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Broad inhibition of transmission frequency in multilayered dielectric one dimensional photonic crystal nanostructure

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Abstract

We report the omnidirectional reflection (ODR) in one dimensional photonic crystal (PC) structure consisting of alternate layers of Cryolite (Na_3AlF_6) as material of low refractive index and Germanium (Ge) as material of high refractive index. The effects of the thickness of layers and incidence angles on the spectral reflectance have been investigated using transfer matrix method (TMM). The proposed structure gives 100% reflection within a wide range of wavelengths in the visible-near IR region (600 nm- 850 nm) which can be tuned according to the design parameters. We observe that cryolite based photonic crystal structure can be used as a good candidate for wavelength filter or broad reflector in the near infrared spectrum which is very useful in many imaging sensors in the field of optical technology.

Keywords: cryolite; photonics; photonic crystals; omnidirectional reflector; transfer matrix method; cryolite based 1DPC; 1DPC

1. Introduction

Photonic Crystals (PCs) are optical nanostructures with a periodic modulation in the refractive index on the length scale comparable to optical wavelength. They are characterized by electromagnetic forbidden bands or photonic band gaps (PBGs). In other words, the propagation of electromagnetic waves, whose frequencies lie within the PBGs, is prohibited. This unique feature of the photonic crystal structures controls dramatically the flow of light within the structure and can lead to many potential applications in field of photonics [1-7]. The propagation of photons in PCs is analogous to propagation of electrons in semiconductor crystals where the effect of periodic refractive index in PCs is same as the effect of periodic potential function on propagation of electrons in semiconductors.

In these structures the refractive index is a periodic function in space and if the refractive index is periodic only in one dimension then the structure is called one dimensional photonic crystal (1DPC), if it is periodic in two dimensions and three dimensions then the structure is known as two dimensional photonic crystal (2DPC) and three dimensional photonic crystal (3DPC) respectively. PCs that work in microwave and far-infrared regions are relatively easier to fabricate. However, PCs that work in visible and the infrared (IR) regions, especially, 3DPC are difficult to fabricate because of their small lattice constants, which have to be comparable to the wavelength. Therefore, 1D PCs, which can easily be produced by the thin film deposition techniques, are preferable for use in the visible and IR regions [8-14]. The simplest 1DPC is an alternating stack of two different mediums having reflection properties which find them used in variety of applications including high efficiency mirrors, Fabry Perot cavities, optical filters and feedback lasers [15-22]. In recent time optical reflectors are one of the most widely used optical devices and a great deal of work has been done on the omnidirectional reflectors [23-26]. In metallic reflector 27, light can be reflected over a wide range of frequencies for arbitrary incident angles however, at higher frequencies considerable amount of power is lost due to the absorption. In comparison to metallic reflectors a cryolite based multilayered nanostructures have high reflectivity in a certain range of frequencies, but the reflectivity is very sensitive to the incident angles. The range of reflected frequency of these reflectors can be enhanced by the appropriate selection of the material parameters and layer thickness [28-31].

The space-time dispersion of cryolite conductivity was analyzed and the optical properties of cryolite were studied [32]. Thus, cryolite has unique optical properties which make it useful in designing of opto-electronic devices. In the present study, we have neglected field absorption / attenuation as the constituent materials have negligible absorption coefficients in the wavelength range of interest. We observe that cryolite based photonic crystal structure can be used as a good candidate for wavelength filter or broad reflector in the near infrared spectrum which is very useful in many imaging sensors in the field of optical technology. The paper is organized as follows. In Section 2 we develop the theoretical tool to analyze the ODR properties and linear characteristics of the 1D PC. In Section 3, we discuss the results obtained on the ODR properties of the cryolite based 1DPC. Finally, in Section 4, we conclude the paper.

2. Theoretical Analysis

To calculate the dispersion relation and reflection characteristics for the incident electromagnetic wave the Maxwell's equation is solved numerically by the transfer matrix method [15].

