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Polarization-insensitive self-collimation and beam splitter based on triangular-lattice annular photonic crystals

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This paper systematically investigates the self-collimation behavior in silicon-based triangular-lattice annular photonic crystals (PCs). It is found that, in comparison with normal air-hole PCs, annular PCs more easily suppress the separation between TE-2 and TM-2 bands along the Γ -M direction by increasing the inner radius of annular air rings. Such a feature is quite beneficial in the formation of a flat equi-frequency contour for both polarizations at the same frequency, which means a polarization-insensitive self-collimation (PISC) effect. Further analysis has shown that, to support PISC, the minimum ratio between the inner and outer radii of annular air rings will gradually increase as the outer radius changes from $0.25a$ to $0.49a$. When the ratio is fixed, the annular air rings with larger outer radius will provide wider common frequency area to realize PISC. We have also investigated the transmission feature for different annular PCs and chosen an optimal structure to illustrate the PISC effect. Finally, a polarization beam splitter has been proposed and demonstrated based on the unique PISC and band-gap feature in triangular-lattice annular PCs. © 2013 Optical Society of America

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1. INTRODUCTION

Since the pioneering work of John [1] and Yablonovitch [2] in 1987, photonic crystals (PCs) have attracted great interest due to their having a photonic band gap, based on which people can freely control the propagation of light by using perfect PCs or introducing kinds of defects to confine specific modes in the band gap. In the past several decades, extensive study on the photonic band gap in PCs has resulted in many useful applications, such as reflectors [3], waveguides and bends [4], fibers [5], couplers [6], cavities [7], etc. At the same time, in recent years, more and more interest has also been attracted by the unusual dispersion properties of PCs, such as negative refraction [8,9], slow light [10], and self-collimation [11]. Among these, the self-collimation in PCs provides a brand new way of confining light propagation without diffraction in the PCs, and many attractive applications have benefited from it, such as waveguides [12], beam bends and splitters [13,14], interferometers [15], optical switches [16], optical routers [17], resonators [18], optical interconnectors [19], etc. From the viewpoint of facilitating synchronous functions for both polarizations, it will be very useful if polarization-insensitive self-collimation (PISC) with low propagation losses can be realized in PCs. For instance, the polarization beam splitter, which is based upon the PISC in PCs, is very useful in future micronano photonic integrated chips.

To realize PISC, several approaches have been reported recently. These pioneering works were almost all focused

on square-lattice PCs. For instance, Shen *et al.* [20] investigated the possibility of PISC in a rod-type two-dimensional PC; however, the PISC was found to be realized only when a very large radius of dielectric rods was used. This is due to the separation of the second bands between different polarizations. To solve this problem, Zabelin *et al.* [21] successfully demonstrated the PISC in a hole-type two-dimensional PC and verified a new kind of polarization beam splitter in experiment. Subsequently, to improve the transmittance of self-collimated beams, Xu *et al.* [22] studied the PISC based on the lowest band in square-lattice PCs, rather than the second band in previous works.

In the present study, we will demonstrate that PISC can not only be realized in square-lattice, but also in triangular-lattice, PCs. In fact, the PISC in triangular-lattice PCs has rarely been reported. One important reason may be that in traditional rod-type or hole-type triangular-lattice PCs, it is difficult to suppress the separation of the second bands between different polarizations. To solve this problem, this paper will focus on the study of PISC in a structure known as triangular-lattice annular PCs. It is well known that a rod-type PC tends to support TM-polarization modes, whereas a hole-type PC typically favors TE-polarization modes. An annular PC [23] is usually constructed by merging a rod-type PC into a hole-type one, which means an annular air ring embedded in a dielectric background. As a result, compared with conventional rod-type PCs, the additional dielectric background will provide

extra support for TE-polarization modes than a pure air background. Similarly, the dielectric rods inside the air holes are sensitive to TM-polarization modes more than the pure air holes in conventional hole-type PCs. Recently, annular PCs have been demonstrated to be ideal candidates for realizing polarization-insensitive devices, since they have the unique ability to provide a suppressed band feature between different polarizations. For instance, Hou *et al.* [24] systematically studied the PISC in square-lattice annular PCs and indicated that annular PCs have more freedom to control the performance of PISC. In our previous study [25], the possibility of all-angle negative refraction and the super-lens effect was successfully demonstrated in triangular-lattice annular PCs.

