A fast optical switch for self-collimated beams in a photonic crystal with electromagnetically induced transparency media

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In this paper, a fast optical switch working at 1550 nm that has a very short response time on the order of picoseconds is proposed. The optical switch has a very compact size of 10.14×10.14 μm^2 and a concise structure consists of 16×16 $In_{1-x}Ga_xAs_yP_{1-y}$-InP rods in air. The structure of the switch is optimal designed by analyzing its equi-frequency contours and bandgaps. Its performance is confirmed by finite-difference time-domain simulations. The designed optical switch may find important applications in the photonic integrated circuits.

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1. Introduction

Optical components are of great importance for next generation high density optical interconnects and integration for that they provide the miniaturization of an application specific optical integrated circuit to a scale comparable to the wavelength of light. Optical switch is one of the most fundamental elements for optical circuits [1]. In recent years, there has been a growing effort in the realization of photonic crystals (PhCs) as optical components and circuits, which can be integrated on a single chip. Some PhC optical switches are proposed based on control of light by light, by heat, by electric field, or by magnetic field recently [1-4]. Most of these switches are designed with PhC waveguides that confine the light in the line defects. With the development of PhCs' research, more and more attentions are attracted by its unusual dispersion properties, such as negative refraction [5, 6], self-collimation [7, 8], and superprism [9]. Among them, self-collimation in PhCs provides a brand new way of confining the light propagation besides the conventional PhC waveguides. A self-collimated light beam can propagate without diffraction in the PhCs. It has been reported in recent studies that the frequency range in which the self-collimating phenomenon occurs is sufficient to be a basis for photonic integrated circuits (PICs) [10]. Therefore, there is a rising trend to investigate optical components based on the self-collimation effect in PhCs, such as virtual waveguides [11], beam bends and splitters [12], polarization beam splitters [13], optical interferometers [14], optical switches [15], optical routers [16], resonators [17], and so on.

Electromagnetically induced transparency (EIT) is an electromagnetic phenomenon caused by the quantum coherence that first reported by Harris *et al* in 1990 [18]. Recently, some studies show that the performances of PhC optical components can be greatly improved by introducing EIT materials into PhCs, such as the slow light controlling [19], ultra-high-Q microcavity [20], and so on. Especially, it is found that the EIT applications at 1550 nm can be achieved with the semiconductor quantum well material InGaAs-AlAsSb [21-23]. The refractive index of these materials can be modified rapidly in several picoseconds by varying the frequency of the controlling light. Some optical components based on these materials are suggested, e.g. a directional coupler wavelength filters [23].

In this paper, an ultra-fast PhC optical switch working at 1550 nm for self-collimated light beams with semiconductor quantum well material $In_{1-x}Ga_xAs_yP_{1-y}$-InP is proposed. It has a quick response time of about serval picoseconds and a very compact size of 10.14×10.14 μm^2. For that the light wave is self-collimated in the PhC, so it needs no line defect like the PhC waveguide. As a result, the proposed optical switch thus has a simpler structure than the PhC waveguide-based switch, and can be made more easily.

2. Theory analysis

EIT can be realized in materials with a typical three-level $\wedge$-type system as shown in Fig. 1. Such materials can be made transparent for optical signals at the frequency ω_p coupling the levels a-b (signal field) through appropriate optical pumping at frequency ω_{ac} coupling the levels a-c (control field) [23]. The Rabi frequencies Ω_{ab} and Ω_{ac} relate to the probe (signal) and control fields, respectively. $\Delta_p = \omega_{ab} - \omega_p$ and $\Delta_c = \omega_{ac} - \omega_c$ indicate the frequency detunings of the probe (signal) and control frequencies to the atomic resonance frequency. In this paper the control field is assumed to be in resonance with the a-c transition, i.e. $\omega_{ac} = \omega_c$ and $\Delta_c = 0$. Δ_p is written as Δ throughout.

