Negative refractive index metamaterials aided by extraordinary optical transmission

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Abstract: We study under which conditions extraordinary optical transmission (EOT) structures can be used to build negative refractive index media. As a result, we present a metamaterial with superimposed EOT and negative index at visible wavelengths. The tailoring process starting from a simple hole array until achieving the negative index is detailed. We also discuss the so-called fishnet metamaterial (previously linked to EOT) under the same prism. Using the ideas put forward in this work, other structures with negative index could be engineered in the optical or visible spectrum.

OCIS codes: (160.3918) Metamaterials; (240.5420) Polaritons; (240.6680) Surface plasmons; (350.3618) Left-handed materials

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1. Introduction

Nowadays, periodic sub-wavelength particle and hole arrays constitute a wide research field within nanophotonics [1]. Two of the most sought after phenomena based on these structures are extraordinary optical transmission (EOT) and negative refraction. The former arises from

#103470 - $15.00 USD Received 30 Oct 2008; revised 15 Jan 2009; accepted 27 Jan 2009; published 31 Mar 2009

the coupling from incident light to Surface Plasmon Polaritons (SPPs) in a drilled metallic sheet, where light undergoes an enhanced transmission, higher than that predicted for a single hole in a perfect conductor [2]. The second effect, negative refraction, is directly related to metamaterials, which gain their properties from their shape rather than from their composition and provide a way to attain optical negative refractive index media (NIM) [3,4]. Usually, both phenomena have been treated separately except for some few cases in which the NIM behavior of the known fishnet structure was linked to EOT [5,6]. In this work, we generalize the relation between EOT and NIMs showing that sometimes it is desirable to have the former in order to achieve the latter. From now on and for the sake of brevity, we will refer to this phenomenon as NEOT (Negative refractive index Extraordinary Optical Transmission).

2. Theoretical remarks

Let us begin with some considerations on EOT so as to motivate our exposition. First, in order to unify criterions, we will consider (as usual) that EOT takes place when the normalized transmission T_n exceeds unity, being T_n defined as $T_n = (P_{out}/P_{in})(A_{ucell}/A_{hole}) = T(A_{ucell}/A_{hole})$, where A_{ucell} is the area of the unit cell, A_{hole} is the area of a single hole and P_{in} and P_{out} are, respectively, the input and output electromagnetic power. On the other hand, there exist a number of structures that lead to the EOT phenomenon. They mainly differ in the shape of the holes and the type and thickness of the metal that constitutes the film in which they are pierced. However, if we regard an EOT structure as a homogeneous medium, we can model it with effective electric permittivity $\varepsilon = \varepsilon' + i\varepsilon''$ and magnetic permeability $\mu = \mu' + i\mu''$, whatever features it may have. We will limit ourselves to study normal incidence with the impinging wave oriented as in Figs.1and 3.Thus, despite the tensorial character of ε and μ, the retrieval of their relevant components for that direction can be considered as a scalar problem. Simple EOT structures (made up of one metal layer) normally act as a dilute metal and exhibit a weak magnetic response. This means that their permittivity is negative at frequencies below that of the first EOT peak (and possibly below other EOT peaks) and that their permeability is small and positive (unless otherwise stated, when talking about permittivity, permeability, impedance or refractive index we refer to their real part). For instance, in the structures analyzed below, μ' is between 0.5 and 0.8 from DC to beyond the first EOT peak frequency. Nonetheless, when the transmission T (not normalized) is close to one, as it usually happens in EOT peaks, the equivalent medium must be impedance-matched to air, *i.e.*, the real part of its equivalent characteristic impedance $z = z' + iz''$ has to be $z' = \mathrm{Re}\{(\mu/\varepsilon)^{1/2}\} \approx 1$. As a consequence, the resonances with high T tend to present positive values of ε' similar to those of μ' (provided that ε'' and μ'' are negligible). In other words, the metal film, which has a highly negative ε' in bulk, exhibits positive ε' frequency regions when drilled, where the transmission is enhanced. In order to achieve a low-loss NIM, it is necessary to have $\varepsilon' < 0$ and $\mu' < 0$ [7]. Owing to the continuity of the constitutive parameters, ε' takes small negative values and crosses zero at frequencies right below the resonance because it is negative at lower frequencies as we mentioned above. Hence, we already have the first condition ($\varepsilon' < 0$) below the EOT peak spectral location. We are interested in this moderately negative ε' region with the aim of obtaining an impedance-matched NIM band, since the negative values of μ' that can be typically achievable artificially are small, especially in the visible regime. Finally, if we could insert a magnetic resonance in this region with μ' taking negative values, we would fulfill the second condition. Our argument can be summarized as follows: pick an EOT structure and modify it in order to introduce a magnetic resonance at a frequency slightly lower than that of the EOT peak, where ε' is still negative. Of course, this modification must not significantly alter the electric response of the medium in the working region. *A priori*, it may seem complex to do this, but next, we present a couple examples.

