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RESEARCH ARTICLE

All-optical bistable switching, hard-limiter and wavelength-controlled power source

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Abstract In this paper, an all-optical bistable switching operation of resonant-tunneling devices with ultra-small photonic crystal cavity was demonstrated. The whole structure was based on a square lattice photonic crystal formed by rods of refractive index $n_r = 3.4$ in an air background. The cavity was surrounded by eight nonlinear rods of refractive index $n_{L0} = 3.1$ and nonlinear Kerr coefficient $n_2 = 9\times10^{-17}$ W/m^2. Nonlinear finite difference time domain method was used to get a bistability hysteresis loop. Next, all-optical wavelength controlled power source (WCPS), hard-limiter and switching operation based on optical nonlinearity were shown. And that small cavity structure has a small length of 12 μm. Considering the numerous applications and small length, this proposed structure has various potential function in all-optical circuits.

Keywords all-optical, bistability, Kerr nonlinearity, photonic crystal cavity, switching

1 Introduction

As all-optical devices are micrometer and nanometer scales, their speed and bandwidth will be increased accordingly. All-optical switching is an essential operation in ultrafast communication and signal processing systems [1,2]. As an important subject in nonlinear optics, a practicable understanding on all-optical switching is relied on optical bistability [3]. Optical bistability presents a couple of applications, like all-optical memory [4,5], transistor action [6], switching [7], etc. Based on theoretical and experimental studies, the optical bistability existed in waveguide-ring resonators [8], photonic crystals (PhCs) [9–12], plasmon crystals [13], Fabry-Perot resonators [14] and quantum well [15]. Optical resonators can play an important role in enhancing the nonlinear optical phenomena in terms of optical bistability properties [16]. Various kinds of optical cavities featured by extremely miniature mode volumes with very high quality factors have been presented [17]. Owing to their exemplified confinement mechanism, photonic crystal cavities are considered to have a multi-purposed manner to make new optical integrated devices. All-optical nonlinear bistable switching demonstrated considerable decrease in switching energy by employing ultra-small cavities for large Q/V ratio, wherein Q and V are given for cavity quality factor and cavity mode volume, respectively [18].

Here, it is shown that carefully-designed photonic crystal cavity coupled to input and output waveguides can operate as on-chip optical bistable switching device by employing optical nonlinearity. The paper is organized as follows. In Section 2, the characteristics of the proposed structure is presented. In Section 3, bistable switching operation is shown by calculating the input-output relation for this proposed structure. In Section 4, this structure is employed for wavelength controlled power source (WCPS), hard-limiter and switching operation. Finally, the conclusion is given in Section 5.

2 Characteristics of the proposed structure

The proposed structure was a waveguide-cavity-waveguide based on a square lattice two-dimensional photonic crystal composed of rods with refractive index $n_r = 3.4$ in an air background illustrated in Fig. 1. A cavity that is surrounded by eight nonlinear rods of $Ag_x(As_{0.4}Se_{0.6})_{100-x}$ (chalcogenide glass) was formed by removing the center rod of the structure. The cavity was coupled with two single mode waveguides on the left and right. The structural parameters are as follows: the lattice constant a = 600 nm, the fill factor r/a = 0.2, the radius of nonlinear rods was quite similar to those of silicon rods, refraction

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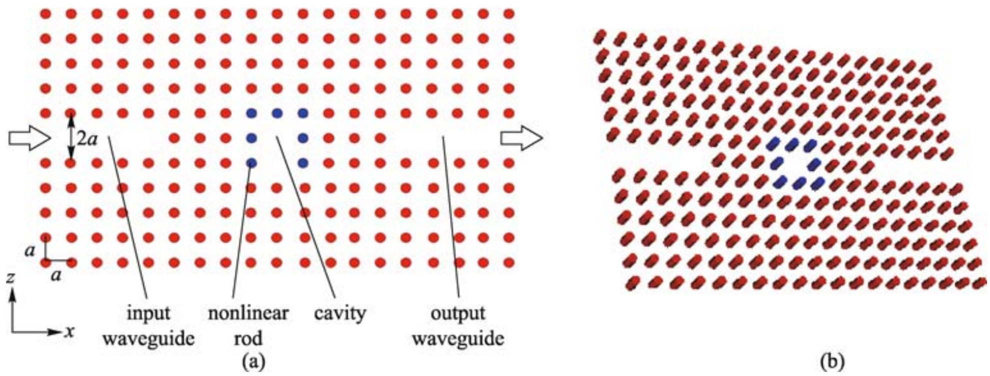

