Broadband DNG response based on high-index materials embedded in a plasmonic host

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Abstract

We show that a metamaterial formed by dielectric inclusions with a suitable geometry and permittivity embedded in a plasmonic host may be characterized by simultaneously negative permittivity and permeability in a broadband frequency range, notably wider than what can be achieved in case of plasmonic particles embedded in a dielectric host. The electromagnetic response of the proposed metamaterial is mildly affected by the arrangement of the cylinders within the plasmonic host, and the metamaterial enables strong broadband negative refraction and superlensing.

1. Introduction

In the last decade, several metamaterial realizations of left-handed media based on materials with a plasmonic-type response have been suggested by several authors [1-4]. These works have demonstrated that a metamaterial formed by an arrangement of closely coupled plasmonic particles embedded in a host material with positive permittivity ε_h can support modes associated with multiple quasi-static resonances (which may occur even for extremely subwavelength particles) that may enable a regime where the metamaterial behaves as a medium with effective permittivity ε_{eff} and permeability μ_{eff} simultaneously negative (DNG material). Nevertheless, in such configurations the frequency band where ε_{eff} and μ_{eff} are simultaneously negative may be relatively narrow (see e.g. Ref [1]) and this is an important drawback. One of the reasons for this narrowband DNG regime is related to the fact that when operating near the plasma frequency of the plasmonic particles, the wavelength of the Bloch modes supported by the metamaterial may be shorter than the length of the unit cell and thus the metamaterial cannot be regarded as an effective medium. Here, we show that somewhat surprisingly it may be possible to overcome these problems simply by interchanging the role of the inclusions and of the host material. We show that in such circumstances the effective medium description is sound and that the DNG response is broadband, enabling strong negative refraction and superlensing. Moreover, we demonstrate that the DNG response does not rely on the particular arrangement of the inclusions in the lattice, and that it may be still quite strong even if the dielectric inclusions are randomly positioned within the plasmonic host.

2. Broadband DNG Response

For simplicity, let us consider a consider a two-dimensional (2-D) geometry, so that the metamaterial is formed by high-index cylindrical dielectric inclusions with radius R, permittivity ε_r and permeability $\mu = \mu_0$, embedded in a plasmonic-type background (see the inset of Fig. 1a). The electric field is assumed to lie in the *xoy* plane, whereas the magnetic field is directed along the z-direction. The permittivity of the host medium is assumed, without loss of generality, to be described by the Drude dispersion model $\varepsilon_h = 1 - \omega_p^2 / [\omega(\omega + i\Gamma)]$, where ω_p is the plasma frequency and Γ is the collision frequency. Using the theory of Ref. [5], we have chosen the permittivity of the dielectric cylinders ($\varepsilon_r \approx 81.42$) and the normalized radius $R/a = 0.42$ in such a way that at $\omega = \omega_p$ the structure behaves as a zero-index material with permittivity and permeability simultaneously near zero. The magnetic response of the metamaterial stems from the excitation of a Mie-type resonance in the high dielectric constant cylinders. Although the focus of Ref. [5] was the realization of a matched zero-index material at some desired frequency of operation, the corresponding theory is also useful to design a DNG metamaterial, because due to causality restrictions for $\omega < \omega_p$ the permittivity and permeability must necessarily be negative in case of low loss. In order to characterize the effective response of the metamaterial, we computed the local parameters $\varepsilon = \varepsilon(\omega)$ and $\mu = \mu(\omega)$ from the nonlocal dielectric function using the full wave method developed in our previous works [7 , 6]. In Fig. 1a we depict the computed results (discrete symbols) as function of frequency. As seen, consistent with the theoretical results of Ref. [5], both the permittivity and the permeability are near zero at the plasma frequency $\varepsilon_{eff}(\omega_p) = \mu_{eff}(\omega_p) \approx 0$. Moreover, $\varepsilon_{eff}(\omega)$ and $\mu_{eff}(\omega)$ are simultaneously negative for $0.81 < \omega / \omega_p < 1$. Notably, the bandwidth of the DNG regime (about 21%) is one order of magnitude larger than what is achievable in the complementary metamaterial configuration, where the role of the inclusions and of the host material is interchanged (see for example Ref. [1]). The solid curves of Fig. 1a represent the effective parameters calculated using the Clausius-Mossotti mixing formulas [8], and concur fairly well with the results computed using our homogenization formalism. In Fig. 1a it is also possible to observe that the effective parameters are such that $\varepsilon_{eff}(\omega) \approx \mu_{eff}(\omega)$. In fact, using the theory of Ref. [5] we are able to fine tune the microstructure in such a way that the material is matched in the DNG regime, ensuring thus a good matching with the free-space for this frequency window of operation.

