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Multi-channel slow light coupled-resonant waveguides based on photonic crystal with rectangular microcavities

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ABSTRACT

The light transmission characteristics through the coupled-resonator optical waveguides (CROWs) based on the two-dimensional square-lattice photonic crystal with rectangular microcavities are systematically studied by the finite-difference time-domain method. Owing to the multiple spatial symmetries of the defective modes localized by the rectangular microcavities, the guiding bands can be adjusted by changing the coupling region between the CROW and the traditional W1-typed input and output channels, and their corresponding group velocities can be quite different from each other through the same CROW structure. Through optimizing the coupling regions between the CROW and three output channels, a kind of device with both the abilities of light beam splitting and frequency selection can be obtained, which has potential applications in the future complex all-optical circuits.

1. Introduction

In the past few decades, photonic crystal (PhC) has attracted much interest and extensive study due to its remarkable properties, characterized by the existence of photonic band gaps [1,2]. By introducing different kinds of defects into a pure PhC, resonant states within the photonic band gap can be created and various optical devices can be achieved, such as optical waveguides [3–5], channel drop filters [6–8], ultrafast optical switches [9,10]. Recently, slow light propagation behaviors in PhC structures also received considerable attention, owing to its compatibility with on-chip integration, room-temperature operation and flexible adjustment for the working wavelength and bandwidth [11–20]. Based on the slow light in PhCs, a lot of devices can be realized with possible applications, such as optical delay lines, optical switches, data processing devices, and biosensors.

When one scatterer is removed away from an otherwise-perfect PhC, or its size and shape is changed, a defect can be constructed. This defect has one or more localized resonant modes with specific spatial electromagnetic field distributions. The coupled-resonant optical waveguides (CROWs) consist of the weakly coupled optical defects arranged at regular intervals in PhCs [11–17]. Light propagation through the CROWs depends on the tunneling of radiation from one microcavity to its nearest neighbor because of the evanescent fields of microcavity modes. Both the low group velocity and the large optical field amplitude can be achieved in a CROW, so it can be employed to enhance nonlinear optical processes significantly, or to construct efficient optical delay lines for high-speed all optical signal processing. Beyond above, through optimizing the structural parameters of the line-defect waveguides and altering their adjacent rows, the slow light behaviors can also be obtained with low group velocity dispersion [18–22].

In this paper, we studied the slow light propagation through the CROWs based on the two-dimensional square-lattice photonic crystal consisting of square rods and rectangular defects. Due to the diverse spatial symmetries of the defective modes at different resonant frequencies, a multi-band CROW structure with different group velocities can be obtained. And the guiding modes can be adjusted by changing the coupling region between the CROW and the traditional W1-typed input and output channels. Through optimizing the coupling regions connecting the central CROW and three output channels, a kind of functional device is achieved, which allows the light beam within three guiding bands travel through a common channel, and two of them also travel along their separate channels, while the third share all the three channels.

2. Proposed PhC waveguide structure and numerical simulation

The CROWs studied in this paper are based on the two-dimensional square-lattice PhC consisting of square silicon rods

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immersed in air, whose refractive index is set to be 3.45 for the near-infrared light beams around 1550 nm. The sidelength of the square is 0.4*a*, where *a* is the lattice constant of the PhC. We employ the finite-difference time-domain (FDTD) method [23,24] with periodic boundary conditions and the supercell technique to calculate the dispersive curves of the CROWs. The FDTD method is a time-domain numerical analysis technique used for modeling computational electrodynamics, and it is widely used in the theoretical study of PhCs and so on [25–27]. We consider the TM-polarized incident light beams, where the electric field is along the central axis of the rods, also perpendicular to the plane of the dielectric rods' distribution. And the light transmission spectra and the spatial electric field distributions through the CROW structures were calculated by the FDTD method with perfect-matched layers as a boundary. In our calculation, the length of a lattice constant is divided into 40 square grids, and the accurate numerical results can be easily obtained especially for a structure consisting of square or rectangular scatterers. The calculated results show that a photonic band gap exists in this PhC with the frequency region from 0.2653 to 0.3832*c*/*a*, where *c* is light velocity in vacuum. Based on the above two-dimensional square-rod PhC, we constructed a microcavity by changing the shape of the central rod from a square to a rectangle and removing its four nearest square rods, whose sketch map is shown in Fig. 1(a). And the two sidelengths of the rectangle are set to be 1.6*a* and 0.4*a*. There are four localized resonant frequencies supported by this microcavity, which are 0.2734, 0.3371, 0.3459, and 0.3701, in unit of c/a. Fig. 1(b) shows the electric field spatial distribution at the resonant frequency 0.3701, which is both even-symmetric along the horizontal and perpendicular directions. The electric field profile at 0.3459 shown in Fig. 1(c) is even-symmetric with respect to the perpendicular central lines and odd-symmetric about the horizontal line, while the spatial mode symmetry of 0.3371 is just opposite to that of 0.3459, as can be seen in Fig. 1(d).

