International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:3, No:6, 2009

Photonic Crystals for Novel Applications in Integrated-Optic Communication Systems and Devices

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***Abstract*—**Photonic Crystal (PhC) based devices are being increasingly used in multifunctional, compact devices in integrated optical communication systems. They provide excellent controllability of light, yet maintaining the small size required for miniaturization. In this paper, the band gap properties of PhCs and their typical applications in optical waveguiding are considered. Novel PhC based applications such as nonlinear switching and tapers are considered and simulation results are shown using the accurate time-domain numerical method based on Finite Difference Time Domain (FDTD) scheme. The suitability of these devices for novel applications is discussed and evaluated.

***Keywords*—** Band gap engineering, Nonlinear switching, Photonic crystals, PhC tapers, waveguides.

I. Introduction

PHOTONIC crystals (PhCs) are relatively recent, flexible and competent tools that control the propagation of light in optical media by allowing the light to propagate over a desired range of frequencies [1]-[3]. These are artificial, periodic dielectric structures prohibiting light propagation in certain frequencies: this range of frequencies is called as the photonic band gap (PBG). Today, almost two decades after their appearance, PhCs are being widely used for design of various optical circuit elements such as waveguides, cavities, tapers, power splitters filters etc [2]-[6]. These devices can be realised by deliberately introducing defects in the otherwise periodic crystal. The defect can be either point- or line-type. Cavities and waveguides can be created by point defects and line defects respectively. The light, that falls in the stopband, can be allowed to guide or confine within the sharp bends, cavities or line defects that causes the propagation of light in a controlled manner. The PhCs, as an extended application, can also be used as switching elements due to the presence of the band gap as these band gaps can be shifted from one position to the other by using nonlinearity of the material involved in making the PhC [7]. These nonlinear PhCs are periodic structures whose optical response depends on the intensity of optical field that propagates through the crystal. They can provide novel and improved optical functionalities that cannot be obtained by using linear PhCs. The PhC taper is another application of great significance in integrated optics. A waveguide taper is used to transform the modal size from an optical fiber to an optical chip or vice versa. Conventional waveguide tapers are not efficient and introduce losses. PhC tapers, on the other hand, provide much better functionality and hence are the potential candidates that can be used for low loss coupling between chip-to-fiber in opto-electronic integrated circuits [8]-[10].

In this paper, we have investigated the properties of nonlinear switches and also tapers based on PhCs, as examples out of numerous such devices that can be realized using PhCs, for illustration. We have found the band gap for linear photonic crystal and also the band structure for the linear photonic crystal with defect. We have also carried out a detailed systematic analysis of the effect of the material parameters on the movement of the band gap which can be helpful to understand the suitability of the photonic crystal as switching device. The analysis of various butt-coupled (non-tapered) waveguides has also been done and the improvement in the transmission characteristics while moving from the butt-coupled to the taper configuration has also been studied. A plane wave expansion method (PWE) along with the Finite Difference Time Domain (FDTD) scheme has been used for the simulations [11], [12].

The rest of the paper is organized as follows: Section II reviews some basic mathematical facts about the photonic band gaps. Section III presents the simulation results. Finally, Section IV concludes the paper.

II. Photonic Band Gap

By using Maxwell's equations, we can describe the propagation of light in photonic crystals using master equation which is [2]:

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

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This work was supported in part by the All India Council for Technical Education (AICTE) through the CAYT Grant and by the British Council through the UKIERI Major Award Grant.

where the symbols have the usual meaning, such as H stands for the magnetic field and ε is the permittivity. The above equation is a consequence of the Bloch-Floquet theorem which signifies that the electromagnetic waves in periodic media can propagate without scattering and their behavior governed by a periodic function modulated by a plane wave [2]. The Bloch modes can be written in the following manner:

$$H(r) = e^{ikr} H_{n,k}(r) \qquad (2)$$

with eigenvalues $\omega_n(k)$, where $H_{n,k}$ is a periodic envelope function that satisfies [2]:

$$(\vec{\nabla} + i\vec{k}) \times \frac{1}{\varepsilon}(\vec{\nabla} + i\vec{k}) \times \vec{H}_{n,\vec{k}} = \left(\frac{\omega_n(\vec{k})}{c} \right)^2 \vec{H}_{n,\vec{k}} \qquad (3)$$

PBG is the range of frequencies in which there are no propagating solutions of Maxwell's equations. The PBG is the main characteristic of the photonic devices and can be observed using the band diagrams obtained using the PWE method [11]. This method requires the periodic structures to be infinite, however it is frequently used to describe the local dispersion and band gap properties of finite periodic devices. The propagation of electromagnetic signals inside these PBG structures and the penetration depth of the field modes can be conveniently and efficiently studied using the FDTD [12] method. FDTD is a time domain numerical method which acts by discretisation of Maxwell's equations. Time domain methods have been established to be the most accurate computational tools for modeling and simulating the classical electromagnetic problems, including periodic media such as PhCs [12]-[15]. This method allows the user to specify the material at all points in computational domain resulting in natural modelling of various materials and defects therein.

