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Slow light transmission in a photonic crystal power splitter with parallel outputs

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Abstract

In this paper, we investigate coupling of light to slow modes in a photonic crystal power splitter composed of a Y-junction and two 60° bends. First, a combination of two cascaded bends which is commonly used in integrated photonic crystal circuits is studied in slow light frequency regime. We propose a structure that its transmission spectrum covers the high group-index frequencies near the band edge. Also, by structural modifications, high transmission near to 95% is achieved in slow light bandwidth. Next, we study the complete structure of a photonic crystal power splitter with parallel outputs based on a Y-junction integrated with two 60° bends. Using modified bends and reducing sharpness of Y-junction, the efficiency of splitting increases in both high and low group-index frequency bands. The optimized structure has an average efficiency of 82% in slow mode regime. This structure can be used in photonic crystal based slow light devices, such as Mach-Zehnder interferometers.

Keywords: Slow light; Photonic crystal; Power splitter

1. Introduction

Photonic crystal (PC) is an appealing structure for fabrication of optical devices and components in the next generation of integrated photonic circuits. In contrast to conventional integrated optical circuits, photonic crystal based devices are smaller and can be designed in wavelength scale [1]. Also, the desired dispersion characteristics and the level of light matter interaction in a PC can be engineered. Low loss waveguides, bends, Y-junctions and cavities can also be made and connected in a PC platform with low mismatch [2–4]. In addition, photonic crystal waveguide (PCW) is one of the most successful devices in generation of slow light [5]. Slow light technology plays an important role in the future of optical buffers, optical logical gates, and optical signal processing. Slow light in a PCW can be engineered by modifying the structure. It works at room temperature for a desired wavelength and also provides larger bandwidths compared with other methods, such as electromagnetically induced transparency [6]. Slow light in PCW can be used in many applications such as optical delay lines, buffers, and switches [6]. By using slow light PCW in an optical switch or modulator, a greater phase shift per unit length

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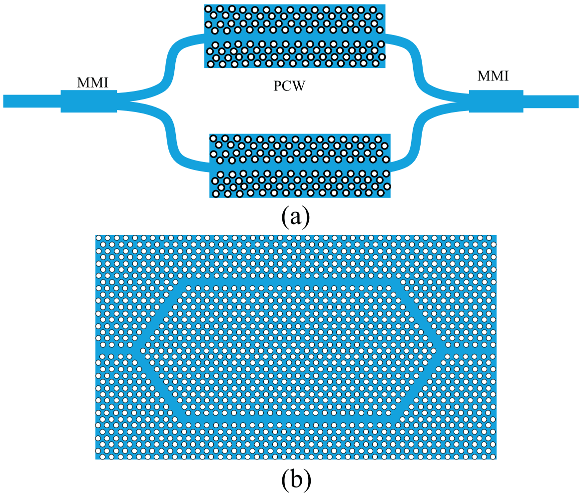

Fig. 1. Slow light MZI structure based on (a) strip waveguides and MMI couplers and (b) PC branches and bends.

is obtained and the switching length or modulation voltage can be reduced. It also enhances nonlinear effects by spatial pulse compression.

Using slow light PCWs, optical modulators based on Mach-Zehnder interferometer (MZI) have been already proposed which demonstrate reduction of modulation voltage and switching length [7–10]. The MZI structures proposed so far have not been based on only PC structure. As shown in Fig. 1(a), they were usually composed of photonic wires connected to PCWs in interferometer's arms for supporting slow modes and increasing the phase shift [7–10]. However, they suffer from the splitting/combining loss and coupling inefficiency from strip waveguide to engineered PCWs even by using coupling parts [10,11]. On the other hand, using photonic crystal based structures as shown in Fig. 1(b), reduces the size of the optical component and increases the device packaging density. For example, lightwaves can be routed around sharp bends with bending radii on the order of a wavelength, while in the MZI structures proposed in Refs. [8,9] which have structures as shown in Fig. 1(a), the bending radii are around 5 μm. Also, in the PC based structure of Fig. 1(b), both PCWs are fabricated in one platform, in one fabrication step and in a distance much lower than the corresponding distance in the structure shown in Fig. 1(a) [8,9,12].

