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A 60° photonic crystal waveguide bend with improved transmission characteristics

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In this paper, a 60° waveguide bend is designed in a two-dimensional (2D) photonic crystal (PC) slab to provide high transmission over a large bandwidth. We apply geometrical modification in the bend region to improve the transmission characteristics. This modification results in increasing the relative bandwidth from 6.5% to 25.7% of photonic band gap width. Using the effective refractive index, the structures designed are simulated by the 2D finite-difference time-domain (FDTD) method. As a specific application, we use the improved bend structure in a PC waveguide directional coupler and show that the drop output increases significantly.

Keywords: photonic crystal, waveguide, bend, bandwidth, slab structures.

1. Introduction

Photonic crystals (PCs) are periodic dielectric structures that exhibit the unique potential of photonic band gap (PBG), *i.e.*, a frequency region in which the propagation of light is not permitted. This property can be utilized to control the light propagation. Unlike 3D structures, 2D PCs can be fabricated easily by integrated circuit technology. PC slabs have vertical confinement using index guiding and confine light in horizontal plane using PBG [1–4]. It was demonstrated that the existence of lossless guided modes can be permitted if their wave vectors are larger than the corresponding values in the cladding medium. This relation is shown with a line which is called light line in the PC band diagram. The modes below the light line are guided modes and those above are leaky [3]. A commonly-used PC structure is manufactured by etching a triangular lattice of air holes in a dielectric slab. This structure provides a suitable band gap for TE-like modes [3].

A linear defect is usually introduced in the PC structure by removing one row of holes and it creates one or more guided modes inside the band gap. Transmission of a PC bend is mainly affected by two characteristics, guided modes of straight waveguides and coupling efficiency between them [3]. The ability to guide light waves in sharp bends of PC integrated circuits is one of the most important properties of PC waveguides. Reducing the reflection from the bend region in a large bandwidth has been investigated widely in the literature [5−26].

The first results on PC waveguide bends have been reported by MEKIS *et al.* [5], where the transmission through a 90° bend in a 2D photonic crystal with a square lattice structure was investigated. Several techniques are used to improve the transmission of PC bends. In one technique, by introducing a resonant cavity in the bend region and placing some point defects, the transmission of the PC bend has been improved [6−8]. Other reported techniques are changing the width of line defect [9], moving the holes [10−13], varying the hole sizes [7, 12−14], replacing the holes at the outer edge of bend by another design using topology optimization [15−19], placing point defect at the bend edge region [10, 20], removing one hole [21], and tapering the defect size [22]. Also, it has been shown that a curvilinear lattice can be used in the bend part to obtain a large coupling efficiency over a broad bandwidth [19, 23−25].

In this paper, we propose a new bend structure and optimize its geometrical parameters in order to increase the transmission bandwidth.

2. A 60° PC waveguide bend

We report the results of our investigation on improving the transmission characteristics of a 60° bend in a GaAs PC slab with a refractive index of 3.4. Among different geometries of PC structures, we consider the structure of air holes in a triangular lattice which provides a suitable band gap for TE-like modes and therefore can be efficiently coupled to the commonly used optical waveguides [2]. We choose a hole radius of $r = 0.3a$, which is proposed for practical applications [3], where a is the lattice constant. By applying the plane wave expansion (PWE) method, the photonic band structure of PC slab and the guided modes of the PC waveguides can be computed.

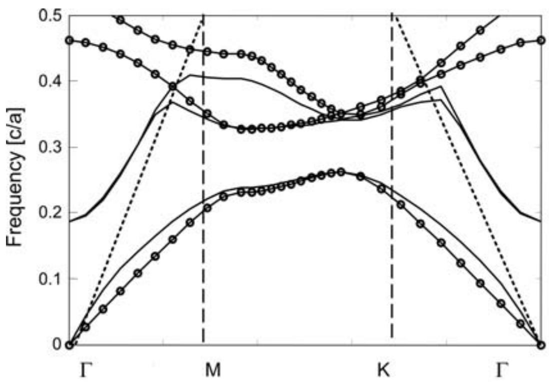


Fig. 1. TE-like band structure of the PC slab shown by solid lines and the corresponding 2D band structure with $n_{\mathrm{eff}} = 2.76$, shown with circles. The dotted lines show the air light lines for air cladding.

