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Investigating the Properties of an Optical Waveguide Based on Photonic Crystal with Point Defect and Lattice Constant Perturbation

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Abstract: In this paper, a photonic crystal waveguide with point defects and lattice constant perturbations of +5%, -5% are being investigated. Firstly waveguide structures with constant and specific parameters are being studied and photonic band gap diagrams for TE/TM modes are depicted; then pulse propagation in the frequencies available in the band gap are shown. After that, effects of parameters like refractive indices and radius of the rods on the band gap diagram of TE/TM modes are evaluated. It has been shown that, by increasing the refractive indices and radius of the rods, band gap diagrams would be shifted to lower frequency amounts.

Keywords: band gap diagram, photonic band gap, photonic crystal, photonic waveguide.

1. Introduction

Photonic crystal (PhC) is a periodic dielectric structure with the capability of guiding and manipulating light at the scale of optical wavelength [1]. If the periodicity is in one dimension, it is called 1D- phonic crystal and if it is in two or three dimensions, it would be called 2 or 3-D photonic crystal. The input light wavelength is about hundreds of nanometer. Photonic crystals due to their unique properties have attracted attention of many researchers. Researchers believe PhC is a promising technology for the integrated optics. A revolution in the fields of optical signal processing and communication is hopefully not far

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from realization, like what happened to electronic circuits by semiconductor technology.
Photonic crystal has many characters among which slow light effect is a very important feature. Defect is formed via removing some of the dielectric materials in photonic crystal and a guided mode emerge in photonic band gap Photonic crystal structures show wide aspects of physical properties because their different electrical structures. As the light enters the photonic crystal, it propagates only in special frequencies available in the band gap diagram. Photonic waveguide is a structure capable of conducting optical pulses form point to point. Photonic waveguides can be constructed by photonic crystal by forming defects in the structure. Point defects are formed in the photonic crystals for optical waveguides, optical filters, lasers, multiplexers and demultiplexers. Forming a defect in the 2-D photonic crystal can also lead to resonance in the cavity.Since first proposed in 1987, photonic crystal has been studied extensively both theoretically and experimentally. In recent years, photonic crystals are being considerably attractive in optical systems. In recent years different optical devices are used in optical communication systemswhich are designed and simulated by photonic crystals such as optical waveguides [2,3], optical filters [4], optical demultiplexers [5], optical switches [6] and optical gates [7,8].

One of the most important and interesting applications of photonic crystals is in the optical waveguides with lattice constant perturbation which forms resonant modes [9].

In this research, properties of photonic crystal waveguides with +5%, -5% perturbations in the lattice constant are being studied. In these structures effects of structural parameters such as rod radius and refractive index on the amount of TE and TM band gaps are shown in different diagrams.

2. Analysis Method

The best way for studying the optical properties of periodic structures like photonic crystals is numerical methods; because Maxwell equations are their fundamental equations. One of these methods is the plane wave expansion (PWE) method. Although it is capable of calculating the band gap of photonic crystals, it can’t define pulse propagation; therefore for investigating the light behavior in photonic crystals, finite difference time domain method (FDTD) is used.

3. Theory and Simulation

A. Design process

In the design process, we have a 16*11 photonic crystal structure. The complete arrays of the sixth row are removed so that the structure functions as a resonant waveguide. The photonic rods are of the materials with 3.4 refractive index, lattice constant of a in the interval of 0.15µm < a < 0.23µm, rod length of 0.6*a and rod radius of 0.3*a. the structure for two states with lattice constant perturbation of +5% and -5% are investigated and the refractive index profile and TE/TM mode band gap diagrams are depicted.

B. Simulation for +5% lattice constant perturbed structure

In the Fig. 1, the waveguide structure based on photonic crystal with +5% lattice perturbation is depicted.

