Optical and Quantum Electronics (2005) 37:889–895
DOI 10.1007/s11082-005-1122-7

Design of ultra compact polarization splitter based on the complete photonic band gap

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Received 24 May 2005; accepted 20 July 2005

Abstract. A novel design of polarization splitter based on the complete photonic band gap has been proposed in this paper. The proposed Photonic Band Gap (PBG) polarization splitter is formed by two photonic crystal waveguides composed of dielectric rods in air in honeycomb structure for which complete photonic band gap is obtained using the plane wave expansion (PWE) method. The splitting properties (i.e. coupling length, extinction ratio and insertion loss) of PBG polarization splitter have numerically been investigated using the finite difference time domain (FDTD) method. It has been shown that polarization splitter of length as small as $32\,\mu m$ can be designed at $\lambda = 1.55\,\mu m$. The proposed polarization splitter offers a large bandwidth of 120 nm.

Key words: complete photonic band gap, finite difference time domain method, photonic crystal, plane wave expansion method, polarization splitter

1. Introduction

Photonic crystals (PhCs) are artificial multidimensional periodic structures with a period of the order of optical wavelength in which the refractive index modulation gives rise to stop bands for optical waves within a certain frequency region known as photonic band gaps (PBGs) (Villeneuve and Piche 1992 a, b; Qiu and He 1999). Only certain select structures exhibit complete photonic band gap i.e. a frequency region where the photonic band gaps for both polarizations (i.e. transverse electric and transverse magnetic modes) exist and overlap. Many applications of photonic crystals are based on the photonic band gaps.

Since the PhCs allow strong control over the propagation of light, one of the most fundamental applications of the PBGs are photonic crystal waveguides. PhC waveguides can be formed by the introduction of line defects into otherwise perfect PhC. A PhC directional waveguide coupler can be designed by placing two 2D PhC waveguides in close proximity of each other, which has further been used to design PBG polarization splitter in this paper (Cuesta-Soto *et al.* 2004; Nagpal and Sinha 2004).

A polarization splitter is one of the key optical components in integrated photonics (Albrecht *et al.* 1990; Lin *et al.* 1999). More recently polarization splitters based on dual core photonic crystal fibers have been reported, in which polarization dependent coupling is significantly enhanced to produce a large difference of coupling lengths for the two polarizations (Zhang and Yang 2004a, b; Saitoh *et al.* 2004). In case of photonic crystal fiber based couplers, the light is guided because of the index guided effect. In this paper we propose the modeling and design of photonic band gap based polarization splitter in which the light is guided because of the photonic band gap effect in 2D photonic crystal. We have exploited the coupling phenomenon in PBG structures in the complete photonic band gap region to propose the design parameters of the photonic band gap based polarization splitter. Further, its coupling and polarization splitting characteristics around 1.55 μm has been numerically investigated using the finite difference time domain (FDTD) method. It has been shown that the PBG polarization splitter of length as small as 32 μm can be designed at $\lambda = 1.55\,\mu$m for the structure with following design parameters.

2. Design parameters

To design a PBG polarization splitter we select a PhC such that it exhibits a complete photonic band gap, which is a necessary condition for the design of the proposed polarization splitter. PhC structure composed of two dimensional (2D) honeycomb pattern of dielectric rods embedded in air with lattice constant $a = 0.86\,\mu$m has been selected for the design of the PBG polarization splitter. The radius and the refractive index of rods are taken as $r = 0.24$a and $n = 3.42$ (Si) respectively. With these parameters the structure provides a large complete photonic band gap around 1.55 μm, which is the useful wavelength region for design and development of optical devices for optical communication systems. The PBG waveguide coupler has been designed by removing two parallel rows of rods that act as PBG waveguides separated by two rows of dielectric rods as depicted in Fig. 1.

Figure 2. shows the photonic band diagrams for the mentioned PBG structure for transverse magnetic (TM) and transverse electric (TE) modes as calculated using the plane wave expansion (PWE) method.

As shown in Fig. 2, this photonic crystal structure exhibits a complete photonic band gap which extends from $\lambda = 1.49\,\mu$m to $\lambda = 1.61\,\mu$m, where λ is the wavelength in free space, providing a large bandwidth of 120 nm.