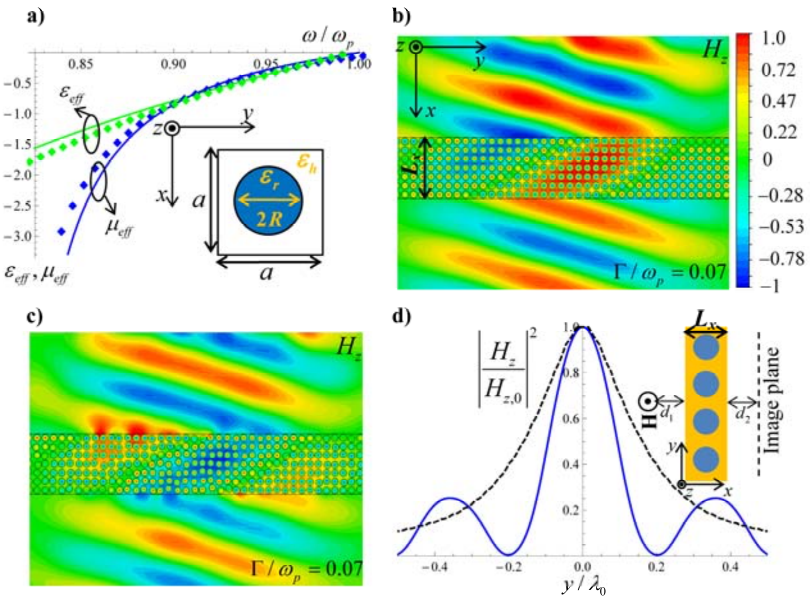

Fig 1 (a) Effective permittivity ε_{eff} (green curves) and permeability μ_{eff} (blue curves) ($\Gamma / \omega_p = 0$) as a function of the normalized frequency ω / ω_p. Discrete symbols: full wave results [7]; Solid lines: Clausius-Mossotti formula. The geometry of the unit cell is shown in the inset: it consists of a cylindrical dielectric inclusion embedded in a host medium described by a Drude-type dispersion model. (b) Snapshot of the H_z field when a Gaussian beam illuminates a metamaterial slab ($L_x = 7a$ and $L_y = 60a$) at an angle of incidence of 33º. (c) similar to (b) but the cylinders and randomly arranged within the metamaterial slab. (d) Normalized amplitude of the magnetic field imaged by the lens at the image plane (located at a distance $d_2 = d_1$ from the interface of the lens) for a source placed at a distance $d_1 = 0.5L_x$ above the lens (solid blue line). The black dashed line corresponds to the magnetic field measured without lens and at a distance $d_1 + d_2$ from the source.

In order to validate our effective medium theory, we used a commercial full-wave electromagnetic simulator [9] to study the refraction of a Gaussian beam by a metamaterial slab with the same microstructure as discussed above. The metamaterial slab is finite along the *x* and *y* directions, with thickness $L_x = 7a$ and with $L_y = 60a$. In the simulation the effect of loss was taken into account by considering that the collision frequency satisfies $\Gamma / \omega_p = 0.07$. The Gaussian beam illuminates the structure along the direction $\theta_i = 33^\circ$. Fig. 1b shows a snapshot in time of the *z*-component of the magnetic field at $\omega / \omega_p = 0.91$, i.e. at the frequency where according to the effective medium model $\varepsilon_{eff} \approx \mu_{eff} \approx -0.7$. The negative refraction effect is clearly seen: the beam is bent in an unusual way, as compared to the refraction in natural dielectrics. An important characteristic of the proposed configuration is that to guarantee the negative refraction, the high-index cylinders do not necessarily have to be periodically arranged within the plasmonic host. In fact, from a theoretical point of view, when operating at the plasma frequency of the plasmonic host, ($\varepsilon_h \approx 0$), a wave that illuminates the slab cannot distinguish if the slab is a continuous medium with $\varepsilon_{eff}(\omega_p) \approx \mu_{eff}(\omega_p) \approx 0$, or a metamaterial implementation of the same medium [5]. Hence, at the plasma frequency the electromagnetic fields cannot sense the granularity of the slab and, in particular, the electromagnetic fields cannot distinguish if the inclusions of the metamaterial slab are periodically or randomly arranged. The reason is that the wave number in the host medium is zero at $\omega = \omega_p$, and hence the electrical size of the inclusions appears to be electrically small, independent of their actual physical size. Even though this property is rigorously valid only when $\omega = \omega_p$, it remains approximately valid for nearby frequencies. To demonstrate this, we consider the refraction of a Gaussian beam by a metamaterial slab with the same geometry as before but now the inclusions are arranged in a random manner. As shown in Fig. 1c, for a frequency of operation close to the plasma frequency ($\omega / \omega_p = 0.91$), the negative refraction is little affected by the random arrangement of the cylinders, consistent with the previous discussion. To study the imaging properties of the proposed metamaterial, we considered the scenario where a magnetic line source is placed at a distance $d_1 = 0.5L_x$ above a slab with $L_x = a$ and $L_y = 50a$. For a frequency of operation $\omega / \omega_p = 0.91$ and considering a low loss scenario ($\Gamma / \omega_p = 0.01$), the magnetic field measured at a distance $d_2 = d_1$ below the interface of the lens is depicted in Fig 1d (solid blue curve). The half-power beamwidth (HPBW) is equal to $0.15\lambda_0$. The normalized magnetic field at the image plane, when the slab is absent and the distance between the source and the image plane is reduced to $d_1 + d_2$ is also shown in Fig. 1d, and has a HPBW of $0.23\lambda_0$. This proves that the lens significantly reduces the effects of diffraction and beam spreading, despite the increased physical distance between the source and image planes.

To conclude, we demonstrated that a metamaterial formed by dielectric inclusions with a suitable geometry and permittivity embedded in a plasmonic host medium may enable a broadband DNG operation, negative refraction, and superlensing. The metamaterial may be realized in the terahertz regime by combining a high dielectric constant material (e.g. TiO_2) and a semiconductor (e.g. HgTe). Furthermore, even if the arrangement of the inclusions within the host plasmonic material is random, the response of the material may be little affected, and a strong negative refraction may still occur. In this talk, we will demonstrate that our results can be generalized to a fully three-dimensional scenario.

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