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Study on the polarization-insensitive self-collimation behavior in two-dimensional all-solid photonic crystals

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Abstract

Due to unavoidable separation of bands for different polarizations, it is usually difficult to realize polarization-insensitive self-collimation (PISC) from conventional rod-type two-dimensional photonic crystals (PCs). In this paper, we have systematically investigated the band, equi-frequency contours, and transmission properties of a special two-dimensional PC that quite resembles the structure of conventional rod-type PCs. By only replacing the air background in rod-type PCs with dielectric background, the so-called all-solid two-dimensional PC can show much closer bands than conventional rod-type PCs. Such suppressed band feature is quite beneficial to the formation of flat equi-frequency contours for both polarizations at the same frequency, namely a PISC effect. By further comparing the PISC in different all-solid PCs and optimizing the cutoff value at PC terminations, we have obtained some useful rules to control the performance of PISC. Finally, based on the special PISC effect in all-solid PCs, we have also given two specific examples to illustrate the potential ability of all-solid PCs in realizing novel polarization-insensitive functional devices.

Keywords: polarization-insensitive self-collimation, all-solid photonic crystals, bends and splitters

1. Introduction

In the past several decades, people have paid great attention to photonic crystals (PCs) [1,2], which belong to a type of artificial material that is usually composed of periodically arranged dielectric rods in air background or air holes in dielectric-material background. The most important feature of PCs is the existence of photonic band gaps, based on which people can freely control the behavior of photons and have developed many useful devices, including reflectors, waveguides and bends, fibers, couplers, cavities, etc. In recent years, more passion is being transferred from band gaps to the unusual dispersion properties of PCs, such as negative refraction [3, 4], slow light [5], and self-collimation. In particular, self-collimating phenomenon means that the electromagnetic waves can avoid significant spreading of energy and can keep almost linearly directions as they propagate in PCs. This phenomenon was initially demonstrated by Kosaka *et al* [6] in three-dimensional PCs and Wu *et al* [7] in two-dimensional PCs. Subsequently, extensive studies were focused on self-collimation and many novel functional devices have been reported, including waveguides [8], beam bends and splitters [9, 10], interferometers [11], optical switches [12], optical routers [13], resonators [14], and couplers [15, 16]. However, most of the previous works are only focused on a certain polarized wave, the transverse-electric (TE) or transverse-magnetic (TM) polarization. From the viewpoint of application in future photonic integrated system, it will be

very useful if self-collimation with low propagation losses can be realized at the same working frequency for both polarizations, which means a polarization-insensitive self-collimation (PISC).

To realize PISC in PCs, people have tried several approaches. In general, these approaches can be summarized as three types according to the basic structure of PCs. The first type is hole-type two-dimensional PCs, which have been most extensively researched. One remarkable work is reported by Zabelin *et al* [17], in whose research, the PISC has successfully been demonstrated from a hole-type two-dimensional PC with square lattice and a novel polarization beam splitter was proposed and verified in experiment. Xu *et al* [18] systematically investigated the possibility of PISC based on the lowest band in hole-type two-dimensional PCs with different lattice types. They pointed out that the square-lattice PC is an ideal candidate to provide a large relative bandwidth of PISC and the PISC working on the lowest band may show an improved transmission than the second band that is used in most previous works. Very recently, Wu *et al* [19] have reported an interesting PISC phenomenon in a hole-type two-dimensional PC with rhombic-lattice. Such PC can support all-angle PISC when the shape of rhombic lattice is appropriately adjusted. The second type is rod-type two-dimensional PCs. It has been found that the rod-type two-dimensional PCs can also support PISC, however, it usually need a very large radius of dielectric rods. For example, in Shen's work [20], PISC was achieved in a square-lattice two-dimensional PC only when radius of dielectric rods is $0.5a$ (a is the lattice constant). This problem is mainly due to the unavoidable and large separation of bands for different polarizations. As a result, it is usually difficult to realize PISC from conventional rod-type two-dimensional PCs with square or triangular lattice and such type of PCs has been rarely further studied in recent years. The third type is composite-type two-dimensional PCs. The representative one of such type is two-dimensional annular PCs. Since a rod-type PC tends to support TM-polarization modes whereas a hole-type PC typically favorites TE-polarization modes, an annular PC which is usually constructed by merging a rod-type PC into a hole-type one has been demonstrated to be an ideal candidate for polarization-insensitive devices [21-23]. As far as the PISC phenomenon is concerned, several works [24-27] have been reported based upon two-dimensional annular PCs. For instance, Hou *et al* [24] systematically studied the PISC in square-lattice annular PCs and indicated that the annular PCs have more freedom to control the performance of PISC. In Turdnev's work [25], a modified square-lattice annular PC that is composed of dielectric rods with off-centered air holes is thoroughly studied. Such annular PC can not only easily support PISC, but also can show PISC with different desired directions by changing the angle of off-centered air holes. Alternatively, in our previous study [26], the PISC based on a triangular-lattice annular PC has also been studied. It is found that it is quite easier to realize PISC in such PC than conventional rod-type triangular-lattice annular PC.

