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INVESTIGATION ON VARIOUS DESIGN PARAMETERS WHICH AFFECT THE BANDGAP OF TWO DIMENSIONAL PHOTONIC CRYSTAL STRUCTURE

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ABSTRACT

An emerging element in optical fiber communication, 2D Photonic Crystal is an artificial periodic structure having a bandgap which shows a prohibition of a range of wavelengths to pass away through it. Various design parameters which affect the bandgap of 2D photonic crystal structure such as lattice structure, shape of rods, r/a ratio, dielectric constant etc. are studied in this paper. The Plane Wave Expansion (PWE) method is used to calculate the bandgap structure of two dimensional photonic crystals.

KEYWORDS: Photonic Crystal, PWE, FDTD, PBG

INTRODUCTION

Over the past several years, there are great advances in practically any application that has to do with information allowance seen by electronic world: following Moore's law, every 18 months the data density on a chip has doubled. This fashion is to be expected to continue for a further decade. The propagation of electromagnetic (EM) waves are affected by Photonic crystals (PhC) which are composed of periodic dielectric nanostructures. These crystals are analogous to semiconductors, as they allow the control of photons as semiconductors do for the electrons. Based upon the variation of refractive index in one, two and three dimensions, these crystals are classified as one dimensional, two dimensional and three dimensional photonic crystals [1, 6]. The photonic crystals possesses photonic band gap (PBG) where the propagation of light is completely prohibited in certain frequency ranges [3]. In particular, we can design and construct photonic crystals with photonic band gap, preventing the light from propagation in certain directions with specified frequencies and allows propagation in anomalous and useful ways [3]. Photonic crystals (PhCs) are unnaturally created materials in which the refractive index varies sporadically between high-index regions and low-index regions. Several optical devices such as wavelength division de-multiplexer [8], channel drop filter [9-10], add/drop filter [11] etc. are also implemented based on 2D photonic crystal structure.

Photonic crystal fibers (PCFs) have attracted a lot of attention of the research society in the last decade and many interesting results have been obtained [2]. Photonic crystals (PC) are composed of periodic dielectric nanostructures that affect the propagation of electromagnetic (EM) waves. Based upon the variation of refractive index, these are classified as one, two and three dimensional photonic crystals. These crystals possesses photonic band gap (PBG) where the propagation of light is completely prohibited in certain frequency ranges [3]. Many phenomena have been predicted theoretically and many application possibilities have been explored [4, 5]. Corresponding studies in the early years most authors paid their attention on the frequency spectrum gaps, and the most convenient method to calculate the band gaps is the plane wave expansion method [6, 7].

THEORETICAL APPROACH

In the PWE method, electromagnetic field and periodic dielectric structure are expanded in a Fourier series where the material is assumed to be linear, locally isotropic and periodic with vector R.

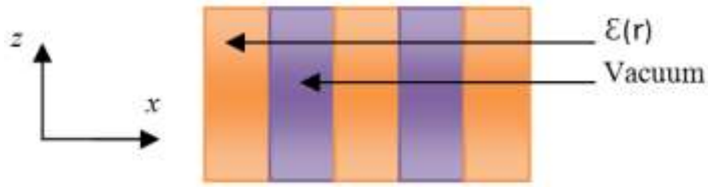

Figure: 1 Cross section view of 2D periodic structure.

The relative permeability μ is taken 1and relative permittivity is described as

$$\mathcal{E}(\boldsymbol{r}) = \mathcal{E}_b + (\mathcal{E}_s - \mathcal{E}_b)\boldsymbol{f}(\boldsymbol{r}) \quad ..(1)$$

($\boldsymbol{f}(\mathbf{r})$ equals 1 inside the column and 0 outside it) where $\mathcal{E}_s$ is the dielectric constant of the columns and $\mathcal{E}_b$ is the dielectric constant of the background. Because of the two-dimensional lattice periodicity, the dielectric constant $\mathcal{E}$ can be described by

$$\mathcal{E}(\boldsymbol{r}) = \mathcal{E}(\boldsymbol{r} + \boldsymbol{R}) \quad ..(2)$$

where ***R*** are 2D lattice vectors.

