Broadening of omni-directional reflection range by cascade 1D photonic crystal

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We show theoretically that it is possible to broaden the omni-directional reflection range by cascading one-dimensional photonic crystals (PCs). For the purpose of designing the broadband reflector at a certain incident angle, the criterion is that the stop bands of cascaded PCs should be adjacent (or overlapped) to each other. We display the reflection spectra of cascaded structure taking air/$(AB)_5$/$(AC)_n$/$(AB)_5$/substrate(SiO_2), where $(AC)_n$ means that this layer consist n sub layers of AC. We choose SiO_2, Te and Ge as A, B and C materials respectively. By increasing the value of n and choosing the appropriate value of lattice period of AC, we can obtain desired range of omni-directional reflection.

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1. Introduction

Since last two decades, photonic band-gap materials (a class of photonic crystals, PCs) have drawn interest of many researchers [1, 2]. PCs are periodic array(s) of dielectric materials; generally, exhibiting characteristic electromagnetic stop bands known as photonic band gaps (PBGs). That is, the PCs can prohibit the propagation of electromagnetic waves whose frequencies lie within the PBGs.

Omni-directional dielectric reflector is a mirror having cent percent reflectivity at any angle of incidence for both TE and TM polarized electromagnetic waves. Recently, such mirrors have been realized and manufactured; and the conditions for their existence have been formulated. For the first time in 1998, Fink et al. reported that one-dimensional dielectric lattice displays total omni-directional reflection for incident light under certain conditions [3, 4]. They constructed a stack of nine alternate layers of polystyrene/tellurium having a thickness of a few micrometres and demonstrated omni-directional reflection over the wavelength range from 10-15 micrometres. Further works by various researchers found many interesting results. Gallas et al. [5] reported the annealing effect in the Si/SiO_2 PBG based omni-directional reflectors. Chigrin et al. [6, 7] fabricated a lattice consisting of 19 layers of Na_3AlF_6/ZnSe and found that omni-directional photonic band gap exists in the spectral range 604.3 nm to 638.4 nm. Also, Wang et al. [8] theoretically showed that overlapping two photonic crystals could enlarge the range of total omni-directional reflection. In the present communication, we show theoretically that it is possible to broaden the wavelength range of omni-directional reflection (ODR) to a great extent by using periodic multi-layered stack of finite thickness in cascade one-dimensional photonic crystal.

2. Theoretical analysis

The multilayered structure considered in the present investigation consists of alternate layers of high and low refractive indices along the x-axis and placed between semi-infinite media of refractive indices n_i (refractive index of the incident medium) and n_s (refractive index of the substrate), as shown in Fig. 1.

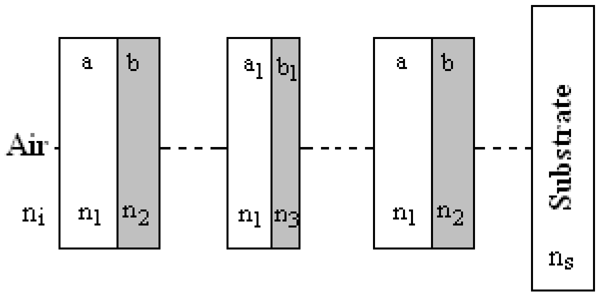

Fig. 1. Schematic representation of one-dimensional photonic quantum well structure in the form of a periodic multi-layered stack.

Applying the transfer matrix method (TMM), the characteristic matrices for the TE and TM waves can now be written in the following form as [9]

$$M_j = \begin{bmatrix} \cos\beta_j & -\dfrac{i.\sin\beta_j}{q_j} \\ -iq_j\sin\beta_j & \cos\beta_j \end{bmatrix} \quad (1)$$

where $q_j=n_j\cos\theta_j$, (j=1,2) for the TE polarization and $q_j=\cos\theta_j/n_j$ for the TM polarization, $\beta_j=(2\pi/\lambda)n_jd_j\cos\theta_j$, θ_j

is the ray angle inside the layer of refractive index n_j and λ is the wavelength in the incidence medium. The total characteristics matrix for the structure having N periods is given by

$$M = (M_j)^N = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{2}$$

Thus, the reflection coefficient of the multi-layered structure for TE and TM polarizations are given by

$$r = \frac{(M_{11} + q_s M_{12})q_i - (M_{21} + q_s M_{22})}{(M_{11} + q_s M_{12})q_i + (M_{21} + q_s M_{22})} \tag{3}$$

where $q_{i,s}=n_{i,s}\cos\theta_{j,s}$ for TE wave and $q_{i,s}= \cos\theta_{j,s}/ n_{i,s}$ for TM wave with j=1,2; also i and s represents incident medium and substrate respectively.

