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Enlargement of Omnidirectional Reflection Range Using Cascaded Photonic Crystals

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Abstract

The enlargement of omnidirectional reflection range is theoretically investigated by using cascaded 1-D photonic crystals. Using transfer matrix method, the reflectivity of each photonic crystal is plotted as a function of normalized frequency and omni directional photonic band gaps (PBGs) are identified. It is seen that one can use more 1-D PCs to form multiple photonic heterostructures to get a very wide omni-directional total reflection frequency range. For this, the directional PBGs of the adjacent 1-D PCs at any incident angle cascade each other in tandem.

Keywords: Photonic bandgap (PBG), omnidirectional reflector, cascade photonic crystals.

INTRODUCTION

Photonic crystals with forbidden photonic bands have drawn considerable attention of many researchers for the study of their fundamental physical properties as well as for their possible potential applications in many electronic and optical devices [1–3]. It is worth to mention that PBG materials can be designed to exhibit cent percent reflectivity at any angle of incidence for both TE and TM polarized electromagnetic waves. Such a structure generally known as omni-directional dielectric reflector is an important optical component in many systems. Recently, such mirrors are realized and have been manufactured; and the conditions for their existence have been formulated. Thus, periodic structure systems have become significant structures of photonics [4–5].

B. Suthar and A. Bhargava [6] studied 1-D photonic crystal in which alternate layers are of materials like chalcogenide $As_{40}Se_{60-x}S_x$ and silica. They studied the effect of cascading omni-directional photonic band gaps (PBGs) and found that large range of

omni-directional PBG can be obtained by cascading chalcogenide $As_{40}S_{60-x}Se_x$/silica system. V. Kumar *et al.* [7] studied the 1-D photonic crystal in which alternate layers are made up of materials like Na3AlF6 and Ge. They studied three different structures PC1, PC2 and PC3 and another structure PC4 which is a combination of PC1/PC2/PC3 to study the effect of cascading. They found that large frequency range of omni-directional PBG can be obtained from Na3AlF6/Ge system by cascading photonic band gap structures.

The problem of omnidirectional reflection (ODR) of electromagnetic waves from aperiodic and periodic 1-D photonic crystal has been considered [8, 9]. It is assumed that layers with different refractive indices alternate in a crystal according to the Fibonacci generation scheme. It is found that we can broaden spectral range with high refractive index at different incidence angles by increasing in thickness of layers linearly or stepwise. M. A. K. Othman *et al* [10] proposed a new approach leading to giant gain enhancement. It is based on unconventional slow-wave resonance associated with a degenerate band edge (DBE) in the dispersion diagram for a special class of photonic crystals supporting four modes at each frequency.

Here, the possibility of broadening the wavelength range of omni-directional reflection (ODR) by using the periodic multi-layered stack of finite thickness in cascade one-dimensional photonic crystal is theoretically investigated.

Theoretical Details

The schematic diagram of the dielectric multilayer structure is shown in figure 1 where n_i is the refractive index of the ambient media and n_s is the refractive index of substrate. I have taken x-axis in the direction normal to the layers. The refractive indices of the system are given as,

$$n(x) = \begin{cases} n_H & d_L < x < d_H \\ n_L & 0 < x < h_L \end{cases} \qquad \text{with } n(x) = n(x+d), \tag{1}$$

where d_L and d_H are the thicknesses of the layers with refractive indices n_L and n_H and $d=d_L + d_H$ is the period of the structure.