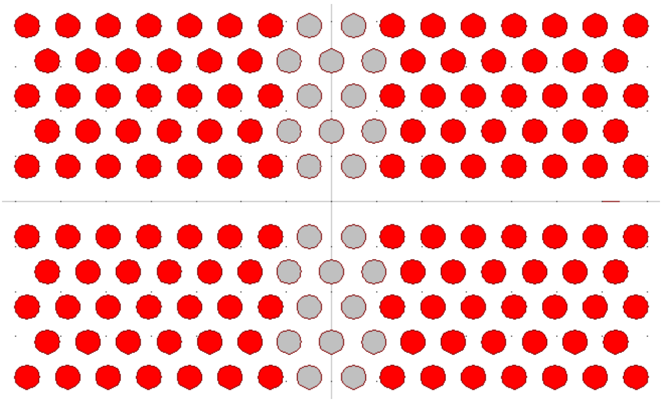


Fig. 1. Photonic crystal waveguide with +5% lattice constant perturbation. (Light gray cells are the +5% perturbed lattice constant rods).

The refractive index profile of the structure with +5% and -5% lattice constant perturbation would be like Fig. 2. As can be seen in the figure, the rods with refractive indices of 3.4 are placed in the background of air.

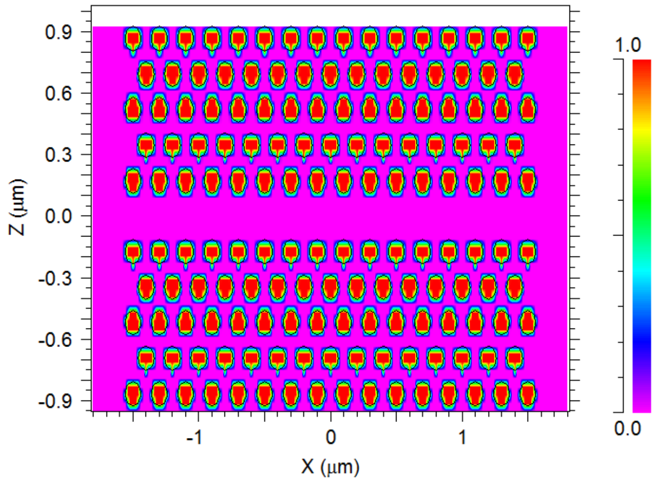


Fig. 2. Refractive index profile of photonic crystal.

For studying the TE/TM band diagrams, lattice constant of 0.2 µm in the middle of the interval related to a (lattice constant) is chosen and the PWE method is done for it. The TE/TM band diagram for the structure of Fig. 1. is depicted as follows.

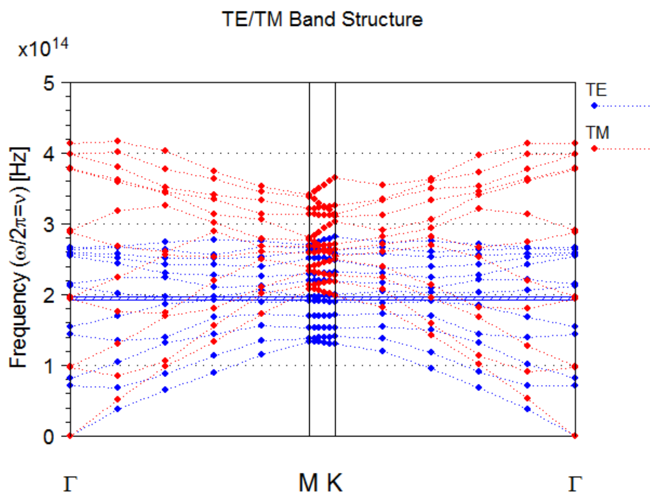


Fig. 3. The TE/TM band diagram for a structure with a=0.2µm and +5% lattice constant perturbation.

As can be seen in Fig. 3, the frequency band gap from 193e12 to 196e12 can be viewed in TE mode; even though there is no band gap in the TM mode.

C. Simulation for -5% lattice constant perturbed structure

In this section, waveguide structure based on -5% lattice constant perturbed photonic crystal as in Fig. 4, is being studied.

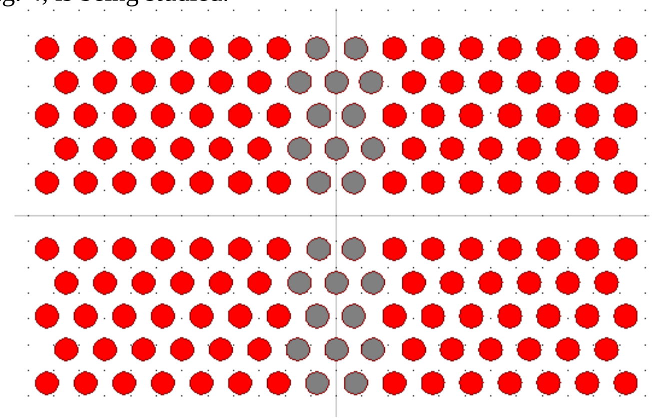


Fig. 4. Photonic crystal waveguide with -5% lattice constant perturbation. (dark gray cells are the -5% perturbed lattice constant rods).