In construction of interferometer structures, such as MZI, power splitters are fundamental elements. The 1×2 splitter which is the common one has been designed and fabricated in PC by direct splitting mechanism, such as Y-junctions [3,4], T-junctions [13], and also by directional coupling [14] and multi-mode interference [15,16]. Y-junction has a compact size, broad bandwidth and low losses; hence, it is usually used for constructing a power splitter in PC integrated circuits. A common 1×2 PC power splitter is also composed of two sharp bends for directing light signals. Sharp bends and Y-junctions which are fundamental elements for photonic crystal integrated circuits have been widely studied [4,17–21]. Although a significant amount of work has been done for improving the transmission of 60° bends and Y-junctions in triangular PC lattices, the fast wave parts of modes were mainly considered in these researches. It means that structures with high transmission were achieved in wave numbers far from the band edge [4,17–20]. For example, Yang et al. investigated the structure of a power splitter with parallel outputs based on a Y-junction integrated with 60° bends and they studied the fast-mode transmission far from the band edge [4]. To directly excite the slow light in a power splitter, Ref. [16] used the multimode interference (MMI) structure. In this structure, the two output ports are in a distance of four lattice constants from each other. This is not suitable for integrated circuit devices, such as MZI.

In this paper, we study the transmission from a PC power splitter based on Y-junction and bends with two parallel outputs in slow mode frequency region. In the first part, we study the transmission of slow light to a PCW through two cascaded 60° waveguide bends and propose a method for increasing the transmission over slow light bandwidth. The proposed structure of two cascaded waveguide bends can support slow light frequencies. Then, we study a Y-junction based splitter. Using modified bends and reducing the Y-junction sharpness result in a power splitting structure which can transfer slow modes to two output ports. Optimization of Y-junction parameters increases the efficiency of structure in slow band to more than 80%.

2. Slow light transmission through a 60° bend

Guiding lightwaves around sharp corners with high efficiency is very important in photonic integrated circuits. In three dimensional (3D) photonic crystals, the lightwave can be guided through sharp bends with very high transmission efficiency due to photonic band gap (PBG) effect and the absence of radiation loss [19]. Another way to obtain a PBG is to use a two-dimensional (2D) PC slab. In a PC slab, the lightwave is guided in the in-plane direction, and the refractive index contrast confines light in the vertical direction [2]. One constrain in using 2D PC slabs is the existence of leaky modes. To overcome this problem, a simple way is to use only nonleaky modes which are below the light line and do not radiate into the cladding [2].

In Ref. [22], nonleaky modes of a PCW are considered and the transmission spectrum of a 60° bend in a PC slab is calculated by 2D FDTD using effective refractive index and 3D FDTD. It is shown that the 3D and 2D results are similar. This means that the 2D analysis using effective index is a good approximation of the 3D analysis. This can be used to reduce the computational resources [22]. Hence, in some papers, 2D FDTD is applied to find the transmission in a PC slab bend even in the low group velocity frequency region [19,21].

In this research, the PCW is considered on a membrane silicon on insulator (SOI) structure with a height of 220 nm and an air hole radius (r) of 0.286a, where a is the lattice constant. The lattice constant is assumed to be 390 nm to support slow light of wavelengths near to 1550 nm. Due to the computation cost of 3D analysis, 2D simulation is performed using a slab effective index of $n_{eff} = 2.87$. The dispersion curve and group-index versus frequency of a TE polarized even guided mode in a PCW created by removing one row of air holes (W1) are shown in Fig. 2. This figure shows that, the slow light frequencies corresponding to high group indices are between 0.252 and 0.257[c/a] depicted by gray region. Since the propagation of slow modes near the band edge is based on bandgap-guiding mechanism, changing the direction of propagation path in 60° bend which alters the periodicity of the lattice results in more reflection for slow waves rather than index-guiding modes. Hence, the transmission of high group-index modes is very low or near to zero in PC sharp bends. In this part, we investigate this matter and propose a method for increasing the efficiency of slow light transmission through a 60° bend.

