Study of transmission properties for waveguide bends by use of a circular photonic crystal

Sanshui Xiao and Min Qiu

Laboratory of Optics, Photonics and Quantum Electronics, Department of Microelectronics and Information Technology, Royal Institute of Technology (KTH), Electrum 229, 16440 Kista, Sweden

Abstract

We study the transmission properties for the waveguide bends composed by a circular photonic crystal. Two types (Y and U type) of the waveguide bends utilizing the circular photonic crystal are studied. It has been shown, compared with the conventional photonic crystal waveguide bends, transmission properties for these bends can be significantly improved. Over a 6.4% bandwidth, less than 1-dB loss/bend are observed. U bent waveguide, i.e., 180° bend, can be easily realized with low loss using the circular photonic crystal.

PACS numbers: 42.70.Qs, 78.20.Bh, 02.70.Bf
I. INTRODUCTION

Photonic Crystals (PhCs) are artificial structures with periodically modulating refractive indices and have photonic bandgaps wherein the propagation of photons is prohibited \[1, 2, 3\]. PhCs have received considerable attention owing to their abilities for the realization of ultra-compact and multi-functional devices for high-density photonic integrated circuits (PICs) \[4\]. It is inevitable for introducing waveguide bends in the high-density PICs. This kind of waveguide bends, specifically sharp corners, represents a discontinuity for a wave propagating through the waveguide and becomes one of the main contributions in not only generating loss but also limiting the bandwidth of the transmitted signal. Various alternative approaches for bend designs have been theoretically or experimentally studied, e.g., deforming the PhCs lattice near the bend \[5, 6\], adding a defect at the bend \[7\], optimization the waveguide bends \[8, 9, 10, 11, 12\] and using of polycrystalline PC lattice \[13\]. Most of these works are based on the optimization method for the bends, in which the structure of the waveguide bends are always much complicated.

In this paper, we propose a simple method for designing waveguide bends and demonstrate the use of a circular photonic crystal as a waveguide bend to improve transmission property of the bend in a two-dimensional triangular photonic crystal. Y and U type of waveguide bends are considered in the following text.

II. DESIGN AND SIMULATION RESULTS

The two-dimensional photonic crystal we considered here is a triangular lattice of air holes in a dielectric medium with a lattice constant \(a\) and a hole radius \(r = 0.3a\). The refractive index of the dielectric medium 3.24 has been assumed, corresponding to the index of InP/GaInAsP around \(\lambda = 1.55\mu m\). It can be obtained by the plane-wave expansion method \[14\] that such a structure has a bandgap for transverse-electric (TE) modes from \(0.22(a/\lambda)\) to \(0.29(a/\lambda)\). To guide light, photonic crystal waveguides (PhCWs) are then introduced by removing one row of air holes, which are oriented along \(\Gamma K\) direction. For the triangular lattice configuration, a conventional PhCW bend is naturally bent in steps of 60°, which is shown in Fig. \(\text{II}.a\). Due to the discontinuity of the generic PhCW bend, light will be scattered by air holes around the corner when going through it, which leads to high bending
loss and narrow bandwidth of the transmitted signal. To overcome these limitations, we design the waveguide bend by use of part of a circular photonic crystal (CPC) instead of the generic PhC bend, which is shown in Fig. 1(b). The CPC is non-periodic but systematic arrangement of air holes, which exhibits sixfold symmetry. The air holes are arranged in the form of concentric circles with radial distance \( d = \sqrt{3a/2} \), matched with the triangular photonic crystal. The positions of the air holes in the \( xy \) plane for such a CPC are given by

\[
x = dN \sin \left( \frac{2m\pi}{6N} \right), \quad y = dN \cos \left( \frac{2m\pi}{6N} \right),
\]

where \( N, d, \) and \( m \) denote the number of concentric circles, the difference of radii of neighboring concentric circles and the number of air holes \((0 \leq m \leq 6N)\), respectively. Results of transmission spectra for the whole CPC \((0 \leq N \leq 9)\) show that there exists an isotropic bandgap for TE modes between \(0.22(a/\lambda)\) to \((0.3a/\lambda)\), which makes it possible that light can be guided by the waveguide of the CPC. For the CPC is non-periodic, it should be noted that there is no bandgap in the region of large radial distance, where the CPC is almost like a square lattice of air holes in a dielectric medium (without bandgap for TE modes). Looked again back to Fig. 1(b), compared with the conventional PhCW bend (as shown in Fig. 1(a)), the CPC makes the bend much smoother, e.g., the discontinuity at the bend becomes much smaller. Moreover, we also keep the symmetry of the corner, which is vital for improvement of transmission efficiency as described by Jensen et. al [8]. In our all simulations, we use a dielectric waveguide as input and output waveguide and put a detector in the output waveguide. In order to accurately obtain transmission spectra of the waveguide bend, we need to separate the transmission spectra of the bend from the complicate propagation loss, as well as the in/out coupling loss when light travels through the photonic crystal waveguide. Here we use a straight photonic crystal waveguide as a reference, which has same propagation length, as well as identical in-coupling and out coupling mechanisms. The transmission of the bend can then be defined as the ratio of the output power \( P_0 \) for the waveguide bend to the reference power \( P_i \) for the corresponding straight waveguide, which is given by \( T = 10\log_{10}(P_i/P_0) \). Numerical simulations for the bends are performed by the two-dimensional finite-difference-time-domain (FDTD) computational method with a boundary treatment of perfectly matched layers.

