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A heuristic approach to the realization of the wide-band optical diode effect in photonic crystal waveguides

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Abstract
In this paper a highly efficient optical diode is demonstrated in photonic crystal waveguides with broken spatial symmetry. The structure is made of isotropic linear materials and does not need high power optical beams or strong magnetic fields. While the proposed structure shows almost complete light transmission (>99%) in one direction, it blocks light transmission in the opposite direction. This unidirectional transmission is retained within a wide range of frequencies (>4% of central frequency). In order to achieve an optical diode effect, the optical mode of the waveguide is manipulated by designing an ultra-compact mode converter and an efficient mode filter. The dimensions of the proposed mode converter are less than two wavelengths long.

Keywords: photonic crystal waveguides, integrated optics, mode converter, optical diode

(Some figures may appear in colour only in the online journal)

1. Introduction

The most natural way to realize an optical diode effect is via optical isolation in magneto-optic materials [1–8]. Nonlinear materials can also demonstrate optical isolation for certain intensities of the incident wave [9, 10]. Relatively weak magnetic properties and the need for high intensity optical waves for nonlinear materials have hindered the progress of optical diodes as one-way waveguides. Therefore, realization of the optical diode effect by using linear and isotropic structures is highly desirable. Recently, the optical diode effect was reported by achieving highly unidirectional transmission in spatially asymmetric yet linear and isotropic structures [11–18]. Thanks to the broken spatial symmetry, optical mode power transfer from mode m to n ($T_{m\text{–}n}$) is different in the forward and backward directions. It should be noted that this process is still reciprocal, because optical mode power transfer $T_{m\text{–}n}$ and $T_{n\text{–}m}$ are the same [19].

Matched periodic modulations of both refractive index and loss/gain of the structure have been previously proposed for unidirectional optical mode power transfer [11]. The optical diode effect is also demonstrated in photonic crystal heterostructures, plasmonic slot waveguides, photonic crystal gratings and gratings with metallic layers [13–17]. Most recently, Liu *et al* have devised an ultra-compact mode converter by following a numerical optimization method in two phases [18]. In both phases of optimization, in order to limit the design space, they consider a region with rods centered on the 20 possible lattice sites. In the first phase, a combinatorial search is performed where every possible combination of rods (presence or absence) on the 20 lattice sites in the region is considered. Any structures encountered in the combinatorial search that show promising conversion behavior are selected as the initial candidates for further optimization. In the second phase, the initial candidates are fine-tuned by adjusting the rod radii using a simple gradient descent method. Finally, they design an optical diode by applying the same optimization strategy [18]. Although their approach is straightforward, it requires several numerical simulations. For instance, in the first phase about a million structures have to be analyzed [18].

Here, instead of a brute-force numerical optimization algorithm, a heuristic approach is followed and, interestingly, a higher level of unidirectionality is achieved at a broader frequency range for the same structure. In this approach, to achieve unidirectional transmission of optical modes, a transmission channel is manipulated to be open in one direction and closed in the other. This approach requires two main components: a mode converter and a mode filter. In this fashion, the incident mode coming from the left side is first converted to a higher order mode by passing through the mode converter. The converted incident mode then passes through the mode filter, which is designed to filter out the incident mode and convey the higher order mode. Given that the mode converter has high conversion efficiency, light transmission from left to right is guaranteed. On the contrary, the incident mode coming from the right side is filtered out by the mode filter.

In this paper this strategy is employed to realize almost complete (>99%) unidirectional transmission in a photonic crystal waveguide. Unidirectional transmission in the proposed structure is retained within a relatively wide range of frequencies. In order to achieve such a performance, an efficient mode converter and mode filter blocks are designed along a line defect photonic crystal waveguide. The mode converter block splits the incoming even mode into two separate waves, imposes a phase shift on one of them, and then recombines them to form an odd mode. The mode filter block obstructs the even mode and lets the odd mode pass. Therefore, the output wave is an odd mode while the input wave is an even mode and thus the proposed circuit can also be regarded as a one-way mode converter.

