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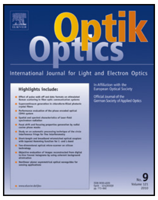

Thermally controlled multiband, mode-switching plasmonic filter operating at terahertz frequencies

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ABSTRACT

A thermally controlled multiband, mode-switching plasmonic filter with periodic subwavelength metal asterisk-shaped air hole arrays has been proposed in the terahertz range. Utilizing the changing properties to terahertz wave propagating on the metal-semiconductor interface and in the semiconductor InSb at varying temperature, thermally controlled multiband, mode-switching plasmonic filter owns an excellent tuning ability to terahertz wave. The simulation results show that the maximum transmittance of the structure is 99.8% at 434 GHz, 80 K, the bandwidths at 80 K are 56 GHz at 0.434 THz, 14 GHz at 944 GHz and maximum intensity modulation depth could reach to 99.8% at 434 GHz between 80 K and 373 K.

1. Introduction

Terahertz (THz) wave is located between microwave and infrared wave and its frequency range is between 0.1 THz and 10 THz. Compared to infrared wave, THz wave has some unique natures, such as visible to plastics, paper and cardboard and biologically innocuous. In contrast to microwave, THz wave has higher frequency and shorter wavelength leading to carry more information, own better directivity and achieve higher spatial resolution. Therefore, THz wave has great potentials to high-capacity wireless communication and imaging applications [1–5]. Tunable THz filter or THz modulator is a key component in THz wireless communication system and THz imaging system [6,7]. In order to achieve tunable THz filter or THz modulator with lower insert loss, higher modulation depth, better modulation speed and wider tuning frequency range than it was before, lots of works have been reported, such as tunable metamaterial [8,9], photonic crystal [10,11] and plasmonic [12–15].

As most metals were nearly perfect conductors in THz range, metal films perforated with arrays of holes or slits had near unity transmittance to THz wave at certain frequencies [16] and the underlying principles were demonstrated in [17]. This structure had no tuning abilities to THz wave. However, the semiconductor InSb had certain tuning abilities to THz wave at different temperatures [18]. Fan et al. [19] had proposed a magnetically tuned plasmonic lens with undoped InSb partly filled, which had good properties. In this paper, we have proposed a thermally controlled multiband, mode-switching plasmonic filter with periodic subwavelength metal air asterisk-shaped air hole arrays and, meanwhile, the semiconductor undoped InSb is partly filled in the structure. The advantages of this structure are multiband, frequency-tunable and temperature-controlled.

2. Design and analysis

The schematic of thermally controlled multiband, mode-switching plasmonic filter is shown in Fig. 1(a). Incident THz wave looks through the structure from the top side to the bottom side. The red, yellow, white parts indicate the semiconductor undoped InSb, metal copper and air, respectively. Fig. 1(b) shows the top view on the unit cell of the structure with the parameters: the period of the unit cell $P = 300\ \mu\text{m}$, the width of slits $W = 25\ \mu\text{m}$, the total length of slits $L = 250\ \mu\text{m}$, the length of undoped InSb $T = 50\ \mu\text{m}$. The thickness of the structure H is $30\ \mu\text{m}$.

With the help of finite element method (FEM), the relationship between THz transmittance and frequency is performed. In the inset of Fig. 3(a)–(d), the unit cell is assigned with master-slave boundaries conditions in the X and Y directions and perfectly matching layers along the Z direction. An incident plane wave illuminates the unit cell and its E field is parallel to the XY plane. The angle between the E field and X direction is assumed to be θ, shown in Fig. 1(a). The electromagnetic parameters of metal copper at THz frequencies fit well with the Drude model and, hence, the complex dielectric constant is expressed as $\varepsilon_r(\omega) = -1.7 \times 10^5 + i1.1 \times 10^6 \times 2\pi/\omega$, where ω is angular frequency in terahertz [20]. For the semiconductor

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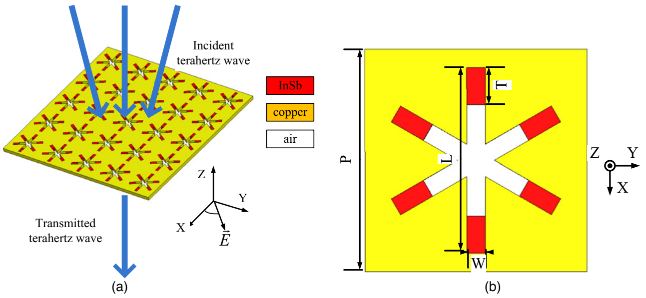

Fig. 1. Schematic of the thermally controlled multiband, mode-switching plasmonic filter ((a) total view of the frequency-tunable plasmonic filter; (b) top view the unit cell of the structure).

InSb, the experimental data below 1 THz fits well with the Drude model between 80 K and 360 K; the complex dielectric function, $\mathrm{Re}(\varepsilon_{\mathrm{InSb}})+i\mathrm{Im}(\varepsilon_{\mathrm{InSb}})$, is expressed as

$$Re(\varepsilon_{\mathrm{InSb}})=\varepsilon_{\infty}-\frac{Ne^2\tau^2}{m_e^*\varepsilon_0(1+\omega^2c^2)}$$

$$Im(\varepsilon_{\mathrm{InSb}})=\frac{Ne^2\tau}{m_e^*\varepsilon_0\omega(1+\omega^2c^2)} \qquad (1)$$

where N, τ, ω, e, m_e^*, ε_∞, and ε_0, are the carrier density, carrier relaxation time, angular frequency of incident radiation, electron charge, electron effective mass, high frequency dielectric constant, and free space permittivity, respectively [18]. The carrier density N of InSb depends on the temperature T, which is expressed as [21]

$$N(\mathrm{cm}^{-3})=5.76\times10^{14}\ T^{1.5}\exp\left[\frac{-0.26}{2\times8.625\times10^{-5}T}\right] \qquad (2)$$

The conductivity σ_{InSb} of semiconductor InSb can be expressed as $\sigma=Ne^2\tau/m_e^*$ [22]. Fig. 2(a) shows the relationship between the temperature and σ_{InSb}; Fig. 2(b) shows the relationship between the temperature, frequency and $\mathrm{Re}(\varepsilon_{\mathrm{InSb}})$.