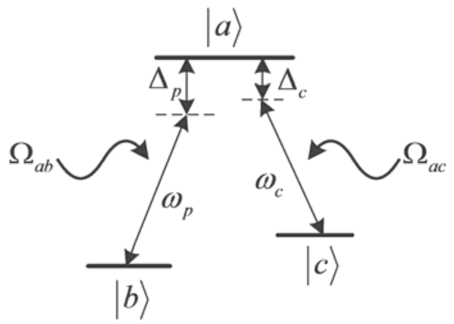


Fig.1. A typical three-level Λ-type system.

By applying density matrix formalism to the three-level system, the real and imaginary parts of the complex susceptibility of this system can be calculated as follows [23]:

$$\chi' = \frac{N_a |P_{ab}|^2 \Delta}{\varepsilon_0 \hbar} \times \frac{\gamma_3(\gamma_1+\gamma_3) + (\Delta^2 - \gamma_1\gamma_3 - \frac{\Omega_{ac}^2}{4})}{(\Delta^2 - \gamma_1\gamma_3 - \frac{\Omega_{ac}^2}{4})^2 + \Delta^2(\gamma_1+\gamma_3)^2} \tag{1}$$

$$\chi'' = \frac{N_a |P_{ab}|^2}{\varepsilon_0 \hbar} \times \frac{\Delta^2(\gamma_1+\gamma_3) - \gamma_3(\Delta^2 - \gamma_1\gamma_3 - \frac{\Omega_{ac}^2}{4})}{(\Delta^2 - \gamma_1\gamma_3 - \frac{\Omega_{ac}^2}{4})^2 + \Delta^2(\gamma_1+\gamma_3)^2} \tag{2}$$

where N_a is the atom number density, P_{ab} is the dipole matrix element, Ω_{ac} is the Rabi-frequency of the control field, γ_1 and γ_3 are the decay constants. The real part (χ') and imaginary part (χ'') of this first-order susceptibility determines the material dispersion and the material loss, respectively.

For small χ, the material loss and the (real) refractive index relates to the susceptibility in this case can be expressed as [23]:

$$\alpha \approx \frac{k_0 \chi''}{n_0} \tag{3}$$

$$n \approx n_0 + \frac{\chi'}{2n_0} \tag{4}$$

Where n_0 is the background refractive index due to polarization from bound charges in the dielectric.

The typical parameters of EIT material $In_{1-x}Ga_xAs_yP_{1-y}$-InP are as: γ_1 =1 THz, γ_3 =1 THz, N_a=1×10^{23}, P_{ab}=1 nm·e, and n_0=3.54 [23, 24]. The relationship between the refractive index and the frequency detuning $\Delta = \omega_{ab} - \omega_p$ with and without the control field with Rabi-frequency Ω_{ac}=2 THz are shown in Fig. 2.

It is found that when the frequency detuning Δ=-0.7 THz, the refractive index of the EIT media is 3.358 if the control filed is off, and it becomes to 3.725 if the control field is on. As the properties of PhCs are strongly influenced by the refractive index of the media, so if a PhC is composed of EIT media, its self-collimation frequency and bandgaps can be changed by turning the control field on or off. In this way, an ultra-fast optical switch can be investigated.

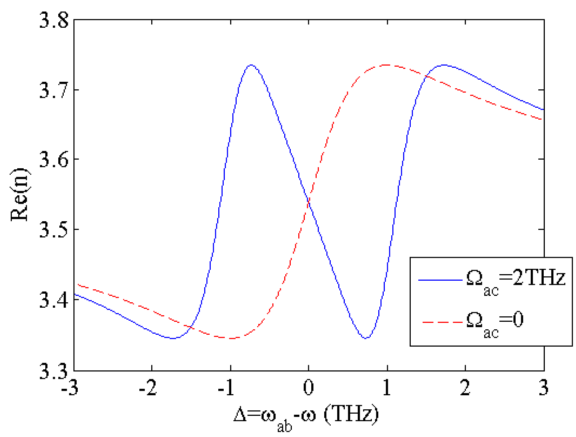


Fig. 2. The refractive index as a function of Δ with and without control field.

