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Active terahertz directional coupler based on phase transition photonic crystals

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ABSTRACT

A phase transition photonic crystals (PhC) based silicon column arrays with VO_2 coating have been proposed and fabricated, which can be actively converted between PhC directional coupler and metallic PhC waveguide by the thermal means to form a switchable directional coupler. The bandgap and transmission properties of this device have been investigated by the numerical simulation. With the changes of temperature, this device exhibits three different modulation and coupling effects. The direct output port shows the two opposite intensity modulation processes, of which transmissions decrease from dielectric PhC coupling state to the loss state and then increase from the loss to the metallic PhC waveguide state; the coupling port realizes another intensity modulation from the coupling state to non-coupling state. This device can realize switching, modulation, actively splitting and routing functions in the future's THz applications.

1. Introduction

Terahertz (THz) waves show great potential applications in THz sensing [1], imaging [2], spectroscopy [3], and communication [4]. For the construction of compact application systems, it is crucial to develop THz directional couplers for their capability of THz power splitting and wave routing. In the THz regime, directional couplers based on dielectric subwavelength fibers and waveguides have been theoretically and experimentally demonstrated [5–10]. However, these directional couplers are all passive devices, and so far, there have not been any active directional couplers reported in the THz regime. Once the directional couplers can be actively controlled by the external field, such as temperature, optical or electrical field, these devices can realize more powerful capability such as switching, modulation, actively splitting and routing.

Photonic crystal (PhC) has been proved to be an effective way to guiding, switching and filtering for THz waves due to its photonic band gap properties [11–13], which is also a good candidate structure for directional coupler [14,15]. In recent researches, vanadium dioxide (VO_2) shows great potential application in THz wave modulation. It undergoes an insulator–metal transition (IMT) at the critical temperature $T_c = 340$ K [16], and its lattice structure changes from insulating phase to metallic phase with its conductivity (unit: S/m) changing 3–5 orders of magnitude induced by thermal means [17,18], and it can be also induced rapidly by electrical [19] and optical [20] means.

To obtain active THz PhC devices, we propose a phase transition photonic crystals (PTPhC) based silicon column arrays with VO_2 films coating [21,22]. The PTPhC can be actively controlled by the thermal or optical field: when the VO_2 is insulating phase, the PTPhC shows a dielectric PhC state; when the VO_2 is excited by the thermal or optical field, the PTPhC turns to be a metallic PhC state. In this process, the THz transmission property of the PTPhC will be greatly changed since the transmission properties as well as bandgap structures are quite different in these two kinds of PhC state in the same device geometry. In this paper, we apply this PTPhC into active THz directional coupler. The device structure has been proposed, and the bandgap and guided mode characteristics have been numerically investigated. We focus on the transmission and coupling properties of this device controlled by the thermal means. At last, the actual fabrication of this device has also been demonstrated. The results show that these devices can realize important applications such as switching, modulation, actively splitting and routing for THz waves.

2. Device structure

The structural illustration of this PTPhC directional coupler is shown in Fig. 1. The PhC chip is composed of high-resistivity Si column arrays, which is coated by a layer of thin VO_2 film with

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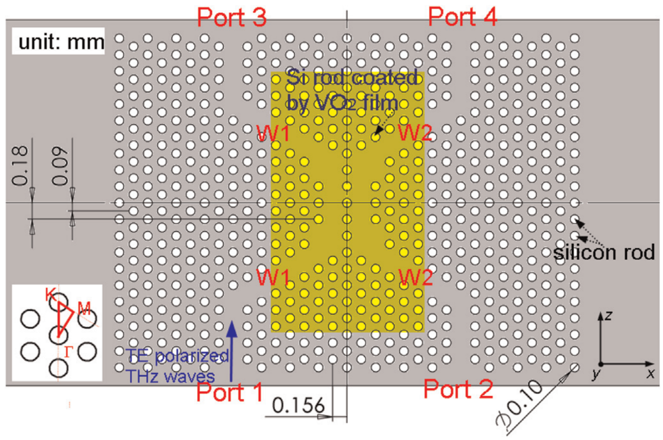

Fig. 1. Structural illustration of the PTPhC directional coupler (top view). The yellow region represents to be coated by the VO_2 film. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

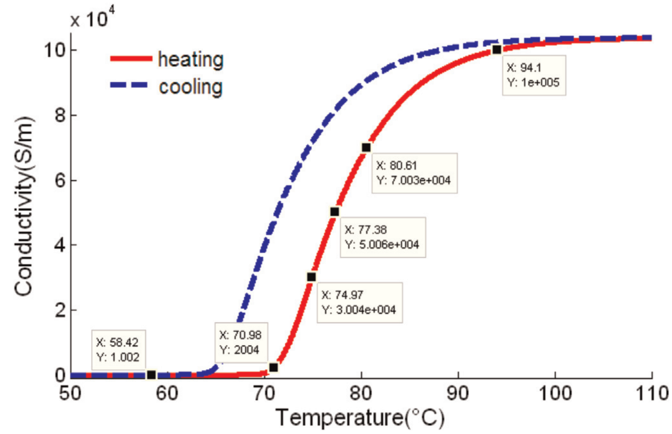

Fig. 2. The temperature dependence of the conductivity of VO_2 film with IMT process. Some important points with conductivity (Y) vs temperature (X) are labeled on the heating process curve.

