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High-contrast controllable switching based on polystyrene nonlinear cavities in 2D hole-type photonic crystals

Roohollah Paghousi, Kiazand Fasihi *

Department of Electrical Engineering, Golestan University, Gorgan, Iran

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ABSTRACT

We present a new high-contrast controllable switch, which is based on a polystyrene nonlinear cavity, and is implemented in a two dimensional (2D) hole-type photonic crystal (PC). We show that by applying a control signal, the input power can be transmitted to the output waveguide with a high contrast ratio. The operation of the proposed device is investigated through the use of coupled-mode theory (CMT) and finite-difference time-domain (FDTD) method. The contrast ratio of the proposed device varies between 18 and 23, which is higher than the corresponding value in the previous investigations. Based on the simulation results, with increasing the control power the range of operating power will be increased, while the contrast ratio will be decreased. It has been shown that in a modified structure, at the expense of the range of operating power and the contrast ratio, the control power can be decreased, considerably.

1. Introduction

The Photonic crystals (PCs) have attracted significant attention due to their prominent applications in high-density integrated optical circuitry [1]. The PC nonlinear microcavities due to having ultra-small sizes and high quality factors, are very good candidates for implementing of realistic low-power and high-speed all-optical integrated switches. Moreover, the PC waveguides have low group velocities which can enhance the efficiency of coupling between short pulses and resonators [2,3]. So far, several structures have been suggested for nonlinear PC switches, based on the waveguide microring-resonators [4], the nonlinear directional-couplers [5,6], the waveguide microcavity structures [7–13], and etc. There are only a few designs which have been proposed for all-optical controllable switches (with a separate control signal) [4,6,11–13], and all of them have been implemented using 2D rod-type PC structures. These types of PC structures suffer from out-of-plane losses [1]. Refs. [4,6] suggest that using a control signal in a modified nonlinear PC directional coupler, which is implemented in a triangular lattice of dielectric rods, a controllable switching mechanism can be achieved. These structures have large sizes, and their operating powers are relatively high. It has been shown that in the rod-type PC cross-waveguide based switches, the transmission between the input and output waveguides can be switched using a control input power with a high contrast ratio [11–13]. The cross-waveguide based schemes, with a nonlinear elliptical microcavity centered at the intersection, due to compactness and low-level operating powers, are one of the best choices for designing the controllable all-optical switches. The basic features of some above-mentioned all-optical PC switches are summarized in Table 1. The square-lattice hole-type PCs have a small photonic band gap and a small bandwidth single-mode region comparing the rod-type PCs, but are much easier to fabricate. Furthermore, in these structures the out-of-plane losses can be reduced, considerably. The contrast ratio between the two bistable states of the switching transmission curve is an important factor that affects on some switching key features such as the detection error, immunity to noise, and fan-out [8]. In this paper, we proposed a new design of a high contrast ratio controllable all-optical switch, based on a polystyrene nonlinear cavity centered at the intersection of a hole-type PC cross-waveguide scheme. Polystyrene due to having an extremely fast response time and a large Kerr nonlinearity is used extensively in the design of ultra-fast, high-contrast and low power all-optical switching devices [14–19]. The coupled-mode theory (CMT) is used to provide qualitative descriptions for the operation of the proposed controllable switch. Furthermore, the proposed device is simulated numerically using a commercial finite-difference time-domain (FDTD) software, RSoft (FullWave), and the simulation results prove the validity of the theoretical descriptions.

2. Theoretical approach for the proposed high-contrast controllable hole-type PC switch

The proposed design is composed of a cross-waveguide based structure, which is implemented in a 2D hole-type square lattice PC, and a

* Corresponding author.
E-mail address: k.fasihi@gu.ac.ir (K. Fasihi).

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Table 1
The basic features of some all-optical PC switches.

Reference	Type of PC	The used nonlinear material	Controllable (with a separate control signal)	Contrast ratio	Control power
[4]	Rod-type	AlGaAs	Yes	–	6 (W/μm)
[5]	Rod-type	$Ag_x(As_{0.4}Se_{0.6})_{100-x}$, $X = 20$	No	–	–
[6]	Rod-type	GaAs	Yes	–	More than 32 (W/μm)
[8]	Rod-type	AlGaAs	No	Can be very-high	–
[9]	Rod-type	AlGaAs	No	4	–
[11]	Rod-type	AlGaAs	Yes	10	0.205 (W/μm)
[12]	Rod-type	AlGaAs	Yes	12–40	0.190 (W/μm)
The proposed switch	Hole-type	Polystyrene	Yes	18–23	3.08 (W/μm)

polystyrene nonlinear elliptical cavity, as depicted in Fig. 1. In order to achieve a controllable all-optical switch using cross-waveguide-based structure the crosstalk between the signal and control waveguides must be eliminated. Johnson et al. proposed general criteria on the basis of symmetry for the intersection with very low crosstalk and high throughput and investigated it in a rod-type PC structure [20]. In the next section, we will show that using a proper design, it can be possible to qualify the criteria in a hole-type PC structure. The equations that depict the temporal changes of the cavity normalized mode amplitudes in a cross-waveguide based structure can be described by two coupled differential equations [11]. Due to the complexity of the analysis of the governing CMT equations, we use a qualitative manner to describe the operation of the suggested controllable switch. In the absence of the control input and in the linear regime, for the X-mode of the cavity, from the CMT, the ratio between the input and outgoing light powers that has a Lorentzian shape can be expressed as [3]

