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A COMPACT 90° BENT EQUAL OUTPUT PORTS OF PHOTONIC CRYSTAL BEAM SPLITTER WITH COMPLETE BAND GAP BASED ON DEFECT RESONANCE INTERFACE

Wayne Yang* **and Yuan-Fong Chau**

Department of Electronic Engineering, Chien Hsin University of Science and Technology, No. 229, Jianxing Road, Zhongli City, Taoyuan County 32097, Taiwan, R.O.C.

Abstract—A compact 90° bent equal output ports of photonic crystal (PC) beam splitter (BS) with complete band gap (CPBG) based on the effect of defect resonance interface (DRI) in PC waveguides is designed and analyzed. The finite-difference time-domain method is adopted to simulate the relevant structures of defect mode in a two dimensional square lattice circular dielectric rods of anisotropic PC. The device size reduction and flexibility in polarization dependence compared with the conventional PCBS can be attributed to the same resonant frequency for both transverse-magnetic and transverse-electric polarization, because the PC structures designed here have a CPBG. The merit of our proposed PCBSs with identical lights at the output ports possess the short coupling length with direct coupling (the coupling length is the same as that of the width of DRI, $3a$) and the short distance without cross-talk among the output ports (only three lattice constant, $3a$), thus helping the design flexibility of the PCBSs in IOCs.

1. INTRODUCTION

Photonics Crystals (PCs) have the capability to control electromagnetic waves on the micrometer scale due to the existence of photonic bandgap (PBGs) [1, 2]. As is required for the development of device now envisage for use in integrated optical circuits (IOCs). Various types of optoelectronic devices have been presented [3–5]. The devices based on PC structures usually have the merit of substantial

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* Corresponding author: Wayne Yang (wayen@uch.edu.tw).

size reduction compared with their conventional counterparts [4]. This unique capability may lead to miniaturization and large-scale integration of optical and optoelectronic devices. Photonic crystal beam splitters (PCBSs) [5] are used to separate an incident light beam into two beams with orthogonal linear polarizations (often denoted by transverse-magnetic (TM-mode) and transverse-electric (TE-mode) polarization) that travel in different directions. Conventional beam splitters (BSs) employ bulk crystal optics [6] or multilayer interference coatings that are embedded in a prism [7]. More recently, BSs that use diffraction gratings [8] and PCs have also been introduced [9, 10].

The optical BS is an important component in IOCs. PCBSs based on T-, Y-junction and cross-type waveguides have been analyzed [11, 12]. In this paper, we present a unique design of PCBS based on the effect of defect resonance interface (DRI) in PC waveguides. DRI is one of important components for PC and IOCs due to its simple structure, low polarization dependence, low loss, and large optical bandwidth [3]. Two output ports of PCBSs are required to realize 3-dB couplers, Mach–Zehnder interferometers (MZIs), ring lasers, and optical switches [4, 13, 14]. T- or Y-type PCBSs or directional couplers can be used to divide the input light into two identically powered output ports, as in the $1 \times N$ BSs [15]. These N identical lights should interfere with each another in the other BS. However, the coupling length of the PCBSs and the distance between the two waveguides are usually an integer multiple of the lattice constant, thus limiting the design flexibility of the PCBSs in IOCs.

BS with more than two output ports are needed to be used in photonic networks and $1 \times N$ PCBS can become building blocks for compact BSs with more output ports. In this paper, the emphasis will be on the design and analysis of 1×2, 1×3 and 1×5 90° bent waveguide of equal output ports of PCBSs with the complete PBG (CPBG) based on the effect of DRI in PC structures. For the sake of flexibility, the PCBSs presented here for the same resonant frequency for two polarizations, i.e., the TM-mode and TE-mode mode, because of the PC structures designed here have a CPBG. This idea can be easily extended to more complex PC structures such as $N \times M$ DRI couplers, where N and M are the number of input and output waveguides, respectively. The merit of our proposed PCBSs with identical lights at the output ports possess the short coupling length (direct coupling) and the short distance without cross-talk among the output ports, thus helping the design flexibility of the PCBSs in IOCs.