The refractive index profile of Fig. 4 is the same as Fig. 2.
In this section, for investigating the TE/TM band diagrams we select the lattice constant value as 0.2µm in the middle of a (lattice constant interval) and do the PWE method. The TE/TM band diagram for Fig. 4 is depicted in Fig. 5.

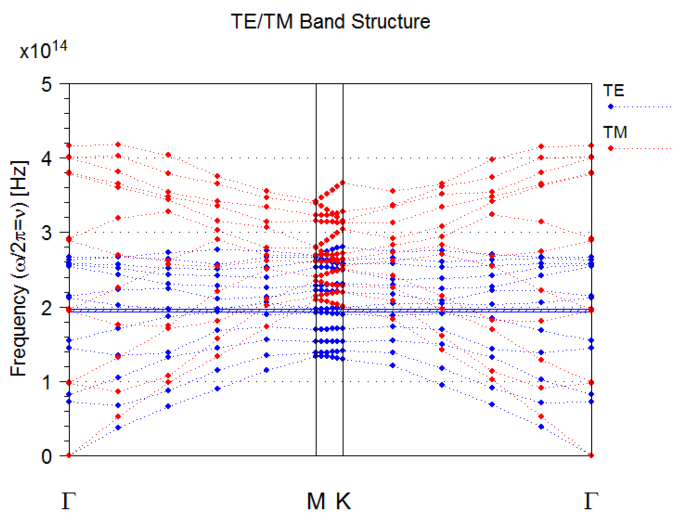


Fig. 5. The TE/TM band diagram for a structure with a=0.2µm and -5% lattice constant perturbation.

In this structure, we also see the band gap for TE mode in the interval of (192e12, 197e12).

By comparing the structures with +5% and -5% lattice constant perturbations, it can be concluded that, the structure with negative perturbation makes the optical band gap broader.

D. Pulse propagation in Fig. 1 and Fig. 4.

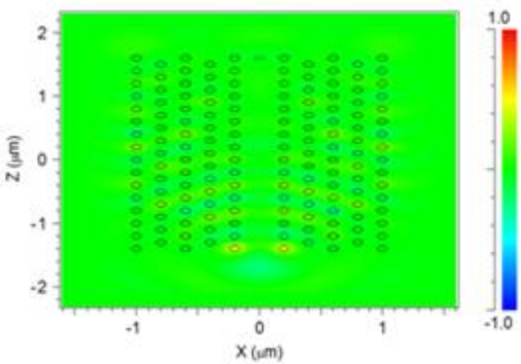
After studying the TE/TM band diagrams for Fig. 1 and Fig. 4, now optical pulses with different wavelengths are propagated in the waveguide and the following results are obtained.

i. If in this structure wavelengths between 0.8µm and 0.9µm are chosen (not in the band gap interval)

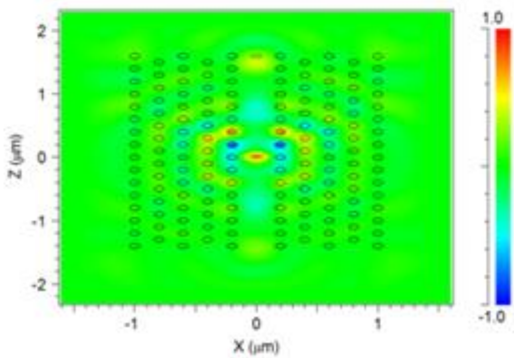
In this condition, the wavelengths of the input pulse are not in the forbidden region, so the input pulse would totally propagate in the photonic crystal structure and would be gradually attenuated. Fig. 6 indicates the pulse propagation with 0.8µm and 0.9µm wavelengths.

ii. If the wavelength of the input pulse is chosen as 1.55µm.