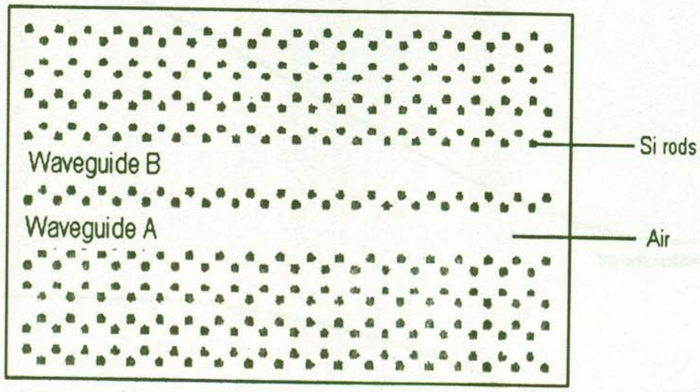

Fig. 1. Schematic diagram of the proposed PBG polarization splitter.

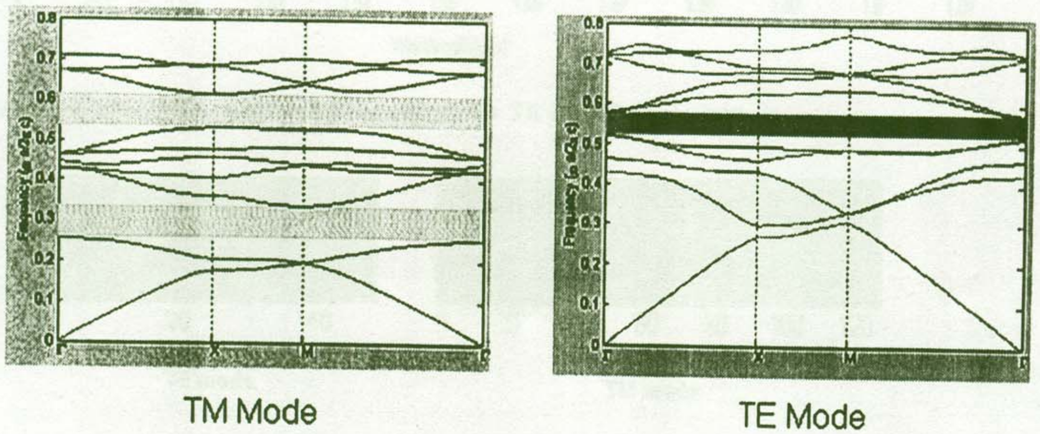

Fig. 2. Band diagrams for the PBG structure composed of Si rods with r = 0.24a in honeycomb lattice for TM and TE polarizations.

3. Numerical analysis

The FDTD method has been employed for the modeling of the PBG polarization splitter. Since the PBG structure used exhibits a complete photonic band gap, light of both TE as well as TM polarization can be guided in the defects created in the proposed structure in the calculated complete photonic band gap region. Designing a polarization selective coupler, in which one polarization can couple between the two channels, while another one cannot, can make a polarization splitter. The coupling between the two waveguides takes place because the evanescent tail of the input wave crosses the thin barrier between the two waveguides. Theoretically, the splitter length can be taken equal to the coupling length of the polarization state coupled. Thus, the coupling lengths at various wavelengths for both polarizations have been calculated using the FDTD method and are shown in Fig. 3.

