Narrow gaps for transmission through metallic structured gratings with subwavelength slits

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Transmission dips in the response of metallic compound gratings formed by several wires and slits in each period have been recently reported for normal illumination. These anomalies are generated by a particular arrangement of the magnetic field phases inside the subwavelength slits, and they are characterized by a significant enhancement of the interior field. We investigate the microwave response of such systems under non-normal illumination and show that new phase modes appear in this configuration. Contrary to the effect produced by a defect in a photonic crystal, these systems exhibit forbidden channels within a permitted band. We also found that the appearance of these resonances is not highly dependent on the slits' width and thickness, even though these parameters modify the overall transmittance.

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I. INTRODUCTION

The interest of the scientific community in periodic gratings with subwavelength slits has increased considerably in the last few years. Among recent applications, nanowire gratings have been proposed for the characterization of attosecond pulses [1], integrated polarizers [2], optical data storage, and external storage media. Gratings with subwavelength slits have also attracted much theoretical interest due to their capability to produce enhanced transmission. This phenomenon has been first reported by Ebbesen and his group [3,4] in metallic plates with subwavelength holes. These investigations led many researchers to investigate the possibility of enhanced transmission in different structures. In particular, one-dimensional (1D) transmission gratings have been widely studied [5,6]. Although there is not complete agreement on the origin of enhanced transmission [7,8], many efforts have been devoted to understand the physical mechanism responsible for the enhancement. These include the analysis of the response of a single slit [9–14]. Many authors propose that surface plasmons (SPs) play an important role in the enhanced transmission process [3–6,9,15–18]. However, it is also known that in 1D transmitting structures, waveguide mode resonances (WM) also contribute to this phenomenon [5,6,19].

The excitation of SPs and WMs are two of the mechanisms known to produce anomalies in the response of 1D metallic gratings. Rayleigh anomalies, produced by the appearance or disappearance of a diffracted order, also produce sudden changes in the diffracted efficiency [20]. The above three mechanisms take place in simple gratings, i.e., gratings formed by a single slit in each period. However, there is another kind of resonance that might arise in a periodic grating only when its period comprises several cavities or slits (compound gratings). These are called phase resonances and were first reported in structures comprising a finite number of cavities on a perfect conductor [21,22], and later observed in infinitely periodic compound reflection gratings under normal [23–25] and oblique [26] illumination. Phase resonances appear in the reflected and/or transmitted response of a grating as sharp features, like peaks or dips. For a particular wavelength, the field distribution inside the different cavities or slits takes a particular form so its phase in adjacent cavities is opposite to each other and its amplitude maximizes the inner field. In simple gratings, the condition of pseudoperiodicity of the fields imposes that all periods of the grating are equivalent and therefore all the grooves have the same field (with the exception of a phase factor). On the other hand, the addition of cavities or slits to the period of the grating introduces new degrees of freedom regarding the possible near field configurations (magnitude and phase). These new arrangements give place to phase resonances, a promising type of anomaly that can have multiple applications in nonlinear devices, selective surfaces, etc.

Recently, we have investigated the generation of phase resonances in transmission wire gratings [27,28], in the particular case of normal incidence. As in the case of reflection structures [23–25], the symmetry imposed by normal illumination leads to a minimum of three cavities or slits in each period necessary to produce a phase resonance. In this paper, we investigate the response of transmission compound metallic gratings under oblique illumination and discuss the dependence of phase resonances on the geometrical parameters of the structure.

In Sec. II we outline the modal method used to solve the diffraction problem of a p-polarized plane wave by a compound grating, and in Sec. III we show examples of the far field response of such complex structures for different numbers of slits in the period, for varying incidence angles. We also give maps of the near field under resonant and nonresonant conditions and discuss the dependence of the resonances on the width and depth of the slits. Finally, concluding remarks are given in Sec. IV.

