Multi Photonic Band Gap Silica Gallium Nonlinear Omnideirectional 1 D Photonic Crystal

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Abstract : We theoretically design a one dimensional (1D) dielectric/semiconductor (silica/gallium) nonlinear Omnideirectional photonic crystal. We have investigated a 10 layers 1 D Photonic crystal, where silica and gallium are respectively a low refractive index material (n_L) and a high refractive index material (n_H).The refractive index of both the materials nonlinearly depends on the wavelength; both materials are nonlinear optical materials. The proposed quarter wave stack structure is investigated in the form air $(n_L n_H)^{10}$air. Reflectivity for these structures at normal incidence has been calculated by using transfer matrix method (TMM).The results show that if the incident wavelength in the visible region then by varying the critical wavelength of controlling wave, the complete Omnidirectional (ODR) photonic band gap varies that means a single device can be used as multi ODR photonic band gap. This device may be used for optical communication, optoelectronic devices, etc., where multi ODR photonic band gap necessary.

Keywords: *Photonic crystal, Transfer matrix method, Omnidirectional reflection, Photonic band gap, Omnidirectioal band gap.*

Introduction:-

A photonic crystal is a periodic optical nanostructure that affects the motion of photons in much the same way that ionic lattices affect electrons in solids. Photonic crystals occur in nature in the form of structural coloration and in different forms. In 1887 the English physicist Lord Rayleigh experimented with periodic multi-layer dielectric stacks, showing they had a photonic band-gap in one dimension. Research interest grew with work in 1987 by Yablonovitch and John on periodic optical structures with more than one dimension which are now called photonic crystals. Photonic crystals can be fabricated for one, two, or three dimensions. One-dimensional photonic crystals can be made of layers deposited or stuck together.

The propagation of electromagnetic waves (EM waves) in periodic dielectric structures in one, two, three spatial directions has received much attention on the experimental and theoretical investigations works of Yablonovitch [1] and John [2]. Such kind of periodic dielectric structures is called photonic crystals (PCs), and can generate spectral regions named photonic band gaps (PBGs), which is equivalent to the electronic band gaps in a semiconductor. The propagation of EM waves with frequency located in the PBG is strongly forbidden in PCs. The earlier studies have been demonstrated [3–5,16] that a PBG can be formed as a result of the interference of multiple Bragg scattering in a periodic dielectric structure. If EM wave incident at any angle with any polarization cannot propagate in PCs, the total OBG can be achieved. The larger OBGs have been widely used in various modern applications, such as omnidirectional high reflector [6], all-dielectric coaxial waveguide [7], and omnidirectional mirror fiber [8]. The multilayer periodic structure has been always applied in enhancement the OBGs as described in most works [9–11, 16].

Theoretical analysis of Light propagation in periodic layered media solved by transfer matrix method

The 1 D photonic crystals usually defined as media which are periodic in one spatial direction. Such structures are widely used in modern optoelectronics, ranging from Bragg mirrors for distributed-feedback lasers. A typical example of a one-dimensional periodic medium is a Bragg mirror which is a multilayer made of alternating transparent layers with different refractive indices. Assuming a laser beam is incident on a Bragg mirror; the light will be reflected and refracted at each interface. Constructive interference in reflection occurs when the condition

$$m\lambda = 2T\cos\theta_i \quad (1)$$

is satisfied [12]. Here, λ is the wavelength of the incident light, T is a period of the periodic medium, *m* is an integer number and θ_i is an angle of incidence. This relation is known as the *Bragg condition*. It can be easily derived by considering the phase difference between rays reflected from successive layers. Constructive interference occurs when the optical path difference between rays reflected from successive lattice planes contains an integer number of wavelengths. Thus, reflection spectrum of a Bragg mirror consists of alternating regions of strong and weak reflection, with a strong reflection corresponding to the Bragg condition (1).

The simplest periodic medium is one made up of alternating layers of transparent dielectric materials with different refractive indices, n_α and n_β . Here it is assumed, that alternating layers have thicknesses, t_α and t_β. Further, subscripts α and β are used for low and high index layers, respectively. Formally, then such a structure is

Figure 1: Schematic representation of a one-dimensional periodic medium. The coordinate system and light rays refracting and propagating through a stack are shown. The angle of incidence is designated by θ_i. Refractive indices of alternating regions and an ambient medium are n_α, n_β ($n_\alpha < n_\beta$) and *n*, respectively. Thicknesses of alternating regions are t_α and t_β. T = $t_\alpha + t_\beta$ is a period.

