Research Article

Realization Of 3-D Reflectors By Using Metal-Air And Semiconductor-Air Based Photonic Structures At Three Communication Windows

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Abstract:
The present study is based on analysis of three dimensional photonic crystal(PhC) to envisage a photonic reflector pertaining to suitable optical communication wavelengths (850/1310/1550nm). The said photonic reflector application is envisaged separately by two 3D PCSs, which comprised of semiconductor (germanium) and metal (iron) based circular rods respectively, arranged on a square lattice having air as the background material. A detailed assay of photonic band gap is the cornerstone of this work, which is studied through manipulating the plane wave expansion (PWE) technique. PBG is meticulously controlled by suitably selecting the geometrical parameters like refractive index of the background material, height of the structure, lattice constant andradius of the rods. Simulation outcomes explored that semiconductor based PhC reflects 850nm, 1310nm and 1550nm by selecting diameter of the circular rods as 282 nm, 608 nm and 771 nm respectively, whereas metal based PCS reflects the aforementioned wavelengths for diameter of the circular rods as 335 nm, 1070 nm and 871 nm respectively. Further, we investigated the variation in reflected wavelength for change in the diameter of the circular barsin both the proposed structures. Thus, the proposed optical reflectors open up an avenue for wide range of applications vis-à-vis three communication windows.

Keywords: 3D photonic structure, optical reflector, PWE, PBG analysis.

1. Introduction

Over the last few decades, scientists and researchers are greatly influenced by the photonic crystal fibers (PCF) towards design of novel optoelectronic devices [1]. Being one of the most burgeoning photonic elements, photonic structures can be realized through 1D, 2D and 3D. Nevertheless, 1D and 2D photonic structures have already been commercialized, but researchers are still working towards exploring feasible fabrication techniques of 3D PhC. So, rapid researches on 3D PhC are going on around the globe to achieve feasible fabrication techniques. Moreover, three dimensional photonic crystal fiber has come up as a crucial device for future integrated light wave circuits. Owing to its noteworthy optical properties, 3D photonic structures can be best suited for numerous optical devices like optical computing [2], solar cell [3], photonic clocking devices [4], optical beam splitter [5] and optical mirror [6]. Aside from this, the favourable feature of 3D PhC is the presence of PBG, which allows complete control over light by prohibiting the propagation of electromagnetic signal in some specific wavelength ranges. As far as literature studies pertaining to the photonic structures are concerned, various types of structures are employed for application in sensing and communication field. In reference [7-11], authors represented simple 1D grating structures, which act as optical interconnect with feeble losses, whereas in reference [12-13], authors emphasized on 2D photonic crystal structures for efficient guiding of light. Further, other applications related to communications are demonstrated, which are related to the realization of logic gate [14], filter [15], multiplexer/ De-multiplexer [16]. Nonetheless, research on 3D photonic structures is still in the emerging stage, few works [17-20] are carried out in recent times related to communication, sensing applications and photonic waveguide structures.Optical reflectorshave emerged as an apt candidate in photonic integrated circuits owing to its noteworthy applications in the broad research domain of sensing, solar cell, optical communication and networking,.In the recent past, the authors have studied 1D grating structure with narrow band and broad band mirrors to realise optical reflectors [21-24]. Further, researches are carried out on 2D photonic structures to envisage optical reflectors [25-26]. But in the aforesaid references, authors failed to achieve sharp reflectance characteristics.

In the present research, we reported a novel application of 3D PCS. To the best of author's knowledge, no one in the past has addressed optical reflector application by employing 3D photonic structures. Band gap present in the proposed structure has been investigated, which is the most accurate method to compute the reflected wavelengths from the structure. Apart from this, we realized the optical reflector by considering 3D PCS with different materials like semiconductor (germanium) and metal (iron), which add novelty to the present research. Moreover, the suggested structures do not contain any defects, which leads to simple analysis and cost effective fabrication process.

2. Proposed structure and methods

In this research, we deal with two types of 3D photonic crystal structures, comprising of 3×3 circular rods periodically arranged on square lattice, which is shown in figure 1(a) and 1(b).

