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Analysis and Simulation of High Transmission 60° Bending

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ABSTRACT
In this study a different type of waveguides 60° bend high transmission photonic crystal with a broad bandwidth has been presented. This structure has been investigated using the numerical methods of plan wave expansion and finite-difference time-domain. The results indicated that bandwidth has broadened significantly from 19 to 116 nm while transmission is higher than 90%.

Key words: Bandwidth, plan wave expansion method, finite-difference time-domain, photonic crystal and waveguide bend

INTRODUCTION
Photonic crystals are structures which allow only certain frequencies of light to pass through. From another prospective, any material with a periodically altering refractive index can be considered as a Photonic crystal. Photonic crystal slabs are two-dimensional periodic structures with a constant thickness in the third dimension; and this is the difference between three-dimensional photonic crystals and slabs (Dekkiche and Naoum, 2007). Slabs control light through the use of band gaps in two dimensions and the guiding index in the third. Holy slabs often consist of a triangular lattice of air holes enclosed by dielectric and are often used for the polarization of TE (Transverse-electric). On the other hand rod slabs have a square lattice of dielectric bars placed in air and are used to polarize TM (Transverse-Magnetic). Photonic crystal waveguides have the benefit of low-loss and high compactness created from a defect in photonic crystal slabs (Mansourabadi *et al*., 2009). In photonic integrated circuits, different basic units bond together by low-loss photonic crystals. In a straight photonic crystal waveguide, the loss of light signals can be low due to effect of a unique photonic band gap. It consider that a waveguide bend is exposed to light waves, often due to the acute bending angle, they can bear high losses (Khatibi *et al*., 2007). In addition, bandwidth will be limited to a narrow range in the presence of high transmission. Overall, it can be said that the more obtuse the bend, meaning the smaller the bending angle, the greater the loss (Danaie *et al*., 2008). Usually, triangular lattice is used to create a bend of 60° and square one is used to create a bending of 90°; although same method is used to create both bending types (Noda and Baba, 2003).

Several attempts have been made, often at great cost, in order to reduce bending loss and broaden bandwidth. One of these attempts include adjusting air holes on the corner of the bend to create an open cavity-resonated bend (Zhang and Li, 2008). Another smoothing the bend and changing the local width of the waveguide (Chutinan *et al*., 2002) and adding a suitable defect to the structure (Xiao and Qiu, 2005). Most of these methods operate to improve the waveguide structure around the bending point. It is important to note that even though some of these improvements can even enable designers to create suitable bends in different angles, they can also disrupt the symmetry of the entire structure. This means that the periodic pattern of the photonic crystal will not be the same before and after the bending process. For example, topology optimization (TO) has been used as a numerical method in designing bends over the recent years (Borel *et al*., 2004; Watanabe *et al*., 2007).This method despite increasing transmission in broad bandwidths but tends to neglect the physical principles of a low-loss bending design.

Various numerical methods can be used to analyze photonic crystals. Some of these methods perform the analysis in the realms of frequency and others in the realms of time (Koshiba and Saitoh, 2002; Khorasani, 2005; Khorasani *et al*., 2006). Plan Wave Expansion method (PWE) and finite-difference time-domain (FDTD) are the two powerful numerical methods commonly used in the analysis of photonic crystals. In spite of all the advantages in the FDTD method, it is known to be quite time consuming. One way to tackle this is by using two-dimensional FDTD along with an effective index, which can replace the three-dimensional FDTD and decrease calculation time without causing any considerable change in the accuracy of calculation (Strasser *et al*., 2008). We have used a known effective index in each of our simulation tasks.

In this study, the accuracy of the codes written during PWE and 2D FDTD with the analysis of an optimized bending structure previously reported was tested. Furthermore, an optimized, simple, high transmitting bending structure in a broad bandwidth is suggested.

