Electromagnetic tunneling in heterostructures containing single-negative and double-positive media

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Abstract

In this paper, we deal with electromagnetic tunneling phenomena that can take place in certain classes of heterostructures composed of a *single-negative* slab suitably paired with one or two *double-positive* (possibly anisotropic) layers. In this framework, we also explore the sensitivity with respect to frequency and direction of the impinging wave, taking into account material dispersion and losses.

1. Introduction

In [1], Alù and Engheta showed that pairing, under suitable matching conditions, two (homogeneous, isotropic) planar slabs made of *epsilon-negative* (ENG) and *mu-negative* (MNG) materials, respectively, *perfect tunneling* (with zero phase delay) of electromagnetic (EM) waves may occur, in spite of the *inherent opaqueness* of the two constituents when taken alone. This intriguing result motivated a growing interest in the transmission properties of heterostructures containing *single-negative* (SNG) materials, with a variety of extensions and generalizations proposed in the recent literature (see, e.g., [2-10]).

Particularly interesting is the configuration proposed by Zhou *et al.* in [3], which features an ENG slab symmetrically sandwiched between two identical, high-permittivity DPS layers, for which EM tunneling was predicted numerically and observed experimentally at microwave frequencies.

In a series of recent and ongoing investigations [10,11], we have considered similar configurations, but with *asymmetrical* geometries, i.e., with the DPS layer(s) at one side only. In what follows, we compactly summarize the main results and provide some physical insights into this anomalous phenomenon.

2. Summary of our results

In [10], we considered a tri-layer composed of an ENG slab paired with a DPS bi-layer, all assumed homogeneous, isotropic, and non-magnetic (see Fig. 1(a)). For the ideal *lossless* case, assuming time-harmonic, normally-incident, plane-wave excitation, we were able to analytically derive the conditions for *total transmission*. Such conditions, not given here for brevity (see [10] for details), allow to design the DPS bi-layer so as to "compensate" a given ENG slab. In particular, we showed that the relative permittivity ε_2 of the central DPS layer may be *arbitrarily* chosen (even vacuum), while four

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distinct classes of solutions for the remaining parameters generally exist to achieve total tunneling through the system.