If the wavelength of the input pulse would be 1.5µm (in the middle of the frequency band gap), the input pulse would completely reflect while striking the photonic crystal. In this case, the light would propagate in the waveguide and the output pulse gains its maximum intensity. This condition can be seen in Fig.7.



(a)



(b)

Fig. 6. Optical pulse propagation in photonic crystal in,(a) 0.8 μm, (b) 0.9μm wavelengths.

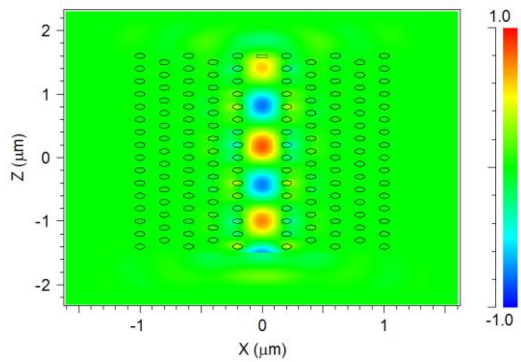


Fig. 7. Pulse propagation in photonic crystal at the wavelength of 1.55μm.

In the previous sections, photonic crystal with +5% and -5% lattice constant perturbations were studied, also their band gap diagrams for lattice constant of 0.2μm were depicted; finally pulse propagation figures for the frequencies in the forbidden region and out of that were shown.

E. Effects of rod radius on the TE/TM mode diagrams

i. +5% lattice constant perturbed structure

In the structure of Fig. 1, by using fixed values for all parameters, we change the rod radius and illustrate the obtained results for band gap width of TE/TM modes in the following figures.

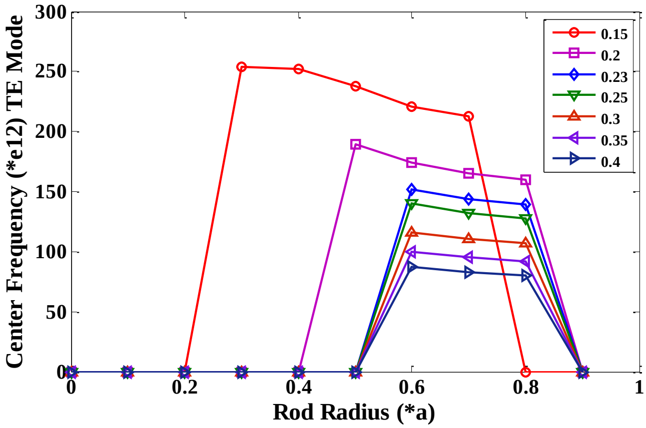


Fig. 8. Center frequency of the band gap vs. rod radius for different lattice constants for TE mode.

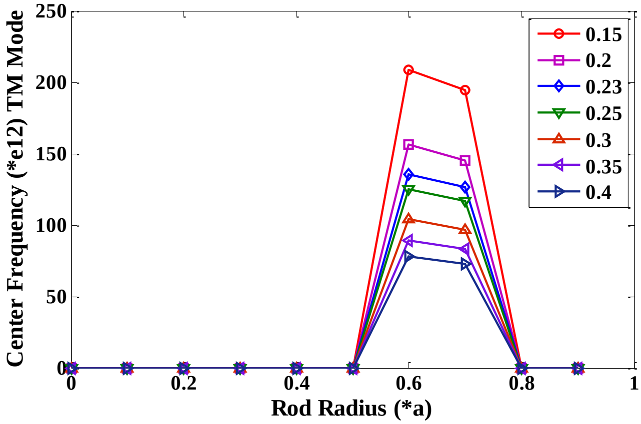


Fig. 9. Center frequency of the band gap vs. rod radius for different lattice constants for TM mode.

It can be seen from Fig. 8 and 9 that by increasing the rod radius, TE/TM mode band gap would be shifted to lower frequencies but at the same time would be increased till R=0.8*a. the next conclusion is that for some ring radii, TE and TM modes can be seen simultaneously. The optimum case for TE/TM band gap diagram for R=0.7*a is depicted.

