Ultra-wideband optical diode based on photonic crystal 90° bend and directional coupler

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We propose an ultra-wideband optical diode device based on two-dimensional square-lattice photonic crystals. For the device, the odd mode is completely transmitted in one direction and converted to the fundamental even mode, but completely reflected in the other direction. The operation bandwidth of the device is preserved within a rather wide range of frequencies, which is over 6.5% of the central frequency. A directional coupler and 90° bend are utilized as the composite function device with mode filter and mode converter. It is possible that the photonic crystal device can help to construct on-chip optical logical devices and benefit greatly to the optical systems with multiple spatial modes.

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As is known to all, electrical diode plays a crucial role in electronic circuits owing to the ability of unidirectional flow of the current flux. An all-optical diode is a one-way device that can control unidirectional flows of optical signals, which will greatly benefit the development of the all-optical signal processing. In order to realize the on-chip integration of the optical devices, photonic crystals (PCs) have been put forward to pave the way, where the propagation of light resembles the movement of electron in semiconductors[1–20]. The unidirectional non-reciprocal PCs waveguides have attracted much interest of many researchers[3,4]. By means of breaking the reciprocity or time-reversal symmetry, the unidirectional light propagation can be achieved based on magneto-optic effect, optical nonlinearity, opto-acoustic effect, indirect inter-band photonic transitions, and so on[5–12]. Although the functions of these devices realize the complete optical isolation, the on-chip integrated characteristics cannot be effectively satisfied due to the fabrication problems or operation bandwidths.

Recently, a unidirectional on-chip optical diode has been presented by Wang *et al.*[13–15]. The device consists of two different silicon two-dimensional (2D) square-lattice PCs with a hetero-structure and its operation mechanism results from the directional band-gap difference with spatial inversion symmetry breaking. However, the wavelength operation bandwidth has only scores of nanometers. A kind of unidirectional wavelength filter was proposed by Feng *et al.*[16] based on the rectangular defects in a 2D square-lattice PCs and its operation principles are the match and mismatch of mode's symmetry between the defect and the adjacent waveguides. However, it is clear that the rectangular defects lead to the rather narrow operation bandwidth and fabrication difficulties. Liu *et al.*[17] presented an ultra-compact mode converter by using an aperiodic design methodology. In both phases of optimization, the straightforward approach requires a lot of numerical simulations. Moreover, these radii of optimized rods in coupler region have low order of magnitude, which will result in great challenge to the fabrication of these devices. Khavasi *et al.*[18] proposed unidirectional transmission within a relatively wide range of frequencies. In the structure, an efficient mode converter and mode filter are engineered along a line defect PC waveguide, respectively, where the mode converter with multiple path is rather complex, and the high conversion efficiency also requires the irregular location shift of the rods.

Here an optical diode device with the ultra-wideband is proposed. In this case, the mode converter and mode filter functions are jointly realized by a directional coupler and 90° bend. The mode filter consists of a PC directional coupler and it prevents the even mode and allows the odd mode to pass. The mode converter block can combine the high-order odd mode to form an even mode by one directional coupler and two 90° bends. Hence, the output wave is an even mode, whereas the input wave is an odd mode and thus the presented device can also be optical diode with unidirectional propagation.

The functionality of an optical diode is shown in Fig. 1. The input and output waveguides only support a fundamental even mode and a higher order odd mode. For the structure, the higher order odd mode A from the left is converted into the even mode C on the right, whereas the fundamental even mode A from the left entrance is completely reflected back to the

