ISSN: 2349- 5197
Impact Factor (PIF): 2.138

INTERNATIONAL JOURNAL OF RESEARCH SCIENCE & MANAGEMENT

ANALYSIS OF PHOTONIC BAND STRUCTURE IN PHOTONIC CRYSTALS CONTAINING SINGLE NEGATIVE MATERIALS BY COMPUTATION OF FIELD DISTRIBUTION AND DISPERSION DIAGRAMS

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Keywords: Forbidden gap, PWE, FDTD, Eigen states, Photonic band gap, single-negative (SNG) materials, dispersion.

Abstract
A photonic crystal (PC) is said to be an artificially periodic layered structure that is known to possess photonic band gaps (PBGs) at certain frequency ranges. In this paper we have analysed one dimensional band structure by computational method in single negative material photonic crystals using plane wave expansion and finite difference time domain.

Introduction
Some of the similarities between Photonic crystals [1] and solid-state physics include similar lattice structure, behaviour of photons is similar to electron and hole behaviour, due to the lattice periodicity both provide the band gap and most important is the determination of Eigen functions in a Photonic crystal is very similar to calculation of the quantum mechanical particle wave functions in the solid-state.

Vectorial property of EM fields is the crucial reason to justify why photonic bands precisely predict the behaviour of light. The photonic crystals [2] are known to be the special class of optical media with periodic modulation of the refractive index and permittivity.

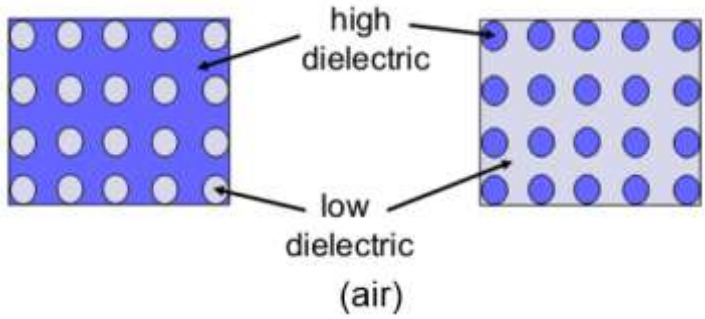

Fig. 1 The key point of photonic crystal is structures with periodic variations in the dielectric constant.

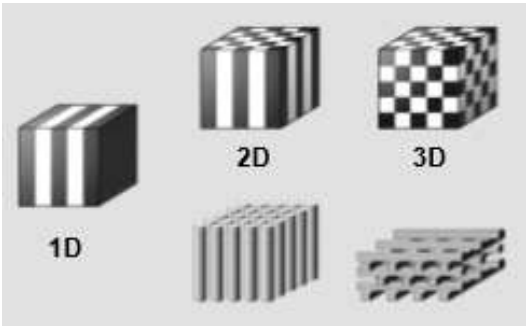

Fig. 2 Schematic view of photonic crystals with different dimensionalities

The paper is divided into: Section II includes the design of basic equations, Section III contains the heart of entire writing and discussions i.e. numerical results and discussions and Section IV consists of summary and future research followed by section V that contains the conclusion of the paper.

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Basic equation

These are the differential form of Ampere's Law and Faraday equations, respectively. These two equations are correspondingly used to solve numerical calculation in PWE and FDTD method.

$$\nabla \times H = \varepsilon \frac{\partial E}{\partial t} + \sigma E$$

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$

Where, E and H are the electric field and magnetic field, respectively; ε is the electrical permittivity and μ is the magnetic permeability; σ is the electric conductivity loss; t is the time.

