Resonant enhancement of the field within a single ground-plane cavity: Comparison of different rectangular shapes

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The resonant properties of a single cavity in a plane surface are investigated, when it is illuminated by an *s*- or *p*-polarized Gaussian beam. We focus our attention on the rectangular geometry, and consider three different shapes of the grooves: (i) rectangular, (ii) bottle shaped, and (iii) bivalued. A modal approach in its simplest formulation is used to solve the problem for cases (i) and (ii), whereas the multilayer approximation is applied to model the third case. The numerical results exhibit a resonant behavior of the structures at certain wavelengths which can be associated with the resonant wavelengths of a cylindrical waveguide. In particular, a strong enhancement of the field within the cavity is observed for the open rectangular groove when it is illuminated by a *p*-polarized beam. However, we show that *s* resonances are also very important when a bottle-shaped groove is considered. *s* resonances have also been found in a groove with square cross section, showing that in the case of a single ruling there is no need to have a narrow cavity to evidence a resonant behavior. [S1063-651X(99)06903-2]

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I. INTRODUCTION

Resonant effects on rough surfaces have been investigated during the last decades in connection with intensification phenomena such as Raman scattering, second-harmonic generation, and backscattering enhancement of light. It is well known that an air-perfect conductor plane interface can support *p*-polarized surface waves, which are capable of being excited by adding roughness to the surface [1]. On the contrary, it is not feasible for *s*-polarized surface waves to be supported if the surface has shallow corrugations. However, for a large-amplitude roughness of the surface, backscattering enhancement of the light reflected by an *s*-polarized beam was observed for a random rough surface [1]. Andrewartha *et al.* [2] verified that infinite perfectly conducting lamellar gratings exhibit a resonant behavior for certain wavelengths, and Wirgin and Maradudin [3] organized, unified, and completed the work done two decades before by Hessel and Oliner [4] and by Andrewartha *et al.* [2] on the excitation of *s* resonances in infinite gratings. The relationship between this phenomenon and the excitation of surface waves in the structure was also studied later in [5], where the existence of critical values of the corrugations height at which the equivalent surface impedance changes from inductive to capacitive was proved, suggesting also the possibility of supporting *s*-polarized surface waves along lamellar gratings.

The resonant behavior of open cavities had also been studied by many authors. Ziolkowski and Grant [6] studied the resonant characteristics of a slit cylinder enclosing another concentric impedance cylinder, and Colak *et al.* [7,8] studied the resonant properties of a cavity-backed aperture of circular cross section with a lossy material coating. Veremey and Shestopalov [9] and Veremey and Mittra [10] investigated the superdirective properties exhibited by an array of slotted cylinders used as a passive antenna. Recently, numerical evidence of the excitation of *s* and *p* resonances within a circular cavity in a flat surface was also given [11].

In spite of the considerable amount of papers devoted to study the scattering from grooves with circular cross section, only a few authors investigated the resonant features of surfaces having a finite number of cavities with rectangular geometry. Based on the work by Wirgin and Maradudin on lamellar gratings [3], Zuniga-Segundo and Mata-Mendez studied the resonant enhancement of the field within a rectangular groove in a ground plane under *s*-polarized illumination [12]. They arrived at the conclusion that the resonant wavelengths at which this enhancement is present are those corresponding to the rectangular waveguide modes. This result was criticized in a later paper by Maradudin *et al.* [13], where the authors state that the dips observed in the frequency scan in Ref. [12] occur at frequencies for which the surface with the groove acts as a mirror, and not at the frequencies at which the field enhancement occurs. However, in a recent paper by Mata-Mendez and Sumaya-Martinez [14] the authors investigate the resonant enhancement of TE-polarized waves in the vicinity of a finite grating of rectangular grooves. In their work, they insist on considering the resonant wavelengths of the cavities as those of the rectangular waveguide, and they performed numerical calculations for one and two grooves, where they analyze the enhancement of the field and the coupling between grooves for those particular wavelengths.

The research carried out on resonant phenomena in finite gratings is also oriented to the use of these structures in many applications, such as frequency-selective devices, recognition of targets, and passive antennas. For instance, a recent work exploits the resonant characteristics of an array of rectangular grooves and the coupling between them under

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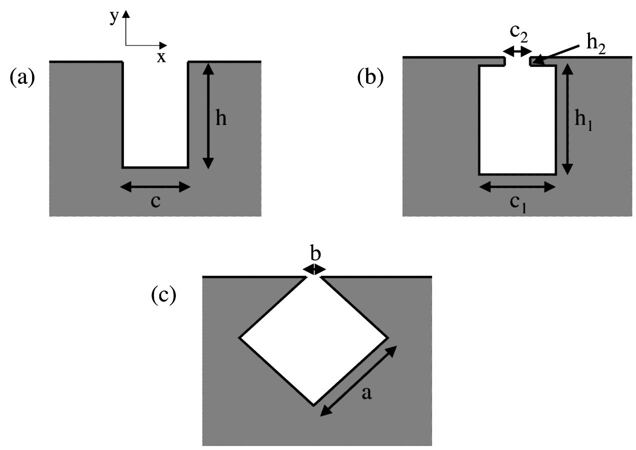

FIG. 1. Rectangular profiles of the cavities considered: (a) open rectangular, (b) bottle shaped, and (c) bivalued.

p-polarized illumination, to obtain superdirectivity in the far-field pattern [15].

The purpose of this work is to investigate the resonant features of a single cavity of rectangular shape in a ground plane and the effect produced by closing gradually the throat of the cavity (bivalued profile) in the excitation of s and p resonances within the groove. The modal method is applied to solve the scattering problem, adapted to deal with the different shapes of the grooves considered: open rectangular [16], bottle shaped, and bivalued [17]. The formalism is briefly outlined in Sec. II, since it is developed in detail in the references above. The results of our numerical calculations are illustrated in Sec. III, where we show the evolution of the frequency response of the structure as the aperture of the groove is gradually closed, for both basic modes of polarization. Contour plots of the field inside the cavity are also given for several interesting situations. Finally, concluding remarks are given in Sec. IV.