This paper is organized as follows. In Section 2, we will present the main model and analyze bands and equi-frequency contour (EFC) features for different polarizations to qualitatively study the relations between the structural parameters of annular PCs and their self-collimation behavior. In Section 3, we will discuss the transmittance of different annular PCs and illustrate a clear PISC effect through a PC slab with definite thickness. In Section 4, we will give a design of polarization beam splitters based on the PISC and band-gap features in annular PCs. A brief conclusion will be made in Section 5.

2. BANDS AND EFC FEATURES

Figure 1 shows a model of a triangular-lattice annular PC in the X-Y plane. The air rings with outer radius R and inner

Fig. 1. Representative model for a triangular-lattice annular PC. The annular air rings with outer radius R and inner radius r are arranged in a triangular lattice (a is the lattice constant) and embedded in a silicon background.

radius r are arranged in a triangular lattice and embedded in a silicon background (the representative dielectric constant is 12 at 1550 nm). The TE-polarization modes have an electric field perpendicular to the Z axis of the air rings, and the TM-polarization modes have a magnetic field perpendicular to the Z axis of the air rings. As main calculation methods, a popular free software “MPB” [26], which treats the Maxwell’s wave equation as the Hermitian eigenvalue problem with the plane wave expansion technique, is utilized to obtain photonic band structures and EFCs of PCs.

We first investigated the band structures of such PCs. Figure 2 shows the band structures of a triangular-lattice annular PC when the outer radius of the air rings is fixed and the inner radius changes. When the inner radius r is 0, which indicates a conventional hole-type PC, there is no band gap for TM polarization but a big gap between the lowest two TE bands. It can be obviously found that, as the inner radius increases, there is still no band gap for TM polarization, but the band gap for TE polarization will gradually shrink. This is due to the contribution of inner dielectric rods, which can compensate for the phase of TE-polarization modes and gradually pull down the TE-2 band to lower frequency, finally resulting in a decreased TE band gap and a closer distance between TE-2 and TM-2 bands. In fact, the most important reason to prevent the conventional PCs from supporting a similar dispersion curve for different polarizations is the unavoidable phasing difference and band separation in pure periodically arranged dielectric rods or air holes. However, the annular PC can naturally combine the band feature of a pure rod-type and a pure hole-type one to show a less separated dispersion curve along some propagation vectors. As a result, the annular PC is regarded as a better candidate to realize polarization-insensitive devices than conventional PCs.

To further investigate the possibility of PISC in the triangular-lattice annular PCs, we have systematically calculated the corresponding EFCs for TE-2 and TM-2 bands. The EFCs are actually a series of cross sections of the full band surface at different constant frequency. Since the light propagation in a PC is controlled by its dispersion surfaces and the direction of light propagation is given by the group velocity, which is

Fig. 2. TE (solid lines) and TM (dashed lines) band structures of the triangular-lattice annular PC when $R = 0.35a$ and (a) $r = 0$, (b) $r = 0.1a$, (c) $r = 0.2a$, and (d) $r = 0.3a$, respectively. The yellow area (or gray area for black and white version) represents the band gap of TE polarization.

Fig. 3. TE-2 and TM-2 EFCs of the triangular-lattice annular PC when $R = 0.35a$ and (a) $r = 0$, (b) $r = 0.2a$, and (c) $r = 0.3a$, respectively.

perpendicular to the EFCs, the self-collimating phenomenon usually happens when the EFC at a specific frequency is flat and PISC may be realized when the above condition can be satisfied for both polarizations. As shown in Fig. 3, when the inner radius r is 0, the corresponding EFCs for the TE-2 band show flat shape perpendicular to the Γ -M direction when the normalized frequency is roughly between $0.3835\omega a/2\pi c$ and $0.3933\omega a/2\pi c$, while the effective flat EFCs for the TM-2 band can be observed in a much lower frequency range, which is about 0.2415 – $0.2573\omega a/2\pi c$. This means there is no possibility to support the PISC in such a PC. However, when the inner radius increases, the frequency range of effective flat EFCs for TE-2 and TM-2 bands will gradually become closer. In particular, when r is $0.3a$, which is about $0.857R$, there occurs a common frequency range to show flat EFCs for both polarizations. The predicated frequency range is about 0.2874 – $0.3043\omega a/2\pi c$ with a relative bandwidth of about 5.71%.