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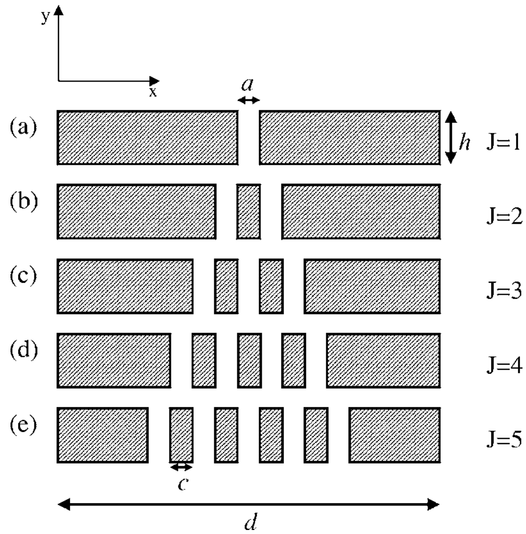

FIG. 1. Scheme of the simple and compound gratings.

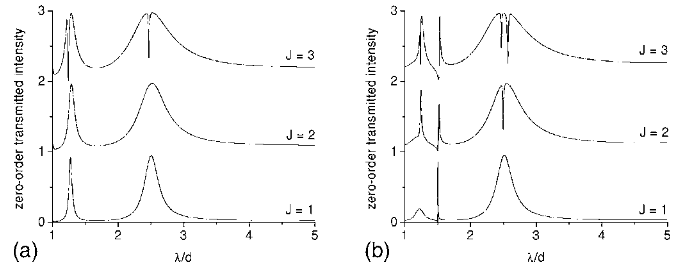

FIG. 2. Zero-order transmittance as a function of the wavelength for a p-polarized plane wave impinging on a metallic grating with $a/d=c/d=0.08$ and $h/d=1.14$. The conductivity of the metal is $\sigma=5.17\times10^{17}\ \mathrm{s}^{-1}$. The different curves correspond to different numbers of slits in the period: $J=1$, 2 and 3. (a) $\theta_0=0°$, (b) $\theta_0=30°$.

II. MODAL APPROACH

We consider a p-polarized plane wave of wavelength λ illuminating the compound array of metallic wires immersed in vacuum. The metallic wires are characterized by the conductivity σ. The different structures under study are schematically shown in Fig. 1. Grating (a) is the simple transmission grating, with a single slit of width a in the period d. The number of slits in the period is J and so the number of thin wires is $J-1$. Each period of grating (b) comprises two slits ($J=2$) of equal width, separated by a thin wire of width c. Cases (c), (d), and (e) correspond to $J=3$, 4, and 5, respectively.

Owing to the rectangular cross section of the wires, the modal method [29,30] appears to be very suitable to solve this diffraction problem. The surface impedance boundary condition (SIBC) [31,32] is applied to account for the finite conductivity of the metal.

The reflected and the transmitted magnetic fields are represented by Rayleigh expansions. Then the field in the incident and in the transmission medium are given by

$$H_{z\ \mathrm{inc}}(x,y)=\exp[i(\alpha_0 x-\beta_0 y)]+\sum_n R_n \exp[i(\alpha_n x+\beta_n y)] \tag{1}$$

and

$$H_{z\ \mathrm{trans}}(x,y)=\sum_n T_n \exp[i(\alpha_n x-\beta_n y)], \tag{2}$$

respectively, where

$$\alpha_n=\frac{2\pi}{\lambda}\sin\theta_0+n\frac{2\pi}{d}, \tag{3}$$

$$\beta_n^2=\left(\frac{2\pi}{\lambda}\right)^2-\alpha_n^2, \tag{4}$$

θ_0 is the angle of incidence, and R_n and T_n are the reflected and transmitted Rayleigh amplitudes, respectively.

Inside the slits the fields are expanded in terms of eigenfunctions that take into account the SIBC on the lateral walls of each slit [30]:

$$H_{z\ \mathrm{slits}}(x,y)=\sum_{m=0}^{\infty}\left\{\cos[u_m(x-x_j)]+\frac{\eta}{u_m}\sin[u_m(x-x_j)]\right\}\times\{a_{mj}\cos[v_m y]+b_{mj}\sin[v_m y]\}, \tag{5}$$

where $\eta=-ikZ$, Z is the surface impedance of the wires, ω is the incident frequency, and u_m and v_m are the separation constants of the Helmholtz equation that satisfy

$$u_m^2+v_m^2=k^2, \tag{6}$$

and are found by solving a transcendental equation which results from the imposition of the boundary conditions at the walls of the slits:

$$\tan u_m a=\frac{2\eta u_m}{u_m^2-\eta^2}. \tag{7}$$

The surface impedance of the highly conducting wires can be expressed in terms of the conductivity σ as $Z=(1-i)\sqrt{\omega/(8\pi\sigma)}$. The x_j are the positions of the left wall of each slit (the subscript j denotes the slit), and a_{mj} and b_{mj} are unknown complex amplitudes.