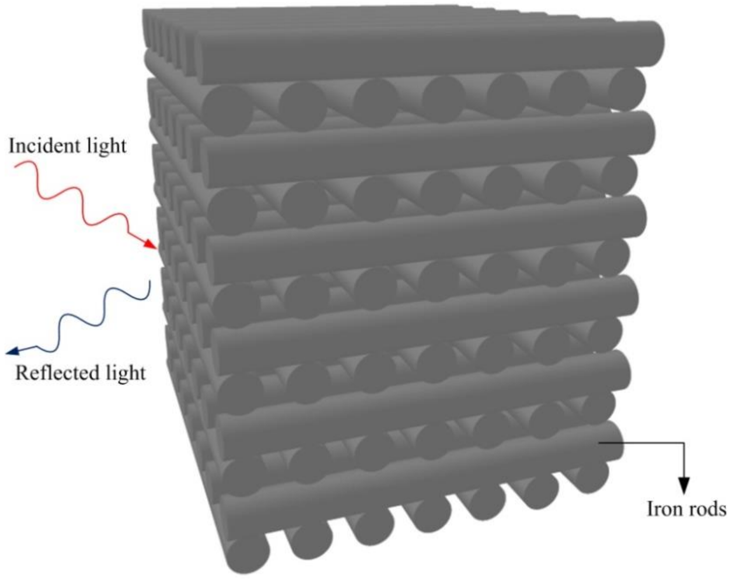

Figure 1(a): Schematic figure of Iron based 3-D photonic crystal structure

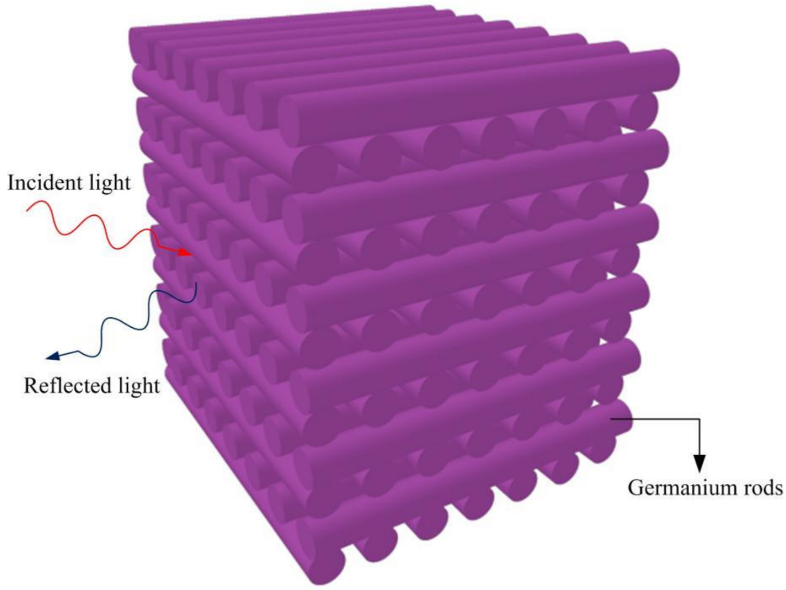

Figure 1(b): Schematic figure of Germanium based 3-D photonic crystal structure

In the first structure, the circular rods are designed with iron (metal) whereas in the second structure, the circular rods are realized using germanium (semiconductor)with air considered as the background material in both. The light guiding principle in the proposed structure is the index guiding mechanism, where the core of large refractive index is surrounded by lower refractive index cladding. Further, upon applying light in the wavelength range 780nm-1600nm on the said structure, some wavelengths get transmitted through the structure and those wavelengths fall in the bandgap get reflected from the same. The bandgap formed in the said structure is intensely influenced by structural design parameters. In the present work, diameter of circular rods inboth the germanium based and iron based photonic structure are varied and chosen in such a way that the structure reflects only single wavelength (850nm/ 1310nm/ 1550nm) and passes all the other wavelength signals, whereas lattice constant is kept constant of 1200 nm for both types of structures throughout the analysis. This reflected wavelength is realized through investigation of bandgap present in the structure by employing plane wave expansion technique.

As far as fabrication techniques of 3D photonic structures are concerned, different methods such as self-assembly of colloidal spheres [29], direct laser writing [27], layer-on-layer fabrication [28] etc.have proven to be potential methods. Apart from this, the holographic lithographic process has been extensively used for successful fabrication of 3D PhCs [30]. So, following the aforesaid techniques, our proposed structures can certainly be fabricated.

