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Band gaps and nonlinear defect modes in one-dimensional photonic crystals with anisotropic single-negative metamaterials

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ABSTRACT

We propose a one-dimensional photonic crystal (1DPC) with multilayered periodic structures containing dispersive anisotropic single-negative (ASNG) (permittivity- or permeability-negative) metamaterials. The influences of the ratio of d_A/d_B and their scale on ASNG gaps are discussed. Moreover, the effect of a nonlinear defect layer introduced into the proposed structure is also analyzed, and the results show that the defect mode has two peaks of electrical fields in the defect layer and its bistability property is also different from a defect mode in PCs with isotropic SNG gaps.

1. Introduction

Negative refraction index material (NIM), also known as left-handed material (LHM), was firstly postulated theoretically by Veselago in 1967 [1], and has attracted a great deal of attention recently due to its unusual electromagnetic properties, which can be used in many fields. One of the potential applications of NIM is photonic crystals (PCs) compact and robust against disorder and scale proposed by Li et al. [2]. This new type of photonic band gap (PBG) in one-dimensional PC (1DPC) containing double negative (DNG) material is called zero averaged refractive index (zero-$\bar{n}$) gap, and possesses a lot of remarkable properties, such as invariance upon a change of scale and independence of incident angles and polarizations. Recently PCs with single-negative (SNG) materials are also proposed and analyzed, including epsilon-negative (ENG) material and mu-negative (MNG) material [3,4]. But typical metamaterials with ENG or MNG are realized by stacking sheet of substrate with printed split-ring resonators (SRRs) on their surface [5] or embedded thin metal wires [6], and they always exhibit anisotropic property and have tensor material parameters. Thus, it will be more realistic to analyze the PCs containing anisotropic epsilon-negative (AENG) and anisotropic mu-negative (AMNG) metamaterials [7].

In this paper, to explore an influence of the anisotropy of the single-negative material on PBG and tunneling modes, we propose a 1DPC with multilayered periodic structures containing dispersive AENG and AMNG metamaterials. In the AENG layer, the permittivity is negative but the permeability is positive, which are contrary to that in the AMNG layer. Considering the influence of anisotropy on 1DPC, we assume the permittivity in the AENG media and the permeability in the AMNG media are anisotropic and all the elements are negative. Meanwhile the permeability in the AENG media and the permittivity in the AMNG media are taken as positive constants. We call the special PBG in this structure an anisotropic single-negative (ASNG) gap, and then its different properties from isotropic SNG gaps are analyzed and discussed. In addition, we consider the effect of a nonlinear defect layer introduced into the proposed structure; the electrical field distributions and bistability properties of defect modes are found to be different from that of defect modes in PCs with isotropic SNG gaps.

2. Theoretical model and numerical results

2.1. Band gaps without defect layer

We consider a 1DPC created by alternating layers of uniaxial AENG (white area A) and AMNG (gray area B) material as $(AB)^N$ in Fig. 1, where N is the period number. The two layers are characterized by

$$\vec{\varepsilon}_A = \varepsilon_0 \begin{pmatrix} \varepsilon_{\parallel} & 0 & 0 \\ 0 & \varepsilon_{\parallel} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix}$$

and relative permeability μ_A in layer A and relative permittivity ε_B and

$$\vec{\mu}_B = \mu_0 \begin{pmatrix} \mu_{\parallel} & 0 & 0 \\ 0 & \mu_{\parallel} & 0 \\ 0 & 0 & \mu_{\perp} \end{pmatrix}$$

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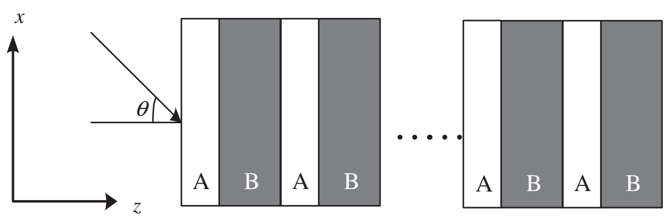

Fig. 1. Schematic of the PC with double-layer unit cells of AENG and AMNG metamaterials.