Based on the above analysis, it can be found that the triangular-lattice annular PC has the possibility to support PISC when the ratio between the inner and outer radii of

the air rings is larger than a certain value. Figure 4 shows the scanned results of the minimum possible value of such ratio and the corresponding filling factor of air rings [defined as $2\pi(R^2 - r^2)/\sqrt{3}a^2$] when the outer radius changes from $0.25a$ to $0.49a$. We can observe that both the minimum ratio and the filling factor will nearly linearly increase with R in the same direction, and the filling factor is much more sensitive to the change of R than the minimum ratio. This implies that the minimum ratio is a critical factor to dominate the occurrence of PISC in triangular-lattice annular PCs and the filling factor of air rings can more sensitively influence PISC.

To gain some further insight about the influence of the filling factor on the performance of PISC, we have calculated the band structures for different triangular-lattice annular PCs when the ratio r/R is fixed to be 0.9 and the outer radius R is assumed to be $0.3a$, $0.4a$, and $0.49a$, which corresponds to a filling factor of 6.2%, 11.0%, and 16.5%, respectively. From Fig. 5, it can be found that, under the same ratio, the annular PC with a larger filling factor of air rings will have less separation between the TE-2 and TM-2 bands near the high-symmetry point Γ in the first Brillouin zone. On the other hand, such separation will gradually get bigger along the Γ -M direction. This means that the filling factor may sensitively influence the effective frequency range of PISC. To make a verification of the above conclusion, the corresponding EFCs were also calculated as shown in Fig. 6. It should be pointed out that, from Fig. 5, we can find that the main frequency area of the second and third bands is overlapped. Hence, an overlapping of contours with both second and third bands is presented in Fig. 6 to show the influence of high-order band on PISC. By carefully calculating the second band, the predicated frequency range to support PISC is about 0.2902 – $0.2946\omega a/2\pi c$, 0.2747 – $0.2967\omega a/2\pi c$, and 0.2744 – $0.2755\omega a/2\pi c$ for three PCs. The corresponding relative bandwidth is about 1.5%, 7.7%, and 0.4%, respectively. In particular, Fig. 6 shows specific EFCs at central frequency of about $0.292\omega a/2\pi c$, $0.286\omega a/2\pi c$,

Fig. 4. To realize PISC, the minimum possible value of the ratio between the inner and outer radii of the annular air rings when the outer radius R varies from $0.25a$ to $0.49a$.

Fig. 5. TE (solid lines) and TM (dashed lines) band structures of the triangular-lattice annular PC when $r = 0.9R$ and (a) $R = 0.3a$, (b) $R = 0.4a$, and (c) $R = 0.49a$, respectively.

and $0.275 \omega a/2\pi c$ for three PCs, respectively. It can be found that, at these special frequencies, the contour of the third band resembles a gate that encloses the contour of the second band. Such a gate can influence the performance of PISC for both TE and TM polarizations because the beam will suffer extra scattering when it propagates along different angles between Γ -M and Γ -K directions. However, as the filling factor of an annular PC gradually increases, such a gate will gradually open and even finally disappear [see Fig. 6(c)]. Consequently, to realize PISC with large relative bandwidth in the triangular-lattice annular PCs, and in order to decrease the influence from the higher-order band, a relatively large ratio r/R and a relatively large filling factor of air rings are required simultaneously.

3. TRANSMISSION AND PISC EFFECT SIMULATIONS

To characterize the performance of PISC, besides the relative bandwidth, the beaming efficiency is also very important. As a result, we have also systematically investigated the transmission behavior when light is propagating through the triangular-lattice annular PCs with different structural parameters. To tackle the transmittance problem and in order to avoid

time-consuming calculation, an efficient finite-difference time-domain (FDTD) technique [27] was adopted, which is based on the pulse light source and the fast Fourier transform method. In particular, a Gaussian pulse point source with a width of $4a$ was set in front of a 19-layer triangular-lattice annular PC (along the Γ -M direction), while a time monitor with a width of $4a$ was put near the other termination of the PC. The distance from both the light source and the monitor to the PC-air interface is $2a$. To eliminate the influence of impedance mismatch at the input PC-air interface, a silicon strip waveguide of a width of $4a$ is used to connect the source with the input surface of the PC. The final normalized transmittance was obtained as shown in Fig. 7. From Figs. 7(a1) and 7(a2), it can be found that, when R is fixed to be $0.35a$, the transmission peaks for annular PCs are obviously larger than in the case of bulk silicon ($r = R$). When r/R changes from 0.86 to 0.9 , the transmittance spectrum shows a small red shift, while there is an apparent separation of peaks for different polarizations. This means that it is difficult to reach large transmission for both polarizations at the same frequency by adjusting the ratio of r/R . However, when the ratio r/R is fixed to be 0.9 , we can see from Figs. 7(b1) and 7(b2)

Fig. 6. TE-2 and TM-2 EFCs of the triangular-lattice annular PC when $r = 0.9R$ and (a) $R = 0.3a$, (b) $R = 0.4a$, and (c) $R = 0.49a$, respectively.