NUMERICAL ANALYSIS

The plan wave expansion method was the first method in analyzing the theory of Phc structures (Ghaffari *et al*., 2008). This method is based upon the principle that special modes (ω_n) in periodic structures can expand as a cluster of plane waves. When light is projected through a two-dimensional photonic crystal, two different states (TM and TE) are likely to happen depending on the polarization of the projection. TM_z and TE_z have no common field components; therefore, they can be used independently in the analysis of different structures. Maxwell equations in two-dimensional TE mode can be simplified into the following equations:

$$\begin{aligned} \frac{\partial E_x}{\partial t} &= \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \sigma E_x\right) \\ \frac{\partial E_y}{\partial t} &= \frac{1}{\varepsilon}\left(-\frac{\partial H_z}{\partial x} - \sigma E_y\right) \\ \frac{\partial H_z}{\partial t} &= \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - \sigma^* H_z\right) \end{aligned} \tag{1}$$

where, σ stands for electric conductivity, σ* for equivalent magnetic loss, ε for electrical permitivity and μ for magnetic permeability.

Bellow illustrates how equations of special amounts for Fourier expansion components in TE state will turn out as a result of expanding wave functions as Bloch waves and placing them in Helmholtz equations:

$$\sum_{G_\parallel} \chi(G_\parallel - G'_\parallel)(k_\parallel + G_\parallel)(k_\parallel + G'_\parallel) H_{z,k_\parallel n}(G'_\parallel) = \frac{\omega_{k_\parallel n}^{(H)2}}{c^2} H_{z,k_\parallel n}(G_\parallel) \tag{2}$$

This is the main equation for two-dimensional photonic crystals. In this formula, $G_{\parallel}$ and $G'_{\parallel}$ represent in-plane reciprocal lattice vectors, $k_{\parallel}$ represents in-plane wave vector and $\omega^{(H)}_{k_{\parallel}n}$ the eigen-frequency for TE polarization.

The method of expand plane, despite being an accurate and elegant method for examining the dispersion of structures, has some major limitations. Since it merely examines the guided modes, it cannot calculate the spectrum of transmission and field distribution. Another method widely used for calculating the spectrum of transmission and field distribution is solving Maxwell equations using FDTD. Both methods of PWE and FDTD have been used in this study.

Differences in the codes written to investigate different structures are often due to the formation of holes as well as the refractive index. Its low transmission is mainly due to the fact that discontinuities within the bending range simulate other unstable modes in the photonic crystal waveguide. With respect to the one dimensional dielectric potential model (Mekis *et al*., 1996), the reflective coefficient of a waveguide bend has been shown below:

$$R(\omega)=\left[1+\left(\frac{2k_1(\omega)k_2(\omega)}{\left[k_1^2(\omega)-k_2^2(\omega)\right]\sin\left[k_2(\omega)L\right]}\right)^2\right]^{-1} \tag{3}$$

where, k_1 (ω) and k_2 (ω) represent the number of mode waves in the straight waveguide and the waveguide bend, respectively. Also L stands for the length of bending. The relation shows that the closer these modes together, the less the reflection.

The transmission and reflection spectrum can be obtained by integrating the pointing vector S on the waver surface A:

$$S\,(r,\omega)=\frac{1}{2}E\,(r,\omega)\times H^*(r,\omega),\quad P=\mathrm{Re}\left[\int_A S\,(r,\omega)\,dA\right] \tag{4}$$

where, H and E represent the Fourier transforms of electric and magnetic field, respectively. We used the 2D FDTD to obtain these elements. With the TE mode in mind, we found the field components (E_x, E_y and H_z) in the outer section of the bending. MALTAB software has been used to write the FDTD codes for a two-dimensional 20a*20a photonic crystal and the grid resolution of $\Delta x = \Delta y = a/32$.

Moreover, for the sake of algorithm stability, the time step amount has been calculated through the following relation (Nozhat and Granpayeh, 2007):

$$\Delta t\leq 1/(c\sqrt{1/(\Delta x)^2+1/(\Delta y)^2} \tag{5}$$

In this relation, C represents the speed of light in vacuum. FDTD is a time consuming method, which is why it may cause problematic reflections on the outer shell of the structure. In fact we must make sure that the wave reflected on the outer layer of the structure does not obstruct our calculations. In the course of the (2D FDTD) process, we have taken the perfectly matched layer (PML) border conditions into account (Taflove and Hagness, 2005). In fact we covered the structure in 12 PML layers to ensure the safety of our calculations.

Examining the accuracy of the codes written in PWE and FDTD: As mentioned earlier, photonic crystal waveguides with triangular structure are often used to create a bend of 60 degrees; Fig. 1 illustrates an optimized 60 bend suggested in the reference (Danaie *et al*., 2008).