3. Mathematical treatment

In this research, PWE technique ischosen over other methods like FDTD, TMM, FEM for its ability to compute accurate band gap. The band gap analysis is based on the Maxwell equations, which is manipulated to establish Helmholtz differential equation, which takes the following mathematical form

$$\nabla \times \left\{\frac{1}{\varepsilon(x)} \nabla \times \mathrm{H(x)}\right\} = \frac{\omega^2}{c^2} H(x) \quad (1)$$

where, x denotes the 3D vector in coordinate space, $\varepsilon(x)$ represents the space dependent dielectric function, $H(x)$ denotes the magnetic field vector, c is the velocity of EM signal propagating with a frequency of ω.

As we are interested in finding Eigen state of an infinite periodic structure, the magnetic field can be represented in the form of Bloch theorem, which is stated below,

$$H(r) = H_{kn}(r) e^{j.k.r} \quad (2)$$

Where $H_{kn}(r)$ represents periodic function having wave vector k and n number of Eigen states, $e^{j.k.r}$ denotes the number of plane waves.

Since $H_{kn}(r)$ is periodic in nature, so the function should satisfy the following conditions,

$$H_{kn}(r+R) = H_{kn}(r)(3)$$

where, R denotes the lattice vector.

The above stated equations are in coordinate space, thus it is quite difficult to solve the Helmholtz equations. So to deduce a possible solution, wave functions are represented in terms of wave vectors instead of coordinate space, where the wave function is expressed in terms of reciprocal lattice vector (K) as stated below,

$$H_{kn}(x) = \sum_{G} H'_{kn}(K) e^{(j(k+K)x)} \quad (4)$$

The periodically varied dielectric function can be expressed as in Fourier series form as below,

$$\frac{1}{\varepsilon(x)} = \sum_{K} X(K) e^{j.K.r} \quad (5)$$

where, $X(K)$ is the Fourier expansion coefficient.

Now, substituting the equation (4) and (5) in equation (1), we can write,

$$-\sum_{G'} X(K-K')\,(k+K) \times \{(k+K') \times H_{kn}K'\} \frac{\omega_{kn}{}^{(H)^2}}{c^2} H_{kn}(K) \quad (6)$$

Equation (6) act as the master equation, whose solutions represent the Eigen states of the 3D photonic crystal structure. Further, Eigen values are calculated for different wave vectors, which lead to computation of band gap.

4. Result and discussion

Bandgap analysis is the mainstay of this research, which is envisaged by employing PWE method. Also, in section 2, it is declared that diameter of the circular rods plays key role in deciding the bandgap. Hence, it is asserted that 3D photonic crystal structures with different configurations of circular rods possess different band gaps. We optimized the proposed germanium based photonic structure by selecting appropriate value ofdiameters of circular rods such that for a particular diameter, only one communication wavelength (lies inside the PBG) will be prohibited to enter through the structure and others will be transmitted. Simulations are carried out separately by selecting the circular rods diameter of 282 nm, 608 nm and 771 nm for the proposed germanium based photonic structure. Simulation outcomes inferred that the said structure reflects wavelength of 850 nm for the circular rods of diameter of 282 nm. Similarly, 1310 nm wavelength is reflected for circular rods diameter of 608 nm and 1550 nm wavelength is reflected for circular rods diameter of 771 nm. Moreover, the mainpurposeof selecting the aforementioned diameter values is, reflected wavelength of 850nm, 1310nm and 1550nm are realized only at these values of diameters of circular rods only. Figure 2, figure 3 and figure 4 show the bandgap of germanium (semiconductor) based photonic structure for circular rod diameters (d) of 282nm, 608nm and 771nm respectively. In these figures, we have considered wave vector along the x-axis and the corresponding normalized wavelength is plotted along the y-axis. Also, the presence of bandgap is highlighted by arrow marks in all the figures.