Solving Maxwell's equations for the magnetic field $\boldsymbol{H}_\omega$,

$$\nabla \times \left(\frac{1}{\mathcal{E}(\mathbf{r})} \nabla \times \boldsymbol{H}_\omega(\boldsymbol{r})\right) = \left(\frac{\omega}{c}\right)^2 \boldsymbol{H}_\omega(\boldsymbol{r}) \quad ..(3)$$

$\boldsymbol{H}_\omega$ is expanded into plane waves of wave vector **k** with espect to the 2D reciprocal lattice vector ***G***

$$\mathrm{H}_\omega(\boldsymbol{r}) = \sum_{G\lambda} h_{G\lambda}\, \hat{e}_\lambda e^{[i(k+G).r]} \quad ..(4)$$

Using Eq. (4) in the master equation (3) provides an equation for the coefficient $h_{G\lambda}$,

$$\sum_{G'\lambda'} \mathrm{E}^{k}_{G\lambda,G'\lambda'} h_{G'\lambda'} = \omega^2 h_{G\lambda} \quad ..(5)$$

The matrix ***E*** in the eigen value equation is defined as

$$\mathrm{E}^{k}_{G\lambda,G'\lambda'} = [(k + G) \times \hat{e}_\lambda]\left[(k + G') \times \hat{e}_{\lambda'}\right]\varepsilon^{-1}(G, G') \quad ..(6)$$

The Fourier transform of the inverse dielectric constant

$$\varepsilon^{-1}(G, G') = \varepsilon^{-1}(G - G') \quad ..(7)$$

depends on the difference of the reciprocal lattice vectors only. The properties of $\mathcal{E}$(r) are given by

$$\varepsilon^{-1}(G) = \frac{1}{A}\int_A \varepsilon^{-1}(r)\, e^{-iGr} d^2 r \quad ..(8)$$

where ***A*** is the area of the unit cell.

INVESTIGATED DESIGN PARAMETERS

After theoretical approach, in this section we investigated various design parameters such as shape of rods, lattice structure r/a ratio etc. which affect the bandgap structure of the 2D photonic structure. To achieve effective results on bandgap variation we considered a 2D photonic crystal structure [8] having circular dielectric rods with refractive index 3.376 suspended in the air, r/a ratio is 0.20µm and the lattice constant 'a' is 0.57µm.

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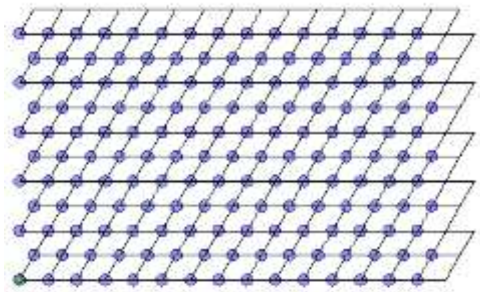

***Figure**: 2 Considered 2D photonic crystal structure [8]*

The major photonic TE bandgap of considered 2D photonic crystal structure is 0.2818 < a/λ < 0.45205. In the following subsections we will study various parameters which affect the bandgap of the Photonic Crystal.

Shape of Dielectric Rods

In this sub-section we changed shape of the dielectric rods circular, ellipse, square and rectangular keeping other parameters same as in [8]. The concept used to change the shape of dielectric rods is keeping filling factor constant i.e. area of circle (πr^2) = area of ellipse ($\pi\, r_1 r_2$) = area of square (l^2) = area of rectangle ($l_1 l_2$) as shown in Figure 3.