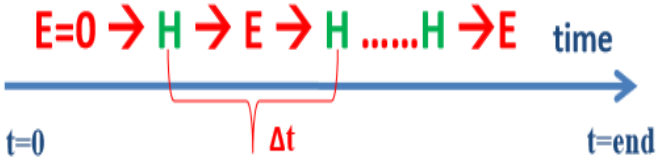

Fig.3 General FDTD field update procedure

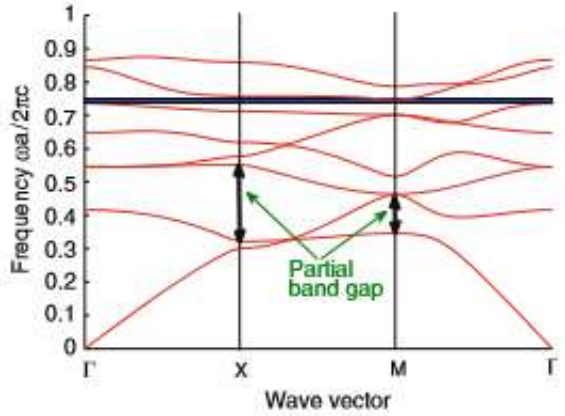

Fig.4 1D- Partial photonic band gaps of the PhC

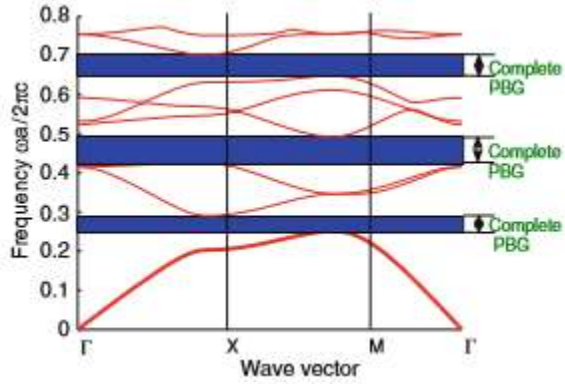

Fig.5 1D- Complete photonic band gaps of the PhC

To start the computation, we derived the wave equation from the system of Maxwell's equation.

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$$\nabla \times \mathbf{E}(\mathbf{r},t) = -\frac{\partial \mu_0 \mathbf{H}(\mathbf{r},t)}{\partial t},$$
$$\nabla \times \mathbf{H}(\mathbf{r},t) = \frac{\partial \varepsilon_r(\mathbf{r})\,\varepsilon_0 \mathbf{E}(\mathbf{r},t)}{\partial t}.$$

Take curl from both left and right sides of the first equation and then substituting second equation into the first one we obtain the following relation:

$$-\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = \varepsilon_r(\mathbf{r})\,\mu_0 \varepsilon_0 \frac{\partial \mathbf{E}(\mathbf{r},t)}{\partial t^2}$$

Besides, investigating the band structure, it is possible to obtain the group velocity of radiation inside the PhC. The group velocity is determined as the first wave vector derivative of the band structure. Consequently, the more flat the band of the PhC, the lower the group velocity at the corresponding frequency. Thus, the band structure of PhC gives the possibility to find and analyse the photonic band gap which is the crucial moment for a number of practical applications and group velocities which allows predicting the radiation propagation conditions in different directions inside PhC.

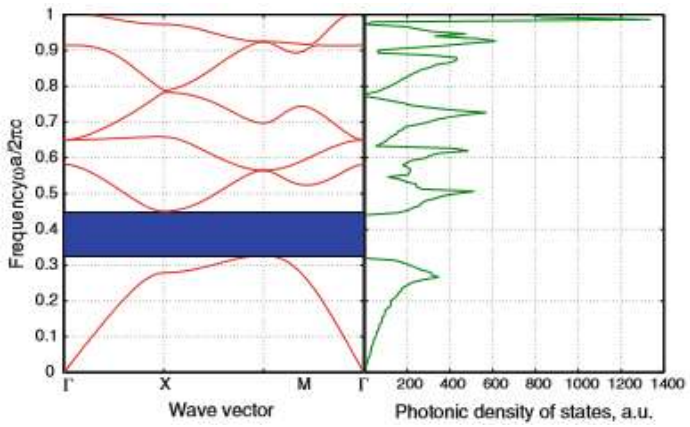

Fig.6 1D- Photonic density of states of 2D PhC

Low or zero Photonic density of states (PhDOS) [5] corresponds to the absence of the eigen-states within corresponding frequency range, i.e. the PBG. If the Photonic density of states is large, this corresponds to high number of eigen-states. In other words, the large number of eigen-states correspond to large number of paths the radiation can pass through PhC and, consequently, larger the PhDOS, the larger the transmittance of the PhC.
Latest techniques involve in the Finite difference time domain [6] simulations of "metamaterials".

Numerical results and discussions

1. Computation of field distribution in non-uniform optical medium

The program consists of three blocks-
During the first block, the program initialization is carried out. Here, we set up parameters of the computation domain and initialize arrays for permittivity distribution, field components computation and the graphical output. Inside this block we are also computing the time step. This gives stability to the method.
In the next block, we are setting up the permittivity distribution inside the computation domain.
The third block is for FDTD computation itself. No necessity in redrawing the field distribution at each computation step. That is why we introduced the computation step counter and redrawing the field each fifth step.
In Fig 7, The computation results are shown. The first figure depicts the field distribution at almost the beginning of the computation process while the second one is after a time interval. We can see the interaction between the radiation and the structure. Setting up custom structures and taking into consideration the material properties, it is possible to compute the field distribution inside any optical device.