Finally, the reflectivity of the structure is given by

$$R = |r|^2 \tag{4}$$

In one-dimensional PCs, there is no absolute photonic band gap (PBG) owing to the two factors. The first factor is that the edges of the directional PBGs (PBGs at a certain direction) will shift to higher frequencies with the increase in incident angle, usually leading to the closure of the overall PBGs. The second factor is that at the Brewster angle, the TM mode cannot be reflected. However, the absence of an absolute PBG does not mean that there is no omnidirectional reflection. The criterion for the existence of total omnidirectional reflection is that there are no propagating modes that can couple with the incident wave [8]. From Snell's law, we have $n_i\sin\theta_i=n_1\sin\theta_1$ and $n_1\sin\theta_1=n_2\sin\theta_2$ which give $\theta_1 = \sin^{-1}(n_i \sin\theta_i / n_1)$ and $\theta_2 = \sin^{-1}(n_1 \sin\theta_1 / n_2)$, where n_1 *and* n_2 are the refractive indices of the alternate layers of the structure and n_i is the refractive index of the incident medium. The maximum angle of refraction is defined as $\theta_2^{\max} = \sin^{-1}(n_i / n_2)$ and the Brewster angle is $\theta_B = \tan^{-1}(n_1 \sin\theta / n_2)$. If the maximum angle of refraction is smaller than the Brewster's angle then the incident wave from the outside cannot couple to Brewster's window which results the total reflection for all incident angles. Thus, the condition for omnidirectional reflection without the influence of the Brewster's angle is $\theta_B = \theta_2^{\max}$. This condition is satisfies by the selected parameters that we have taken in our numerical computations. Hence, in the present analysis there is no influence of Brewster's angle on the omni-directional reflection bands.

3. Result and discussion

In this section, numerical calculations on the reflection properties of the one-dimensional photonic crystals using Equation (4) have been presented. We propose air/$(AB)_5$/$(AC)_n$/$(AB)_5$/substrate(SiO_2), where $(AB)_5$ means that the periodic multi-layered stack consists of five sub-layers of AB; and $(AC)_n$ means that this multilayer consist of n sub-layers of AC. The stack AC is a reflecting stack whose spectral response overlaps with the spectrum of the primary stack. The AC layers play a role of a refractive index well or barrier depending on the wavelength of electromagnetic waves.

In our computations, the materials of different layers A, B and C are considered to be SiO_2, Te and Ge respectively with refractive indices 1.5, 4.6 and 4.2 respectively. For the stack of AB layers, we take lattice period d to be 400 nm and the thickness of A and B layers (a and b) are taken as 0.8d and 0.2d respectively. But for the stack of AC layers, we take lattice period d_1=220nm and the thickness of A and C layers (a_1 and b_1) are taken as $0.7d_1$ and $0.3d_1$ respectively. Here all the regions are assumed to be linear, homogeneous and non-absorbing. The 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.

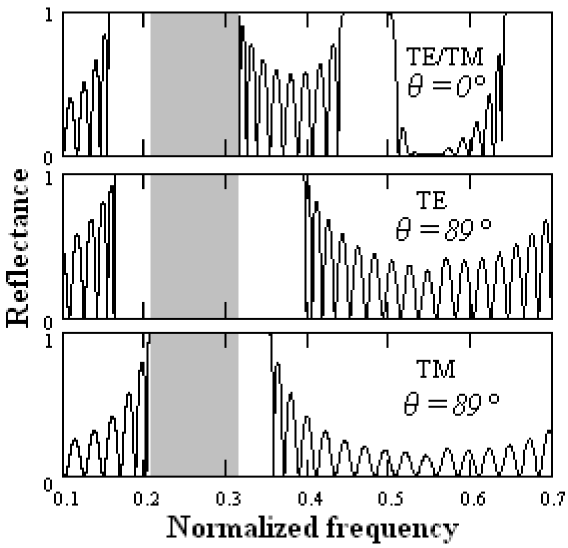

Fig. 2. Reflectance spectra for n=0, (a) TE polarization (b) TM polarization.

When n=0, the proposed structure can be treated as conventional photonic crystal with 10 unit cells of AB layers. The reflectance spectra for n=0 is shown in Fig. 2. The spectra are plotted in terms of normalized frequency ($\omega d/2\pi c$). We observe that TE polarization has its ODR range from 0.156 $\omega d/2\pi c$ to 0.304 $\omega d/2\pi c$ and the ODR range for TM polarization is from 0.206 ωd/2πc to 0.313 ωd/2πc. Therefore, total ODR ranges (for both TE and TM polarization) for n=0 has a bandwidth of 0.098 ωd/2πc from 0.206 ωd/2πc to 0.304 ωd/2πc.

