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Omnidirectional reflection in one-dimensional ternary photonic crystals and photonic heterostructures

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ABSTRACT

Designing dielectric systems to create omnidirectional band gaps (OBGs) is an attractive topic in the field of photonic band gap (PBG) structures. In this Letter, we propose a new approach to create OBGs by ternary photonic heterostructures (TPHs) composed of three kinds of materials with different refractive indices and obtain the formulae of the structures of TPHs, i.e., those of the thicknesses of materials and the number of sub-ternary photonic crystals. It may provide a powerful technique for designing the structures being able to produce OBGs by use of usual materials, lowcost materials, and materials with low refractive indices, etc.

1. Introduction

Photonic crystal (PC) is a kind of interesting structure, where dielectric is periodically arranged. Optical propagation in PC can produce photonic band gaps (PBGs) and photonic localizations, which can be used for controlling and confining light propagations. Since PC was proposed [1,2], it has caused people's widely concerns for more than twenty years both in theories and experiments.

As the simplest type of PBGs, one-dimensional (1D) PC is now known as a dielectric omnidirectional reflector [3,4], which can reproduce omnidirectional reflection losslessly and has applications in the all-dielectric coaxial waveguide [5], improving planar microcavity [6], and optical fibers [7], etc. As a result, how to make use of 1D PC to design artificial dielectric structure to create omnidirectional band gap (OBG) has been one of the attractive topics in PBG studies. Lekner [8] deduced band edges at oblique incidence for a general binary photonic crystal (BPC). Xiang et al. [9,10] derived the analytic expressions for frequency locations of the zero-effective-phase and zero-average-index photonic band edges of the photonic multilayers. Composing several BPCs can construct a binary photonic heterostructure (BPH) and consequently, the width of the OBG created by a BPH will be greater than that of the OBG generated by a single sub-BPC [11]. Furthermore, based on this result the general criterion of OBG produced by BPHs was deduced and the frequency range of OBG and the range of refractive indices of materials chosen to construct BPH were both extended [12]. Even so, the refractive indices of these two kinds of materials of BPHs and the ratio of them are still both limited, i.e., for two kinds of materials with different refractive indices, whether the BPCs or BPHs don't always result in OBGs. The components of a ternary photonic crystal (TPC) are one kind of material more than those of a BPC or a BPH and then the structure of the former is more complex and flexible than those of the latter. So there should exist differences between their physical features. Therefore, the studies on TPC attract widely attentions, the incomplete list includes: Lusk et al. [13] derived the dispersion relation of TPC. Wu et al. [14] enlarged OBG by metal–dielectric TPC. By means of plasma TPC Kong et al. [15] obtained a superior feature in the enhancement and modulation of the range of OBGs. Wen et al. [16,17] extended OBGs by use of TPCs containing single-negative materials and superconductor.

According to the researches on 1D binary dielectric systems [11,12], one knows that constructing a BPH by several BPCs can extend not only the range of OBG but also the range of refractive indices of materials of the BPH. For a 1D ternary dielectric system, naturally, one would ask that whether constructing a ternary photonic heterostructure (TPH) by several TPCs can generate similar results, i.e., whether it can extend the range of the OBG reproduced by a single TPC and/or the range of refractive indices of materials of the TPHs.

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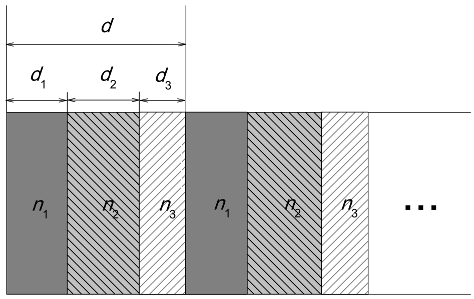

Fig. 1. Configuration of a 1D ternary photonic crystal. n_1, n_2 and n_3 are, respectively, the refractive indices of the three kinds of materials and d_1, d_2 and d_3 are, respectively, their layer thicknesses. $d = d_1 + d_2 + d_3$ is the thickness of the periodic unit cell.

In this Letter we compare in detail the differences among BPCs, BPHs and TPCs in producing OBGs, propose a model of dielectric TPH composed of three kinds of materials with different refractive indices, and present the quantitative formulae of material thicknesses and number of sub-TPCs for the TPHs being able to create OBGs. We find that (i) for the selection of materials, the BPCs, BPHs and TPCs being able to generate OBGs are all limited, but our proposed TPHs are unlimited; (ii) the width of OBG produced by our designed TPH is optimal and will not smaller than the sum of the widths of OBGs generated by all sub-TPCs. It may be useful for the designing of dielectric omnidirectional reflectors and the all-optical devices based on omnidirectional reflector.

We organize this Letter as follows. The models of 1D TPC and TPH and the theory of the dispersion relation of 1D TPCs are introduced in Section 2. In Section 3, we study the properties of OBGs created by the TPCs based on two types of BPCs, respectively. In Section 4, we mainly investigate the characteristics of the OBGs reproduced by our proposed TPHs based on two types of TPCs, respectively. Finally, a brief summary is given in Section 5.