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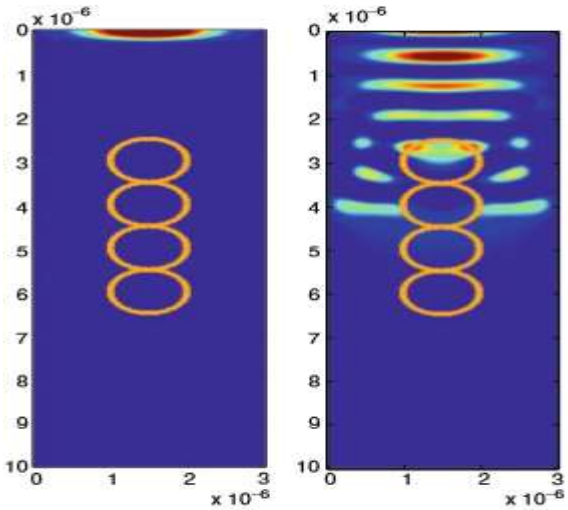

Fig.7 Field distribution at different moments inside the considered structure

2. Computation of the fundamental mode distribution in micro structured fiber by means of plane wave expansion method

Micro structured fiber is an optical wave guiding structure in which main element is PhC cladding providing light localization inside the core region. This fiber possesses wide spectrum of features such as single- mode operation within wide frequency range and with large core, strong light localization within the core region, peculiar dispersive properties according to PhC surrounding the core region, namely, 1D or 2D photonic crystal, and according to optical confinement mechanism, namely, total internal reflection or the PBG.

Computation of the characteristics of the micro-structured fiber as well as mode field distribution can be made by plane wave expansion method. The band gap diagram is the characteristic of the PBG fiber which allows determining its operating frequency range.

In Fig 8, the plot is made for the field strength distribution. In Fig 8(1), Light localization appears inside high-index areas of the PhC but not in the PhC defect area which has low refractive index. These modes are known as cladding modes.

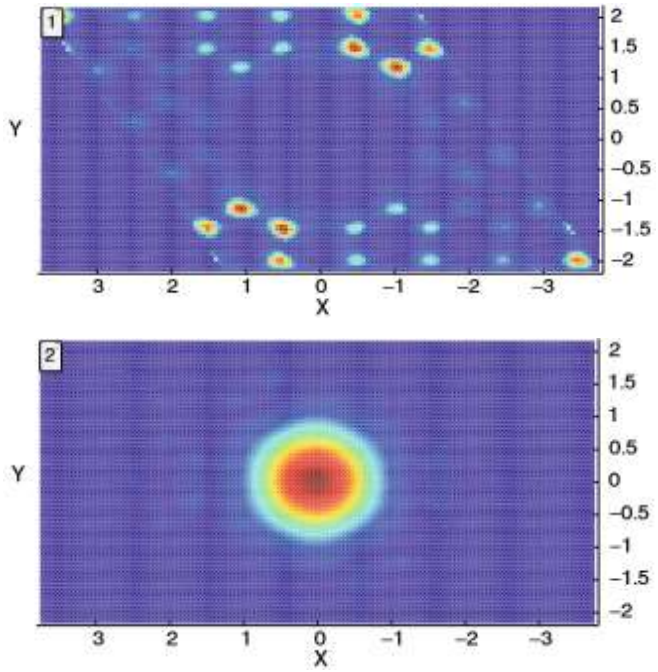

Fig.8 Modes field distribution

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In Fig 8(2), If the eigen-frequency lies above the light line, the radiation forms "leaky" modes which are able to flow out from the high-index medium to the low-index defect of the PhC and to be localized there in the region itself.
Application: It can be used both for technological purposes and for telecommunication purposes to transmit information and compensate dispersion within short communication line sections.