The fields are matched on the horizontal boundaries by imposing the continuity of the tangential components in the open sections, and by applying the SIBC in the metallic surfaces. This method leads to a system of coupled equations that are projected in convenient bases to get a matrix system for the unknown reflected and transmitted amplitudes.

III. RESULTS

To give a general idea of the phase resonances and their effects on the reflected and transmitted response of compound wire gratings, we draw on some of the results obtained for normal incidence [27] and analyze the dependence of the resonances on the number of slits, width, and thickness of the wires, and incidence angle.

Figure 2 shows examples of the transmitted response of three of the complex structures considered in this paper. The parameters used for these examples are $a/d=c/d=0.08$,

$h/d=1.14$, $\sigma=5.14\times10^{17}$ s^{-1} (corresponding to copper for low frequencies at room temperature [33]), for a p-polarized normally incident plane wave. The lower curve in Figs. 2(a) and 2(b) corresponds to a simple grating, i.e., a periodic structure with a single slit in the period. For normal incidence [Fig. 2(a)], two peaks are observed in the curves, which correspond to waveguide modes established in the slits [6,27]. For two slits in the period ($J=2$), the response is very similar to the $J=1$ case, although the peaks are slightly widened and shifted. However, for $J=3$ (three equal narrow slits, two equal narrow wires, and a wider wire within the period), a significant change in the behavior is found: each peak is split into two by a deep and sharp dip.

The physical origin of these dips can be explained in terms of phase resonances, which are generated by a particular arrangement of the phases within the slits [22,23,25,27]. In every periodic structure, the use of the pseudoperiodic property of the fields allows us to reduce the treatment of the diffraction problem to a single period. Consequently, the fields are essentially equal in all slits of a simple grating. However, if the grating comprises several slits in the period (compound grating), the distribution of field phases in the slits can have different configurations. This new possibility gives rise to the phase resonances under study, usually found within the Fabry-Perot resonance peaks produced in the slits. The number of allowed resonances within each waveguide resonance peak is mainly governed by the number of slits in the period (J); nevertheless, the angle of incidence is of great importance when analyzing the possibility of excitation of phase resonances. In the $J=3$ case and under normal illumination, the only phase configuration allowed (different from having equal phases in all the slits) is the one known as the π mode [22]. This resonance is characterized by a phase reversal between the central and the external slits, and it is also called the $(+\ -\ +)$ mode. Simultaneously, when the compound structure is illuminated by a plane wave with the resonant wavelength, the electromagnetic field inside the slits is strongly intensified. For one slit in the period, and for two slits in the period under normal illumination, different phases in adjacent slits cannot occur, and therefore no dips are present in the corresponding curves of Fig. 2.

One of the requirements for a phase resonance to occur is to have at least one phase reversal of the magnetic field in adjacent slits. In a previous letter [27], we analyzed the response of compound transmission gratings under normal illumination, and we showed that, due to the symmetry imposed by normal incidence, the number of possible configurations with at least one phase reversal in adjacent slits is determined by J. For instance, for $J=3$ and $J=4$ there is only one possibility [$(+\ -\ +)$ and $(+\ -\ -\ +)$, respectively], for $J=5$ there are three possibilities [$(+\ -\ +\ -\ +)$, $(+\ +\ -\ +\ +)$, and $(+\ -\ -\ -\ +)$], etc. Thus by increasing J we increase the number of possibilities of exciting phase resonances in the structure.

When the array is illuminated by an oblique plane wave, new possibilities open up. In Fig. 2(b) we show the transmitted intensity for oblique incidence ($\theta_0=30°$) for the same three structures considered in Fig. 2(a) for normal incidence. The curve for $J=1$ is similar to that corresponding to normal incidence, with a difference near $\lambda/d\approx1.5$. At this wavelength the -1 diffraction order appears, producing a Rayleigh anomaly. Phase resonances are not found in this case since $J=1$ corresponds to a simple grating, and then no different phases are allowed within the slits. An interesting feature appears in the curve for $J=2$. The sharp dip that only appeared for $J=3$ under normal illumination is now present when the structure comprises just two slits ($J=2$). For oblique incidence, the symmetry condition imposed by normal illumination is now removed, thus allowing new phase configurations inside the slits. In particular, the phase resonance mode excited in this case is a π mode, which has opposite phases in adjacent slits, as can be observed in Fig. 3(a). Also, the removal of the symmetry condition produces new dips for $J=3$, with two dips within each waveguide resonance peak instead of the single dip found for normal illumination [upper curve in Fig. 2(a)].