The periodic refractive index

$$n(z) = \begin{cases} n_\alpha, & 0 < z < t_\alpha \\ n_\beta, & t_\alpha < z < t \end{cases} \tag{2}$$

with

$$n(z) = n(z + t) \tag{3}$$

where the *z* axis is normal to the layer interfaces and T = $t_\alpha + t_\beta$ is the period. The geometry of the structure is sketched in figure 1.

To solve for the electromagnetic field in such a structure, the approach described in [13, 14] is followed. The general solution of the wave equation for the multilayered structure can be written in the form

$$E(r) = E(z)\, e^{i(-k_y y + \omega t)} \tag{4}$$

where it is assumed that the plane of propagation is the *yz* plane (Fig. 1), k_y is the *y* component of the wave vector k, which remains constant throughout the medium. The electric field within each homogeneous layer can be expressed as a superposition of an incident and a reflected plane wave.

Consider a periodic layered medium with *N* unit cells placed in a dielectric medium with refractive index n=n_α (Fig.1). Assuming an incident field coming from the left, the reflection coefficient is given by

$$r_N = \frac{a_0}{b_0} \quad (5)$$

where a_0 and b_0 are complex amplitudes of incident and reflected field, correspondingly.

Here, it is assumed that there is no wave incident on the periodic medium from the right (i.e., b_m = 0). We have

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} A_p & B_p \\ C_p & D_p \end{pmatrix}^N \begin{pmatrix} a_m \\ b_m \end{pmatrix} \quad (6)$$

where the N-th power of the unimodular matrix can be simplified by the following matrix identity

$$\begin{pmatrix} A_p & B_p \\ C_p & D_p \end{pmatrix}^N = \begin{pmatrix} A_p U_{N-1} - U_{N-2} & B_p U_{N-1} \\ C_p U_{N-1} & D_p U_{N-1} - U_{N-2} \end{pmatrix} \quad (7)$$

With U_N are chebyshev polynomials of the second kind $U_N = \frac{\sin(N+1)KT}{\sin KT}$ (8)

and the Bloch wave number K given by

$$K(\omega, k_y) = \frac{1}{2}\cos^{-1}[\frac{1}{2}(A_p + D_p)] \quad (8a)$$

The complex reflection coefficient is obtained from equations (5-8) as

$$r_N = \frac{C_p U_{N-1}}{A_p U_{N-1} - U_{N-2}} \quad (9)$$

and the reflectivity of the periodic medium is obtained from (9) by taking the square

of the complex reflection coefficient r_N:

$$|r_N|^2 = \frac{|C_p|^2}{|C_p|^2 + \left(\frac{\sin KT}{\sin NKT}\right)^2} \quad (10)$$

The term $|C_p|^2$ in (10) is roughly equal to the reflectivity of a single unit cell. This follows from the equation (10) with N = 1 and by taking into account that the reflectivity of the unit cell is usually much less than unity. For a large number of periods N, the second term in the denominator of relation (10) is a fast-varying function of the Bloch wave number K, or equivalently, of the tangential component of the wave vector k_y and frequency ω. This term dominates the structure of the reflectivity spectrum of the layered periodic medium. Within allowed bands, the reflectivity oscillates with frequency having exactly N−1 nodes where the reflectivity vanishes. For frequencies within a forbidden band, the Bloch wave number (8a) is complex

$$K = \frac{n\pi}{T} + iImK$$

and reflectivity formula (10) becomes

$$|r_N|^2 = \frac{|C_p|^2}{|C_p|^2 + \left(\frac{\sinh Im(K)T}{\sinh N Im(K)T}\right)^2} \quad (11)$$

For large N, the second term in the denominator of relation (11) approaches zero exponentially as $\exp[-2(N-1)Im(K)T$ .So, the reflectivity of a Bragg mirror (one- dimensional photonic crystal) is near unity for the medium with a substantial number of periods and a Bragg mirror acts as a high reflector within the frequency range of a forbidden band of the periodic medium.

The existence of omnidirectional photonic band gap or omnidirectional reflection band in one dimensional photonic crystal requires the incident waves to be launched from vacuum or from a low refractive index ambient medium [15]. This is because at the Brewster's angle the TM mode cannot be reflected. From Snell's law we know that $n_0 \sin\theta_0 = n_\alpha \sin\theta_\alpha$, where n_0 and n_α are the refractive indices of ambient medium and dielectric layer adjacent to n_0 and θ_0 is the incident angle. We can see that the refracted angle θ_β is restricted to a certain range. If the maximum restricted angle $\theta_\beta^{max.} = \tan^{-1}\left(\frac{n_0}{n_\beta}\right)$ is smaller than the internal Brewster's angle $\theta^B = \tan^{-1}\left(\frac{n_\alpha}{n_\beta}\right)$, the incident wave from the outside cannot couple to the Brewster's window, leading to the total internal reflection from all incident angles.