Using the two-dimensional finite difference time domain (2D FDTD) method, the transmission and reflection spectra of a 60° bend and two cascaded bends are computed and the results are shown in Fig. 3. As can be seen in Fig. 3(b), in the structure of two cascaded PC bends, no slow mode is transferred in the frequency range of 0.252–0.257[c/a], while the bending loss is low in a part of fast wave frequency region (0.262–0.265[c/a]). Therefore, by excitation of slow mode frequencies in the input waveguide, we cannot couple energy to the output.

The transmission through a bend or junction usually depends strongly on the relationship between the mode which propagates in the straight PCW and the resonance modes of the bend or junction region [18,19]. For example, to obtain high transmission through a 60° bend, the pattern and wave number of bend mode should match well with the pattern and wave number of straight waveguide mode. To improve this matter, the obvious choice is modification of the bend region. Regarding to mode matching between the PCW and a 60° bend, the structures proposed in references [17,19] enhance the transmission and bandwidth of fast modes by changing the bend region geometry and introducing air holes inside the bend.

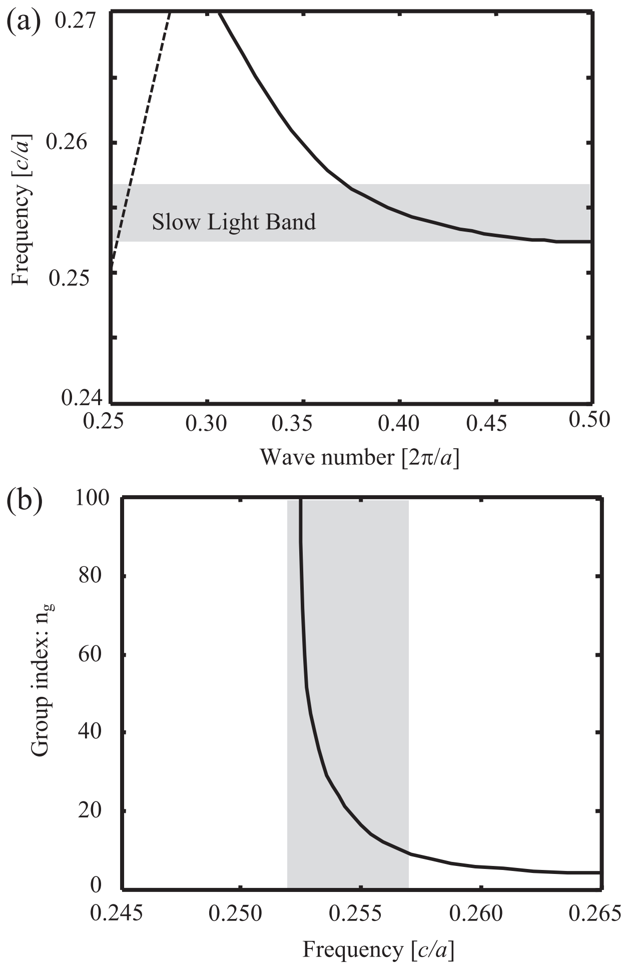

Fig. 2. (a) The even guided modes of a conventional PCW. Dashed line is the air light line. (b) Group index versus frequency. Gray regions show the slow light frequency band.

