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Multi-channel unidirectional and bidirectional wavelength filters in two dimensional photonic crystals

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ABSTRACT

The unidirectional and bidirectional filtering properties of the two-dimensional square-lattice photonic crystal devices are thoroughly studied. Through carefully designing the coupling regions between the single defect and the neighboring waveguides, the multi-channel unidirectional and bidirectional wavelength filtering can be synchronously realized in the same structure. Moreover, the designed photonic devices can effectively function as beam splitters except for wavelength filters, which may be potentially applied in the complex optical integrated circuits.

1. Introduction

Photonic crystals (PCs) [1,2] are periodic nanostructures designed to control the motion of photons in a similar way that periodic semiconductor crystal affects the motion of electrons. The two-dimensional (2D) PCs have attracted much attention for their photonic band gaps and easier fabrication than their 3D counterparts. By introducing artificial defects into PCs, various photonic devices can be realized, such as waveguides [3,4], splitters [5–7], directional couplers [8,9], and filters [10–13], which play important roles in the optical integrated circuits. Particularly, filters are the key components for the extraction of light with specific wavelength trapped in a point-defect cavity to the neighboring waveguides. Over the past few years, different kinds of filters have been designed and discussed, which allow the bidirectional light propagation at resonant wavelengths. Recently, the concept of all-optical diode has been proposed, which will play a key role in the optical integrated circuits owing to its capability of unidirectional propagation of light beams. Therefore, great efforts have been dedicated to studying the unidirectional light propagation in linear and nonlinear PCs [14–18]. Especially, light unidirectional propagation in linear PC devices just like a mode converter [19,20]. And Feng et al. [21] designed linear and passive PC devices to realize unidirectional light propagation and wavelength filtering functions for the incident light beams.

In this paper, we propose multi-channel unidirectional and bidirectional filters based on a two-dimensional square-lattice PC with a single defect and input/output waveguides. Owing to the coupling between the defect cavity and the neighboring waveguides, the unidirectional and bidirectional wavelength filtering are realized synchronously in the same PC structures at different resonant wavelengths. Moreover, the designed PC devices can effectively function as beam splitters except for wavelength filtering. Therefore, multifunctional devices can be realized in only one PC structure, which may be potentially applied in the future complex optical integrated circuits.

2. Optical properties of the multi-channel wavelength filters

The 2D PC is made of square lattice of square silicon rods immersed in air background. The refractive index of silicon is set to 3.45 for the near-infrared light around 1550 nm. The length of the PC's lattice constant is set as a and the side length of the square silicon rod is $0.1256a$. For the sake of convenience, we use the same rectangular defect as that proposed in Ref. [21], whose side lengths are $1.367a$ and $0.5a$, respectively. The schematic diagram is shown in Fig. 1(a) and it has similar shape with that mentioned in Ref. [21] except for introducing different shapes of silicon rods, which increases the diversity for the device design. The 2D finite-difference time-domain (FDTD) method [22] is used to calculate the transmission spectrum of TM-polarized modes for above PC structure. In our simulations, 50 pixels per lattice constant a together with Berenger's perfect matched layer (PML) boundary condition

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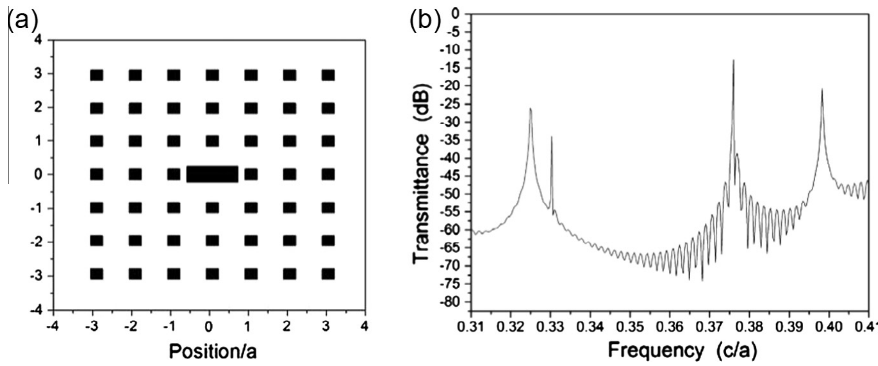

Fig. 1. (a) Schematic diagram of the 2D square-lattice PC with a central rectangular defect whose side lengths are 1.367*a* and 0.5*a*, respectively. The side length of square silicon rods is 0.1256*a*. (b) The transmission spectrum for above structure simulated by 2D FDTD method.

are used and good accuracy can be guaranteed. Fig. 1(b) shows the calculated transmission spectrum and there are four defect modes whose frequencies are 0.3247*c/a*, 0.3303*c/a*, 0.3758*c/a*, and 0.3983*c/a*, where "*c*" is the light velocity in vacuum. Meanwhile, the profiles for the defect mode of 0.3247*c/a* are even-symmetric with respect to the horizontal and vertical central lines, and those of 0.3758*c/a* are odd along the above referred two orthogonal directions. The mode symmetry of 0.3303*c/a* is odd along the horizontal line, and is even along the vertical line, while the mode symmetry of 0.3983*c/a* is even along the horizontal line and is odd along the vertical line, whose symmetries are just opposite in each direction. By comparison, we find that the defect modes' profiles can remain similar when only changing the shape of silicon rods from circle to square while making the central rectangular defect unchanged.

