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Photonics and Nanostructures – Fundamentals and Applications 13 (2015) 89–96

PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications

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Low-cross-talk and high-contrast all optical bistable switching based on coupled defects in a nonlinear photonic crystal cross-waveguide geometry

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Received 12 August 2014; received in revised form 23 November 2014; accepted 24 November 2014
Available online 2 December 2014

Abstract

We present a photonic crystal all-optical bistable switch configuration consisting of crossing perpendicular waveguides geometry with instantaneous Kerr nonlinearity. A microcavity is added to the signal waveguide which is coupled with the defect at the waveguide intersection to increase the transmission contrast. We demonstrate with the finite-difference time-domain method that such a configuration can function as a low crosstalk and high contrast all-optical switch.

Keywords: All-optical switching; Photonic crystal defect; Crossing waveguides

1. Introduction

Photonic crystals (PCs) formed by periodic modulation of dielectric constant represent a promising platform for manipulating the flow of light. By intentionally introducing defects into perfect PCs, various functional devices and large-scale integration of optical components can be constructed. All-optical switches, as one of the key components for future all-optical signal processing, have attracted much attention and have been extensively studied, and various methods for realizing switching function have been proposed such as those based on non-reciprocal media, liquid crystals, or nonlinearity [1–8]. Among these approaches, it has been shown that the use of nonlinear bistability in PC microcavities allows the construction of ultra-compact all-optical switches that operate with high speed. The structures of those bistability-based switches can be one dimensional multilayer designs or other PC waveguide-based geometries [9–14].

For practical applications of switching devices, an important consideration is the contrast ratio in transmission between the ON state and the OFF state. A high contrast ratio would be beneficial for effective immunity to noise and detection error. Recently, Fano resonance has been employed for improving the switching contrast [15,16]. For an optical bistable switch, the upper branch and the lower branch of its bistable states denote the ON and OFF states, respectively. The transmission can transit from the lower branch to upper branch making use of a control pulse, thereby realizing the switching action from OFF state to ON state. Therefore, the most

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http://dx.doi.org/10.1016/j.photonics.2014.11.001
1569-4410/

effective way to increase the contrast ratio is to lower the transmittance of the lower branch of the bistable states. To increase the contrast, Yanik et al. proposed a side coupled PC configuration [17]. With this configuration, extremely high contrast between the bistable states can be generated. In our previous work, we suggested a direct-coupling configuration which utilizes a PC coupled defects consisting of two misaligned optical resonators instead of only one optical resonator to improve the transmission contrast [18]. But for these devices, the control light and the signal propagate along a same waveguide, and the drawback will influence the detection of the signal.

Photonic crystal cross waveguide structures, on the contrary, can overcome the shortcoming because the signal and the control light propagate along different channels. The transmission behavior of crossing perpendicular waveguides was first studied by Johnson et al. [19]. They demonstrated that for crossing perpendicular waveguides with a resonant cavity in the center of the intersection, if each waveguide has a mirror symmetry plane through its axis and the cavity is symmetric with respect to the mirror planes of both waveguides, and moreover, there are exactly two resonant modes which are even with respect to one waveguide's mirror plane and odd with respect to the other exist in the cavity, then, very high throughput and low cross talk can be achieved. It can be seen that it is the symmetry of the waveguides and the cavity that results in the symmetry of the modes in the cavity, and the different symmetry of the mode with respect to the two waveguides makes the electromagnetic field of the mode propagate only in one waveguide, thus eliminating the crosstalk. Afterward, the crosstalk reduction and the bistable switching action making use of the PC cross-waveguide geometry have been intensively studied by several other groups [20–24].

In this paper, we present an alternative all-optical bistable switch structure which combines coupled defects and cross waveguides together. We demonstrate that high transmission contrast can be achieved by making use of the coupled defects in the vertical signal channel, and meaning while, the overlapping problem between the control light and the signal can be eliminated as well.

The remainder of the paper is organized as follows. In Section 2, we describe the switching structure and its operation principle. In Section 3, we simulate the linear and nonlinear transmission behaviors of the geometry based on the finite-difference time-domain (FDTD) method, and the simulation results and discussions are presented. Finally, the conclusions are summarized in Section 4.

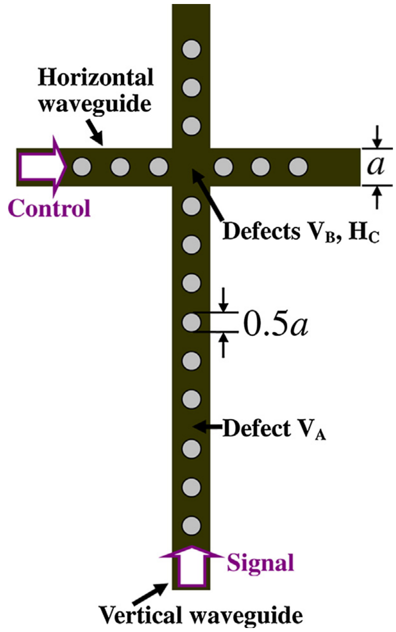

Fig. 1. The geometry of the all-optical cross-waveguide switch. The vertical and horizontal waveguides serve as signal and control channels, respectively.

2. Structure and principle

The structure of such a nonlinear PC bistable switch is schematically shown in Fig. 1. The transmission in the vertical waveguide exhibits the characteristic of bistability, and we can realize the transmission transition from the lower branch to the upper branch of the bistable states by applying a trigger pulse on the left hand side in the horizontal waveguide. The cross waveguide structure is made of a material with Kerr nonlinearity. Six and twelve identical air holes are drilled in the horizontal and the vertical waveguides periodically to form the two-dimensional PC structure, respectively. The two defects denoted as V_A and V_B in the vertical waveguide are introduced by changing the separation between the third and fourth air holes and that between the ninth and tenth air holes, and the defect H_C in the horizontal waveguide is set by changing the separation between the third and fourth air holes. The defect V_B in the vertical waveguide and the defect H_C in the horizontal waveguide are located symmetrically at the intersection area of the two waveguides. As marked in Fig. 1, the signal and the control light propagate along the vertical and the horizontal waveguides, respectively.

Now we analyze the transmission characteristics of the structure. We know that the main mechanism for designing a PC all-optical bistable switch is the shifts of defect modes due to the nonlinear refractive index