Theoretical Model

We theoretically design a one dimensional (1D) dielectric/semiconductor (silica/gallium) nonlinear photonic crystal. We have investigated a 10 layers 1 D Photonic crystal, where silica and gallium are respectively a low refractive index material ($n_\propto$) and a high refractive index material (n_β).The refractive index of both the materials nonlinearly depends on the wavelength; both materials are nonlinear optical materials. The proposed quarter wave stack structure is investigated in the form air$(n_\propto\, n_\beta\,)^{10}$air.Reflectivity for these structures for TE and TM polarisation modes at normal incident angle has been calculated by using transfer matrix method(TMM).

The simplest periodic medium is one made up of alternating layers of transparent dielectric materials with different refractive indices, $n_\propto$ and n_β . Here it is assumed, that alternating layers have thicknesses, $t_\propto$ and t_β. Further, subscripts α and β are used for low and high index layers, respectively.The structure is known as a quarter wave dielectric stack, which means that the optical thickness are quarter-wavelentgh long is

$$n_\propto . t_\propto = n_\beta \, . t_\beta = \frac{\lambda_c}{4} \quad (12)$$

Here λ_c is critical wavelength which is the mid wavelength of the spectrum considered. In this model the wavelength of the controlling wave same as critical wavelength which is responsible to effect or change the refractive index of both nonlinear materials, which due to nonlinearities of the materials with nonlinear optical effects due to interaction between controlling wave and one dimensional (1D) dielectric/semiconductor (silica/ gallium) nonlinear photonic crystal.

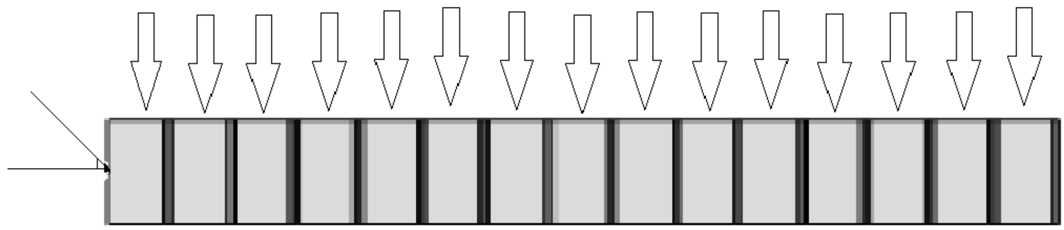


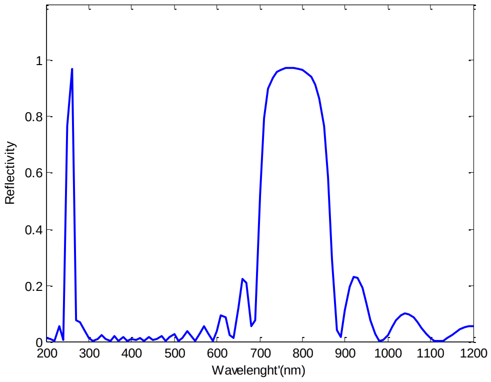
Figure 2 : Schematic representation of a one-dimensional Silica Gallium nonlinear Omnideirectional photonic crystal. The coordinate system and light rays refracting and propagating through a stack are shown. The angle of incidence is designated by θ_i. Refractive indices of alternating regions are $n_\propto$, n_β ($n_\propto < n_\beta$) for silica and Gallium respectively. Thicknesses of alternating regions are $t_\propto$ and t_β. T = $t_\propto + t_\beta$ is a period. The upper incoming big arrows show the controlling wave.

The refractive indices of both materials are dependent on incident intensity that means on wavelength of the controlling wave. The gallium has also property of structural phase change and every phase have different refractive index. We have used the data from Ref.[17-19] and numerical values obtained by using eq.(11,12). The size of the alternate layers are nanoscale thickness and nanoscale thickness of the alternate layers also contributes for these nonlinear optical processes.

We use the TMM for this structure and using three phases of gallium i.e. α-gallium,γ-gallium and liquid gallium, for a single controlling wave wavelength the device behaves as three devices at a time. We have used theoretically three wavelengths –

1.λ = 775nm 2. λ = 1310nm 3. λ = 1555nm

For these three cases we solve this using TMM for TE/TM mode for normal incidence and using MATLAB environment the results shown below.