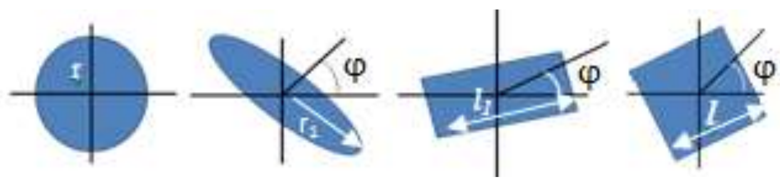

***Figure**: 3 Different shapes of dielectric rods*

The effect of change in the shape of rods having different orientation angles on the major bandgap of Photonic Crystal is tabulated in Table -1 and graphically presented in Chart -1.

Table -1: Major photonic bandgap (a/λ) for different shape of rods

Shape of rods / Orienta-tion Angle	Circular Shaped	Elliptical Shaped	Square Shaped	Rectangular Shaped
0^0	0.19127	0.09130	0.16882	0.14557
45^0	0.19127	0.12142	0.16666	0.17988
90^0	0.19127	0.11662	0.16882	0.16893
135^0	0.19127	0.08417	0.16775	0.14493
180^0	0.19127	0.09130	0.16882	0.14557

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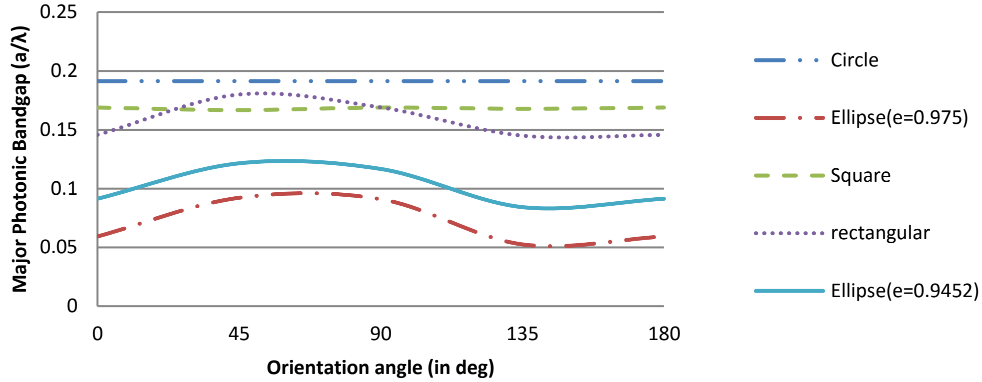

Chart 1. Photonic bandgap for different shape of rods having different orientation angles

Lattice Structure

The lattice structure, a way of arrangement with which dielectric rods are suspended in air, also play a very important role in photonic bandgap variation. Here we consider two lattice structures Hexagonal and Rectangular with different shaped dielectric rods keeping other parameter same as in [8]. Observed photonic bandgap is shown in Table -2 and Chart -2 shows graphical comparison.

Table 2. Major Photonic Bandgap (a/λ) for different lattice structure

Lattice \ Shape of rods	Circular Shaped	Elliptical Shaped	Square Shaped	Rectangular Shaped
Hexagonal	0.19127	0.12142	0.16882	0.17988
Square	0.13256	0.08580	0.12931	0.13296