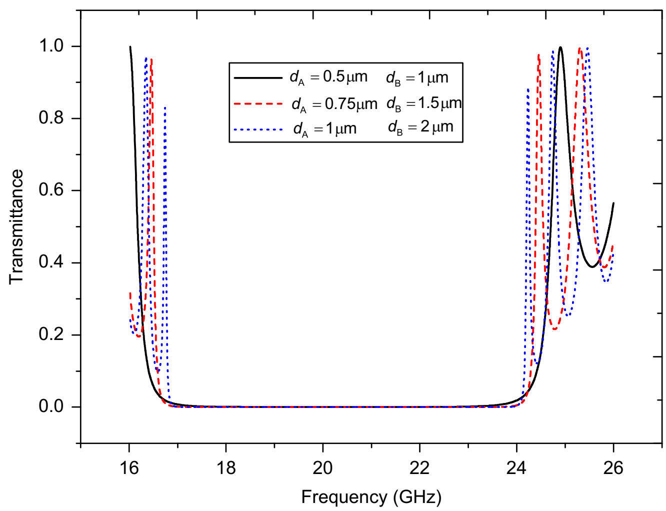

Fig. 2. Transmittance through the 1DPC with a structure of (AB)[19] when $d_A/d_B=0.5$ and $\theta=30^\circ$.

The permittivity of AENG media and permeability of AMNG media are given by the Drude model [3]:

$$\varepsilon_\perp = 1-\frac{f_{ev}^2}{f^2}, \quad \varepsilon_\parallel = 1-\frac{f_{eh}^2}{f^2}, \quad \mu_\perp = 1-\frac{f_{mv}^2}{f^2}, \quad \mu_\parallel = 1-\frac{f_{mh}^2}{f^2} \tag{1}$$

where $f_{eh}(f_{mh})$ and $f_{ev}(f_{mv})$ are the effective electric (magnetic) plasma frequencies in the horizontal and vertical directions, respectively. Here ω is in unit of gigahertz, and we choose $\mu_A=1$, $f_{ev}=34.64$ GHz and $f_{eh}=28.28$ GHz for the AENG material. Also $\varepsilon_B=1$, $f_{mv}=31.63$ GHz and $f_{mh}=29.66$ GHz for the AMNG material. In order to make sure that $\varepsilon_\perp$, $\varepsilon_\parallel$, $\mu_\perp$ and $\mu_\parallel$ are all negative, f must be smaller than 28.28 GHz. So in this paper, we mainly focus on the frequencies between 16 and 26 GHz.

In this case, we take advantage of the transfer-matrix method [8] to investigate the photonic band gap in the PC without defect layer.

Let a TE wave be injected from vacuum into the 1DPC with $N=19$ at an incident angle $\theta=30^\circ$ with $+z$ direction. We discuss the property of ASNG gap as $d_A/d_B=0.5$ and the scale changes from 1.5 to 2 in Fig. 2. It can be found that the PBG is narrowed and its middle is almost unchanged. This is different from the isotropic SNG gaps [3], which are invariant with scale.

In what follows, we will discuss the change of the ASNG gap with d_A/d_B ratio when period length is fixed ($d_A+d_B=3$) as shown in Fig. 3 where the incident angle is also 30°. As d_A/d_B increases from 0.5 to 1, the PBG is narrowed and the electric field of the middle frequency ($f=20.5$ GHz) in the gaps is reinforced in Fig. 4. When d_A/d_B is larger than 1, PBG appears again and becomes wider in Fig. 3 but the electric field ($f=20.5$ GHz) is weakened in Fig. 4 with the increase in d_A/d_B. It can be concluded that wider band gap corresponds to weaker electric field. Here we notice that when $d_A/d_B=1$, there is no obvious band gap and the electric field is resonantly enhanced. This phenomenon is not found in band gaps from isotropic single-negative material.