Fig. 1 (a) Structure of photonic crystal all-optical switch based on nonlinear cavity. The whole structure was based on a square lattice photonic crystal of lattice constant of a = 600 nm, formed by rods of refractive index n_r= 3.4 in an air background. Fill factor of structure was r/a = 0.2 and Kerr coefficient of nonlinear rod was $n_2 = 9\times10^{-17}$ W/m^2; (b) the proposed structure based on slab photonic crystal

coefficient of nonlinear rods n_{L0} = 3.1, nonlinear Kerr coefficient $n_2 = 9\times10^{-17}$ W/m^2 and the total length of structure L = 12 μm. Figure 2 shows the band diagram of this structure for a transverse magnetic (TM)-polarized wave. The photonic band gap was $0.29 < a/\lambda < 0.42$, corresponding to 1429 nm $< \lambda <$ 2068 nm. The cavity had a resonance peak at λ = 1546 nm and estimated unloaded quality factor (Q_{cav}) was 8800. By selecting three rods to separate the cavities from the waveguides, the amount of transmission coefficient ($T = P_{out}/P_{in}$) reached to 100% and the amount of loss was reduced. The coupled cavity quality factor (Q_{cpl}) was 2200.

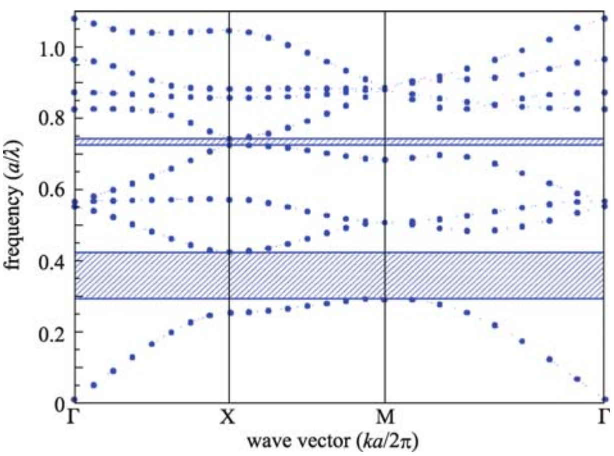

Fig. 2 TM-band structure 2D photonic crystal formed by rods of refractive index n_r= 3.4 in an air background

3 Bistable switching operation

Light is transmitted between the input and the output ports by means of a resonant tunneling process. The transmission spectrum of the structure for P_{in}= 1 and 15 W/μm is shown in Fig. 3. Input waveguide was excited using a TM mode Gaussian continuous wave (CW) and transmission spectrum was calculated at different wavelengths. Figure 3 shows the resonance wavelength of this cavity increase to λ_0= 1547.00 nm. When P_{in}= 1 W/μm, the transmission was about 20% and the switch was considered to be OFF, because low input power cannot significantly change the refractive index of nonlinear rod. When input power was 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 was shifted to λ_0= 1547.00 nm. As the transmission increased to 80%, switching from OFF to ON occurred.

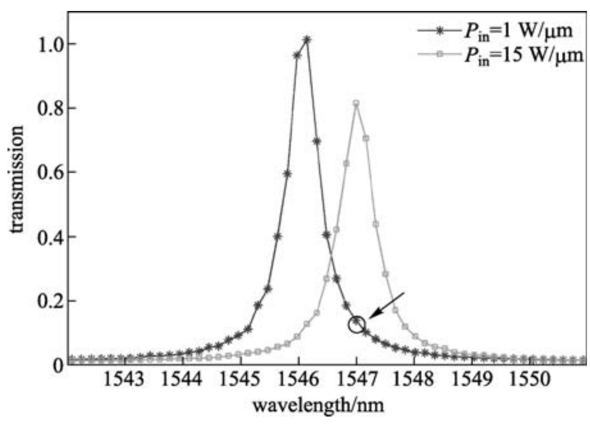

Fig. 3 Transmission spectrum of the proposed structure for P_{in}= 1 and 15 W/μm

Resonance wavelength depends on the energy stored in the cavity. If the input waveguide incited by light with a wavelength greater than λ = 1546.00 nm, the confinement of light in the cavity results in an increase in light intensity, which will cause a shift of the resonance wavelength and the wavelength is larger than λ = 1546.00 nm. This increased light intensity inside the cavity will create positive feedback in the resonant tunneling process. Since the output light intensity is related to the light intensity inside the cavity, the transmission can be considered to be a function of output light intensity and be expected to show bistability. Investigating the bistability of the proposed structure to obtain the output power as function of input power at a wavelength of $\lambda = 1547.00$ nm, the power of the CW was increased slowly and then decreased. Slow changes in input light power were required for obtaining the hysteresis curve structure. Figure 4 shows the bistability of the structure in the obtained curve. From this figure, it can be observed that two input critical values (threshold) of $P_2 = 5$ W/μm and $P_1 = 15$ W/μm as the range of output power with single value is $P_{in} < P_2$ and $P_{in} > P_1$. For $P_2 < P_{in} < P_1$, output power has two distinct stable values, (such as points A and B in Fig. 4). As the input power increased from the second threshold ($P_{in} > P_1$), output light intensity did not show a significant increase and remained approximately constant.

