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Optimization of Photonic Band Gap PBG Width in Photonic Crystal PhC Design using Geometric Parameters

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Abstract: In this study, the optical bandgap PBG is a fundamental property of photonic crystals PhC, significantly controlling their ability to guide and transmit electromagnetic waves within specific frequency ranges. This bandgap arises as a result of the periodic arrangement of the photonic crystal structure, resulting in optical gaps similar to the electronic gaps in semiconductors. The width of the optical bandgap is a critical factor determining the efficiency and utility of photonic crystals in various applications such as routers, filters, and sensors. Several physical and engineering factors, such as material properties, lattice structure, and crystal dimensions, significantly influence the size and behavior of the optical bandgap. Studying the influence of these factors is essential for improving the performance of photonic crystals and adapting them to various applications in fields such as optical communications, imaging, and optical transmission technologies. This research aims to analyze the effect of these factors on the optical bandgap width, contributing to a better understanding of the mechanisms that control the performance of these materials in practical applications.

Keywords: Photonic Crystal (PhC), Photonic Band Gap (PBG), Refractive Index (RI), Plane Wave Expansion PWE, Finite-Difference Time-Domain (FDTD), Transverse Electric (TE), Transverse Magnetic (TM).

1 Introduction

Photonic crystals (PhCs) are artificially engineered materials that share similarities with naturally occurring structures. Their concept is inspired by semiconductor materials, which are distinguished by their periodic arrangement. As a result, photonic crystals are considered periodic insulating structures capable of directing, controlling, and manipulating light at optical wavelengths [1]. PhCs represent a promising research direction in optoelectronics. These periodic dielectric structures feature a lattice parameter comparable to the wavelength of propagating electromagnetic waves. One of their most significant properties is the ability to confine and control light, making them highly versatile for a wide range of applications [2][3]. A photonic crystal consists of a periodic network of dielectric materials with varying refractive index (RI)[4][5]. This periodicity results in unique optical properties, particularly the formation of a photonic band gap (PBG). The PBG enables the crystal to effectively trap, direct, and confine light. Thanks to this characteristic, PhCs have garnered significant interest from researchers and industries due to their high sensitivity, precision, selectivity, and real-time monitoring capabilities [6][7]. The practical application of triangular-shaped integrated photonic circuits has been widely explored, particularly because of their large band gap. For transverse electric (TE) polarization, the largest band gap occurs in connected structures, while for transverse magnetic (TM) polarization, it appears in non-connected structures. This makes triangular photonic structures a promising platform for photonic integrated circuits and ultra-compact optical sensors [8]. It is well known that introducing defects into the periodic lattice of PhCs disrupts their dielectric periodicity. These defects can be created by removing, shifting, or altering the material composition of air holes or columns in the photonic lattice. Such modifications enable precise control over the photonic band gap, allowing for guided modes at specific frequencies. Generally, a wider band gap results in stronger light control, enhancing the stability and performance of photonic crystal devices [9][10][11][12].

To optimize PhC performance, it is essential to study the factors influencing band gap design. The properties of photonic crystal sensors are typically simulated using the Plane Wave Expansion (PWE) method and the Finite-Difference Time-Domain (FDTD) algorithm [13][14]

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Recent research has examined the effects of migrating and rotating various mill-shaped defect structures on the TM band gap. The findings indicate that defect migration distances significantly impact the band gap in two-dimensional PhCs. Additionally, adjustments such as rotation, translation, and displacement can further expand the band gap, offering improved control over optical properties [15][16].

In our work, we proposed a design for a two-dimensional photonic crystal with a triangular and square structure. We based this design on a comparative study of three materials with different refractive indices: silicon (Si), germanium (Ge), and gallium arsenide (GaAS). We reviewed a set of geometric and physical criteria related to the central rod of the design (displacement in one or more dimensions, size change, change in the refractive index of the material), and concluded that it directly affects the length of the photonic band gap (PBG), which facilitates light control, resulting in modular and efficient devices.

2 Parameter and Simulation

The two figures below illustrate the types of designs found in two-dimensional 2D photonic crystals (PhC) Fig.1 rods in air (Discrete structure) and Fig.2. Holes in slab (Connected structure), with the geometric properties of each being show, period a=0.4 and radius r =0.24×a. This triangular structure is a 2D lattice of dimensions 21x21.

