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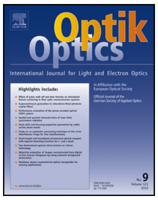

A novel single control all-optical switching and routing in nonlinear photonic crystals

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ABSTRACT

A novel simple control all-optical switching and routing mechanism using two nonlinear photonic crystal (PC) cavities and a T-branch waveguide has been presented. It has been shown that using a single control signal, the input power can be switched with a high-contrast ratio and routed to any of the two output ports. The performance of the proposed device has been investigated through the use of temporal coupled-mode theory (CMT) and two-dimensional (2D) nonlinear finite-difference time-domain (FDTD) simulations in PCs of square lattice.

1. Introduction

So far, various designs have been proposed for nonlinear PC switches [1–11], but among them, the waveguide-microcavity based structures are the most convenient [1,2]. Nonlinear photonic crystal (PC) microcavities can have ultra-small sizes and high-quality factors. Furthermore, the PC waveguides due to having low group velocities can enhance the effective coupling between short pulses and microcavities. These enhancements improve the operation powers and switching times and, as a result, carry out practical high-speed and low-power integrated all-optical processing devices. Two basic implementations of these nonlinear switching devices are provided by either direct or side-coupling of a waveguide with a microcavity. In these devices the transmission of input power can be switched “ON” or “OFF” by a control signal. The contrast ratio in the transmission between the two bistable states is one of the most important factors in practical optical bistable switches that influence on the immunity to noise, fan-out and detection error [7]. In side-coupling based bistable switches the contrast ratio of the transmitted power is very high, but a small deviation of the input power results in a great reduction of the contrast ratio [7]. Direct-coupling based optical bistable switches exhibit a limited contrast ratio, because the transmitted power is proportional to the optical energy inside the cavity [8]. In this paper, we present a novel design of an all-optical switch and router with a simple control mechanism, based on two different cross-waveguide-based nonlinear PC switches and a T-branch waveguide. Our approach is based on the fact that for a certain range of input power, by changing the state of the control signal, the bistability curve of a switch can be varied in such a way to lead to a change in its state [8]. Based on our theoretical and numerical investigations, using only a control signal, the proposed device can route the input power to any of the two output ports with a high-contrast ratio. The coupled-mode theory (CMT) is employed to analyze the behavior of the device in the nonlinear regime. The device is also simulated by two-dimensional (2D) nonlinear finite-difference time-domain (FDTD) method for the structures implemented in PCs of square lattices, and the simulation results show the validity of the presented design.

2. Theoretical description of the proposed single control all-optical switch and router

In this section, the operation of the constituent parts of the proposed device is described, and then is modeled and analyzed using the CMT with more details. This device is made of a T-branch waveguide and two cross-waveguide-based nonlinear PC switches which are symmetrically located on both output waveguides within specified distance from the center of the T-branch, *d*, as depicted

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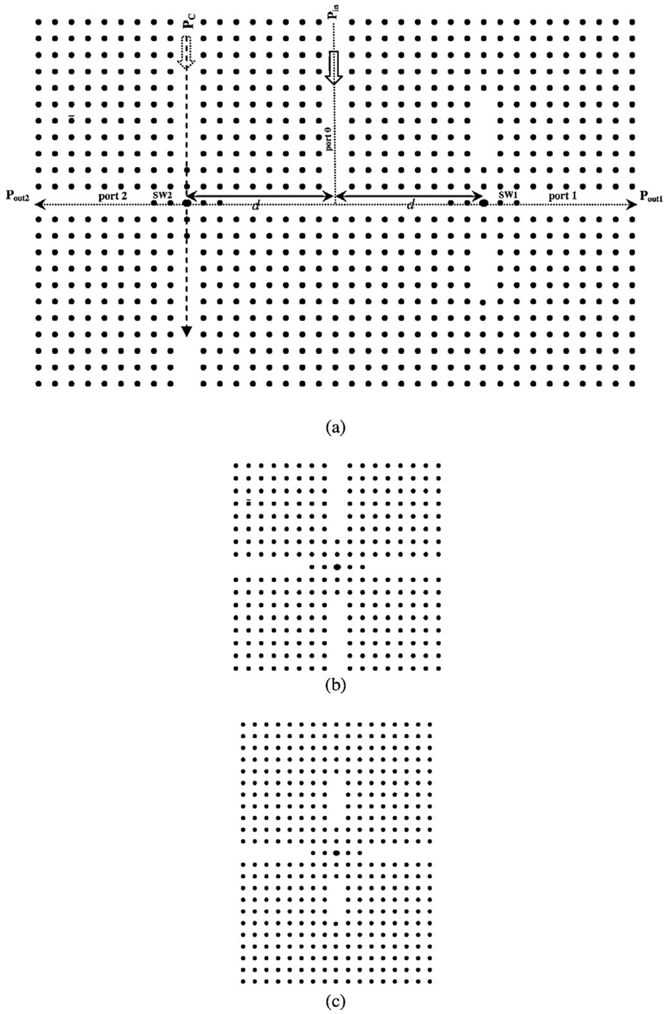

Fig. 1. (a) Structure of the proposed single control all-optical switch and router implemented in 2D PC of square lattice. (b) The cross-waveguide based nonlinear PC switch SW2. (c) The modified cross-waveguide based nonlinear PC switch SW1.