2. The proposed structure and its performance

The proposed structure is depicted in figure 1. It consists of a matching stage, a mode converter and a mode filter created in a line defect waveguide in a two-dimensional square lattice photonic crystal made of dielectric rods in air. The lattice constant is a and the radius and the refractive index of the rods are $r = 0.2a$ and $n = 3.4$, respectively. This is very much like the photonic crystal structure in which an ultra-compact mode converter/filter has been implemented very recently [18]. Unidirectional light transmission is then realized in a line defect waveguide made by removing two rows of rods. The waveguide supports two E-polarized modes (electric field parallel to the rods) with even and odd mode profiles. This waveguide is named waveguide 2 (abbreviated as W2) hereafter. As illustrated in figure 1, another type of line defect waveguide made by removing a row of rods is used in the proposed structure and is named as waveguide 1 (abbreviated as W1) hereafter.

2.1. Matching stage

Here we have realized the matching stage by displacing four rods. This adiabatic transition connects W1 and W2. The presence of this matching stage is necessary to ensure that there is no back reflection.

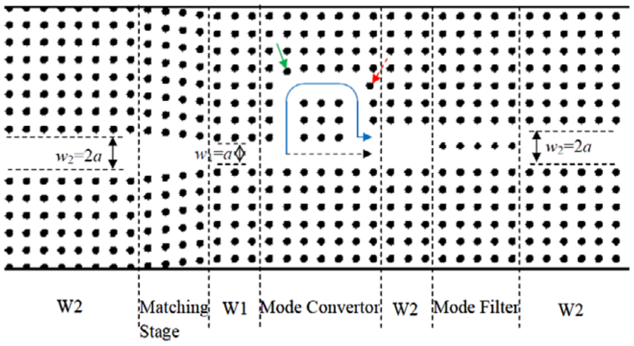

Figure 1. The proposed structure with unidirectional transmission made in a square lattice photonic crystal whose lattice constant is a. The structure is made of an adiabatic matching stage, a mode converter, a mode filter and line defect waveguides created by removing two rows (W2) and one row (W1) of rods. The small solid green and dashed red arrows indicate two rods that are slightly displaced to reduce bending loss. The U-shaped solid blue and straight dashed black arrows show the two different paths traveled by the wave that enters into the mode converter.

2.2. Mode converter block

The high level of unidirectionality in the proposed structure is due to the careful design of the mode converter and mode filter blocks. A closer look at the proposed mode converter block reveals that the lengths of the U-shaped (the solid blue curve in figure 1) and the straight (the dashed line arrow in figure 1) paths are $L_2 \approx 3a + \pi a/2 + 2a + \pi a/2 + 2a$ and $L_1 \approx 4a$, respectively. The first, third and fifth terms in the expression given for the length of the U-shaped path, L_2, correspond to the geometrical length of the left, upper and right arms of the U-shaped path, respectively. The two $\pi a/2$ terms are added to account for the two quarter-circle paths to be traveled at each bend. Inasmuch as both paths are carved within the same waveguide, the exerted phase difference between the two is $\Delta\phi = \beta_1(L_2 - L_1)$, where β_1 is the propagation constant of the waveguide. Given that $\beta_1 = 1.535/a$ at the normalized frequency $\omega_n = a/\lambda = 0.367$ (λ is the free-space wavelength), the exerted phase difference is $\Delta\phi = 3\pi$ and mode conversion is expected. This expectation is fulfilled by the two-dimensional finite difference time domain (FDTD) [20] analysis: almost complete rightward transmission is observed at $\omega_n = 0.367$ and the even mode profile is converted to the odd mode profile (see figure 2).

The designed mode converter block is very compact and occupies an area of 5 × 5 unit cells which means that its dimensions are about 1.85λ. This is even smaller than the mode converter in [18], which occupies an area of 4 × 10 unit cells.

