ODR Range Using Exponentially Graded Refractive Index Profile of GaAs Based 1D Photonic Crystal

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Abstract- A one dimensional semiconductor multilayer structure having refractive index profile of exponentially graded material has been proposed. The theoretical result shows that the proposed structure works as an optical mirror within a certain wavelength range (1550 nm). In order to calculate the reflection properties a transfer matrix method (TMM) has been used. This property shows that one dimensional graded photonic crystal structures have widened omnidirectional reflector bandgap.

Key Words: Exponentially graded photonic crystal, ODR, optical mirror.

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 lasers, 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 [8-13].

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) [14]. It is well known that the band gap of the PC structure depends on the variation of 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 the present communication we propose the design of a broadband optical reflector using a one-dimensional graded photonic crystal having exponentially 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 (n₁ and n₂(x)) which varies exponentially from initial to final values) and thicknesses a and b. In order to calculate the reflection properties, a transfer matrix method (TMM) has been used.

2. THEORY

The one dimensional exponentially graded photonic crystal structure consists of alternate layer of high and low refractive indices along the X-axis and placed between semi infinite media of refractive indices nᵢ (refractive index of incident medium) and nₛ (refractive index of substrate) as shown in Fig. 1.

The exponentially graded refractive index profiles of one dimensional binary photonic crystal structure is given by,

\[
n(x) = \begin{cases} 
  n_1 & \text{for } (n-1)d < x < (n-1)d + a \\
  n_2(x) = n_{g2}(x) e^{\frac{\ln(n_{max})}{b}} & \text{for } (n-1)d + a < x < nd 
\end{cases}
\]  

Where, n₂(x) is the exponentially grading refractive index of semiconductor material and n₀ & nₓₘₐₓ is the initial and maximum value of refractive index of the graded semiconductor at x = 0 to x = b respectively. Also, a and b are the width of dielectric/semiconductor and graded semiconductor layer and x is the grading distance from a to b.
dielectric/semiconductor and semiconductor layers and the grading parameter is $y = \frac{n_1}{n_2}$.

Applying the transfer matrix method (TMM), the characteristic matrices for the TE and TM waves have the form [14, 15],

$$M[d] = \Pi_{i=1}^{N} \begin{bmatrix} \cos \gamma_i & -i \sin \gamma_i \\ -ip_i \sin \gamma_i & \cos \gamma_i \end{bmatrix}$$

$$\times \Pi_{i=1}^{N} \begin{bmatrix} \cos \gamma_i & -i \sin \gamma_i \\ -ip_i \sin \gamma_i & \cos \gamma_i \end{bmatrix} \begin{bmatrix} M_{i1} & M_{i2} \\ M_{i2} & M_{i1} \end{bmatrix}$$

Where, $k = 2$ for binary photonic crystals (1 and 2 signify the layers of refractive indices $n_1$ and $n_2(x)$ respectively),

$$\gamma_i = \frac{2\pi}{\lambda} p_i d_i \cos \theta_i$$, 

$$p_i = n_i \cos \theta_i$$, 

$$\theta_i$$ are the ray angles inside the layer of refractive index $n_i$ and is related to the angle of incidence $\theta$ by

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

The total characteristic matrix of an $N$-period of the structure given by

$$M(d)^N$$

The reflection coefficient of the multilayer is given by,

$$r(\omega) = \frac{(m_0 + m_2 p_0) p_0 - (m_3 + m_2 p_0)}{(m_2 + m_0 p_0) p_0 + (m_3 + m_2 p_0)}$$

Where $p_0 = n_0 \cos \theta_0$

$$R = |r(\omega)|$$

### 3. RESULTS AND DISCUSSION

In this paper, we study the Omni-directional reflection (ODR) property of one-dimensional photonic crystal (PC) structures consisting of alternate layers of CaF$_2$ and GaAs. The theoretical analysis is based on the transfer matrix method. For calcium fluoride (CaF$_2$), the data used for the range 1.5-$\mu$m-9$\mu$m are taken from I. H. Malitson et al. [16].

For our calculations we take GaAs as exponentially grading one-dimensional semiconductor material. We studied CaF$_2$/GaAs structure of binary one-dimensional photonic crystals. The refractive indices of CaF$_2$ is 1.42 and the refractive indices of exponentially grading materials for GaAs is varying from 1.45-3.37. Applying transfer matrix method, we get relations for dispersion characteristics and reflectance. We plotted reflectance of the structures with wavelength for various angles of incidence. The refractive index profile of exponentially grading materials for GaAs is shown in Fig. 2.

We have taken the thicknesses of CaF$_2$ and GaAs layers to be $a=0.9d$, $b=0.1d$ and $d=a+b=90nm$. This particular combination of thickness of CaF$_2$ and GaAs layers is choose such that the structure may exhibit omnidirectional reflection (ODR) for a certain range of wavelength in the reflection spectra of the structure. Fig. 3 shows the reflectance of the structure for different angles of incidence, namely, $0^\circ$, $45^\circ$ and $85^\circ$ for TE and TM mode respectively and the ODR range for angles of incidence from $0^\circ$ to $85^\circ$ is shown in the shaded portion of Fig. 3.

From the plots the plots of reflection spectra of CaF$_2$/GaAs for different angles of incidence, 100 percent reflection ranges for different angles of incidence at grading parameter $y = 2.32$ are tabulated in Table 1. It is clear from Table 1 that the 100% reflectance-range for TE mode is 1425-2035 nm at normal incidence. Similarly, for angles of incidence of $45^\circ$ and $85^\circ$ the respective ranges of wavelength with 100% reflectance are 1310-1955 nm and 1185-1870 nm for TE mode. Also the ranges of 100% reflection for TM mode are 1425-2035 nm, 1360-1830 nm and 1285-1615 nm for angles of incidence at $0^\circ$, $45^\circ$ and $85^\circ$ respectively. Hence the total omnidirectional range of wavelength for this multilayer structure lies between 1425–1615 nm and the width of the omnidirectional wavelength range is 190 nm.

From the above discussion, it is clear that one dimensional structure CaF$_2$/GaAs has the largest ODR range of wavelength (190 nm) and such a structure may be considered for applications in multichannel broadband communications.
4. CONCLUSION

The reflection properties of exponentially graded photonic crystals GaAs having a layer of exponentially graded refractive index profile show interesting properties. It is found that the ODR range of proposed structure can be enhanced by varying the refractive index profile of GaAs exponentially graded photonic crystals. The GPCs can be used as omnidirectional reflectors in fiber optic communication.

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