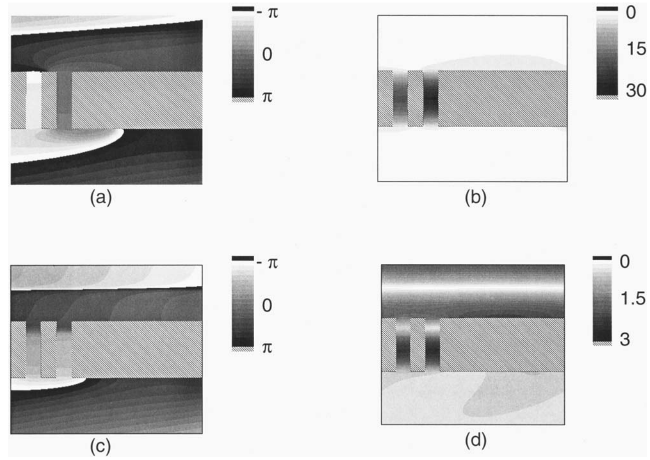

FIG. 3. Magnetic field for an obliquely incident ($\theta_0=30°$) p-polarized plane wave impinging on a metallic grating with $a/d=0.08$, $h/d=1.14$, and $J=2$. The conductivity of the metal is $\sigma=5.17\times10^{17}$ s^{-1}. (a) Phase for $\lambda/d=2.496$; (b) magnitude for $\lambda/d=2.496$; (c) phase for $\lambda/d=2$; (d) magnitude for $\lambda/d=2$.

To get more insight about the characteristics of phase resonances, in Fig. 3 we show contour plots of the magnetic field (magnitude and phase) in the vicinity of the structure for a resonant [Figs. 3(a) and 3(b)] and a nonresonant [Figs. 3(c) and 3(d)] wavelength, in oblique incidence conditions. We observe that the phase of the magnetic field along the x direction is nearly constant within each slit, as is to be expected in the case of narrow slits. When a phase resonance is generated, i.e., when the compound structure is illuminated by the right wavelength, the phases in adjacent slits are opposite to each other, as observed in Fig. 3(a) (notice that the sudden change from black to white in the left slit is a fictitious discontinuity produced by the calculation of the phase, and both values correspond to π radians as can be appreciated in the legend). The magnitude of the field is shown in Fig. 3(b), from which it is clear that the field is concentrated inside the apertures, reaching a value of up to 30 times the incoming amplitude. Note that two characteristics of phase resonances are met in this case: (i) a phase reversal of the magnetic field in adjacent slits, and (ii) a strong enhancement of the interior field. On the other hand, in nonresonant conditions, the phases in adjacent slits are similar [Fig. 3(c)],

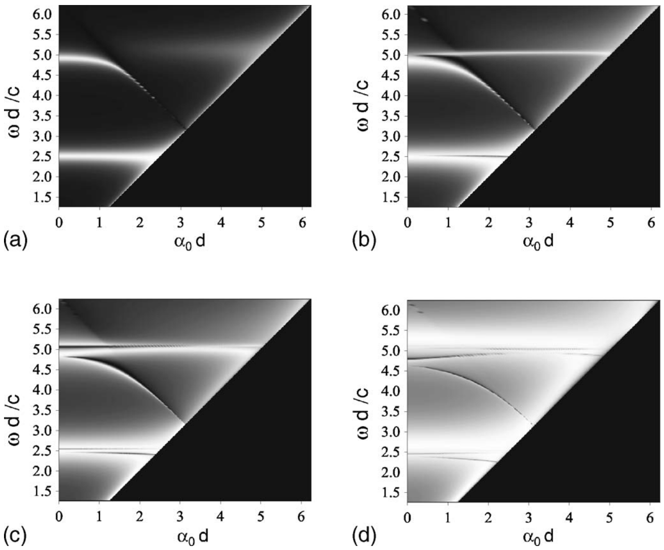

FIG. 4. Contour plots of the transmitted intensity as a function of $\alpha_0\ d$, and $\omega d/c$, for the same parameters as in Fig. 2, and for gratings with different numbers of slits in the period. (a) $J=1$; (b) $J=2$; (c) $J=3$; and (d) $J=5$.

and the maximum interior field is about ten times smaller than in the resonant case [Fig. 3(d)].