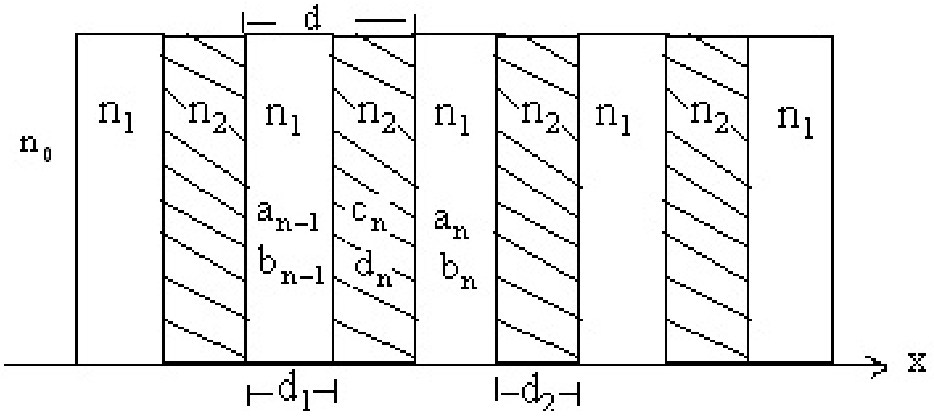


Figure 1. Periodic refractive index profile of the structure having refractive indices n_1 and n_2 respectively

The geometry of the structure under study is shown in the Fig. 1. Consider the propagation of EM wave along x-axis normal to the interface in one-dimensional system composed of periodic arrays of two different materials with a refractive index n_1 and n_2 and layer thickness d_1 and d_2. The indices of refraction of the system are given as,

$$n(x) = \begin{cases} n_1, & 0 < x < d_1 \\ n_2, & d_1 < x < d_2 \end{cases} \tag{1}$$

with n(x) = n(x + d). where d_1 and d_2 are the thicknesses of the layers and $d = d_1 + d_2$ is the period of the structure. The electromagnetic field distribution within each layer can be expressed as the sum of right- and left-hand side propagating wave. The electric field within the both layers of the *n*th unit cell can be written as

$$E_1(x) = \left[\left(a_n e^{-ik_1(x-nd)}\right) + \left(b_n e^{ik_1(x-nd)}\right)\right]e^{i\omega t} \tag{2}$$

$$E_2(x) = \left[\left(c_n e^{-ik_2(x-nd)}\right) + \left(d_n e^{ik_2(x-nd)}\right)\right]e^{i\omega t} \tag{3}$$

Where $k_i = \left[\left(\frac{n_{i\omega}}{c}\right)^2 - \beta^2\right]^{\frac{1}{2}} = \frac{n_{i\omega}}{c}\cos\theta_i$,

θ_i is the ray angle in the i^{th} layer (i = 1, 2), β is the propagation constant and n_i is the refractive index of the constituent layers. The coefficients a_n, b_n, c_n, and d_n are related through the continuity boundary conditions at the interfaces $x = (n-1)d$ and $x = (n-1)d + d_2$. This continuity condition leads to the matrix equations, which relates the coefficient in the first layer of the n^{th} cell, is given as

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = T_n \begin{pmatrix} a_n \\ b_n \end{pmatrix} \tag{4}$$

where T_n is called the transfer matrix given by

$$T_n = \begin{pmatrix} A & B \\ C & B \end{pmatrix} \tag{5}$$

The matrix elements A, B, C and D are

$$A = e^{ik_1d_1}\left[\cos k_2d_2 + \frac{1}{2}\, i\left(\eta + \frac{1}{\eta}\right)\sin k_2d_2\right] \tag{6}$$

$$B = e^{-ik_1d_1}\left[\frac{1}{2} i\,\left(\eta - \frac{1}{\eta}\right)\sin k_2d_2\right] \tag{7}$$

$$C = e^{ik_1d_1}\left[-\frac{1}{2} i\,\left(\eta - \frac{1}{\eta}\right)\sin k_2d_2\right] \tag{8}$$

$$D = e^{-ik_1d_1}\left[\cos k_2d_2 - \frac{1}{2}\, i\left(\eta + \frac{1}{\eta}\right)\sin k_2d_2\right] \tag{9}$$

The parameter η depends on the polarization. For the TE and TM polarizations, η is given by

$$\eta_{TE} = \frac{k_1}{k_2} \tag{10}$$

and

$$\eta_{TE} = \frac{k_1\, {n_2}^2}{k_2 {n_1}^2} \tag{11}$$

For finite stacks, the coefficient of right and left hand side propagating wave in both sides of the multilayer structure a_N and b_N, are calculated by multiplying transfer matrix of each cell as