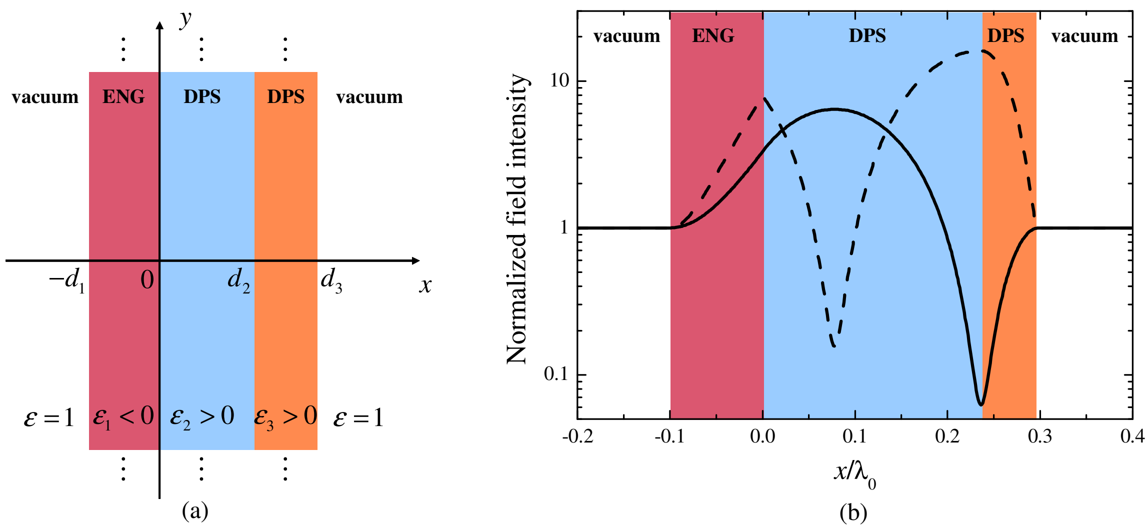

Fig. 1: (From [10]) (a) ENG slab paired with a DPS bi-layer. (b) Normalized resonant electric (solid) and magnetic (dashed) field intensity distributions, for $\varepsilon_1 = -3$, $d_1 = 0.1\lambda_0$, $\varepsilon_2 = 2.5$, $d_2 = 0.236\lambda_0$, $\varepsilon_3 = 16$, and $d_3 = 0.0624\lambda_0$.

In particular, we have shown that the relative permittivity ε_3 of the outermost DPS layer tends to exhibit extreme values for increasing opaqueness of the ENG slab, and that the tunneling phenomenon is always characterized by a nonzero phase delay in this configuration.

Figure 1(b) shows the typical electric and magnetic field distributions at the resonant (total-transmission) wavelength λ_0 for a lossless scenario, characterized by evanescent field growth in the ENG layer and a standing wave distribution in the DPS bi-layer. Figure 2 shows, for a more realistic (dispersive, lossy) parameter configuration, the dependence of the transmittance versus frequency, polarization and incidence direction of the excitation, in which it is seen how the response turns out to be not very selective with respect to the design parameters. More selective responses were obtained by increasing the opaqueness of the ENG slabs, and/or assuming a vacuum central layer (see [10] for more details). For increasing material losses, we observed a degradation of performance qualitatively similar to the case analyzed in [1]. These results effectively indicate that the opaqueness of a lossless SNG layer may, in principle, be somehow perfectly compensated by a dielectric bi-layer for given angle of incidence and polarization.

We are currently working on different configurations featuring a homogeneous, isotropic ENG slab paired with a *single* homogeneous, *anisotropic* (uniaxial), DPS slab. Preliminary outcomes [11] seem promising, and indicate the possibility of achieving, for P-polarization and oblique incidence, complete tunneling (with zero phase delay), with the anisotropy of the DPS slab becoming *extreme* in the limit of normal incidence.

3. Conclusions

In this paper, we have reviewed some recent results from our studies on heterostructures containing SNG and DPS materials. Our results may be extended to other types (e.g., optical, quantum-mechanical, along the lines of [12]) of tunneling mechanisms, and may also suggest more general application scenarios, for which SNG-like responses may be emulated via simpler DPS materials.

Current and future investigations are aimed at exploring the image-formation capabilities of the proposed heterostructures, for possible applications to super-resolution imaging schemes.