III. Simulation Results

For illustration of functionality, a PhC consisting of an array of dielectric rods with a square lattice is considered, where the dielectric rods with an initial radius of r = 0.18a (a=1µm) are embedded in a silicon (n =3.4) background, a and n being the lattice constant of the photonic crystal and the refractive index of dielectric rods. For this uniform structure, the band gap is found to be in range 0.304 (1/λ) to 0.444 (1/λ) for TE mode, as shown in Fig.1.

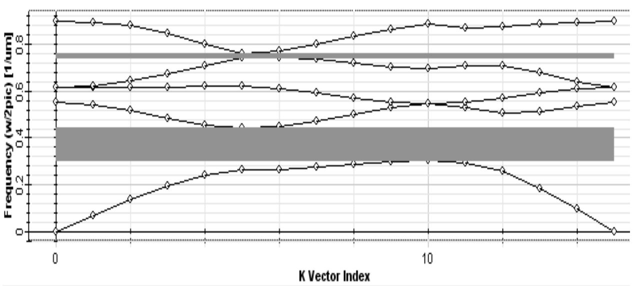


Fig. 1 Photonic band gap for a uniform (without defect) PhC structure. The shaded area represents the band gap.

A defect has been created in the above structure; Fig.2 shows the band structure when the point defect is created in the structure. The inset in Fig.2 shows a schematic representation of the PhC layout with defect: i.e. one rod missing at the centre. As expected, the band diagram with defect shows the modes within the band gap obtained for the usual (i.e. without defect) PhC structure. The propagation can take place in the range 0.387 (1/λ) to 0.389 (1/λ). Fig. 3 shows the location of the defect mode inside the band gap.

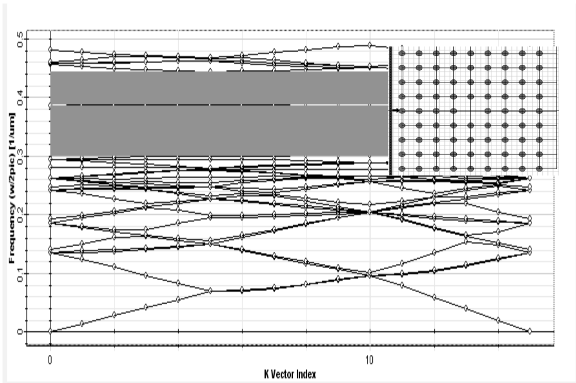


Fig. 2 Photonic band gap PhC with defect. The inset shows the layout for the PhC with a defect introduced in the centre.

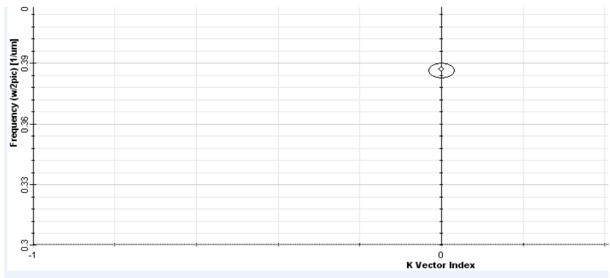


Fig. 3 The location of the defect mode.

A. Band gap Dynamics for Switching

Next, to understand the dynamics of the band gap under varying conditions, a simple PhC lattice is designed consisting of an air-hole PC slab, and also another lattice with material rods, with 2r/a=0.64 in both cases and the material refractive index chosen is 2.73. The two configurations mentioned above (i.e. air-hole type and material-rod type, henceforth called as hole-type or rod-type PhC) are known to provide photonic band gaps for TM and TE polarizations respectively [2]. To investigate the dynamic shifting of the band gap and also the change in the width of the band gap, we gradually and continuously change the value of radius, lattice constant and refractive index one at a time, keeping other parameters constant. Fig.4 shows the comparison of extent of band gap shifting and widening in TM and TE cases respectively for varying radius of air holes/rods.

Fig. 5 and Fig. 6 show the corresponding comparison for the shifting of the band gap central frequency and the width of the band gap as a function of the material parameters such as refractive index and geometrical parameters such as pitch for TE and TM modes.