3. Computation of dispersion diagrams of 2d PhC waveguide
Analysis of dispersion diagrams
The dispersion diagram allows obtaining both group velocity and group velocity dispersion.
The group velocity of the mode is determined as first derivative of the dispersion curve over the wave vector:

$$V_g = \frac{dw(k)}{dk}$$

The group velocity dispersion is determined as the second derivative of the dispersion relation over the wave vector:

$$\sigma_g = \frac{d^2w(k)}{dk^2}$$

The influence of the waveguide width on its modal properties should also be considered. The larger the waveguide width is, the larger the number of modes allowed for propagation inside the waveguide

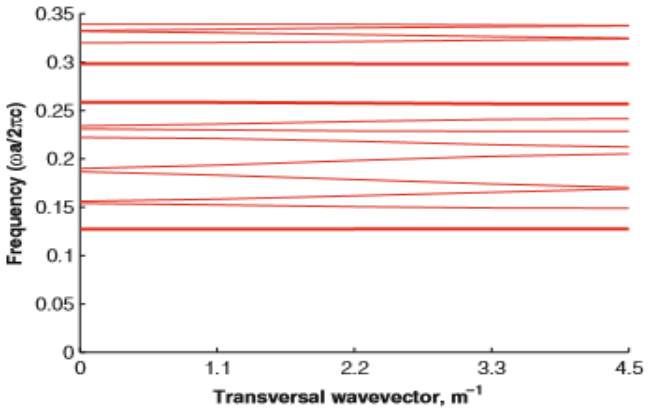

Fig.9 Band structure of PhC waveguide

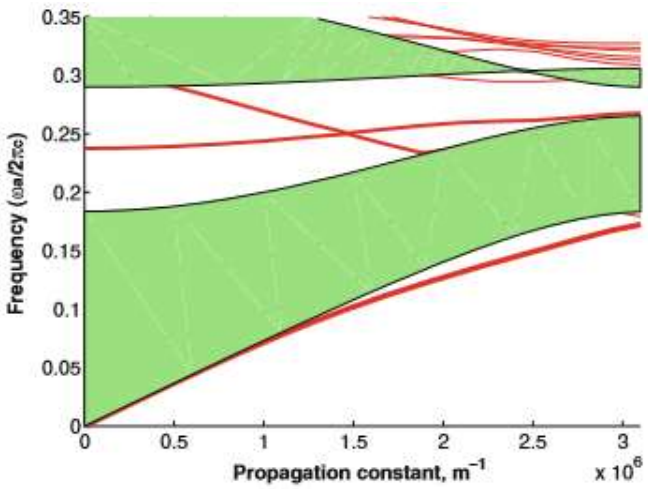

Fig.10 Dispersion diagram of PhC waveguide

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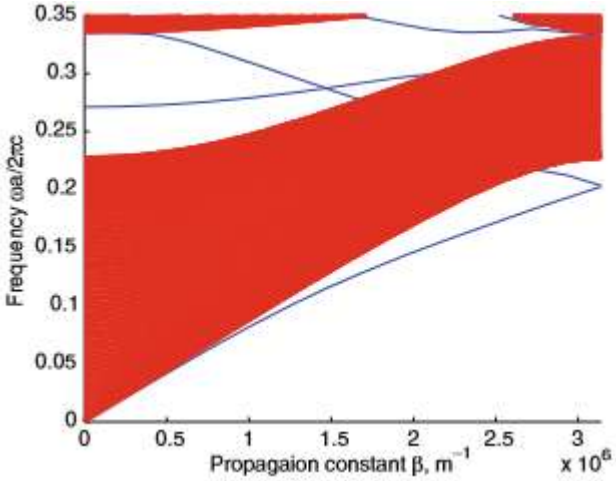

Fig.11 The dispersion diagram of the W1 PhC waveguide

This is very similar to the situation with ordinary planar waveguides. The dispersion diagrams of the waveguides with different width of the guiding area, namely, W1, W2, and W3 have been depicted in Figs 11, 12 and 13 respectively. It is seen that even in the simplest case of the W1 waveguide, there are two defect eigen-states possessing similar frequency, but different wave vectors. In case of larger waveguides, number of modes propagating at similar frequency is growing.

