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Multiple extraordinary optical transmission peaks from evanescent coupling in perforated metal plates surrounded by dielectrics

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Abstract: We study numerically and theoretically the optical transmission of nanostructured gold films embedded in dielectric claddings. We show how multiple transmission peaks appear as the claddings thickness increases. These transmission peaks come not only from surface plasmon polariton excitations but also from the excitation of Fabry-Perot modes sustained at the claddings, coupled through the metal, as long as a periodic pattern is milled in the metal film. We propose that this structure could be used as an ultracompact all-optical switch by surrounding the metal film with Kerr nonlinear dielectric layers.

OCIS codes: (050.2230) Fabry-Perot; (050.6624) Subwavelength structures; (240.5420) Polaritons; (240.6680) Surface plasmons.

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1. Introduction

Transmission of light through reflecting screens has always been fascinating. Such a phenomenon is typically associated with the excitation of some kind of resonances. In that way, the excitation of surface plasmon polaritons (SPPs) using prism couplers can induce high transmission through opaque films [1]. High transmission from subwavelength apertures arrays has also been reported, where the extraordinary optical transmission (EOT) is widely related to SPPs excitation [2]. However, other types of excitations have been shown to play an important role in achieving EOT, such as localized resonances observed in isolated holes and aperiodic arrays [3], or Fabry-Perot (FP) resonances due to the fact that *propagating* modes inside slits set up standing waves between the two ends of the slit [4]. Also, complete tunnelling of light through opaque *flat* slabs where only evanescent waves are allowed can be possible, as long as such a slab is surrounded by two identical slabs with high permittivity [5].

Unlike other studies through perfect electrically conducting (PEC) plates perforated by doubly periodic array of subwavelength holes [6], in this letter we study the case of gold films milled with a square array of holes that allows the coupling of the incident light to both the TE and TM modes supported by the dielectric claddings. In that way, we present how the dielectric claddings thickness and the periodic lattice affect the light transmission through a subwavelength metallic hole array. Multiple transmission peaks appear when increasing the cladding thickness only if the metal film presents a periodic pattern. We present a model that predicts these multiple peaks to come from FP resonances, due to propagating (TE and TM) waves inside the claddings, evanescently coupled through the metal film as long as the metal periodicity is considered in the wavevector component tangential to the metal surface. These transmission resonances are not related to either tunnelling transmission, since for flat metal films no enhanced transmission is observed or FP inside the holes as no propagating modes are allowed inside the metal film. In addition to these FP resonances, transmission peaks induced by SPPs resonances due to the metal periodicity are also present in the spectrum. These transmission features can be used to implement optical filters more compact than those obtained with dielectric multilayers.

2. Numerical and theoretical results

The considered structure consists of a gold metal film milled with a square array of subwavelength holes with radius a of 1μm surrounded at both sides by dielectric claddings with a variable thickness d. The lattice period, P, is 5.5μm and the gold film thickness, d_m, is 100nm. A schematic picture of the structure is shown in Fig. 1(a). In Fig. 1(b) we show the simulated transmission spectrum corresponding to a dielectric cladding thickness d = 4μm for normal incident radiation with its electric field E pointing along the x direction obtained with the licensed software CST Microwave Studio, a general purpose electromagnetic simulator based on the finite integration technique. The relative dielectric constant of gold is fitted by the Drude model with the bulk plasma frequency $\omega_p = 1.36\text{x}10^{16}$ rad/s and damping rate $\gamma = 10^{14}$ Hz [7]. Both cladding slabs are SU8 layers with $\varepsilon_r = 2.25$. From the transmission spectrum of the periodic array (solid line) it can be seen how multiple peaks emerge showing extraordinary transmission. However, these multiple peaks are not expected to appear *only* from SPP theory. The transmission spectrum considering an unpatterned gold film (dashed line) reveals that these resonances are neither due to tunnelling of light by evanescent waves in the gold film nor to FP modes in the SU8 slabs coupled through opaque *flat* metal slabs. In addition, the transmission level is very low as expected for a *flat* optically thick metal film. Thus, only when the structure is periodically patterned the multiple transmission peaks are observed, showing the influence of the lattice in the transmission through subwavelength metallic hole arrays.

