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Realization of 3D reflectors by using metal-air and semiconductor-air based photonic structures at three communication windows

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Abstract. This study is based on analysis of 3D photonic crystal structure (PCS) for realization of photonic reflector pertaining to suitable optical communication wavelengths of 850, 1310 and 1550 nm. The said photonic reflector application is envisaged separately by two 3D PCSs, which comprise semiconductor (germanium) and metal (iron) based circular rods respectively, arranged on a square lattice having air as the background material. The plane wave expansion (PWE) technique is employed to investigate the photonic band gap (PBG) vis-à-vis all the aforementioned wavelengths. PBG is meticulously controlled by suitably selected various structure parameters, such as lattice spacing, diameter of the circular rods and nature of their material. Simulation outcomes explored that semiconductor based PCS reflects wavelengths of 850, 1310 and 1550 nm, when selecting the diameter of the circular rods as 282, 608 and 771 nm, respectively, whereas metal based PCS reflects the aforementioned wavelengths for diameters of the circular rods close to 335, 1070 and 871 nm, respectively. Further, we assayed the variation in reflected wavelength with respect to different diameters of circular rods for both proposed structures. Thus, the proposed optical reflectors can find a wide range of applications vis-à-vis three communication windows.

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

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1. Introduction

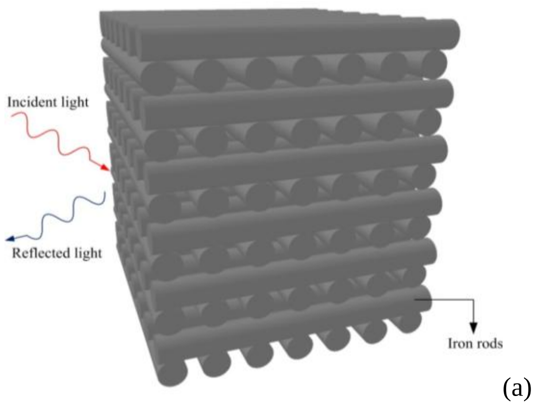
Over the recent few decades, scientists and researchers are greatly influenced by the photonic crystal fibers (PCF) towards design of novel optoelectronic devices [1]. Being one of the most burgeoning photonic elements, photonic structures can be realized through 1D, 2D and 3D versions. Nevertheless, 1D and 2D photonic structures have already been commercialized and in the mature research stage, but fabrication of 3D photonic structure is still a challenge. So, rapid researches on 3D PCS are going on around the globe to achieve feasible fabrication techniques. Moreover, a 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 find suitable applications in the design of various photonic devices such as optical computing [2], solar cells [3], photonic clocking devices [4], optical beam splitters [5] and optical mirrors [6]. Besides, the favourable feature of 3D photonic crystal structure is the presence of photonic band gap, 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 the references [7–11], the authors have represented simple 1D grating structures, which act as optical interconnect with feeble losses, whereas in the references [12, 13], the authors have 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 gates [14], filters [15], multiplexers/de-multiplexers [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 reflectors find noteworthy applications in the field of sensing, communication, networking, solar cells, thus they came up as an apt candidates in photonic integrated circuits. In the recent past, the authors have studied 1D grating structure with narrow-band and broad-band mirrors to realize optical reflectors [21–24]. Further, researches are carried out on 2D photonic structures to envisage optical reflectors [25, 26]. But in the aforesaid references, the authors have failed to achieve sharp reflectance characteristics.

In this research, we have reported a novel application of 3D PCS. To the best of authors' knowledge, no one in the past has addressed optical reflector application by employing 3D photonic structures. Moreover, the 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 have 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.