First we study the case of Y type waveguide bend, i.e., 60° bend, in a W1 channel waveguide oriented along \( \Gamma K \) direction. The conventional bend in the triangular photonic
FIG. 1: Schematics of photonic crystal waveguide for the 60° bend. Generic bend configuration is shown in (a). The bends using the circular photonic crystal are shown in (b), (c) and (d). Only difference for three structures is the position of the center (O) for the circular photonic crystal.

crystal is shown in Fig. 1(a). It has been shown by several authors [5, 10, 11, 12] that the transmission of this generic waveguide bend is quite small. Light will be strongly scattered by air holes around the corner due to the mismatch of the guided mode. In order to minimize the scattering, we use a matched circular photonic crystal to connect the conventional PhCW, which are shown in Fig. 1(b), (c) and (d). The regions between two solid lines are the transition region for the bends. Only difference for these three structures is the position of the center (O) for the CPC. Waveguides in the CPC can be denoted by N, where N = 5, 7 and 9 represent the waveguide structures of Fig. 1(b), (c) and (d), respectively. Transmission spectra of the bend, i.e, bend loss, can be obtained by the method mentioned before in order to eliminate the coupling and the propagation loss. Bend losses for the structures shown in Fig. 1 are plotted in Fig. 2. The solid line with asterisk markers represents the bend loss for the conventional PhCW bend and the solid, dotted and dashed line represent the bend loss for the three waveguide bends utilizing the CPC, respectively. It is obviously seen that the bend loss for the generic bend is much large in our considered frequency region, which is in agreement with other results [5, 10, 11, 12]. For the bends by use of the CPC, the bend losses are quite small in a large frequency domain, which agrees well with what we expected above. It can also be seen from Fig. 2 that less than 1-dB loss/bend can be obtained in a
FIG. 2: Bend loss for the waveguide bends. The solid line with asterisk markers represents the loss for the generic PhCW bend. The solid, dotted and dashed line represent the loss for the CPC waveguide structure shown in Fig. 1(b), (c) and (d), respectively. All spectra have been normalized to the transmission through straight PhCWs of the same length to eliminate the coupling and the propagation loss in straight waveguide.

Normalized frequency range from $0.272(a/\lambda)$ to $0.288(a/\lambda)$. As for the working wavelength $\lambda = 1.55\mu m$, the bandwidth is about 90nm. Compared other corresponding work in the literatures [9, 10, 11], although the bandwidth for the low bend loss in this paper is not the best result, the bandwidth is still enough wide for the practical application. Moreover, the structure of the waveguide bend is much simpler than those in Ref. [9, 10, 11].

Figure 3 shows the steady-state magnetic field distribution ($\omega = 0.276(a/\lambda)$) of the mode profile when light goes through the waveguide bends. The left image shows the mode behavior for light travelling through the generic PhCW bend and right image is for the bend by use of the CPC, the corresponding structure of which is shown in Fig. 1(b). One can clearly see from the Fig. 3(a) that transmission is quite small for such a generic PhCW bend. However, shown in Fig. 3(b), the CPC waveguide bend guides the light nicely, which is in agreement with the description above.

As for the high-density, it is necessary to introduce different type of waveguide bend in PICs. Next we consider U type photonic crystal waveguide bend, i.e., $180^\circ$ bend, by use of the circular photonic crystal. The CPC bend structure can be introduced by removing
FIG. 3: Steady-state magnetic field distribution \( (\omega = 0.276(a/\lambda)) \) for the waveguide bends for (a) mode profile through the generic PhCW bend; (b) mode profile through the waveguide bend utilizing the CPC, the corresponding structure is shown in Fig. 1(b).

FIG. 4: Schematics of U type photonic crystal waveguide bends by use of the circular photonic crystal. Left regions of solid lines are the half circular photonic crystal and the right are the conventional triangular photonic crystal. The filled circles are the center circles of the CPC. One row of air holes with same radial length, which are shown in Fig. 4. Left regions for solid lines in Fig. 4 are the half circular photonic crystal and the right are the conventional triangular photonic crystal. The filled circles are the center circles of the CPC. The CPC
FIG. 5: Bend losses for four different U type waveguide bends by use of the circular photonic crystal, whose corresponding structures are shown in Fig. 4. The solid, dotted and dashed line represent the loss of CPC waveguide structures shown in Fig. 4(a), (b) and (c), respectively. The solid with asterisk markers represents the loss for the structure of Fig. 4 (d).

