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High efficiency all-optical diode based on photonic crystal waveguide

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ABSTRACT

A high efficiency all-optical diode based on photonic crystal (PC) waveguide has been proposed and numerically investigated by finite-difference time-domain (FDTD) method. The structure is asymmetrically coupled by a Fano cavity containing nonlinear Kerr medium and a F–P cavity in PC waveguide. Because of interference between two cavities, Fano peak and F–P peak can both appear in transmission spectra. Working wavelength is set between the two peaks and approaching to Fano peak. For forward launch with suitable light intensity, nonlinear Kerr effect of micro-cavity can be excited. It would result in red shift of Fano peak and achieving forward transmission. But due to the asymmetric design, backward launch need stronger incidence light to excite Kerr effect. This design has many advantages, including high maximum transmittance (> 90%), high transmittance contrast ratio, low power threshold, short response time (picosecond level), ease of integration.

1. Introduction

All-optical diodes have great potential applications in integrated optical circuits and optical interconnection systems, because of function of forward transmission and backward cut-off just like electron diodes in circuit. In 1994, Michael Scalora firstly presents an all-optical diode using one-dimensional nonlinear photonic crystals with a spatial graduation in the linear refractive index [1,2]. Recently, various designs of all-optical diode have been proposed, including two-dimensional nonlinear photonic crystal micro-cavities with asymmetric structure [3–5], left-handed periodic structures [6], tunable surface plasmon polaritons in a silver grating coated with a nonlinear organic material [7], light tunneling heterostructures with one-dimensional PCs and lossy metallic film [8], low-symmetry magnetic photonic crystals [9], periodically poled lithium niobate waveguides [10], asymmetric nonlinear absorption material layers [11], photonic crystal fibers [12]. Electro-tunable optical diode based on liquid-crystal photonic crystal heterojunctions [13,14]. However, these schemes are still some deficiencies in some respects.

In the paper, we study a PC-based all-optical diode belong to the self-inducing type, i.e., the unidirectional transmission is accomplished by the input signal without involving any external pumps. It is designed as an asymmetrical configuration composed by a nonlinear micro-cavity and a F–P cavity. The transmission characteristics are simulated by using nonlinear FDTD technique. The important parameters of all-optical diode performance, including maximum transmittance, forward and backward transmittancy, power threshold, and response time are systematically analyzed. Our compact structure has important potential applications for all-optical information processing in highly integrated optical circuits.

2. The model

The structure of all-optical diode is shown in Fig. 1. There is a line defect waveguide in an air-bridge PC consisting of the square lattice. The lattice constant is a, and the radii of dielectric cylinders is $r=0.33a$. The refractive index of air and GaAs set as $n_0=1$ and $n=3.46$. An elliptical defect is set in the side of PC waveguide as a Fano micro-cavity. Two reflecting layer R1 and R2 compose a F–P cavity in the waveguide. To obtain a complete picture of the photonic properties of both the individual components and their combined implementation, both time-domain and frequency-domain computational methods were employed. Since the computational methods used in this analysis rely on Maxwell's equations, which are scale invariant, all geometric parameters in the simulations were scaled to the PC lattice constant.

An elliptical point defect is introduced in the second layer below PC waveguide [shown in Fig. 3(a)], of which major and minor axes are $0.534a$ and $0.3a$. The coupling by point defect micro-cavity and PC line defect waveguide forms a Fano resonance. The resonance peak can be effectively adjusted by changing the structure parameters of elliptical point defect. We The structure is

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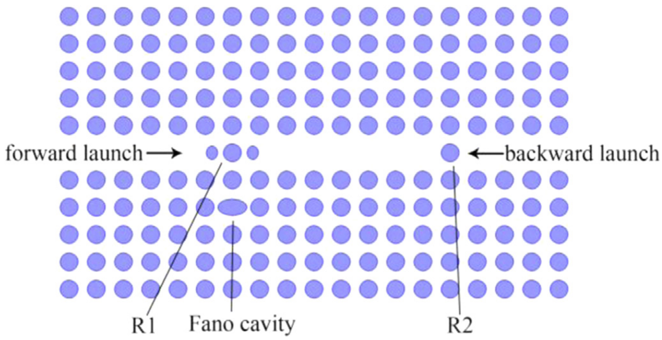

Fig. 1. Schematic diagram of the all-optical diode structure based on PC waveguide.

very advantageous to design new functional devices.

3. Simulation results and analysis

First, we study the transmission characteristics under the linear condition (without Kerr effect) by FDTD simulation. The simulation of light propagation characteristics is conducted by FDTD with a commercial software Lumerical FDTD Solutions. For only the point defect in the structure [shown in Fig. 2(a)], the transmission spectra in Fig. 2(b) shown a reflecting peak (normalized frequency 0.4363). The optical field highly focus in micro-cavity to benefit inducing Kerr nonlinearity of GaAs. The wavelength of the peak can be fine-tuned by changing the structure and refractive index of micro-cavity.