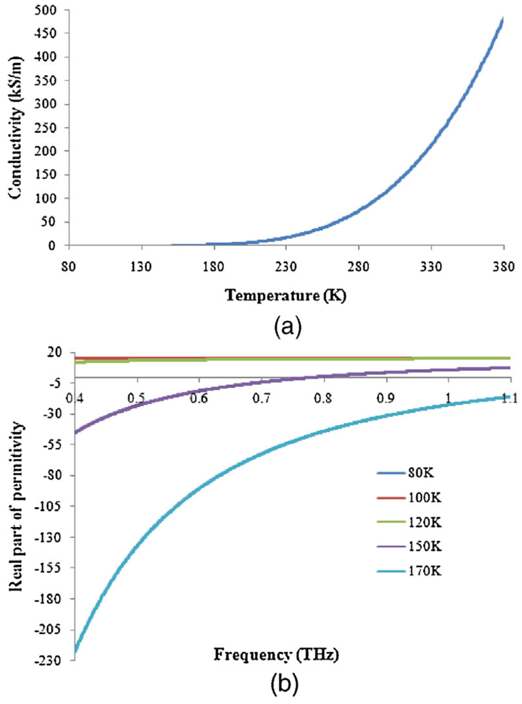

Fig. 2. (a) Relationship between the temperature and σ_{InSb}; (b) relationship between the temperature, frequency and $\mathrm{Re}(\varepsilon_{\mathrm{InSb}})$.

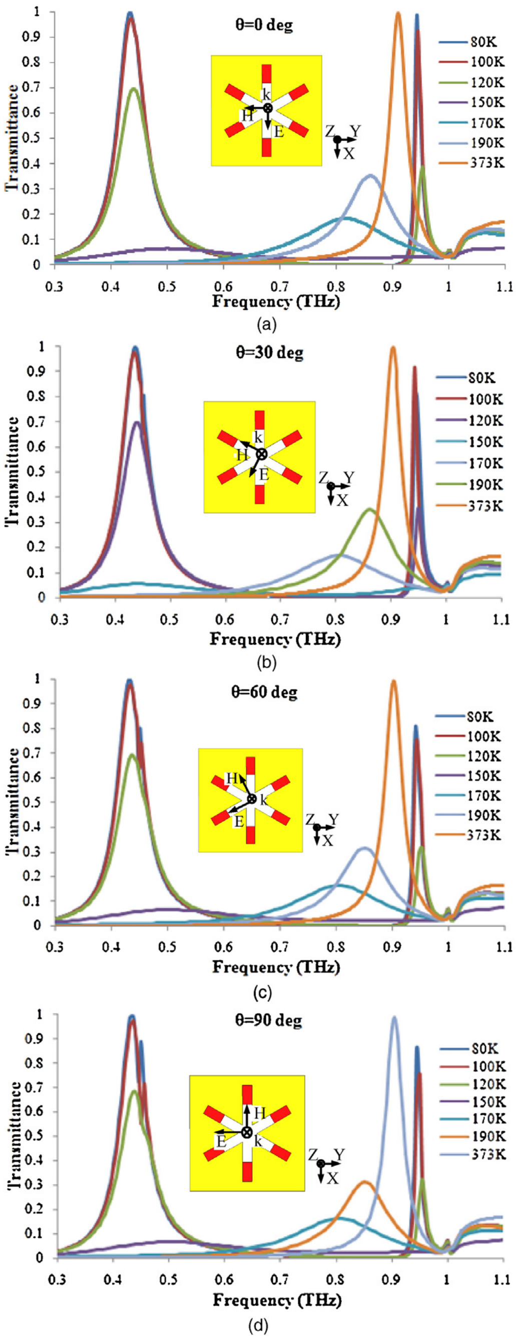

Fig. 3. THz transmittance spectra at varying temperatures ((a) $\theta=0$ deg; (b) $\theta=30$ deg; (c) $\theta=60$ deg; (d) $\theta=90$ deg).

Fig. 3(a)–(d) shows the THz transmittance spectra at varying temperatures when $\theta=0$, 30, 60, 90 deg, respectively. Though the THz transmittance spectra at 80 K when $\theta=0$ deg, $\theta=30$ deg, $\theta=60$ deg, $\theta=90$ deg differ a little from each other, the changing trends of THz transmittance spectra with the temperature increasing are consistent. Hence, we take X linearly polarized ($\theta=0$ deg) plane wave condition for an example

For X linearly polarized ($\theta=0$ deg) plane wave condition, shown in Fig. 3(a), when temperature is 80 K, the transmittances at $f_1=0.434$ THz and $f_2=0.944$ THz are 99.8% and 98.7% separately. The E, H field and electricity J distributions on the surface of metal copper are presented in Fig. 4(a)–(c) at 0.434 THz, 80 K and Fig. 4(d)–(f)