The writer has reported the effective index to be n = 2.7 and the hole radius as 0.3a and added 5 holes near the bend in order to improve the high transmitting bandwidth (90%< transmission).

The radius of the added middle hole equals 0.19a and the other four 0.11a. Initially, we find the permitted frequency range of the wave using the 2D PWE method. Figure 2 shows the band structure of waveguide bend, as shown in Fig. 1. In this Figure, n_a represents the refractive index of the holes and n_b the refractive index of the background material. According to this figure, there is a band gap in the normalized range 0.26 to 0.29(a/λ) (area between the red dashed lines). An input wave within this range must be applied to the waveguide for it to gain maximum transmission. Then we can calculate the transmission spectrum of this bend using our FDTD codes. Figure 3 shows the transmission spectrum of this waveguide bend. It is clear that the normalized frequency range 0.265 to 0.285(a/λ) has a transmission more than 90%. The results obtained from our analysis quite adequately match the results reported in reference (Danaie *et al*., 2008) (Table 1); hence confirms the accuracy of the written codes.

Analysis and design of a high transmission bend: This time, we have considered a simple 2D waveguide bend with a triangular lattice of air holes surrounded by GaAl with a refractive index of n = 3.32, as in Fig. 4. The lattice period equals a = 380 nm and the radius of air hole is r = 0.36a. The obtained transmission spectrum for this simple bending structure has been shown in Fig. 5.

Table 1: Comparing the results obtained from our analysis and the results reported in reference (Danaie *et al*., 2008)

Transmission	Spectrum (a/λ)>90
Danaie *et al*. (2008)	0.265 to 0.29
Simulation	0.265 to 0.288
Accuracy	93%

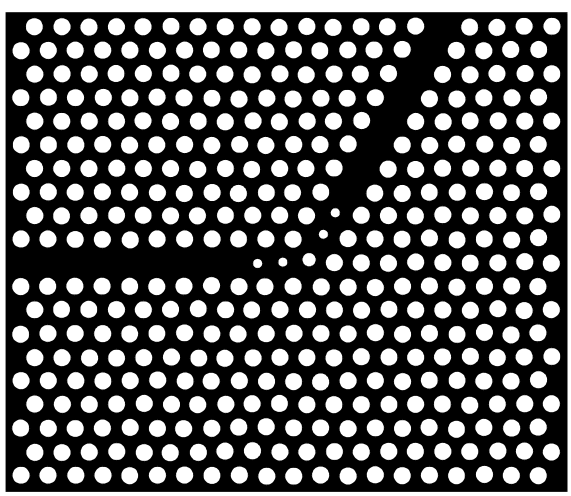

Fig. 1: Optimized 60 bend suggested in the reference (Danaie *et al*., 2008). The radius of the added middle hole equals 0.19a and the other four holes 0.11a