3. NEOT structures

Consider a simple array of cylindrical holes pierced in a metal film as starting point, with periodicities $a_x = 500$ nm, $a_y = 330$ nm, a hole radius $r = 110$ nm, and a film thickness $t = 130$ nm [Fig. 1(a)]. To obtain the transmission T and reflection R spectra of this structure, we

#103470 - $15.00 USD Received 30 Oct 2008; revised 15 Jan 2009; accepted 27 Jan 2009; published 31 Mar 2009

simulate a unit cell with periodic conditions along the dimensions normal to propagation. All numerical calculations are performed using commercial software (CST MICROWAVE STUDIO). Due to its low loss in the range of interest, we choose silver to be the film metal. The plasma frequency for silver is $\omega_p = 1.37\times10^{16}$ s^{-1}. In general, the collision frequency ω_c is highly influenced by the structure geometry and roughness [8]. Nevertheless, in order to be able to compare our results with previous works, we will assume that $\omega_c = 8.5\times10^{13}$ s^{-1}. This value of ω_c is more than twice as higher as that in bulk [9]. The effective index of refraction $n = n' + \mathrm{i}n''$ and impedance of the medium are retrieved from the calculated T and R using the conventional extraction method [10]. Then, ε and μ are obtained as $n = (\varepsilon\mu)^{1/2}$ and $z = (\mu/\varepsilon)^{1/2}$.

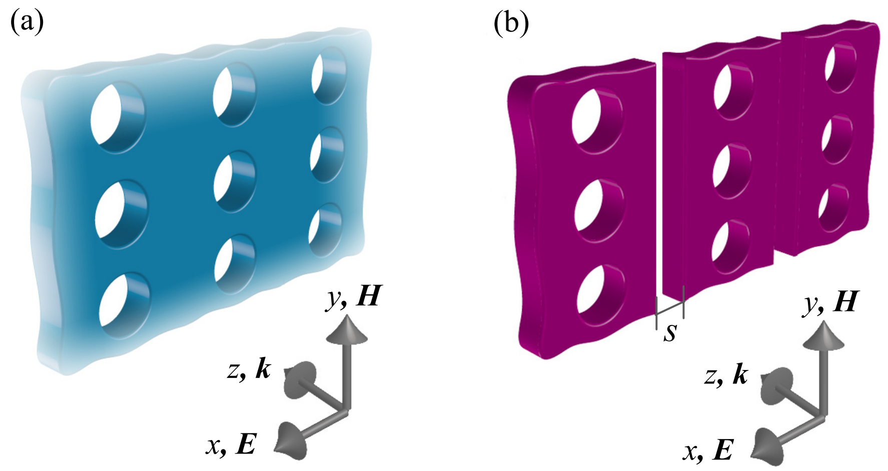

Fig. 1. (a) Silver periodic hole array exhibiting EOT. (b) NEOT structure resulting from adding slits to the structure in (a).

