, and for the resonant $\lambda_R=532$ nm. (b) Cut along the line $x=0$ of previous picture (black line) and the corresponding ones for different values of the set (a,h) that also give maximum beaming (see Fig. 3). (c) Cut along the line $z=46.3$ μm of panel a (black line) and the corresponding ones for the same set of (a,h) values of panel (b). Note that in panels (b) and (c), the curves corresponding to $a=20$ nm (blue) and $a=40$ nm (black) are practically the same.

We have found that for fixed N, there is a combination of (a,h) values that give the same λ_R. Furthermore, as shown in Figs. 2(b) and 2(c), the corresponding EM-field profiles are, in the subwavelength regime ($a \ll \lambda$), virtually the same for all those cases; that is, they depend only on λ_R. This, combined with the fact that Maxwell equations are scale invariant for systems comprised of perfect metals, means that all lengths defining the focus at λ_R (when defined in terms of a d, which we have chosen as length scale) depend only on N. This allows us to **fully** characterize the focus by the curves rendered in Fig. 3. Those curves are *universal*; that is, by scaling appropriately all lengths defining the structure by a common factor, this type of structure

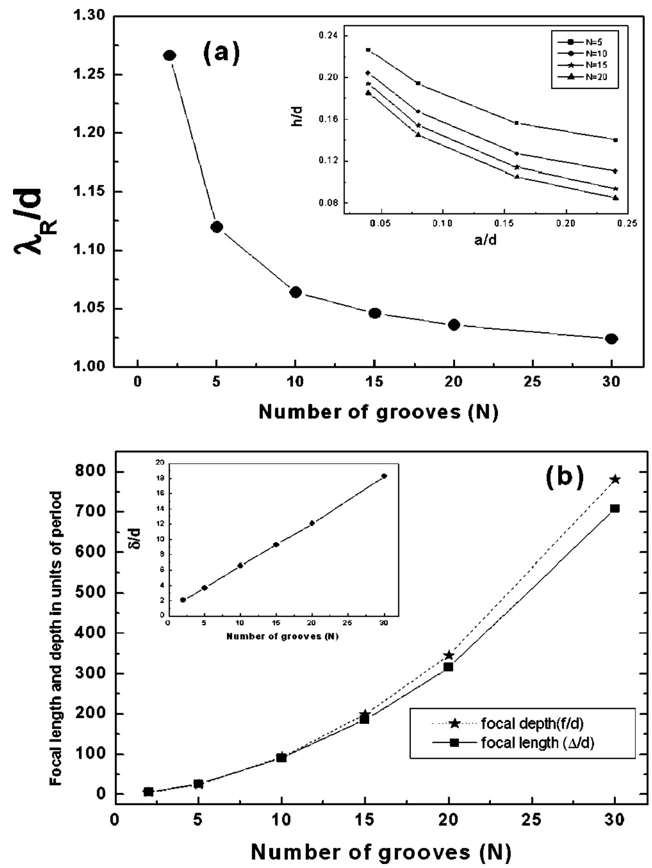

FIG. 3. (a) Universal curve of the resonant wavelength in units of the period of the array (λ_R/d) as a function of the number of grooves in the output corrugation (N). In the inset, we plot the a/d versus h/d curves that give maximum beaming for different values of N, $N=5,10,15$, and 20. (b) Universal curves for the geometrical parameters defining the focus (f, Δ, and δ) in units of the period of the array (d) as a function of N.

could be used to focus EM radiation in frequency ranges other than optical, and those curves would still characterize the focus. Panel 3(a) shows the dependence of λ_R/d with N, while the inset to this figure presents the locus in the $a-h$ parameter space at which maximum beaming appears for $N=5,10,15$, and 20. Panel 3(b) presents the N dependence of the geometrical characteristics of the focus: f/d, Δ/d and δ/d (inset of the figure). Both focal depth and length show a N^2 dependence, whereas the focal width is linear in N. Therefore, as N increases, the focus becomes more elongated. These dependencies are reminiscent of what occurs in a diffraction grating (a finite array of slits); for normal incident radiation, there is also a focus in the z axis with the corresponding f, Δ, and δ following the same functional dependencies with N, as we have found for our structures, although with different prefactors. Nevertheless, the corrugated aperture system presents two properties, not present in the canonical diffraction grating: (i) the location of the focus and its geometrical properties are independent of the angle of incidence; therefore light impinging from different directions could be focused at the same spot in the output region and (ii) the focusing effect is a resonant phenomenon that only occurs within a very narrow range of wavelengths around the resonant condition.

In conclusion, we have analyzed theoretically the focusing properties of single subwavelength apertures flanked by finite arrays of grooves that are equally spaced. We have found that, associated with the resonant beaming effect previously reported,[12,13] this type of structures also displays a lensing effect that appears at the same wavelength range. Universal curves for this resonant wavelength and for the geometrical parameters defining the focus (focal depth, length, and width) have also been given, as functions of the number of grooves. This lensing ability is controlled by the output corrugation, whereas its transmissive properties are governed mainly by the input corrugation only. The reported focusing property represents yet another step forward for controlling light through its interaction with patterned metals.

This type of lens could be used to improve performance in a variety of optical devices useful for wavelength multiplexing, wavelength dispersion, filtering, optical data storage, near-field microscopy, photolithography, light emission, and optical switching.

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[1] T. W. Ebbesen, H. J. Lezec, H. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[2] J. A. Porto, F. J. García-Vidal, and J. B. Pendry, Phys. Rev. Lett. **83**, 2845 (1999).
[3] H. E. Went, A. P. Hibbins, J. R. Sambles, C. R. Lawrence, and A. P. Crick, Appl. Phys. Lett. **77**, 2789 (2000).
[4] E. Popov, M. Neviere, S. Enoch, and R. Reinisch, Phys. Rev. B **62**, 16100 (2000).
[5] Y. Takakura, Phys. Rev. Lett. **86**, 5601 (2001).
[6] J. M. Vigoureux, Opt. Commun. **198**, 257 (2001).
[7] F. Yang and J. R. Sambles, Phys. Rev. Lett. **89**, 063901 (2002).
[8] A. Barbara, P. Quemerais, E. Bustarret, and T. López-Rios, Phys. Rev. B **66**, 161403(R) (2002).
[9] A. P. Hibbins, J. R. Sambles, and C. R. Lawrence, Appl. Phys. Lett. **81**, 4661 (2002).
[10] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, Phys. Rev. Lett. **86**, 1114 (2001).
[11] T. Thio, K. M. Pellerin, R. A. Linke, H. J. Lezec, and T. W. Ebbesen, Opt. Lett. **26**, 1972 (2001).
[12] H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martín-Moreno, F. J. García-Vidal, and T. W. Ebbesen, Science **297**, 820 (2002).
[13] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, A. Degiron, and T. W. Ebbesen, Phys. Rev. Lett. **90**, 167401 (2003).
[14] F. J. García-Vidal, H. J. Lezec, T. W. Ebbesen, and L. Martín-Moreno, Phys. Rev. Lett. **90**, 213901 (2003).