This paper is also focused on the study of PISC in two-dimensional square-lattice PCs. However, different from previous works, the PCs we are concerning here belong to neither the hole-type nor rod-type PCs. Instead, they are actually defined as a new type of PCs called as all-solid PCs, in which the dielectric rods are embedded in dielectric background, rather than air background. The all-solid PCs can be regarded as a combined type of hole-type and rod-type PCs and their dispersion properties may resemble that in both hole-type and rod-type PCs to some extent. As a result, the all-solid PCs have a potential ability to support both TE and TM modes simultaneously. In fact, such PC can also be regarded as an extremely case of an annular PC when the radius of annular air rings is zero. Since the annular air rings can sensitively affect the performance of PISC and they are usually difficult to be precisely fabricated in experiment [26], consequently, the all-solid PCs have obvious advantage in fabrication and may support more stable PISC performance compared with conventional annular PCs. In particular, in our previous work [28], we have successfully demonstrated a polarization-insensitive negative refraction behavior in a triangular-lattice all-solid PC. In the present study, we will also demonstrate a PISC phenomenon in the square-lattice all-solid PCs and we will give two examples of functional devices based on PISC.

2. The bands and PISC behavior in all-solid PCs

Figure 1 shows the model of two square-lattice all-solid PCs in x-y plane. One PC has periodically arranged circular dielectric rods (ϵ_1) embedded in dielectric background (ϵ_2), while in the other PC the circular dielectric rods are replaced by square dielectric rods. In particular, the TE-polarization modes have electric field perpendicular to the z-axis of dielectric rods, and the TM-polarization modes have magnetic field perpendicular to the z-axis of dielectric rods. In following discussions, the photonic band and corresponding equi-frequency contours (EFCs) feature of PCs for both polarizations are calculated by a free software ‘MPB’ [29], which treats the Maxwell's wave equation as the Hermitian eigenvalue problem with the plane wave expansion (PWE) technique. The transmission and field distribution of each PC are simulated by the finite-difference time-domain (FDTD) technique.

We firstly discuss the band feature of above two kinds of all-solid PCs. To make a comparison, the band structures of conventional rod-type PCs are also considered here. As illustrated in Fig. 2(a), when $\epsilon_1=1$ and $\epsilon_2=12$, which means silicon rods in air background, there is an obvious separation between TE-2 and TM-2 bands along Γ -X direction. However, when the air background is replaced by a SiO₂ background ($\epsilon_1=2.334$ at 1550 nm), seen in Fig. 2(b), the dispersion curves of TE bands are dramatically changed in the whole 1st Brillouin Zone. This is attributed to the phase contribution of SiO₂ background. In particular, the TE-2 band is effectively suppressed to lower frequencies, resulting in a closer distance between TE-2 and TM-2 bands along Γ -X direction. Because the light propagation in a PC is controlled by its dispersion surfaces and the direction of light propagation is given by the group velocity, so less separated dispersion surfaces between different polarizations are very beneficial to support an identical or very similar prorogation behavior for different polarized light at some common frequencies. When it turns to the PC case as shown in figure 1(b), similar band feature can be found as shown in figures 2(c) and (d). Consequently, we can conclude that, under the same condition, the square-lattice all-solid PCs have bigger chance to support polarization-insensitive behavior of light propagation than conventional rod-type PCs.