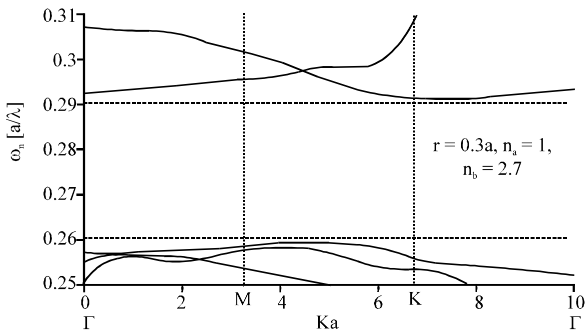

Fig. 2: Band structure of waveguide bend in Fig. 1

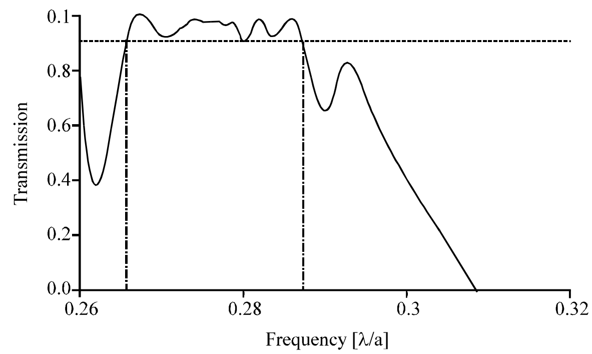

Fig. 3: Transmission spectrum of the waveguide bend in Fig. 1

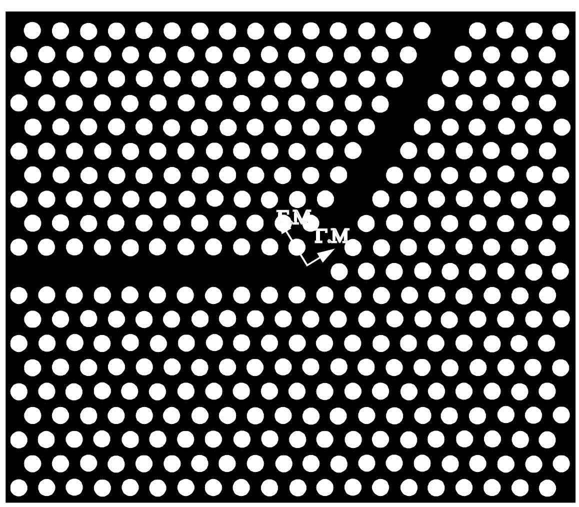

Fig. 4: Schematic view of the simple 2D 60° waveguide bend

It is clear that the high transmission area (90 %< transmission) only exists within the frequency range of 1.527 to 1.546 μm, meaning that the bandwidth is just 19 nm.

The waveguide bend in Fig. 4 consists of two straight waveguides directed toward Γ-K and a short waveguide toward Γ-M. For maximum transmission ability, the allowed area of direction must be equal in the bend waveguide and straight waveguide. With the help of PWE, the band structure

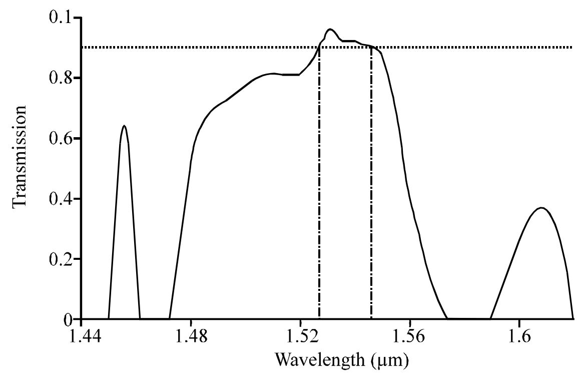

Fig. 5: Transmission spectrum of the simple 2D PC waveguide bend with n = 3.32, a = 380 nm, r = 0.36a

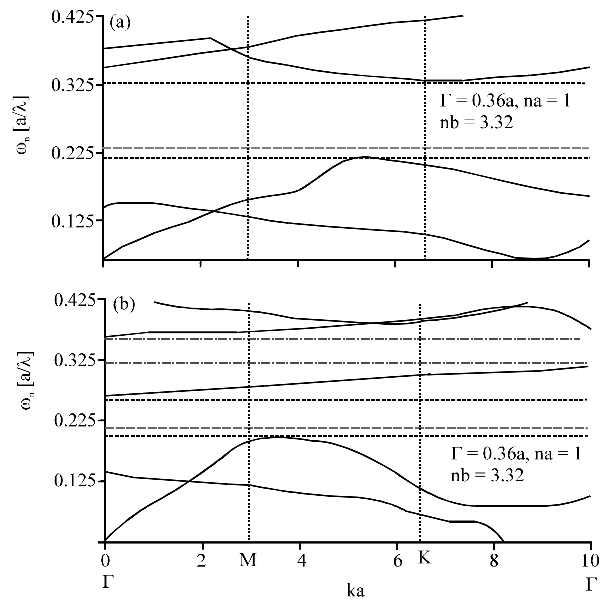

Fig. 6(a-b): (a) Band structure of the straight waveguide; (b) Photonic band of bend waveguide

of the straight waveguide and the bend waveguide turned out to be as shown in Fig. 6a and b. It is quite clear that the straight waveguide has one band gap within the normalized frequency ranges of 0.225 to 0.325(a/λ) while the bend waveguide contains two band gaps within the normalized frequency ranges of 0.23 to 0.3(a/λ) and 0.335 to 0.375(a/λ). In Fig. 6a-b, the normalized frequency of 0.247(a/λ) has been shown by green dashed line, where maximum transmission has taken place in Fig. 5. By adjusting the size and position of the air hole near the bending corner, we changed the waveguide bend band structure in such a way as to have a wide frequency range with high transmission.