1 μm thickness in the yellow region shown in Fig. 1. The lattice constant a = 180 μm and the column radius r = 50 μm with triangle lattice. Two columns are removed to form a typical symmetric dual waveguide directional coupler. Due to the symmetry, two waveguides (W1 and W2) are totally the same, and four ports are also equivalent. In our discussion, Port 1 is the input port and the broadband TE polarized THz waves are incident into it. Thus, Port 3 is direct output port, Port 4 is coupling output port, and Port 2 is idle.

3. Material properties for THz waves

Before the research of our device, we investigate the dielectric properties of the materials composed of this device in the THz regime. The dielectric constant of high-resistivity Si is 11.7, and its loss can be neglected for THz waves. The insulating phase VO_2 film is transparent for THz waves, and its dielectric constant $\varepsilon_i = 9$ [16–18]. The permittivity and conductivity of the metallic phase VO_2 follows the Drude form [16,17]:

$$\varepsilon(\omega) = \varepsilon_\infty + i\frac{\omega_p^2}{\omega(\omega + i/\tau)} \tag{1}$$

$$\sigma(\omega) = \frac{\sigma_{dc}}{1 - i\omega\tau} \approx \varepsilon_0\omega \mathrm{Im}(\varepsilon(\omega)) \tag{2}$$

where ε_∞ is the contribution from bound electrons, here $\varepsilon_\infty = \varepsilon_i$, τ is the relaxation time, ω_p is plasma frequency with $\omega_p^2 = Ne^2/\varepsilon_0 m_*$, and σ_{dc} is the static conductivity. According to previous reports [16,17,23], the effective mass $m^* = 2m_e$, m_e is the mass of free electron, the carrier density is $N = 1.3 \times 10^{22}$ cm^{-3}, and the carrier mobility is $\mu = 2$ cm^2/V s. We can obtain $\tau = m_*\mu/e = 2.27$ fs. By Eqs. (1) and (2), we can calculate the permittivity and conductivity of the metallic phase VO_2 in the THz regime.

Previous experiments have shown that the conductivity of VO_2 film can change from 1 S/m to more than 1×10^5 S/m [17,18]. This process experiences a series of intermediate state. The intermediate state of VO_2 can be explained as the coexistence of metallic and insulating phase domains, the changes of macroscopic dielectric constant of VO_2 during the IMT can be well described by the Bruggeman's effective medium theory [16,21,23–25]:

$$\varepsilon_{eff} = \frac{1}{4}\Big\{\varepsilon_i(2 - 3f_V) + \varepsilon_m(3f_V - 1) + \sqrt{[\varepsilon_i(2 - 3f_V) + \varepsilon_m(3f_V - 1)]^2 + 8\varepsilon_i\varepsilon_m}\Big\} \tag{3}$$

where f_V is the volume fraction of metallic phase. For the temperature change, f_V is given by

$$f_V = \left\{1 - \frac{1}{1 + \exp[(T - T_0)/\Delta T]}\right\} f_{Vmax} \tag{4}$$

where the maximum volume fraction $f_{Vmax} = 0.5$. By Eqs. (1)–(4), we calculate the temperature dependence of the effective conductivity σ_{eff} of VO_2 in the heating (T_0 = 68 °C) and cooling (T_0 = 62 °C) processes with the hysteresis of ΔT = 6 °C. The results are shown in Fig. 2. The above parameters and calculation results will be used in the following discussion.

4. Bandgap and mode characteristics of PTPhC directional coupler

We calculate the band structures of this PhC by using the plane wave expansion (PWE) method [26]. The electric vector direction of the incident wave is along the axial direction of the PC rods, i.e. TE wave (E polarization). Fig. 3 shows the band structure of the Si PhC with a single line defect waveguide, the calculation unit cell for the PWE method is also shown in the figure. Because a/λ = 180 μm/300 μm = 0.6, the normalized frequency 0.6 corresponds to 1 THz, which is labeled by the red line in the Fig. 3. The frequency bands of the guided modes are labeled by the yellow region, and other frequency bands are composed of leaky modes and forbidden bands. Only the light in the guided band can propagate through the PhC waveguide. Here, we focus on the guided band of 0.45–0.56 (i.e. 0.75–0.93 THz).

Fig. 4 shows band structures and guided mode patterns of the PTPhC coupler region with dual line defect waveguides. This is the core of this directional coupler. We discuss two extreme cases: ideal dielectric state and metallic state. For the dielectric state as shown in Fig. 4(a), there are two different guided modes compared with single mode shown in Fig. 3. Their merged frequency band of 0.44–0.57 are slightly larger than that of single line defect waveguide. Because W1 and W2 are totally the same, the phase constant difference between two waveguide $\Delta\beta = 0$. In this case,