Design of an omni directional reflector using one dimensional photonic crystal with a single defect

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An analytical study of a one-dimensional photonic crystal with a defect has been presented. It is found that omni-directional reflection (with cent percent reflectivity) range of a dielectric multilayered structure can be enhanced by introducing a defect in the conventional photonic crystal (PC). In the present communication, we study the omnidirectional reflection in visible and infrared region. We choose the Si/SiO$_2$ multilayer system for our study. It is found that introduction of a single defect in the structure considered is sufficient to increase omni-directional reflection band widths.

(Received December 18, 2009; accepted January 19, 2010)

Keywords: Photonic crystal, Omnidirectional reflection, Multilayer system

1. Introduction

Since the publication of the seminal works of Yablonovitch and John, study of photonic crystals has drawn attention of many investigators [1-3]. Subsequently, a class of photonic crystals exhibiting photonic band gaps has become a field of intense research. Photonic band gap (PBG) materials which are nothing but photonic crystals exhibiting photonic band gaps may be designed in one, two and three dimensions. But one-dimensional PBG materials (i.e. multilayered periodic structure with different refractive index materials) are attractive because such structures can be fabricated more easily at any wavelength scale and their analytical study and numerical calculations are simpler. 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 are realized and have been manufactured; and the conditions for their existence have been formulated. Thus, systems with periodic structure have become significant structures in photonics [4-8].

In 1998, Fink et al. [9] reported for the first time that one-dimensional dielectric lattice displays total omni-directional reflection for incident light under certain conditions. They constructed a stack of nine alternate polystyrene/tellurium layers having a thickness of a few micrometres. Further works by various researchers found many interesting results. Gallas et al. [10] reported the annealing effect in the Si/SiO$_2$ PBG based omni-directional reflectors. Chen et al. [11] fabricated six bi-layers of SiO$_2$ and TiO$_2$ quarter wave films using the sol gel method and found an omni-directional photonic band gap of about 70nm in near infrared region. Chigrin et al. [12,13] fabricated a lattice consisting of 19 layers of Na$_3$AlF$_6$/ZnSe and found that omni-directional photonic band gap exists in the spectral range 604.3 to 638.4nm.

Much later in 2003, Lee and Yao [14] studied theoretically and experimentally a wide range of structures for the realistic fabrication of omni-directional photonic crystals having photonic band gaps (PBGs) in one dimension. C. J. Wu [15] has theoretically studied microwave transmission and reflection in a periodic superconductor/dielectric film multilayer structure in mixed state.

Ojha et al. [16] theoretically studied omni-directional high reflectors for infrared wavelengths, large omni-directional reflection using combination of periodic and Fibonacci structures respectively. They found that the range of omni-directional reflection can be increased by overlapping these photonic crystals. J. Zi et al. [17] showed that it is possible to enlarge the range of low transmission in one-dimensional photonic crystals by introducing a defect in the photonic quantum well structures and found that defect modes have very high quality factor.

In the present communication, it is shown that by introducing a defect in photonic band gap materials, very large ranges of omni directional reflection with cent percent reflectivity can be realised. The defect in the normal photonic band gap structure can be created by removing a part of or the entire layer of a single material slab.

2. Theoretical analysis

To study the propagation of electromagnetic waves in one dimensional photonic crystal, let us consider a structure of alternate layers of two materials with different refractive indices n1 and n2 respectively having high refractive index contrast in which a and b are the thicknesses of the two layers respectively and also the unit cell thickness, d=a+b [Fig. 1(a)]. Suppose an electromagnetic wave incident obliquely on the interface of a one dimensional photonic crystal with an incident angle θ_0. We assume that the wave vector has components only in the x and z directions, then according to the Bloch wave theory $E(x+d) = exp(ikd).E(x)$, the dispersion relation for this periodic dielectric layers is given by

$$k(\omega) = \frac{1}{d}\cos^{-1}\left[\cos(k_1 a)\cos(k_2 b) - \frac{1}{2}\left(\gamma + \frac{1}{\gamma}\right)\sin(k_1 a)\sin(k_2 b)\right] \tag{1}$$

where $k_i=[(\omega n_i/c)^2-\beta^2]^{1/2}=(\omega n_i/c).cos(\theta_i)$, $\theta_i=sin^{-1}[(n_0/n_i).sin(\theta_0)]$, $i=1,2$ and $\gamma = \frac{k_1}{k_2}$ for TE mode and $\gamma = \frac{k_1 n_2^2}{k_2 n_1^2}$ for TM mode of polarization

