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Investigation of Photonic Band Gaps of One-Dimensional Heterostructure Magnetic Photonic Crystals

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Multiple structures in one-dimensional photonic crystals have great potentials for ultrawide omnireflectors and tunable switches. In this paper, we study the propagation of electromagnetic waves in a one-dimensional heterostructure magnetic photonic crystal for both TE and TM incidence polarizations by means of the transfer matrix method. Results show that by stacking two magnetic photonic crystals as a heterostructure magnetic photonic crystal the omnidirectional total reflection frequency range for any polarization enlarged due to overlapping of photonic band gaps of both magnetic photonic crystals. Omnidirectional band gaps in the heterostructure magnetic photonic crystal is enhanced rather than that in a single magnetic photonic crystal.

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1. Introduction

Periodic dielectric structures, i.e., photonic crystals (PCs) that exhibit electromagnetic stop bands, i.e., photonic band gaps (PBGs), have attracted a lot of attention because of their ability to control the propagation of electromagnetic waves [1]. One-dimensional (1D) PCs have attracted a lot of attention because of their easy fabrication. There is a range of frequencies which incident light from arbitrary angles cannot transmit out through the 1D PCs which is called the omnidirectional band gaps (OBGs) [2]. The OBG is useful to design of total reflector mirror, microcavities, antenna substrates, coaxial waveguide, omniguide fiber, filters, optical switches and more efficient lasers, etc. [3, 4].

Up to now, magnetic materials have not attracted much attention for PCs, since the relative permeability of magnetic material is equal to 1.0 in the optical range. However, most ferrites such as Z-type hexaferrite [5, 6] have values of magnetic permeability quite different from 1 in the microwave range and thus can be exploited for microwave PBGs. Sigalas et al. have studied the PBG, for both the dielectric permittivity (ε) and magnetic permeability (μ) vary in the periodic materials [7]. Therefore, a growing interest in magnetic photonic crystals (MPCs) has resulted from their PBG effect and the large Kerr and Faraday effects [8]. Moreover, the employment of magnetic materials in PCs can broaden the OBGs and allow the tuning of OBGs due to the dependence of their optical properties on an external magnetic field and temperature [9]. Wang and Liu have pointed out a general condition for OBG by investigation of PBG in materials with both various ε and μ for both transversal electric (TE) and transversal magnetic (TM) polarizations [10].

The enlargement of omnidirectional total reflection frequency range can be obtained by using photonic heterostructures in 1D PCs [11]. However, an overall analysis for obtaining OBG in MPCs made with different materials has not yet been reported. Indeed, the general criteria for the formation of OBG remain to be demonstrated. The central idea is that the omnidirectional PBGs of the neighboring MPCs overlap each other.

In this paper, we show theoretically that by combining two 1D MPCs to form heterostructure MPC (HMPC), it is possible to enlarge the total reflection frequency range of an omnidirectional reflector for both TE and TM polarizations. We study the PBG and reflection characteristics of HMPC made of two different MPCs. We have assumed that the dielectric and magnetic absorptions of the layers are negligible and ε and μ are to be constant.

2. Theoretical formalism

We consider two 1D MPCs which are made of N periodic arrays of alternating layers. Each MPC was characterized by the following physical parameters: the ε_1 and ε_2, μ_1 and μ_2, the thicknesses d_1 and d_2, respectively and $\Lambda = d_1 + d_2$ is the period of the MPC. Here we consider that ε has equal value for all layers. However, PBG can be can affected by varying the ε. The MPC is supposed to be coupled to a homogeneous medium, characterized by ε_0 and μ_0, at the interfaces.

We assume that the layered structure is periodic in the z direction and homogeneous in the xy plane. Electro-

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magnetic wave hits HMPC at an angle θ_0 with respect to z axis, in xz plane, from the homogeneous medium. There are two independent electromagnetic modes: TM and TE modes. The vector E of TE wave and the vector H of TM wave are in y direction and perpendicular to xz plane. The incident electromagnetic wave has a wave vector $k = k_x\hat{x} + k_z\hat{z}$ and an angular frequency ω, where $\hat{x}$ and $\hat{z}$ are unit vectors.