2. DRI STRUCTURE WITH COMPLETE PBG IN A 2D ANISOTROPIC PC

It is well known that the CPBG exists for a two-dimensional (2D) PC only when band gaps in both polarization (E-polarization (TM mode) and H-polarization (TE mode)) are present and they overlap each other. Nature offers many anisotropic crystals which are lossless and transparent in visible or infrared regime. The anisotropy in atom dielectricity can break the degeneracy of photonic bands such that partial PBGs can be created in fcc, bcc, and simple cubic lattices [16]. In this paper, we use such anisotropy in dielectricity to increase CPBGs in 2D PC structures, which have two different principal refractive indices known as ordinary refractive index n_o and extraordinary refractive index n_e. For simplicity, we choose the extraordinary axis of uniaxial crystal parallel to the extension direction of cylinders. Then Maxwell's equations for such an anisotropic 2D PBG structure can be decomposed into two equations satisfied by the TM- and TE- modes, respectively. They are the same as in the case of isotropic PBG structures, except that the dielectric constants for the two modes are now different. As the electric field vector in the TM-mode is parallel to the extraordinary axis, while perpendicular to the extraordinary axis in the TE-mode, the refractive indices are n_e and n_o for the TM- and TE-modes, respectively.

As a practical use, we consider 2D PBG structures made from Te (Tellurium), which is a kind of positive uniaxial crystal with principal indices of $n_e = 6.2$ and $n_0 = 4.8$ in the wavelength regime between 2.5 μm and 35 μm [16]. The PBG structures for square lattices of Te cylinders in air calculated by use of Finite difference time domain (FDTD) [17] are displayed in Figure 1. The filling fraction of cylinder is $f = 0.4$ and the extraordinary axis of Te is chosen parallel to the extension direction of cylinders. It is evident that a CPBG is present and is consistent with the result shown in [16], calculated by plane wave expansion (PWE) [18] for the square lattice has a width of $\Delta\omega = 0.035$ $(2\pi c/a)$, and a band gap to midgap ratio of $\Delta\omega/\omega_g = 14.8\%$ [16].

PCs also have the ability to trap a particular wavelength of light around a defect. This behavior is realized by changing the radius of r_1 and r_2 at the center inside the square PC of 7×9 lattice of dielectric rods as shown in Figure 2(a) (enclosed by a red dashed line), which shows the structure of a resonant-coupling-type BS based on the PC waveguide with the effect of DRI proposed here. The optimum DRI radius r_1 and r_2 are determined by scanning the radius of point defect from zero to a maximum value illumined by an incident light with a magnitude of 1 V/m and by measuring the field intensity

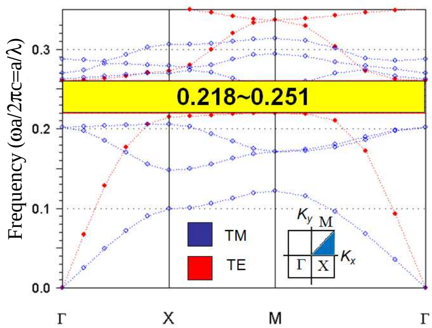

Figure 1. 2D PBG structure made from Te (Tellurium), which is a kind of positive uniaxial crystal with principal indices of $n_e = 6.2$ and $n_0 = 4.8$ in the wavelength regime between 2.5 and 35 μm. The photonic band structures for square lattices of Te cylinders are embedded in air. The filling fraction of cylinder is $f = 0.4$ and the extraordinary axis of Te is chosen parallel to the extension direction of cylinders.