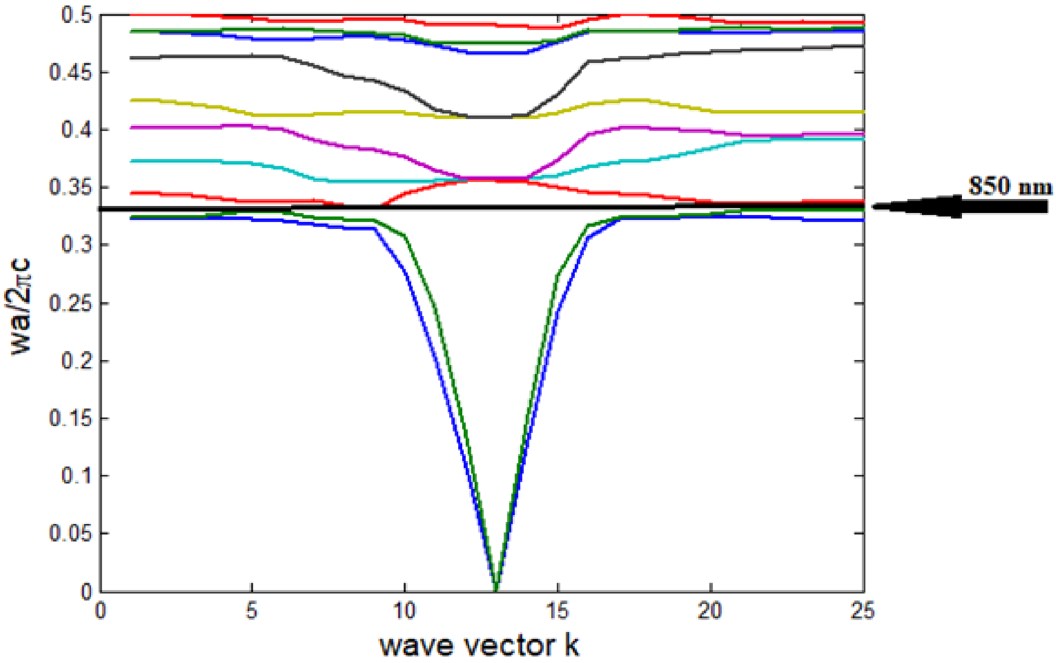

Figure 2: Band structure of semiconductor (Ge) based 3D PCS ford = 282 nm.

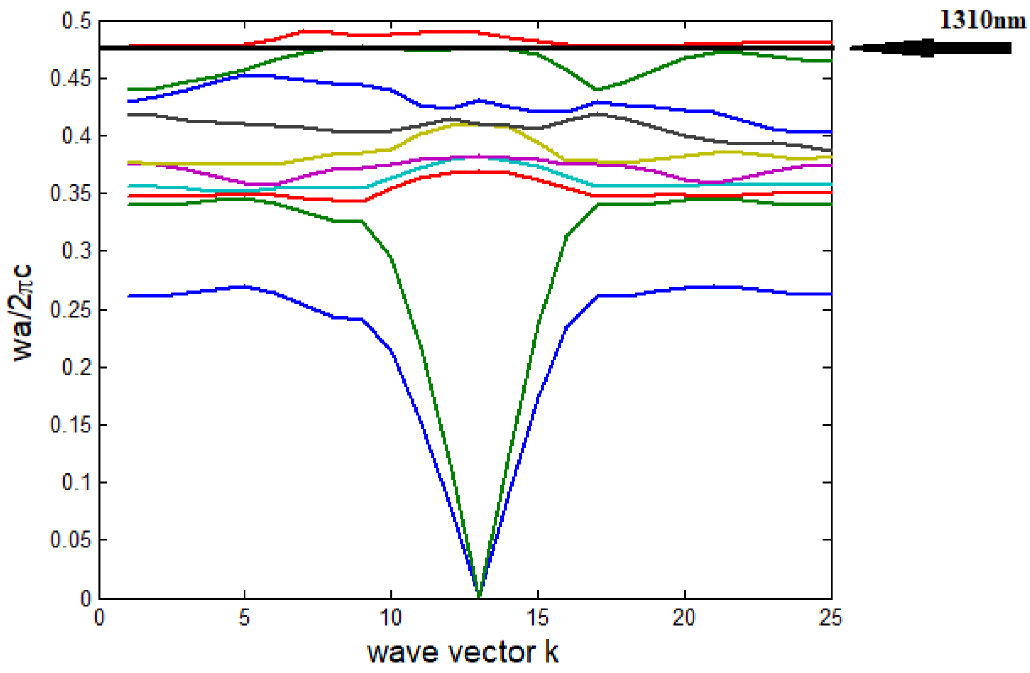

Figure 3: Band structure of semiconductor (Ge) based 3D PCS ford=608 nm.