In order to calculate the transmittance and reflectance for a periodic multilayered structure, we have used the transfer matrix method (TMM) [12]. According to this method, we must, in advance, set up the characteristic matrix corresponding to one period, with the result

$$M = \begin{pmatrix} \cos\alpha_1\cos\alpha_2 - \frac{p_2}{p_1}\sin\alpha_1\sin\alpha_2 & \frac{\mathrm{i}}{p_2}\cos\alpha_1\sin\alpha_2 + \frac{\mathrm{i}}{p_1}\cos\alpha_2\sin\alpha_1 \\ \mathrm{i}p_2\cos\alpha_1\sin\alpha_2 + \mathrm{i}p_1\cos\alpha_2\sin\alpha_1 & \cos\alpha_1\cos\alpha_2 - \frac{p_1}{p_2}\sin\alpha_1\sin\alpha_2 \end{pmatrix}, \tag{1}$$

where $\alpha_1 = \frac{2\pi}{\Lambda}W\sqrt{\varepsilon\mu_1}d_1\cos\theta_1$, $\alpha_2 = \frac{2\pi}{\Lambda}W\sqrt{\varepsilon\mu_2}d_2 \times \cos\theta_2$, $W = \omega\Lambda/2\pi c$ which is normalized frequency and c is the speed of light in vacuum and the angles θ_1 and θ_2, determined by Snell's law of refraction, are the propagation angles for layer 1 and 2. The parameter p_i is dependent on the polarization. For the TE polarization p_i is given by $p_i = \frac{1}{c\mu_0}\sqrt{\frac{\varepsilon}{\mu_i}}\cos\theta_i$ and for the TM polarization, $p_i = \frac{1}{c\mu_0}\sqrt{\frac{\varepsilon}{\mu_i}}\frac{1}{\cos\theta_i}$, where μ_0 is the magnetic permeability of vacuum. In a structure with an infinite number of layers, according to Bloch's theorem, the dispersion at any incidence angle follows the relation:

$$\cos(\kappa\Lambda) = \frac{1}{2}\mathrm{Tr}(M), \tag{2}$$

where κ is the Bloch wave number. From Eq. (2) one can calculate the usual band structures. Solution of the infinite system can be propagating or evanescent, corresponding to real or imaginary Bloch wave number, respectively.

Generally, the Brewster angle is defined as the incidence angle for which there is no reflection. In order to create an OBG in a 1D MPC, the incidence angle must be smaller than the Brewster angle. Particularly, in a 1D MPC where μ alternates and ε is constant, Brewster's angle only happens for TE mode and is given by $\theta_B^{TE} = \tan^{-1}\left(\sqrt{\frac{\mu_2}{\mu_1}}\right)$. However, having a Brewster angle does not mean that there is no omnidirectional total reflection. From Snell's law $\sqrt{\varepsilon_0\mu_0}\sin\theta_0 = \sqrt{\varepsilon_1\mu_1}\sin\theta_1$, we can see that the refracted angle θ_1 is restricted to a certain range, where $\sqrt{\varepsilon_0\mu_0}$ and $\sqrt{\varepsilon_1\mu_1}$ are the refractive indices of ambient medium and the dielectric layer adjacent to ambient medium, respectively, and θ_0 is the incidence angle. If the maximal angle of refraction is smaller than the internal Brewster angle $\theta_B^{TE} = \tan^{-1}\left(\sqrt{\frac{\mu_2}{\mu_1}}\right)$, the incident wave from the outside cannot couple to the Brewster window, leading to the total reflection for all incidence angles.

3. Results and discussion

In this paper, two 1D MPCs which they stacked to make an HMPC are considered. The first MPC (denoted by MPC1) consists of two dielectric layers repeating alternatively. The magnetic permeability and the thickness of the two layers are as follows: $\mu_1 = 1$, $\mu_2 = 8$ and $d_1 = 0.8\Lambda$ and $d_2 = 0.2\Lambda$. The magnetic permeability and thickness parameters of the second MPC (denoted by MPC2) are $\mu_1 = 1$, $\mu_2 = 12$ and $d_1 = 0.6\Lambda$ and $d_2 = 0.4\Lambda$. For both MPCs ε is constant and has real value of 4. Photonic band structures in terms of normalized frequency and incidence angle for the both MPC1 and MPC2, obtained from Eq. (2), are shown in Fig. 1. Electromagnetic waves are incident from air. As can be seen, for normal incidence, the TE and TM polarizations are degenerate. The white areas represent the propagation bands and the gray areas are the forbidden bands. The OBGs lie between the upper frequency edge (W_H) at $\theta_0 = 0°$ for TE (TM) polarization and the lower frequency edge (W_L) at $\theta_0 = 90°$ (here, 89°) for TE polarization. The regions between the two dashed lines in the gray area correspond to the OBGs. The parameters W_L and W_H in Fig. 1 are evaluated and their values which determining OBGs are summarized in Table. It can be seen from Fig. 1 that the directional PBGs for MPC1 and MPC2 overlap each other at any incidence angles. The first OBG obtained for HMPC is constituted from overlapping of the first OBG of MPC1 and two first OBGs of MPC2.