The normalized transmission spectra T_n of the above-mentioned hole array is depicted in Fig. 2(a), where we see two EOT peaks. They can be identified with the even and odd modes of the first plasmonic resonance, which splits into two, due to the coupling between the SPPs excited at both metal-air interfaces of the silver sheet [11]. In Fig. 2(b), it can be seen that z' is near unity where the transmission reaches its maximum, as mentioned before. In addition, the permittivity takes small negative values at frequencies lower than those at which the two resonances are located, mainly near the first one [blue line in Fig. 2(c)], whose maximum transmission is $T = 0.95$. This is the situation that we were searching for. The next step is to introduce magnetic activity at wavelengths slightly higher than that of the resonance. To this end, we propose a modification of the structure in Fig. 1(a) that consists of adding slits in the manner shown in Fig. 1(b). The reason is that it exhibits a magnetic resonance owing to the anti-symmetric mode induced by the incident H field, which generates currents flowing in opposite directions at both sides of the slits, similar to those of the metamaterial studied in [12]. These currents have a resonant nature and are going to give rise to a negative μ' band at frequencies higher than the resonance frequency. Carefully choosing the slit width s, this magnetic resonance including a negative μ' region appears right below the spectral position at which the first EOT peak takes place, where ε' is still negative. In this case $s = 30$ nm and all other dimensions (a_x, a_y, t and r) are the same as before. The addition of the slits strongly modifies the hole array DC response. This is because the slits support a TEM mode without cutoff frequency and allow for a large transmission at high wavelengths. However, the values of T and R are very similar to those obtained before the modification in the region of interest [see Fig. 2(a)]. Even more important is the fact that the permittivities of the EOT and NEOT media are very similar within this band [see Fig. 2(c)]. The extracted part of μ' for the NEOT structure, together with its index of refraction are also shown in Fig. 2(c). We can see that the slits create a negative index band exhibiting EOT as expected. Note that if we had inserted the

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magnetic resonance at lower frequencies, the impedance mismatch would have reduced the transmitted power, since ε' would have been much more negative than μ'. That is why it is better to place the magnetic resonance close to the EOT one. As usual, we can model the losses through the figure of merit (FOM), defined as FOM = $|n'/n''|$. In this case, the FOM is approximately 2.5, which is quite good for this part of the spectrum. Moreover, it could be better, since ω_c might be lower in practice. For instance, the FOM is around 6 when ω_c = 4x10^{13} s^{-1}, a value somewhat higher than the one that can be found in [9]. Further optimization of this structure could also improve its figure of merit.

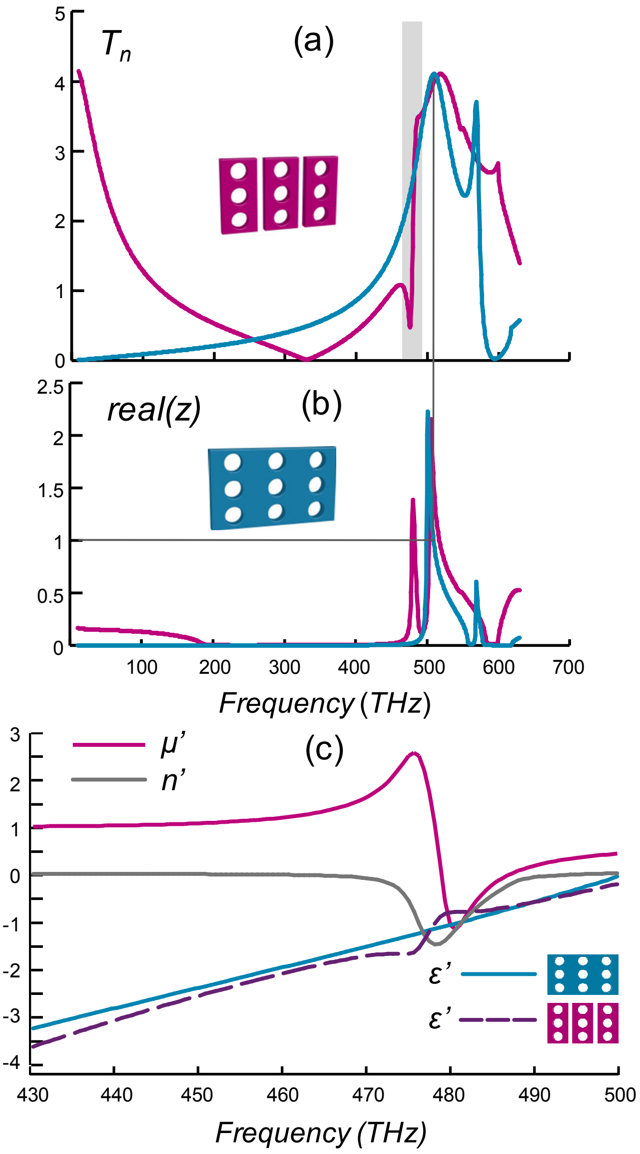

Fig. 2. (a) Normalized transmission of the structures depicted in Fig. 1(a) (blue) and Fig. 1(b) (magenta). (b) Real part of z for both structures (correspondence by color). (c) Comparison of effective ε' for the hole array with (dashed purple) and without slits (solid blue). Retrieved μ' (magenta) and n' (grey) of the hole array with slits [NEOT structure in Fig 1(b)].