waveguide can also be denoted by $N = 3, 5, 7$ and 9 for four kinds of U type waveguide bends. Our simulation results are shown in Fig. 5. The solid, dotted, dashed line and solid line with asterisk markers represent the bend loss for the four bends shown in Fig. 4 respectively. One can see from Fig. 5 the bend loss are quite small in a relative wide band for these U type waveguide bends. Over 6.4% bandwidth, less than 1-dB loss/bend can be observed for the structure shown in Fig. 4 (a). As for the working wavelength $\lambda = 1.55\mu m$, the bandwidth is about 100$nm$, which is enough wide for application. It can be also seen from Fig. 5 that the bandwidth for large transmission becomes narrow, especially for the results of the dotted line, with increasing of the bend radius. This is mainly caused by the effect that the bandgap for the CPC will shrink with the increase of the radial length due to its non-periodic structure. Figure 6 shows the steady-state magnetic field distribution for the light $\omega = 0.2827(a/\lambda)$. The mode behavior for light travelling through the bend (corresponding structure is shown in Fig. 5 (a)) is shown in the left image. Right image shows the mode behavior for light going through the structure shown in Fig. 5 (b). They both show that such these CPC waveguide bends can realize 180° turning with much low bend losses. For the structure of Fig. 5(a), the bend radius is about 1$\mu m$ for the working
FIG. 6: Steady-state magnetic field distribution ($\omega = 0.276(a/\lambda)$) for the waveguide bends. The corresponding structure of the bends are shown in Fig. 5 (a) and Fig. 5 (b).

wavelength $\lambda = 1.55 \mu m$, which is quite small.

III. CONCLUSION

In conclusion, we have studied the waveguide bends by use of a circular photonic crystal. Compared with the conventional generic PhCW bends, the bends with CPC have shown good transmission properties not only of the transmission efficiency, but also of the bandwidth with the large transmission. Two types (Y type and U type) of the waveguide bends utilizing the circular photonic crystal are considered in this paper. Over a 6.4% bandwidth, less than 1-dB loss/bend are observed. For the working wavelength $\lambda = 1.55 \mu m$, the bandwidth is about 100nm, which is enough wide for the application. Moreover, very small bend radius of about 1$\mu m$ for U type bend can be easily obtained. Further work on experimental verification of our results mentioned above has been in the progress, which will be presented in the future.
IV. ACKNOWLEDGMENTS

This work was supported by the Swedish Foundation for Strategic Research (SSF) on IN-GVAR program, the SSF Strategic Research Center in Photonics, and the Swedish Research Council (VR) under project 2003-5501.

[1] E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987).
[2] S. John, Phys. Rev. Lett. 58, 2486 (1987).
[3] J. D. Joannopoulos, R. D. Meade, and J. Winn, *Photonic Crystals: Modeling the Flow of Light* (Princeton Univ. Press, Princeton, NJ, 1995), 1st ed.
[4] C. Manolatou, S. G. Johnson, S. Fan, P. R. Villemuve, H. A. Haus, and J. D. Joannopoulos, J. Lightwave Technol. 17, 1682 (1999).
[5] I. Ntakis, P. Pottier, and R. M. De La Rue, J. Appl. Phys. 96, 12 (2004).
[6] A. Talneau, L. Le Gouezigou, N. Bouadma, M. Kafesaki, C. M. Soukoulis, and M. Agio, Appl. Phys. Lett. 80, 547 (2002).
[7] A. Chutinan, M. Okano, and S. Noda, Appl. Phys. Lett. 80, 1698 (2002).
[8] J. S. Jensen and O. Sigmund, Appl. Phys. Lett. 84, 2022 (2004).
[9] P. I. Borel, A. Harpoth, L. H. Frandsen, and M. Kristensen, Opt. Express 12, 1996 (2004).
[10] L. H. Frandsen, A. Harpoth, P. I. Borel, M. Kristensen, J. S. Jensen, and O. Sigmund, Opt. Express 12, 5916 (2004).
[11] B. Miao, C. Chen, S. Shi, J. Murakowski, and D. W. Prather, IEEE Photon. Tech. Lett. 16, 2469 (2004).
[12] J. Smajic, C. Hafner, and D. Erni, Phys. Rev. Lett. 11, 1378 (2003).
[13] A. Sharkawy, D. Pustai, S. Shi, and D. W. Prather, Opt. Lett. 28, 1197 (2003).
[14] S. G. Johnson and J. D. Joannopoulos, Opt. Express 8, 173 (2001).
[15] N. Horiuchi, Y. Segawa, T. Nozokido, K. Mizumo, and H. Miyazaki, Opt. Lett. 29, 1084 (2004).
[16] A. Taflove, *Computational Electrodynamics: The Finite-Difference Time-Domain Method* (Artech House INC, Norwood, 2000), 2nd ed.
[17] J. P. Berenger, J. Comput. Phys. 114, 185 (1994).