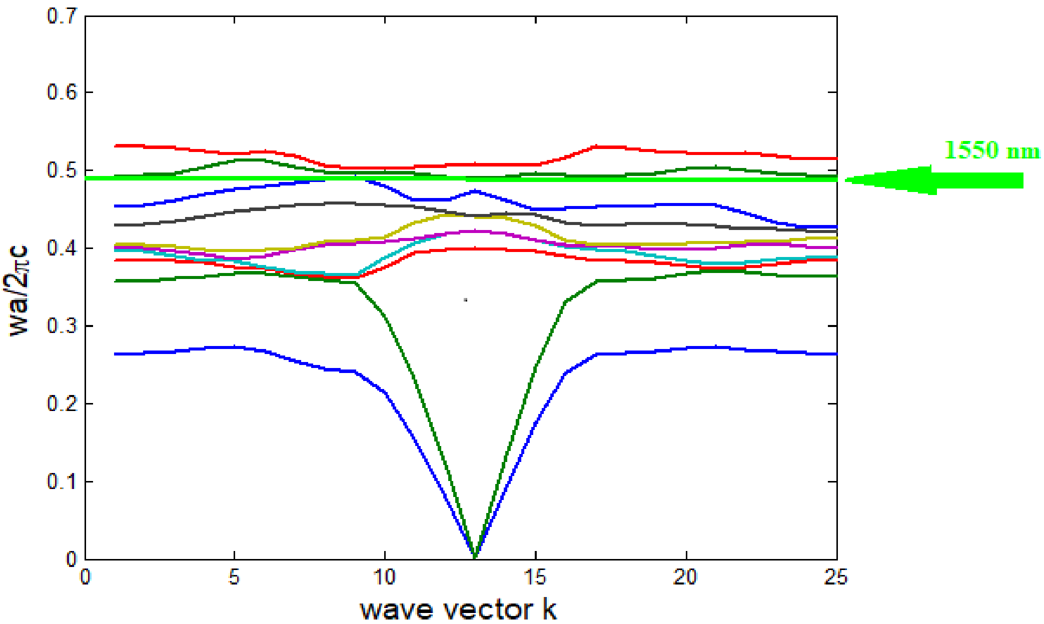

Figure 4: Band structure of semiconductor (Ge) based 3D PCS for d= 771 nm.

Similarly, simulations are performed separately by selecting the circular rods diameter of 335 nm, 1070 nm and 871 nm of the proposed metal (Iron) based photonic structure. From the simulation upshots, it is divulged that the said structure reflects wavelength of 850 nm for the circular rods diameter of 335 nm, which is shown in figure 5. Similarly, 1310 nm wavelength is reflected for circular rods diameter of 1070 nm and 1550 nm wavelength is reflected for circular rods diameter of 871 nm, which are represented in figure 6 and figure 7 respectively. We selected the aforementioned values for diameter of circular rods because at these values only perfect bandgap is obtained pertaining to 850nm, 1310nm, 1550nm wavelength.