inside the defect region. It is expected that strong coupling between the DRIs and the waveguides occurs around the resonant frequency of the DRI [18, 19] In these structural parameters, CPBG exists between $\omega = 0.218a/\lambda$ and $0.251a/\lambda$ (see Figure 1), and single-mode operation for both TE and TM modes is realized at $\omega = 0.2466a/\lambda$ (see Figures 2(b) and (c), respectively), which is one of the resonant frequency in the range of CPBG. Figures 2(d) shows the steady-state field pattern of TM modes at the resonant frequency $\omega = 0.2466a/\lambda$ in a 90° bent PC waveguide with a line defect. From Figure 2(d), the field can be confined well in the PC waveguide. However, it is hard to design a $1 \times N$ 90° bent equal out ports of PCBS in a compact area in PC due to the loss and physical mismatch at the 90° bent corners. In addition, these lights should interfere with each another in the other waveguide. Moreover, the coupling length of the PCBSs and the distance between the two waveguides are usually an integer multiple of the lattice constant, thus limiting the design flexibility of the PCBSs in IOCs. In order to overcome this drawback, a direct coupling element by using the DRI is proposed, which separates the input port and output port and forms a resonant center between the input waveguide and output waveguide. The DRI element can couple directly the light from the input waveguide to the output waveguide in a 90° bent corner. Figure 2(e) shows the steady-state field pattern of TM localized modes at the resonant frequency $\omega = 0.2466a/\lambda$ in a 90°

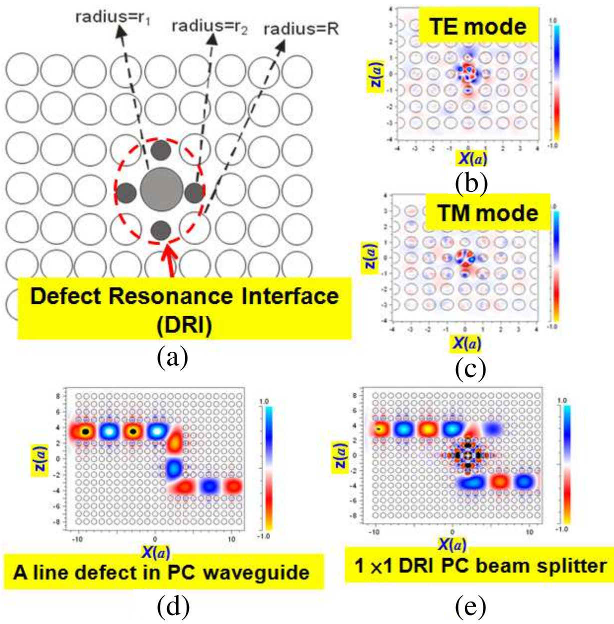

Figure 2. (a) Schematic diagram of a square PC of 7×9 lattice of dielectric rods with a defect (enclosed by a red dashed line) formed by the radius of $R = (f/\pi)^{1/2}a$, $r_1 = 0.55a$ and $r_2 = 0.26a$ at the center, where a denoting the lattice constant of the PC and f =0.4 denoting the filling factor of the PC, (b) TE-mode at the resonant frequency $\omega = 0.2466a/\lambda$, (c) TM-mode at the resonant frequency $\omega = 0.2466a/\lambda$, (d) conventional 1×1 90° bent PCBS, (e) 1×1 90° bent DRI PCBS.

bent PC waveguide with a DRI. Note that the coupling length between input port and output port is the same as that of the width of DRI. Instead of using one DRI as the coupling element, which supporting a degenerate monopole state, it expects that a 1×2 or $1 \times N$ 90° bent equal output ports of PCBS can be designed and will be discussed in next section.

3. 1×2, 1×3 AND 1×5 90° BENT EQUAL OUTPUT PORTS OF PCBS WITH CPBG BASED ON THE EFFECT OF DRI

Ones the PC structure with CPBG has been selected, the basic components for the DRI 1×2 and 1×3 90° bent equal output ports