Based on above microcavity characterized by a central rectangular rod, we constructed a kind of CROW by arraying these

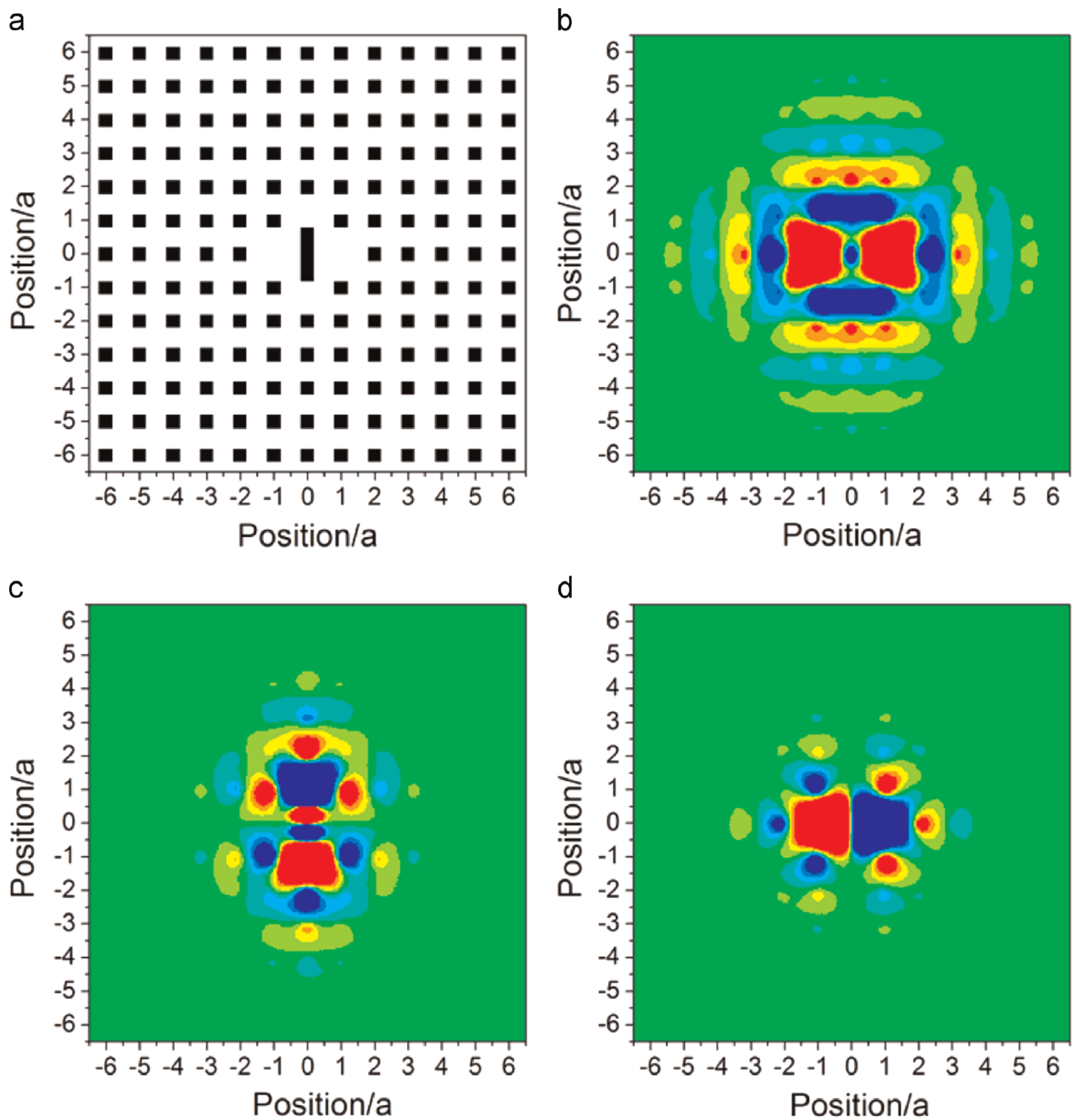

Fig. 1. Schematic geometry of the microcavity constructed by a central rectangular rod and removing its four nearest square rods from a two-dimensional square-lattice PhC (a), and the electric field profiles of the defective modes localized by this microcavity at frequencies of 0.3701 (b), 0.3459 (c), and 0.3371 (d) c/a. The sidelength of the square rods is 0.4*a*, and the sidelengths of the central rectangle are 1.6*a* and 0.4*a*.