In almost all previous works, the EFCs have been widely used to verify the self-collimation behavior. 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 perpendicular to the EFCs, as a result, the self-collimating phenomenon usually occurs when a flat EFC is available at a specific frequency. Usually, for a square-lattice PC, the shape of EFC is nearly square to support the self-collimating phenomenon. Figure 3 shows the corresponding EFCs for TE-2 and TM-2 bands in figure 2. It can be clearly observed that, under the same condition, there is no big difference between the EFCs for TM-2 band in conventional PCs [figures 3(a) and (c)] and all-solid PCs [figures 3(b) and (d)]. Both kinds of PCs can support self-collimation phenomenon at some frequencies close to point Γ . However, when it turns to TE polarization, only the TE-2 band of all-solid PCs can show nearly square EFCs at some frequencies close to point Γ , while there is an obvious vacant area of EFCs for conventional PCs. It means that under such condition, only all-solid PCs have possibility to support PISC. This conclusion is in good agreement with that is made from the band analysis in figure 2. In particular, the predicated working frequency range of PISC is about $0.3614\text{--}0.3701 \omega a/2\pi c$ and $0.3418\text{--}0.3529 \omega a/2\pi c$ for all-solid PCs in figures 2(b) and (d), respectively.

In following paragraphs, we will further investigate the transmission behavior in two kinds of square-lattice all-solid PCs when different r (i.e. the radius of circular dielectric rods or the half edge length of square dielectric rods) is considered. By choosing an appropriate value of r , we will give clear FDTD simulations to illustrate the PISC phenomenon in all-solid PCs and discuss the relationship between the transmission and cutoff value at PC terminations.

Figure 4 shows the normalized transmittance in a 20-layer square-lattice all-solid PC with circular rods and square rods respectively. In order to avoid time-consuming calculation, an efficient FDTD technique which is based on the pulse light source and fast-Fourier transform method [30] was adopted. In particular, a Gaussian pulse point source with width of $0.5a$ was set in front of the input surface of PC along Γ -X direction, while a time monitor with width of $0.5a$ was put near the output surface of PC. The distance from both light source and monitor to PC/air termination is $2a$. It can be found from Fig. 4 that, when r increases, the

peak of transmittance will gradually shift to lower frequency for both polarizations in either circular-rods or square-rods all-solid PC. However, the shift velocity is different between TE and TM polarizations. When r is relatively small, the TE polarization is more insensitive to the frequency than TM polarization, and as r increases, the shift sensitivity for both polarizations will gradually get closer. In particular, when $r=0.35a$, the frequency difference of peak location for TE and TM polarizations is smaller than other values of r , and the peak value of transmittance is also relatively satisfactory. As a result, in following discussions, all PCs are studied when $r=0.35a$.

Figure 5 shows the TE-2 and TM-2 EFCs of two kinds of square-lattice all-solid PCs when $r=0.35a$. As shown in figure 5 (a1), for the case of square-lattice all-solid PC with circular rods, the predicated working frequency range of PISC is about $0.33\text{--}0.34 \omega a/2\pi c$ with a relative bandwidth of 2.99%. A further combined TE-2, TM-2, and the air background EFCs at normalized frequency $0.333 \omega a/2\pi c$ are presented in figure 5(a2). We can find that at this frequency both polarizations have nearly square-shape EFC and the EFC for TE-2 band has closer distance to the EFC for air background than TM-2 band. This means that the EFC for TE-2 band has larger working incident angle to support self-collimation behavior than TM-2 band. At the same time, we can find from figures 4(a1) and (a2) that, at this frequency, the transmittance for TE and TM polarizations can almost simultaneously reaches maximum value. Consequently, we will choose working frequency as $0.333 \omega a/2\pi c$ in following simulations and designs. Similarly, when it turns to the case of square-lattice all-solid PC with square rods, as shown in figures 5(b1) and (b2), the predicated working frequency range of PISC is about $0.28\text{--}0.29 \omega a/2\pi c$ with a relative bandwidth of 3.51%. In particular, at frequency $0.283 \omega a/2\pi c$, the best square-shape EFC is available for both TE-2 and TM-2 bands. From figures 4(b1) and (b2), it can be found that this frequency nearly reach the peak location for TM polarization and is centered between two adjacent peaks in the curve for TE polarization. Furthermore, we can find that, compared with all-solid PC with circular rods, the EFCs for both TE-2 and TM-2 bands in all-solid PC with square rods are farther away from the EFC of air background. This means that at frequency $0.283 \omega a/2\pi c$, such PC has relatively narrow working incident angle to support self-collimation behavior than the circular-rods type one.