II. THEORETICAL FORMULATION

We consider a perfectly conducting plane with a one-dimensional groove. The analysis carried out in the present paper is restricted to rectangular shapes of the grooves, such as those shown in Fig. 1. The invariance of the structure along the ruling direction ($\hat{z}$) allows us to express the six components of the fields in terms of only the z components E_z and H_z. Then, both basic modes of polarization are considered separately: s (electric field perpendicular to the plane of incidence) and p (magnetic field perpendicular to the plane of incidence). We unify the treatment of both cases by denoting $f^q(x,y)$ $(q=s,p)$ to $E_z(x,y)$ for $q=s$ and to $H_z(x,y)$ for $q=p$.

The coordinate origin is set at the left of the mouth of the groove, on the top surface of the structure. The surface is illuminated from the region $y>0$ by a limited beam of wavelength λ and spatial width w, at an angle θ_0 from the y axis:

$$f^q_{\mathrm{inc}}(x,y)=\int_{-k}^{k}\mathcal{A}(\alpha)e^{i(\alpha x-\beta y)}d\alpha, \tag{1}$$

where

$$\beta=\begin{cases}\sqrt{k^2-\alpha^2} & \text{if } k^2>\alpha^2,\\ i\sqrt{\alpha^2-k^2} & \text{if } k^2<\alpha^2,\end{cases} \tag{2}$$

$\mathcal{A}(\alpha)$ is a Gaussian distribution function,

$$\mathcal{A}(\alpha)=\frac{w}{2\sqrt{\pi}}\exp\left\{-(\alpha-\alpha_0)^2\left(\frac{w}{2}\right)^2\right\}\exp[i(\alpha-\alpha_0)b], \tag{3}$$

$$b=\frac{\alpha_0 h+\beta_0 x_0}{k}, \tag{4}$$

$$\alpha_0=k\sin\theta_0, \tag{5}$$

$$\beta_0=k\cos\theta_0, \tag{6}$$

$k=2\pi/\lambda$ is the absolute value of the wave vector, (x_0,h) is the position of the center of the beam, and i is the imaginary unit. The total field in the upper half space is the sum of the incident and the scattered fields,

$$f^q_{\mathrm{total}}(x,y)=f^q_{\mathrm{inc}}(x,y)+f^q_{\mathrm{scatt}}(x,y), \tag{7}$$

where the second term is expressed as a continuous superposition of plane waves,

$$f^q_{\mathrm{scatt}}(x,y)=\int_{-\infty}^{\infty}\mathcal{R}^q(\alpha)e^{i(\alpha x+\beta y)}d\alpha, \tag{8}$$

β is defined in Eq. (2), and $\mathcal{R}^q(\alpha)$ is an unknown complex function.

In the interior of the groove, the fields are represented in terms of the eigenmodes of the cavity. Different approaches are used for the three cases depicted in Fig. 1. For the rectangular groove of depth h and width c [Fig. 1(a)], the field inside the cavity is represented by a modal expansion

$$f^q(x,y)=\sum_{m=0}^{\infty}u^q_m(x)\mathcal{W}^q_m(y), \tag{9}$$

where

$$u^q_m(x)=\begin{cases}\sin\left[\frac{m\pi}{c}x\right] & \text{for } q=s,\\ \cos\left[\frac{m\pi}{c}x\right] & \text{for } q=p\end{cases} \tag{10}$$

ensures the fulfillment of the boundary conditions at the vertical walls of the groove,

$$\mathcal{W}^q_m(y)=\begin{cases}a_m\sin[\mu_m(y+h)] & \text{for } s \text{ polarization},\\ b_m\cos[\mu_m(y+h)] & \text{for } p \text{ polarization},\end{cases} \tag{11}$$

$$\mu_m=\begin{cases}\sqrt{k^2-\left[\frac{m\pi}{c}\right]^2} & \text{if } k^2>\left[\frac{m\pi}{c}\right]^2,\\ i\sqrt{\left[\frac{m\pi}{c}\right]^2-k^2} & \text{if } k^2<\left[\frac{m\pi}{c}\right]^2,\end{cases} \tag{12}$$

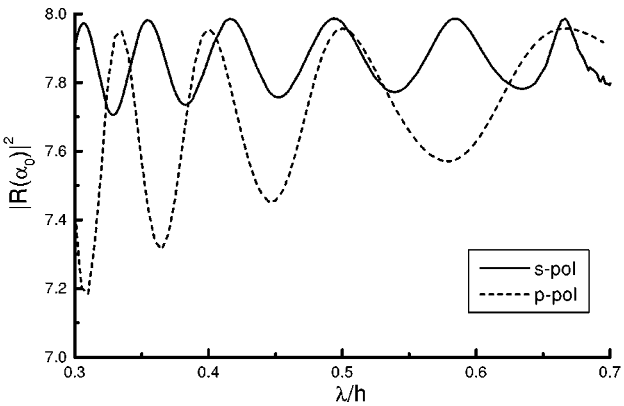

FIG. 2. Intensity reflected in the normal direction versus wavelength, for an open rectangular groove of width-to-depth ratio $c/h = 0.35$. The normally incident Gaussian beam has width $w=100h$. The solid curve corresponds to s polarization and the dashed one corresponds to p polarization.

and a_m and b_m are unknown complex amplitudes. The problem is solved by matching the fields at the surface $y=0$, which results in a pair of x-dependent equations for the unknown function $\mathcal{R}^q(\alpha)$ and the coefficients a_m (or b_m, depending on the incident polarization). These equations are projected on convenient bases, and after discretization and truncation of the integrals the problem is reduced to the solution of a matrix equation, which is solved by standard numerical techniques [16].