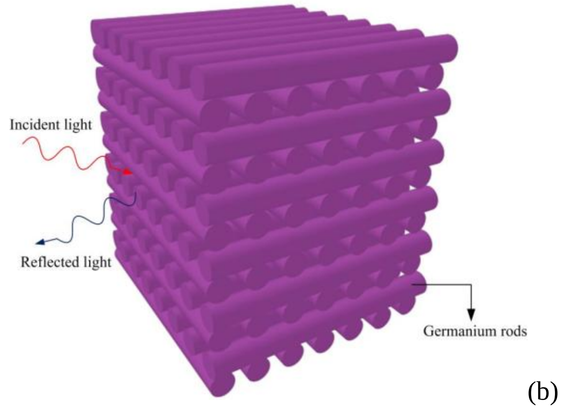
2. Proposed structure and methods

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

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 within the wavelength range 780 to 1600 nm on the said structure, some wavelengths get transmitted through the structure and those wavelengths fall in the band gap get reflected from the same. The band gap present in the photonic crystal structure is influenced by structure parameters, namely: lattice constant, diameter of circular rods, nature of the background material and nature of the material used in design of the circular rods. In this research, the diameter of circular rods in both the germanium based and iron based photonic structures are varied and chosen in such a way that the structure reflects only single wavelength (850, 1310 or 1550 nm) and passes all the other wavelength signals, whereas lattice constant is kept constant at the level 1200 nm for both types of structures throughout the analysis. This reflected wavelength is realized through investigation of the band gap present in the structure by employing the plane wave expansion technique.



(a)



(b)

Fig. 1. Schematic figure of 3D photonic crystal structure based on iron (a) and germanium (b).

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

3. Mathematical treatment

In this research, the plane wave expansion (PWE) technique has been chosen over other methods like FDTD, TMM, FEM for its ability to compute an accurate band gap value. The band gap analysis is based on the Maxwell equations. The well-known Maxwell equations can be employed to write the Helmholtz differential equation that can be expressed as

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

where r denotes the 3D vector in coordinate space, $\varepsilon(r)$ represents the space dependent dielectric function, $\mathbf{H}(r)$ denotes the magnetic field vector, c is the light speed, and ω – frequency component.

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

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

where $H_{kn}(r)$ represents periodic function having the 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 its nature, so the function should satisfy the following conditions

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

where R denotes the lattice vector.

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

$$H_{kn}(r) = \sum_G H'_{kn}(G) e^{(j(k+G)r)}\,, \tag{4}$$

where G represents the reciprocal lattice vector.

As the dielectric function is also periodic in its nature, so it can be expressed in the Fourier series form written below

$$\frac{1}{\varepsilon(r)} = \sum_G X(G) e^{j,G,r}\,, \tag{5}$$

where $X(G)$ is the Fourier expansion coefficient.

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

$$-\sum_{G'} X(G-G')(k+G) \times \{(k+G') \times H_{kn}G'\} =$$

$$= \frac{\omega_{kn}(H)^2}{c^2} H_{kn}(G). \tag{6}$$

The equation (6) act as the master equation, which solution represents the eigen states of the 3D photonic crystal structure. Further, the eigen values are calculated for different wave vectors, which leads to computation of the band gap.

4. Results and discussion

Band gap analysis is the key principle that lies behind the present research, which is envisaged by employing the PWE method. Also, in Section 2, it is declared that diameter of the circular rods plays key role in determining the band gap. 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 values of diameters of circular rods in such a manner that for a particular diameter, only one communication wavelength (lies within the band gap) will be reflected, while others will be transmitted. Simulations are carried out separately by selecting the circular rods diameters as 282, 608 and 771 nm for the proposed germanium based photonic structure. Simulation outcomes inferred that the said structure reflects the wavelength 850 nm for the circular rods of diameter close to 282 nm. Similarly, 1310-nm wavelength is reflected for circular rods with the diameter 608 nm, and 1550-nm wavelength is reflected for circular rods diameter close to 771 nm. Moreover, the primary reason behind selecting the aforementioned diameter values is that reflected wavelength of 850, 1310 or 1550 nm are realized only at these values of diameters of circular rods. Figs 2, 3 and 4 show the band gap of germanium (semiconductor) based photonic structure for circular rod diameters of 282, 608 and 771 nm, respectively. In these figures, the horizontal axis denotes the wave vector, whereas the vertical axis denotes the normalized wavelength. Also, the presence of band gap is highlighted by arrow marks in all the figures.

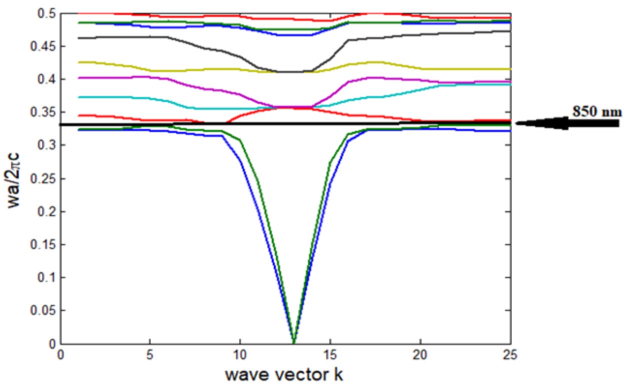


Fig. 2. Band structure of semiconductor (Ge) based 3D PCS for d = 282 nm.