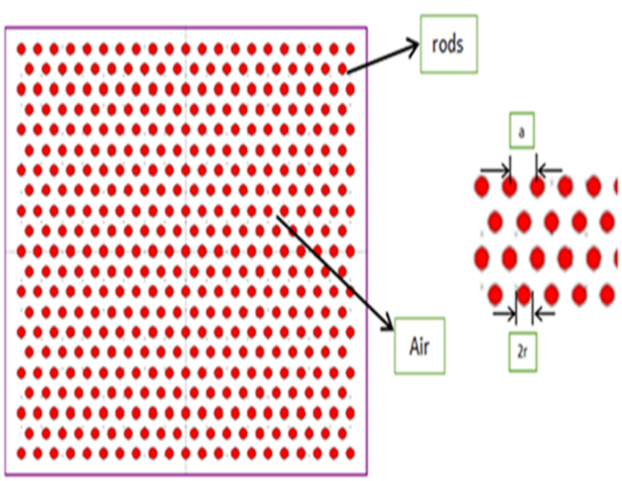

Fig. 1: Discrete structure (rods in air) of photonic crystal PhC in the 2D triangular.

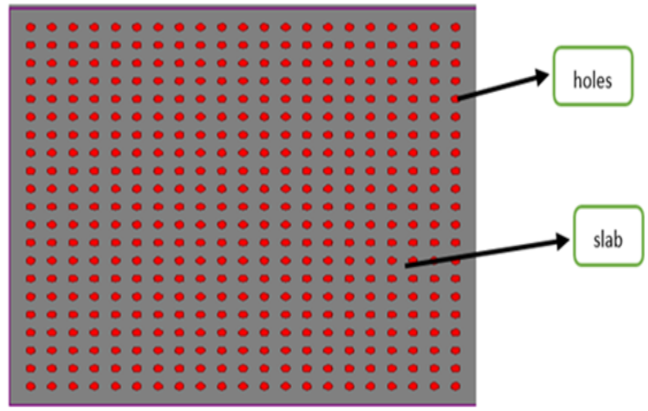

Fig. 2: Connected structure (holes in slab) of photonic crystal PhC in the 2D triangular.

Fig.3 and Fig.4 show the regular and periodic distribution of the refractive index RI of the two different compositions, knowing that the refractive index RI of air is n air = 1 and the refractive index RI of silicon is n Si = 3.42 in both cases.

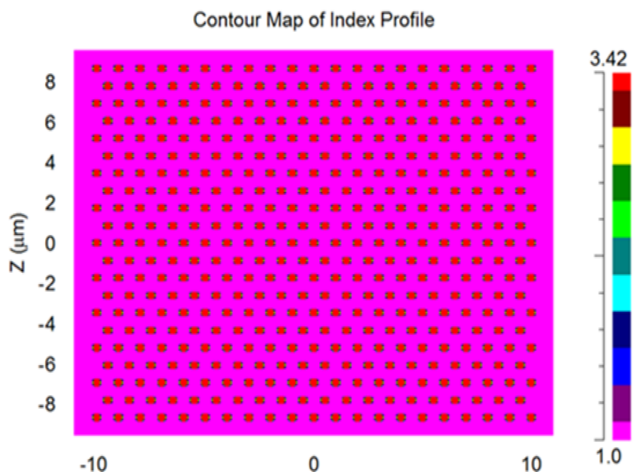

Fig. 3: Distribution of refractive index RI in the discrete structure.

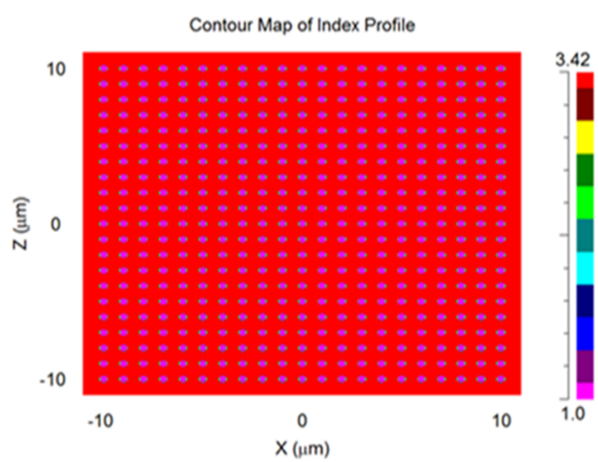

Fig. 4: Distribution of refractive index RI in a Connected structure.