As mentioned before, the scattering characteristics of the rectangular groove shown in Fig. 1(a) have been discussed previously by other authors. A novelty of this paper is to address the study of the scattering characteristics of other ''rectangular'' geometries as those shown in Figs. 1(b) and 1(c). Even though these geometries are different from that in Fig. 1(a), we will show that the response curves of the three shapes of cavities in Fig. 1 are intimately connected to each other. Besides, the new geometries considered here will help us to understand better the scattering response of surfaces with cavities.

For the bottle-shaped profile depicted in Fig. 1(b), the treatment is similar to the one described above. However, since the cavity has now two different widths, two different modal expansions are used to represent the fields in each zone. Although the x-dependent part of the modal function $u_m^q(x)$ keeps essentially the same expression for both zones [the only differences are that the width c should be substituted by the corresponding width c_j and the variable x should be substituted by $(x-x_j)$, where x_j is the x coordinate of the beginning of the groove at the zone j], the y-dependent part $\mathcal{W}_m^q(y)$ in the upper part of the groove must be written as

$$\mathcal{W}_m^q(y)=s_m^q \sin[\mu_m y]+t_m^q \cos[\mu_m y]. \tag{13}$$

There are now two additional unknown vectors for each polarization, which correspond to the modal coefficients in the region of smaller width. However, another two matching conditions must be satisfied at the interface between these zones, which provides us with the set of equations necessary to get a complete solution of the problem. The subsequent procedure consists in the inversion of a matrix after the appropriate discretization and truncation of the integrals and series.

TABLE I. Resonant wavelengths for a rectangular groove with $c=0.35h$ given by the condition $\mu_1 h = m\pi/2$, with m odd.

m	λ_{1m}/h
1	0.68952132
3	0.61977853
5	0.52680368
7	0.44266354
9	0.37520569
11	0.32269287

The formalism used to deal with the third situation considered in this paper [see Fig. 1(c)] is substantially different, even though the same idea of modal expansions is used. In this case we apply the multilayer modal method (MMM), which was first used by Li to solve the problem of diffraction from infinite gratings of arbitrary profile [18], and later was extended to solve the problem of scattering by nonperiodic rough surfaces of different profiles and materials [17,19–23]. In particular, the case of multivalued profiles of the corrugations was treated in Ref. [17], where the reader can find the details of the procedure, which is outlined in the next paragraph.

Roughly speaking, the MMM uses the multilayer approximation, which consists in the representation of the actual profile of the groove by a stack of rectangular layers, in each of which the fields are expressed in terms of their own eigenfunctions. Enforcing the matching conditions on the fields at every interface between adjacent horizontal layers, a large system of equations is obtained for the unknown modal coefficients of each layer. At this stage the R-matrix algorithm [24,25] is used to propagate the fields from layer to layer, to finally get a matrix relation between the modal amplitudes of the layer at the bottom and at the top of the cavity. The final step is to invert a matrix to find the function $\mathcal{R}^q(\alpha)$ at certain discrete values. The R-matrix algorithm was shown to be an efficient method for dealing with the problem of scattering by corrugated surfaces, especially when the depth of the cavities is large.

III. RESONANT ENHANCEMENT

The main aim of this work is to study the resonant enhancement of the field produced within a groove in a per-

TABLE II. Resonant wavelengths for a rectangular groove with $c=0.35h$ given by the condition $\mu_0 h = kh = m\pi/2$, with m odd.

