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Photonic crystal all-optical switch based on a nonlinear cavity

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ABSTRACT

We demonstrate high-speed all-optical switch structure using an ultra-small nonlinear cavity coupled to input and output waveguide. The whole structure is based on a square lattice photonic crystal formed by rods of refractive index $n_r = 3.4$ in an air background. Finite-difference time-domain method is used to analyze the device characteristics. By analyzing of behavior of structure, we show that switching from OFF to ON occurred because resonant wavelength shift is caused by Kerr effect. The simulation result shows that switch has a high-speed response of ~26 ps. Since the structure has an ultra-small length of 12 μm, it has a potential to use in integrated optical-circuits.

1. Introduction

As the dimensions of optical devices advances toward micrometer and nanometer scales, speed and bandwidth will be increased. All-optical switch is considered as key component in ultrafast communication and signal processing systems. In an all-optical switch, by using nonlinear optical material, light will be controlled by light signal. The driving energy and smallest size of photonic devices are restricted by the low confinement of light in a weak light-matter interaction and small space. Photonic crystals (PhCs) are structures wherein refractive index changed periodically. Such structures are expected to overcome this limitation [1,2]. There are various methods for realization of photonic crystal all-optical switches such as directional coupler structures [3–5], Mach–Zehnder interferometer [6–8] and resonators [9–11]. The main problem in directional coupler and Mach–Zehnder structure is their long device lengths, that are a most important drawback for its integration [5,8,12]. Micro and nano-cavities constraint the light in a highly limited region. In such a situation, it increases the interaction of the light with matter and at the same time reduces the size of the device. By employing micro and nano-cavities for large Q/V ratio, all-optical nonlinear switch will exhibit significant reduction on switching energy [13,14], wherein Q and V are cavity quality factor and cavity mode volume respectively. Here, the high Q factors tend to limit the speed owing to long photon lifetime [15–18].

Here we show that silicon PhC microcavities coupled to input and output waveguides can operate as high-speed all-optical switching devices by employing optical nonlinearity. The paper is organized as follows. In Section 2, we present the designing of the proposed structure based on waveguide–cavity–waveguide, and investigate the conditions of coupling between cavity and waveguide modes. In Section 3, we show switching operation by calculating the transmission spectra of device. Temporal behavior of switching is demonstrated in Section 4. At last, the conclusion is given in Section 5.

2. Design of proposed structure

Our proposed structure is a waveguide-cavity-waveguide based on the photonic crystal illustrated in Fig. 1. This structure based on a square lattice two-dimensional photonic crystal formed by rods of refractive index $n_r = 3.4$ in an air background. The lattice constant (a), the fill factor (r/a) and length of structure (L) are 600 nm, 0.2 and 12 μm, respectively. By removing the middle rod of the structure, a cavity is formed surrounded by 8 nonlinear rods of $Ag_{(x)}(As_{0.4}Se_{0.6})_{(100-x)}$ (chalcogenide glass). The radius of rods is quite similar to those of silicon rods wherein refraction coefficient of $n_{L0} = 3.1$, and nonlinear Kerr coefficient of $n_2 = 9 \times 10^{-17}$ W/m^2. This cavity has been coupled with two input and output single mode waveguides. To achieve a structure with transmission of almost 100%, it is necessary to have symmetrical waveguide-cavity-waveguide system with input/output waveguides in single mode. The photonic band gap is $0.29 < a/\lambda < 0.42$, corresponding to 1429 nm < λ < 2068 nm.

Fig. 2a and b shows the E_y field pattern of waveguide guided mode and cavity confined mode, respectively. A comparison of these two figures show the matching of the field pattern of the two modes. The corresponding field patterns are required to obtain efficient coupling between the cavity and the waveguide modes.

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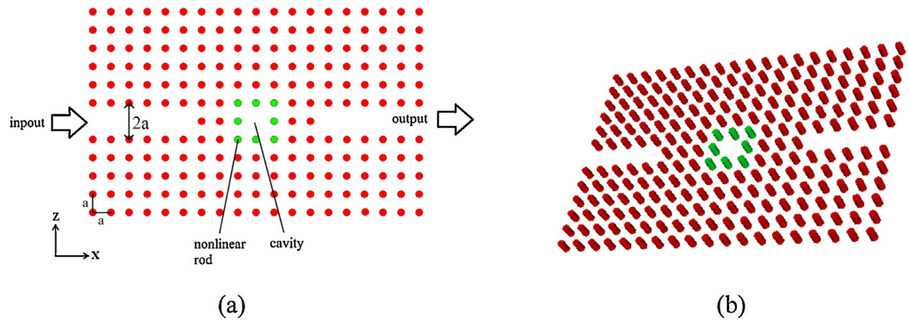