2.3. Mode filter block

Similarly, a more detailed examination of the mode filter block proves that it has minimal effect on the odd mode

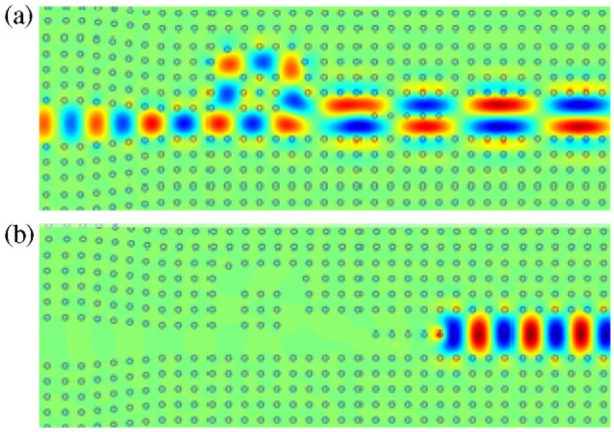

Figure 2. The electric field pattern at the normalized frequency of $\omega_n = 0.367$ for (a) rightward and (b) leftward transmission scenarios.

profile. This is numerically demonstrated in figure 3, where a dispersion diagram of the original W2 is compared with that of the mode filter block, which is in actual fact a specific type of line defect photonic crystal waveguide. The dispersion diagrams of the odd and even modes supported by the mode filter block (obtained by the rigorous approach of [21]) are depicted by the dotted blue and the dashed–dotted green curves, respectively. The fundamental mode of the mode filter block has odd symmetry. The dispersion diagrams of the odd and even modes supported by W2 are depicted by the solid blue and the dashed red curves, respectively. Since the dispersion diagram of the odd modes supported by the mode filter block accords with the dispersion diagram of the odd modes supported by the original waveguide, the high level of rightward transmission is no surprise. Then again, the considerable mismatch between the dispersion diagrams of the even modes supported by the original waveguide and the mode filter block—in particular the absence of the even mode in the mode filter block when the normalized frequency is $\omega_n < 0.396$—explains the very low level of leftward transmission.

3. Detailed study of unidirectionality

3.1. Rightward transmission

Two scenarios are considered for understanding how this device works. In the first scenario; hereafter referred to as rightward transmission, the even mode (the principal mode) is excited at the left entry of the waveguide and travels rightward. In accordance with figure 1, the incoming wave goes through a four-layer adiabatic matching stage to enter into W1.

The principal mode then enters the mode converter block, where it is split into two separate propagating waves. One travels straight ahead (along the dashed black line) and the other travels along the upper U-shaped path (along the solid blue curve). To ensure that the latter path retains high transmission, two dielectric rods, indicated by solid green and dashed red arrows in figure 1, are displaced by 0.2*a* with respect to their original positions downward and leftward, respectively [22].

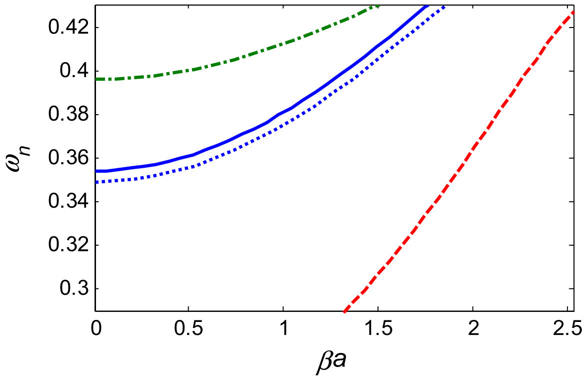

Figure 3. Dispersion diagrams for the even and odd modes of W2 and the mode filter.

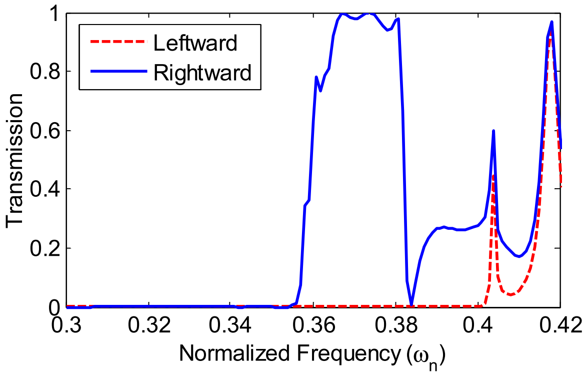

Figure 4. The transmission spectra of the leftward and rightward moving principal modes obtained by the FDTD simulator [20].