m	λ_{0m}/h
1	4
3	1.3333
5	0.8
7	0.5714
9	0.4444
11	0.3636
13	0.3076

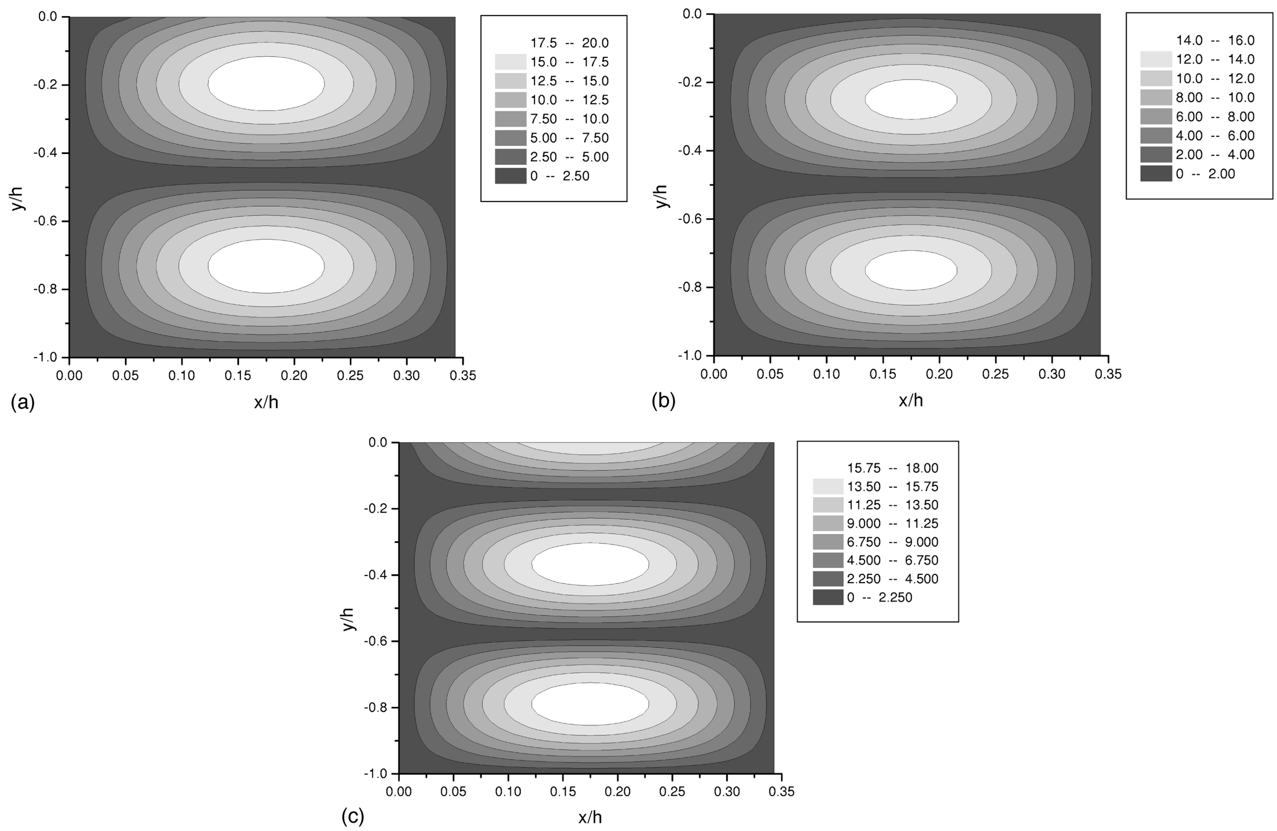

FIG. 3. Absolute value of the electric field inside a rectangular groove of the same parameters considered in Fig. 2 and for s polarization, for different incident wavelengths: (a) $\lambda = 0.586h$, (b) $\lambda = 0.5734h$, and (c) $\lambda = 0.5386h$.

fectly conducting plane, for the rectangular geometries shown in Fig. 1. One of the possible ways to investigate this phenomenon is to analyze the intensity scattered by the structure in a fixed direction as a function of the incident wavelength, for the different profiles considered. In the next figures we show the evolution of the resonant curve from the case of a rectangular groove (open rectangular cavity) to the almost closed bottle-shaped cavity [see Fig. 1(b)]. Both fundamental polarization modes are considered.

We start with the simplest case of a rectangular open cavity, and show in Fig. 2 the intensity scattered in the specular direction [$|\mathcal{R}^q(\alpha_0)|^2$, which for normal incidence coincides with the backscatter and normal direction] as a function of the normalized incident wavelength λ/h. The width of the groove is $c = 0.35h$, and the normally incident beam has a spatial width $w = 100h$, which is nearly equivalent to a plane wave. The curves for s (solid) and p (dashed) polarization are smooth and oscillating, and at a first sight do not exhibit any resonant characteristics. However, it is interesting to notice that the minima of both curves are located at the wavelengths at which a resonance would be expected for the open rectangular waveguide, that is, the wavelengths that satisfy the condition

$$\mu_n h = \left[\left(\frac{2\pi}{\lambda} \right)^2 - \left(\frac{n\pi}{c} \right)^2 \right]^{1/2} h = m\frac{\pi}{2}, \quad \text{with } m \text{ odd.} \tag{14}$$

In terms of the eigenmodes of the cavity, condition (14) corresponds to an odd number of quarter-wavelengths in the y coordinate, i.e., to have a node of the electric field at the bottom of the groove (as required by the vanishing electric field condition at the perfect conductor) and an antinode at its top. For s polarization, the lowest value of n allowed is $n = 1$, which corresponds to the fundamental mode of oscillation in the x direction. Then, the values of the resonant wavelengths are given by

$$\frac{\lambda_{1m}}{h} = \frac{2}{h[(m/2h)^2 + (1/c)^2]^{1/2}}, \tag{15}$$

and the first ones are listed in Table I.

For p polarization, on the other hand, the fundamental mode corresponds to $n = 0$ and then the resonant wavelengths are given by

$$\frac{\lambda_{0m}}{h} = \frac{4}{m}, \tag{16}$$

which take different values than those for s polarization, as can also be checked in Table II.

We remark that the resonant condition (14) is different from the condition given in Eq. (12) of Ref. [12] which, in fact, corresponds to the case of a closed rectangular waveguide. In Ref. [12] the authors studied the resonant wavelengths of a groove with the same geometrical parameters as those considered in Fig. 2, under s-polarized illumination. They based their estimation of the resonances on the existence of poles in the modal expansion of the fields inside the cavity, and found that these poles correspond to the wavelengths associated with the closed waveguide with side

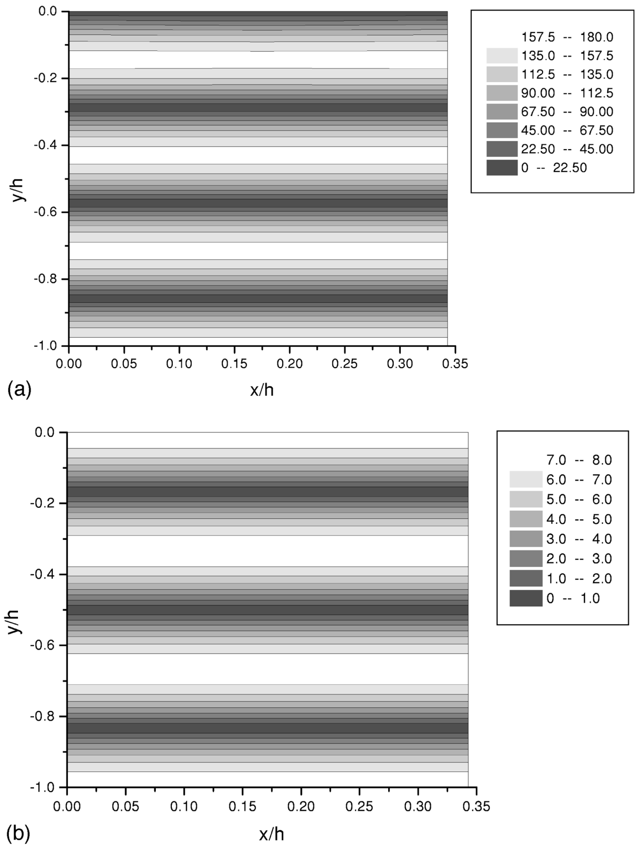

FIG. 4. Absolute value of the magnetic field inside a rectangular groove of the same parameters considered in Fig. 2 and for p polarization, for different incident wavelengths: (a) $\lambda=0.57h$ and (b) $\lambda=0.66h$.