In order to create the suggested optimized structure, w e increased the periodic lattice to a = 450 nm, but kept the radius of air hole as r = 0.36a. We also decreased the size of the air hole in the inner corner of the bend and added another hole to the outer corner of the bend. We set the radius of the two air holes as r = 0.75r and pulled them apart along the symmetric axis of bend

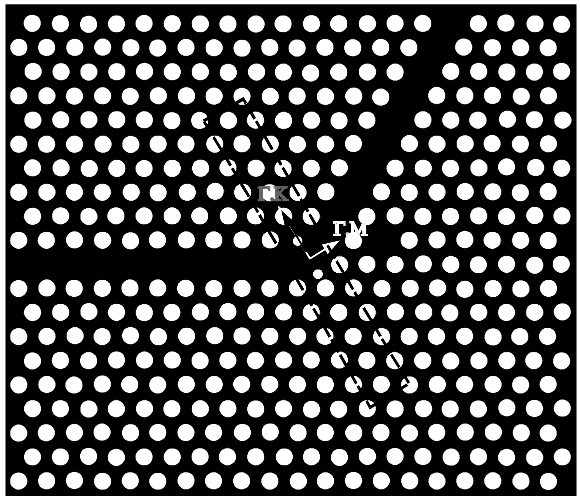

Fig. 7: A view of the proposed 2D PC waveguide bend

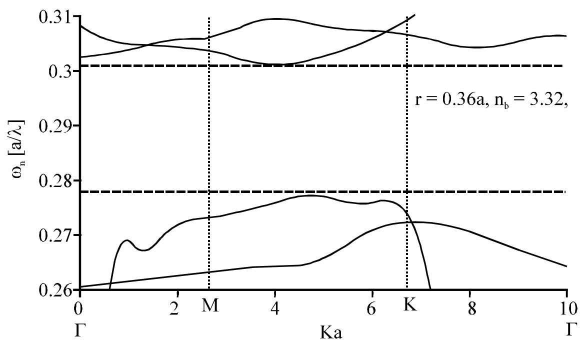

Fig. 8: Band structure of the proposed waveguide bend

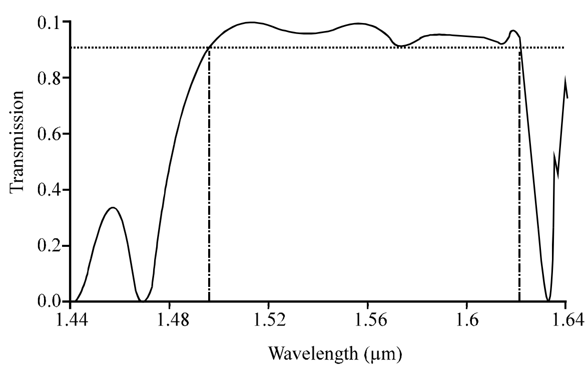

Fig. 9: Transmission spectrum of the proposed waveguide bend

by 0.3a. When the bend is symmetric on both sides of the bend, it will guarantee that the transient guided mode in the bend will have the same symmetric mode distribution with the guided mode in the straight waveguide, hence providing suitable circumstances for the mode to match up. Figure 7 illustrates this efficient structure.

Applying PWE codes in such a formation will illustrate the band structure in Fig. 8. We examined the normalized frequency range of 0.278 to 0.3(a/λ). Also, the transmission spectrum of this waveguide calculated through the 2D FDTD method, which can be seen in Fig. 9. The transmission range has spread over 1.496 to 1.612 μm which is similar to the frequency range in the band structure. The bandwidth equals 116 nm which presents a considerable improvement in broadening the high transmitting bandwidth.

CONCLUSION

In this study, we conducted an analysis on an optimized PC 60° waveguide bend previously reported in order to confirm our PWE and FDTD codes. We then suggested an geometry of efficient simple high- transmission bend in a broad bandwidth. With this suggested structure, the high transmission bandwidth improved from 19 to 116 nm. This bandwidth contains the entire C band of optical communication. The waveguide bend presented here can be used in optical circuits.

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