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Fast-response terahertz wave switch based on T-shaped photonic crystal waveguide

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ABSTRACT

We design an ultra-fast terahertz wave switch based on T-shape photonic crystal waveguide. The polymer rod is added in the junction as a point defect, the refractive index of which can be varied by adjusting the external pump laser intensity. The transmission spectrum is calculated by finite-difference time-domain method, which shows that the output energy of the two output ports is closely related to the refractive index of the polymer rod. By continuous wave excitation of the guided mode, the simulation results show that the T-shaped photonic crystal waveguide can flexibly tune the power in two output ports. The tuning rate of the device is about 0.3 ns. These results provide a useful guide and a theoretical basis for the developments of terahertz wave functional components.

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1. Introduction

The terahertz wave region is considered to be one of the last unexplored frequency bands in the electromagnetic spectrum. Terahertz wavelengths, which cover the range from 30 μm to 3 mm, are located in microwave and infrared regions. With the developments of terahertz wave generation and detection techniques, increasing attention has been drawn to the study of terahertz wave functional components and applications. As we known, the photonic crystals have many remarkable features, such as photonic band gaps (PBGs, i.e., frequency ranges where propagation of electromagnetic wave is forbidden inside the structure) and photon localization. These properties are widely used in optical communication components and other scientific areas. Recently, photonic crystal research has experienced explosive growth and attracted comprehensive attention [1–3], especially in the field of the photonic crystal technology combined with the terahertz technology [4,5]. Using the unique properties of photonic crystals, some novel terahertz photonic crystal components like waveguides [6], filters [7], modulators [8], and switches [9] have been widely investigated. Despite significant efforts have been focused on the search for terahertz device components, much work remains.

In this paper, we propose a new terahertz wave switch based on T-shaped photonic crystal. A polymer rod is added in the junction as a point defect, the refractive index of which can be almost instantaneous varied by adjusting the external pump laser intensity. The polymer materials that have Kerr nonlinearity can exhibit ultrafast terahertz wave switching when the samples are pumped by optical pulses due to the change of the refractive index of polymer and subsequent shift of defect state resonant frequency. The terahertz wave switch 'on' and 'off' mechanism is based on adjusting the defect mode frequency under external excitation. The finite-difference time-domain method is used to verify and analyze the characteristics of the proposed terahertz wave switch. Simulation results show that the presented terahertz wave switch has a high extinction ratio, small size, low insertion loss and a rapid switching time.

2. Design of T-shape waveguide structure

The schematic of the proposed terahertz wave switch is shown in Fig. 1. These lattice structures are composed of the high-resistivity silicon rods embedded in air background. The high-resistivity silicon with the refractive index of 3.42 is the material of the rods due to its transparency and low absorption in the terahertz region. The T-shaped defect photonic crystal waveguide is formed by introducing T-type defect in periodic silicon rods. The fill factor $r/a = 0.2$, where r is the radius of the silicon rod and a is the lattice constant. A polymer rod (big rod) is added in the junction as a point defect in the T-shape defect photonic crystal waveguide. The radius of the polymer rod is denoted by $R = 0.4a$. Because of the scaling properties of Maxwell's equation, the value of lattice constant a is not defined in the simulation process, and all other structural parameters are based on a. The refractive index of

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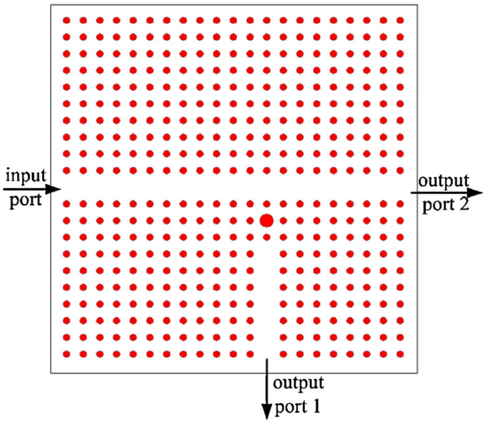

