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PHOTONIC CRYSTAL IN ELECTRICAL ENGINEERING

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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. The band gap properties of PhCs and their typical applications in optical waveguide have been considered. Novel PhC based application such as nonlinear switching and tapers are considered and simulation results are shown using the accurte 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, photonic crystal, optical waveguide.

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. 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. These devices can be realized 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. 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.

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.

Photonic crystal structure and bandgap calculation Method:

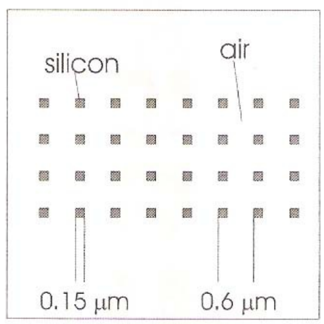

Fig.-1 Two-dimensional photonic crystal composed of square silicon rods in air.

We have considered a crystal as shown in Fig. 1, consisting of a square lattice of silicon rods in air, having a lattice constant of 600 nm. The rods have a 150 x 150 nm square cross- section and a refractive index of 3.4 (assumed constant in the wavelength region of interest around λ =1550 nm). For a very similar structure a bandgap is known to exist around λ =1.5 μm for TE polarization (i.e. E-field parallel to the rods, perpendicular to the calculation window).

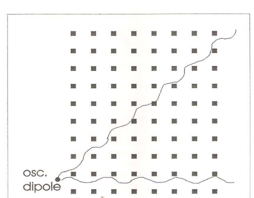

Fig.-2 Configuration for determining the bandgap: a dipole radiator is positioned at the left-hand side of the crystal, while the transmission is determined along a vertical line at the right-hand side.

A straightforward method for determining the bandgap is to calculate the transmission of a broad-band electromagnetic signal through the crystal for all directions in the reduced Brillouin zone. For that purpose, a 2-dimensional finite difference time domain (FDTD) scheme is used. As shown in Fig. 2, a finite crystal of 8 rods width is defined. To the left of this, a dipole is oscillating at a central frequency corresponding to a wavelength of 1.5 μm; it is modulated with a pulse that is short enough (50fs) that the resulting electromagnetic wave contains all wavelengths in the bandgap. This dipole will radiate in all directions. Taking the time-domain Fourier transform of the transmitted field at the right hand side of the crystal for a range of propagation angles between 0 and 45^0 covering the reduced Brillouin zone of the square lattice, yelds the transmitted amplitude for a sufficiently wide wavelength range around the bandgap.

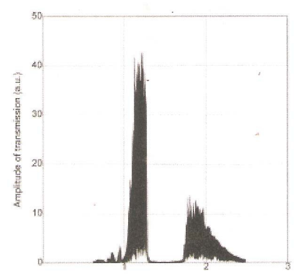

Fig.-3 Superposition of the transmission amplitudes across all relevant angles.

Fig. 3 shows a superposition of the graphs of the transmitted amplitude versus the wavelength, fro 100 uniformly distributed propagation angles between 0 and 45^0. In the wavelength range from $\approx$ 1.3-1.7 μm, the transmission is nearly zero for all directions, revealing the photonic bandgap.

Although other methods which use a single unit cell for the band-structure calculation, are more accurate, this method is fast and gives a good approximation of the total bandgap of the crystal, similar to the bandgap for the similar structure studied in.

SIMULATION RESULTS AND DISCUSSION:

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 =1 μm) 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.-4.

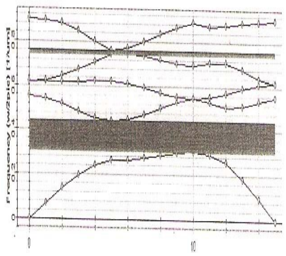

Fig.-4 Photonic band gap for a uniform (without defect) PhC structure. The shaded area represents the band gap.

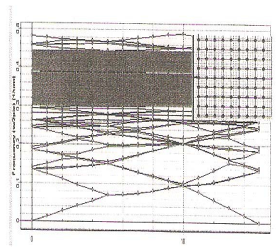

Fig.-5 Photonic band gap PhC with defect. The inset shows the layout for the PhC with a defect introduced in the centre.

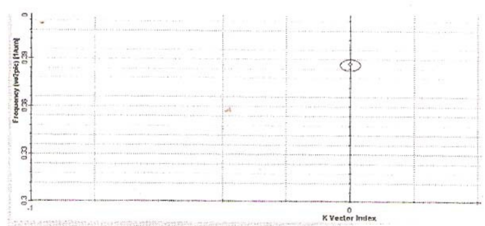

Fig.-6 The location of the defect mode.

A defect has been created in the above structure: Fig.5 shows the band structure when the point defect is created in the structure. The inset in Fig.5 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. 6 shows the location of the defect mode inside the band gap.

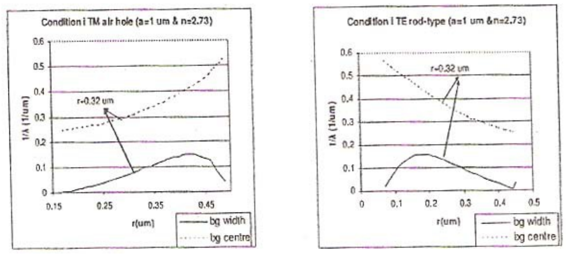

Fig.-7 Variation of band gap centre and width with radius of air holes/rod for TM and TE cases.

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 is chosen. 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. 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.7 shows the comparison of extent of band gap shifting and widening in TM and TE case respectively for varying radius of air holes/rods.

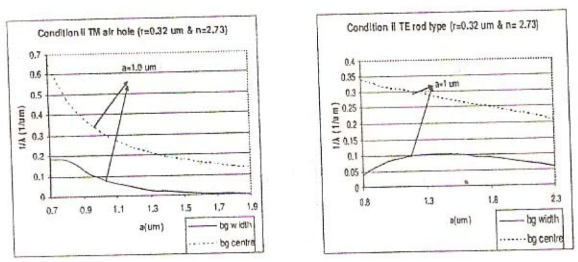

Fig.-8 Variation of band gap centre and width with the pitch of the lattice structure

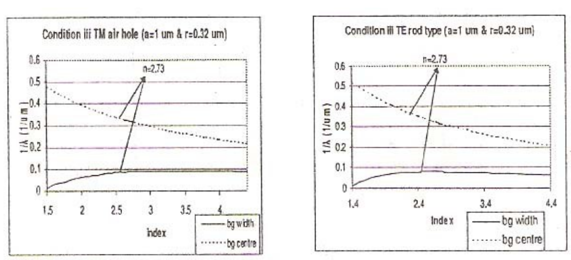

Fig.-9 Variation of band gap centre and width with refractive index of material for TM (index of background material varies) and TE (index of rods varies) cases.

Fig.8 and Fig.9 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.

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 decrease. 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 wave. This results because the effective refractive index of the PhC lattice changes in opposite direction in hole-type and rod-type structures 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.

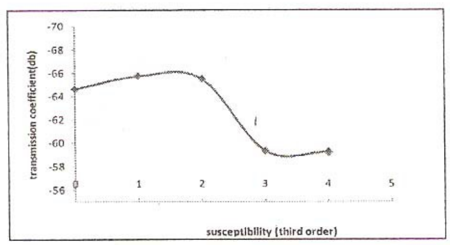

Fig.-10 Transmission coefficient of a nonlinear PhC lattice as a function of the nonlinearity

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. 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 and a third order susceptibility. For the convenience 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.10 shows the variation in output (transmission coefficient) as the susceptibility is being varied.

It can be clearly observed from the graph shown in Fig.10 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.

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