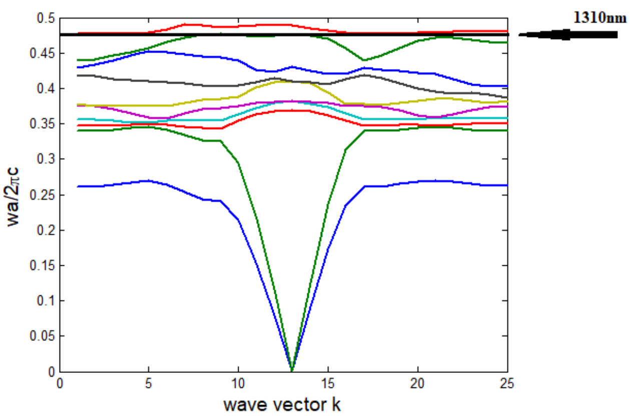


Fig. 3. Band structure of semiconductor (Ge) based 3D PCS for d = 608 nm.

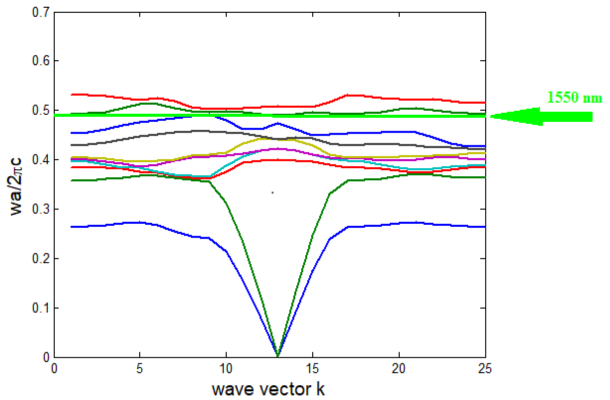


Fig. 4. Band structure of semiconductor (Ge) based 3D PCS for d = 771 nm.

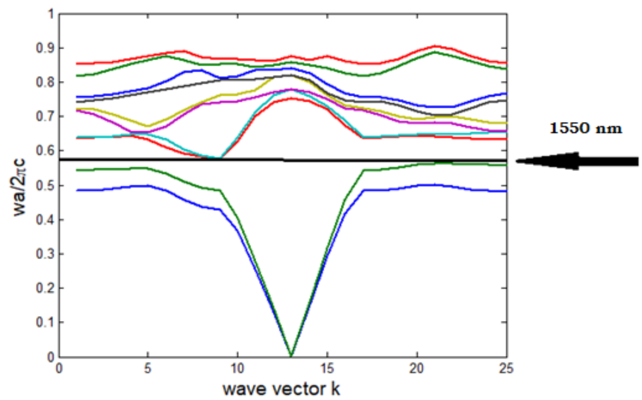


Fig. 7. Band structure of metal (iron) based 3D PCS for d = 871 nm.

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

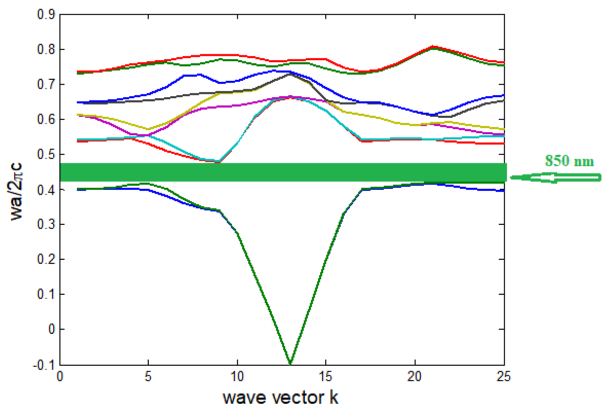


Fig. 5. Band structure of metal (iron) based 3D PCS for d = 335 nm.