In Fig. 4 we show maps of transmitted intensity as functions of α_0 (the x component of the incident wave vector) and the frequency ω, for gratings with different numbers of slits in the period and the same parameters as in Fig. 2. The lighter zones represent higher transmitted intensities. In Fig. 4(a) we show the contour plot for a simple structure, i.e., with a single slit per period ($J=1$). As expected, this map exhibits permitted bands, which correspond to waveguide resonances within the slits. The transmittance associated with these resonances is almost independent of θ_0, and therefore they appear as flat bands. A similar behavior can be found in the photonic band structure shown in Fig. 2(b) of Ref. [5]. In the range of frequencies considered, the two permitted bands are located at $\omega d/c \approx 2$ and 4.5, which correspond to the peaks at $\lambda/d \approx 1.2$ and 2.5 observed in Fig. 2(a) for normal incidence.

For $J=2$, i.e., when the structure comprises two slits separated by a narrow wire and a wide wire in the period (see Fig. 1), a new characteristic appears in the map [Fig. 4(b)]. Even though the behavior of the bands tends to be that of the $J=1$ case for θ_0 approaching 0, a narrow minimum (light gray zone) appears within each permitted band for $\alpha_0 d > 0.4$, which roughly corresponds to incidence angles $\theta_0 = 10^{\circ}$ and 5° for the lower and upper bands, respectively. This result is in agreement with the second curve in Fig. 2(a), which does not present minima for $\theta_0=0^{\circ}$. However, when $\theta_0 \neq 0$ new phase configurations of the magnetic field can be formed inside the slits, producing phase resonances and allowing dips within the Fabry-Perot resonances. When the number of slits within the period is further increased [$J=3$, Fig. 4(c)], the permitted bands become less localized, the overall transmittance of the structure increases, and a new dip appears within each maximum. This dip corresponds to the symmetric mode discussed above, since it is present not only for oblique but also for normal illumination. Finally, for $J=5$ [Fig. 4(d)] the structure becomes mostly transmitting, although several narrow dark curves can be identified which correspond to transmission minima in the structure response produced by phase resonances.

The phenomenon illustrated in Fig. 4 for a particular set of geometrical parameters is a general characteristic of compound gratings: phase resonances always produce dips in their transmission response. The width and depth of the dips, along with their location within the waveguide resonances, vary with constructive parameters such as slit width and thickness, separation between slits and period of the grating, and also with the conductivity (or refraction index) of the metal. Even though the SIBC is valid for highly conducting metals, it is important to take into account that the skin depth is approximately given by $\delta=\lambda/4\pi\sqrt{\omega/2\pi\sigma}$. Since in the case under study the width of the metal wires is $c=0.08d$ and $\lambda/d\in[1,5]$, one gets for the skin depth-wire width ratio $\delta/c \sim 4\times10^{-5}(\lambda/d) \sim 4\times10^{-5}[1:5] \approx [4\times10^{-5},\ 2\times10^{-4}]$ (for $\sigma=5.17\times10^{17}\ \mathrm{s}^{-1}$, which is a typical value for metals in low frequencies). As expected, the skin depth is negligible for copper under low frequency incidence, and the use of the SIBC is justified in the microwave and millimeter wave regime [34]. However, within the optical range metals are characterized by their complex refraction index ν, and the corresponding skin depth can be comparable to the wire width, in which case the SIBC could not be applicable for the solution of the problem with the geometrical parameters considered in the examples. Then, a rigorous method including the exact boundary conditions should be applied.

This phenomenon can be viewed as the photonic crystal counterpart. A typical band diagram of a photonic crystal presents band gaps, i.e., frequency ranges that are not allowed to propagate inside the crystal and therefore, if the structure is illuminated by a plane wave of a frequency within the gap, all the power is reflected [35]. However, if the perfect periodicity of the photonic crystal is broken by a defect in the structure, allowed states arise within the gap, enabling transmission within the originally forbidden gap.