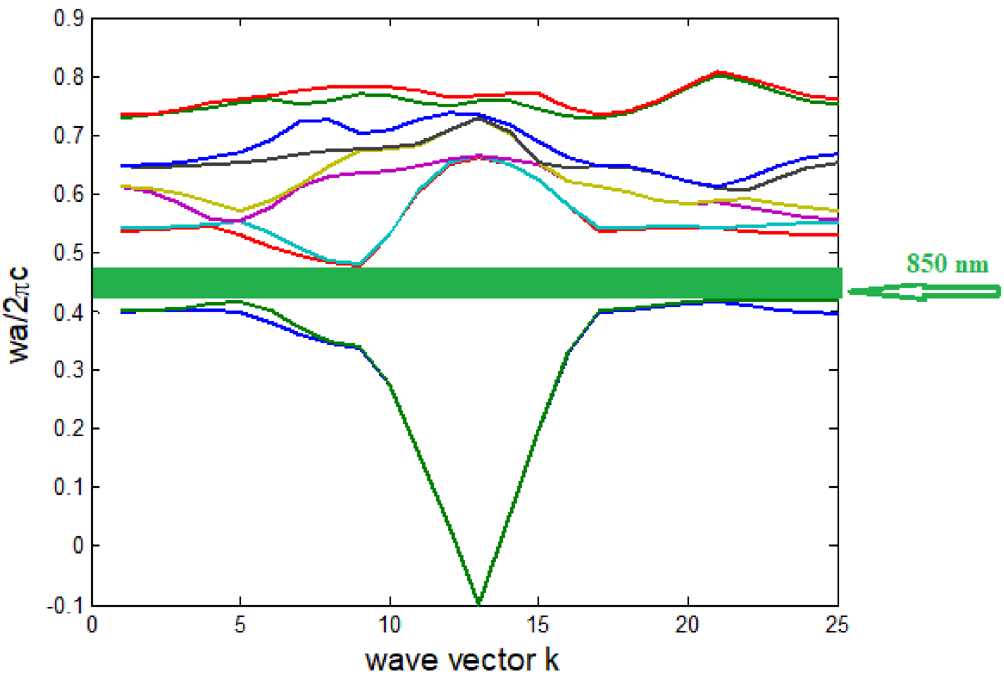

Figure 5: Band structure of metal (Iron) based 3D PCS for d = 335 nm.

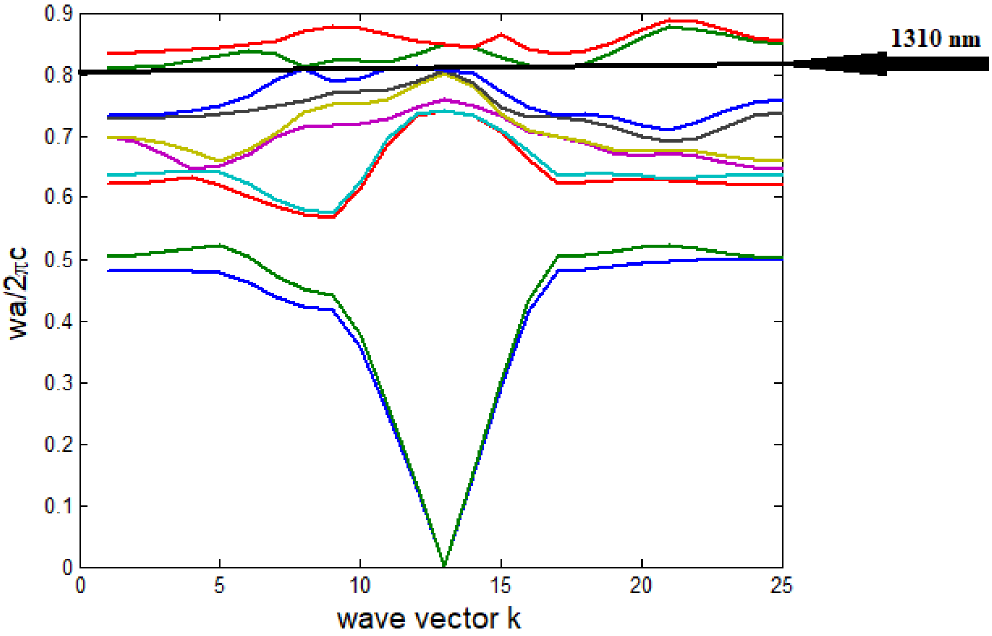

Figure 6: Band structure of metal (iron) based 3D PCS for d = 1070 nm.