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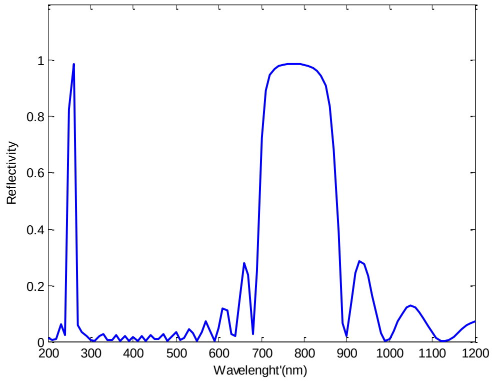

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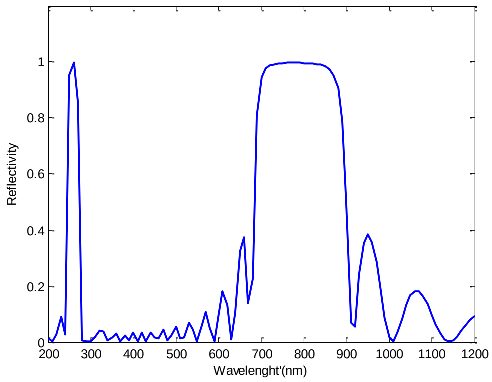

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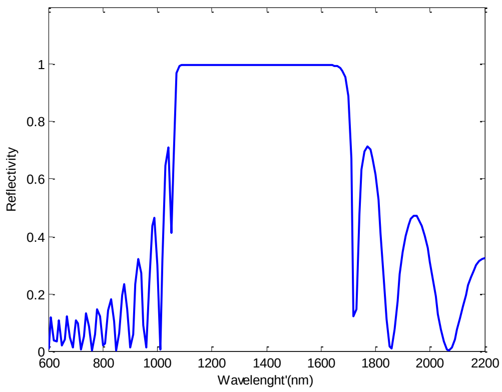
Figure3: Reflectivity spectrum of Silica-Gallium Nonlinear Omnideirectional 1 D Photonic Crystal for TE/TM mode for normal incidence using analytical TMM method, at λ=775nm for three different phases (a) silica-γ Gallium (b) silica-α Gallium (c) silica-liquid Gallium.



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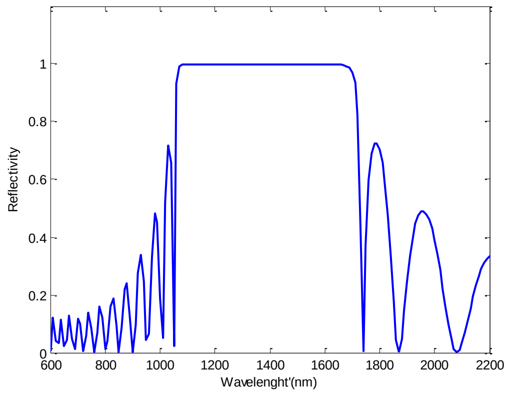

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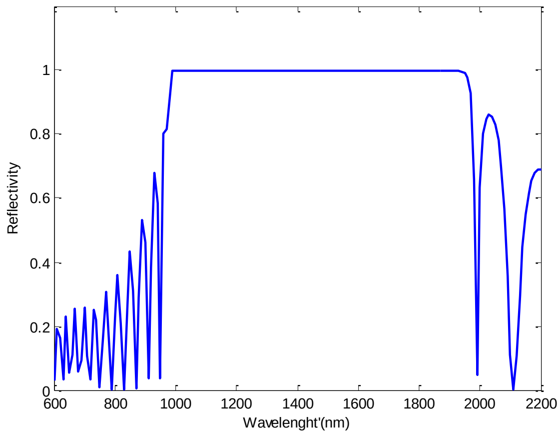

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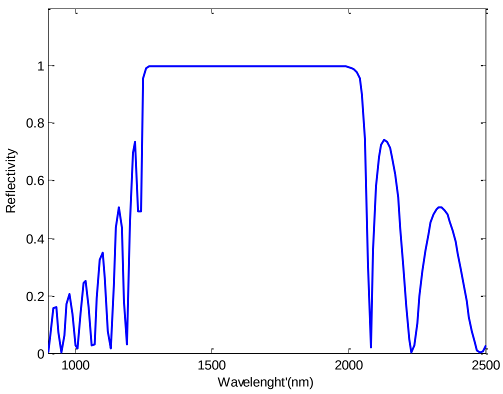
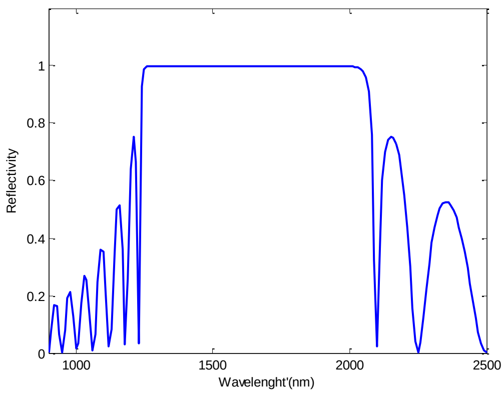
Figure4: Reflectivity spectrum of Silica-Gallium Nonlinear Omnideirectional 1 D Photonic Crystal for TE/TM mode for normal incidence using analytical TMM method, at λ=1310nm for three different phases (a) silica-γ Gallium (b) silica-α Gallium (c) silica-liquid Gallium.