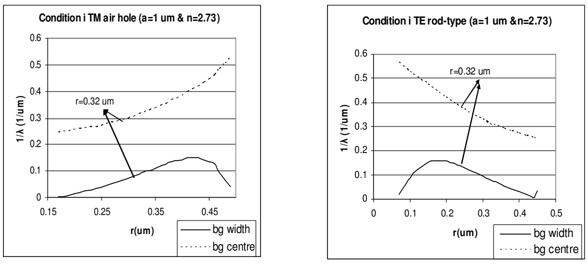


Fig. 4 Variation of band gap centre and width with radius of air holes/rod for TM and TE cases.

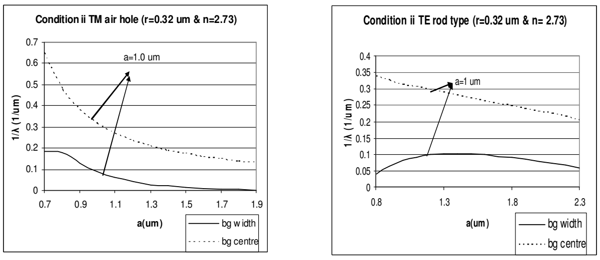


Fig. 5 Variation of band gap centre and width with the pitch of the lattice structure

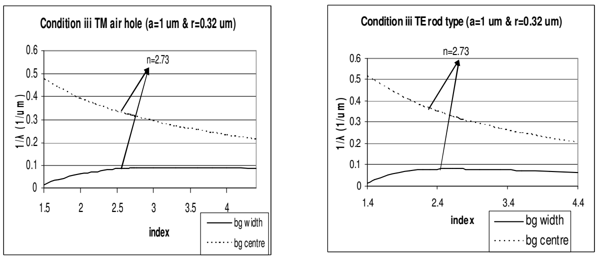


Fig. 6 Variation of band gap centre and width with refractive index of material for TM (index of background material varies) and TE (index of rods varies) cases.

It can be observed from the above results that for TM polarization (hole-type structure), an increasing radius of holes results in increase of the width upto a certain point where it reaches to maximum value, and thereafter it decreases. The movement of the centre of the gap can also be observed from the figures. An increase in the lattice constant results in downward movement of the position of band gap. However, with change in refractive index, no point of inflexion is observed in the plots within the given range of frequencies. For the TE case, a change in radius results in a movement of band gap that is opposite to the corresponding TM case. This results because the effective refractive index of the PhC lattice changes in opposite direction in hole-type and rod-type structrures with change in the radius. When lattice constant is varied, an increasing lattice constant results in the band gap width increase that reaches to a maximum value and then decreases. Similarly, a change in refractive index results in dynamic shifting of band gap.

We have used the above analysis in realizing a switching element based on the movement of the band gap based on nonlnearity of the material involved. Nonlinear materials have been established to be potential candidates for ultrafast optical switching applications [7], [15]. For the analysis of photonic crystal device as switching element we have considered for illustration a nonlinear photonic crystal with rod type structure having the refractive index as 5 and a third order susceptibility. For the convenience of simulations, the intensity of the input signal is kept constant, and susceptibility is varied. The similar effect is expected when input intensity is changing and susceptibility is fixed, as for any practical material. The radius and pitch is assumed to be 0.18 µm and 1 µm respectively. An input signal consisting of the continuous wave (CW) at wavelength 2.78 µm is being applied. The frequency of the input signal is so chosen that it lies at the band edge, and so that when the signal passes through the nonlinear lattice, it can affect a change in band structure resulting in self switching. Fig. 7 shows the variation in output (transmission coefficient) as the susceptibility is being varied.

Fig. 7 Transmission coefficient of a nonlinear PhC lattice as a function of the nonlinearity.

It can be clearly observed from the graph shown in Fig.7 that the transmission is increasing with increasing nonlinearity. This is due to the signal which, while passing through the lattice, evokes nonlinearity, resulting in movement of band gap which results in jumping of the signal frequency from inside of the band gap to the outside at a particular point. This principle can be used for fast optical switching, and results can be further explored.

B. *PhC Tapers*

As another potential application for PhCs, we have investigated in detail the properties of PhC taper structures used to couple modes of different sizes, such as in fiber-to-chip coupling or vice versa. A square lattice of high index rods (n=3.45) in air (n=1) is considered for simulation. The lattice constant a for the structure is considered to be 0.55 µm. The radius of the rods is taken as 0.2a i.e. 0.11 µm. An input signal consisting of a Gaussian modulated continuous wave with a center wavelength of 1.55 µm falling within the band gap is used, as shown in Fig. 8. The transverse width of the signal is taken to be 10 µm.