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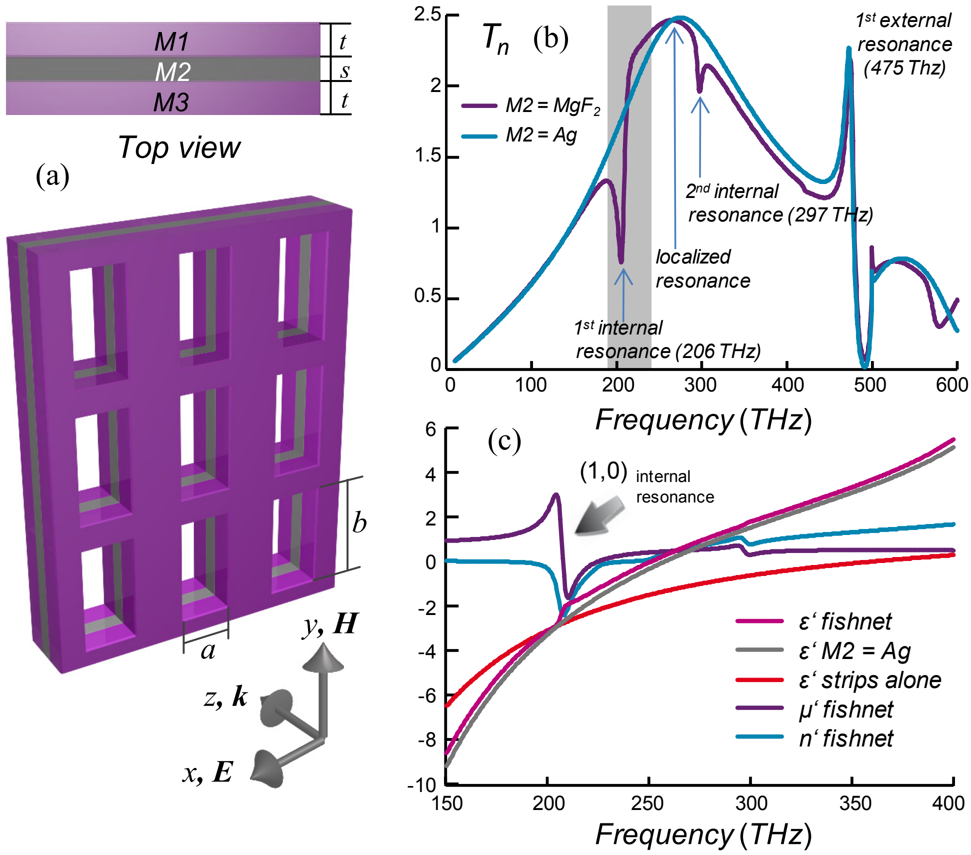

Fig. 3. (a) 3-layer metamaterial. (b) Normalized transmission with M2 = MgF_2 (purple) and M2 = Ag (blue). NEOT region in grey. (c) Fishnet ε' (magenta). ε' of structure in (a) with M2 = Ag and fishnet dimensions (grey) and with b=600 nm, *i.e.*, only horizontal strips (red). Fishnet μ' (purple) and n' (blue).

The structure that we have just studied is not the only NEOT medium. For instance, the fishnet structure is also a very good example of the ideas presented in section 2. Basically, this metamaterial is a rectangular hole array perforated in a metal-dielectric-metal 3-layer structure [Fig. 3(a)]. To analyze it, we can take for instance the dimensions and materials employed in [13], which give a negative n' at telecommunication wavelengths: t = 45 nm, s = 30 nm, a = 284 nm, b = 500 nm, and a lattice constant $l_x = l_y = l$ = 600 nm. The material M1 is silver and M2 is MgF_2, whose refractive index is n = 1.38. It was only very recently that the true mechanisms giving rise to the negative refractive index of the fishnet structure were elucidated [6] and, as in the previous example, it is possible to show that its NIM behaviour can be derived from a simple EOT structure, resulting from replacing MgF_2 by Ag. Thus, this time the starting point is the rectangular hole array of Fig. 3(a) with M1 and M2 being silver. Its normalized transmission is shown in Fig. 3(b). Again we have two EOT peaks. The high frequency one, next to Wood's anomaly, corresponds to the first external SPP resonance and plays no role in achieving a negative n'. The other one, centred at 274 THz, is a localized resonance which occurs at the cutoff frequency of the holes [6]. This will be the high T peak that we demanded in the previous section. Figure 3(c) shows ε' for this hole array. There is almost no difference with the permittivity of the fishnet metamaterial. This fact indicates that the electric response arises from the interaction of the field with the holes and the external surfaces rather than just from the strips parallel to E. The value of ε' generated by these strips