3. Structure design and analysis

The optical switch is proposed with the following thinking: when the control filed is not applied, the light wave should propagate through the PhC in a self-collimated line with a high transmittance. This is the "on" state of the optical switch. Otherwise, when the control field is applied, the self-collimating frequency should fall into the band gaps of the PhC, so that the light wave should be reflected and can not pass through the PhC, which referring to the "off" state. That is to say, the "off" and "on" states of the optical switch depend on if the control field is applied or not.

The propagation of light in a PhC structure is governed by its dispersion surfaces. Incident light propagates in directions normal to the dispersion surfaces. A cross-section of the dispersion surface at a given frequency is referred to as an equi-frequency contour (EFC). EFCs record eigen-frequencies of the Maxwell's equations in **k**-space and provide visual information to predict the way of light propagation. The direction of light propagation is given by the group velocity $\mathbf{v}_g = \partial\omega / \partial\mathbf{k}$ [8, 12], which is perpendicular to the EFCs. The self-collimating phenomenon occurs where the EFC corresponding to a frequency is flat. The EFCs can be obtained by the plane wave expansion (PWE) method, which is frequently used to solve the eigenvalue problem of the Maxwell's equations.

To make the light wave at 1550 nm can be self-collimated, the PhC structure of the optical switch is optimal designed as shown in Fig. 3. It consists of 16×16

$In_{1-x}Ga_xAs_yP_{1-y}$-InP rods that arranged in air in a square lattice. The radii of the rods are r=0.30a (179.0 nm) where a=596.7 nm is the lattice constant. The whole structure has a very compact size of 10.14×10.14 μm^2. The light beam is supposed to be input from the left side and output from the right side.

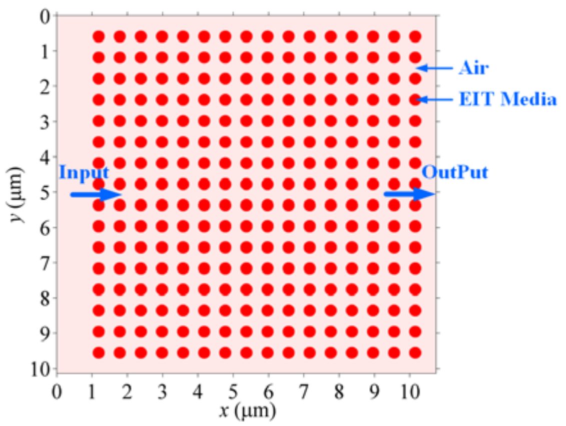


Fig. 3. Structure illustration of the optical switch.

To obtain the EFCs of the PhC, the eigen-frequencies at all **k** points in the first Brillouin zone are computed by employing the PWE method. Fig. 4 shows the EFCs of the second band for TM mode whose electric-field is parallel to the axes of the rods. It can be seen clearly that the EFC of frequency f=0.385c/a (λ=1550 nm) is a rounded rectangle and the EFC is perpendicular to the ΓX direction, where c is the speed of light in free space. As depicted above, it indicates that the light wave will propagate as a collimated beam in the ΓX direction that corresponding to the "on" state of the optical switch. Of course, it must be ensured that the light frequency is out of the band gaps.

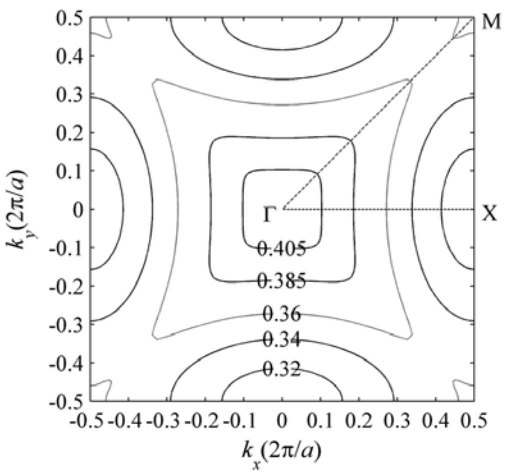


Fig. 4. The EFCs of the second band for TM mode of the designed PhC.