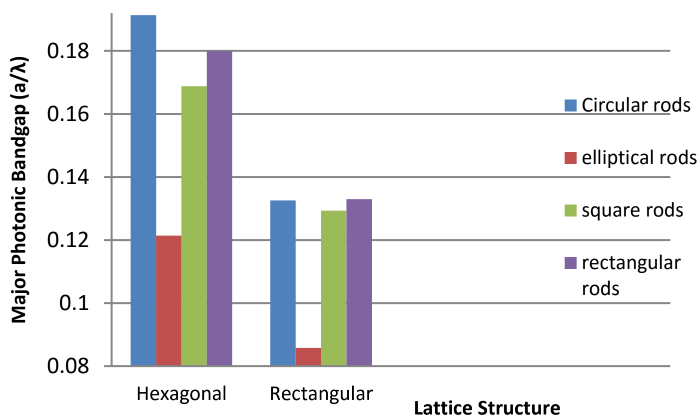

Chart 2. Major photonic bandgap for Hexagonal and Rectangular lattice structure

Eccentricity of ellipse

In this section we observed that eccentricity of ellipse also affects the bandgap of 2D photonic structure. Ellipse has major (r_1) and minor radius (r_2), here eccentricity is $e = \sqrt{1-(r_2/r_1)^2}$. It is cleared that the major radius must be less than $a/2$ where *'a'* is lattice constant. So the major radius r_1 is taken as 85%, 80%, 75% and 70% of $a/2$ to observe the effect of eccentricity of ellipse on bandgap variation at different orientation angle keeping other parameters same as in [8]. Analysis on eccentricity of ellipse is shown in Table -3 and its graphical view is observed in Chart -3.

Table 3. Effect of Eccentricity of Ellipse on Major Photonic Bandgap

Eccentricity / Orientation Angle	e = 0.9750 (r_1=85% of *a*/2)	e = 0.9682 (r_1=80% of *a*/2)	e = 0.9586 (r_1=75% of *a*/2)	e = 0.9451 (r_1=70% of *a*/2)
0^0	0.059229	0.069257	0.079825	0.091304
45^0	0.092150	0.100994	0.110985	0.121429
90^0	0.090321	0.098764	0.107200	0.116624
135^0	0.052489	0.062917	0.073474	0.084171
180^0	0.059229	0.069257	0.079825	0.091304

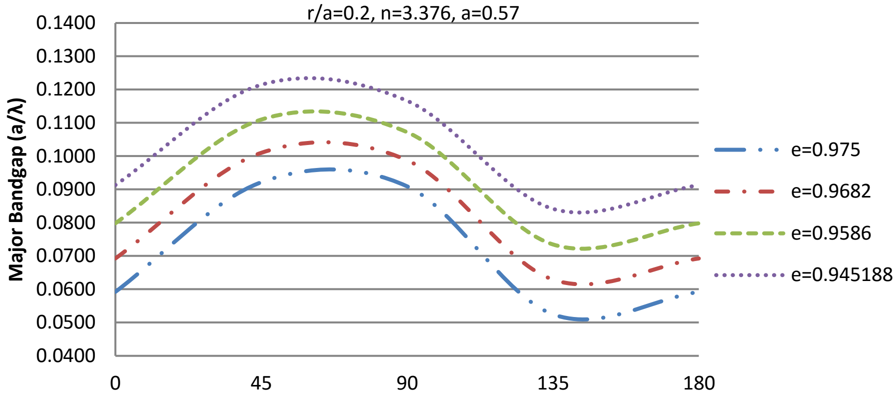

Chart 3. Effect of eccentricity of ellipse on photonic bandgap

Ratio r/a

Next observation parameter is ratio *r/a* where '*r*' is radii of circular rods and '*a*' is lattice constant. The change in ratio *r/a* shows change in eccentricity of elliptical dielectric rods having same area. Here ratio *r/a* is taken as 0.20, 0.22, 0.24, 0.26 and 0.28µm keeping lattice constant as *a* = 0.57µm and refractive index as 3.376. We considered major radius of ellipse as r_1 = 70% of *a*/2 to show maximum bandgap observed in Table -3. Analysis on bandgap variation due to change in ratio *r/a* is shown in Table -4 and Chart -4 shows graphical representation of analysis.

Table 4. Effect of Ratio r/a on Major Photonic Bandgap (a/λ)

Ratio *r/a* / Orientation angle	0.20 (e=0 .9451)	0.22 (e= 0.9186)	0.24 (e= 0.8825)	0.26 (e= 0.83395)	0.28 (e= 0.7683)
0^0	0.09130	0.08955	0.08612	0.08299	0.07855
45^0	0.12142	0.11738	0.11322	0.10918	0.10494
90^0	0.11662	0.11292	0.10910	0.10478	0.10072
135^0	0.08417	0.08253	0.07982	0.07681	0.07309
180^0	0.09130	0.08955	0.08612	0.08299	0.07855
Circular rods	0.19127	0.15316	0.13576	0.11935	0.10370