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = T_1T_2 \ldots T_N \begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{12}$$

where N is the total number of the cell. The coefficient of reflection is given by solving above matrix equation with the condition $b_N = 0$ as

$$r_N = \left(\frac{b_0}{a_0}\right) \tag{13}$$

Thus the reflectivity (or reflectance) of the structure may be calculated as

$$R_N = |r_N|^2 \tag{14}$$

Now, according to Bloch theorem, the electric field vector is of the form $E(x) = E_{K(x)}e^{i(\omega t - Kx)}$ where $E_{K(x)}$ is periodic with 'd'. For the determination of K as a function of eigenvalue, the equation is written as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} a_n \\ b_n \end{bmatrix} = e^{iKd}\begin{bmatrix} a_n \\ b_n \end{bmatrix} \tag{15}$$

The solution of this matrix equation leads to the dispersion relation for the PC structure

$$K(\omega) = \left(\frac{1}{d}\right)\cos^{-1}\left[\cos(k_1d_1)\ \cos(k_2d_2) - \frac{1}{2}\left(\eta + \frac{1}{\eta}\right)\sin(k_1d_1)\ \sin(k_2d_2)\right] \tag{16}$$

The existence of omnidirectional photonic band gap in one dimensional photonic crystal requires the incident waves to be launched from vacuum or from a low refractive index ambient medium [5].

3. Result & Discussion

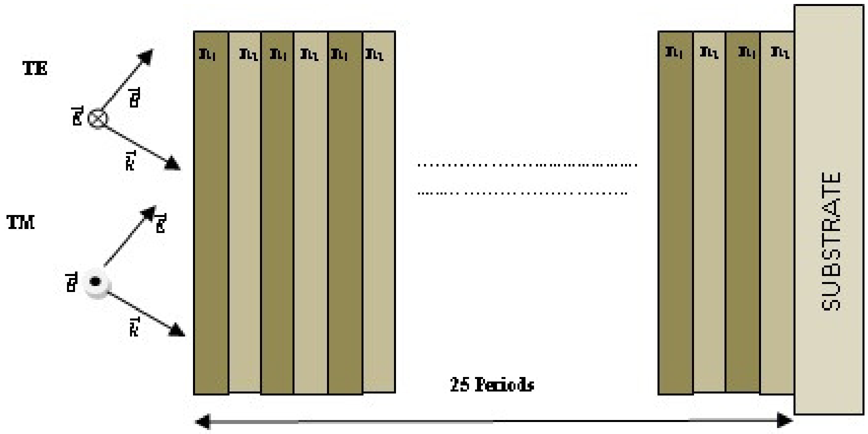


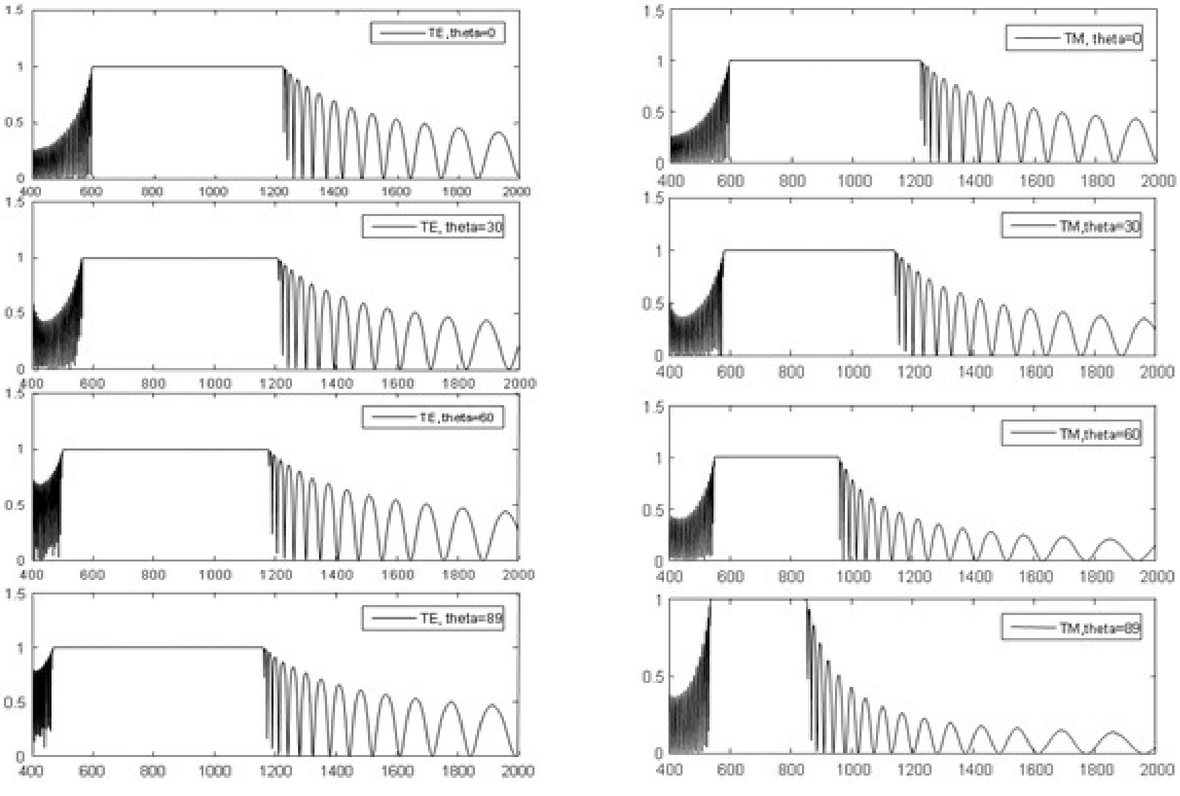
Figure 2: Schematic representation of proposed structure $(AB)^{25}$

