Polarization insensitive self-collimation waveguide in square lattice annular photonic crystals

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Abstract
The frequency bands for self-collimation at both TE and TM polarizations in square lattice annular photonic crystals are studied systematically by plane-wave expansion and finite difference time domain methods. By increasing the inner ring radius or reducing the outer ring radius, the self-collimation band will be moved to a lower frequency. Compared with the TM modes, TE ones have different frequency sensitivities to both the inner ring radius and outer ring radius tuning. Using these features, a polarization insensitive self-collimation waveguide in a high dielectric contrast system with bandwidth up to 102.9 nm is demonstrated as an example of the implementation of photonic integration circuits.

1. Introduction
Self-collimation (SC) phenomenon [1] in photonic crystals (PC) [2,3] – by which a beam of light can propagate with almost no diffraction in a perfectly periodic PC has attracted considerable interest from the research community. It allows arbitrary beam crossing in a very high-density fashion without imposing limitations due to structural interactions or cross talk by introducing defects in PC [4,5]. With these advantages, various applications such as beam collimating [6–8], reconfigurable non-defect waveguide [9], waveguide bend [10,11], light focusing [12], light splitting [13,14] and other important components for high-density optical integration have been recently demonstrated. However, among most of the applications [6–14], only one polarization state is used, which limits the applications for ultra compact and configurable optical interconnects. Actually, the SC frequency bands for different polarization lights vary greatly. Although SC PC polarization beam splitters have been implemented by PC heterostructure [15,16], a simple structure to tune the frequency band for SC with expected polarization has not yet been well studied. Additionally, there are still many difficulties in obtaining polarization insensitive SC devices with a broad bandwidth.

In this paper, we try to solve above problems through a novel structure known as annular PC [17–19]. The ring-shaped-hole in annular PC offers two parameters: the inner ring radius \( r \) and the outer ring radius \( R \), so as to more easily tailor the photonic dispersion curves and SC behavior with expected frequency and polarization. In Section 2, we analyze constant frequency contours obtained by plane-wave expansion method (PWE) to qualitatively study the relations between the structural parameters and the SC frequency bands for both TE and TM modes. The TE modes have the electric field perpendicular to the axis of the air rings, and the TM modes have the magnetic field perpendicular to the axis of the air rings. In Section 3, we adopt the finite difference time domain (FDTD) method to calculate the transmittance spectra of the SC waveguides in annular PC at both polarizations. By increasing \( r \) or reducing \( R \), the SC frequency band will move to a lower frequency. Through optimizing the \( r \) and \( R \), a overlap region of SC frequency bands between TE and TM modes may be obtained, in which the SC process will be polarization insensitive. In Section 4, we offer the conclusion of this paper.

2. Structural analyses
Lattices of circular holes or pillars are the dominant PC geometry. Annular PC, as depicted in the insets of Fig. 1, can be thought as the combination of dielectric pillars in low refractive index background and holes in high dielectric background [17]. In this paper, we chose to study square lattice PC formed by air rings in silicon
The region where $r < x < R$ is air ($\varepsilon_0$), the other is silicon, and $a$ is the PC lattice constant. Hence, two parameters are available to tailor the photonic dispersion curves for SC. First of all, we need to find the relation between $r$ and the SC frequency band, and then the relation between $R$ and the SC frequency band. On one hand, a large $R$ should be used, so that $r$ can be changed through a very broad range. But if the holes diameter is too large, then thin veins between holes may lead to fabrication difficulties and eventually mechanical instability [18]. Considering these tradeoffs, we set $R$ as 0.45$a$ with $r$ changing from 0$a$ to 0.35$a$. For the latter case, we set $r = 0a$ unchanged, while changing the $R$ from 0.25$a$ to 0.45$a$. This corresponds to a circular hole type PC, which means that the dependence found in this paper is also suitable to the normal PC geometries.

Fig. 1 shows the constant frequency contours of the second band of the extreme situations of annular PC for both TM and TE polarizations. For TM modes, in Fig. 1a, the lines centered at normalized frequency of 0.3607 form squares, and in Fig. 1b, the normalized frequencies centered at 0.2602 are the SC zone. So we expect that changing the $r$ can tune the SC center frequency from 0.2602 to 0.3607, while keeping $R = 0.45a$ unchanged. For TE modes, in Fig. 1c, the contours of normalized frequency between 0.3826 and 0.3693 form squares, and in Fig. 1d, the SC frequency zone is near 0.3101. In the same way, for TM modes, we can change the $r$ from 0$a$ to 0.35$a$ to tune the peak frequencies of SC between 0.3101 and 0.3826. Therefore, we find that there is a common frequency range for TE and TM modes by tuning the structure parameters. There would be some specific parameters, which can hold SC states for both polarization states.