Fig. 5 shows the photonic band gap PBG length observed at TE polarization around an average frequency related to a wide natural photonic bandgap (a/λ) of 0.3185, occupying natural frequencies between 0.252 (a/λ) and 0.385 (a/λ). The frequency range is between 1.03896 um and 1.5783 um, high lighting the important optical properties of our studied design.

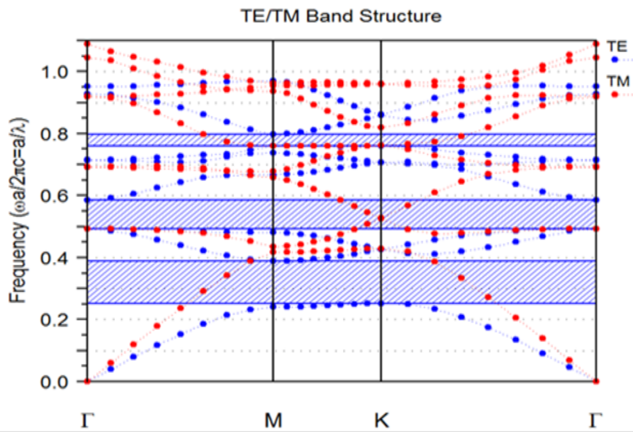

Fig. 5: Dispersion curves and Photonic Band Gap (PBG) for TE polarizations.

3 Numerical Methods

Numerical methods are tools that facilitate optimal access to and efficient analysis of mathematical and differential data and equations. Among these methods are those used to plot and analyze photon frequency bands, such as the plane wave broadening (PWE) method and the FDTD method, which are integrated into Rsoft software.

The plane-wave expansion (PWE) method is an effective numerical technique for analyzing photonic crystals (PhCs). It is specifically used to determine photonic band structures (PBG) by solving Maxwell's equations in regular periodic dielectric structures [17][18].

The finite-difference time-domain (FDTD) numerical method is integrated into the widely used rsoft software to solve Maxwell's equations and complex electromagnetic problems. It is particularly used to simulate the interaction of light with nanostructures, such as photonic crystals (PhCs), plasmonic materials, and metamaterials [19][20][21].

4 Results and Discussion

Through our research, which presents a comparative study of three different materials silicon n Si=3.42, gallium arsenide n GaAS=3.3, and germanium n Ge=4 in both triangular and square configurations, aiming to compile and document the parameters affecting the bandgap width, our results revealed a significant effect of the central rod design, especially with regard to the introduction of a new material. Additionally, we examined the front and back radius of curvature, as shown in Fig.6, clearly demonstrating that the radius plays a crucial role and directly affects the photonic band gap width (PBG). The (front radius/back radius) value of 0.9 × r was the highest for all the materials analyzed. Among all the measurements examined, we obtained a wavelength of 736.85 nm for triangular germanium.

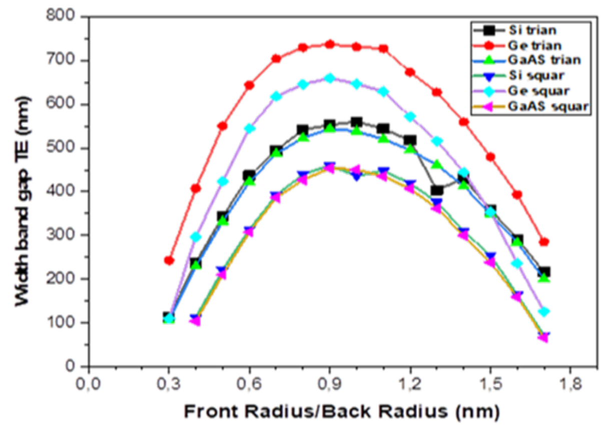

Fig. 6: The variation of the band gap width TE as a function of the front and back radius (Front Radius/Back Radius).