The band diagrams for TM mode of the PhC without (Ω_{ac}=0) and with the applied control field (Ω_{ac}=2 THz) are also calculated with PWE method as shown in Figs. 5(a) and (b), respectively. It is observed that when the control field is applied, the band gaps have a little shift-down with compare to that no control field. Especially, the first gap changes from 0.238c/a~0.310c/a to 0.215c/a~0.285c/a when the control field is applied. it is also noticed that the frequency 0.385c/a (λ=1550 nm) falls into the second bad gap in this case. This means that the light wave with frequency 0.385c/a will transmit through the PhC when the control field is not applied; on the contrary, it will be reflected by the PhC when the control field is applied for the bandgap effect. These are with corresponding to the "on" and "off" state of the optical switch, respectively.

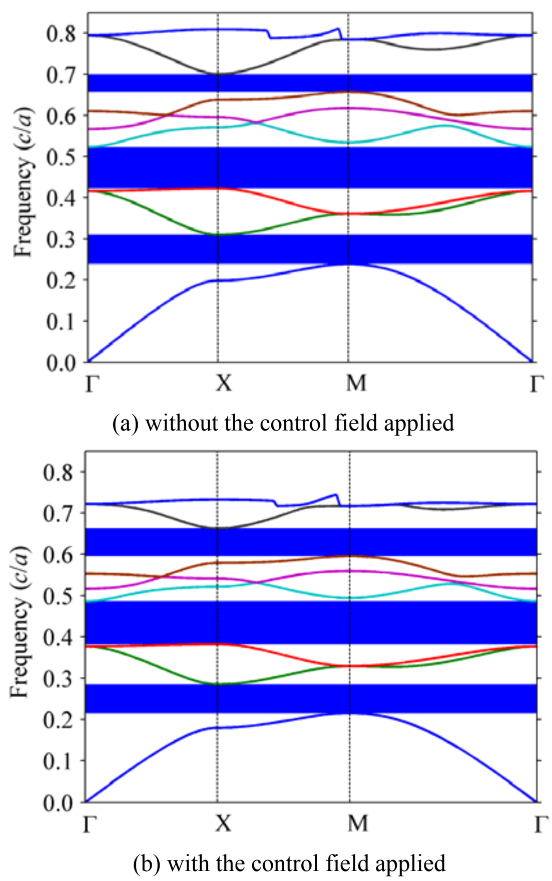


Fig. 5. Band diagrams for TM mode of the PhC (a) without and (b) with the contrl field (Ωac=2 THz) applied.

To verify the calculations above, the transmission spectra are also simulated. The FDTD method with a perfectly matched layer (PML) absorbing boundary conditions is employed to accomplish this work. An E-polarized Gaussian beam with a width of 4a (2.387 μm) at frequency f=0.385c/a (λ=1550 nm) is launched from the left-hand side of the PhC. A detector with a width of 8a (4.774 μm) is placed at the right-hand side of the PhC to collect the output power. The normalized transmission is defined as the output power divided by the input power.

The simulated results are shown in Fig. 6. It can be clearly seen that for frequency f=0.385c/a (λ=1550nm), the normalized power is almost zero when the control field is applied, which means that the light wave could not pass through. On the contrary, it gives a high transmittance of

91.09% when the control field is not applied, which suggest that most of the energy are pass through the PhC structure.