As a widespread physical phenomena, Fano resonance attracted the interest of a large number of researchers to study the physical characteristics and potential applications [15–19]. One of the hot spots is PC bistability switching [20,21]. The resonance peak is transmission peak or resonant peak depending on the interference between micro-cavity and waveguide or waveguide reflector. The micro-cavity in PC has an ultra-high quality factor $Q=\omega/\Delta\omega$. $\Delta\omega$ is full width half maximum, and ω is center frequency. For a single-mode cavity, whatever it is transmission or reflection type Fano resonance cavity, the optical intensity which is coupled into cavity is proportional to Q factor $I_{cav}=I_0\frac{Q}{\pi}$ [22]. I_{cav} is the optical intensity in cavity, and I_0 is the input optical intensity. If the cavity medium is the third order nonlinear Kerr material, it means that the nonlinear effect can be enhanced $\frac{Q}{\pi}$. The high quality PC micro-cavity has a good effect for enhancing nonlinear effect.

By adding a dielectric cylinder (radii is 0.33a) above the micro-cavity as reflector layer (R1) to block the PC waveguide [shown in Fig. 2(c)], the transmission spectra is calculated in Fig. 2(d). We can see that a transmission peak appear instead of original reflecting peak. A transmission type Fano resonant cavity is formed. The reflector layer R1 is optimized by employing two small elliptical cylinders (the major and minor axis are 0.25a and 0.21a, respectively) in Fig. 2(e). Then, the extinction ratio (ratio of transmission peak and the other region) can be effectively improved [shown in Fig. 2(f)]. The peak is very steep, especially for the right side, and the Q factor is calculated about 5000. Only a very small change of refractive index of point defect will achieves the move of resonance peak. If the Kerr nonlinear effect is introduced into the medium, And we change the working wavelength approximate to Fano peak. For a weak input light, there is a resonant reflection. If input light is growing, Fano peak will red shift due to Kerr nonlinear effect. In this process, the state of resonant reflection will converts to resonant transmission in a certain light intensity. A switch process from off to on is achieved. But, for input light from strong to weaken process, the state of resonant transmission converts to resonant reflection in another light intensity. This is a switch process from on to off. The two light intensities corresponding to mutation of transmittance is different. It can be designed as optical bistability switch devices.

All-optical diode requires two conditions: one is an asymmetrical structure, and the other is nonlinear. another reflector layer R2 is adding in the PC waveguide in Fig. 3(a). The reflective layer and original reflective layer R1 form a F–P cavity. The transmission spectra of the F–P cavity is shown in Fig. 3(b). Length of F–P cavity is effectively adjusted by changing the distance between R1 and R2. Now, the distance between reflector layer R1 and R2 is set to eight lattice constants. It make resonant wavelength close to Fano peak. This design ensure effectively interfere with each other between F–P cavity and Fano cavity, and form the asymmetrical structure.

Now, we combine the Fano cavity and F–P cavity together as Fig. (1). First, the transmission spectra is calculated without nonlinear effect. Seen in Fig. 4(a), two transmission peaks can be observed in the transmission spectra due to coupling each other between the two cavities. The narrow one is Fano peak close to short-wave, and the other wide one is F–P peak close to long-wave.

Then, nonlinear Kerr effect is introduced, the Kerr coefficient of GaAs is set as $n_2=1.5*10^{-5}$ μm^2/w. Due to the local effects of micro-cavity, the distribution of optical field in the point defect is far stronger than others. The nonlinear effect except micro-cavity can be ignored. If the frequency of input light set to ω_0 close to Fano peak, the transmittance will suddenly change from weak to strong. The reason is that optical field greatly focus on the point defect and produce Kerr nonlinear effects. Fano peak will red shift to ω_0, due to the refractive index of micro-cavity is changed.

The forward launch is defined from left to right. At working frequency ω_0, the forward input light will be reflected by R1. But the micro-cavity is next to R1, so evanescent wave inevitably couple into micro-cavity to produce Kerr effect. This effect increase with optical intensity. For backward launch, the input light is reflected by R2. R2 is far away from micro-cavity. So the evanescent wave entered micro-cavity is less than forward launch. Under the same input intensity, the change of refractive index of micro-cavity for forward launch is more than backward launch. Using above effect, we can design an efficient optical diode.

We select the working wavelength $\omega_0=0.43535$, which is in the reflection band between Fano peak and F–P peak, and close to Fano peak. Fig. 4(b) shows the distribution of optical field with forward launch at input power density $P=0.1$ mW/μm. We can see that most input light is reflected from R1 and micro-cavity. Because the input light is so weak that it cannot produce Kerr effect. If $P=1.6$ mW/μm, the Kerr effect in the micro-cavity is produced. Then, we can see that the light transmit through the waveguide on forward launch [shown in Fig. 4(c)]. For backward launch at the same power density $P=1.6$ mW/μm, Fig. 4(d) reveals that the light still cutoff. So at $P=1.6$ mW/μm, the structure achieve the function of forward transmission, backward cut-off. If we continue to increase power density $P=4.3$ mW/μm, the light also can transmit through the waveguide on backward launch [shown in Fig. 4(e)].

In addition, we analyze the response time of device. At $P=1.6$ mW/μm, the changes of transmittance over time are shown in Fig. 5(a) and (b) corresponding to forward launch and backward launchs, respectively. Seen in Fig. 5(a), the forward transmission has been stable after $t=40$ ps. But Fig. 5(b) shows that backward is always cut-off. The result demonstrates that the response time is at picosecond level.

At last, we study the relationship between forward and backward transmittances with power density of light at $\omega_0=0.43545$ and 0.43535. Seen in Fig. 6(a), solid line and dashed line indicate forward and backward launch respectively, at $\omega_0=0.43545$. The transmittance of forward launch suddenly change from low to