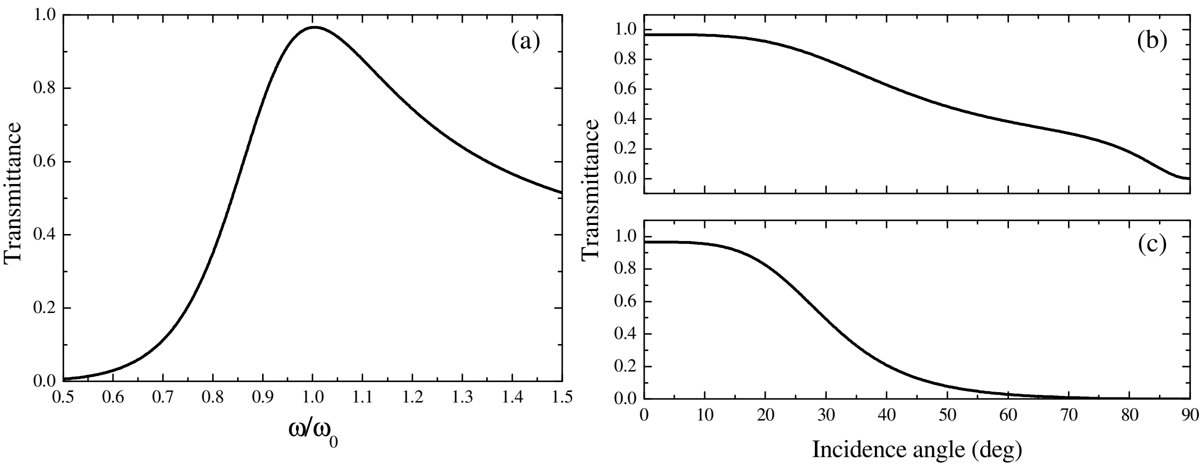

Fig. 2: (From [10]) (a) Transmittance as a function of the normalized angular frequency for the parameter configuration in Fig. 1(b), but using for the ENG slab a Drude-type dispersive, lossy model $\varepsilon_1(\omega) = 1-\omega_{p1}^2/\left[\omega(\omega+i\gamma_1)\right]$, with $\omega_{p1} = 2\omega_0$, $\gamma_1 = 3.75 \times 10^{-3}\omega_{p1}$ (i.e., $\mathrm{Re}[\varepsilon_3(\omega 0)] \approx -3$), and a loss tangent of 10^{-3} for the DPS layers. (b), (c) Resonant transmittance as a function of the incidence angle for the P and S polarizations, respectively.

References

[1] A. Alù and N. Engheta, Pairing an epsilon-negative slab with a mu-negative slab: resonance, tunneling and transparency, *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2558-2571, 2003.

[2] H. Jiang, H. Chen, H. Li, Y. Zhang, J. Zi, and S. Zhu, Properties of one-dimensional photonic crystals containing single-negative materials, *Phys. Rev. E*, vol. 69, no. 6, 066607, 2004.

[3] L. Zhou, W. Wen, C. T. Chan, and P. Sheng, Electromagnetic-wave tunneling through negative-permittivity media with high magnetic fields, *Phys. Rev. Lett.*, vol. 94, no. 24, 243905, 2005.

[4] G. Guan, H. Jiang, H. Li, Y. Zhang, H. Chen, and S. Zhu, Tunneling modes of photonic heterostructures consisting of single-negative materials, *Appl. Phys. Lett.*, vol. 88, no. 21, 211112, 2006.

[5] X. Zhou and G. Hu, Total transmission condition for photon tunnelling in a layered structure with metamaterials, *J. Opt. A: Pure Appl. Opt.*, vol. 9, no. 1, pp. 60-65, 2007.

[6] K.-Y. Kim and B. Lee, Complete tunneling of light through impedance-mismatched barrier layers, *Phys. Rev. A*, vol. 77, no. 2, 023822, 2008.

[7] Y. Fang and S. He, Transparent structure consisting of metamaterial layers and matching layers, *Phys. Rev. A*, vol. 78, no. 2, 023813, 2008.

[8] T. Feng, Y. Li, H. Jiang, Y. Sun, L. He, H. Li, Y. Zhang, Y. Shi, and H. Chen, Electromagnetic tunneling in a sandwich structure containing single negative media, *Phys. Rev. E*, vol. 79, no. 2, 026601, 2009.

[9] G. Castaldi, I. Gallina, V. Galdi, A. Alù, and N. Engheta, Transformation-optics generalization of tunnelling effects in bi-layers made of paired pseudo-epsilon-negative/mu-negative media, *J. Opt.*, vol. 13, no. 2, 024011, 2011.

[10] G. Castaldi, I. Gallina, V. Galdi, A. Alù, and N. Engheta, Electromagnetic tunneling through a single-negative slab paired with a double-positive bilayer, *Phys. Rev. B*, vol. 83, no 8, 081105(R), 2011.

[11] G. Castaldi, V. Galdi, A. Alù, and N. Engheta, in preparation (2011).

[12] I. R. Hooper, T. W. Preist, and J. R. Sambles, Making tunnel barriers (including metals) transparent, *Phys. Rev. Lett.*, vol. 97, no. 5, 053902, 2006.