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Omnidirectional reflector using linearly graded refractive index profile of 1D binary and ternary photonic crystal

Sanjeev Sharma[a], Rajendra Kumar[a], Kh.S. Singh[b], Arun Kumar[c,*], Vipin Kumar[b]

[a] Department of Physics, Gurukul Kangri Vishwavidyalaya, Haridwar 249404, Uttarakhand, India
[b] Department of Physics, D.J. College, Baraut 250611, Uttar Pradesh, India
[c] Amity Institute of Telecom Engineering and Management, Amity University, Noida, India

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ABSTRACT

The effect of the refractive index profile on the omnidirectional reflector (ODR) of one dimensional dielectric and semiconductor multilayer structure having linearly graded material has been simulated using transfer matrix method. The theoretical analysis shows that the proposed structure works as a perfect mirror within a certain wavelength range. These wavelength ranges can be completely controlled by the refractive index profile of a graded semiconductor layer and also observed that these wavelength ranges are also controlled by refractive index parameters. Reflectance characteristics of 1D binary and ternary photonic crystal (PC) structure have been studied. This property shows that the ODR range of structure increased when a third layer of semiconductor added in a binary photonic crystal.

1. Introduction

One dimensional Photonic crystals (PCs) are periodically structured electromagnetic media in which a certain range of electromagnetic (EM) waves are forbidden to propagate through the structure. This range of frequencies is called photonic band gaps (PBGs). The periodicity of the structure and the periodic variation of dielectric constant of different materials are the essential parameters for the formation of these PBGs [1]. Such types of PCs have drawn the attention of a large section of researchers because of its numerous possible applications such as omnidirectional reflectors, filters, optical switches, waveguides, cavities and design of more efficient layers, etc. [2–7]. Recently, optical reflectors are one of the most widely used optical devices and a great deal of work has been done on the omnidirectional reflectors [8–11]. Reflectors are mainly of two types: one is metallic and other is a multilayer dielectric reflector. In a metallic reflector light can be rejected over a wide range of frequencies for arbitrary incident angles; however, at higher frequencies, a considerable amount of power is lost due to the absorption. In comparison to metallic reflectors, multilayer dielectric reflectors have high reflectivity over a certain range of frequencies, but the reflectivity is very sensitive to the incident angles. The range of rejected frequency of the multilayer dielectric reflector can be enhanced by the appropriate selection of the material parameters and layer thickness.

On the other hand, graded multilayered structures have been studied and investigated as a heterogeneous composite material. It has been found that the physical properties of the graded material are different from those of the homogeneous material and conventional composite materials [12,13]. Recently, some researchers have studied the transmission and reflection properties of graded multilayered structures [14,15]. In general, graded photonic crystal (GPC) structures have a variation in either the refractive indices of the alternate layers (keeping the thickness of the constituent layers constant). It is well known that the band gap of the PC structure depends on the contrast in the refractive indices of the alternate layers and their thickness ratio. Thus, in order to study the band gaps and reflection/transmission properties of the PC structure one can vary any of these parameters for the desired result. In this paper, we propose the design of a broadband optical reflector using a one-dimensional graded photonic crystal having linear gradation in the refractive index of the alternate layers for a certain number of layers and having a periodic repetition of this unit. In binary photonic crystal, the proposed structure consists of a periodic array of two alternate layers of some dielectric/semiconductor materials with low and high values of refractive indices (n_1 and n_2) and thicknesses a and b and in ternary photonic crystal the proposed structure consists of a periodic array of three alternate layers of some dielectric/semiconductor materials with low and high values of refractive indices (n_1, $n_2(x)$ and n_3) and thicknesses a, b

* Corresponding author. Tel.: +91 9873537228.
E-mail address: arun_mtech@yahoo.co.in (A. Kumar).

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and c, respectively. In order to calculate the reflection properties, a transfer matrix method (TMM) has been used.

In this paper, we describe the linear grading index characteristics of one-dimensional photonic crystal and design omnidirectional reflectors.

2. Theory

Plane TE and TM mode electromagnetic waves with angular frequency ω are assumed to be incident on the 1D-PCs structure having linearly graded refractive index profile in one layer of the unit cell. The unit cells of considered 1D-PCs have periodic arrangement of dielectric and semiconductor materials. The unit cell is shown in Fig. 1. The refractive index profiles of one dimensional binary and ternary photonic crystal structures are given by,

$$n(x)=\begin{cases} n_1 & (n-1)d<x<(n-1)d+a \\ n_2(x)=n_0+\dfrac{n_{\max}-n_0}{b}x & (n-1)d+a<x<nd \end{cases} \tag{1a}$$

$$n(x)=\begin{cases} n_1, & (n-1)d<x<(n-1)d+a \\ n_2(x)=n_0+\dfrac{n_{\max}-n_0}{b}x & (n-1)d+a<x<(n-1)d+a+b \\ n_3, & (n-1)d+a+b<x<nd \end{cases} \tag{1b}$$

where $n_2(x)$ is linearly grading refractive index of dielectric material and n_0 and n_{max} are the initial and maximum value of refractive index, respectively, for the layer with linear refractive index variation parameter $x = n_{max} - n_0$. Also, a and b are the widths of the layer of semiconductor and linearly graded refractive index profile of dielectric (SiO_2) material, respectively.