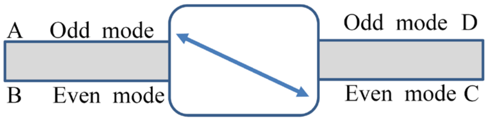
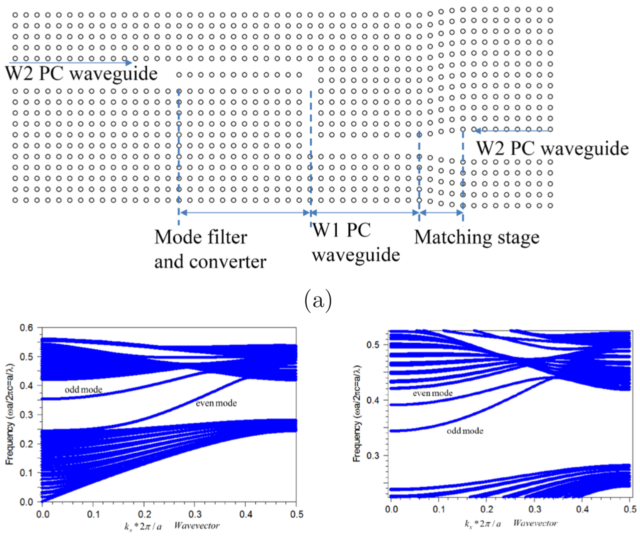


Fig. 1. Schematic representation of an optical diode. An input odd mode A from the left is converted into an even mode C on the right, and vice versa. But an even mode B from the left or an odd mode D from the right is completely prevented.

same even mode A at the left. From the right, the device obstructs the odd mode and allows the even mode to pass. It is observed that the device behavior shows obvious asymmetry unidirectional transmission as the same mode is excited at either side of the device. The even or odd mode is absolutely prevented in one direction, but completely transmitted in the other direction. According to the exact definition of an optical diode in Ref. [17], the device must not have inversion symmetry because the relationship between the right-to-left and left-to-right conversion processes is not symmetry. It means that the optical diode only allows a single odd or even mode to pass entirely while completely obstructing all other modes.

Next, we design the optical diode based on a background PC, which consists of silicon rods ($\varepsilon = 12$) of radius $0.2a$ in air ($\varepsilon = 1$) with a square lattice of constant a, as shown in Fig. 2(a). The structure is made of an adiabatic-matched region, a mode filter, and mode converter, and line defect waveguides created by removing two rows (W2) and one row (W1) of rods with two 90° waveguide bend.

The input and output waveguides are formed by removing two lines of rods in the parallel direction, which is called the PC W2 waveguide. Their dispersion relations have been calculated by plane wave expansion (PWE) as illustrated in Fig. 2(a). It is clear that the photonic band-gap is present in the frequency range of $0.29(c/a) < f < 0.42(c/a)$ only for the transverse magnetic mode, and the electric field is parallel to the rods, where f is the normalized frequency. The waveguides support two modes: a fundamental even-symmetric mode and a higher order odd-symmetric mode at $0.354(c/a) < f < 0.4(c/a)$, where c is the light velocity in free space. Then, the parallel input waveguide is connected to the region of directional coupling waveguide. Such a region is formed by laying one line of silicon rods with a radius value of $0.2a$ in the center of the W2 waveguide. As can be seen in Fig. 2(b), the projected band diagrams for the directional coupling waveguide are also calculated by the PWE. From Fig. 2(b) it can be seen that only odd mode is present in the region at $0.344(c/a) < f < 0.39(c/a)$ due to directional coupling mode-splitting mechanism. It is worth noting that electric field pattern of the odd mode is similar to that of the higher order odd mode in the PC W2 waveguide or input waveguide. It means that the fundamental even mode is absent in this frequency range for the directional coupler region. For the design of the optical diode, the region has a function of mode filter, and it is necessary that a mode converter also needs to be introduced to convert the higher order odd mode into the even mode.



(a)

(b) (c)

Fig. 2 (a) Proposed structure with unidirectional transmission made in a square-lattice PC whose lattice constant is a. The structure is made of an adiabatic-matched region, a mode filter and mode converter, and line defect waveguides created by removing W2 and W1 of rods with two 90° waveguide bend. Projected dispersion relations for (b) the W2 PC waveguide and (c) Directional coupler region, the mode splitting generating between the even mode and odd mode in the certain frequency region.

To realize the function of the mode converter, a 90° waveguide bend is engineered at the end of the directional coupler region, where the PC waveguide is formed by removing a line of rods in the perpendicular direction, which is called PC W1 waveguide. The conversion principle is as follows: the odd mode is symmetric about the parallel direction in the directional coupler waveguide, whereas the fundamental even mode in the PC W1 waveguide is also symmetric about the parallel direction. After the 90° waveguide bend, a higher order odd mode in the directional coupler can be completely converted into the fundamental even mode in the PC W1 waveguide for this frequency range of $0.354(c/a) < f < 0.39(c/a)$.