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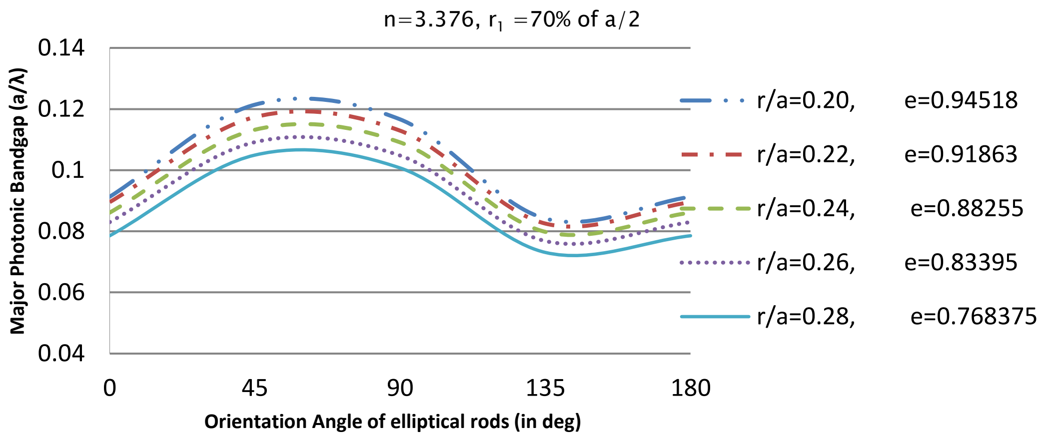

Chart 4. Effect of ratio r/a on photonic bandgap variation

Refractive Index

The *refractive index* of dielectric rods also shows bandgap variation. In this section we observed on generally used Si and GaAs rods having refractive indexes such as 3.255, 3.376, 3.47 and 3.59. The results are achieved by taking major radius as r_1 = 70% of *a*/2 and keeping other parameters same as in [8]. The observation is done on the structure having elliptical and circular rods shown in Table – 5

Table 5. Effect of Refractive Index of Dielectric Rods on Photonic Bandgap

Refractive Index / Orientation Angle	n_1 3.255	n_2 3.376	n_3 3.47	n_4 3.59
0^0	0.091523	0.091304	0.090951	0.090310
45^0	0.123439	0.121429	0.119796	0.117653
90^0	0.118378	0.116624	0.115185	0.113278
135^0	0.084224	0.084171	0.083953	0.083493
180^0	0.091523	0.091304	0.090951	0.090310
Circular rod	0.187850	0.191278	0.193353	0.195324

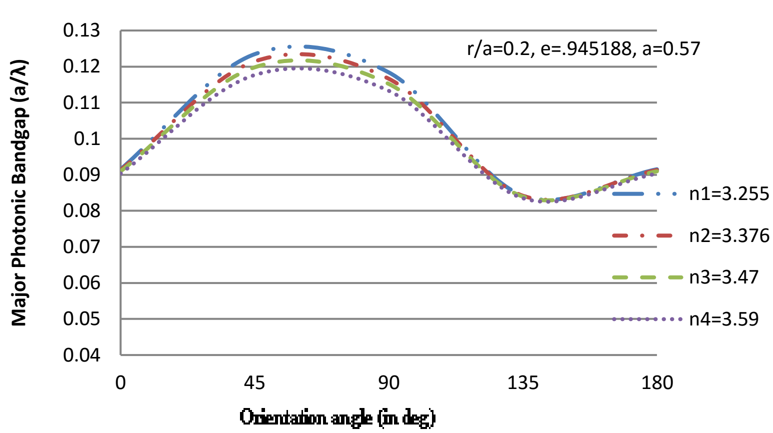

Chart 5. Effect of refractive index on bandgap variation

Number of Rods in Structure

After all observation and analysis still one question arises in mind that 'Is there any effect of number of rods on bandgap variation?'. So we analyzed different 2D photonic crystal structures with change in number of rods. The result is shown in Table -6.