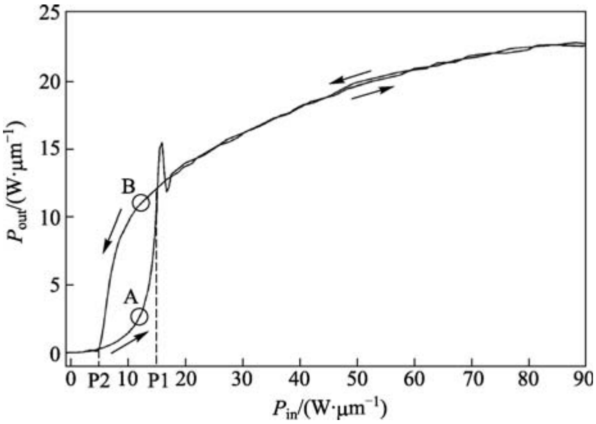

Fig. 4 Dependence of P_{out} as a function of P_{in} for $\lambda = 1547.00$ nm

4 Structure operation

4.1 Wavelength controlled power source (WCPS)

Figure 5(a) shows the output power as function of P_{in} at six different wavelengths ($\lambda = 1546.70$ nm to 1547.45 nm at 0.15 nm increments). With the enhancement of input light wavelength, the critical power values of P_1 and P_2 and the range of bistability ($P_2 < P_{in} < P_1$) were increased. Figure 5(a) shows that for the input power range of $P_{in} > 30$ W/μm, the output power remained approximately constant. In this input power range, the output power increased with increasing of the input wavelength. Figure 5(b) shows the dependence of P_{out} on input wavelength for $P_{in} = 55$ W/μm (in the range of $P_{in} >$ 30 W/μm). According to this figure, with the increase of the input light wavelength, the output power of the structure begins to increase linearly. The slope of the line in Fig. 5(b) is $K = 7$ (W/μm)/nm, where the proposed

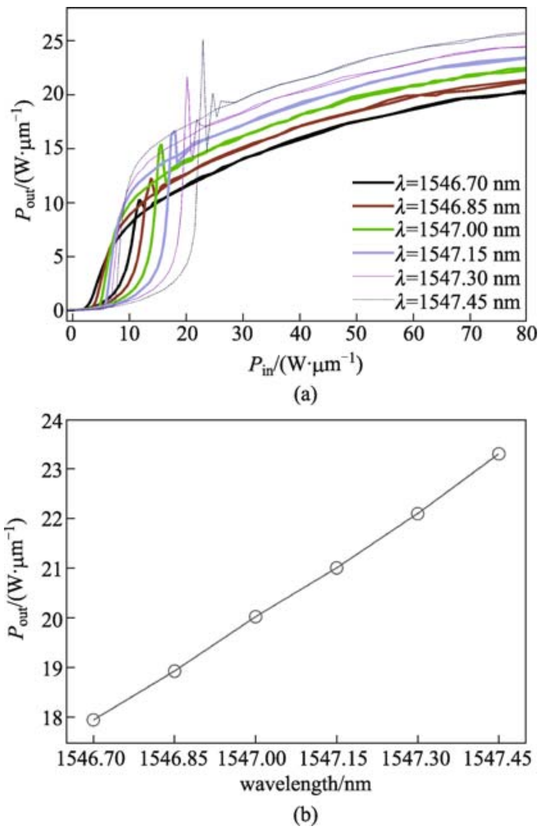

Fig. 5 (a) P_{out} as a function of P_{in} for $\lambda = 1546.70$ to 1547.45 nm; (b) dependence of P_{out} on the wavelength for $P_{in} = 55$ W/μm (in the range of $P_{in} > 30$ W/μm)

structure can be used as a WCPS for the input power range of $P_{in} > 30$ W/μm reinforced by the gain of K.

4.2 Hard-limiter

As input power increased from the second threshold, i.e., $P_{in} > P_1$, the output power did not show a significant increase. For a range of input powers, output power did not show considerable sensitivity to changes in input power. Figure 6 shows input and output pulses for $\lambda = 1546.70$, 1547.00, 1577.30 nm. According to Fig. 6, the output pulse is not symmetric contrary to the input pulse. By making the P_1 and P_2 critical values close to each either, the pulse symmetry can be maintained. As the achieved curves of lower input wavelengths having critical powers of P_1 and P_2 are close to each other, then by selecting appropriate wavelength it is possible to coincide input/output pulses for power value of less than P_1. Figure 6 shows more symmetry of pulse for $\lambda = 1546.70$ nm than for $\lambda = 1547.00$ and 1547.3 nm. This figure also indicates that the height cross section can be controlled using the input light wavelength while with increasing the wavelength, the height is increased, too. The results show that the behavior of the proposed structure can be used in hard-limiting or pulse shaping.