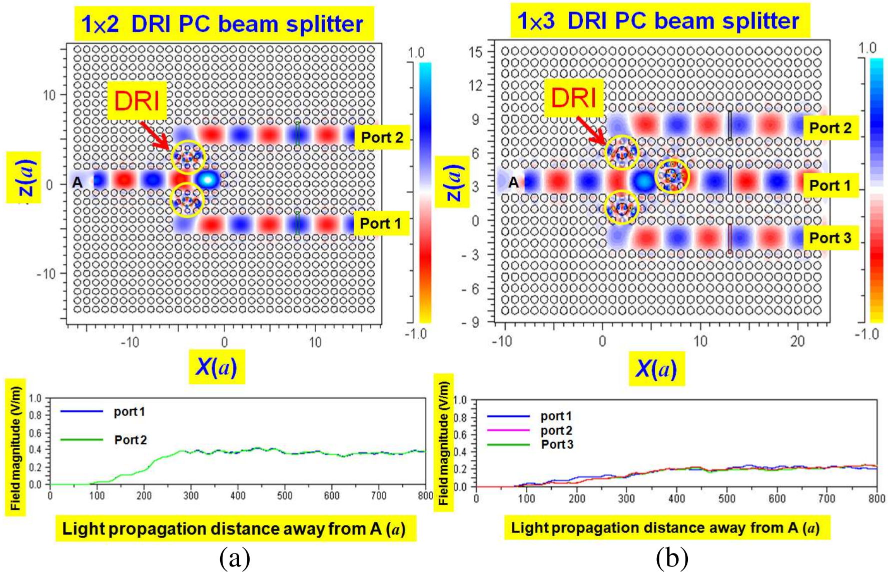

Figure 3. Electric field patterns (upper part) and field magnitude vs. light propagation distance away from point A (bottom part) of (a) 1×2 90° bent equal output ports of DRI PCBS, (b) 1×3 90° bent equal output ports of DRI PCBS. The incident light is lunched at point A at the resonant frequency $\omega = 0.2466a/\lambda$.

of PCBS that we investigate is obtained by removing two rows from a square lattice of Te cylinders in air. The FDTD method is performed to calculate the photon propagation in PCBSs. The parameters are the same as used in Figure 2.

The beam in PC waveguide is split by two and three DRIs as shown in Figures 3(a) and 3(b), respectively. The bottom part of Figures 3(a) and 3(b) are also shown the field magnitude versus the light propagation distance away from point A (the unit is lattice constant, a). The steady state of electric field can be found as the light propagation distance away from point A over 275 µm for 1×2 case and 375 µm for 1×3 case, respectively. It can be clearly seen from Figure 3 that the incident beam can be divided into two/three equal magnitude of field measured at each output port. As revealed in Figure 3(b) that the width among the three waveguides is the same as that of the width of DRI ($3a$). Thus a compact 90° bent equal output PCBS with CPBG based on the effect of DRI can be achieved due to the fact that the direct coupling among waveguides and short distance without cross-talk among the output ports. It has been reported that the PC-coupler-based polarization splitter in [18] can be realized with a length of $21a$. On the other hand, the PCBS proposed here has a length of $3a$ (the width of DRI), which is one-seventh as long as the device length in [18]. Moreover, considering the actual device application, in the structure in [18], bending waveguides are required to separate the upper and lower waveguides, but, in the present structure, not required. The merit of our proposed PCBSs with identical lights at the output ports possess the short coupling length ($3a$, direct coupling) and the short distance without cross-talk among the output ports (only three lattice constants, $3a$), thus helping the design flexibility of the PCBSs in IOCs.