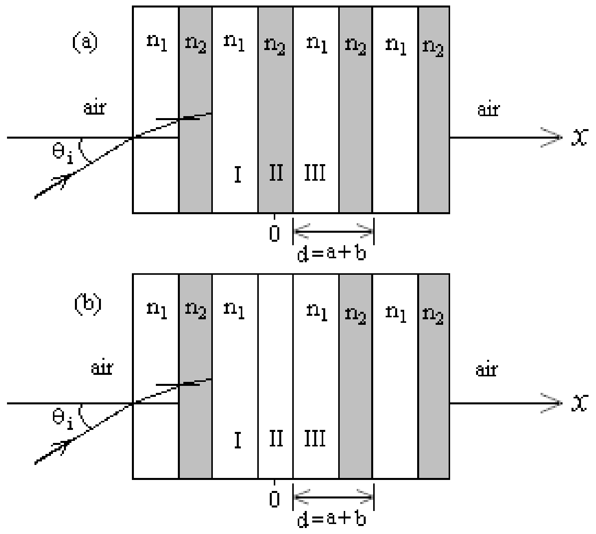


Fig. 1. Schematic diagram of periodic structure (a) normal structure (b) defect structure.

Dispersion relation for defect structure: The removal of a part or all of a single dielectric slab may now be considered within the above analytical model. Identifying the defect region as region II, we note that, from region I proceeding to left, we have a semi infinite lattice with a solution that increases exponentially to the right. Thus, equation (1) continues to hold, with e^{ikd} replaced by σe^{Kd}, where K is real and positive and the sign factor $\sigma = \pm 1$ is determined by that of the right hand side of equation (1). Hence the dispersion relation for a defect PBG structure can be written as [19]

$$K(\omega) = \frac{1}{\sigma.d}\cosh^{-1}\left[\cos(k_1 a)\cos(k_2 b) - \frac{1}{2}\left(\frac{k_1}{k_2} + \frac{k_2}{k_1}\right)\sin(k_1 a)\sin(k_2 b)\right] \tag{2}$$

The reflection and transmission can be related easily between the plane wave amplifications.

$$\begin{pmatrix} t \\ 0 \end{pmatrix} = M \begin{pmatrix} 1 \\ r \end{pmatrix} \tag{3}$$

and $M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$ with $M_{11} = m_{11}U_{N-1} - U_{N-2}$, $M_{21} = m_{21}U_{N-1}$, $M_{12} = m_{12}U_{N-1} - U_{N-2}$, $M_{22} = m_{22}U_{N-1} - U_{N-2}$ and $U_N = \frac{\sin[(N+1).K(\omega).d]}{\sin[K(\omega).d]}$ and transmission and reflection coefficients are given by

$$t = M_{11} - \frac{M_{12}.M_{21}}{M_{22}} \tag{4}$$

$$r = \frac{M_{21}}{M_{22}} \tag{5}$$

The associated reflectance (R) is obtained by taking the absolute square of *r*

$$R = |r|^2 \tag{6}$$

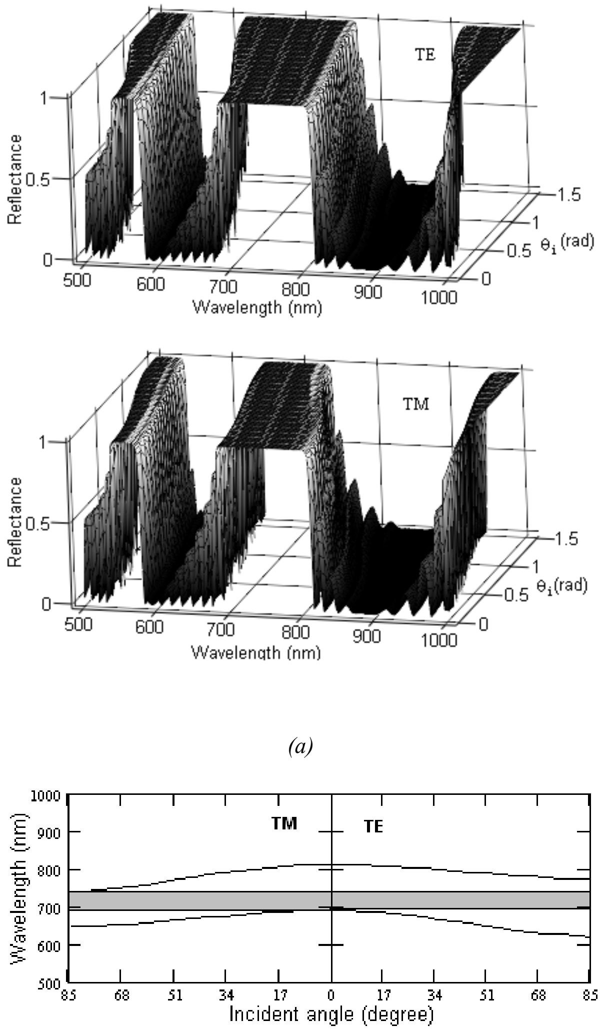
In the next section, we study the reflection properties of one dimensional photonic crystal by using equation (6).