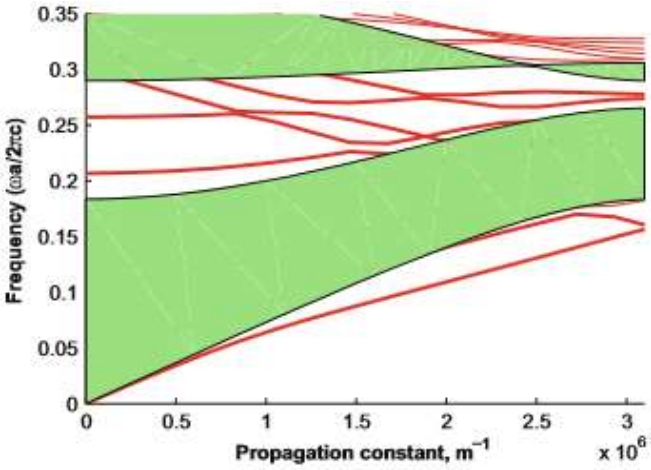

Fig.12 The dispersion diagram of the W2 PhC waveguide

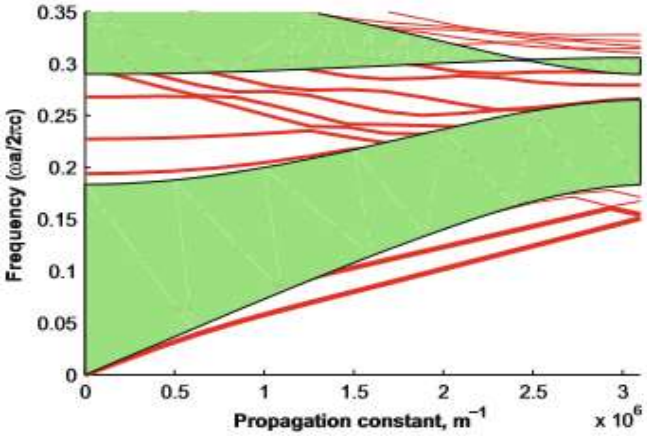

Fig.13 The dispersion diagram of the W3 PhC waveguide

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Filled areas -All the radiation i.e., the frequency and wave vector of which hit these areas will be able to propagate inside the PhC surrounding the waveguide. Therefore, such radiation will not be localized inside the wave guiding area.
The second conclusion which can be made from the dispersion diagram is: The presence of the eigen-states inside the bandgap of the PhC. The eigen-states appear due to the introduction of the defect into the periodic structure. However, the eigen-frequency of the defect levels strongly depends on the propagation constant. This causes group velocity dispersion effects when radiation propagates over the wave guiding area.

Summary & future research

Future work includes Finite difference time domain combined with SPICE and GPU (graphics processing units). Message passing interface (MPI) could be used to make parallel computing for FDTD and SPICE respectively. To overcome the GPU memory limitation of large scale structure simulation with FDTD, divided computational region can be utilized. Now this is a well promising area and will be useful especially for the ever-growing high frequency of the scientific and commercial applications.
Due to such exuberant and wide range of properties exhibited by these crystals they are widely used in nano-manipulation techniques, self-organization techniques, semiconductor process techniques, holographic techniques, quantum computing and communications etc.
The slab waveguide is represented by uniform optical medium the refractive index of which is lower than one of the surrounding medium. The wave guiding effect is possible due to total internal reflection. Further, modal properties of the slab waveguide may be determined by the solution of eigenvalue problem. The PhC waveguide is represented by the set of optically connected defects. Due to peculiar properties of photonic crystals, the light within specific frequency range will be localized inside the waveguide.
The dispersion diagram is most important one for determination of modal and dispersion properties of the PhC waveguide. It can be computed by the means of PWE method. The guiding modes are subdivided by two categories, namely, even and odd modes. The kind of mode depends on what number of maxima, namely, even or odd, transversal field distribution of the mode possesses.

Photonic crystal planar waveguides

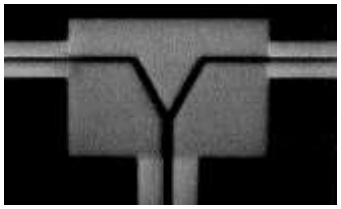

Fig.14 PhC waveguide

Creating a bend radius of more than few millimeters is difficult in conventional fibers because the conditions for TIR fail leading to leaky modes.
Photonic crystal waveguides [8] operate using a totally different principle. A line defect is created in the crystal which supports a mode that is in the band gap. This mode is forbidden from propagating in the crystal because it falls in the band gap. When a bend needs to be created in the waveguide, a line defect of the same shape is introduced. It is impossible for light to escape (since it cannot propagate in the bulk crystal). The only possibility is for the mode to propagate through the line defect (which now takes shape of a sharp bend) leading to lossless propagation.

Conclusion

To increase the frequency range or to increase the band gap so that reflectance should occur for maximum frequency range. Ideally it should act as a mirror for the maximum range of frequencies and not for a particular range of frequency. Our aim is always to increase the forbidden gap so that maximum reflections should occur inside the material itself.
Since the main use of photonic crystals is as low-loss mirrors characterizing high reflectivity and low absorption loss per single reflection thus, for maximum reflectivity we should choose a crystal geometry that has the maximum photonic bandgap.

Acknowledgement

I would like to express my sincere gratitude and respect to my guide who have made this work possible and helped me a lot during my entire research based learning program.

ISSN: 2349- 5197
Impact Factor (PIF): 2.138

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