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Effects of multi-layer stacking along the propagation direction of an infrared metamaterial on the electromagnetic response of the structure

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ABSTRACT

We numerically study a metamaterial structure with unit cells composed of two silver rods standing on a silver plate. While no left-handed behaviour is observed in the case of a single-layer structure, a multi-stacked-layer structure represents a left-handed behaviour at 300 THz. The electromagnetic response is different for different number of stacked layers along the propagation direction, however when the number of stacked layers is large enough, increasing the number of layers has no influence on the EM response of the structure. We also investigate the influence of the lattice constants along different directions on the LH (left-handed) behaviour of the structure.

1. Introduction

According to Maxwell's laws of electromagnetism, materials with negative refraction (left-handed behaviour) are allowed [1]. Although such materials can not be naturally found, negative refraction has been achieved via use of some artificial structures which are called metamaterials [2]. Many researchers have been motivated to investigate in negative refractive index materials because of the importance of the exceptional properties of such materials such as superlensing and light storage and some extraordinary characteristics such as reversal of Doppler effect, negative radiation pressure, etc. [3,4].

A very common way in investigation of metamaterial structures is using of the 'retrieval method' which exploits the complex scattering parameters S_{21} and S_{11} for a thin single layer of a structure to extract the effective refractive index n and effective material parameters such as the complex permittivity ϵ and the complex permeability μ [5–11]. Many different metamaterial structures operating in different regions of the electromagnetic spectrum have been introduced in literature for which the effective electromagnetic parameters have been retrieved by this method [12–20]. Although everything seems to go well, there are two problems; First, this method uses complex S_{21} and S_{11} and because of phase wrapping, there is an ambiguity in determining the phase of the complex transmission and reflection coefficients [11]. Therefore, there is an ambiguity in the retrieved parameters, specially in experimental cases. The second problem arises from the fact that usually, we are interested in constructing 3D MMs (metamaterials). A general method to do this is the layer-by-layer fabrication technique [21,22]. In general, the results obtained by retrieving parameters from a single unit cell layer cannot be extended to the corresponding bulk multi-layered metamaterial. Some cases have been reported in which, at a special frequency, a single layer metamaterial structure represents a negative refractive index whereas the stacked multilayered structure composed of those single layers represents a positive refraction [24].

Another method that is used to extract frequency regions of negative refractive index, specially in experimental cases, is a direct observation of left-handed transmission under normal to plane propagation. This method has been successfully applied to the two widely used metamaterial structures, i.e., the structure composed of split-ring resonators and continuous wires [25] and the structure with short-wire pairs and continuous wires [26–28]. In this method, the negative refractive index frequency region is determined by comparing the electromagnetic transmission spectra from the magnetic structure (the main structure) and the non-magnetic (electrically-shorted) structure. Although this method does not quantitatively determine the material parameters, it qualitatively determines them and does not have the above mentioned problems of the retrieval method and can easily be used for multi-layered structures.

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In this paper, we introduce a metamaterial structure with a unit cell composed of two silver bars standing on a silver plane, exhibiting no left-handed behaviour in a single-stacked-layer along the propagation direction case but representing a LH behaviour at 300 THz in a multi-layered case. No such a structure with this special characteristic has already been introduced in literature. Using the method of direct observation, which is confirmed by the standard retrieval method, no LH behaviour is observed when just one single layer of the metamaterial is considered along the propagation direction. As the number of layers along the propagation direction is increased to three, some evidences of a negative refractive index start to appear. By increasing the number of layers to 5, 7 and 9, the optical response seems to approach a constant trend. Finally, we investigate the influences of the lattice constants in the lateral directions and the lattice constant along the propagation direction (stacking periodicity) on the LH behaviour of the structure.

2. Proposed metamaterial structure

As shown in Fig. 1(a), in each unit cell we use a silver slab deposited on a dielectric layer. The dielectric layer thickness is 100 nm and fills the entire unit cell in the $x-y$ plane. The silver slab lengths along the y and z directions are both 250 nm and its thickness (along the x direction) is 100 nm. A pair of silver rods with a 80 nm length and a square cross section of 40 nm × 40 nm are symmetrically deposited on the slab, perpendicular to its surface. The structure is periodic in the $x-y$ plane with periods of 280 nm and 350 nm, respectively, along the x and y directions. For multilayered structures, we take a stacking periodicity of 400 nm in the propagation direction. See Fig. 1(c).