$$\frac{P_{out_x}}{P_{in_x}} = \frac{\gamma_x^2}{\gamma_x^2 + (\omega - \omega_{res_x})^2}, \tag{1}$$

where $\gamma_x = \omega_{res_x}/(2Q_x)$ is the decay rate in the cavity, ω_{res_x} is the resonant frequency, and Q_x is the quality factor of the cavity. It has been shown that in the linear regime, in a cross-waveguide-based structure obeying the basic criteria, the energy exchange between the input and control light powers can be eliminated [11]. In the nonlinear regime, it has been shown that $\omega_{res_x} \to \omega_{res_x}(1 - P_{out_x}/(2p_{0_x}Q_x))$ [3,13], where p_{0_x} is the characteristic power of the system for the X-mode and is defined as

$$p_{0_x} = \frac{c}{\kappa Q_x^2 \omega_{res_x} n_2(\vec{r})|_{\max}}, \tag{2}$$

where κ is the nonlinear feedback parameter, $n_2(\vec{r})|_{\max}$ is the maximum value of $n_2(\vec{r})$ anywhere ($n_2(\vec{r})$ is the nonlinear coefficient of the cavity,) and c is the speed of light. In this case, the transmitted power ratio of the structure for the cavity X-mode can be calculated as [3]

$$\frac{P_{out_x}}{P_{in_x}} = \frac{1}{1 + (P_{out_x}/p_{0_x} - \delta_x)^2}, \tag{3}$$

where $\delta_x = (\omega_{res_x} - \omega_x)/\gamma_x$ is the detuning of the incident light frequency from the cavity resonant frequency and $\gamma_x = \omega_{res_x}/(2Q_x)$. Now, we investigate the effect of the presence of control input power on the behavior of the proposed structure. When only the control input is applied, for a detuning factor of δ_y (the detuning of control signal frequency from the cavity Y-mode resonant frequency), the nonlinear refractive index of the central elliptical cavity can be expressed as

$$n(\vec{r}) = n_0 + n_2 I_c(\vec{r}), \tag{4}$$

where $I_c(\vec{r})$ is the intensity of light in the cavity due to the applying the control signal. Due to the nonlinear dependency of the output power versus the input power, the intensity of light in the cavity can be considered as a function of the output power (P_{out_c}). Based on the electromagnetic variational theorem, the increase in the refractive index of an elliptical cavity (see (4)) is corresponding to a reduction in its resonant frequencies. On the other hand, it can be shown that by increasing the separation of resonant frequencies of the cavity (more

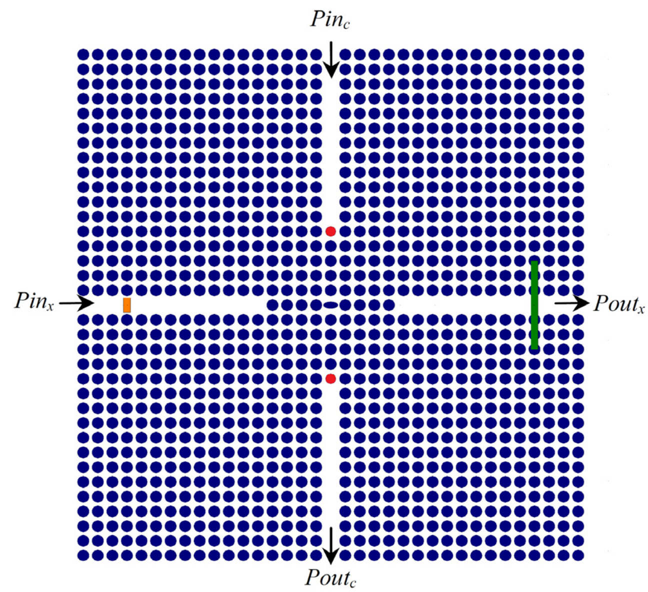

Fig. 1. The structure of proposed switch, which is constructed using a hole-type PC cross-waveguide based scheme and infiltration of the elliptical air hole with polystyrene. The red circles are two extra holes that will be used in the modified structure for reduction of the control power. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than the width of resonances), and also the frequencies of the input and the control light powers, the nonlinear energy exchange between the signal and control inputs, which lead to the mutual modulation of the control and signal light powers and as a result output power fluctuations, can be reduced, considerably.

Therefore, assuming that the above mentioned conditions are satisfied, when both input and control signals are applied, the resonant frequency shift of X-mode can be expressed as $\gamma_x(P_{out_x})/p_{0_x} + F(P'_{out_c})$, where $F(P'_{out_c})$ represents the resonant frequency shift due to applying the control signal as a function of P'_{out_c} (the measured power in the vertical output waveguide in the presence of input signal). It must be noted that in a controllable switching design, the desired values of control input power are at the upper level of the bistability curve of the Y-mode, and far apart from its upward threshold level, and as a result $P'_{out_c} \cong P_{out_c}$. Hence, in this case the transmitted power ratio of the cavity X-mode can be expressed as

$$\frac{P_{out_x}}{P_{in_x}} = \frac{1}{1 + (P_{out_x}/p_{0_x} - (\delta_x - \delta'_x))^2}. \tag{5}$$

where $\delta'_x \cong F(P_{out_c})/\gamma_x$ and can be calculated through the fitting of the curve of the above equation with the numerical results. As can be seen, applying a control signal shifts the resonant frequency of the cavity X-mode by an amount that is approximately proportional to $\gamma_x\delta'_x$ and a new bistability curve, corresponding to the detuning factor of $\delta_x - \delta'_x$