2. Model and theory

2.1. TPC model

In this Letter we investigate the properties of omnidirectional reflection of a 1D TPC. The configuration of a 1D TPC is shown in Fig. 1. From Fig. 1 one can see that the TPC is made up of three kinds of materials, which refractive indices are n_1, n_2, and n_3, respectively, and which layer thicknesses are d_1, d_2, and d_3, respectively. Then the thickness of the periodic unit cell is $d = d_1 + d_2 + d_3$.

2.2. TPH model

In this Letter we also study the features of omnidirectional reflection of a 1D TPH. The configuration of a 1D TPH composed of num sub-TPCs is shown in Fig. 2, where S_i ($i = 1, 2, \ldots, \text{num}$) is the ith sub-TPC and the lattice constants of the sub-TPCs are different from each other.

2.3. Dispersion relation

It is reported that the dispersion relation of a 1D TPC can be expressed as follows [13,18]:

$$\cos Kd = \cos\delta_1\cos\delta_2\cos\delta_3 - \Lambda_1\sin\delta_1\sin\delta_2\cos\delta_3 - \Lambda_2\cos\delta_1\sin\delta_2\sin\delta_3 - \Lambda_3\sin\delta_1\cos\delta_2\sin\delta_3, \tag{1}$$

where K is the Bloch wave vector which is confined in the first Brillouin zone,

$$\delta_i = \frac{\omega}{c}D_i \quad (i = 1, 2, 3) \tag{2}$$

is the phase shift of waves with angular frequency ω traversing the TPC, c is the light speed in the vacuum, the parameter

$$D_i = d_i\sqrt{n_i^2 - n_0^2\sin^2\theta_0} \quad (i = 1, 2, 3), \tag{3}$$

n_0 is the refractive index of the incident medium, θ_0 is the incident angle, and the function Λ_i ($i = 1, 2, 3$) takes the following forms:

$$\Lambda_i = \frac{1}{2}\left(x_i + \frac{1}{x_i}\right) \quad (i = 1, 2, 3), \tag{4}$$

where

$$x_i = \begin{cases} \sqrt{\frac{n_i^2 - n_0^2\sin^2\theta_0}{n_k^2 - n_0^2\sin^2\theta_0}} & \text{for an } s \text{ polarization} \\ (\frac{n_k}{n_i})^2\sqrt{\frac{n_i^2 - n_0^2\sin^2\theta_0}{n_k^2 - n_0^2\sin^2\theta_0}} & \text{for a } p \text{ polarization.} \end{cases} \tag{5}$$

In Eq. (5), when $i = 1, 2$, $k = i + 1$; and when $i = 3$, $k = 1$. By use of this dispersion relation one can calculate the optical band structure of a 1D TPC for incident angle θ_0 and then obtain the width of the largest stopband for this incident angle. In Sections 3 and 4 we use Eqs. (1)–(5) to deduce the values of OBGs of 1D TPCs.

3. OBGs generated by TPCs

In this Letter we mainly investigate the characteristics of the omnidirectional reflections of TPCs and TPHs and compare the results with those of BPCs and BPHs, where the structures of TPCs and TPHs are tightly related to those of BPCs and BPHs. The relationships are as follows. From Section 2.1 one can see that the TPCs studied in this Letter are made up of three kinds of materials, which refractive indices are n_1, n_2, and n_3, respectively, and which layer thicknesses are d_1, d_2, and d_3, respectively. The BPCs researched in this Letter are made up of two kinds of materials, which refractive indices are n_1 and n_3, respectively, and which layer thicknesses are d_1 and d_3, respectively. It means that the former is equivalent to be constructed by inserting one kind of new material, n_2, in the latter. They all satisfy the following aplanatic rule:

$$n_1d_1 = n_2d_2 = n_3d_3. \tag{6}$$

In this section we discuss in detail the conditions of generating OBGs by two types of representative TPC structures.

3.1. TPCs based on BPCs being able to produce OBGs

It is reported that [4] the criterion for the existence of omnidirectional reflectivity can be stated as the occurrence of a frequency overlap between the gap at normal incidence and the gap of the TM mode at 90°. From Eqs. (4) and (5) one can see that at normal incidence, for s and p polarizations the stopband edges are all the same. So, the width of omnidirectional reflection of a 1D TPC can be expressed as $\Delta\lambda = \lambda_p^+(90^\circ) - \lambda_p^-(0^\circ)$, where λ_p^+ (λ_p^-) is the wavelength value of the right (left) boundary of OBG.

In order to compare the advantage of producing OBGs and the flexibility of materials between a BPC and a TPC, we construct a TPC on the basis of a BPC being able to reproduce OBGs following the rule at the beginning of Section 3, i.e., adding one kind of new material into the unit cell of BPC, which refractive index is n_2. For a BPC, Lekner [8] obtained the formula for calculating the boundary of OBG. For a TPC, one can calculate the boundary of OBG by use of the dispersion relation introduced in Section 2.3.

In this subsection, on the basis of a BPC introduced in Ref. [8] and being able to result in OBGs we construct a TPC being able