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Photonic band gap and defect mode from a layered periodic structure with anisotropic nonmagnetic right-handed and left-handed metamaterials

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ABSTRACT

We demonstrate a photonic band gap (PBG) from a layered periodic structure containing anisotropic nonmagnetic right-handed and left-handed metamaterials whose permittivity elements are partially negative. A set of criteria imposed on materials and structures to realize a PBG is derived, and the transmission spectra are also discussed. When a defect layer is introduced, some unusual properties are found in contrast to that of a defect mode in ordinary PBG structures.

1. Introduction

Left-handed metamaterial (LHM) is a type of artificial composite [1–3] with a large number of unusual electromagnetic properties, such as negative refractive index, antiparallel group and phase velocities. It has potential applications in optics, material science, biology, and biophysics. Photonic crystals (PCs) [4] is a another type of artificial material with periodically dielectric modulated function, and it received considerable attention in recent years because of its property for stopping photons with forbidden frequencies from propagating in the structure. In particular, PCs containing LHM were shown to have several extraordinary properties. For example, a new type of PC with zero-Φ_{eff} gap can be realized in a layered system combining both isotropic positive- and negative-index material, which is robust against weak disorder and lattice scaling and possesses omnidirectional gaps [5,6]. Because most LHMs are dispersive and anisotropic, one-dimensional photonic band-gap (PBG) structure with dispersive LHM [7,8] and two-dimensional PBG structure with anisotropic LHM [9] are also presented. In Ref. [9] all elements of permittivity and permeability tensors of the anisotropic LHM discussed are assumed to be negative. However, this is not generally practical. A novel nonmagnetic LHM is proposed in Ref. [10] which is based on the strongly anisotropy of the dielectric response, and does not have any magnetic response ($\mu=\mu_0$). It has an anisotropic uniaxial dielectric constant $\vec{\varepsilon}$, with $\varepsilon_x=\varepsilon_y=\varepsilon_0\varepsilon_\parallel>0$ and $\varepsilon_z=\varepsilon_0\varepsilon_\perp<0$. The author also pointed out that if $\varepsilon_\parallel<0$ and $\varepsilon_\perp>0$, the metamaterial is shown to be regular right-handed material (RHM).

In this paper, we propose and demonstrate a PBG from a layered periodic structure containing the above RHM and LHM. It is different from the system in Ref. [9] because the RHM and LHM in our structure are both anisotropic with partially negative elements of $\vec{\varepsilon}$ tensor, while in Ref. [9] only one anisotropic layer is contained in the unit cell (the other one layer is air) and all elements of $\vec{\varepsilon}$ and $\vec{\mu}$ tensors are negative. Moreover, our structure does not require completely magnetic resonance which is necessary in all the PBG structure we have mentioned above. Here we call the special PBG as a double anisotropic nonmagnetic (DANM) gap which differs from the traditional Bragg gap and zero-Φ_{eff} gap. By analyzing the trace of the transfer matrix a set of criteria imposed on the materials and structures to realize a DANM gap is derived. Then the transmission spectra are also discussed by utilizing the transfer-matrix method [11]. In addition, we consider the effect of a defect layer introduced into the presented structure, and some unusual properties are found in contrast to that of a defect mode in PCs with Bragg gap or zero-Φ_{eff} gap.

2. Criteria to realize a DANM gap

We consider a one-dimensional periodic layered stack created by a double-layer unit cell with alternate anisotropic RHM

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Fig. 1. Schematic of the PBG structure with a double-layer unit cell of anisotropic RHM and LHM.

(black area A) and LHM (grey area B) layers of thicknesses d_A and d_B, as shown in Fig. 1. They are characterized by permittivity tensors

$$\varepsilon^A = \varepsilon_0 \begin{pmatrix} \varepsilon_\parallel^A & & \\ & \varepsilon_\parallel^A & \\ & & \varepsilon_\perp^A \end{pmatrix}$$

and

$$\varepsilon^B = \varepsilon_0 \begin{pmatrix} \varepsilon_\parallel^B & & \\ & \varepsilon_\parallel^B & \\ & & \varepsilon_\perp^B \end{pmatrix}$$

respectively, where $\varepsilon_\parallel^A = \varepsilon_\perp^B = \varepsilon_\perp < 0$ and $\varepsilon_\perp^A = \varepsilon_\parallel^B = \varepsilon_\parallel > 0$. In our case, we focus on the propagation of extraordinary TM-polarized waves which are affected by both $\varepsilon_\parallel$ and $\varepsilon_\perp$ [10], while the propagation of ordinary TE wave depends only on $\varepsilon_\parallel$.