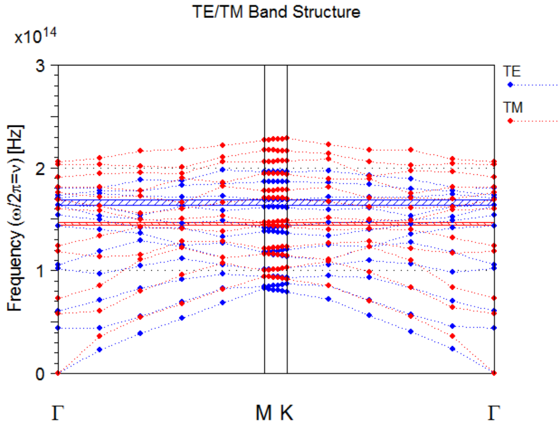


Fig. 10. The optimum TE/TM band diagram for the +5% lattice constant perturbed structure with a=0.2μm by changing rod radius.

ii. Structure with -5% lattice constant perturbation.

After analyzing the positive perturbed structure, we study the structure of Fig. 4. with -5% lattice constant perturbation.

In this case, we also fixed all the parameters but the rod radius. The following figures are obtained for TE/TM band gap diagrams.

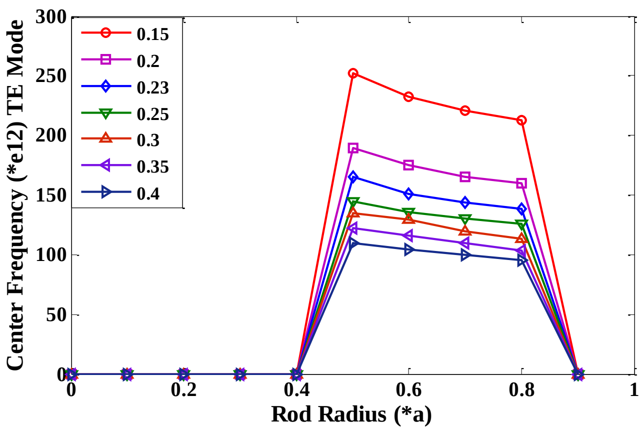


Fig. 11.Center frequency of the band gap vs. rod radius for different lattice constants for TE mode.

From Fig. 11 and 12 can be concluded that by increasing the rod radius, TE/TM mode band gap would be shifted to lower frequencies and at the same time increases the intensity; this will happen till R=0.8*a. Also it can be seen that for some rod radius there would be band gap for TE and TM at the same time.

TE/TM band diagram for the optimum case where R=0.7*a is depicted as follows.

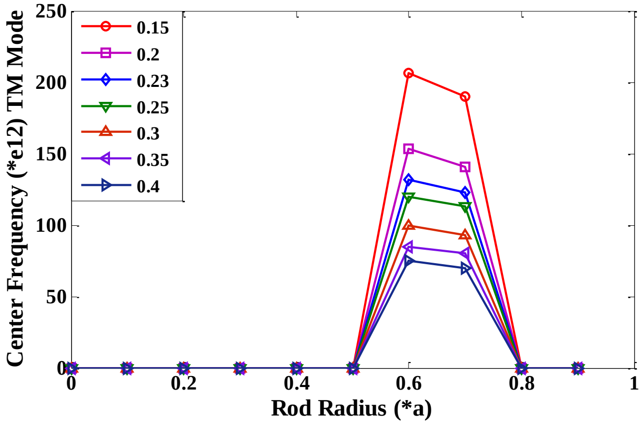


Fig. 12.Center frequency of the band gap vs. rod radius for different lattice constants for TM mode.

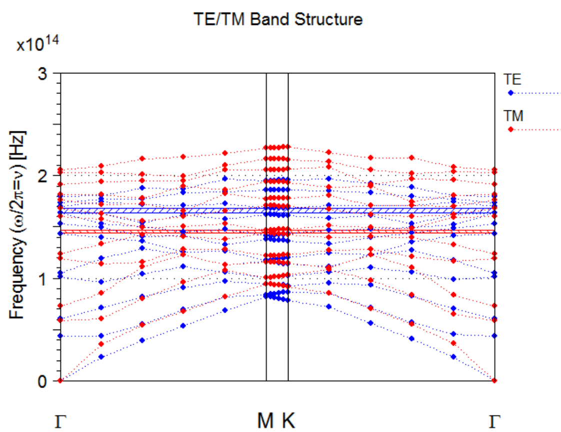


Fig. 13.The optimum TE/TM band diagram for the -5% lattice constant perturbed structure with a=0.2μm by changing rod radius.