In the compound gratings considered in this paper, the structures are essentially transmitting, at least within the waveguide resonances peaks, as observed in Figs. 2 and 4. Thus when a simple grating is illuminated by a plane wave of a wavelength within the waveguide resonance peak, most of the power is transmitted through the structure. The addition of complexity to the period in the form of a group of identical slits can be regarded as a defect in the perfect periodicity, and in this case one or more forbidden channels are formed within the allowed bands. Based on the mechanism of phase resonances, structures with a prescribed number of resonances at specified wavelengths could be designed.

To have an idea about the sensitivity of phase resonances to the geometrical parameters of the structure, we performed calculations for structures having different widths a of the slits, while keeping the depth and the distance between slits (c) fixed. It can be observed that as a increases, the waveguide resonance peaks widen, resulting in higher transmission (see Fig. 5). This behavior was already observed in Ref.

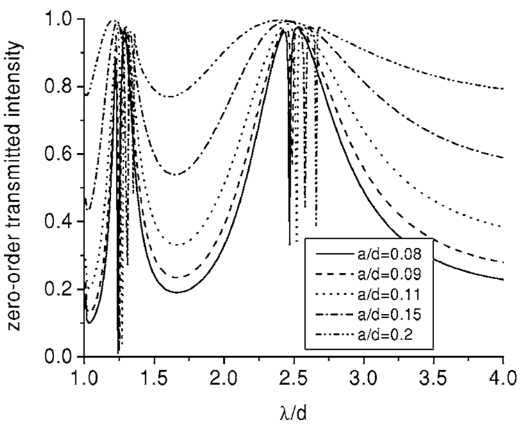

FIG. 5. Zero-order transmittance as a function of the wavelength for a normally incident p-polarized plane wave impinging on a metallic grating with $c/d=0.08$, $h/d=1.14$, $J=3$, and for several values of a/d. The conductivity of the metal is $\sigma=5.17\times10^{17}\ \mathrm{s}^{-1}$.

[27], and it is consistent with the increase in the "open parts" of the structure. Also, the phase resonance dips shift to slightly different wavelengths. The curves in Fig. 5 suggest that the appearance of phase resonances is not particularly sensitive to the slit width, and that the resonant wavelengths depend not only on the width but also on the distance between slits. The dependence of the resonant wavelengths on the depth of the slits can be understood by recalling that phase resonances occur in the vicinity of the waveguide resonances of cavities. If the grating is perfectly conducting, these wavelengths are $\lambda_{res}=2h/m$, with m integer. Then, as the depth varies, the waveguide resonant wavelengths shift, and consequently the dips also move. For reflection gratings, phase resonances appear at different wavelengths since in this case the resonant wavelengths for a perfect conductor are given by $\lambda_{res}=4h/m$, with m integer. Another difference between the behavior of phase resonances in transmission and reflection gratings is that in the reflection case, the power is either reflected or absorbed by the structure, and then, in the wavelength range considered here ($\lambda/d\in[1,5]$), phase resonances are manifested as absorption dips [25]. In the transmission case, on the other hand, the transmittance dips are accompanied by absorption as well as by reflection peaks [28]. Regarding the angular behavior of phase resonances, the requirement to have a phase resonance under normal incidence in both cases is the same: to have at least three slits or grooves within the period. For oblique illumination, it is enough to have two slits or grooves to get a phase mode.

IV. CONCLUSIONS

We have shown that the transmission response of compound gratings can have unexpected features for the p polarization. When these structures are illuminated by an obliquely incident plane wave, sharp dips are found within the well known maxima produced by the Fabry-Perot resonances inside each slit. These dips appear even for a structure with only two slits in the period, in sharp contrast to what occurs for normal illumination. The nature of these anomalies has been explained in terms of phase resonances, characterized by a particular distribution of the phase and a significant enhancement of the field inside the slits. The capability of exciting phase resonances in compound gratings opens up new possibilities for practical applications, such as polarization sensitive aperture shapes for field enhancement devices.