in Fig. 1(a). As can be seen, one of the cross-waveguide-based nonlinear PC switches is modified (switch SW1), such that its vertical branches are blocked. It has been shown that in a modified T-branch waveguide, in which one of the output waveguides is terminated with a reflector, most of the reflected power is diverted to the other output waveguide, if the overall phase-shift of the electromagnetic (EM) waves traveling between the reflector and the reference plane, 2φ, be around $(2N+1)\pi$ (where N is an integer) [10]. A PC nonlinear switch can be treated as a reflector, in which for a specified frequency, the reflectance is contingent upon the input power and can be determined from its bistability curve [10]. Consequently, from Fig. 1(a) one can see that when the overall phase-shift of the EM waves traveling between every of the switches and the reference plane, be around π, a considerable portion of the reflected power from each of the switches will be diverted to the other switch. This leads to an increment in the contrast ratio parameter of our proposed device. Now, we consider the switch SW2, (see Fig. 1(b)), and investigate its bistability features. Generally, in a nonlinear PC switch with the quality factor of Q, for an input power with the frequency of ω_{inX}, regarding the resonance frequency of the cavity (ω_{res}), the detuning factor and the transmission power can be written as

$$\delta = 2Q\left(\frac{1-\omega_{inX}}{\omega_{res}}\right), \tag{1}$$

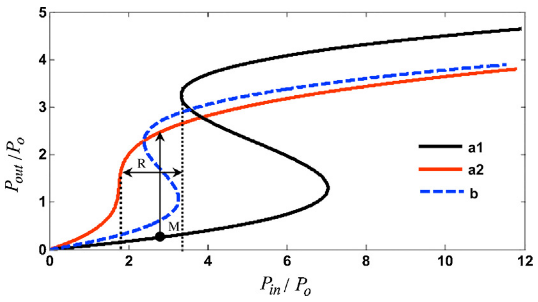

Fig. 2. Dependencies of the transmission on incoming light power (based on Eq. (2)), in a PC switch with direct coupling when: (a) δ = 3.4 (the curve labeled with the letter a1), (b) δ = 1.4 (the curve labeled with the letter a2), and (c) δ = 2.63 (the curve labeled with the letter b).

$$\frac{P_{out}}{P_{in}} = \frac{1}{1+(P_{out}/P_0-\delta)^2} \tag{2}$$

where P_0 is the characteristic power of the system [9]. When $S_{inY} = 0$, the bistability curve for a typical value such as $\delta_2 = 3.4$, can be shown by the curve labeled with the letter a1 in Fig. 2. Applying a control signal (i.e., non-zero S_{inY} and S_{outY}) leads to decreasing of the transition threshold, and the bistability curve, for a typical value such as $\delta_2 = 1.4$, can be shown as the curve labeled with the letter a2. It can be seen that, for a given input power (such as M) within the specified range of R, the control signal can stimulate transitions between the bistable states. Now, we consider the modified cross-waveguide-based nonlinear PC switch SW1 (see Fig. 1(c)). In this switch, the radius of the central cavity is slightly smaller than the value of the corresponding parameter of the switch SW2, so ω_{res_2} is slightly bigger than ω_{res_1}. In the proposed device, since the PC cavities have nearly similar in-plane confinements, their quality factors are very close to each other, and we can suppose that $Q_1 \cong Q_2 = Q$. Therefore, from (1), δ_1 will be smaller than δ_2, and the bistability curve of the switch SW1, for a typical value such as $\delta_1 = 2.63$, can be shown as the curve labeled with the letter b in Fig. 2. When the control signal of the proposed device is disabled, from the bistability curves of the switches, it can be deduced that there is a specified range of the input power, P_{in} in Fig. 1(a), in which the switches SW1 and SW2 act as mirrors with low and high reflectance, respectively. In this case, regarding the length of the terminated output waveguides, d (which is chosen such that 2φ to be around π), most of the input power is diverted to the switch SW1, and favorable conditions for transmission to the port 1 will be achieved. Hence, we can say that the switches SW1 and SW2 are in “ON” and “OFF” states, respectively. In another case, when the control signal is enabled, the switches SW1 and SW2 act as mirrors with high and low reflectance, respectively. Accordingly, most of the input power is diverted to the switch SW2, and favorable conditions for transmission to the port 2 will be obtained; so the switches SW1 and SW2 are in “OFF” and “ON” states, respectively.

In the remaining of this section, we describe the operation of the proposed device using CMT with more details. Fig. 3 shows the CMT based schematic diagram of the device [13]. As can be seen, S_{+0}, S'_{+0} and S''_{+0} represent the incoming EM waves into the PC cavity a_0 from its up, right and left sides, respectively, while S_{-0}, S'_{-0} and S''_{-0} represent the corresponding outgoing EM waves. Furthermore, S'_{+1} and S_{+1} (S_{+2} and S'_{+2}), represent the incoming EM waves into the PC cavity a_1 (a_2) from its right and left sides, respectively, while S'_{-1} and S_{-1} (S_{-2} and S'_{-2}) represent the corresponding outgoing EM waves. $1/\tau_0$, $1/\tau'_0$ and $1/\tau''_0$ denote the decay rates of the cavity a_0 into the ports 0, 1 and 2, respectively and $1/\tau_1$ and $1/\tau'_1$ ($1/\tau_2$ and $1/\tau'_2$) denote the decay rates of the cavity a_1 (a_2) into the ports 1 and 1′ (ports 2 and 2′), respectively. In our previous investigation, assuming that $\tau'_0 = \tau''_0 = k\tau_0$, we showed that when