Fig. 1. Schematic of terahertz wave switch based on T-shape photonic crystal waveguide with a point defect.

polymer is rapidly changed due to the Kerr effect. The variation of refractive index with the pump laser intensity is decided by

$$n = n_0 + \Delta n = n_0 + n_2 I \qquad (1)$$

where I is the pump light power, $n_2 = (\pi \times 10^4 \times Rex^{(3)})/(\varepsilon_0 c^2 n_0^2)$ is the nonlinear refractive index, $x^{(3)}$ is third-order nonlinear susceptibility, ε_0 is vacuum permittivity, c is the speed of light in vacuum, n_0 is the linear refractive index. In Ref. [10], we know that the third-order nonlinear susceptibility of the polymer is in the order of 10^{-6} to 10^{-7} esu. In this article, the linear refractive index and third-order nonlinear susceptibility of the polymer are set to be 1.3 and 1×10^{-6}, respectively. Furthermore, Jin et al. [11] measured the absorption coefficient of polymer material with less than 0.01 cm^{-1} in terahertz region by terahertz time-domain spectroscopy. So, during the simulated calculation, we do not need to consider terahertz wave transmission loss in polymer rod.

3. Simulation results analysis

The powerful, accurate numerical two-dimensional finite difference time domain analysis method was employed to simulate and evaluate the characteristics of the terahertz wave switch based on T-shaped photonic crystal waveguide. The setup for the finite difference time domain computation is shown in Fig. 1 and the length of calculating region is $21a$. Since a finite structure is considered here, the whole computational domain is surrounded by perfectly matched layers to absorb the outgoing waves. The continuous-wave is launched at the entrance and the Poynting vector penetrating through the line detectors is integrated to calculate the output port1 and port2. To avoid the back reflection at entrance, the width of the input field is spatially adjusted so that full width at half maximum of the input pulse is set to $0.6 \times \sqrt{3}a$. The grid size of finite difference time domain computational domain is set to $a/32$. The time step t satisfies the stability condition. The lattice constant is set to be $a = 100$ μm. In this letter, considering TE mode is incident into the input port position. During the simulated calculation, we choose the refractive index of the polymer rod changes from 1.3 to 1.5. When the pump laser intensity is zero, the refractive index of the polymer rod is 1.3, and the normalized transmission spectrum is shown in Fig. 2(a). From the figure, one can see that the transmission value of the output port1 is of 0.87 at the frequency of 1.03 THz. When the external pump laser intensity 12.5 MW/cm^2 is applied, the refractive index of the polymer rod is rapidly changed to be 1.5 owning to the Kerr effect, and the normalized transmission spectrum is shown in Fig. 2(b). It can be noted that the transmission value of the output port1 is of 0.045 at the frequency of 1.03 THz. The frequency of the defect mode shifts to be 0.95 THz.

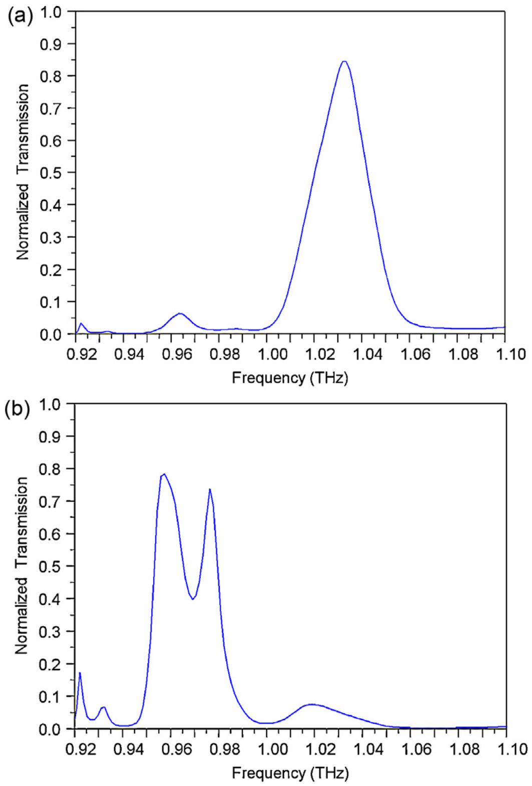

Fig. 2. Normalized transmission spectrum of output port1 with (a) $n = 1.3$ and (b) $n = 1.5$.