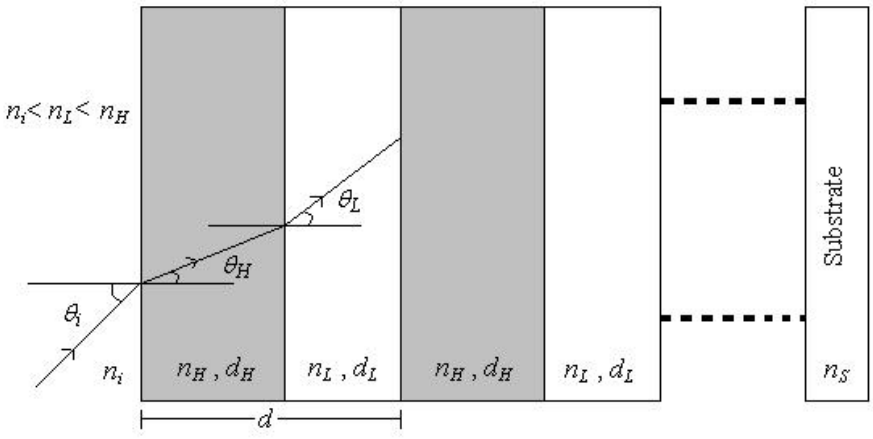

Figure 1 Schematic diagram of a dielectric 1-D PC structure.

Using the transfer matrix method [11-13], the photonic spectra of this periodic structure are derived. The electric field for the Maxwell's equation can be written as

$$E = E(x)e^{i(\omega t-\beta z)}, \tag{2}$$

where β is the z- component of the wave vector and ω is angular frequency.

The electric field within each layer can be expressed as the sum of an incident plane wave and reflected plane wave. Coefficients in the first layer of the n^{th} unit and $(n-1)^{th}$ unit cell are related by a matrix

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = T_n \begin{pmatrix} a_n \\ b_n \end{pmatrix}, \tag{3}$$

where $T_n = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}$ is the transfer matrix, and a_n and b_n are the coefficients of the right and left hand side propagating waves in the first layer of the n^{th} unit cell respectively, and

$$T_{11} = \exp(ik_{1x}d_H)\left[\cos k_{2x}d_L + \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}d_L\right] \tag{4}$$

$$T_{12} = \exp(-ik_{1x}d_H)\left[\frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} - \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}d_L\right] \tag{5}$$

$$T_{21} = \exp(ik_{1x}d_H)\left[-\frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} - \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}d_L\right] \tag{6}$$

$$T_{22} = \exp(-ik_{1x}d_H)\left[\cos k_{2x}d_L - \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}d_L\right] \tag{7}$$

For a periodic structure with N period of layers with refractive indices n_H and n_L of constituent layers and thicknesses d_H and d_L, the coefficients of right and left hand side propagating states in both sides of multilayer structures are calculated by multiplying transfer matrices of each cell as shown below,

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = T_1T_2.....T_N \begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{8}$$

The coefficient of reflection is given by

$$r_N = \begin{pmatrix} a_0 \\ b_0 \end{pmatrix}_{b_N=0} \tag{9}$$

The reflectance is obtained by taking the absolute square of r_N,

$$R_N = |r_N|^2 \tag{10}$$

RESULTS AND DISCUSSION

I proposed a cascaded structure air/$(AB)^6$/$(AC)^n$/$(AB)^6$/substrate(SiO2), where $(AB)^6$ means that the periodic multi-layered stack consists of six sub-layers of AB; and $(AC)^n$ means that this multilayer consist of n sub-layers of AC. The spectral response of the reflecting stack AC overlaps with the spectrum of the primary stack. Here, the AC layers act as a refractive index well or barrier which depend on the wavelength of electromagnetic waves used.

In these computations, all the regions are assumed to be linear, homogeneous and non-absorbing. The materials of different layers A, B and C are considered to be SiO2, Te and Si respectively with refractive indices 1.5, 4.6 and 3.7 respectively. We take lattice period d to be 400 nm for the stack of AB layers and the thickness of A and B layers are taken as 0.8d and 0.2d respectively. But for the stack of AC layers, we take lattice period d_1=250nm and the thickness of A and C layers (a_1 and b_1) are taken as $0.7d_1$ and $0.3d_1$ respectively. The omni-directional reflection (ODR) photonic band gap for both TE and TM polarization is defined by the upper photonic band gap edge at 0^O incident angle and the lower photonic band gap edge at normal incidence. The ODR photonic band gap for TM polarization lies completely within ODR photonic band gap of TE polarization. Therefore, complete ODR photonic band gap is the ODR photonic band gap of TM polarization.