At the other end of the PC W1 waveguide, another 90° waveguide bend is used, and it is connected with another PC W1 waveguide in the parallel direction. It is well known that very high transmission (>95%) over wide frequency range can be obtained through the PC 90° waveguide bend.

Subsequently, the parallel PC W1 waveguide requires to be related to the PC W2 waveguide. The background lattice array for the PC W2 waveguide is shifted $0.5a$ vertically based on the original lattice structure. The adiabatic transition is elaborately designed to ensure that no back reflection occurs between PC W1 and W2 waveguides. The matching transition stage is obtained by displacing four columns of rods vertically, where various rows of holes are displaced symmetrically about the waveguide axis, and the step parameter with the value of $0.1a$ describes the deviation of each row from the original ideal lattice.

For the unidirectional structure proposed in Fig. 2(a), in the frequency range of $0.344(c/a) < f < 0.39(c/a)$, as the higher order odd mode is excited at the access port to the left of input W2 PC waveguide, the odd mode in PC W2 waveguide will be completely converted into the odd mode in the directional coupler. The reason results from the perfect match between two odd modes due to their similar electric field patterns. In contrast, the even mode will be completely obstructed because the even mode is absent for the directional coupler region. With the light with the odd mode arriving at the 90° waveguide bend, the odd mode is converted into the fundamental even mode in the PC W1 waveguide, where the bend lies between the directional coupler in the horizontal direction and the W1 waveguide in the vertical direction. The principle of the mode converter is the same even symmetry characteristic of their electric field pattern about the vertical direction. Due to almost complete transmission through the 90° waveguide bend, the PC W1 waveguide in the horizontal direction allows the light to pass entirely. After the matching stage between the PC W1 and W2 waveguides, the light with the fundamental even mode can be achieved in the output W2 waveguide.

At the operating frequency $f = 0.375(c/a)$, the field patterns of both input modes from the left and right at normalized frequency $f = 0.375(c/a)$ are obtained by calculating the unidirectional structure using the finite-difference time domain (FDTD) method with perfectly matched layer (PML) absorbing boundary condition. When the light with odd and even modes are launched at the left access port of input W2 waveguide, the steady electric field patterns at the operating frequency are as shown in Figs. 3(a) and (b), respectively. In Fig. 3(a), the odd mode is completely converted into the even mode, whereas the even mode is completely prevented in Fig. 3(b). Figures 3(c) and (d) also show the steady electric field patterns when input modes are excited from the right at normalized frequency $f = 0.375(c/a)$. In Fig. 3(c), the even mode is firstly transmitted through the PC W1 waveguide completely after the matching stage. Then, the PC W1 waveguide mode is permitted to pass through the 90° waveguide bend. At the second 90° waveguide bend, the PC W1 waveguide mode will be completely converted into the odd mode in the directional coupler. Finally, the odd mode is excited in the input PC W2 waveguide and is transmitted to the access port. In Fig. 3(d), the odd mode is completely reflected back to the right as it is launched at the right entrance to the W2 waveguide because the PC W1 waveguide mode must be symmetric about the waveguide axis.

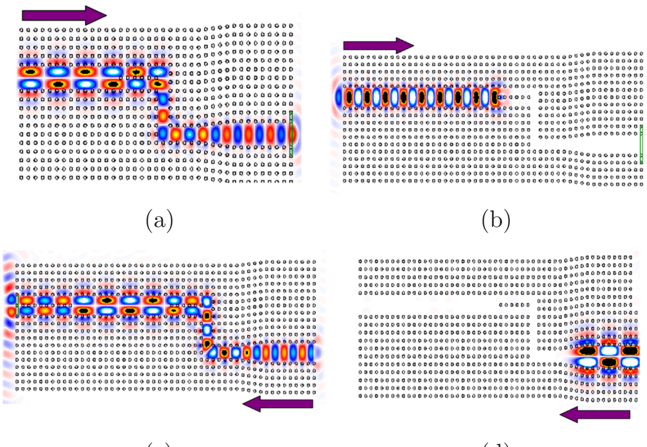


Fig. 3. Representative field patterns of both input modes from the left and right at normalized frequency $f = 0.375(c/a)$. The top row shows excitation from the left, whereas the bottom row shows excitation from the right.