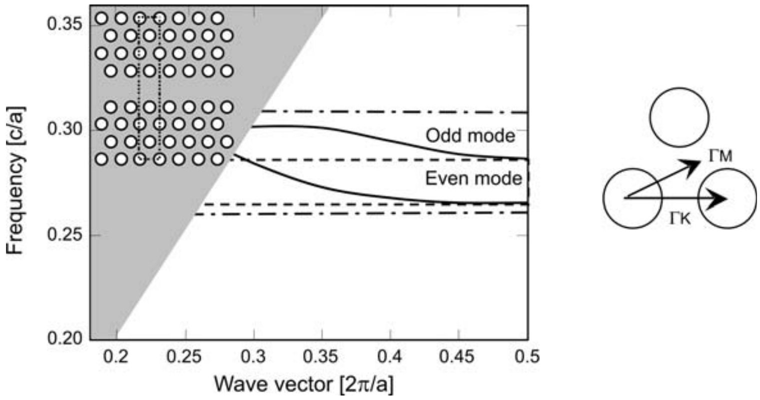


Fig. 2. The guided modes of the PC waveguide in the PBG. The gray region is the continuum of extended modes above the light line. Dashed lines show the boundary of single mode frequency region and dash--dotted lines are the upper and lower frequencies of the PBG.

For the PC structure considered above, the band gap occurs in the frequency range of 0.256–0.32 [c/a], where c is the velocity of light.

There are two main categories of PC slabs, namely low-index-contrast and high--index-contrast PC slabs, in which the difference between the refractive index of PC and cladding is low and high, respectively. For a low-index-contrast slab, the effective index of slab modes changes slightly for a wide frequency range. Therefore, an average effective index could be used for a wide frequency region in 2D approximation [26]. In a high-index-contrast structure, *e.g.*, the air/Si/air, the effective index method is invalid for such a wide frequency region due to the large changes in index. However, for a narrow frequency range of interest, the 2D approximation using the effective index method may remain valid. As shown in Fig. 1, the 2D PC with $n_{\text{eff}} = 2.76$ has the same PBG as the PC slab considered in this paper. As a result, to investigate the transmission and reflection spectra of the 60° PC bend, we utilized 2D approximation of the PC slab, *i.e.*, we applied the 2D finite-difference time-domain (FDTD) method[1] to the structure using a refractive index equal to the effective index of the fundamental mode, which is 2.76 [7, 26]. This approximation reduces the required computational resources (CPU time and memory) significantly.

Figure 2 shows a simple waveguide which is created by introducing a line defect along ΓK direction and illustrates the dispersion curves of corresponding guided modes. As shown in this figure, the frequency range of the even mode below the light line extends from 0.265 to 0.288 [c/a]. However, the odd mode limits the single mode region of the even mode to the frequency band of 0.265–0.287 [c/a]. As shown in Fig. 2, the group velocity of even mode is reduced near the frequency of 0.265. This low group velocity decreases the accuracy of FDTD results near the above frequency.

[1]The FDTD code is written in MATLAB for a $20a\times20a$ PC lattice. Each unit cell has a dimension of $13\delta x\times15\delta y$, where δx and δy represent the mesh size in the FDTD method.

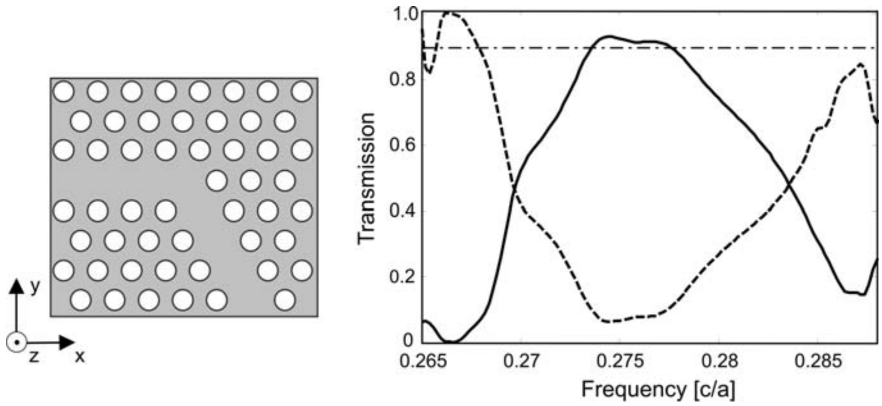


Fig. 3. The 60° waveguide bend and its transmission (solid line) and reflection (dashed line) spectra. The dash-dotted line represents the transmission coefficient of 0.9.