As shown in Fig. 4, introducing air holes in the waveguide bend results in increasing the transmission bandwidth overlap with the slow light region. According to our previous research [17], the transmission spectrum can be improved by including three air holes of radius $r_i = 0.14a$ in the bend region. The arrow in Fig. 4 shows that the edge of transmission spectrum

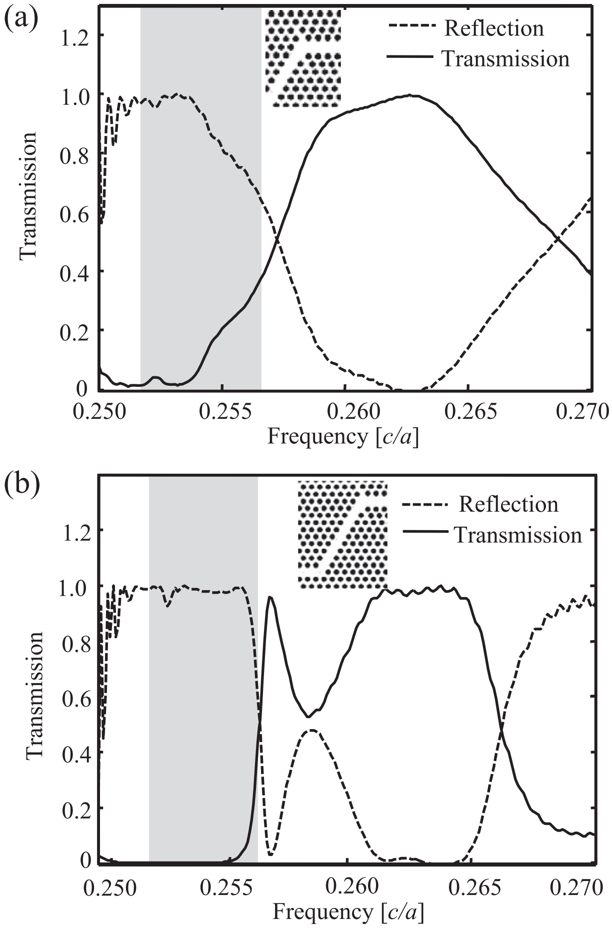

Fig. 3. (a) Transmission and reflection of a 60° waveguide bend. (b) Transmission and reflection of two cascaded waveguide bends. Gray regions show the slow light frequency band.

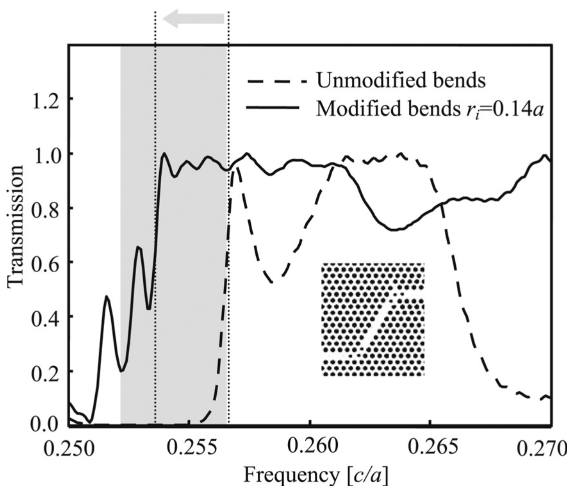

Fig. 4. Comparison of the transmission through unmodified bends and modified bends with $r_i = 0.14a$.

shifts about 0.004[c/a] to lower frequencies and covers the lower group velocities part. It means that by stimulating this frequency band at the input of PCW, the energy can be transferred to the output. Although the transmission in slow light regime increases by introducing air holes, the oscillations due to the Fabry-Perot effect between two bands are also noticeable. The PC bends play roles of two reflectors. The free spectral range (FSR), which shows the frequency distance between two frequency peaks in a Fabry-Perot interferometer, can be computed according to

$$FSR = \frac{c}{2(n_g L_d + L_{b_1} + L_{b_2})} \tag{1}$$

where L_d is the distance between two PC bends and L_{b_1} and L_{b_2} are the average lengths of the first and second bends, respectively [23]. Also, FSR strongly depends on the group index, n_g, of the waveguide mode propagating between reflectors. For frequencies near the band edge which support high group indices the FSR reduces and oscillations increase. For example, for two cascaded bends structure with $L_d = 10a$ and slow frequencies with group index near to 50, $FSR \approx 0.001[c/a]$. Although the oscillation is inevitable and appears in the transmission spectra, the oscillation peaks can be controlled by engineering the reflectivity of bends which depends on reflectors shape, size, and effective index.