If the photonic band gap (PBG) refers to an optical phenomenon such as interference, the focal point in the design can play a role in influencing the transmission or bandwidth. Therefore, changing the position of the center can change the bandwidth. By modifying or moving the center point, the interference angles and convergence points can also be affected, creating a tangible shift in the BIP structure. In Fig.7, we adjusted the position of the main column along the (x, -x, z, and -z) directions to study its effect on the band gap width. Initially, the band width was fairly stable before it began to decline, until it became geometrically unattainable. The highest value was recorded in the triangular figure at a displacement of (-z) axis =0.1 nm. The length of the photonic band gap was 591.96 nm.

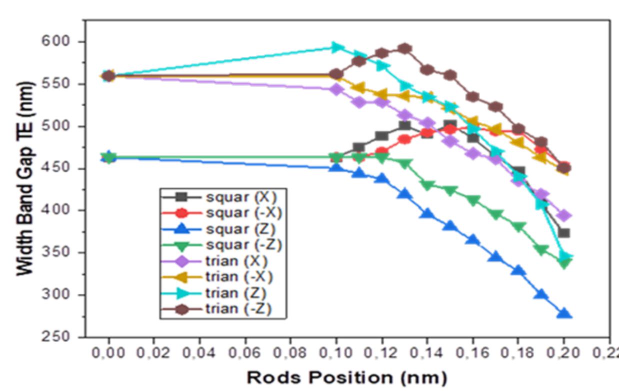

Fig. 7: The variation of the width band gap TE as a function of the Rods Position along the axis (x, -x, z, -z).

In this part of the research Fig.8, we varied the position of the main column along four different directions (xz, x-z, -x-z, and -xz) to evaluate its effect on the forbidden spectrum width. Initially, the bandwidth remained relatively constant, peaking at different positions. For the triangular design, the displacement in both directions (-x and -z) axis reached its maximum value at 0.13 nm. The photonic bandwidth reached 593.51 nm, before gradually decreasing until it was no longer geometrically feasible.

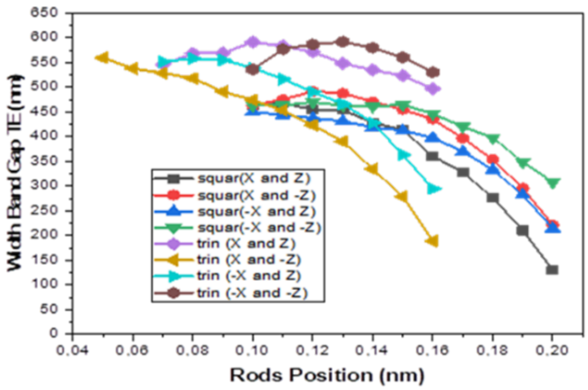

Fig. 8: The variation of the band gap width TE as a function of the position of the tig along the axis (x and z, x and -z, -x and -z, -x and z).

Table 1: Comparison of the proposed design with different similar PhC designs in terms of photonic band gap length.

References	Width Band Gap (nm)
[22]	241
[23]	608
[15]	586.6
[24]	625.6
[25]	324.7
[26]	464
In this work	**736.85**

In Table 1 above, we compare the proposed design, in which we achieve a photonic bandgap (PBG) width of 736.85 nm, with several similar designs from previous studies in terms of band gap length.

5 Conclusion

In our research and through our results, we concluded that it is necessary to carefully select the key parameters to achieve an optimal design. The optimal bandgap length value was TE = 736.85 for a (front/back) radius ratio (Ge) of 0.9. Additionally, TE = 591.96 was obtained for a position along the (-z) axis = 0.1 µm, and TE = 593.51 for positions along the (-x) axis = 0.13 µm and the (-z) axis = 0.13 µm. We would like to note that the results for this design without introducing any defects reached TE = 559.58, hence the difference. Various data collected for a range of triangular 2D photonic crystal designs indicate a bandgap of approximately 1.55 µm for silicon in air. To achieve good results, careful parameter tuning and careful selection of crystal components are required. The topology of the photonic crystal, including its type and shape, must also be carefully chosen.

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