Fig. 7. (a1) and (a2) Normalized transmittance in a 19-layer triangular-lattice annular PC when $R = 0.35a$ and $r = 0.86R$, $r = 0.9R$, and $r = R$ for different polarizations. (b1) and (b2) Normalized transmittance in a 19-layer triangular-lattice annular PC slab when $r = 0.9R$ and $R = 0.25a$, $R = 0.35a$, and $R = 0.45a$ for different polarizations.

that the transmittance spectrum is more sensitive to changes in the outer radius of air rings. In particular, the triangular-lattice annular PC with $R = 0.45a$ shows a better peak response for either TE or TM polarization when the frequency is around $0.275 \omega a/2\pi c$. As a result, to reach high transmittance for both polarizations, a relatively large outer radius is recommended.

Following the above analysis, we will give a specific example to illustrate PISC in the triangular-lattice annular PCs. We consider a PC when $R = 0.45a$ and $r = 0.9R$. The corresponding EFCs were calculated as shown in Fig. 8. From Figs. 8(a1) and 8(a2), we can predicate possible frequencies to support PISC in the range of 0.2771 – $0.2922 \omega a/2\pi c$, the relative bandwidth of which is about 5.3%. In particular, Fig. 8(b) shows the combined EFCs of the second and third bands at frequency $0.279 \omega a/2\pi c$. It can be found that both TE-2 and TM-2 EFCs are almost flat and perpendicular to the Γ -M direction. At the same time, the TM-2 EFC is closer to the EFC of the air background than TE-2 EFC, which means the TE-polarization mode will have a larger range of incident angle

for self-collimation and the effective angle of PISC is mainly decided by the TM-2 EFC. At the same time, compared with TE-2 and TM-2 EFCs, the gate of TE-3 EFC is obviously wider than TM-3 EFC. The PISC based on TE-2 EFC will nearly suffer no influence from TE-3 EFC, whereas a little interference from TM-3 EFC is unavoidable on the PISC performance based on TM-2 EFC when the beam propagates with large incident angles.

To show a clear PISC effect, a further simulation was done by still using the FDTD method in a 19-layer triangular-lattice annular PC (along the Γ -M direction). However, the Gaussian pulse point source was replaced by a continuous one with a width of $4a$, and the time monitor was replaced by a power type with a width of $4a$. Since the cutoff value at PC terminations can strongly affect the total transmittance, we have also scanned the relationship between cutoff value δ_y and the time-average power passing through the whole monitor. As shown in Fig. 9(a), the transmittance oscillates periodically as the cutoff value changes and there is an apparent phasing difference of oscillation between TE and TM polarizations. To keep

Fig. 8. TE-2 (a1) and TM-2 (a2) EFCs of the triangular-lattice annular PC when $R = 0.45a$ and $r = 0.9R$. (b) Combined TE-2 and TM-2 and the air background EFCs at normalized frequency $0.279 \omega a/2\pi c$.

Fig. 9. (a) Relationship between cutoff value δ_y and transmittance. (b) and (c) show the magnetic/electric field distributions in the whole X-Y plane for both polarizations when $\delta_y = 0.09a$. The subfigure on the top of (b) or (c) is the cross-section normalized absolute magnetic/electric field at the location of the monitor. The solid lines represent the termination of the PC, and the dashed line represents the location of the monitor. The normalized frequency used in simulations is $0.279 \omega a/2\pi c$.

high transmittance for both polarizations, we have chosen a specific cutoff value, i.e., $\delta_y = 0.09a$, to finally give a simulation of the PISC effect. From Figs. 9(b) and 9(c), we can see a clear self-collimated beam through the whole PC for both polarizations. The output beam in the air background can also keep a Gaussian-like distribution from the cross-section map of the magnetic/electric field for either TE or TM polarization.

