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Photonic crystal with left-handed components

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ABSTRACT

We show that the periodic array of left-handed cylinders possesses a rich spectrum of guided modes when the negative permeability of cylinders equals exactly to minus value of permeability of embedding media. These resonances strongly influence propagation of electromagnetic waves through photonic structures made from left-handed materials. A series of Fano resonances excited by incident wave destroys the band frequency spectrum of square array of left-handed cylinders and increases considerably the absorption of transmitted waves.

1. Introduction

Left-handed (LH) materials which possess, in certain frequency interval, simultaneously negative electric permittivity $\varepsilon < 0$ and magnetic permeability $\mu < 0$ exhibit interesting physical and optical properties, not observed in standard dielectrics or metals [1–3]. Although LH materials are not commonly available in nature, they may be prepared in laboratories and used for construction of devices with prescribed optical properties.

Physical and optical properties of LH materials have been studied during last 15 years from two different points of view. The first, microscopic, approach concentrates on the analysis of the design of individual "atoms" from which periodic macroscopic LH structure is constructed. The aim of this research is to optimize the structure of individual "atom" with respect to its resonant response which guarantee required properties of resulting macroscopic material [4–7]. The second, macroscopic, approach considers homogeneous LH medium with negative ε and μ and investigates its physical properties as well as possible application of LH material in various photonic devices. Typical example of these studies is detailed theoretical and numerical investigations of one dimensional layered structures composed from alternating LH and dielectric layers [8–11].

Recently it has been shown that components made from LH materials may strongly influence optical properties of 2D photonic structures and lead to unexpected phenomena, not observable in conventional photonic structures made from dielectric materials. For instance, the square periodic array of cylinders made from LH material can possess a non-standard band frequency spectrum which contains the so-called folded bands [12,13]. Such results motivate further investigation how the application of LH materials influences the functionality of optical composites.

In this paper we discuss another unusual property of LH photonic structures. We consider periodic arrangements of LH cylinders shown in Fig. 1 and calculate numerically the frequency dependence of the transmission coefficient of incident electromagnetic (EM) wave. Instead of regular transmission bands and gaps, typical for spectra of spatially periodic dielectric structures [14,15], we observe, for small frequencies, a series of irregular maxims and minims in the frequency dependence of transmission coefficient. An example of such irregular frequency dependence is shown in Fig. 2(b). We show that physical origin of these irregularities lies in the excitation of high number of leaky eigenmodes of the structure and consequent interference of excited field with incident electromagnetic field [16–18]. Similar resonances were observed previously in dielectric photonic structures [19] and their influence on the optical response has been analyzed in Refs. [20–22]. We found that the spectrum of excited resonances strongly depends on actual values of negative permittivity and permeability and is extremely rich if one of these parameters coincides with the minus value of the corresponding parameter of embedding media.

The paper is organized as follows. In Section 2, we calculate transmission coefficient of perpendicularly incident EM wave propagating across the linear array of cylinders and through slab constructed from finite number of parallel arrays. We identify a

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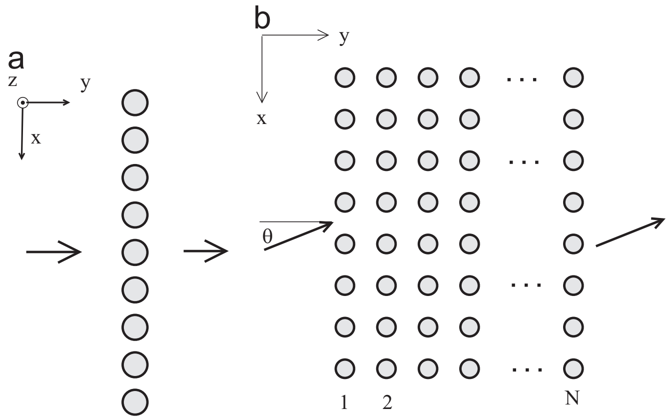

Fig. 1. (a) Periodic linear chain of homogeneous cylinders. Cylinders are parallel to the z-axis, their radius is R, permittivity $\varepsilon = -12$ and permeability $\mu = -1$. The entire structure is periodic in the x direction with spatial period a which is used as a length unit throughout this paper. (b) N parallel chains of cylinders located in planes $y = na$, $0 \le n \le N-1$. The embedding medium is vacuum with permittivity $\varepsilon_1 = 1$ and permeability $\mu_1 = 1$. The incident electromagnetic wave propagating along the y direction with either E_z ($E \| z$) or H_z ($H \| z$) polarization has the wavelength λ and dimensionless frequency $f = a/\lambda$.

series of resonances in the frequency dependence of transmission coefficient. To find their physical interpretation, we analyze the complete spectrum of guided modes of the linear chain of cylinders and show that maxima and minima of the transmission coefficient are associated with Fano resonances excited in the photonic structure by incident EM wave. In Section 3 we study how the electromagnetic response of the structure depends on material parameters: radius of cylinders, magnetic permeability and absorption. Of particular interest is the model with frequency dependent negative permittivity and permeability which also exhibit a series of resonances in the transmission spectra in the frequency interval where either permittivity or permeability approaches the value -1. Since the resonance causes a strong enhancement of electromagnetic field inside the structure, we calculate the absorption of transmitted wave. Conclusion is given in Section 4. Finally, numerical method used for the calculation of the transmissions coefficient is described in Appendices.