Fig. 1. Structure of photonic crystal all-optical proposed switch based on nonlinear cavity. The whole structure is based on a square lattice photonic crystal of lattice constant of a = 600 nm, formed by rods of refractive index n_r = 3.4 in an air background. Fill factor of structure is r/a = 0.2 and Kerr coefficient of nonlinear rod is $n_2 = 9 \times 10^{-17}$ W/m^2; (b) proposed structure by slab photonic crystal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

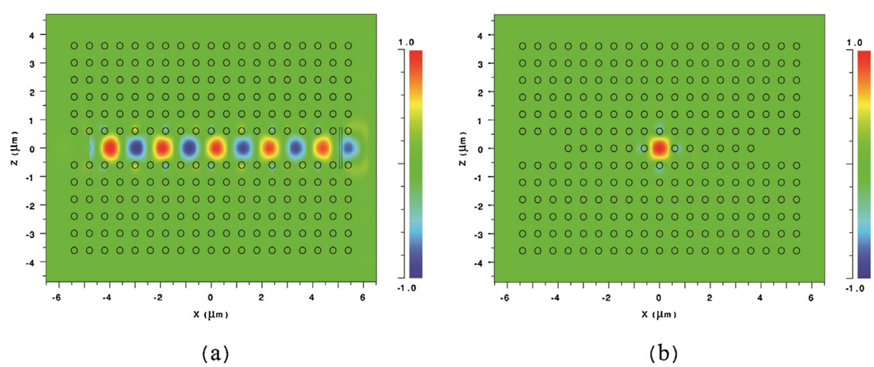

Fig. 2. E_y field pattern of (a) guided mode of waveguide and (b) confined mod of cavity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 shows the power spectrum of the confined mode in the cavity with a resonance peak for wavelength where λ = 1546 nm, as the estimated unloaded quality factor (Q_{cav}) is 8800. In the coupling structure, cavity and waveguides are separated by a number of PhC lattice rods. Therefore, selection of the separating rods is of high importance here. The parameters of coupled cavity quality factor (Q_{cpl}) and structure transmission coefficient ($T = P_{out}/P_{in}$) are important factors in obtaining a reduced amount of loss and low switching power structure. Fig. 4a and b shows T and Q_{cpl} as a function of separation rod, respectively. When rod-1 or rod-2 separated the cavity from the waveguides, T reached 100%; however, Q_{cpl} remained to less than 1000. With selecting four or more than four rods, then the amount of Q_{cpl} is increased to 8800 while T is decreased to less than 0.2. By selecting 3 rods to separate the cavities from the waveguides, the amount of T reached to 100% while Q_{cpl} decreased to 2200. This indicates that choosing 3 separating rods provide a tradeoff between the two parameters of Q_{cpl} and T.

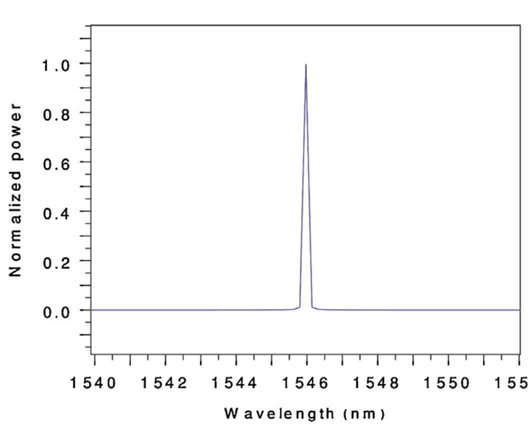

Fig. 3. Power spectra of cavity mode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Switching operation

In demonstrating the switching behavior of the structure to obtain the switching threshold power, it is necessary to examine the frequency spectrum on transmission of the structure at different levels of input power (P_{in}). The transmission spectrums of the structure for P_{in} = 1 W/μm and P_{in} = 15 W/μm are shown in Fig. 5. The figure shows that switching operation of structure is calculated at λ = 1547 nm. When P_{in} = 1 W/μm, the transmission is about 20% and the switch is considered to be OFF, because low input power can't significantly change the refractive index of nonlinear rod. When input power increased to P_{in} = 15 W/μm, the refractive index of nonlinear rod of surrounding the cavity increased because of the Kerr nonlinear effect and the resonance wavelength shifted toward higher wavelengths. As shown in Fig. 5, when P_{in} = 15 W/μm, the resonance wavelength is shiftthed to λ = 1547 nm. As the transmission value increased to 0.8, we observed clear all-optical switching from OFF to ON.

Fig. 6, better illustrates the switching operation of structure at λ = 1547 nm. This figure shows transmission as a function of P_{in}. When input light power is less than the threshold value of P_{th} = 15 W/μm, the nonlinear Kerr effect is not significant and the switch operated in a linear regime. When $P_{in} \geq P_{th}$, the interaction of light with nonlinear material changed structure behavior and transmission increased to 0.8.