When an eigen TM electromagnetic wave propagating in a PBG structure, it possesses a Bloch wave vector $\vec{k} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z}$, and k_z can be found explicitly for a two-layered periodic structure by the trace of a transfer-matrix [9]

$$Tr(T) = 2\cos(k_z d) = \frac{1}{4}\left\{ \begin{array}{l} (2+\Omega+\Omega^{-1})[e^{i(k_z^B d_B + k_z^A d_A)} + e^{-i(k_z^B d_B + k_z^A d_A)}] \\ +(2-\Omega-\Omega^{-1})[e^{i(k_z^B d_B - k_z^A d_A)} + e^{-i(k_z^B d_B - k_z^A d_A)}] \end{array} \right\} \quad (1)$$

where $k_z^A = \pm\sqrt{\varepsilon_\parallel^A k_0^2 - (\varepsilon_\parallel^A/\varepsilon_\perp^A)(k_x^2+k_y^2)}$, $k_z^B = \pm\sqrt{\varepsilon_\parallel^B k_0^2 - (\varepsilon_\parallel^B/\varepsilon_\perp^B)(k_x^2+k_y^2)}$, $\Omega = (\varepsilon_\perp/\varepsilon_\parallel)\cdot(k_z^B/k_z^A)$ and $d = d_A + d_B$. It is easy to find that when $\left|Tr(T)\right| > 2$, no propagating wave is allowed inside the structure and then a PBG is generated. Because of the permittivity distribution of the anisotropic metamaterial, k_z^B is always real but k_z^A can be real or imaginary. If the cutoff frequency is defined as $\omega_c = c\sqrt{(k_x^2 + k_y^2/\varepsilon_\parallel)}$, we can divide the whole frequency domain into two ranges of $\omega > \omega_c$ and $\omega < \omega_c$. In what following, we will study the condition $\left|Tr(T)\right| > 2$ in two separate cases to search for the criteria to realize DANM gaps imposed on material and structure parameters.

2.1. $\omega < \omega_c$

In this case, both k_z^A and k_z^B are real, Eq. (1) can be rewritten as

$$Tr(T) = 2\cos k_z d = 2\cos(k_z^B d_B - k_z^A d_A) - (\Omega + \Omega^{-1} + 2)\sin k_z^A d_A \sin k_z^B d_B \quad (2)$$

For simplicity, we suppose $d_A = d_B$ and $\left|(\varepsilon_\perp/\varepsilon_\parallel)\right| < 1$. Then we take into account the condition

$$k_z^B d_B - k_z^A d_A = m\pi \quad (m = 0,\ 1,\ 2,\ 3,\ \ldots) \quad (3)$$

It is interesting to note that one can create an odd-numbered and an even-numbered DANM gap which is different from the only odd-numbered Bragg gap in Ref. [9]. When m is an odd (even) number, $\sin k_z^A d_A$ and $\sin k_z^B d_B$ are of opposite (same) sign. Considering the fact that $\Omega + \Omega^{-1} < -2$ and $2\cos(k_z^B d_B - k_z^A d_A) = -2$ $(2\cos(k_z^B d_B - k_z^A d_A) = 2$, $\left|Tr(T)\right| > 2$ is satisfied.