F. Effects of rod refractive index on the TE/TM mode diagrams.

In this section we investigate the effects of rod refractive indices on the band gap diagram.

i. +5% lattice constant perturbed structure.

In the structure of Fig. 1. by fixing all the parameters and selecting R=0.7*a, we study the effects of refractive index on the TE/TM mode band diagram.

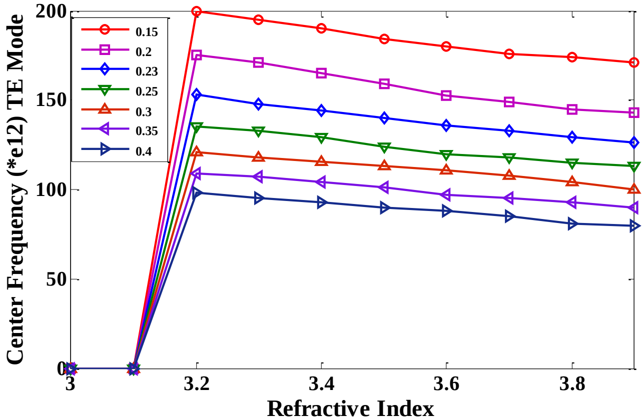


Fig. 14. Center frequency of the band gap vs. refractive index for different lattice constants for TE mode.

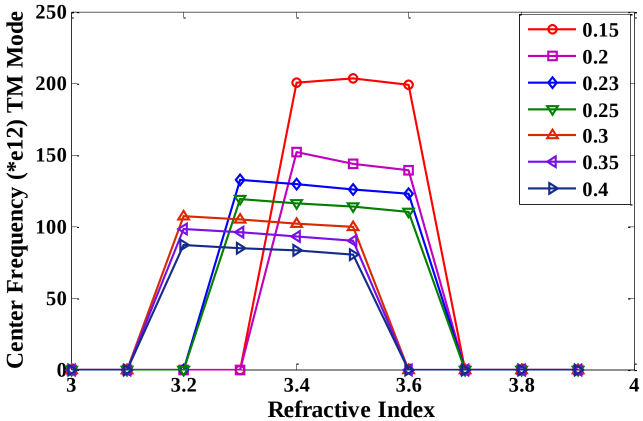


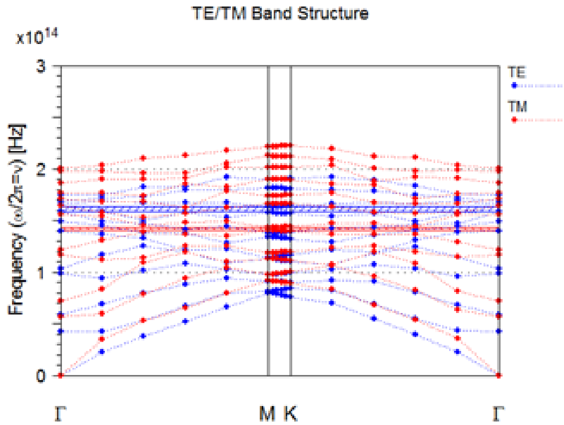
Fig. 15. Center frequency of the band gap vs. refractive index for different lattice constants for TM mode.

As can be seen in Fig. 14 and 15, by changing rod refractive index, the TE/TM band diagram would be shifted to lower frequencies. Another interesting observation is the appearance of two different band gaps for TE mode for refractive indicesequaling 3.8 and 3.9; which attract great attentions in special applications.

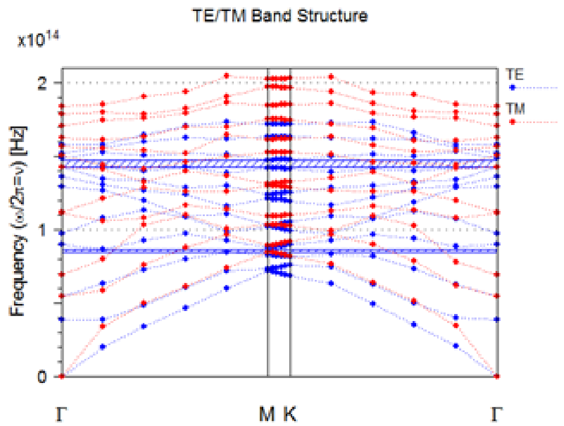
In this lattice constant, by changing rod refractive indices the best case for TE band diagram in refractive index of 3.5 and 3.9 were depicted in Fig. 16.

ii. -5% lattice constant perturbed structure

In the Fig. 1, by fixing all the parameters and choosing R=0.7*a, the effects of refractive index on the TE/TM band diagrams are being investigated.