In order to investigate the operating bandwidth of the optical diode, the unidirectional structure is calculated by using the FDTD method with PML absorbing boundary condition as the time Gaussian pulse from an odd mode light beam is launched at the left and right sides of the optical diode. Figures 4(a) and (b) show the transmission of rightward- and leftward-moving principal modes plotted versus normalized frequency, respectively. In Fig. 4(a), obviously, the rightward transmission depicted by the thin solid curves is close to 95% in the frequency range of $0.366(c/a) < f < 0.3928(c/a)$, and little back reflection occurs at the left entrance to the input PC W2 waveguide. While in Fig. 4(b), almost zero leftward transmission is observed at $0.36(c/a) < f < 0.39(c/a)$, and it is indicated by the thick curves. It is noted that the unidirectional extinction ratio is close to 80 dB, and the value is rather higher than that of other optical diodes[18], where the isolation level is defined as the ratio of the power with the allowed mode at the output port to the power with prevented mode at the same port, when the even mode and odd mode are excited on the left and right, respectively. But it is only theoretical value under 2D structure, and the real device based on the design of optical diode must be have a lower isolation level considering the real three-dimensional structure and fabrication imperfection.

In this case, the unidirectional propagation structure is still reciprocal because the structure with the ordinary dielectric materials cannot break Lorentz reciprocity and must have a symmetric scattering matrix. Figures 3(a) and (c) show the case as the device is excited with the even mode, which is completely opposite of the propagation when the device is launched with the odd mode.

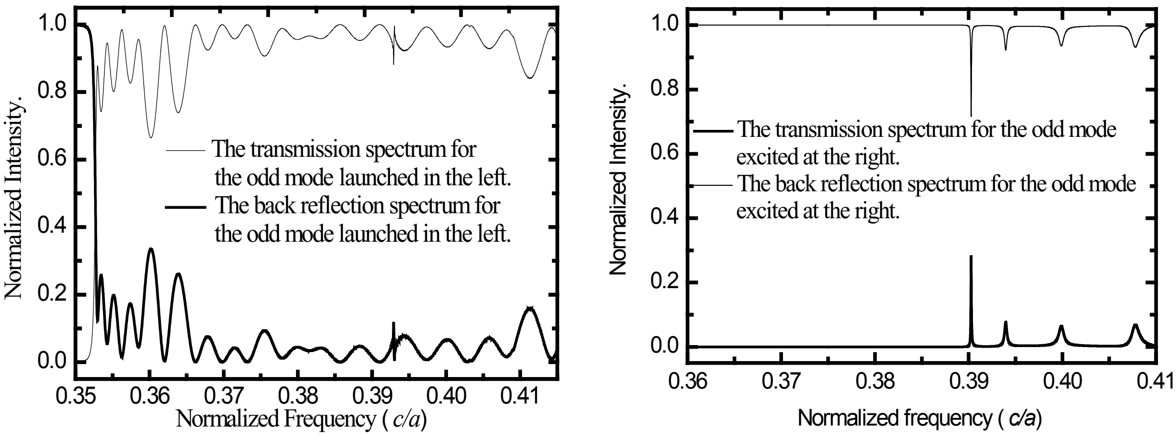


Fig. 4 (a) Light transmittances through the diode from an odd mode light beam at the normal incidence from the left side of the input W2 waveguide. (b) The transmission and reflection spectra through the unidirectional propagation structure for the odd mode launched on the right side.

In conclusion, we propose an optical diode with ultra-wide bandwidth based on 2D square-lattice PCs, and the PCs consist of conventional isotropic linear materials. For the odd mode light beam from the left, almost complete transmission can be obtained through the unidirectional structure, and the odd mode can be completely converted into the even mode. However, the odd mode can be completely prevented in opposite direction. The functionality of an optical diode consists of a mode filter and mode converter. Although the fully reciprocal diode cannot perform optical isolation, it provides an interesting ability for controlling the spatial modes and thus might have potential applications in optical systems with multiple spatial modes.

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