These two waves are combined with each other at the output of the mode converter block but excite the odd mode of W2 when there is a $(2K + 1)\pi$ phase difference between the two where K is an integer number. Given that the mode filter block is designed by placing a row of rods in the middle of W2, the odd mode can pass through but the even mode is blocked. This is due to the fact that the electric field profile of the odd mode is zero at the middle of the waveguide, where the rods are placed while the electric field profile of the even mode reaches its maximum and is thus reflected back. To ensure a higher level of transmission for the odd mode profile, the radius of dielectric rods in the mode filter block is 0.18*a*, slightly smaller than the original size of the rods.

3.2. Leftward transmission

In the second scenario, hereafter referred to as leftward transmission, the even mode (the principal mode) is excited at the right entry of the waveguide and travels leftward. This time, the even mode is reflected back rightwards as it first encounters the mode filter block. This is shown in figure 4, where the transmission of the leftward moving principal mode is plotted versus normalized frequency. Interestingly,

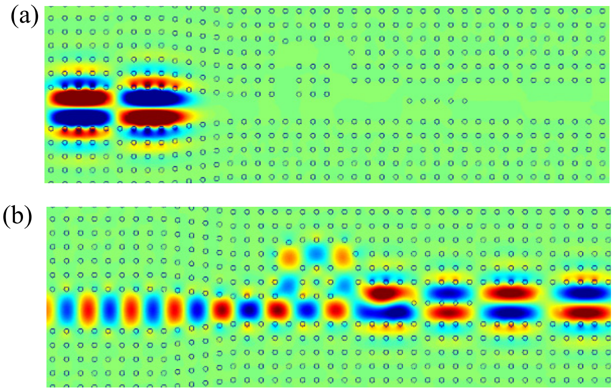

Figure 5. The electric field pattern at the normalized frequency of $\omega_n = 0.367$ for (a) rightward and (b) leftward transmission scenarios. The structure is excited with the odd mode.

the leftward transmission depicted by the dashed red line is almost zero for $\omega_n < 0.4$.

4. Results and conclusion

The result of the rightward transmission scenario is depicted by the solid blue line in figure 4, where the transmission of the rightward moving principal mode is plotted versus normalized frequency; $\omega_n = a/\lambda$ (λ is the free-space wavelength). Almost complete rightward transmission is observed at $\omega_n = 0.367$ while a very high level of transmission (more than 94%) is retained for $0.366 < \omega_n < 0.381$. It is worth noting that the achieved level of unidirectionality is about 78 dB. This happens to be higher than the achieved level of unidirectionality in the recently proposed structure [18], which is about 35 dB. However, it should be noted that although such a high level of unidirectionality is demonstrated in a two-dimensional structure, in practice the real device will be three dimensional and inevitably will suffer radiation loss. Therefore, the real device might have a lower level of unidirectionality.

The structure was studied when it was excited by the even mode from left or right, and it is shown in figure 2 that the rightward transmission was very high while the leftward transmission was negligible. It is worth noticing that if the device is excited with the odd mode its performance will be reversed, i.e. it will allow complete leftward transmission (due to reciprocity) and it blocks the odd mode coming in from the left (because W1 does not support an odd mode and will behave like a mode filter, blocking the incoming odd mode). This is illustrated in figure 5.

In conclusion, we have demonstrated a highly efficient unidirectional device made in a two-dimensional square lattice photonic crystal. It shows almost complete transmission in one direction and almost complete isolation in the opposite direction. The proposed device can be made with conventional isotropic linear materials and has relatively wide-band characteristics. The proposed structure is also composed of a novel ultra-compact mode converter and mode filter blocks which can be separately used in other applications which utilize multiple spatial modes in optical systems to increase information processing capacity [23, 24].

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