Firstly I consider the case when n=0 i.e. the proposed structure can be treated as conventional photonic crystal with 12 unit cells of AB layers. The reflectance spectra for n=0 is shown in Fig. 2 which is plotted in terms of normalized frequency ($\omega d/2\pi c$). It is observed that the ODR range for TE polarization is from 0.154 ($\omega d/2\pi c$) to 0.313 ($\omega d/2\pi c$) and TM polarization has its ODR range from 0.204 $\omega d/2\pi c$ to 0.313 $\omega d/2\pi c$. Therefore, total ODR ranges (for both TE and TM polarization) has a bandwidth of 0.099 $\omega d/2\pi c$ from 0.204 $\omega d/2\pi c$ to 0.313 $\omega d/2\pi c$ for n=0.

When we introduce ten AC layers in the form of a stack in the middle of 12 pairs of AB layers, i.e. n=10, an appreciable change is observed in the reflection spectra of the overall structure. The reflectance spectra are shown in Fig. 3. From this figure, we observe that for the case of the TE polarization, the structure has its ODR range from 0.145 $\omega d/2\pi c$ to 0.494 $\omega d/2\pi c$ and the ODR range for the TM polarization is from 0.194 $\omega d/2\pi c$ to 0.494 $\omega d/2\pi c$. Therefore, total ODR range, in case there is a stack of ten AC layers, has a bandwidth of 0.300 $\omega d/2\pi c$ from 0.194 $\omega d/2\pi c$ to 0.494 $\omega d/2\pi c$. The shaded region gives the total ODR band in Fig. 3.

Thus, it is observed that we can increase the total ODR range by introducing a stack in the middle of AB layers. The total width of ODR range depends on the number of layers of AC.

In conclusion, the design of omni-directional reflector using cascade 1-D photonic crystal has been suggested here. This enlargement of ODR range of electromagnetic waves can be made possible by properly choosing the geometric and dielectric parameters of the constituent materials. It can have potential applications in photonics.