A simple 60° PC bend can be introduced in a triangular structure as shown in Fig. 3. Due to the existence of PBG, light is confined to the bend region and no power will be radiated out of the waveguide. In this simple bend structure, the discontinuity along the guidance path causes large reflection and hence it provides low transmission. The main reason for the low transmission is that the discontinuity at the bend region stimulates higher order modes that are evanescent in the PC waveguide. It should be mentioned that in the frequency range of 0.265–0.287 [c/a] the fundamental waveguide mode is below the light line and it cannot be coupled to the cladding mode. Therefore, the transmission is not affected by leakage of the fundamental mode to the cladding.

The transmission and reflection spectra are obtained by integrating the Poynting vector **S**, over a surface A, normal to the waveguide path:

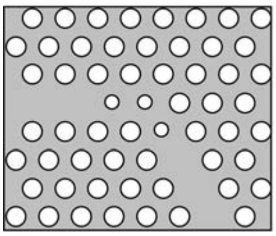
$$\mathbf{S}(\mathbf{r},\,\omega) \;=\; \frac{1}{2}\,\mathbf{E}(\mathbf{r},\,\omega)\times\mathbf{H}^{*}(\mathbf{r},\,\omega) \tag{1}$$

$$\mathbf{P} \;=\; \mathrm{Re}\left(\int_{A}\mathbf{S}(\mathbf{r},\,\omega)\,\mathrm{d}\,A\right) \tag{2}$$

where **E** and **H** are the Fourier transforms of the electric and magnetic field components, respectively. Also, as pointed out before, we use 2D FDTD method to extract all field components (E_x, E_y, and H_z) at the output ports of the bend. In Figure 3, the transmission and reflection spectra of the simple waveguide bend are shown by solid line and dashed line, respectively. We define the bandwidth of a bend as the frequency interval in which its transmission is more than 0.9. Using this definition, the simple bend structure has a bandwidth of 6.5% (normalized to the width of PC band gap). The PC bend consists of three parts: two waveguides in the ΓK direction; each having two guided modes and one waveguide in the ΓM direction, having one guided mode. In a simple bend structure, the coupling of energy between these parts is not efficient and, therefore, the transmission of the bend is low.

3. Improving the bend characteristics

The low transmission problem can be solved by placing small holes in the bend so as to decrease the effective index of the waveguide [7]. This modification results in shifting the waveguide modes at the ΓM direction upward in the diagram and hence brings about a better coupling of energy between the ΓM and ΓK direction waveguides. As a result, the bandwidth is increased and the spectrum is made flatter. Figure 4 shows this new structure of the waveguide bend which is realized by placing three holes in the bend region. The transmission spectra for various radii of the introduced holes r_d are shown in this figure. Table 1a presents the computed bandwidth for different values of r_d. As can be seen, the maximum bandwidth which is equal to 22.9% is obtained for $r_d = 0.14a$. Introducing more than three holes in the bend region may produce different results. Assuming $r_d = 0.14a$, Tab. 1b presents the bandwidths computed for bend structures with one, three and five holes in the bend region. As shown in this table, the best structure is obtained for three holes.



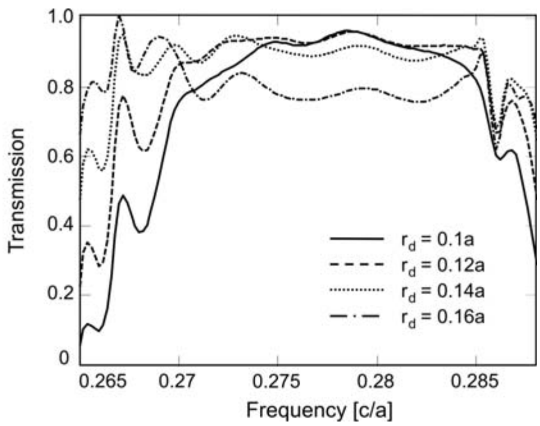


Fig. 4. The transmission spectra a 60° waveguide bend with three additional holes (of radius r_d) at the bend region.

T a b l e 1a. Bandwidth of the bend structure shown in Fig. 3 versus radius of middle holes r_d. (The bandwidth is normalized to the width of PC band gap.)

r_d	Bandwidth [%]
$0.1a$	14.2
$0.12a$	21.7
$0.14a$	22.9
$0.16a$	12.3

T a b l e 1b. Bandwidth of the bend structure shown in Fig. 3 versus number of holes N, with $r_d = 0.14a$. (The bandwidth is normalized to the width of PC band gap.)