Based on our analysis, introducing more than three air holes in the bend region does not result in higher transmission in the slow light regime. Therefore, we consider three air holes of radius r_i in the bend region and search the optimum value of r_i. In addition, increasing radius of air holes which surround the bend (r_a) enlarges the transmission bandwidth in the slow light band and helps us in improving the structure (Fig. 5(a)). Therefore, we optimize the bending by introducing three air holes in the middle of the bend with radii of 0.1a–0.17a and in each case compute the transmission spectrum for different values of r_a between 0.286a and 0.32a. Due to oscillations in high group index frequencies, the average transmission in slow band (0.252–0.257[c/a]) is used as the objective in our optimization. The optimization is based on search algorithm in average transmissions computed for different values of r_i and r_a and results are depicted in Fig. 5(b). As can be seen in this figure, the optimum value is obtained for $r_i = 0.14a$ and $r_a = 0.31a$ with average transmission of 95%. Fig. 6(a) shows the transmission through the optimized bends in comparison with the transmission of unoptimized bends and Fig. 6(b) depicts the propagation of slow continuous

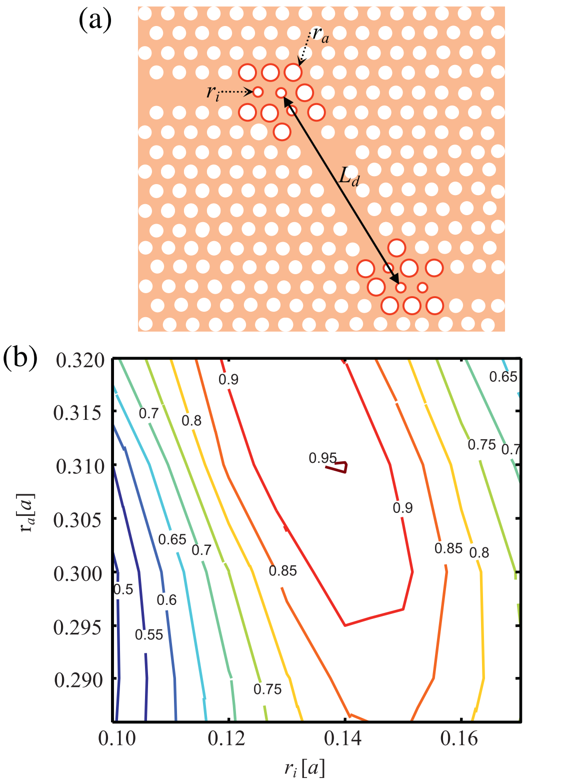

Fig. 5. (a) Bend structure and parameters. (b) The average transmission for different values of r_a and r_i.

wave with frequency of 0.253[c/a] in optimized bend structure.

Using the method described in this section, we obtained a structure of two cascaded bends of 10a apart having an average transmission of 95% over the slow light frequency band. We use this optimized slow light bend to design a slow light power splitter in the next section. The power splitter is composed of a Y-junction connected to two bends in a distance of 10a.