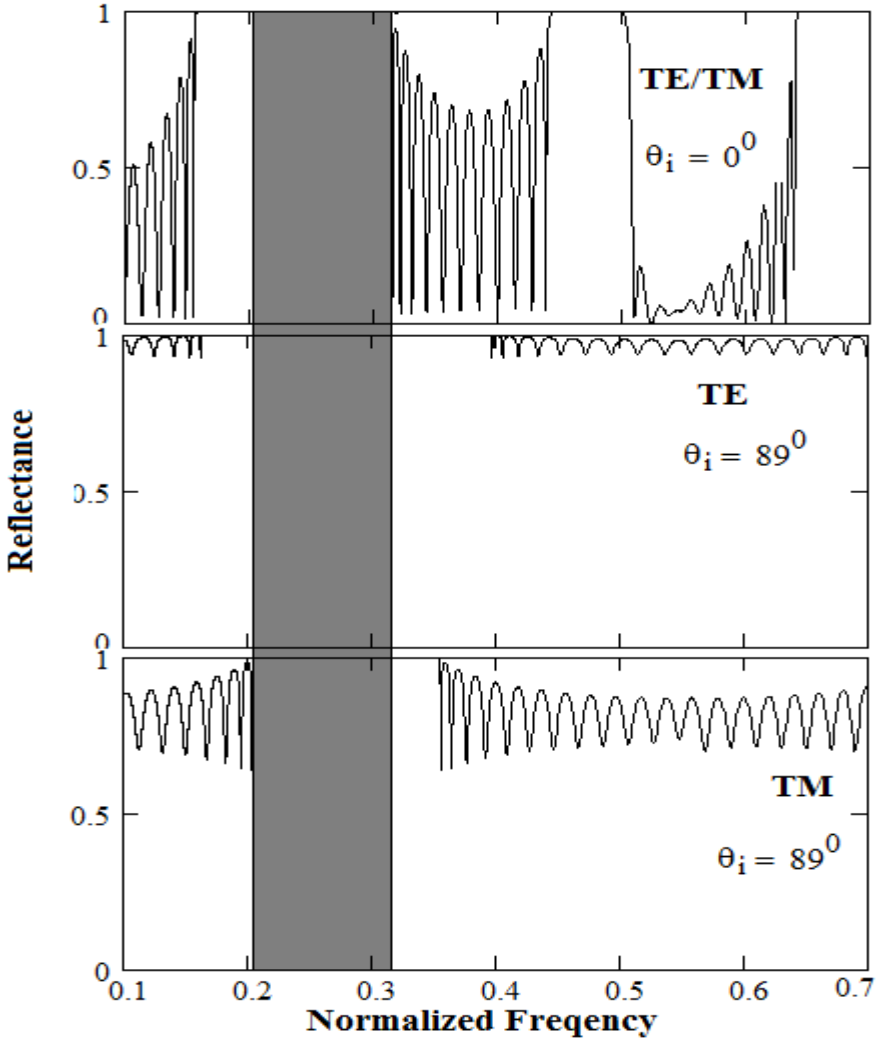

Figure 2 Reflectance spectra of TE and TM polarizations for n=0

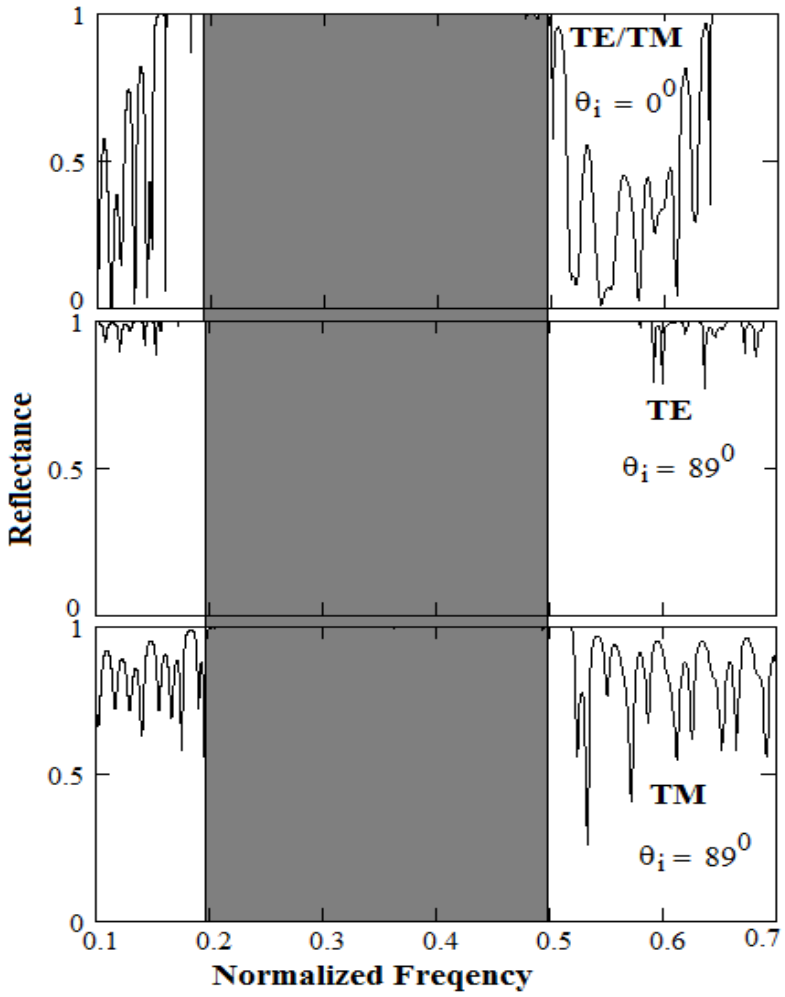

Figure 3 Reflectance spectra of TE and TM polarizations for n=10

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