When n=3, i.e. when we introduce three AC layers in the form of a stack in the middle of 10 pairs of AB layers, there is an appreciable change in the reflection spectra of the overall structure. The reflectance spectra of proposed structure for n=3 is shown in Fig. 3. In Fig. 3, shaded region gives the total ODR band. From this figure, we observe that for the case of the TE polarization, the structure has its ODR range from 0.158 ωd/2πc to 0.460ωd/2πc and the ODR range for the TM polarization is from 0.202 ωd/2πc to 0.460 ωd/2πc. Therefore, total ODR range, in case there is a stack of three AC layers, has a bandwidth of 0.258 ωd/2πc from 0.202 ωd/2πc to 0.460 ωd/2πc.

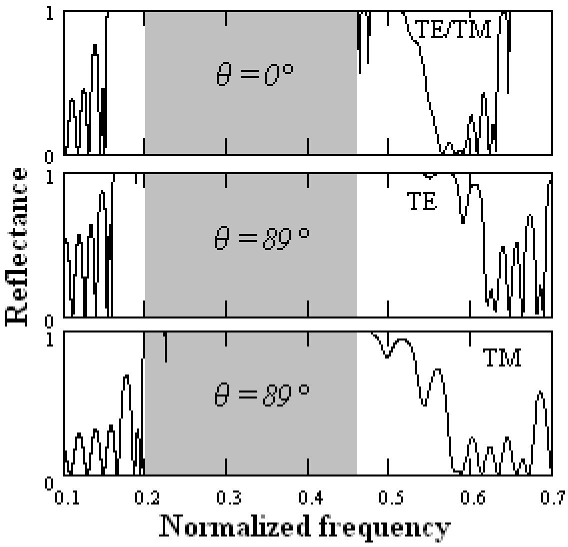

Fig. 3. Reflectance spectra for n=3, (a) TE polarization (b) TM polarization.

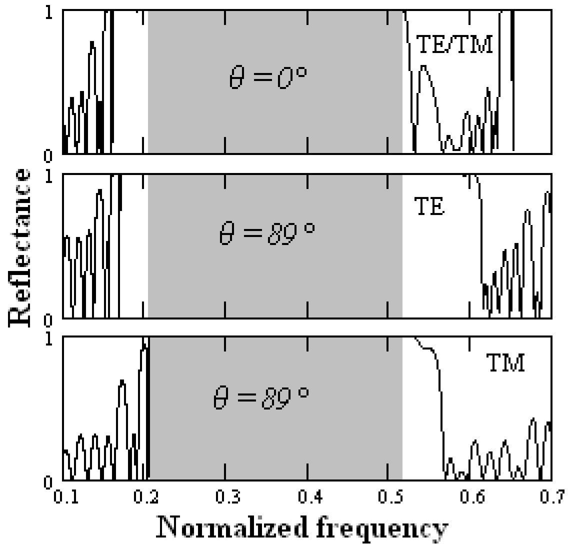

Fig. 4. Reflectance spectra for n=6, (a) TE polarization (b) TM polarization.

Finally when n=6 (i.e. when we introduce six AC layers in the form of a stack in the middle of 10 pairs of AB layers), the reflectance spectra are shown in Fig. 4. In Fig. 4, shaded region gives the total ODR band. From this figure, we observe that for the case of the TE polarization, the structure has its ODR range from 0.160 ωd/2πc to 0.516 ωd/2πc and the ODR range for the TM polarization is from 0.201 ωd/2πc to 0.516 ωd/2πc. Therefore, total ODR range, in case there is a stack of three AC layers, has a bandwidth of 0.315 ωd/2πc from 0.201 ωd/2πc to 0.516 ωd/2πc.

In this way, we can increase the total ODR range by introducing a stack in the middle of AB layers. It is found that for n=3 & 6, the ODR range is 2.6 & 3.2 times respectively that of the ODR range for n=0. Thus, the number of layers of AC is an important key for controlling the total omni-directional reflection range.

4. Conclusions

In conclusion, a simple design of omni-directional reflector using cascade one-dimensional photonic crystal in the form of a stack of periodic multi-layers has been suggested. By properly choosing the geometric and dielectric parameters of the constituent materials, broadening of wavelength range of omni-directional reflection of electromagnetic waves is possible, which may have potential applications in photonics.

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