To directly observe the PISC effect in square-lattice all-solid PCs, we have made several corresponding FDTD simulations to illustrate the magnetic/electric filed distributions in PCs. This time, all PCs were still considered to be 20 layers. However, the Gaussian pulse point source was replaced by a continuous one with width of $4a$. The final results are shown in Fig. 6. It can be clearly found from figures 6(a1) and (a2) that, a self-collimated beam is available for both TE and TM polarizations when working frequency is $0.333 \omega a/2\pi c$ in the circular-rods type PC. In particular, the cross-section map of normalized magnetic/electric filed at PC/air interface shows several parallel peaks and the output beam can also keep nearly straight waveform. When it turn to the case of square-rods type PC, we can still find an ideal self-collimated beam for the TE polarization, but the performance of TM polarization gradually gets worse when light is propagating along Γ -X direction. The main reason is due to the relatively narrow working incident angle as mentioned above in figure 6(b2). Consequently, in practical application, the square-lattice all-solid PC with circular rods is more recommendable to support PISC.

Usually, due to the Fresnel reflection losses at PC/air interface, the cutoff value at PC/air interfaces can strongly affect the performance of self-collimation. As a result, we have investigated the relationship between cutoff value δ_x (along Γ -X direction) and total transmittance of the output beam. As shown in figure 7, for either circular-rods type PC or square-rods type PC, the transmittance oscillates periodically as the cutoff value changes and there is slight phasing difference of oscillation between TE and TM polarizations. In practical application, a specific cutoff value, i.e. $\delta_x=0.11a$ in Fig. 7(a) and $\delta_x=0.12a$ Figure 7(b), can be considered to keep high transmittance for both polarizations.

3. Examples of functional devices based on PISC in all-solid PCs

In this section, we will give two specific examples of functional devices based on PISC in all-solid PCs. In particular, the all-solid

PC, the cutoff value at PC/air interfaces, and the working frequency used here are in agreement with that in figure 7(a). As shown in figure 8(a), the first instance is a 90-degree waveguide bend that is constructed by introducing a parallelogram air defect into an all-solid PC with circular rods. Both TE and TM light will be reflected by the air mirror. For such a bend, we can define the bend efficiency as I_1/I_0 . The second instance is a polarization beam splitter [seen in figure 8(b1)] which is constructed by replacing a parallelogram area of all-solid PC with another defect PC. The defect PC is composed of air holes with radius r' in silicon background. As shown in the inset of figure 8(b1), the working mechanism of such polarization beam splitter resembles the one proposed in Zabelin's work [17]. For example, when $r'=0.45a$, the defect PC exhibits a TE band gap [seen in figure 8(b2)] that can cover the working frequency $0.333 \omega a/2\pi c$ while no TM band gap is available at this frequency. As a result, the TE-polarization light will be reflected by the defect PC while the TM-polarization light can pass through the defect PC 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, which can be further written as $-10\log(I_{1-TE}/I_{1-TM})$ and $-10\log(I_{2-TM}/I_{2-TE})$ for output 1 and output 2, respectively.

Since the cutoff value at the defect/PC interface, represented by δ , can influence the final performance, we have investigated the relationship between cutoff value δ and bend efficiency. As shown in figure 9(a), when $\delta=0.51a$, both TE and TM polarizations show relatively high bend efficiency. At this specific value, we have made a FDTD simulation to show the bending effect. The magnetic/electric field distributions in figures 9(a) and (b) indicate a clear self-collimated and nearly totally reflected beam for TE and TM polarizations. At the same time, the output beam can still keep Gaussian-like profile. Similarly, in order to optimize the extinction coefficient at both outputs, we have investigated the relationship between the extinction coefficient and the cutoff value δ . As shown in figure 10(a), the extinction coefficient at both output 1 and output 2 will gradually oscillate as the cutoff value increases. We chose a specific value $\delta=0.56a$ to make a simulation for the polarization beam splitting effect. As can be observed from figures 10(b) and (c), when the working frequency is $0.333 \omega a/2\pi c$, the TE-polarization light is collimated in the main all-solid PC and highly reflected by the defect PC, while the TM-polarization light can also be collimated in the main PC but will penetrate the defect PC with a slight positive refraction. The final output beam can also keep Gaussian-like profile. To further improve the performance of such polarization beam splitter, an anti-reflection layer [31] can be used at the defect/PC interface to enhance the transmission of TM-polarization light in defect PC.