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[1] E. Goulielmakis, G. Nersisyan, N. Papadogiannis, D. Charalambidis, G. Tsakiris, and K. Witte, Appl. Phys. B: Lasers Opt. **74**, 197206 (2002).
[2] Jian Jim Wang, Feng Liu, Xuegong Deng, Xiaoming Liu, Lei Chen, Paul Sciortino, and Ron Varghese, J. Vac. Sci. Technol. B **23**, 3164 (2005).
[3] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[4] H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, Phys. Rev. B **58**, 6779 (1998).
[5] J. A. Porto, F. J. García-Vidal, and J. B. Pendry, Phys. Rev. Lett. **83**, 2845 (1999).
[6] F. J. García-Vidal and L. Martín-Moreno, Phys. Rev. B **66**, 155412 (2002).
[7] M. M. J. Treacy, Phys. Rev. B **66**, 195105 (2002).
[8] Y. Xie, A. R. Zakharian, J. V. Moloney, and M. Mansuripur, Opt. Express **13**, 4485 (2005).
[9] T. Thio, K. M. Pellerin, R. A. Linke, H. J. Lezec, and T. W. Ebbesen, Opt. Lett. **26**, 1972 (2001).
[10] A. P. Hibbins and J. R. Sambles, Appl. Phys. Lett. **81**, 4661 (2002).
[11] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, A. Degiron, and T. W. Ebbesen, Phys. Rev. Lett. **90**, 167401 (2003).
[12] F. J. García-Vidal, H. J. Lezec, T. W. Ebbesen, and L. Martín-Moreno, Phys. Rev. Lett. **90**, 213901 (2003).
[13] J. Bravo-Abad, L. Martín-Moreno, and F. J. García-Vidal, Phys. Rev. E **69**, 026601 (2004).
[14] Y. Xie, A. R. Zakharian, J. V. Moloney, and M. Mansuripur, Opt. Express **12**, 6106 (2004).
[15] 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).
[16] A. Krishnan, T. Thio, T. J. Kim, H. J. Lezec, T. W. Ebbesen, P. A. Wolff, J. B. Pendry, L. Martín-Moreno, and F. J. García-Vidal, Opt. Commun. **200**, 1 (2001).
[17] W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature (London) **424**, 824 (2003).
[18] S. A. Darmanyan and A. V. Zayats, Phys. Rev. B **67**, 035424

(2003).
[19] E. Popov, M. Neviere, S. Enoch, and R. Reinisch, Phys. Rev. B **62**, 16100 (2000).
[20] A. Hessel and A. A. Oliner, Appl. Opt. **4**, 1275 (1965).
[21] V. V. Veremey and R. Mittra, IEEE Trans. Antennas Propag. **46**, 494 (1998).
[22] D. C. Skigin, V. V. Veremey, and R. Mittra, IEEE Trans. Antennas Propag. **47**, 376 (1999).
[23] A. N. Fantino, S. I. Grosz, and D. C. Skigin, Phys. Rev. E **64**, 016605 (2001).
[24] S. I. Grosz, D. C. Skigin, and A. N. Fantino, Phys. Rev. E **65**, 056619 (2002).
[25] D. C. Skigin, A. N. Fantino, and S. I. Grosz, J. Opt. A, Pure Appl. Opt. **5**, S129 (2003).
[26] R. A. Depine, A. N. Fantino, S. I. Grosz, and D. C. Skigin, Optik (Jena) (to be published).
[27] D. C. Skigin and R. A. Depine, Phys. Rev. Lett. **95**, 217402 (2005) [paper selected for publication in the Virtual Journal of Nanoscale Science and Technology http://www.vjnano.org/nano/12, (22) (2005)].
[28] D. C. Skigin and R. A. Depine, Opt. Commun. **262**, 270 (2006).
[29] J. R. Andrewartha, J. R. Fox and I. J. Wilson, Opt. Acta **26**, 69 (1977).
[30] H. Lochbihler and R. Depine, Appl. Opt. **32**, 3459 (1993).
[31] R. A. Depine, in *Scattering in Volumes and Surfaces*, edited by M. Nieto-Vesperinas and J. C. Dainty (North-Holland, Amsterdam, 1990), pp. 239–253.
[32] R. A. Depine, Appl. Opt. **26**, 2348 (1987).
[33] M. Born and E. Wolf, *Principles of Optics*, 7th edition (Cambridge University Press, Cambridge, UK, 1999).
[34] E. Moreno, L. Martín-Moreno, and F. J. García-Vidal, J. Opt. A, Pure Appl. Opt. **8**, S94 (2006).
[35] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton University Press, Chichester, W. Sussex, UK, 1995).