3. Results and discussion

To accurately analyze the SC, FDTD method for various air rings configurations is adopted. Fig. 2 shows the scheme of SC waveguide studied by the method. Perfectly matched absorbing boundary layers are applied to the surroundings of the structure. The crystal is truncated at [0 1] surface according to the constant frequency contours analysis. A silicon strip waveguide of width 5$a$ is represented by the rectangle centered at the left, in which a Gaussian pulse beam is excited. The monitor is located at 32$a$ from the crystal boundary at the input port. The source and the monitor have a width 5$a$ and are parallel to the input port. The spectra are normalized with respect to the pulse source so as to eliminate interference from the reflection [9]. The frequency ranges of the spectra are selected according to the previous PWE analysis in Fig. 1.

Fig. 3 shows the TM spectra transmission curves with the same structure parameters of the outer radius $R = 0.45a$, and different inner radius $r$ of the air rings. The peak frequency of $r = 0.35a$ is in the normalized frequency range of 0.252–0.278, which matches well with the result from previous constant frequency contours. As expected, while the $r$ decreases, the peak frequency moves higher. But when the $r$ becomes very small and reaches approximately 0$a$, there are no obvious peaks. The loss of transmittance in these frequency ranges is caused by the existing states in higher bands, whose constant frequency contours are not flat in the $I\times X$ direction. We can see that the transmittance curves have a lot of small oscillations. It may mainly result from the reflections of the interface between dielectric zone and PC zone, which will be explained later.

Fig. 4 shows the TM spectra transmission curves of $r = 0a$, and varying $R$. Since the $r = 0a$ curve in Fig. 3 and the $R = 0.45a$ one in Fig. 4 are of the same parameters, the curves are also the same.
Comparing with Fig. 3, we can see that both methods can tune the frequency peaks very well, and the relations between the peak of the spectra and the dielectric volume are the same. While the dielectric volume increases, the transmittance peak shifts to lower frequency. Similar to the guide mode control [5] in PC waveguide, the phenomena of transmittance peak shifting can be qualitatively explained by the photonic band theory as follows. For PC with air holes in dielectric background, the higher band of the band structure is usually called as air band, and the lower band is called as dielectric band. When increasing the amount of dielectric, higher frequency modes can be pushed down and the band gets lower in the band structure. The constant frequency contours of the bands are also changed to lower frequency, and the SC bands move to lower frequency accordingly. So the peak frequency in the figure moves to lower frequency. It also can be understood by the effective medium theory, as the dielectric volume increases, the effective dielectric index increases accordingly and the bands in the band structure change to lower frequency. So the self-collimation bands move to lower frequency.

With the same method, the relations are also presented for TE modes. Fig. 5 shows the TE spectra transmission curves with various inner ring radius $r$ while $R = 0.45a$ is conserved, and Fig. 6 shows the TE spectra transmission curves with various outer ring radius $R$ and $r = 0a$. The $r = 0a$ in Fig. 5 and the $R = 0.45a$ in Fig. 6 are of the same parameters, so the curves are the same. Like the TM cases, changing either the $r$ or the $R$ can tune the frequency peaks of TE modes very well. The peak shifts to lower frequency while the dielectric volume increases. Because the large $R$ of the ring holes are usually used to obtain a large bandgap for TE modes, the low transmittances in the Fig. 5 are mainly caused by the loss of coupling external light source into PC. In Fig. 6, there are two peaks for $R = 0.25a$, and the right peak is caused by the SC state in higher bands of the annular PC.

From these transmittance spectra, we find that the TE modes are less sensitive to small values of $r$ and $R$ than the TM modes, but once they exceed a critical value, the modes are seriously influenced by both $r$ and $R$. Since there is an overlapping frequency range for TE and TM polarizations in our constant frequency contours analysis and also in the transmittance spectra, we can obtain a common frequency range for specific parameters $r$ and $R$ due to their different polarization sensitivities to $r$ and $R$. From that, we can obtain the polarization insensitive SC waveguides as expected. In the figures below, we show a polarization insensitive SC waveguide using this novel annular PC. As shown in Fig. 6, the loss of TE modes is more sensitive to the $R$, and a change of $r$ does not make much improvement. Also considering the limit of the tuning extent of $r$, we set $R$ to 0.325$a$, and then an optimized $r$ value of 0.15$a$ can be obtained accordingly. Fig. 7 shows the constant frequency contours of both TE and TM polarizations for the optimized annular PC. For TE modes, the SC frequency band observed is within normalized frequency 0.2659–0.2832, while for TM modes, the corresponding SC frequency band is centered at 0.2737. So there are common SC frequency bands for both the TE and TM polarizations in this structure.