3. Result and discussion

To evaluate the reflectivity of the defect photonic crystal, we used the transfer matrix method introduced by P. Yeh [18]. For the numerical computation, we have considered $[n_a/(n_1n_2)_5/(n_1n_a)_n/(n_1n_2)_5/n_a]$ multilayer system, where n_1 and n_2 are the materials with low and high refractive index materials respectively and n_a is the refractive index for air. We have used SiO_2 (n_1=1.5) as low refractive index material and Si (n_2=3.7) as the high refractive material. The thickness of the two layers taken a=0.59d and b=0.41d respectively.

From Snell's law $n_a \sin\theta_i = n_1 \sin\theta_1$, we can see that the refracted angle θ_1 is restricted to a certain range, where n_a and n_1 are the refractive indices of air and the dielectric layer adjacent to air, respectively, and θ_i is the incident angle. If the maximal refracted angle is smaller than the internal Brewster angle $\theta_1^B = \arctan(n_2/n_1)$, the incident wave from the outside can not couple to the Brewster window, leading to the total reflection for all incident angles.

From Fig. 2 (a) it is clear that, there is a region of unit reflectance with omni-directional reflection for TE polarization from 689nm to 772nm and for TM polarization from 689nm to 738nm. Fig. 2 (b) shows the combined photonic band structure for both polarizations. From Fig. 2 (b), it is clear that there is a common region of unit reflectance with omni-directional reflection both for the TE and the TM modes of polarization from 689nm to 738nm in the scale of wavelength. The total bandwidth of this region is 49nm.

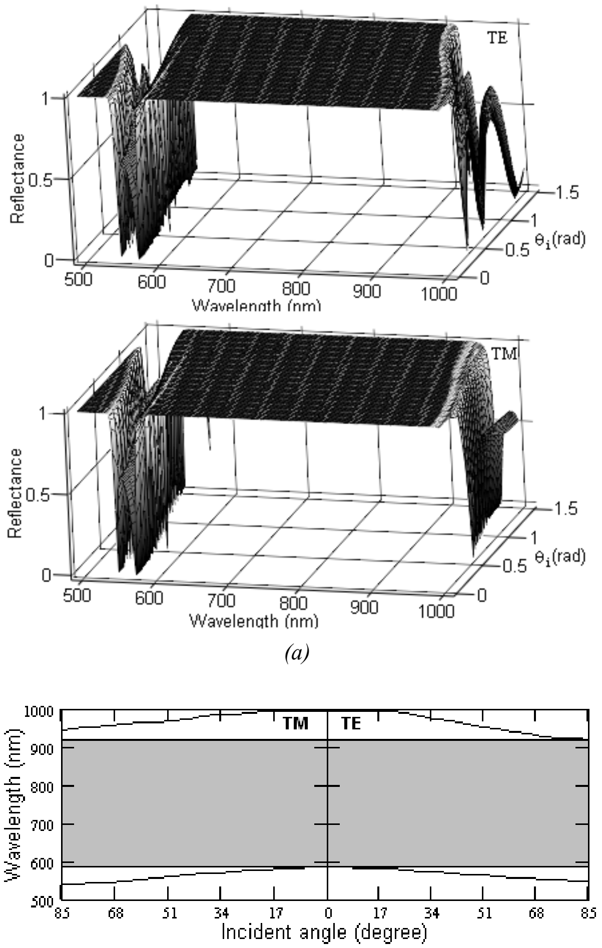


(a)

(b)

Fig. 2. (a) Reflectance spectra of 1-D PC (n=0) for TE and TM polarizations; (b) Photonic band structure of 1-D PC for n=0.

Fig. 3. (a) shows the reflectivity spectra for TE and TM mode of polarizations for n=1 i.e. one defect introduced in the middle of conventional photonic structure containing 10 pairs of lattice period. From Fig. 3 (a) it is clear that, there is a region of unit reflectance with omni-directional reflection for TE polarization from 685nm to 918nm and for TM polarization from 585nm to 952nm. Fig. 3 (b) shows the combined photonic band gap structure for both polarizations. From Fig. 3 (b) it is clear that, there is a common region of unit reflectance with omni-directional reflection both for the TE and the TM modes of polarization from 585nm to 918nm. The total bandwidth of this region is 333nm.



(a)

(b)

Fig. 3. (a). Reflectance spectra of 1-D PC (n=1) for TE and TM polarizations; (b) Photonic band structure of 1-D PC for n=1.

So, we can say that we can increase the omnidirectional band width by introducing a defect in the conventional PC. It is clear that by introducing a defect in a one-dimensional photonic crystal, the region of omni-directional refection with reflectance equal to unity can be enlarged to 6.8 times of that of an photonic crystal without a defect.

4. Conclusions

It is possible to enlarge the range of omni directional reflection in one dimensional photonic crystal by introducing the defect. By introducing some defects in the photonic crystal, defects modes with very large quality factor may appear. Such a structure may be used in the design of optical resonators and mirrors in which reflectivity is independent of the angle of incidence.

Acknowledgements

One of the authors, Vipin Kumar wishes to express sincere gratitude to Dr K. B. Thapa for their valuable suggestions and critical comments.

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