lengths c and h. However, Maradudin *et al.* [13] showed in a later paper that this result is not correct, since the dips found in the wavelength scan in Ref. [12] for certain wavelengths do not correspond to an enhancement of the field but to the condition of vanishing electric field at the top of the groove. Our results also show that there is no significant enhancement of the interior field neither at these wavelengths nor at those given by Eq. (14). In Fig. 3 we plot the field inside the groove for three different wavelengths that correspond to a maximum [Fig. 3(a)], and to a minimum [Fig. 3(c)] of the solid curve in Fig. 2, as well as to the wavelength determined by the waveguide condition [Eq. 15, Fig. 3(b)]. It can be noticed that the electric field vanishes at the walls of the cavity (perfect conductor requirement), and reaches its maximum value at its symmetry axis. Besides, the number of lobes in the groove corresponds to the number of half-wavelengths that it holds. For instance, in Fig. 3(b) the wavelength is such that $\mu h=2\pi$ $(m=2)$, and consequently two lobes appear in the figure. Notice that the intensities in Figs. 3(a)–3(c) are quite similar, which shows that from the point of view of their enhancement characteristics these situations are almost equivalent. The situation is quite different for p polarization: at the resonant wavelengths, which are coincident with the minima of the dashed curve in Fig. 2, a significant enhancement of the magnetic field is found, as shown in Fig. 4. Notice that the maximum of the amplitude $|H_z(x,y)|$ obtained for $\lambda=0.57h$ [Fig. 4(a)], which corresponds to a minimum of the curve, is more than 20 times larger than that

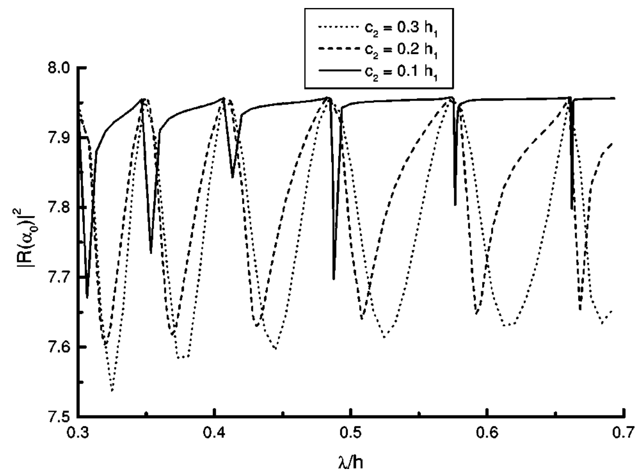

FIG. 5. Intensity reflected in the normal direction versus wavelength, for a bottle-shaped groove of $c_1=0.35h_1$, $h_2=0.01h_1$, and for different values of c_2: $0.3h_1$, $0.2h_1$, and $0.1h_1$. The normally incident Gaussian beam is s polarized and has width $w=100h_1$.

achieved for $\lambda=0.666h$ [Fig. 4(b)], corresponding to the waveguide condition and also very close to a maximum in Fig. 2 (dashed line).

The question that we will try to answer next is how the behavior of the structure is modified when we close gradually the aperture of the cavity. We are going to show that a significant resonant behavior within the groove appears for s polarization only when the throat of the cavity is extremely narrow. In Fig. 5 we plot the response curve for a bottle-shaped groove as depicted in Fig. 1(b), for incident s polarization. The geometrical parameters are $c_1=0.35h_1$ and $h_2=0.01h_1$, and c_2 takes different values. The incident conditions are the same as for Fig. 2. We observe that as c_2 is decreased, the curve tends to form sharp dips at the wavelengths at which the condition of the rectangular waveguide is satisfied:

$$\mu_n h_1=m\pi, \tag{17}$$

which are given in Table III. This condition corresponds to a node of the electric field at the bottom and at the top of the groove, i.e., an integer number of half-wavelengths in the y-dependent part of the eigenfunctions. The dips in Fig. 5 evidence the presence of a singular phenomenon at those wavelengths or, at least, a particular distribution of the fields inside the cavities which modifies the reflected field. Notice that, contrary to what was observed for a rectangular groove (Fig. 2), the resonant wavelengths are now easily identified.

TABLE III. Resonant wavelengths for a rectangular waveguide with $c=0.35h$ given by the condition $\mu_1 h=m\pi$.

m	λ_{1m}/h
1	0.6607008
2	0.5734623
3	0.4827586
4	0.4068667
5	0.3472972
6	0.3009535