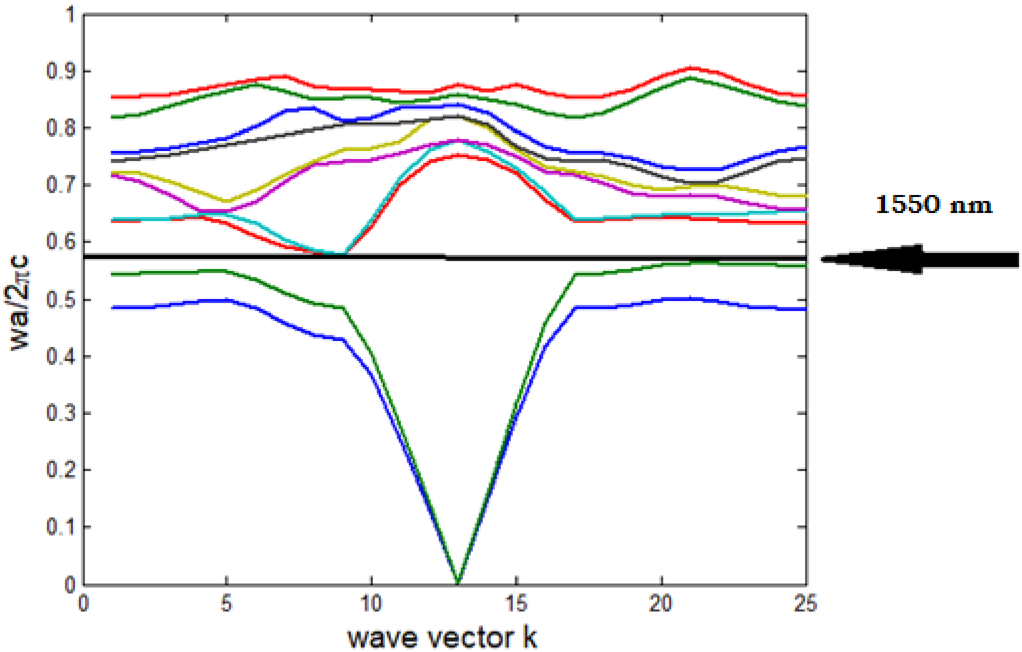

Figure 7: Band structure of metal (iron) based 3D PCS ford = 871 nm.

Finally, variation of reflected wavelengths from the proposed structures with respect to the change in diameter of circular rods is plotted in figure 8. In this figure,the primary vertical axis shows the diameter of semiconductor based photonic crystal structure, whereas diameter of metal based photonic crystal structure is represented in reverse order along the secondary vertical axis. Here, an exciting variation between the aforementioned parameters is marked. For the case of semiconductor based PhC, we observed a linear change in the reflected wavelength with reference to the diameter of circular rods with R^2=0.999, whereas for the case of metal based PhC, the variation among the aforementioned parameters follow polynomial trend line with R^2=1. Thus, it is confirmed that reflected wavelengths form the proposed structures are strongly related to the structure parameters.

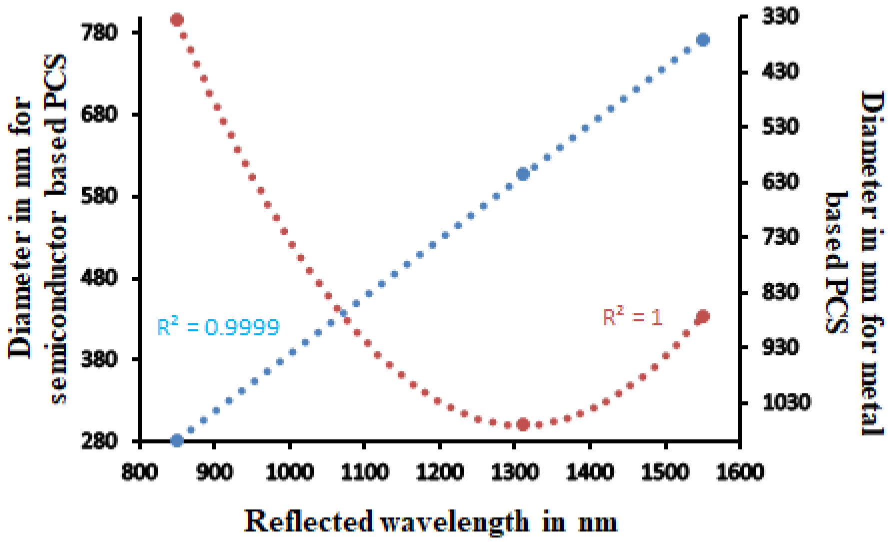

Figure 8: Variation of reflected wavelength with diameter of circular rods.

For the above mentioned structure parameters, the proposed structures reflect only single wavelength (850/1310/1550nm), which corresponds to the ultralow loss optical communication windows. Thus, the proposed structures can be efficiently used in communication applications.

5. **Conclusions**

Semiconductor based and metal based 3D photonic crystal structures are meticulously studied in this research at three optical windows for application in optical communication systems. The primary principle lies behind this research is the investigation of PBG, which is envisaged by employing PWE technique. Further, the present study divulged that diameter of the circular rod of the PCS is a key factor in controlling the photonic bandgap, which leads to realization of the reflected wavelength. Moreover, both the structures are optimized with suitable values of diameter of the circular rods such that the reflected wavelength corresponds to 850/1310/1550nm only, thereby the structures are convenient for use in optical window. With the above upshots, authors beleive that the proposed structures can be suitable candidates for communication applications in the photonic integrated circuits.

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