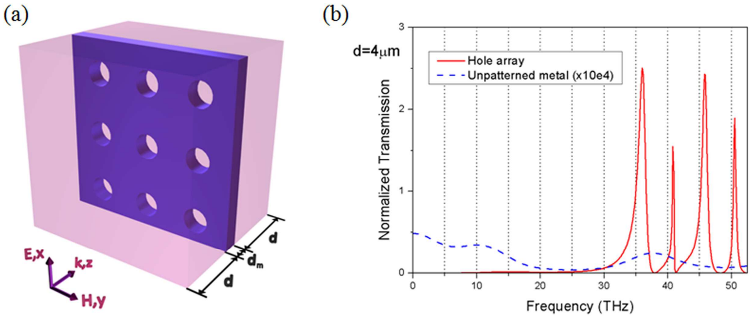

Fig. 1. (Color online) (a) Schematic view of the structure under study and the corresponding reference system used. (b) Transmission through a hole array (solid red line) and an unpatterned gold film (dashed blue line) with dielectric thickness d = 4 μm obtained from numerical simulation.

On the theoretical side, in order to understand the physical origin of the unexpected peaks we derive the conditions required for light transmission from FP resonances through drilled metallic films sandwiched between two surrounding dielectric claddings. Figure 2 depicts a diagram of the FP scheme. A monochromatic transverse magnetic (TM) polarized plane wave is considered as the impinging light in the x-z plane. For simplicity, we consider a flat metal slab with no holes to obtain the transmission coefficient T as a function of the frequency and the transversal wavevector (k_x). Only then, we consider the periodicity in the transversal plane by forcing k_x to have the values given by the reciprocal lattice vectors associated to the periodicity in the metallic hole array. Although this procedure has to be considered as an approximation because the scattering effects caused by the holes are ignored, the predictions of the model are very accurate. In that sense, in analogy with the well accepted model to predict the SPP dispersion relation for single layer hole arrays [8–10], this model provides a simple means to predict analytically an approximate resonant frequency for the EOT peaks coming from the excitation of FP modes without requiring the use of more complex methods that consider the scattering of the holes.

Specifically, the fields in each layer considering propagating waves in the claddings slabs and evanescent in the metal film can be expressed as follows, where the common factor $\exp\left(j\left(k_x x - \varpi t\right)\right)$ is omitted in all the expressions:

$$H_y = A_l^+ e^{jk_l z} + A_l^- e^{-jk_l z}, \quad k_l = \left(k_0^2 - k_x^2\right)^{1/2}. \tag{1}$$

for $z \le 0$,

$$H_y = A_i^+ e^{jk_d z} + A_i^- e^{-jk_d z}, \quad k_d = \left(k_0^2 \varepsilon_d - k_x^2\right)^{1/2}. \tag{2}$$

for the two (i = 1,2) claddings,

$$H_y = B_m^+ e^{k_m z} + B_m^- e^{-k_m z}, \quad k_m = \left(k_x^2 - k_0^2 \varepsilon_m\right)^{1/2}. \tag{3}$$

for the metal film, and

$$H_y = A_t^+ e^{jk_t z}, \quad k_t = \left(k_0^2 - k_x^2\right)^{1/2}. \tag{4}$$

for $z \ge 2d + d_m$.

In the expressions (1)-(4) k_0 is the free-space wave number and ε_d, ε_m are the relative permittivity of the claddings and the metal slab, respectively; $A_n^+ \left(A_n^-\right)$ represents the complex amplitude of the forward-propagating (backward-propagating) waves in the corresponding layer; $B_m^+ \left(B_m^-\right)$ denotes the forward-decaying (backward-decaying) evanescent wave in the metal slab. In particular, A_t^+ corresponds to a transmission amplitude t. The square of its magnitude corresponds to the transmission T coefficient, respectively.

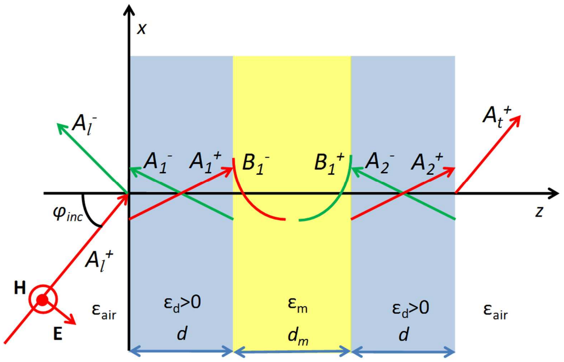

Fig. 2. (Color online) Schematic diagram of the FP configuration for a flat metal slab (ε_m,d_m) surrounded with dielectric claddings (ε_d,d).