3. Slow light transmission in a PC power splitter

In this section, we evaluate the performance of a PC slow light power splitter with parallel output waveguides connected to a Y-junction by two 60° bends and try to obtain a power splitting structure with high transmission efficiency in slow light band (0.252–0.257[c/a]). The distance between PC bends and Y-junction is considered 10a, which is the same distance considered between two bends in the previous section. The structure of PC power splitter is shown in Fig. 7. The reflection at the input port (R) and transmissions to the output arms (T1 and T2) are shown in Fig. 7 for the TE polarized even-guided mode. Reflection should

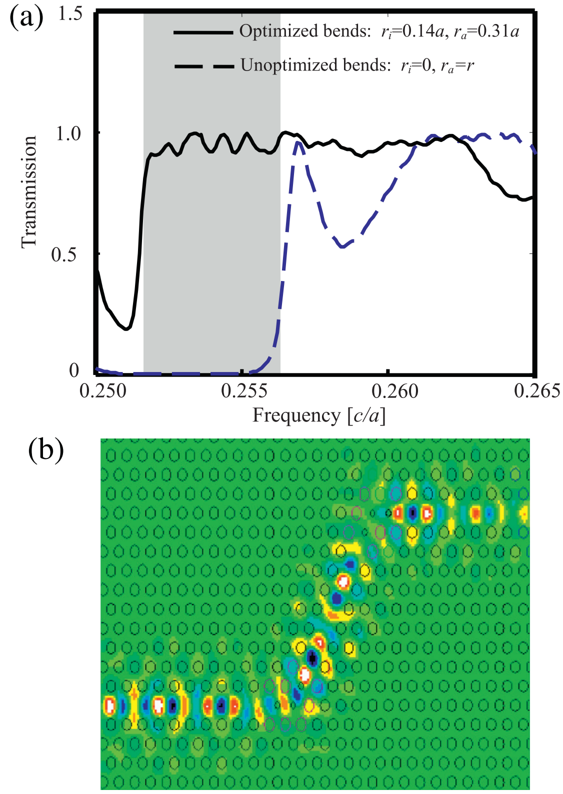

Fig. 6. (a) Transmission through cascaded waveguide bends for optimized structure with $r_i = 0.14a$ and $r_a = 0.31a$ in comparison with unoptimized structure. (b) Propagation of slow continuous wave of frequency 0.253[c/a] in the optimized structure.

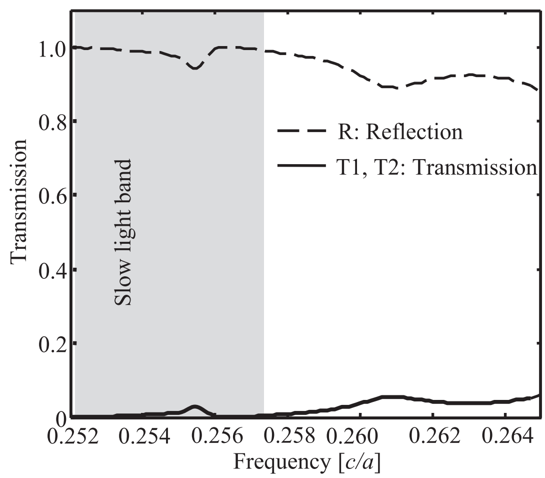

Fig. 7. The structure of PC power splitter with Y-junction and its transmission and reflection spectra.

obey the relation $R = 1 - T1 - T2$ and due to the symmetry of the structure, we have T1 = T2. This figure shows that the splitting structure cannot support slow light frequencies as T1 and T2 are both near to zero in the frequency region of 0.252–0.257[c/a].

The above power splitter has two main parts which cause signal reflections; Y-junction and two waveguide bends. We first examine the effect of bends on PC splitter performance. We estimate higher excitation in the slow light frequencies and also higher transmission in the slow light bandwidth by using modified bends proposed in the previous section ($r_i = 0.14a$, $r_a = 0.31a$) in the structure of the power splitter. The transmission of the power splitter using modified bends is shown by dashed line in Fig. 8(a). In comparison with the solid line corresponding to the non modified splitter, it can be seen that we obtain higher transmission with maximum of T1 = T2 = 0.27 (transmission efficiency of T = T1 + T2 = 0.54). Fig. 8(b) shows the propagation of a narrow band continuous wave of frequency $f_0 = 0.255[c/a]$ in slow light region. As can be seen in this figure, the Y-junction has significant role in the reflection of light signal in this frequency.