Finally, variation of reflected wavelengths from the proposed structures with respect to the change in diameter of circular rods is plotted in Fig. 8. In this figure, the diameter of semiconductor based photonic crystal structure is plotted along the primary vertical axis, whereas the diameter of metal based photonic crystal structure is plotted along the secondary vertical axis in the reverse order. Here, an exciting variation between the aforementioned parameters is marked. For the case of semiconductor based PCS, the variation of reflected wavelength with respect to the diameter of circular rods is fitted nicely with linear trend line (R^2 = 0.9999),

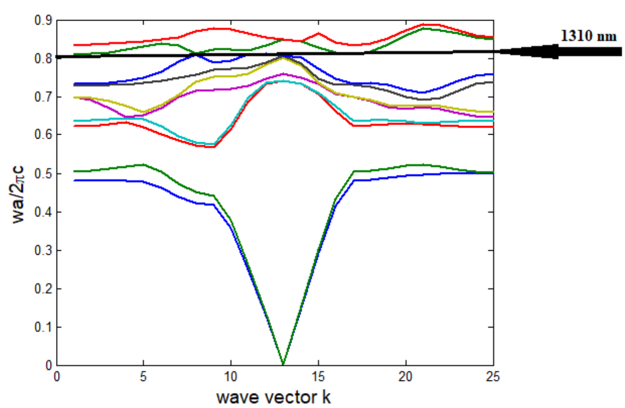


Fig. 6. Band structure of metal (iron) based 3D PCS for d = 1070 nm.

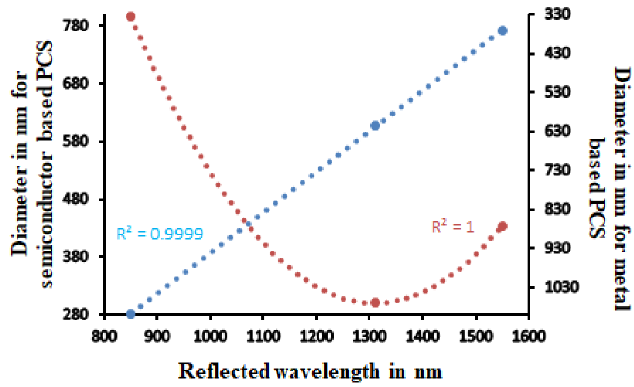


Fig. 8. Variation of reflected wavelength with diameter of circular rods.

whereas for the case of metal based PCS, the variation among the aforementioned parameters follow polynomial trend line ($R^2 = 1$). Thus, it is confirmed that the wavelength reflected from the proposed structures is strongly related to the structure parameters.

For the abovementioned structure parameters, the proposed structures reflect only single wavelength of 850, 1310 or 1550 nm, which correspond to 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 for three optical windows applied in optical communication systems. The primary principle lies behind this research is photonic band gap, which is envisaged by employing the plane wave expansion technique. Further, the present study divulged that diameter of the circular rod of PCS plays a vital role in controlling the photonic band gap, which leads to realization of the reflected wavelength. Moreover, both structures are optimized with suitable values of diameter of the circular rods such that the reflected wavelength corresponds only to 850, 1310 or 1550 nm, which is in agreement with optical communication windows. With the above upshots, the authors claim that the proposed structures can be a suitable candidate for communication application in the photonic integrated circuits.

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Реалізація 3D відбивачів за допомогою фотонних структур на основі шарів метал-повітря та напівпровідник-повітря на трьох комунікаційних вікнах

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Анотація. Це дослідження базується на аналізі тривимірної структури фотонного кристала для створення фотонного відбивача, що відноситься до відповідних довжин хвиль оптичного зв’язку 850, 1310 і 1550 нм. Зазначене застосування фотонного відбивача передбачається окремо двома 3D структурами фотонного кристала, які містять напівпровідникові (германій) або металеві (залізо) кругові стрижні відповідно, розташовані на квадратній решітці, що містить повітря як фоновий матеріал. Метод розширених плоских хвиль застосовується для дослідження фотонної забороненої зони по відношенню до всіх вищезазначених довжин хвиль. Фотонна заборонена зона ретельно контролюється за допомогою відповідно вибраних різних параметрів структури, таких як відстань між гратами, діаметр кругових стрижнів та властивості матеріалу. Результати моделювання показали, що структура фотонного кристала на основі напівпровідника відбиває хвилі довжиною 850, 1310 і 1550 нм, у випадку діаметра кругових стрижнів 282, 608 і 771 нм відповідно, тоді як структура фотонного кристала на основі металу відбиває хвилі згаданої довжини для діаметра кругових стрижнів 335, 1070 та 871 нм відповідно. Далі ми проаналізували зміну відбитої довжини хвилі щодо різного діаметра кругових стрижнів для обох запропонованих структур. Таким чином, запропоновані оптичні відбивачі можуть знайти широкий спектр застосувань щодо трьох комунікаційних вікон.

Ключові слова: 3D фотонна структура, оптичний відбивач, розширена плоска хвиля, аналіз фотонної забороненої зони.