4. POLARIZATION BEAM SPLITTER DESIGNS BASED ON PISC

Based on the PISC in triangular-lattice annular PCs, we have further proposed a polarization beam splitter to verify the possibility of such PISC in realizing polarization-insensitive devices. As illustrated in Fig. 10, the polarization beam splitter is constructed by two different triangular-lattice annular PCs. The structural parameter of the main annular PC is in agreement with that in Fig. 8, while the other defect annular PC, which is enclosed by the dashed line, has a different inner radius r' of air rings compared with the main PC. As shown

Fig. 10. Schematic of a polarization beam splitter based on different triangular-lattice annular PCs. The main triangular-lattice annular PC has the same structure as in Fig. 8, while the defect triangular-lattice annular PC enclosed by the dashed line has a different inner radius r' of air rings. The inset on the right side of the defect PC gives a simple schematic diagram to illustrate the working mechanism.

in the inset of Fig. 10, the working mechanism of such a polarization beam splitter resembles the one proposed in Zabelin's work [21]. The main annular PC acts as a PISC device and the defect PC actually works as a polarization-selective reflector based on the band-gap feature of the defect PC. For instance, as shown in Fig. 11, when $R = 0.45a$ and $r' = 0.33a$, the defect PC only shows a band gap for TE polarization. Since the working frequency $0.279 \omega a/2\pi c$ lies in the TE band gap, the defect PC will nearly totally reflect the TE-polarization light and let the TM-polarization light penetrate it accompanied with a positive or negative refraction.

Usually, the performance of a polarization beam splitter can be evaluated by the extinction coefficient at the output. Take the inset in Fig. 10 as an example; the extinction coefficient at output 1 and output 2 can be written as $-10 \log(I_{1-TE}/I_{1-TM})$ and $-10 \log(I_{2-TM}/I_{2-TE})$, respectively. To optimize the extinction coefficient at both outputs, we have investigated the relationship between the extinction coefficient and the inner radius r' of air rings. As shown in Fig. 12(a), the extinction coefficient at output 1 will gradually decrease when r' increases, while there is an obvious peak in

Fig. 11. TE (solid lines) and TM (dashed lines) band structures of the defect triangular-lattice annular PC when $R = 0.45a$ and $r' = 0.33a$. The yellow area (or gray area for black and white version) represents the band gap of TE polarization.

Fig. 12. (a) Relationship between the inner radius r' and the extinction coefficient at two outputs. (b) and (c) show the absolute magnetic/electric field distributions in the whole X-Y plane for both polarizations when $r' = 0.347a$. The subfigure near the output shows the cross-section normalized magnetic/electric field at the location of the monitor, which is marked by the dashed line and is $2a$ away from the output surface. The cutoff value at all terminations is still $0.09a$.

the curve for output 2. Finally, we chose a specific value of r' , i.e., $r' = 0.347a$, to give a simulation for the polarization beam splitting effect. As shown in Figs. 12(b) and 12(c), when the working frequency is $0.279 \omega a / 2\pi c$, the TE-polarization light is collimated in the main triangular-lattice annular PC and is nearly totally reflected by the defect annular PC, while the TM-polarization light can also be collimated in the main triangular-lattice annular PC but penetrate the defect annular PC with a slight positive refraction.

5. CONCLUSION

In conclusion, we have successfully demonstrated the PISC behavior in silicon-based triangular-lattice annular PCs. Since the annular PCs possess a combined band structure of conventional rod-type and hole-type PCs, we can easily obtain a much suppressed band feature that has less separation between the TE-2 and TM-2 bands along the Γ -M direction. Such a unique ability of annular PCs is very helpful in forming a series of common frequencies with nearly flat EFCs for both polarizations, finally resulting in PISC in such PCs. It has been found that the ratio between the inner and outer radii of annular air rings can dominate the occurrence of PISC and the filling factor of air rings will influence the performance of PISC more sensitively. In theory, to realize PISC with a large relative bandwidth and high transmittance, and in order to decrease the influence from the higher-order band, a relatively large ratio between inner and outer radii and a relatively large outer radius are both required. However, it should be addressed that an annular PC with a larger ratio between inner and outer radii will be more difficult to fabricate than conventional PCs in practical application. This issue can be more serious in the infrared band. As a result, the inner/outer ratio should be considered as small as possible to facilitate the fabrication. At the same time, to improve the fabrication precision of annular PCs as much as possible, some useful approaches can be adopted, such as using ZEP520A as an electron-beam resist [28] and controlling the exposing time during the electron-beam lithography process. Besides the polarization beam splitter, some other potential devices, including polarization-insensitive one-to-six waveguides, polarization-insensitive Y-shaped beam splitters, and 60 deg optical switches and bends, are also worthwhile to study based on such PISC.

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