Modification of Y-junction is the next step to enhance slow light transmission in PC power splitter. According to our study, among different methods of increasing transmission of slow light in a Y-junction, we obtain the best result by reducing the sharpness of the Y-junction and making a smooth shape. This is obtained by shifting air holes in the bending region toward inside the lattice. We choose three air holes shown dark in Fig. 9(a) and shift them by d_j in directions shown by arrows. On the other hand, gradual changes in the refractive index in the discontinuity made by Y-junction results in decreasing the reflection. We focus on three holes shown by black boundaries in Fig. 9(a). Reducing radii of these three holes (r_j) will increase the

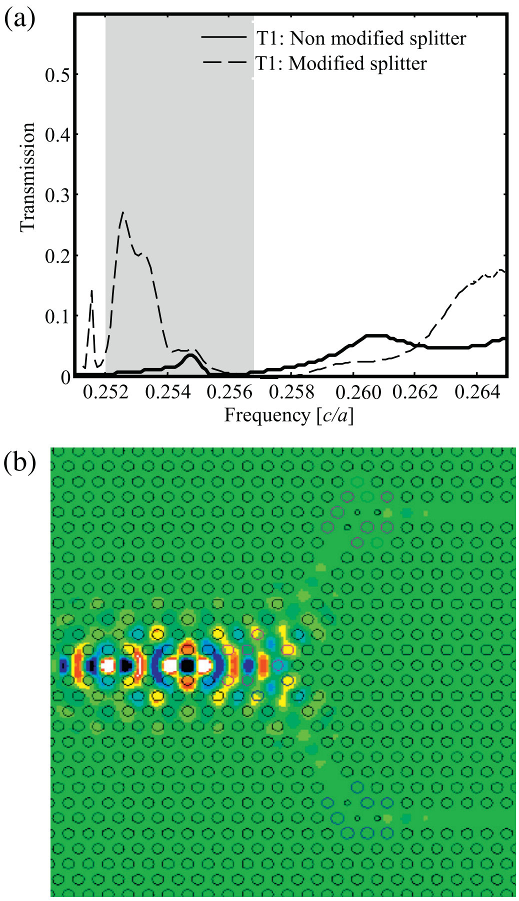

Fig. 8. (a) Transmission in non modified splitter and the modified splitter. (b) Propagation of slow continuous wave in the modified splitter.

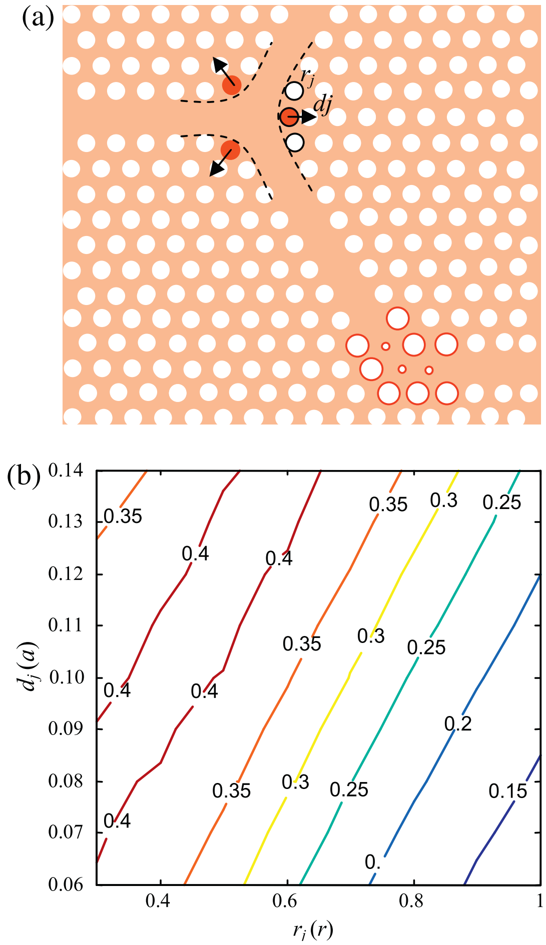

Fig. 9. (a) Reducing sharpness of PC Y-junction and using modified bends in structure of slow light power splitter. (b) The average transmission for different values of r_j and d_j.