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alone is also depicted in Fig. 3(c). Again, we will focus on the small negative ε' spectral region next to the peak maximum. Obviously, the modification for this structure so as to introduce a magnetic resonance is the insertion of a dielectric layer inside the silver film (making M2 to be MgF_2), that results in a milled MIM (metal-insulator-metal) structure. The electromagnetic modes supported by MIM composites (without holes) have already been studied and it is well-known that internal or gap SPPs appear at the inner metal-dielectric interfaces [14]. In [6,14] it is shown that similar modes are also excited in the fishnet metamaterial. Since the parallel momentum must be conserved, light can couple to internal SPPs when $k_{SPP} = k_0 \sin\theta + iG_x + jG_y$, with $G_x = G_y = 2\pi/l$. For this fishnet configuration and normal incidence ($\theta = 0$), three internal SPP resonances are excited within the frequency range of Fig. 3(b), corresponding to (i,j) equal to (1,0), (1,1) and (2,0) at 206, 297 and 422 THz, respectively. The (2,0) resonance is hardly excited and can roughly be seen in Fig. 3. The (1,0) internal resonance originates currents flowing in opposite directions at each of the Ag layers, generating a negative μ' band in the target negative ε' region. As we mentioned, the insertion of the dielectric does not affect the electric response and consequently a negative n' band appears. This is how a NIM is created from our simple hole array exhibiting EOT. Note that in the case of the structure in Fig. 1(b) we did not employ the localized resonance associated with the cutoff frequency of the holes, which is out of the considered spectral region, but an SPP based resonance. This gives a general character to the ideas described in section 2, where we just demand the existence of a high transmission peak regardless of its physical nature. It is irrelevant whether the peak comes from a Fabry-Perot, shape or SPP resonance as long as its transmission (not normalized) is close to one (and the transmission is small at lower frequencies in such a way that ε' is negative, which is usually the case when dealing with metallic composites). The generation of the magnetic activity by introducing slits also differs from the way it is achieved in the fishnet. As seen, there exist several possibilities for building NEOTs playing with different kinds of EOT peaks and magnetic resonances. This point of view offers a wider perspective when it comes to obtain a NIM with the aid of extraordinary transmission structures. For instance, we could have designed the fishnet in order to use the SPP resonance instead of the localized one, other magnetic resonance source, or any combination that one could think of. The shaded regions in Figs. 2 and 3 correspond to the spectral range where EOT and the negative index occur simultaneously, that is, the NEOT region. Although usually unnoticed, the existence of EOT in the fishnet thanks to the above-mentioned localized resonance is very important in order to achieve a low reflectivity. Otherwise, the equivalent plasma frequency of this structure, and thus the impedance mismatch, would be much higher.

4. Conclusion

In summary, we have shown that EOT structures allow for the creation of negative refractive index composites by taking advantage of high transmission peaks, as long as it is possible to modify the structure in order to create magnetic activity at frequencies slightly lower than those of the peaks. This is the case of the fishnet metamaterial, in which a magnetic resonance exhibiting negative permeability is generated in the proximity of a high T localized resonance. In addition, we have presented a structure with superimposed extraordinary transmission and negative index of refraction at visible frequencies. Although based on the same ideas, the physical origin of EOT and the magnetic activity in the proposed structure is different from the fishnet one, supporting the generality of the described procedure, which opens up the way for building new NEOT structures at optical wavelengths.

Acknowledgments

Financial support by the Spanish MCyT and EU-FEDER under contract TEC2005-06923-C03-03 is gratefully acknowledged. C. García-Meca, R. Ortuño and F.J. Rodriguez-Fortuño also acknowledge financial support from grants FPU of MICINN, FPI of Universidad Politécnica de Valencia, and from a grant of La Caixa, respectively.

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