(a)



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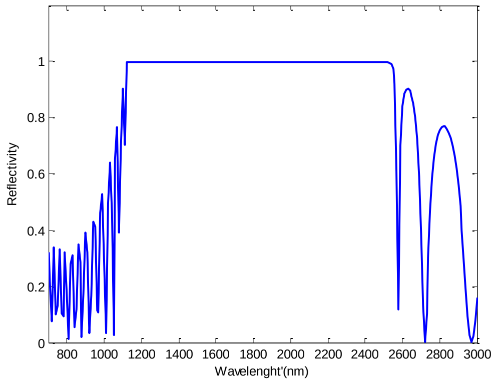

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Figure5: Reflectivity spectrum of Silica-Gallium Nonlinear Omnideirectional 1 D Photonic Crystal for TE/TM mode for normal incidence using analytical TMM method, at λ=1550nm for three different phases (a) silica-γ Gallium (b) silica-α Gallium (c) silica-liquid Gallium.

The combined results from these Reflectivity spectrums shown below in tables-

Table1: -Silica-Gallium Nonlinear Omnideirectional 1 D Photonic Crystal for normal incidence TE/TM mode complete Omnideirectional range (ODR) at λ=775nm

S. No.	Phase of gallium	Complete ODR range (nm)	Complete ODR (nm)	Mid of ODR range (nm)
1	γ Gallium	680-890	210	775
2	α Gallium	685-900	215	775
3	liquid Gallium	670-920	250	775

Table2: - Silica-Gallium Nonlinear Omnideirectional 1 D Photonic Crystal for normal incidence TE/TM mode complete Omnideirectional range (ODR) at λ=1310 nm

S. No.	Phase of gallium	Complete ODR range (nm)	Complete ODR (nm)	Mid of ODR range (nm)
1	γ Gallium	1060-1710	650	1310
2	α Gallium	1070-1750	680	1310
3	liquid Gallium	920-2000	1080	1310

Table3: - Silica-Gallium Nonlinear Omnideirectional 1 D Photonic Crystal for normal incidence TE/TM mode complete Omnideirectional range (ODR) at λ=1550 nm

S. No.	Phase of gallium	Complete ODR range (nm)	Complete ODR (nm)	Mid of ODR range (nm)
1	γ Gallium	1250-2100	850	1550
2	α Gallium	1240-2120	1080	1550
3	liquid Gallium	1180-2590	1410	1550

RESULTS AND DISCUSSION

We present the analytic analysis of the proposed PC structures and show the omnidirectional reflection bands for normal incidence. In this model for the computation we consider three cases in which we have taken alternate layers for varying refractive index of both nonlinear materials which is due to nonlinearities of the materials. The nonlinear optical effects due to interaction between controlling wave and one dimensional (1D) dielectric/semiconductor (silica/gallium) nonlinear photonic crystal are responsible for this kind of omnidirectional photonic band gap for normal incidence.The nanoscale thickness of the alternate layers also contribute for these nonlinear optical processes.

The results show that if the incident wavelength in the visible region then by increasing the applied wavelength of controlling wave, the complete ODR, photonic band gap increases. The proposed photonic crystal structure can be used for 210nm to 1410nm as width of complete Omnideirectional range (ODR) and in between 610nm to 2500nm wavelength of incident wavelength. The results show that the proposed photonic crystal structure can be used as multi photonic band gap due to nonlinearities of both materials and structural phase change property of Gallium .The proposed photonic crystal structure can be used as good candidate for the complete inhibition of transmission of frequency in the wide range of visible region and a very narrow range of the near IR region for any normal incidence. Hence the proposed structure can be used as an omnidiretional reflector in the field of optical technology.This device may be used for optical communication, optoelectronic devices, etc., where variable photonic band gap necessary. Our small but innovative idea and concept is now a challenge for experimentalists to fabricate this kind of device for futuristic scientific development and applications.

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