According to the results of Fig. 2, we set the continuous wave excitation frequency to be 1.03 THz, and the corresponding electric field time domain steady-state response distribution pattern was simulated and shown in Fig. 3. From Fig. 3(a), as it can be clearly seen, the guide mode is completely confined inside the wave-guide and the wave travels smoothly around the junction and corner. The

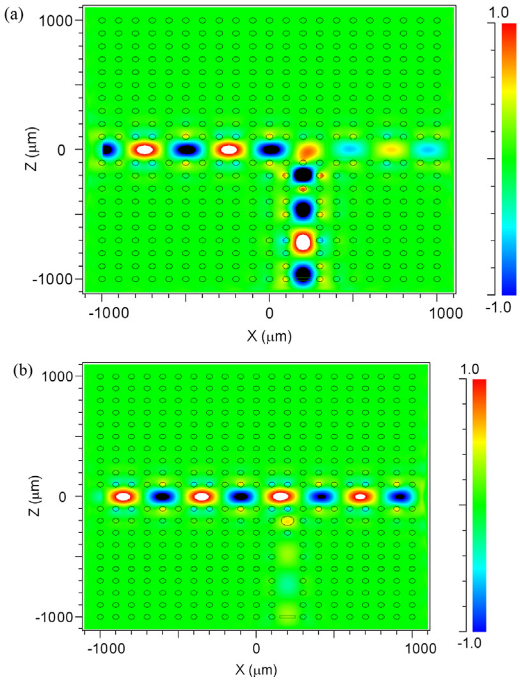

Fig. 3. Steady state electric field distribution of the terahertz wave switch (a) "on" state and (b) "off" state.

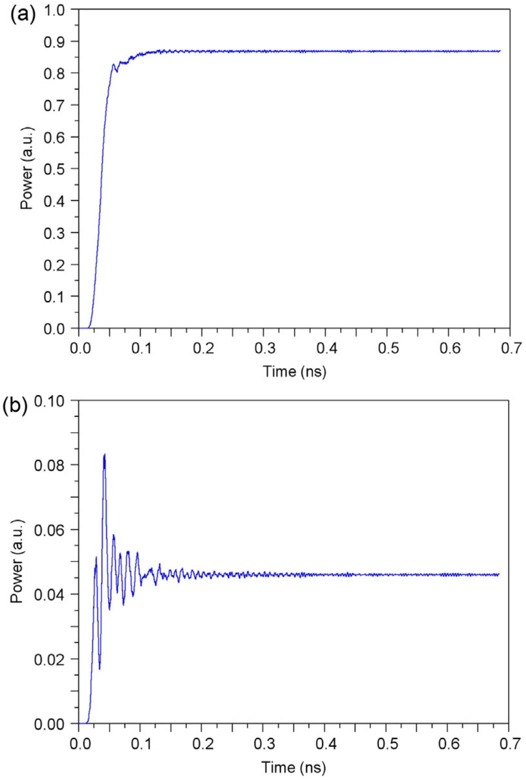

Fig. 4. Time domain steady state intensity response of (a) "on" state and (b) "off" state.

observation can be explicated by the photonic crystal basic feature that prevent terahertz wave of specified frequencies from propagating in certain directions. The external pump laser intensity is zero, we can see that the most electromagnetic energy converged at output port1, and only a little energy leakage to output port2. The terahertz wave switch is at the "on" state, and the terahertz wave corresponding to the defect mode frequency can propagate along the vertical line defect. However, the defect mode frequency can be changed as the pump laser applied. As shown in Fig. 3(b), when the external pump intensity is of 12.5 MW/cm^2, the most electromagnetic energy propagates through horizontal line defect to output port2, while only a little energy converged at output port1. At this moment, it indicated that the terahertz wave switch is at the "off" state for output port1. Thereby, we realized a novel terahertz wave switch at output port1.