Table -6: Observation on Number of Rods

S. No.	Parameters	Reference	No. of Rods	Bandgap (a/λ)
1.	n = 3.376, a = 0.57 µm, r = 0.2*a µm	[7]	11×15, 15×15, and 11×11	0.191278
2.	n = 3.46, a = 0.54 µm, r = 0.185*a µm	[8]	23×23, 15×15 and 27×27	0.140672
3.	n = 3.46, a = 0.567 µm, r = 0.17*a µm	[9]	21×21, 15×15 and 15×21	0.144027
4.	n = 3.255, a = 0.54 µm, r = 0.1 µm	[10]	21×18, 21×21, and 18×12	0.132856

CONCLUSION AND FUTURE SCOPE

In this paper, analyzed various parameters which affect the photonic bandgap of two dimensionol photonic crystal structure. It was observed that structure containing circular shaped dielectric rods exhibit the maximum photonic bandgap. For the structure with different orientation angles of different shapes, elliptical rods at 45^0 show highest bandgap. The Hexagonal lattice structures provide more bandgap than Rectangular lattice structure as observed in Chart-2. On using elliptical rods in crystal structure, minimum eccentricity of ellipse shows maximum major photonic bandgap as shown in Chart -3. It is observed in Chart -4 that larger r/a ratio provides minimum bandgap for 2D photonic structure having *elliptical* and *circular* rods keeping some parameters unchanged as mention in subsection 3.4. The Refractive index plays an important role, Chart -5 show the bandgap variation with respect to change in refractive index of dielectric rods. The lower refractive index of structure containing elliptical rods shows higher bandgap whereas that containing circular rods shows minimum photonic bandgap. Last but not the least, number of rods in 2D photonic crystal structure does not affect the photonic band gap.

The photonics revolution is akin to the improvements seen in computers, where mobiles now have the same functionality as the discrete supercomputers that took up entire bin decades ago. Photonics is also likely to lead to many new applications. Circuits are already being refined for preparing analog radio-frequency signals, specially for the frequency ranges that are crucial to control electrically. These are likely to return ultra-stable oscillators, analog communication systems, or large sensitivity Terahertz imagers. By controlling the relative phase of the light it is also possible to steer light beams expeling from the chip (e.g., phased arrays), which will be particularly useful to self-driving cars or robotics. It can also be used to realize sensors that, when implemented with another chemical or biological technologies, can be used to observe small changes in the environment, which will benefit fields from health to safty. And one of the lattermost aim of photonics has always been to realize an optical computer. While it is very difficult due to obstruction of photons (do not combine strongly with each other), there are inevitable computing technologies that photons may benefit, such as quantum computing. There are many applications which make photonic and optics important for future.

The incoming computing devices, be it quantum computers or for that matter even simple photonic integrated circuits, have already given us a new perspective to the power and versatility of computation in the future. With the ever growing interest for quick and more efficient computing, photonics seems to be a promising candidate. Technology giants such as Intel, IBM and Google already have made huge investments in this direction.

Imaging allows us to see the many chemical and physical changes taking place in a system. With the device similar to camera known as *camera obscura* to the modern day DSLRs, our cameras and imaging systems have changed rapidly. Imaging plays a crucial role particularly in life science, medicine and security issues but is also important in many fields of physics and chemistry.

Metamaterials are predicted to be of great use particularly in defence applications to impart covertness and cloak units. Other applications of metamaterials include superlenses which are lenses that are almost free of mutation and that can focus images below the diffraction limit. We can expect better antennas and other devices based on metamaterials in our mobile phones in the future.

The importance of light in material processing was understood after the hike of photography. Since various other processes were developed including laser-cutting of metallic blocks in the industry. Today, material processing has become highly sophisticated using light. 3D printing has been used so widely and in surprising ways. Material processing and nanofabrication at the nanoscale are very important not only for key research but also for industrial purposes. The applications for photonics are endless and will have encounter on future supercomputers, improved faster telecommunications, and longer lasting mobiles.

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