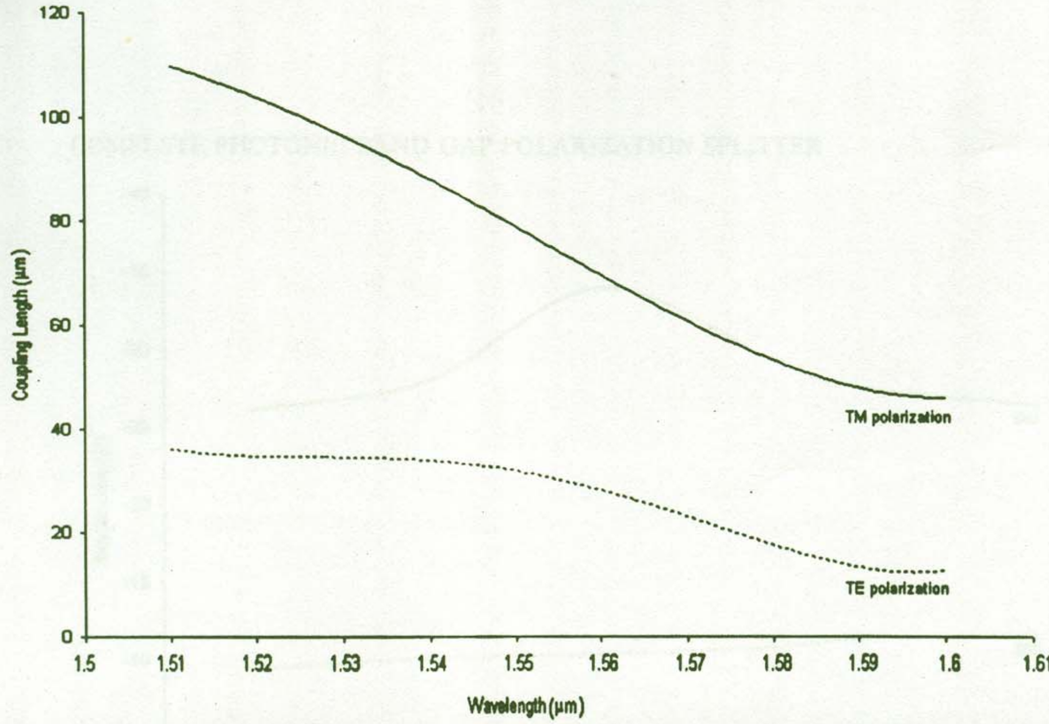

Fig. 3. Variation of coupling length with wavelength for TE and TM polarizations.

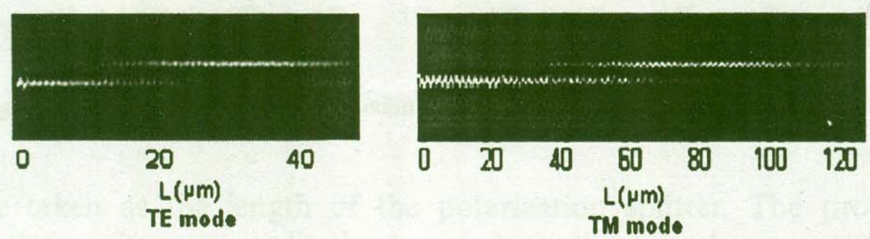

Fig. 4. Snapshots of the coupling phenomena in the proposed PBG polarization splitter for TE and TM modes at $\lambda = 1.55\,\mu$m.

From the graph it is evident that the coupling length, the length at which the light of a specific polarization couples from one waveguide to another, for TE polarization is smaller than that for the TM polarization. Moreover, the coupling length for both the polarizations decreases with the increase in wavelength. This is because as the wavelength increases it becomes easier for the evanescent tail of the input waveguide to cross the barrier between the two waveguides. Figure 4 shows the snapshots of the coupling phenomena for TE and TM polarizations for the wavelength $\lambda = 1.55\,\mu$m which exhibits a considerable difference in the coupling lengths of the two polarization states. Thus, the light of the TE polarization couples faster compared to that of TM polarization. Hence, this phenomenon can be used to design PBG polarization splitter and the coupling length for TE polarization can