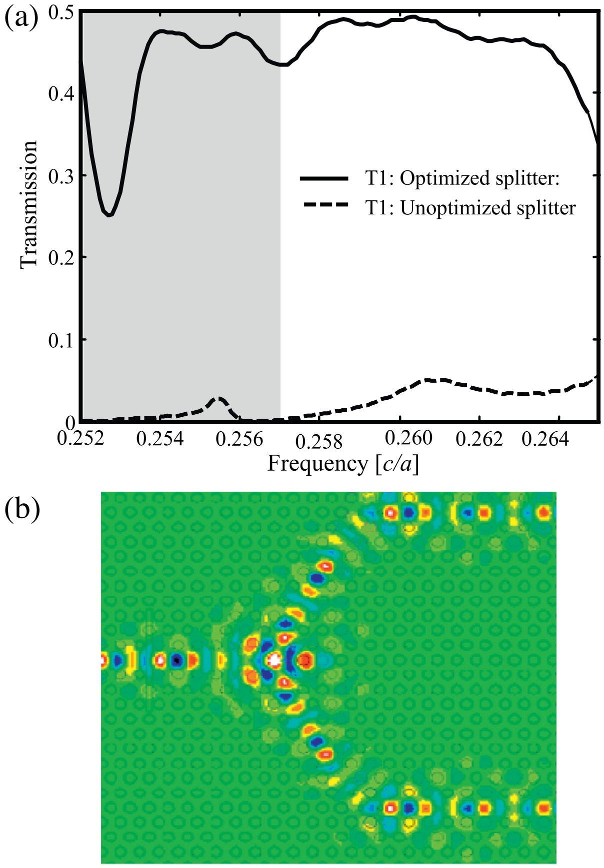

Fig. 10. (a) Transmission in output PCW in optimized proposed structure and unoptimized. (b) Propagation of slow continuous wave in the proposed structure.

transmission and also produces flatter transmission spectrum by decreasing Fabry-Perot oscillations.

In order to find the optimum values of r_j and d_j, we search the highest average transmission for the structure composed of modified bends and Y-junction considering $r_j = 0.3r$–r and $d_j = 0.06a$–$0.14a$. We obtain maximum transmission value of 0.4 as shown in Fig. 9(b). Based on this result, different cases can be selected to achieve the average transmission of T1 = 0.4. With more precise calculations, the optimum value is obtained for $d_j = 0.12a$ and $r_j = 0.5r$ with average transmission of $T1_{av} = T2_{av} = 0.411$ in slow light bandwidth (0.252–0.257[c/a]) and maximum transmission of $T1_{max} = 0.475$. In other words, the average efficiency of structure can be increased to $T_{av} = (T1 + \text{-} T2)_{av} = 0.82$ in slow light frequencies. Fig. 10(a) shows the transmission spectra for optimized structure composed of modified bends and Y-junction and also for unoptimized structure. Propagation of a narrow band continuous wave with frequency of $f_0 = 0.255[c/a]$ in slow light region is depicted in Fig. 10(b) that shows light coupling in both arms in the optimized structure.

4. Conclusion

In this paper, we investigated the transmission of slow mode frequencies in a photonic crystal power splitter composed of a Y-junction and two 60° bends. We started with improving the transmission of two cascaded 60° bends and an average transmission of 95% was achieved in slow light bandwidth for the proposed structure. Next, using modified bends connected to the Y-junction, we improved the power splitter efficiency in slow light band. By optimization of Y-junction geometry for reducing the sharpness of junction, an average transmission of 82% was achieved. It shows that we can excite slow light frequencies near the band edge in output waveguides with an acceptable efficiency.

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