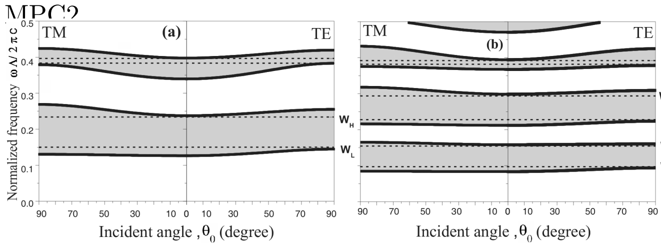

Fig. 1. Photonic band structures in terms of normalized frequency for the incidence angle θ_0 for (a) MPC1 and (b) MPC2. The white areas represent the propagation bands and the gray areas are the forbidden bands. The regions between two dashed lines in the gray area correspond to the OBGs which lie between W_H and W_L.

Enlargement of the omnidirectional total reflection frequency range of HMPC and reflection spectra of the constituent MPCs for TE polarization at different incidence angles obtained by TMM are given in Fig. 2. Let us note that the omnidirectional PBG for the TE polarization is

TABLE
Normalized frequency for OBG in MPC1, MPC2 and HMPC. Values of ΔW are defined as $W_{\mathrm{H}} - W_{\mathrm{L}}$.

MPC-types	PBG	W_{L}	W_{H}	ΔW
MPC1	PBG1	0.148	0.233	0.085
MPC2	PBG1	0.096	0.154	0.058
MPC2	PBG2	0.227	0.295	0.068
HMPC	PBG1	0.094	0.298	0.204

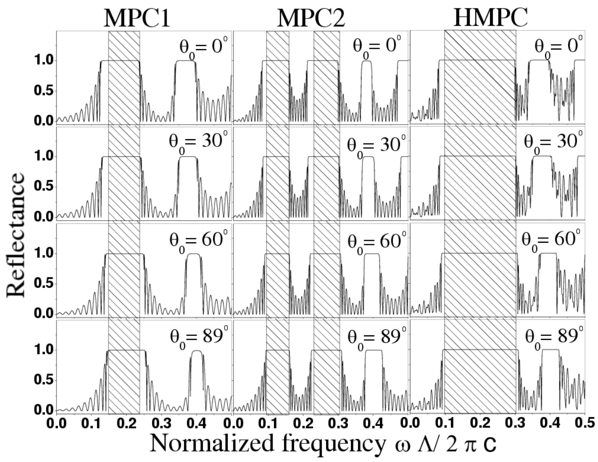

Fig. 2. Calculated reflectance of MPC1, MPC2 and HMPC (MPC1/MPC2) at different incidence angles for TE polatization. The MPC1 and MPC2 consist of ten periods. The total reflection frequency range is shown as cross-hatch area.

completely located within that for the TM polarization. Therefore, the omnidirectional PBG for the TE polarization is no more than the overall omnidirectional PBG for any polarization. For the both MPCs, the total reflection frequency range is shown as cross-hatch area which are in consistence with data in Table. After forming the HMPC by stacking MPC1 and MPC2 together (denoted by MPC1/MPC2), the enlarged total reflection normalized frequency range is finally from 0.094 to 0.298. From the aforementioned discussions, the total reflection frequency range is substantially enlarged for all incidence angles and for both TM and TE polarizations.

4. Conclusion

We have theoretically investigated the formation of an ultrawide OBG by introducing the concept of 1D HMPCs. The HMPCs can show great potential for ultrawide omnireflectors operating in an interval frequency range. The normalized frequency range for OBG in HMPC is enhanced approximately threefold than that in single MPC.

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