N	Bandwidth [%]
1	9.3
3	22.9
5	4

The continuity of field in the bend interface, that is necessary for high transmission, depends on the bend length [5]. In addition, if we consider the bend region as a cavity structure, a longer bend which means a bigger cavity may cause more resonance frequencies in the frequency region of interest. By shifting one defect in the bend a longer bend can be achieved. Taking advantage of both the defect shifting and the index reduction, the structure shown in Fig. 5 is obtained. This structure includes five holes in the middle of the bend. Holes adjacent to the waveguide in the bend have an important role on the distribution of fields. Our investigation shows that increasing the radius of holes can result in increasing the transmission bandwidth. We consider three parameters to modify the structure. These parameters are the number of middle holes N, radius of middle holes r_d, and radius of the holes adjacent to the bend r'.

First, we analyze the transmission spectrum of the bend by changing the number of middle holes, where their radius is $0.14a$. Table 2a shows the results of bandwidth computation for this case. It can be seen that $N = 5$ is the best choice for which a normalized bandwidth of 22% is achieved.

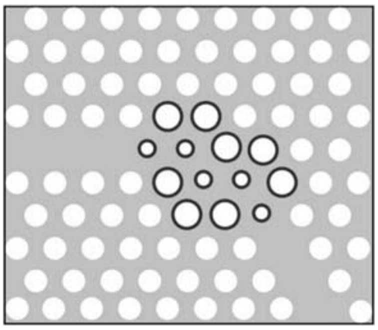


Fig. 5. The bend structure which is to modify the transmission characteristic. The air holes with variable radii are shown with a circle around them.

T a b l e 2a. Bandwidth of the bend structure shown in Fig. 5 versus number of middle holes N, with $r_d = 0.14a$. (Bandwidth is normalized to the width of PC band gap.)

N	Bandwidth [%]
0	9.3
1	13.7
3	21.4
5	22
7	3.7

T a b l e 2b. Bandwidth of the bend structure shown in Fig. 5 versus radius of adjacent holes r'; $r_d = 0.14a$, $N = 5$. (Bandwidth is normalized to the width of PC band gap.)

r'	Bandwidth [%]
$0.3a$	22
$0.31a$	24.8
$0.32a$	25.7
$0.33a$	23.2
$0.34a$	22.8
$0.35a$	17.5

T a b l e 2c. Bandwidth of the bend structure shown in Fig. 5 versus radius of middle holes r_d; $N = 5$, $r' = 0.32a$. (Bandwidth is normalized to the width of PC band gap.)

r_d	Bandwidth [%]
$0.11a$	12.0
$0.12a$	13.1
$0.13a$	25.3
$0.14a$	25.7
$0.15a$	22.3
$0.16a$	10.7
$0.2a$	0

Next, we increase the radius of the holes adjacent to the bend r', which changes the effective index along the ΓM direction. The bandwidth of the structure for each r' is computed and shown in Tab. 2b. In this case, we assume that $N = 5$ and $r_d = 0.14a$. It can be seen that a normalized bandwidth of 25.7% is obtained for $r' = 0.32a$.

Finally, we investigate the effect of the radius of middle holes on the frequency characteristic of the proposed PC waveguide bend which has five holes in the middle

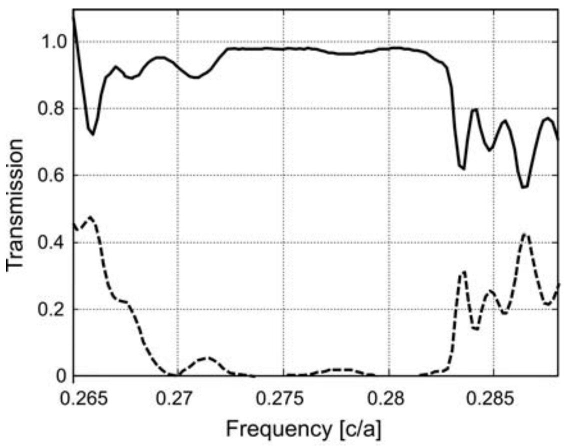


Fig. 6. The transmission and reflection spectra of the PC waveguide bend proposed.

of the bend and the radius of its adjacent holes is increased to 0.32*a*. As can be seen in Tab. 2c, a good performance (25.7% bandwidth) is obtained for $r_d = 0.14a$. Figure 6 illustrates the transmission and reflection spectra for the bend structure proposed, in which five middle holes are included and radii of adjacent holes and middle holes are 0.32*a* and 0.14*a*, respectively.