(a)



(b)

Fig. 16. The optimized TE/TM band diagrams for the +5% lattice constant perturbed structure with refractive index of (a) 3.5, (b) 3.9.

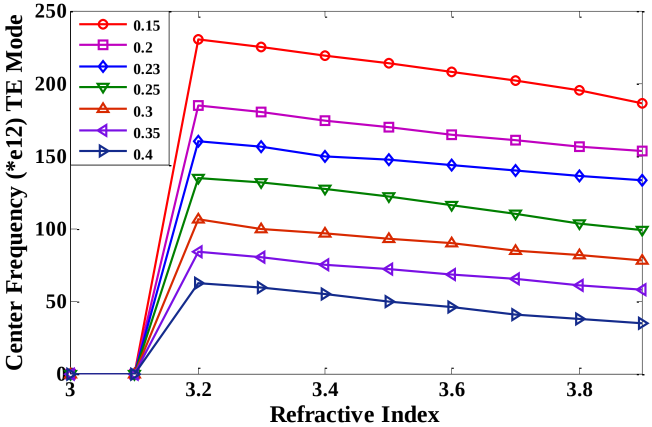


Fig. 17.Center frequency of the band gap vs. refractive index for different lattice constants for TE mode.

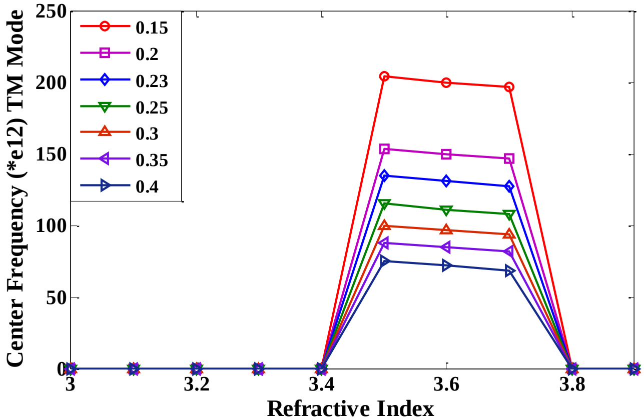


Fig. 18.Center frequency of the band gap vs. refractive index for different lattice constants for TM mode.

In this lattice constant, by changing rod refractive indices the best case for TE/TM band diagram in refractive index of 3.7 is depicted in Fig. 19.

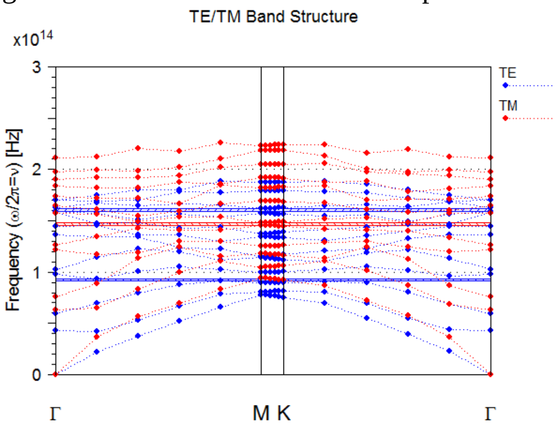


Fig. 19. The optimized TE/TM band diagrams for the -5% lattice constant perturbed structure with refractive index of 3.7.

4. Conclusion

In this paper, we have studied the photonic crystal waveguides with point defect and lattice constant perturbation. At first, band gap diagram for fixed structural parameters were depicted and concluded that band gap is broader for negative lattice perturbation. After that, pulse propagation figures for different wavelengths were depicted. At last by changing the radius and refractive index of the rods, it was indicated that band gaps were broader than before and frequencies of the band gap were shifted to lower amounts.

5. References

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