2. Linear chain of left-handed cylinders

In this section, we study the response of linear chain of LH cylinders to incident electromagnetic wave. The structure, shown in Fig. 1(a), consists from an infinite periodic chain of cylinders embedded in the vacuum with permittivity $\varepsilon = +1$ and permeability $\mu = +1$. The spatial periodicity of the structure along the x direction, given by distance a between neighboring cylinders, defines the length unit. Cylinders are infinite along the z direction and are made from homogeneous material with relative permittivity $\varepsilon = -12$ and permeability $\mu = -1$.

Incident plane wave with wavelength λ propagates along the y direction. We calculate the transmission and reflection coefficient as a function of dimensionless frequency $f = a/\lambda$. The method is described in Appendix A. Here we only note that electromagnetic field is expanded in series of cylinder functions [23] given by Eqs. (A.2) and (A.3). Expansion on coefficients α and β are calculated from the requirement of continuity of tangential components of electric and magnetic intensity at the boundary of cylinders.

The frequency dependence of the transmission coefficient of the E_z-polarized plane EM wave for both dielectric and LH cylinders is shown in top panels of Fig. 2(a, b). For dielectric cylinders, we identify three deep minima in T which correspond to Fano

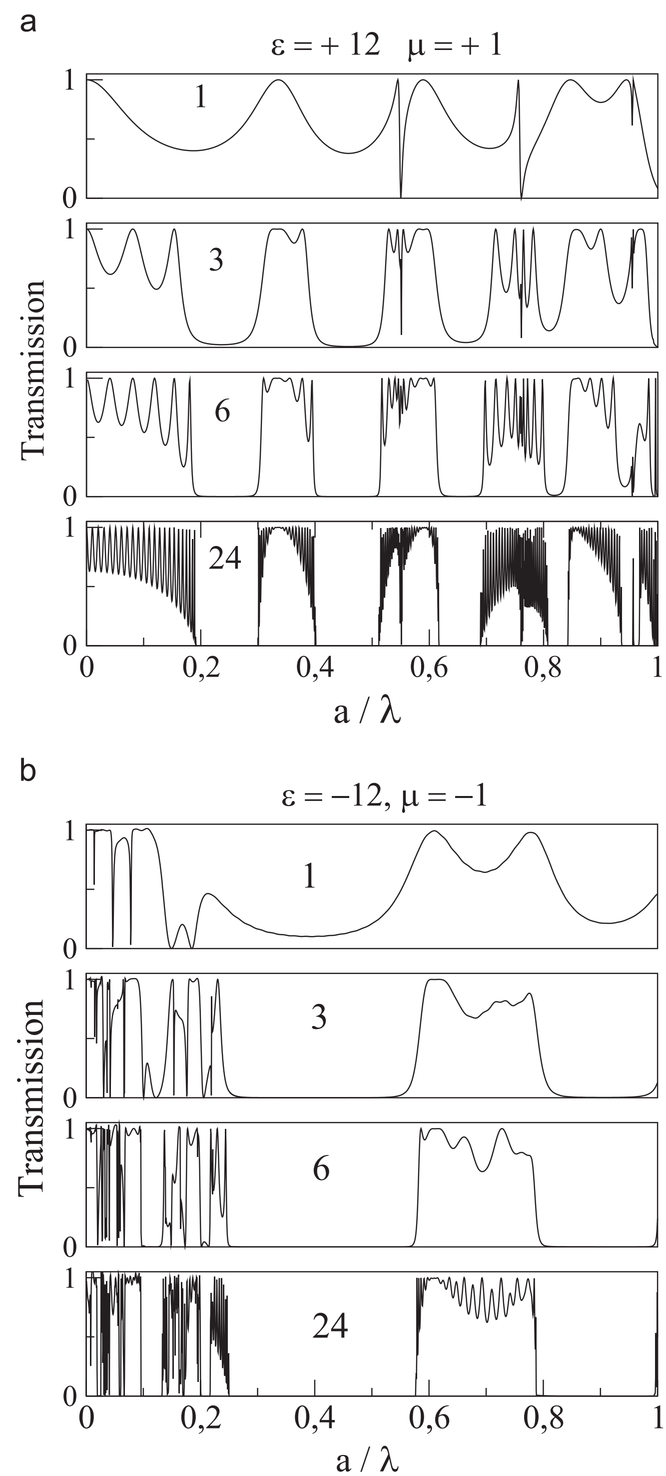

Fig. 2. Transmission spectra for E_z-polarized electromagnetic wave propagating through arrays of (a) dielectric and (b) LH cylinders. The spectra were calculated for N = 1, 3, 6 and 24 rows of cylinders shown in Fig. 1. The cylinder radius $R = 0.3a$. For dielectric cylinders, the spectrum evolves to transmission bands and gaps when the number of rows increases [29]. In contrast, for LH cylinders, the typical band structure arises only for sufficiently high frequencies, $a/\lambda > 0.2$. For smaller frequencies, the transmission spectrum consists from highly irregular series of maxims and minims.

resonances excited by incident wave [16,22]. Similar resonances were found in the LH structure, but their number is much higher and resonant frequencies are located in the region of small frequencies $a/\lambda < 0.2$. Detailed frequency dependence of the transmission coefficient is given in Fig. 3.