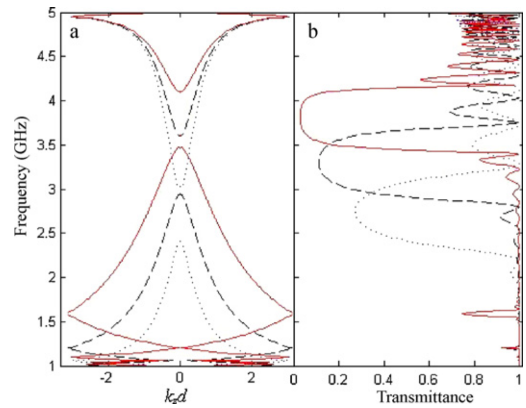

Fig. 2. (a) Dispersion relationship of a PBG structure with 16 unit cells of anisotropic RHM and LHM with parameters as shown in Eq. (7). Red solid line: d_A = 8 mm and d_B = 4 mm. Black dashed line: $d_A = d_B$ = 4 mm. Blue dotted line: d_A = 2 mm and d_B = 4 mm. (b) Transmittance through the 16 unit cells, corresponding to the band gaps in (a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.2. $\omega > \omega_c$

In this case, k_z^A is imaginary but k_z^B is real. Here we suppose $k_z^A = i\alpha$ (α is positive real), Eq. (1) can be rewritten as

$$Tr(T) = -(e^{-\alpha d_A} + e^{\alpha d_A}) - 2\cosh(\alpha d_A)\left[\frac{1}{2}\cdot\left(\frac{k_z^B\varepsilon_\perp}{\alpha\varepsilon_\parallel} - \frac{\alpha\varepsilon_\parallel}{k_z^B\varepsilon_\perp}\right)\sin k_z^B d_B \tanh \alpha d_A - 2\cos^2\left(\frac{k_z^B d_B}{2}\right)\right] \quad (4)$$

We assume $A = -(e^{-\alpha d_A} + e^{\alpha d_A})$, $B = -2\cosh(\alpha d_A)$, $C = (1/2)\cdot((k_z^B\varepsilon_\perp/\alpha\varepsilon_\parallel) - (\alpha\varepsilon_\parallel/k_z^B\varepsilon_\perp))\sin k_z^B d_B \tanh \alpha d_A$ and $D = -2\cos^2(k_z^B d_B/2)$, Eq. (4) can be rewritten as $Tr(T) = A + B(C + D)$.

Once $C + D > 0$, $Tr(T) < -2$ is satisfied as $A < -2$ and $B < -2$. First we suppose $0 < k_z^B d_B < 2\pi$ and $(\varepsilon_\parallel + \varepsilon_\perp) > 0$, and then assume there is a equilibrium position where $k_{ze}^B d_B = \pi$ and $\left|k_{ze}^B\varepsilon_\perp\right| = \left|\alpha_e\varepsilon_\parallel\right|$. If $k_z^B = k_{ze}^B$ and $\alpha = \alpha_e$, $(C + D)$ equals zero. Else if $k_z^B < k_{ze}^B$ $(k_z^B > k_{ze}^B)$, $((k_z^B\varepsilon_\perp/\alpha\varepsilon_\parallel) - (\alpha\varepsilon_\parallel/k_z^B\varepsilon_\perp)) > 0$ $((k_z^B\varepsilon_\perp/\alpha\varepsilon_\parallel) - (\alpha\varepsilon_\parallel/k_z^B\varepsilon_\perp) < 0)$ and $\sin k_z^B d_B > 0$ $(\sin k_z^B d_B < 0)$ can be derived, in this case C is positive. According to the conclusion in Ref. [9] that C $(C > 0)$ increases more quickly than $\left|D\right|$ when k_x and k_y leave the equilibrium position, $C + D > 0$ can always be guaranteed.

Simple analysis shows that the equivalent position requires that

$$\frac{2d_B}{\lambda}\sqrt{\varepsilon_\parallel\left(\frac{1 - (\varepsilon_\parallel + \varepsilon_\perp)}{2\varepsilon_\perp}\right)} = 1 \quad (6)$$

We emphasize that the criteria discussed above is sufficient to guarantee $\left|Tr(T)\right| > 2$, but it is not a necessary condition. Nevertheless, it is useful to help us to search for suitable parameters for structure and material when a PBG is needed.

3. Numerical results and discussion

We consider a stack with 16 unit cells to illustrate the DANM gap effects. The transmission property is discussed by the transfer-