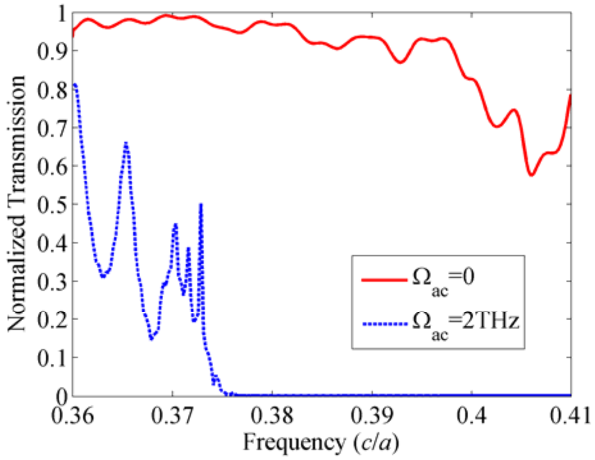
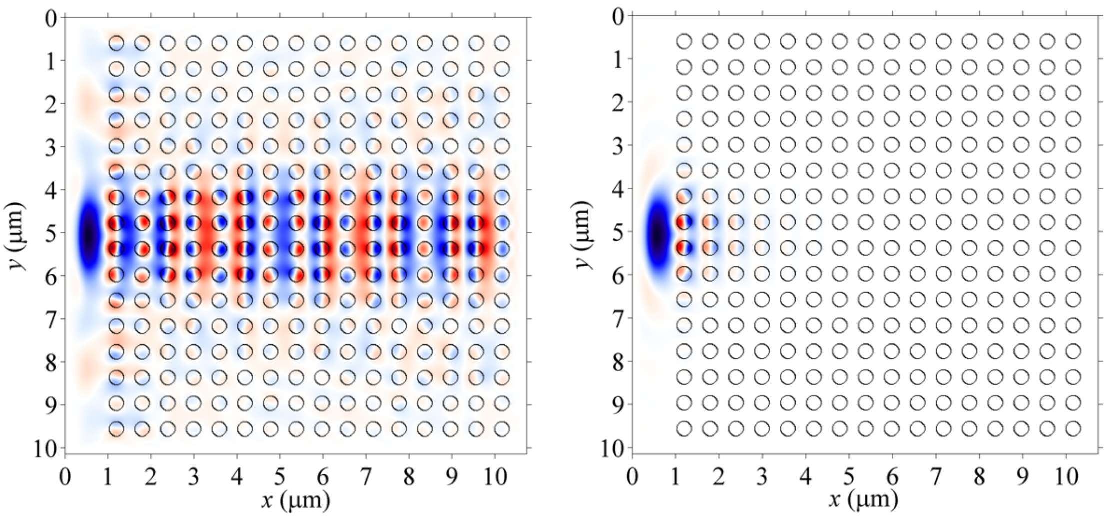


Fig. 6. Transmission spectra of the optical switch with (dashed line) and without (solid line) the control field applied.

The steady-state filed distributions of the *Ez* component are also simulated as shown in Fig. 7 with FDTD method. Simulations are performed with the same source and parameters as that used in the previous simulations. Fig. 7(a) shows the filed distribution when the control file is not applied. It can be observed that the light beam propagates in a collimated line. Most of the energies are transmitted through the PhC. This is the "on" status of the switch. On the contrary, as shown in Fig. 7(b), when the control filed is applied, the light beam is almost totally reflected by the PhC and can't propagate through the PhC. This refers to the "off" state of the switch.

The simulations show that, by applying control field to change the refractive index of the EIT media, the self-collimated light wave can be fast switch off in several picoseconds. This means that the proposed PhC can be functioned as a high efficiency optical switch in the integrated circuits.



(a) without the control field applied (b) with the control field applied

Fig. 7. The FDTD simulations of steady-state field distributions of the Ez component (a) without and (b) with the control field applied.

4. Conclusions

In conclusion, a compact PhC optical switch working at 1550 nm is proposed. The optical switch has a very compact size of 0.14×10.14 μm^2 and a concise structure consists of 16×16 In1-xGaxAsyP1-y-InP rods in air. The light wave in the PhC is guided by self-collimation theory, so the PhC needs no line defects that makes it easier to produce than the PhC waveguide-based switch. The optical switch also has a very short response time on the order of picoseconds. The EFCs and band diagrams are computed by using PWE method to analyze the properties of the structures. Then, the transmission spectra are calculated with FDTD method. Meanwhile, the propagations of light beam in the optical switch are also presented. The simulated results show that, light wave can propagate through the PhC in a collimated line when there is no control filed. As the control field is applied or not, the light wave can be switch off or on rapidly in several picoseconds, respectively. The proposed optical switch may find important applications in the photonic integrated circuits for its high efficiency, compact size and simple structure.

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