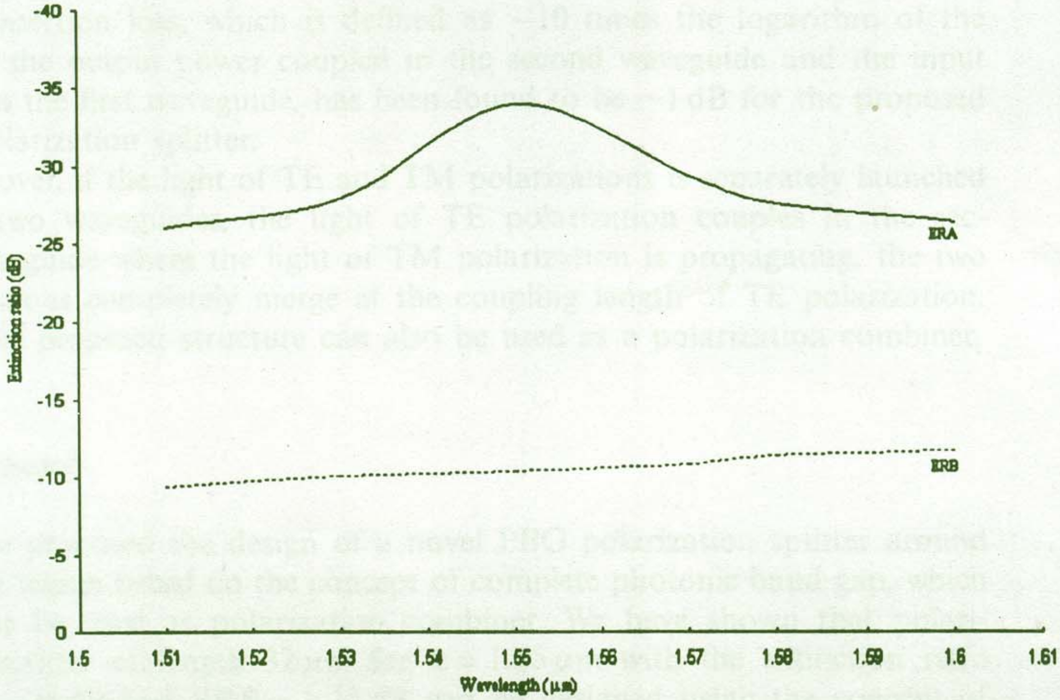

Fig. 5. Spectral response of the extinction ratios at device length of 32 μm.

be taken as the length of the polarization splitter. The proposed polarization splitter can split the two polarizations at the propagation distance of 32 μm for $\lambda = 1.55\,\mu$m, which is the coupling length for TE mode at $\lambda = 1.55\,\mu$m as calculated using the FDTD method.

3.1. EXTINCTION RATIOS AND INSERTION LOSS

Further, the spectral response of the extinction ratios, ERA and ERB at propagation distance of 32 μm, where the separation of the two polarization states is achieved at $\lambda = 1.55\,\mu$m, has been obtained and is shown in Fig. 5. The extinction ratios ERA and ERB are defined as

$$\mathrm{ERA} = 10\log_{10}\frac{\text{fractional output power of TE polarization in waveguide A}}{\text{fractional output power of TM polarization in waveguide A}} \tag{1}$$

and

$$\mathrm{ERB} = 10\log_{10}\frac{\text{fractional output power of TM polarization in waveguide B}}{\text{fractional output power of TE polarization in waveguide B}} \tag{2}$$

FDTD simulation indicates that the extinction ratios are $\mathrm{ERA} = -34$ dB and $\mathrm{ERB} = -11$ dB at $\lambda = 1.55\,\mu$m and the proposed PBG coupler operates as a polarization splitter in 1.55 μm wavelength range.

The insertion loss, which is defined as −10 times the logarithm of the ratio of the output power coupled in the second waveguide and the input power in the first waveguide, has been found to be ~1 dB for the proposed PBG polarization splitter.

Moreover, if the light of TE and TM polarizations is separately launched in the two waveguides, the light of TE polarization couples in the second waveguide where the light of TM polarization is propagating, the two polarizations completely merge at the coupling length of TE polarization. Thus, the proposed structure can also be used as a polarization combiner.

4. Conclusion

We have proposed the design of a novel PBG polarization splitter around 1.55 μm region based on the concept of complete photonic band gap, which can also be used as polarization combiner. We have shown that polarization splitter of length 32 μm for $\lambda = 1.55\,\mu$m with the extinction ratio ERA = −34 dB and ERB = −11 dB can be designed using the concept of complete photonic band gap. The proposed PBG polarization splitter has a large bandwidth of 120 nm. Thus, the proposed PBG polarization splitter can be implemented to design ultra compact all optical integrated circuits.

Acknowledgements

The authors gratefully acknowledge the (i) financial support provided by All India Council of Technical Education, Government of India for the R&D project "Propagation Characteristics of Photonic Crystal Fibers and Waveguides for Telecom and Sensing Applications" and (ii) initiatives towards establishment of "TIFAC-Center of Relevance and Excellence in Fiber Optics and Optical Communications at Delhi College of Engineering, Delhi" through "Mission REACH" program of Technology Vision-2020, Government of India.

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