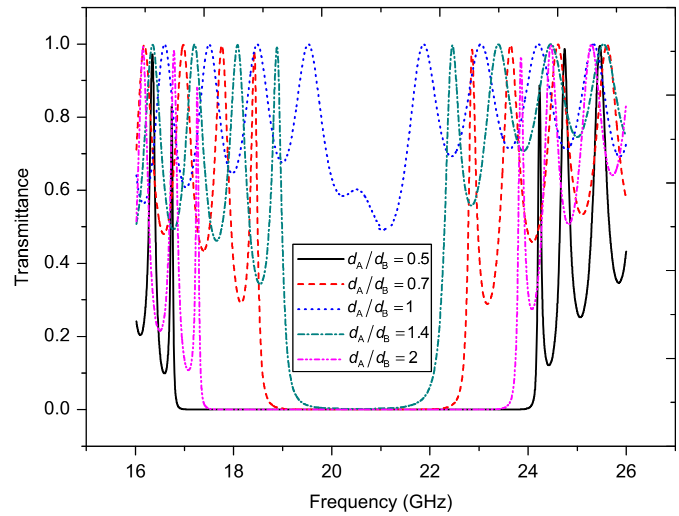

Fig. 3. Transmittance through the 1DPC with a structure of (AB)[19] when $d_A+d_B=3$ and $\theta=30^\circ$.

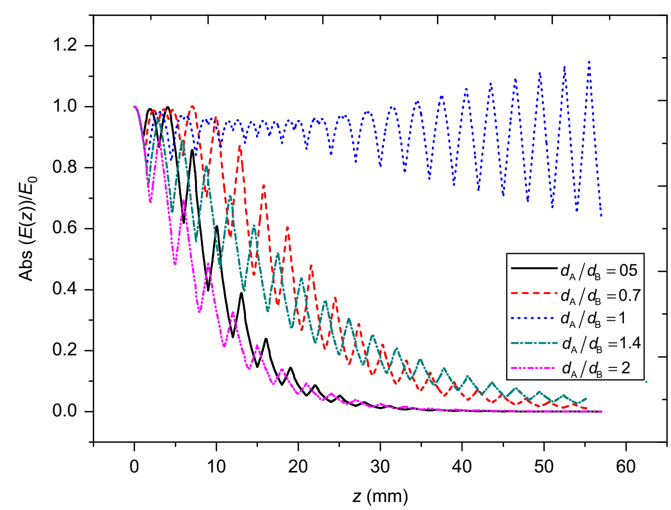

Fig. 4. Electrical field distributions through the 1DPC with a structure of (AB)[19] when $d_A+d_B=3$ mm, $f=20.5$ GHz and $\theta=30^\circ$.

2.2. Nonlinear defect modes

Now we introduce a nonlinear defect layer C into the photonic crystal as $(AB)^9C(BA)^9$, and the nonlinear transfer-matrix method [9] is used to solve this problem. The basic principle of this method is to divide the nonlinear layer into several layers and compute the input power by the output power inversely. We choose $d_C=9$ mm, $d_A=1.75$ mm, $d_B=1.25$ mm, $\mu_C=1$, $\varepsilon_C=3+\alpha|E|^2$ and $\alpha=0.1$. When a TE wave is injected from vacuum into the 1DPC with defect layer at an incident angles of $\theta=0^\circ$, 15° and 30° with $+z$ direction, the corresponding defect mode frequencies are 19.25, 19.28 and 19.36 GHz, respectively. We can find that the frequency of defect mode is also increasing with the increase in incident angle in an isotropic system [10]. For further study, the electrical fields distribution of the proposed PC are shown in Fig. 5 where $E_{out}=1$ V/m and $f=19.25$ GHz. There are two equal peaks of electrical field in the defect layer, and their amplitudes are also enlarged with the increase of incident angle. These properties are totally different from a system with isotropic