Subsequently, a W1-typed waveguide is formed by removing one row of square silicon rods along the ΓX direction of above PC. The schematic diagram is shown in Fig. 2(a). The well-established 2D plane-wave expansion method [23] is used to calculate its TM-polarized band structure. The calculation results are shown in Fig. 2(c) and there exits a fundamental even-mode guiding band ranging from 0.3020*c/a* to 0.4160*c/a*. Then a W2-typed waveguide, shown in Fig. 2(b), is constructed by shifting two rows of square silicon rods, which are most adjacent to the waveguide central axis, by 0.7*a* and 0.35*a*, respectively. The corresponding band structure is shown in Fig. 2(d). The results show that there exits an even-mode guiding band from 0.2746*c/a* to 0.4160*c/a*, and an odd-mode guiding band from 0.3308*c/a* to 0.4160*c/a*, which is similar to that mentioned in Ref. [21].

Based on above analysis, we construct a tri-channel wavelength filter by using two W1-typed waveguides, one W2-typed waveguide and only one rectangular defect, which is shown in Fig. 3(a). The fundamental even-mode light beam at the waveguide central line is incident to the left or upper W1-typed waveguides, and the corresponding transmission spectra for the bottom W2-typed waveguide are shown by the solid line and dotted line in Fig. 3(b), respectively. One can clearly see that in the left incidence case, there are two resonant frequencies of 0.3247*c/a* and 0.3983*c/a*, while in the upper incidence case, there is only one resonant frequency of 0.3758*c/a*.

The electric field distributions for the cavity modes at the frequencies of 0.3247*c/a*, 0.3758*c/a*, and 0.3983*c/a* are calculated and the results are shown in Fig. 4. According to the field patterns, we can have a more clearly visual sight about the light propagating properties. First, we consider the left W1-typed waveguide and the lower W2-typed waveguide as the input waveguides, respectively. When the even-mode light beam at the frequency of 0.3247*c/a* is incident to the lower W2-typed waveguide, the light can be finally exported from the left W1-typed waveguide, which is shown in Fig. 4(a). Similarly, when the same light is launched from the left W1-typed waveguide, the light can also be output from the lower W2-typed waveguide, which is shown in Fig. 4(b). The reason is that resonant field of 0.3247*c/a* in the defect region is even symmetric with respect to the two waveguide central axes and the effective coupling between the waveguides and the defect can be realized. Therefore, the bidirectional wavelength filtering is obtained at the frequency of 0.3247*c/a*. Moreover, when the frequency for the even-mode light is changed to 0.3983*c/a*, it is shown in Fig. 4(g) that if the light is incident upwards to the W2-typed waveguide, no light is output from the left W1-typed waveguide. The reason is that the mode mismatch lies in the defect and the W2-typed waveguide. When the light with same frequency and spatial symmetry is incident rightwards to the left W1-typed waveguide, the odd mode is exported from the W2-typed waveguide owing to the mode match between the defect and the neighboring waveguides, which is shown in Fig. 4(h). Similarly, Fig. 4(i) shows that the even-mode light can be output from the left W1-typed waveguide when the light beam with odd symmetry is incident upwards to the W2-typed waveguide at the frequency of 0.3983*c/a*. Fig. 4(j) shows that there is no light coupling out from the lower W2-typed waveguide when the odd-symmetry light is launched from the left W1-typed waveguide owing to the odd-mode band gap. As a result, the unidirectional wavelength filtering is obtained at the frequency of 0.3983*c/a* no matter input light is even mode or odd mode. Then, we consider the upper W1-typed waveguide and the lower W2-typed waveguide as the input waveguides, respectively. Similar results can be obtained when the frequency of the input light is set as 0.3758*c/a* and the detailed results are shown in Fig. 4(c)–(f). From Fig. 4(c)–(j), it is not difficult to find that the unidirectional wavelength filtering can be realized in the same structure at the frequencies of 0.3758*c/a* and 0.3983*c/a*.

In order to realize more functions, we design another tri-channel wavelength filter composed of one W1-typed waveguide, two W2-typed waveguides and one rectangular defect, which is shown in Fig. 5(a). The left W1-typed waveguide is located at the horizontal central line of the defect, while two W2-typed waveguides are symmetrically distributed on the two sides of the central defect. A fundamental even-mode light beam is incident to the left W1-typed waveguide and the transmission spectra for the upper and bottom W2-typed waveguides overlap together due to the symmetry of the structure, which are shown by the solid line in Fig. 5(b). It can be seen that there are two resonant frequencies (0.3247*c/a* and 0.3983*c/a*) and the light at resonant frequency is almost equally exported from two output waveguides, which means the equal beam splitting can be realized. Moreover, when the light beam is incident to the upper or lower W2-typed waveguides, the transmission spectra for the left W1-typed waveguide also overlap each

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