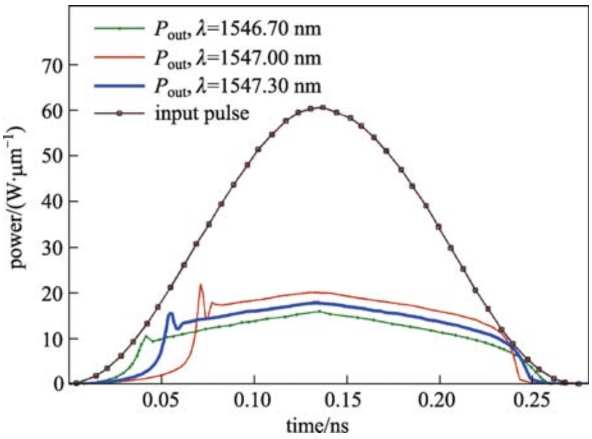

Fig. 6 Input and output pulses for $\lambda = 1546.70$, 1547.00 and 1547.30 nm

4.3 Switch

There are two distinct stable output values in the $P_2 < P_{in} < P_1$ range. The power of the signal light can be set inside the bistable region, and turning the switching to the "ON" state through a control light. In Fig. 7(a), incited input waveguide is a continuous wave $\lambda = 1547.00$ nm with P_{in}= 12 W/μm and a controller pulse characterized by maximum power of $0.8P_{in}$ with same wavelength. Figure 7 (b) shows temporal behavior of the output signal with and without control pulse. Before control pulse, the output reached a steady state at point A in Fig. 4 and switching can only works on the "OFF" state with $T = 0.2$. By controlling the pulse, output power begin to increase and the bistable switching is successfully triggered to the "ON" state, While, with reducing pulse control power, input power decreased to the original value (P_{in}= 12 W/μm). At this time, output power followed a route other than the previous uptrend one. When the control pulse disconnected completely, the output power reached a steady state at point B; thus, the output jumped from state A to state B. This bistability feature can be used for memory [4,5] and transistors [6].

5 Conclusion

An all-optical bistable switch using an ultra-small non-linear cavity coupled to input and output waveguides was demonstrated. By nonlinear finite difference time domain simulation, a bistability hysteresis loop was gotten and a hard-limiter, a WCPS and a switching operation were shown. The ability to switch between two stable output values can be used for memory, transistors, and so on. Device has ultra-small length of 12 μm and switching power of almost 15 W/μm by employing large Q/V ratio micro and nano-cavities, this value can be reduced [18]. Considering the numerous applications of all-optical bistable devices, the proposed structure can play an important role in integrated all-optical circuits.

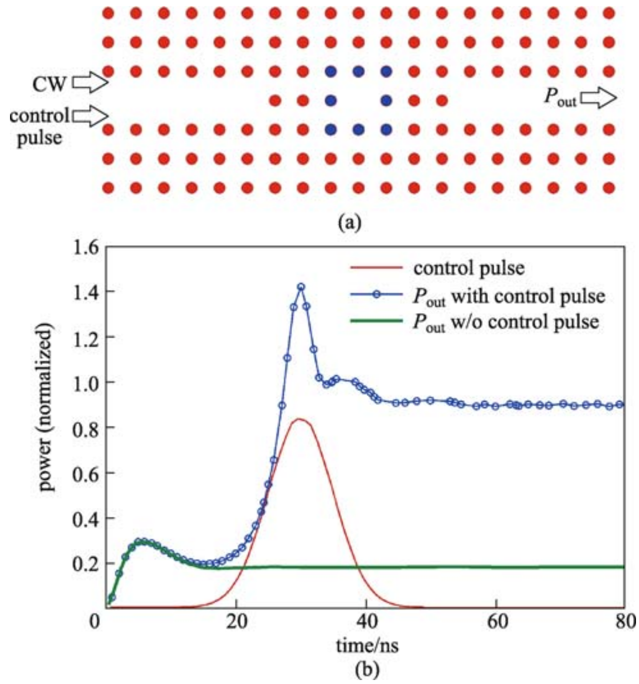

Fig. 7 (a) Schematic of structure with CW input and control pulses; (b) temporal behavior of the control pulse and normalized output signal with and without control pulse

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