Fig. 8 shows the TE and TM transmittance spectra of such polarization insensitive SC annular PC waveguide. The spectra are obtained through normalizing the transmittance spectra to a
position at 3a from the left crystal interface to exclude the coupling loss. And a method of using antireflection structures [20] is also adopted in this FDTD simulation to reduce the reflection oscillations of light beams at the interfaces between a two-dimensional PC and a homogeneous dielectric. As shown in Fig. 9, the crystal is truncated at the center of the rings. The truncated air rings in PC interface are modified to $r = 0.075a$ and $R = 0.225a$, which act as the anti-reflection layers. The anti-reflection layers should be optimized depending on the frequency. For a given frequency, the optimized anti-reflection layers will usually provide excellent performance with a broad bandwidth [20]. Compared with the previous transmittance curves, there is no serious oscillation in the transmittance spectra shown in the Fig. 8. This proves that oscillations in the previous transmittance spectra were mainly caused by the reflection. A comparison of the transmittance spectra to the bulk silicon case where no PC is presented is also provided in

Fig. 7. Constant frequency contours of the second band for the optimized square lattice annular PC, $R = 0.325a$ and $r = 0.15a$.

Fig. 8. Spectra of SC annular PC waveguide with $R = 0.325a$ and $r = 0.175a$ and the spectra of bulk silicon for both TE and TM polarizations.

Fig. 9. TE and TM field distribution of the simulation layouts with $\lambda = 1550$ nm, (a) Hz field distribution for TE modes and (b) Ez field distribution for TM modes. The right figures show the normalized field amplitude profile of the beams at the position 37.5a.
Fig. 8. Poor transmittances of less than 70% are obtained for both the TE and TM mode in the bulk dielectric, which shows that the SC is an excellent improvement to suppress the beam diffraction.

From Fig. 8, it is known that the normalized peak transmittances for the TE and TM polarizations nearly overlap in the same normalized frequency range. The TE modes have a higher transmittance and a wider bandwidth than the TM modes in this structure. A transmittance above 90% is obtained within normalized frequency bandwidth 0.2635–0.2814 for TE modes. Therefore, the polarization insensitive frequency bandwidth is determined by the transmittance of TM modes. A polarization insensitive waveguide is obtained in the normalized frequency range 0.262–0.280 with transmittance up to 80%, 0.267–0.278 with transmittance higher than 85%, and 0.271–0.277 with transmittance above 89%. The results fit in well with the constant frequency contours in Fig. 7.

If we set the lattice constant $a$ to 420.05 nm that corresponds to a center frequency of 1550 nm, a polarization insensitive waveguide in the frequency range 1500.4–1603.0 nm is obtained with transmittance above 80%. The field distributions shown in Fig. 9 are obtained by exciting a Gaussian beam with $\lambda = 1550$ nm at the input of the silicon waveguide in continuous-wave FDTD simulations. The right figures show the normalized field amplitude profile of the beams for the TE modes and TM modes at the position 37.5a, respectively. From the figures, we see that the SC for both TE and TM polarizations operates very well and the diffraction loss is very low in the PC zone.

4. Conclusion

In conclusion, using FDTD and PWE methods, we have analyzed and revealed the relations between the air ring size and the SC frequency bands for both TE and TM polarizations. The relations are also suitable for the usual hole and pillar type PCs. It shows that increasing the inner radius $r$ or decreasing the outer radius $R$ of the air ring will move the SC bands to lower frequency at both polarizations. However, the TE and TM SC bands are differently sensitive to the structure parameters tuning. Compared with normal PCs, the proposed annular PCs have more freedom to form polarization insensitive SC waveguides. At last, an efficient polarization insensitive SC waveguide with a broad band of 102.9 nm is demonstrated in a high dielectric contrast system. Using our methods, various polarization (or frequency) dependent or independent devices would be developed, such as polarization splitters, polarization insensitive waveguide bends and other dense wavelength division multiplexing devices. This work supports the intriguing potentials of SC and annular PC for on-chip integrated photonic circuit applications.

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References