with all A's as Cryolite and all B's as Ge

In this section we present the numerical analysis of the proposed PC structure and show the Omni-directional reflection bands for both TE and TM polarizations. The value of refractive index for the Na3AlF6 is taken as 1.34 and Ge is 4.2 at λ_0=800 nm. The thickness of the layers are taken as according to quarter wave stacks condition i.e. $d_1=\lambda_0/4n_1$=149.25 nm and $d_2=\lambda_0/4n_2$=47.61 nm. The reflection spectra obtained for the total number of layers N=25 is depicted in Fig-3 for both TE and TM polarizations. From the study of these figures it is observed that as the angle of incidence increases the reflection band width increases for TE mode while it decreases for TM mode and at the same time the reflection band is shifted towards lower wavelength region (blue shifted) as shown in (Table 1). The width of reflection band has larger value for the TE mode in comparison to the TM mode. At oblique incidence, different polarizations (TE and TM) exhibit different reflectance. When a PC reflects light of both polarizations incident at any angle within a certain frequency range, the PC is said to have a complete omnidirectional bandgap. We observe that light waves of a wavelength range from (595.8 nm to 845.8 nm) are always reflected from the proposed structure irrespective of the state of polarization. Thus one dimensional multilayered Na3AlF6 –Ge photonic crystal structure shows omnidirectional reflection band in the wavelength region (595.8nm - 845.8nm) and can be used as a good candidate for making wavelength filters in the visible–near infrared spectrum from (595.8nm-845.8nm) wavelength range when N is large enough.

Table 1. Total reflectance region band width for [Cryolite-Ge] at the various incident angles for TE and TM modes for N=25