It should be remarked that with this electromagnetic scheme no SPP excitation is considered as long as k_d remains a real value. However, in the considered frequency range k_l takes imaginary values. Consequently, the fields are evanescent in the air implying that the supported electromagnetic fields correspond to guided modes only in the dielectric cladding giving rise to FP modes. Thus, there is no possibility for incoming light to couple to the FP modes in flat metal slabs. However, the coupling is possible when the metal is drilled with a periodical pattern due to the additional momentum given by the periodicity. It has to be stressed that it is the periodicity of the hole array what enables the coupling from external light to guided modes and, as a result, the multiple EOT peaks. If the holes were randomly distributed, external light would not couple to these modes [11], and only resonances due to the features of isolated holes would be observed [12]. Figure 3 shows the calculated $T(f,k_x)$ coefficient for the same dielectric thickness as in Fig. 1(b), where T was rescaled for a better representation . The insets show how the sustained modes are propagating in the dielectric and evanescent in the air (they lay between the vacuum and dielectric light lines). Now, the unexpected EOT peaks appeared in the transmission spectrum of Fig. 1(b) can be explained if we just consider the values in k_x associated to the periodicity in the metallic hole array, for which light coupling can be possible. With this consideration, it is inferred from Fig. 3 that transmission is achieved at 37.77 THz, 41.21 THz, 48.16 THz and 53.2 THz, in close similarity to the ones obtained in numerical simulation at 36.07 THz, 40.88 THz, 45.58 THz and 50.33 THz. The predicted resonant frequencies are slightly larger than those obtained in simulations because the scattering effects produced by the presence of the holes are not taken into account in our model [8]. It should be remarked that although the TM$_0$ mode is above the dielectric light line, it becomes a SPP mode when the dielectric thickness increases.

Figure 4(a) shows the simulated light transmission spectra, as a function of the cladding thickness d, through the subwavelength metallic hole array for a normal incoming plane wave. The variations of the peaks resonant frequencies show the spectra dependence on the cladding thickness and how more transmission peaks appear when increasing d. These multiple transmission peaks are not all expected to appear *only* from SPPs theory. On the other hand, Fig. 4(b) shows the variation of the theorized transmission coefficient T with the cladding thickness d, after considering the periodicity of the drilled metallic hole array in the transversal wavevector component k_x. The flat line around 36THz is a numerical artifact which corresponds to the trivial solution of the dielectric light line corresponding to the case when all fields are zero [13]. The same scale factor is also used again to represent T.

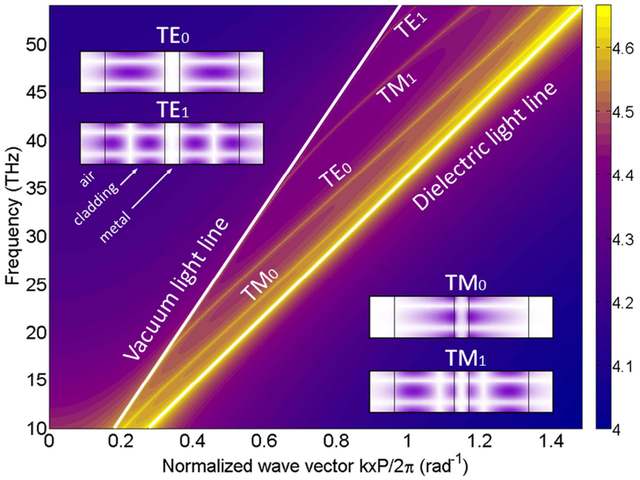

Fig. 3. (Color online) Representation of the theoretical transmission coefficient $T(f,k_x)$ for a dielectric thickness of d = 4 μm. Insets: electric and magnetic fields for TE and TM modes respectively in a structure scaled for better representation.

Comparing Figs. 4(a) and 4(b), leaving the scale factor aside, it can be definitely stated that the multiple transmission peaks observed in the spectra are related to the cladding supported FP modes which are evanescently coupled through the periodically patterned metal slab. In addition, it should be emphasized that for flat metal films no peaks are observed either in the T coefficient of the proposed model or in the simulated spectra. In that way, the holes play a fundamental role in the transmission and in facilitating the FP coupling by means of evanescent coupling through the holes.