Applying the transfer matrix method (TMM), the characteristic matrices for the TE and TM waves have the form [16,17]

$$M[d]=\begin{cases} \prod_{i=1}^{k}\left[\begin{bmatrix} \cos\cos\gamma_i & \dfrac{-i}{p_i}\sin\sin\gamma_i \\ -ip_i\sin\sin\gamma_i & \cos\cos\gamma_i \end{bmatrix}\prod_{j=1}^{n}\begin{bmatrix} \cos\cos\gamma_j & \dfrac{-i}{p_j}\sin\sin\gamma_j \\ -ip_i\sin\sin\gamma_j & \cos\cos\gamma_j \end{bmatrix}\right] & \text{for (binary)} \\ \prod_{i=1}^{k}\left[\begin{bmatrix} \cos\cos\gamma_i & \dfrac{-i}{p_i}\sin\sin\gamma_i \\ -ip_i\sin\sin\gamma_i & \cos\cos\gamma_i \end{bmatrix}\prod_{j=1}^{n}\begin{bmatrix} \cos\cos\gamma_j & \dfrac{-i}{p_j}\sin\sin\gamma_j \\ -ip_i\sin\sin\gamma_j & \cos\cos\gamma_j \end{bmatrix}\prod_{i=2}^{k}\begin{bmatrix} \cos\cos\gamma_i & \dfrac{-i}{p_i}\sin\sin\gamma_i \\ -ip_i\sin\sin\gamma_i & \cos\cos\gamma_i \end{bmatrix}\right] & \text{for (ternary)} \end{cases} \tag{2}$$

where $k=2$ for binary photonic crystals and $k=3$ for ternary photonic crystals (1, 2 and 3 signify the layers of refractive indices n_1, n_2 and n_3, respectively), $\gamma_i=\frac{2\pi}{\lambda p_i d_i\cos\theta_i}$, $p_i=n_i\cos\theta_i$, $\gamma_j=\frac{2\pi}{\lambda p_j d_j\cos\theta_j}$ and $p_j=n_j\cos\theta_j$ with θ_i being the ray angles inside the layer of refractive index n_i and is related to the angle of incidence θ_0 by

$$\cos\theta_i=\left[1-\frac{n_0^2\sin^2\ \theta_i}{n_i^2}\right]^{1/2} \tag{3}$$

The matrix $M[d]$ in Eq. (1) is unimodular as $M[d]$=1.

For an N-period structure, the characteristic matrix of the medium is given by,

$$M(d)^N=\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^N=\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{4}$$

The transmission coefficient of the multilayer is given by,

$$t=\frac{2p_0}{(m_{11}+m_{12}p_0)p_0+(m_{21}+m_{22}p_0)} \tag{5}$$

And the reflection coefficient of the multilayer is given by,

$$r(\omega)=\frac{(m_{11}+m_{12}p_0)p_0-(m_{21}+m_{22}p_0)}{(m_{11}+m_{12}p_0)p_0+(m_{21}+m_{22}p_0)} \tag{6}$$

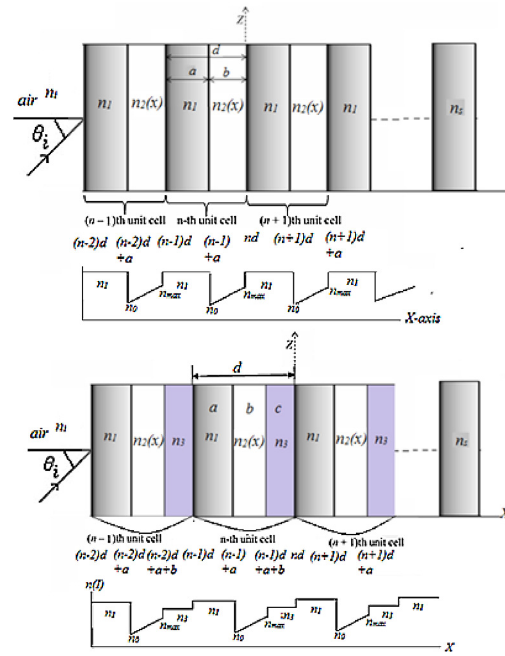

Fig. 1. Periodic variation of one-dimensional binary and ternary photonic band gap structure and linear grading refractive index profile of the structure.

And the reflectance for this structure can be written in the terms of reflection coefficient as,

$$R=\left|r(\omega)\right|^2 \tag{7}$$

where $p_0 = n_0\cos\theta_0$.

3. Results and discussion

In this paper, we study ODR property in one-dimensional binary and ternary PC structures consisting of alternate layers of (i) PbS and SiO_2 (ii) PbS, SiO_2 and ZnS. The theoretical analysis is based on the transfer matrix method. For the optical properties of PbS and SiO_2 the data used for the ranges of wavelengths of our interest are those of, Schoolar et al. [18], Drummond et al. [19] and DeVore et al. [20], respectively.

For our calculations we take PbS and ZnS as the semiconductors materials of high refractive index layers and SiO_2 as the materials of the layers having a linearly graded refractive index profile of the one-dimensional PCs considered here. We studied two different structures of binary and ternary one-dimensional photonic crystals namely:

Structure I: PbS/SiO_2 one-dimensional binary photonic crystal.
Structure II: PbS/SiO_2/ZnS one-dimensional ternary photonic crystal.

The refractive indices of PbS and ZnS are 4.19 and 2.27, respectively, and the linear grading of refractive index for SiO_2 in