In order to analyze the time domain steady state intensity response of the terahertz wave switch, a continuous wave is excited at the input port position. The field pattern of the propagating mode can be observed by a continuous-wave excitation of the guided mode. Fig. 4 shows the corresponding time domain steady state intensity response, and it is as short as around 0.3 ns. The switching rate is related to not only the response time of polymer material, but also the system response time. As we known, the response time of polymer material is supposed to be about tens of femtoseconds which is smaller than the system response time. As a result, the switching rate of the proposed terahertz wave switch is of 0.3 ns.

4. Conclusion

We design an ultra-fast terahertz wave switch based on T-shaped photonic crystals waveguide. A polymer rod was added in the junction, the refractive index of which can be varied by adjusting the external pump laser. So the device can controls the output energy of the two branches automatically at the frequency of 1.03 THz. The polymer has a large Kerr nonlinear susceptibility and almost instantaneous response to pump light, making it suitable for the realization of ultrafast terahertz switching. Simulation results show that the proposed terahertz wave switch has the switching rate up to 0.3 ns, and size of 0.21 mm. Further optimization for the real three-dimensional slab structure remains for future work.

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References

[1] A. Sharkawy, S. Shi, D. Prather, R. Soref, Electro-optical switching using coupled photonic crystal waveguides, Opt. Express 10 (2002) 1048–1059.
[2] M. Qiu, M. Mulot, M. Swillo, S. Anand, B. Jaskorzynak, A. Karlsson, M. Kamp, A. Forchel, Photonic crystal optical filter based on contra-directional waveguide coupling, Appl. Phys. Lett. 83 (2003) 5121–5123.
[3] Y. Vahabzadeh, M. Noshad, Proposal for tunable dual channel transmitter and mechano-optical switch based on photonic crystal, Appl. Opt. 51 (2012) 7784–7787.
[4] C. Lin, C. Chen, G. Schneider, P. Yao, S. Shi, A. Sharkawy, D. Prather, Wavelength scale terahertz two-dimensional photonic crystal waveguides, Opt. Express 12 (2004) 5723–5728.
[5] H. Liu, J. Yao, D. Xu, P. Wang, Propagation characteristics of two-dimensional photonic crystals in the terahertz range, Appl. Phys. B 87 (2007) 57–63.
[6] S. Li, H. Zhang, Q. Wen, F. Bai, W. Ling, Y. Xie, Y. Li, Improved Y-splitter photonic crystal waveguides in terahertz regime, Appl. Phys. B 99 (2010) 709–716.
[7] H. Zhang, P. Guo, P. Chen, S. Chang, J. Yuan, Liquid-crystal-filled photonic crystal for terahertz switch and filter, J. Opt. Soc. Am. B 26 (2009) 101–106.
[8] T. Kleine-Ostmann, P. Dawson, K. Pierz, G. Hein, M. Koch, Room-temperature operation of an electrically driven terahertz modulator, Appl. Phys. Lett. 84 (2004) 3555–3557.
[9] J. Li, J. He, Z. Hong, Terahertz wave switch based on silicon photonic crystals, Appl. Opt. 46 (2007) 5034–5037.
[10] Y. Wang, X. Xie, T. Goodson, Enhanced third-order nonlinear optical properties in dendrimer-metal nanocomposites, Nano Lett. 5 (12) (2005) 2379–2384.
[11] Y. Jin, G. Kim, S. Jeon, Terahertz dielectric properties of polymers, J. Korean Phys. Soc. 49 (2006) 513–517.