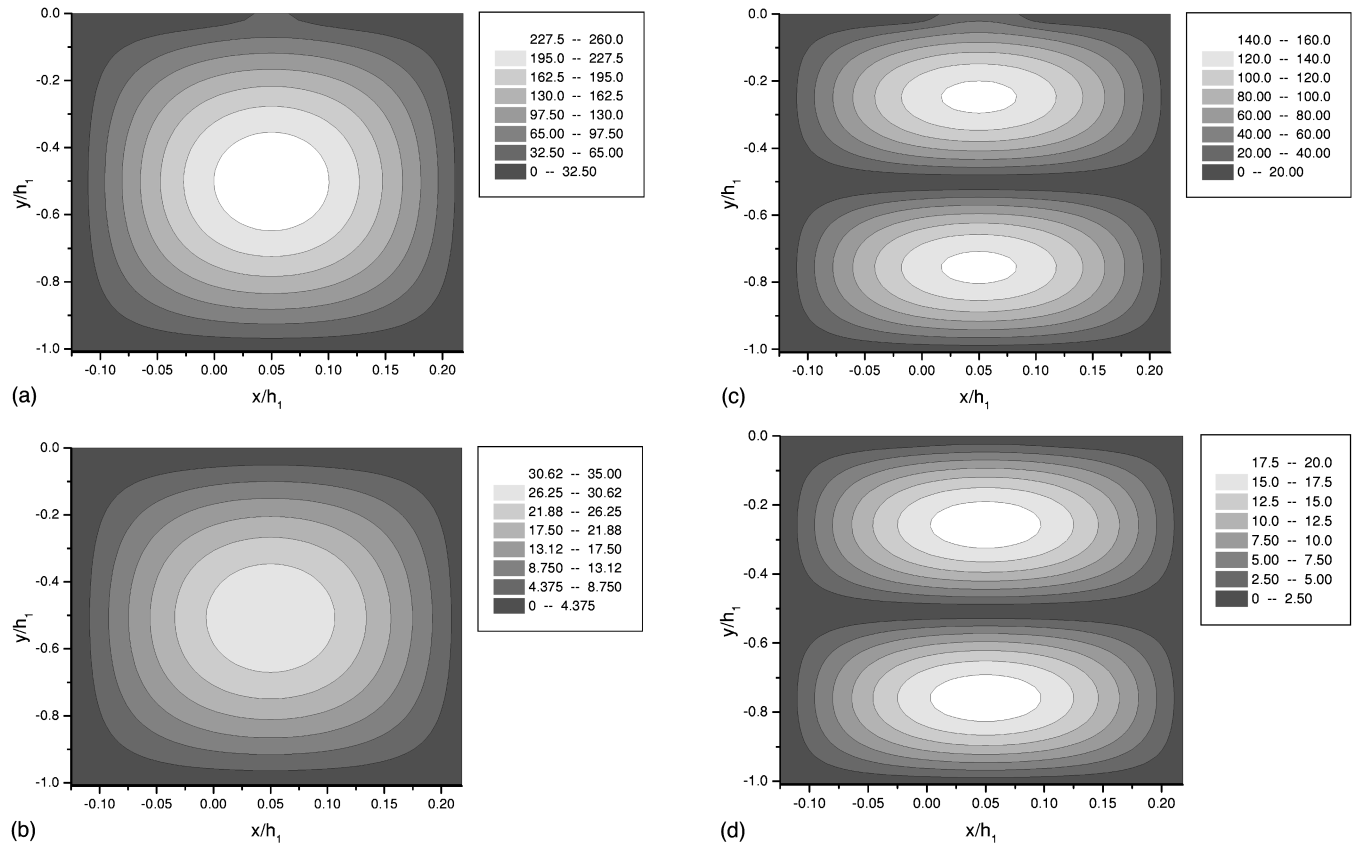

FIG. 6. Absolute value of the electric field inside a bottle-shaped groove of the same parameters considered in Fig. 5, $c_2 = 0.1h_1$ and for s polarization, for four values of the incident wavelength: (a) $\lambda = 0.662h_1$, (b) $\lambda = 0.661h_1$, (c) $\lambda = 0.5765h_1$, and (d) $\lambda = 0.5741h_1$.

To get a better idea of the phenomenon that actually produces the dips in the response curve, we calculated and plotted the absolute value of the electric field $[|E_z(x,y)|]$ inside the cavity, for different values of the incident wavelength. In Fig. 6 we show the contour plots corresponding to the parameters considered in Fig. 5 with $c_2 = 0.1h_1$ for four values of λ: $\lambda = 0.662h_1$ (first resonant value), $\lambda = 0.661h_1$ (just before the first dip), $\lambda = 0.5765h_1$ (second resonant value), and $\lambda = 0.574\,167h_1$ (just before the second dip). The most significant difference that appears between Figs. 6(a) and 6(b) is the enhancement of the field in the groove at the wavelength corresponding to the dip in the resonance curve [Fig. 6(a)], which is about 7 times greater than that of Fig. 6(b). Even though the values of λ considered are very close to each other, and consequently the distributions of the electric field in the cavity are qualitatively very similar, an important intensification takes place for the first wavelength, confirming that the dips are intimately connected with a resonant behavior of the structure. The same characteristics result from a comparison of Figs. 6(c) and 6(d). The presence of two lobes is due to the fact that for this wavelength $m = 2$ in Eq. (17), whereas the former one corresponds to $m = 1$ in the same equation.

As shown next, the behavior is different for incident p polarization. The resonant curves for this case are shown in Fig. 7 for the same geometrical parameters considered in Fig. 5 and for $c_2 = 0.1h_1$ and $0.03h_1$. The response curve of the structure under p-polarized illumination is similar to that exhibited under s polarization: as the throat of the groove is closed, the minima of the curve become sharper, and they get closer to the wavelengths predicted by the waveguide condition (17), which in the case of p polarization correspond to the values given in Table IV. However, for the same width of the aperture, the dips are sharper and better defined for s than for p polarization. This result is in agreement with that shown in [11] for a circular groove. Besides, for the bottle-shaped profile it seems to be more difficult to get a significant enhancement of the magnetic field in p polarization. Even for a width $c_2 = 0.03h_1$ (smaller than the minimum c_2 considered in Fig. 5) an enhancement is found only in a very small region of the groove (the mouth), which does not sug-

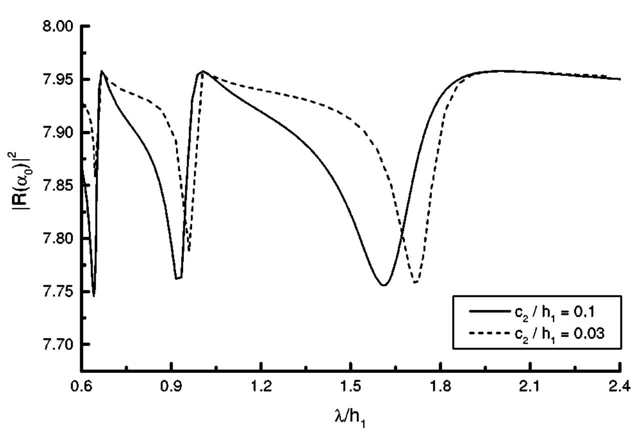

FIG. 7. Intensity reflected in the normal direction versus wavelength, for a bottle-shaped groove of $c_1 = 0.35h_1$, $h_2 = 0.01h_1$, and for different values of c_2: $0.1h_1$ and $0.03h_1$. The normally incident Gaussian beam is p polarized and has width $w = 100h_1$.