In order to see the effect of various types of taper designs, to start with, the configuration shown in Fig. 9(a) is designed that shows the creation of a waveguide by removing a row of rods (i.e. a line defect). No coupling device is used between the input signal and the waveguide, i.e. free space. The arrow on the left indicates the location and direction of the input source.

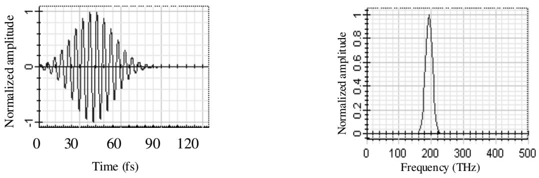
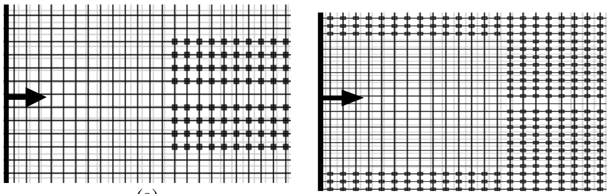


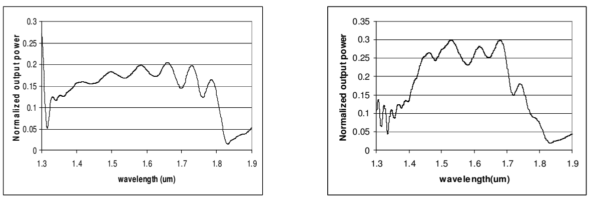
Fig. 8 The Gaussian-modulated CW signal and its spectrum, that is used as the input to the PhC structure.



(a) (b)

Fig. 9 (a) Coupling directly into PhC waveguide (no taper), (b) coupling through coupled taper

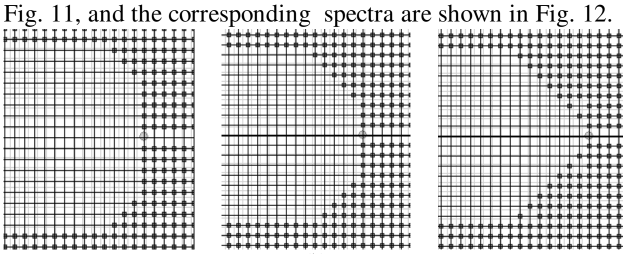
Fig. 10(a) shows the transmittance spectra of the signal in this case, where it represents propagation in the band gap region. The light is guided through the line-defect. A butt-coupled photonic crystal taper can also be designed in the following manner as shown in Fig. 9(b). Here, the PhC WG is connected after a length, upto which the input width (10 μm) is maintained. Fig. 10(b) shows its transmission characteristics.



(a) (b)

Fig. 10 Transmission spectra (a) Coupling directly into PhC waveguide (no taper), (b) coupling through a butt-coupled taper

In order to provide a better low-loss coupling, we have designed the following three designs of tapers, as shown in Fig. 11, and the corresponding spectra are shown in Fig. 12.



(a) (b) (c)

Fig. 11 Various PhC taper designs (all designs are linear tapers)

In the above-mentioned designs, the taper configuration shows improved transmission results with wavelength dependence. In design-1 taper (Fig. 11(a)), the normalized output power increases for a certain range of frequencies. In the band gap region, as shown in figure, the value of output power is high from 1.4 to 1.7 μm. In design-2 taper, the power is again higher for a narrow range of frequencies i.e. from 1.4 to 1.6 μm. In design-3 taper, the normalized output power is more as compared to butt-coupled taper for a broad range of frequencies in the band-gap. The output power increases from 1.35 to 1.49 μm and then again from 1.6 to 1.8 μm, we obtain higher transmission. Therefore, the output power is high for a wider range of frequencies, which is useful to be operated in the optical domain. Thus, as we move towards the more tapered configuration (from the butt-coupled configuration), an improvement in the output power is obtained.

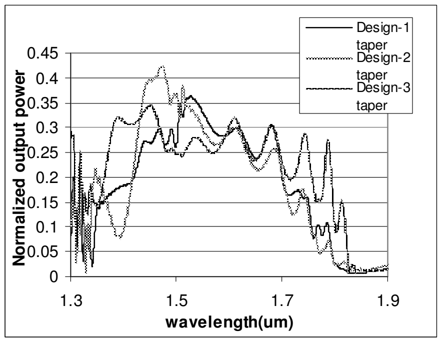


Fig. 12 The transmission spectra for various taper designs.

IV. Conclusion

Novel configurations of nonlinear switching element as well as tapers, both based on PhCs have been considered and studied. The bandgap dynamics have been studied in detail with reference to all-optical switching action. Various taper designd have been simulated and conclusions drawn regarding their relative performance. More detailed analysis can be carried out as a future work.

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