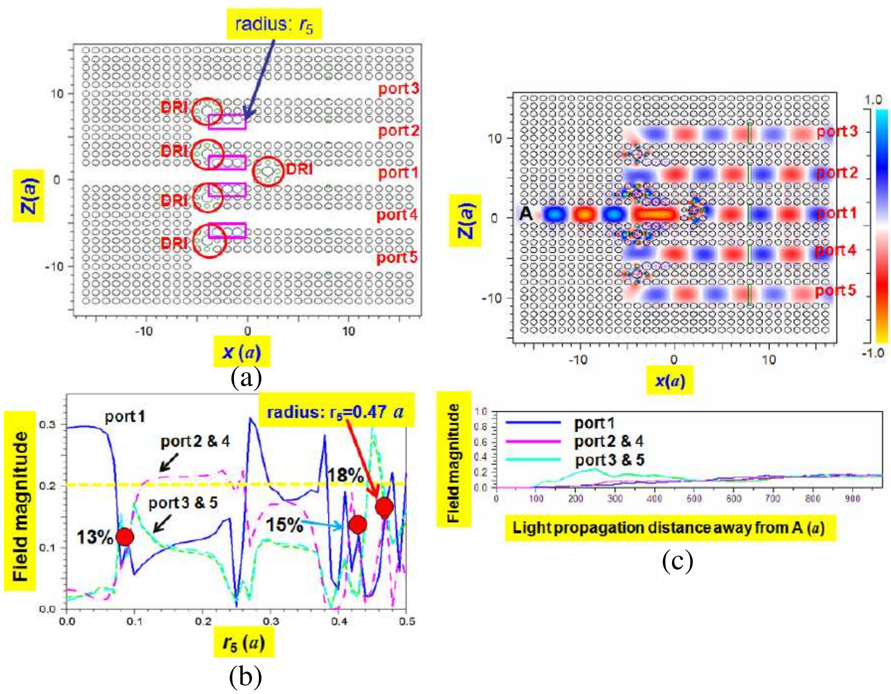

Figure 4. (a) Schematic plot of a 1×5 90° bent equal output ports of PCBS based on the effect of DRI, where the radius, r_5, enclosed by a purple line near the DRI. (b) Electric field magnitude as a function of radius r_5. (c) The electric field patterns (upper part) and the electric field magnitude vs. light propagation distance away from point A (bottom part) of 1×5 90° bent equal output ports of DRI PCBS. The incident field with amplitude of 1 V/m is lunched at point A at the resonant frequency $\omega = 0.2466a/\lambda$.

Splitters with more than two or three output ports are needed to be used in photonic networks and 1×5 $90°$ bent equal output ports of PCBSs can become the building blocks for compact splitters with more output ports. Figure 4(a) shows the schematic plot of a 1×5 $90°$ bent equal output ports of PCBS based on the effect of DRI, where the radius, r_5, is a tuning parameter for the purpose of obtaining the equal field magnitude at output ports. The parameters are the same as used in Figure 2. We increase the radius r_5 from 0 to $0.5a$ in step of $0.01a$, and the FDTD simulations are carried out. The incident field with amplitude of 1 V/m is lunched at point A at the resonant frequency $\omega = 0.2466a/\lambda$. As can be seen in Figure 4(b) that while the radii (r_5) of the three cylinders (enclosed by a purple line near the DRI) are simultaneously modified to a proper value, a 1×5 PCBSs with equal field magnitude measured at output ports can be achieved. With the increasing r_5, the wave-front of the output parallel light is modulated in varying degrees and 1×5 PCBSs with different behavior are obtained. Furthermore, different values of field magnitude measured at the end of output ports 1–5 are obtained, and the relation between field magnitude and r_5 is plotted in Figure 3(b). As an example, Figure 4(c) shows the spatial distribution of field magnitude for the case $r_5 = 0.47a$ and we find that the incident parallel light is split into five equal light beams, namely, a 1×5 PCBSs with symmetrical energy distribution is achieved. The field magnitude of the 1×5 PCBSs is about 0.18 V/m at each port, i.e., the amount field magnitude measured at the five output ports is about 0.9 V/m.

4. CONCLUSION

In conclusion, the design method of a compact $90°$ bent equal output ports of 1×2, 1×3 and 1×5 PCBS with CPBG based on the effect of DRI is proposed and analyzed. The FDTD method is adopted to simulate the relevant structures of defect mode in a two dimensional square lattice circular dielectric rods of anisotropic PC. By utilizing resonant coupling of the PC DRI, the length for PCBS can be shortened. The device size reduction and flexibility in polarization dependence compared with the conventional PCBS can be attributed to the same resonant frequency for both TM and TE polarizations, because the PC structures designed here have a CPBG and possess the short coupling length with direct coupling and the short distance without cross-talk among the output ports. This idea can be easily extended to more complex PC structures such as $N \times M$ DRI couplers, where N and M are the number of input and output waveguides, respectively.

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