TABLE IV. Resonant wavelengths for a rectangular waveguide with $c=0.35h$ given by the condition $\mu_0 h = kh = m\pi$.

m	λ_{0m}/h
1	2
2	1
3	0.6666
4	0.5
5	0.4
6	0.3333

TABLE V. Resonant wavelengths λ_{mn}/h for a square waveguide ($c=h$).

$m\|n$	0	1	2	3
1	2	1.4142	0.8944	0.6324
2	1	0.8944	0.7071	0.5547
3	0.6666	0.6324	0.5547	0.4714
4	0.5	0.4850	0.4472	0.4
5	0.4	0.3922	0.3714	0.3429
6	0.3333	0.3287	0.3162	0.2981

gest a resonant phenomenon inside the whole groove. Moreover, even this local intensification disappears at wavelengths different from those given by the dips in Fig. 7.

One of the interesting applications of the resonant phenomenon described above is the recognition of buried objects. Because of the resonant behavior of this kind of cavity, we do not expect the minima of the response curves to depend strongly either on the incidence conditions or on the particular orientation of the cavity, but only on the geometrical parameters of the groove. Then, the resonant curve of a given cavity is a kind of a fingerprint, which can be used to identify cavity shapes. The next example in Fig. 8 illustrates this feature. There we compare the resonant curves for the bottle-shaped groove with parameters $c_1=h_1$, $c_2=0.1h_1$, and $h_2=0.01h_1$, with the response of a surface with an inclined square groove open in a corner [see Fig. 1(c)], whose parameters ($a=h_1$, $b=0.1h_1$) make it equivalent to the bottle-shaped groove. The incident beam is the same as that considered in the previous figures, and the curves for s [Fig. 8(a)] and p polarization [Fig. 8(b)] are shown. From a careful comparison of both curves in Fig. 8(a) results that all the dips of the solid curve are also present in the dashed curve, which confirms the fact that the resonant wavelengths do not depend on the inclination of the groove but only on its geometrical parameters. It should be noticed that some of the dips are slightly shifted, suggesting that the shapes of the grooves are not exactly the same. However, there is a new dip in the solid curve that corresponds to the rotated square groove. This dip appears at another resonant wavelength of the cavity, which was not allowed to be excited in the bottle-shaped groove under normal incidence because of symmetry reasons. In fact, in this situation only oscillation modes that are symmetric in the x variable are allowed, which correspond to odd values of n in Eq. (17). This is the reason why the authors of Ref. [14] did not find any enhancement for the wavelengths obtained with n even. The resonant wavelengths for a square groove satisfy the relation

$$\lambda_{nm} = \frac{2h}{\sqrt{m^2+n^2}}, \tag{18}$$

and the values of λ_{nm} for the parameters of the example are listed in Table V. It can be noticed that the new minimum appears at $\lambda=\lambda_{22}$, which corresponds to an asymmetric mode in the x variable. Notice also that since the groove has square shape, there is degeneracy in the resonant wavelengths and then $\lambda_{nm}=\lambda_{mn}$. Then, the first minimum in the dashed curve should be understood as the mode λ_{32} instead of λ_{23}. Of course, the depth of the dips of both curves are different, and their relative intensity is connected with the excitation of the resonant modes in each configuration. The investigation of these relations requires a detailed analysis, which is beyond the purpose of the present paper.

The curves corresponding to p polarization exhibit the same kind of behavior. Contrary to what happens for s polarization, the symmetric modes in this case are associated with even values of n in Eq. (17), starting from $n=0$ (see Table V). The solid curve has two more minima (in the range of λ considered) than the dashed one. These additional dips correspond to the wavelengths λ_{11} and λ_{13}, which are not

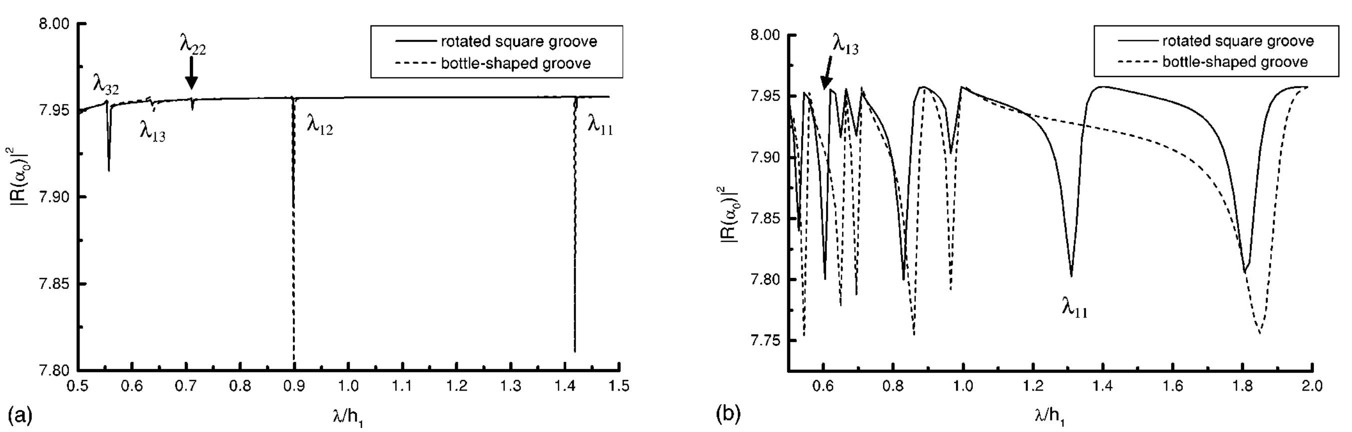

FIG. 8. Comparison between the intensity versus wavelength curves for a bottle-shaped ($c_1=h_1$, $c_2=0.1h_1$, and $h_2=0.01h_1$; dashed curve) and a rotated square groove ($a=h_1$ and $b=0.1h_1$; solid curve). The normally incident Gaussian beam has width $w=100h_1$. (a) s polarization and (b) p polarization.