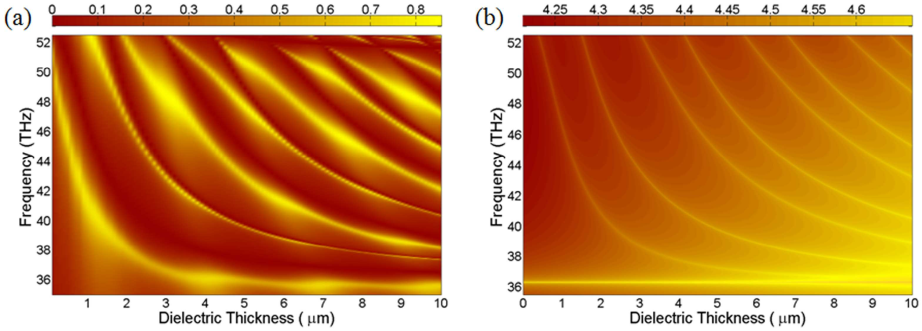

Fig. 4. (Color online) (a) Simulated transmission spectra vs. dielectric thickness d. (b) The same for the calculated transmission spectra T after considering the k_x values associated with the periodicity.

3. Application to ultrafast all-optical switching

The existence of multiple EOT peaks can be used in several applications. Here, we propose that multiple EOT phenomenon can be employed for ultrafast all-optical switching if the metal layer is surrounded by dielectric layers with high Kerr nonlinear coefficients (such as nonlinear polymers [14] or silicon nanocrystals in a silica matrix [15]). The Kerr effect is an instantaneous variation of the refractive index of a dielectric medium proportional to the optical intensity (square of the electrical field). In the structure under consideration (see Fig. 5 inset), high optical intensities inside the dielectric layers are expected even for moderate power levels as a consequence of the strong confinement of the field at the metal-dielectric interfaces. If we assume that there are two different transmission windows (centred at λ_1 and λ_2 respectively) arising from the multiple EOT phenomenon, we can use a high-power pulsed pump signal (tuned at λ_1) to switch a probe signal (tuned at λ_2), as depicted in Fig. 5. When the pump signal is on, the index of the dielectric layers is instantaneously increased owing to the Kerr effect, which results in a red-shift of the EOT peaks. This produces an immediate effective switching of the probe controlled by the pump signal. Compared to other all-optical switching approaches, this structure has the important advantage of being extremely compact in the longitudinal direction, being its size the total dielectric-metal-dielectric thickness. It has to be mentioned that a similar approach (a drilled metal-dielectric-metal structure) has been recently demonstrated to produce subpicosecond all-optical switching by making use of free carriers generated optically [16].

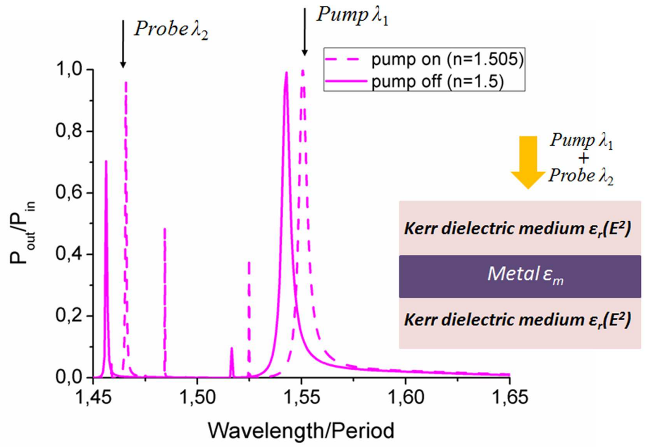

Fig. 5. (Color online) All-optical switch based on multiple EOT through a perforated metal plates surrounded by Kerr nonlinear dielectric media. Pump and probe optical signals are tuned at two different transmission windows (λ_1 and λ_2). The Kerr effect is modelled by slightly increasing the dielectric refractive index n: Pump on n = 1.505, Pump off n = 1.5. Inset: Scheme of the switching structure, which is extremely compact in the longitudinal direction.

4. Conclusion

In conclusion, through theoretical analysis and numerical simulations, we have demonstrated a mechanism for multiple extraordinary light transmission through a classically opaque material independent of conventional tunnelling transmission. The present transmission is characterized by FP modes in the claddings evanescently coupled through the drilled metallic film. Moreover, SPP excitations are also present in the transmission spectrum since the TM_0 mode lies at the right of the dielectric light line for thicker dielectric claddings. Consequently, these results are of great significance as they relate the important role of the periodicity not only to surface modes, like SPPs, but also to propagating modes in the dielectric claddings in the onset of EOT resonances, and also in the design and operation of highly compact optical devices that could become important building blocks in future nano-optical systems.

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