3. Numerical calculations and discussion

To study the electromagnetic response of the proposed structure, we performed a set of finite-difference-time-domain numerical method (FDTD) calculations using an open source software package, MEEP [29]. To ensure the periodicity of the structure in the x and y directions, we use periodic boundary conditions in those directions while two PML absorbing layers are used in both ends in the z-direction. In our calculations, the dielectric constant of the dielectric layer is taken as $\epsilon = 1.5$ and we use the Drude free electron model for the permittivity of silver,

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma},$$

where ω_p is the plasma frequency and γ is the collision frequency. The ω_p and γ values for silver are taken, respectively, as 1.22×10^{16} rad/s and 9×10^{13} rad/s. Since the dimension of the unit cell in the propagation direction is much smaller than incident electromagnetic wavelengths, an effective medium theory can trustfully be applied [30]. The propagating EM wave is incident normal to the $x-y$ plane with the wave vector in the z direction. We choose the polarization of the incident electromagnetic wave in a way that the electric field component of the wave is along the rods, in the x-direction, to be able to induce electric dipoles along the rods, and the magnetic field component is along the y-direction, perpendicular to the U-shape plane, to be able to induce magnetic resonance, see Fig. 1.

The upper ends of the rods act as a capacitor and facilitates the possibility of a magnetic resonance and therefore, a magnetic response of the structure. When those ends are connected by a thin small conductor (being electrically shorted), the structure becomes completely non-magnetic, with no magnetic response. Therefore, the permeability μ will certainly be positive. The shortening metallic element must be narrow compared to other metallic elements of the structure in the electric field polarization direction to not considerably affect the electric response of the structure (we take its thickness as 20 nm along the x-direction).

To directly observe the frequency regions of negative μ only from the transmission and reflection spectra, we should perform the transmission calculations twice; one with a non-magnetic structure (electrically shorted) for which any stop/transmission band in the transmission spectrum might be because of a negative/positive ϵ, and one with a magnetic structure with the possibility of μ to be negative. Any stop/transmission band in the magnetic case corresponding to a transmission/stop band in the nonmagnetic case can be caused by a negative μ [25,26].

In the following, we first consider a single-layered structure along the propagation direction. In this case, we first investigate the electromagnetic response by the method of direct observation and after that, to confirm the results concluded by this method, we

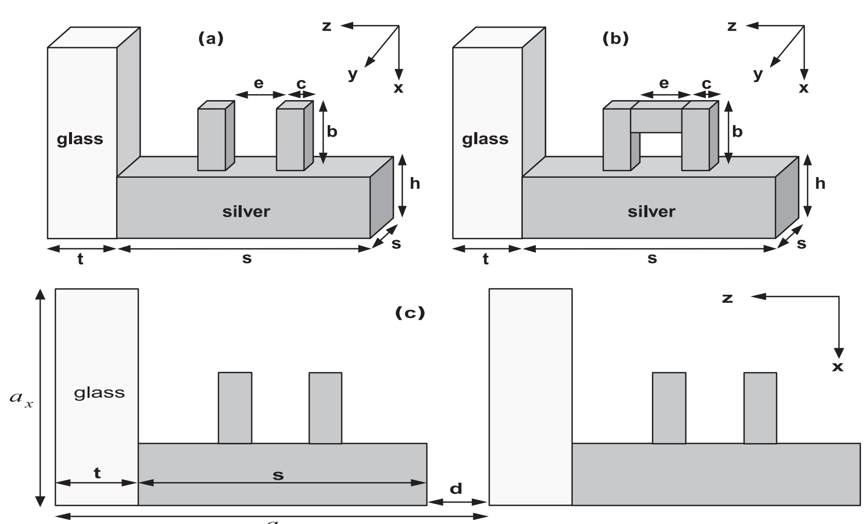

Fig. 1. (a) One unit cell of the metamaterial structure consisting of two silver bars standing on a silver layer, which itself stands on a glass substrate. Numerical values of the parameters are given in the text. (b) The nonmagnetic (electrically shorted) structure. (c) An $x-z$ view of two unit cells in the propagation direction, z. The parameter d shows the stacking distance between cells in the propagation direction. The numerical values of parameters are: $s = 250$ nm, $h = 100$ nm, $b = 80$ nm, $c = 40$ nm, $e = 50$ nm, $t = 100$ nm, $d = 50$ nm, $a_x = 280$ nm, $a_y = 350$ nm and $a_z = 400$ nm.