4. Efficient directional coupler using the bend structure proposed

Directional couplers (DCs) are one of the essential parts of optical integrated circuits [27−29]. They can be used as multiplexers, optical switches or channel drop filters in WDM systems. Photonic crystals can be used to design many optical devices including DCs. Directional couplers are created with two parallel PC waveguides. In this structure, each mode of the separated waveguides splits into two modes. Considering the even mode, it splits into two modes that are known as super-modes, as can be seen in Fig. 7. As shown in this figure, in specific frequency region, super-modes have different wave numbers.

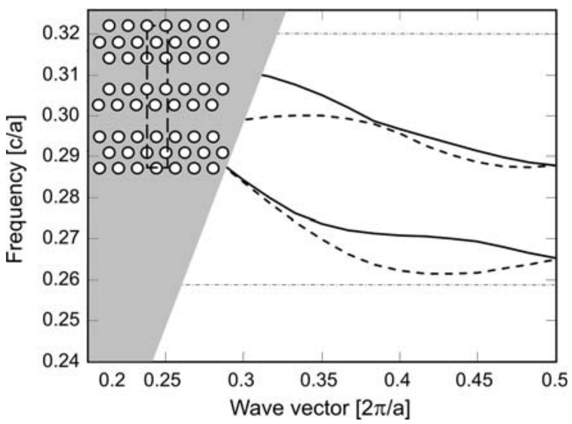


Fig. 7. Guided modes of two parallel waveguides. Super-modes are shown with dark lines, the solid line represents the even mode and the dashed line represents the odd mode. The gray region is the continuum of extended modes above the air light line and the dash-dotted lines show upper and lower frequencies of the PBG.

The coupling in such a structure depends on the overlap of the field patterns of even and odd super-modes. If the phase difference of these modes is equal to an odd multiple of π, power is transferred from one waveguide to the other. This requires that both the even and odd super-modes propagate a specific length which is known as the coupling length [26−28]. Considering a length twice this value, the power is transferred back to the first waveguide. In order to prevent that, we must introduce a waveguide bend after one coupling length to direct light to another path.

We investigate the effect of using the modified 60° waveguide bend, proposed in Section 3, on the DC efficiency. For this structure, in order to have power coupling,

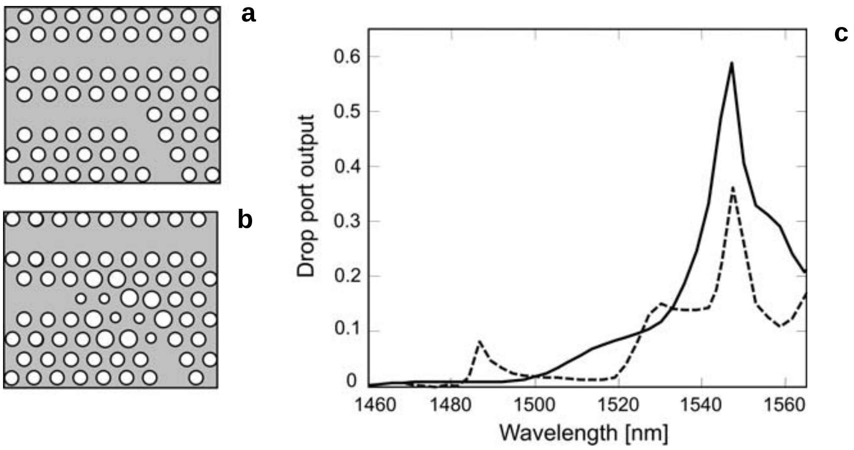


Fig. 8. Directional coupler with a simple bend structure (**a**). Directional coupler with modified bend (**b**). Drop output of both the conventional (---) and modified (—) structures (**c**).

the length should be more than $6a$. In this structure, the phase difference is equal to π when the normalized frequency is 0.269 $[c/a]$. Hence, in order to have a channel drop filter for wavelengths about 1550 nm, we choose $a = 417$ nm. The modified and unmodified directional couplers and their drop output spectra are shown in Fig. 8. As depicted in this figure, the proposed bend structure improves the transmission efficiency of directional coupler significantly.

5. Conclusions

In this paper, a 60° waveguide bend in a photonic crystal slab waveguide was designed for TE modes. By applying geometrical modifications in the bend region, the frequency characteristic of the bend was improved in a frequency band where the waveguide is single mode. It was shown that the structure proposed has a significant improvement in its bandwidth characteristics. We used the bend structure proposed to design an efficient directional coupler and analyzed the effect of bend transmission on the coupler efficiency.

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