4. Conclusions

To sum up, we have investigated the PISC behavior in two-dimensional square-lattice all-solid PCs. When silicon rods are embedded in SiO_2 background, the all-solid PCs can show much suppressed TE-2 band compared with conventional rod-type PCs composed of silicon rods in air background. Such special feature is attributed to the phasing contribution of SiO_2 background, thus make it much easier to realize PISC effect than conventional rod-type PCs. We have further compared the PISC behavior in two kinds of all-solid PCs which have circular silicon rods and square silicon rods, respectively. It has been found that, due to relatively large working incident angle, the circular-rods type all-solid PCs are more recommendable to support PISC with better performance than square-rods type PCs. Based on such all-solid PCs, we have further verified two examples of functional devices, i.e. a 90-degree waveguide bend and a polarization beam splitter. These designs show the potential ability of all-solid PC in realizing kinds of attractive polarization-insensitive devices which have useful application in future micro-nano photonic integrated chips.

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Figures

Fig. 1. (a) Schematic of a two-dimensional square-lattice PC with circular dielectric rods (ϵ_1) embedded in dielectric background (ϵ_2), (b) Schematic of a two-dimensional square-lattice PC with square dielectric rods (ϵ_1) embedded in dielectric background (ϵ_2), (c) The 1st Brillouin Zone of square lattice PCs. a is the lattice constant and the radius of circular dielectric rods or the half edge length of square dielectric rods is represented by r .

Fig. 2. (a) and (b): Band structures of the square-lattice PC with circular dielectric rods when $r=0.3a$ and different dielectric background are considered. (c) and (d): Band structures of the square-lattice PC with square dielectric rods when $r=0.3a$ and different dielectric background are considered.

Fig. 3. The corresponding TE-2 and TM-2 EFCs of the square-lattice PCs as shown in figure 2.

Fig. 4. The normalized transmittance of TE and TM modes in a 20-layer square-lattice all-solid PC with circular rods [(a1) and (a2)] and square rods [(b1) and (b2)] when $r=0.15a$, $r=0.25a$, $r=0.35a$, and $r=0.45a$ respectively.

Fig. 5. The TE-2 and TM-2 EFCs of the square-lattice all-solid PC with circular rods (a1) and square rods (b1) when $r=0.35a$. (a2) The combined TE-2, TM-2, and the air background EFCs at normalized frequency $0.333 \omega a/2\pi c$ for all-solid PC with circular rods. (b2) The combined TE-2, TM-2, and the air background EFCs at normalized frequency $0.283 \omega a/2\pi c$ for all-solid PC with square rods.

Fig. 6. The magnetic/electric field distributions in the whole x-y plane for both polarizations. (a1) and (a2) represent the case of square-lattice all-solid PC with circular rods while (b1) and (b2) represent the case of square-lattice all-solid PC with square rods. The sub figure on the right of each figure is the cross-section normalized absolute amplitude of magnetic/electric field at the output surface of PC. The dashed lines represent the PC/air interfaces.

Fig. 7. The relationship between cutoff value δ_x and total transmittance of the output beam for 20-layer circular-rods type PC (a) and square-rods type PC (b), respectively. The inset in each figure illustrates the cutoff value δ_x at PC/air interface.

Fig. 8. Schematic of a 90-degree waveguide bend (a) and a polarization beam splitter (b1) based on PISC in all-solid PCs. In each figure, the inset on the top left side of the parallelogram defect area illustrates the working mechanism, while the inset on the bottom right side of the parallelogram defect area illustrates the cutoff value δ at defect/PC interface. (b2) The band structures of the defect PC when $r'=0.45a$. The yellow area represents the band gap of TE polarization.

Fig. 9. (a) The relationship between the cutoff value δ and the bend efficiency at output. (b) and (c) show the magnetic/electric field distributions in the whole x-y plane for both polarizations when $\delta=0.51a$. The sub figure near the output shows the cross-section normalized intensity of magnetic/electric field at the location marked by solid line. The working frequency is $0.333 \omega a/2\pi c$.

Fig. 10. (a) The relationship between the cutoff value δ and the extinction coefficient at output 1 and output 2. (b) and (c) show the magnetic/electric field distributions in the whole x-y plane for both polarizations when $\delta=0.56a$. The sub figure near the output shows the cross-section normalized intensity of magnetic/electric field at the location marked by solid line. The working frequency is $0.333 \omega a/2\pi c$.