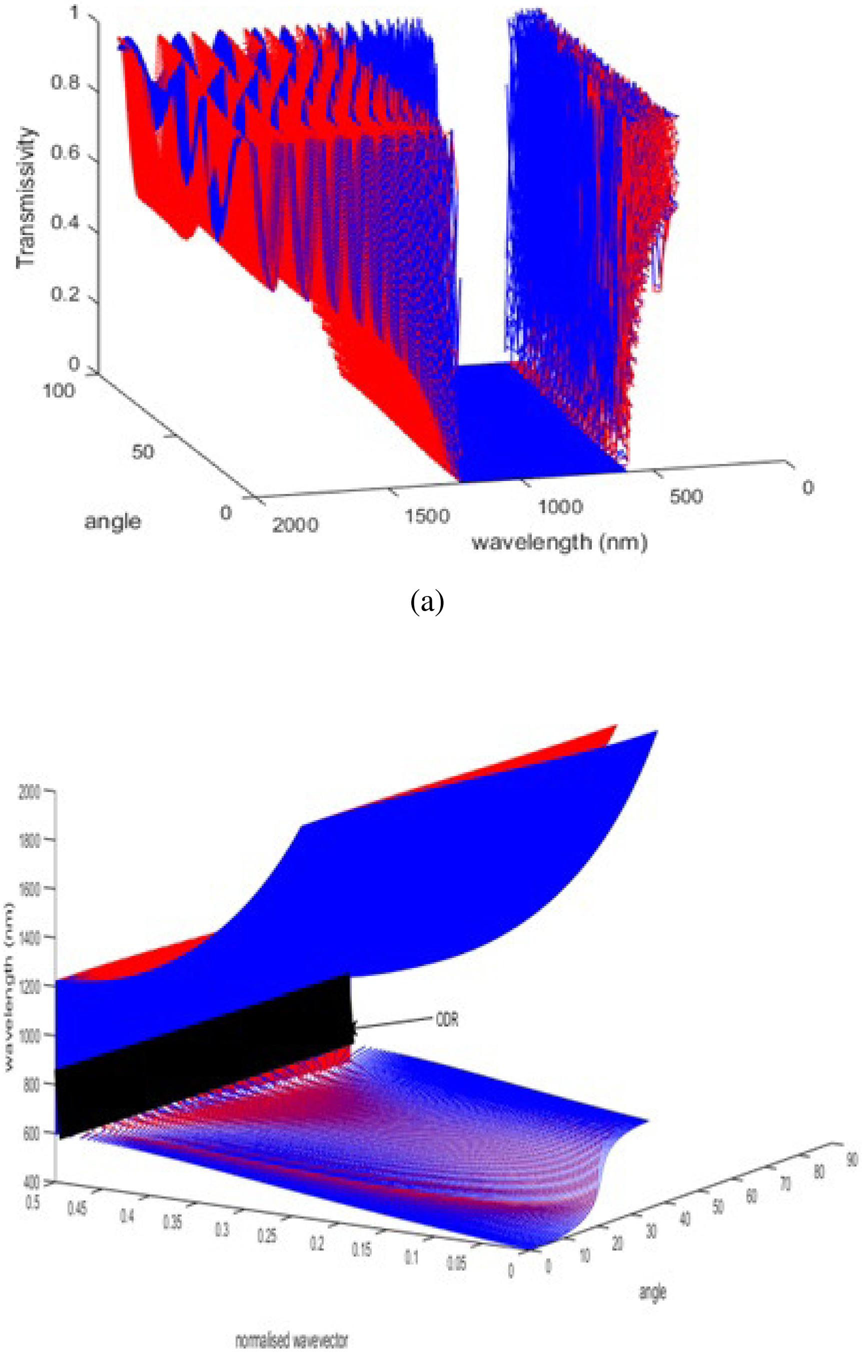
	TE			**TM**		
Na_3AlF_6-Ge N=25	LOWER BAND EGDE (nm)	UPPER BAND EDGE (nm)	BAND GAP (nm)	LOWER BAND EGDE (nm)	UPPER BAND EDGE (nm)	BAND GAP (nm)
$\Theta=0^0$	595.8	1217	621.2	595.8	1217	621.2
$\Theta=30^0$	564.8	1202	637.2	580.8	1136	555.2
$\Theta=60^0$	500.6	1173	672.4	552	952.2	400.2
$\Theta=89^0$	468.3	1158	689.7	538.7	845.8	307.1
Omni directional reflection band = 845.8 nm-595.8 nm=250 nm						



(a) (b)

Figure 3. The reflectance spectra for TE and TM modes showing the total reflection region and bandwidth for $n_1=1.34$, $n_2=4.2$, $d_1=149.25$ nm, $d_2=47.61$ nm and N=25 at various incident angles,

(a) TE, θ=0°,30°,60°,89° (b)TM, θ=0°,30°,60°,89°



(a)

(b)

Figure 4: (a) Transmissivity variation with wavelength and angle of incidence (deg.) for TE modes (Red lines) and TM modes (Blue lines) in multilayered Cryolite-Ge.

(b) Dispersion relation with variation of angle of incidence (deg.) for TE modes (Red lines) and TM modes (Blue lines) for Cryolite-Ge

4. Conclusion

We have investigated theoretically the omnidirectional bandgap properties in proposed 25 layer 1DPC in the range of 150 nm thick cryolite films and 50 nm thick Ge films as alternate layers. The propagation properties and dispersion characteristics for both TE and TM modes for the structure of interest is analyzed using transfer matrix method and it is observed that there exists an omnidirectional band gap of 250 nm from (845.8nm-595.8nm) in the visible-near infrared region which makes this structure to be used as wavelength filters. We observe that cryolite based photonic crystal structure can be used as a good candidate for complete inhibition of transmission of frequency in near IR region and it can be tuned by changing the design parameters. The proposed use of these multilayered nanostructures is as omnidirectional reflectors and near IR wavelength cutoff filters which are used in many imaging sensors in the field of optical technology. . In medical physics this window is useful in Blood oxygenation measurements. This window of wavelength range is also useful in infrared photography

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