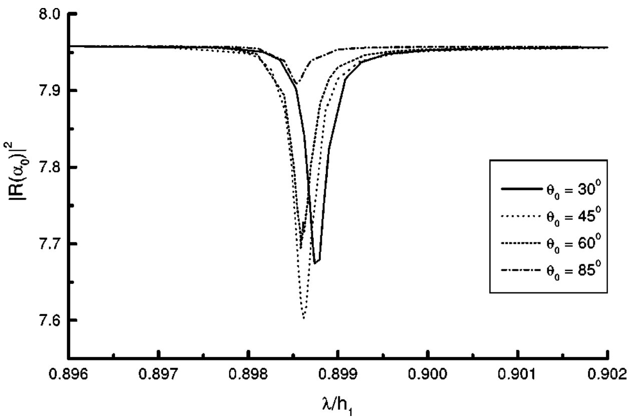

FIG. 9. Intensity reflected in the specular direction versus wavelength, for a bottle-shaped groove with the same parameters considered in Fig. 8 and *s* polarization, for $\theta_0 = 30°$, 45°, 60°, and 85°.

allowed to be excited in the symmetric case. Notice that in *p* polarization the shift between the resonant wavelengths of both curves is more significant. This suggests that this polarization is more sensitive to small variations of the groove shape. In fact, the two cavities considered are not identical in shape.

Another way of exciting the nonsymmetric modes in the bottle-shaped groove is to illuminate the surface via an obliquely incident beam. As an example, we show in Fig. 9 a small portion of the resonance curve which contains the resonant wavelengths λ_{12} and λ_{21}, for different angles of incidence. It can be noticed that the position of the minimum varies only slightly from one curve to the other. The cause of this behavior seems to be that the relative importance of the two resonances, which are extremely close to each other, changes with the angle, causing the dip to move around a given position. The deepest minimum is obtained for $\theta_0 = 45°$, the angle at which the field inside the cavity is more strongly enhanced (not shown).

IV. CONCLUSION

The excitation of resonances in a perfectly conducting surface with a single groove was investigated for different rectangular geometries of the cavity. The modal method was used to solve the scattering problem, helped by the multilayer approximation in the case of a bivalued groove. *s* and *p* polarization of the incident light were considered, and in both cases a resonant behavior was found. Although *s* resonances do not appear in the case of an open rectangular groove, there is a strong enhancement of the electric field inside the cavity when it is gradually being closed, for particular wavelengths that can be associated with those of the closed waveguide. Thus, we conclude that *s* resonances can be excited in a single groove with rectangular shape. For *p* polarization, on the other hand, the intensification is more efficient in the case of an open rectangular cavity. An enhancement of the field is also observed for a square groove in two different positions, confirming that the dips correspond to resonant wavelengths that depend only on the shape of the cavity.

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[1] A. A. Maradudin, T. Michel, A. McGurn, and E. R. Mendez, Ann. Phys. (N.Y.) **203**, 255 (1990).
[2] J. R. Andrewartha, J. R. Fox, and I. J. Wilson, Opt. Acta **26**, 69 (1977).
[3] A. Wirgin and A. A. Maradudin, Phys. Rev. B **31**, 5573 (1985).
[4] A. Hessel and A. A. Oliner, Appl. Opt. **4**, 1275 (1965).
[5] D. C. Skigin and R. A. Depine, Optik (Stuttgart) **94**, 114 (1993).
[6] R. W. Ziolkowski and J. B. Grant, IEEE Trans. Antennas Propag. **35**, 504 (1987).
[7] D. Colak, I. Nosich, and A. Altintas, IEEE Trans. Antennas Propag. **41**, 1551 (1993).
[8] D. Colak, I. Nosich, and A. Altintas, IEEE Trans. Antennas Propag. **43**, 440 (1995).
[9] V. V. Veremey and V. P. Shestopalov, Radio Sci. **26**, 631 (1991).
[10] V. V. Veremey and R. Mittra, IEEE Trans. Antennas Propag. **46**, 494 (1998).
[11] C. I. Valencia and R. A. Depine, Opt. Commun. (to be published).
[12] A. Zuniga-Segundo and O. Mata-Mendez, Phys. Rev. B **46**, 536 (1992).
[13] A. A. Maradudin, A. V. Shchegrov, and T. A. Leskova, Opt. Commun. **135**, 352 (1997).
[14] O. Mata-Mendez and J. Sumaya-Martinez, J. Opt. Soc. Am. A **14**, 2203 (1997).
[15] D. C. Skigin, V. V. Veremey, and R. Mittra, IEEE Trans. on Antennas Propag. (to be published).
[16] R. A. Depine and D. C. Skigin, J. Opt. Soc. Am. A **11**, 2844 (1994).
[17] D. C. Skigin and R. A. Depine, J. Mod. Opt. **45**, 1821 (1998).
[18] L. Li, J. Opt. Soc. Am. A **10**, 2581 (1993).
[19] D. C. Skigin and R. A. Depine, Opt. Commun. **130**, 307 (1996).
[20] D. C. Skigin and R. A. Depine, J. Mod. Opt. **44**, 1023 (1997).
[21] R. A. Depine and D. C. Skigin, J. Opt. Soc. Am. A **15**, 675 (1998).
[22] R. A. Depine and D. C. Skigin, Opt. Commun. **149**, 117 (1998).
[23] D. C. Skigin and R. A. Depine, J. Opt. Soc. Am. A **15**, 2089 (1998).
[24] D. J. Zvijak and J. C. Light, Chem. Phys. **12**, 237 (1976).
[25] J. C. Light and R. B. Walker, J. Chem. Phys. **65**, 4272 (1976).