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Theoretical investigation of semiconductor supported tunable terahertz dielectric loaded surface plasmons waveguides

Chunlin Liu, Xiaoyong He*, Zhenyu Zhao, Hao Zhang, Wangzhou Shi

Department of Physics, Mathematics & Science College, Shanghai Normal University, No. 100 Guilin Road, Shanghai 200234, PR China

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ABSTRACT

The tunable propagation properties of semiconductor-based dielectric loaded surface plasmons (DLSPs) structures have been theoretically investigated in the THz regime, including the effects of temperature, operation frequency, and the thermo-optic effect of dielectric stripe materials. The results show that the waveguide properties of DLSPs structure can be modulated in a wide range via changing the temperature. For instance, when the temperature is changed in the range of 300–600 K, the modulation depth of propagation length can reach more than 80%. With the increase of refractive index of the dielectric stripe, the modulation depth of the effective indices and propagation lengths increase. In addition, the propagation length and figure of the merit can be improved obviously with the hybrid dielectric stripe structure (by coating Si on the SiO_2 layer). The results are very helpful to design novel waveguide devices, such as modulators, switchers, sensors and polarizers.

1. Introduction

The last two decades witness the rapid development of terahertz (THz) technology [1–5]. For its application in the fields of imaging, biological sensor, and wireless communication, the investigation of waveguide devices is vital important, which is closely related to the surface plasmons (SPs) [6]. SPs are two-dimensional (2D) electromagnetic waves confined at the metal–dielectric interfaces [7–10], offering the promise to control the electromagnetic waves at subwavelength scales [11–15]. Considerable efforts have been devoted to develop various SPs waveguide structures, such as metal wire waveguide [16], metal–dielectrics–metal structure [17], air–dielectrics–metal waveguides [18,19], the triangle grooves structure [20], and the hybrid surface plasmonic structure. The hybrid surface plasmonic waveguide displays the merits of strong mode confinement, low propagation loss, and high compatibility with semiconductor fabrication [21]. It mainly includes two kinds of typical structures, i.e. the dielectric fiber–dielectrics–metal waveguide structure and dielectric loaded surface plasmons (DLSPs) waveguides [22,23]. Consisting of a dielectric fiber (Si) with high refractive index separated from a metal layer by a low dielectric gap (SiO_2), the dielectric fiber–dielectrics–metal structure can be applied to fabricate micro and nanolasers and plasmonic integrated circuits [24,25]. Additionally, surface plasmons waveguides have also been widely applied in many research fields, e.g. in the design of high power super-luminescent diodes (SLEDs). For instance, by using active multi-mode interferometer structures, the high power SLEDs has been put forward, which manifests high efficiency and obviously thermal resistance reduction [26,27].

By depositing dielectric stripe on the metallic substrate, the DLSPs waveguides can be realized, manifesting the merits of strong lateral confinement, low bending losses and high component integration density [28–30]. Recently, much experimental and theoretical research has been carried out in this aspect [31–34]. For instance, Sorger et al. first experimental proved that the ultra-small propagating waves at visible wavelength, the mode size reduced down to $50 \times 60\ nm^2$ [28]. By inserting a thin gold strip between two high refractive indices Si spacer, Magno et al. proposed a kind of long-range propagation DLSPs structures [29], which displayed long propagation length and the application to fabricate high sensitivity optical sensors (the resolution can reach about 10^{-6}–10^{-7}). On the base of DLSPs structures, the micro-ring resonator filters and monitors have also been shown, the extinction ratios as high as 17 dB have been attained [31,32]. In 2013, by inserting the graphene layer into the DLSPs waveguides, a new type of electro-optical modulators have been proposed [33,34], the optical bandwidth exceeds 12 THz, the operation speed is about 500 GHz, which shows great potential applications in the fields of integrated on-chip devices and tunable waveguides device design.

But for above mentioned DLSPs waveguides, it is very difficult to vary the permittivity of metal and modulate the propagation properties of hybrid modes, which severely degrades the quality of

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* Corresponding author.
E-mail address: xyhethz@hotmail.com (X. He).

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SPs resonance and limits the practical application of devices. Fortunately, some doped semiconductors (e.g. InSb) also show metallic characters in the THz regime, and the corresponding dielectric constants are similar to that of metal in the visible/UV regime. Furthermore, the plasmonic properties of semiconductor devices can be dynamically modulated by changing the temperature or doping. The tunable DLSPs waveguide structure has been proposed by replacing the metal layer with the semiconductor InSb layer, giving us much more freedom to control the optical properties. With the finite element method (FEM), the tunable propagation properties of semiconductor-supported DLSPs waveguide structure in the THz regime have been numerically investigated and compared with other kinds of waveguide structures, including the influence of operation frequency, different kinds of dielectric stripes, and temperature. Our investigation manifest that via controlling the temperature, the propagation properties of the suggested semiconductor-supported DLSPs structure can be modulated in a wide range, e.g. the modulation depth of propagation length can reach more than 80%.

2. Theoretic model and research method

Fig. 1 shows that the sketch of the DLSPs waveguide structures. The dielectric stripe is deposited on the InSb substrate layer. The length and width of the dielectric stripe is h and w, respectively.

The dielectric constant of the InSb is calculated by using the following formula [35,36]:

$$\epsilon(\omega,\ T) = \epsilon_\infty - \frac{\omega_p^2(T)}{\omega[\omega + i\Gamma(T)]} \tag{1}$$

where $\varepsilon_\infty = 15.75$, ω is the radiation frequency, T is the temperature, Γ is the phenomenological scattering rate, i.e.

$$\Gamma(T) = 1/(m^*\mu(T)/e) \tag{2}$$

in which m^* is the effective mass of the electron, $m^* = 0.015\ \mathrm{m_e}$, $m_e = 9.108 \times 10^{-31}$ kg, $e = 1.602 \times 10^{-19}$ C, and μ is the carrier mobility, its value of is taken from Ref. [37]. The plasma frequency ω_p can be expressed as

$$\omega_p = \sqrt{(e^2 n)/(\varepsilon_0 m^*)} \tag{3}$$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, n is the carrier concentration [38],

$$n = 2.9 \times 10^{11}(2400 - T)^{0.75}(1 + 2.7 \times 10^{-4}T)T^{1.5} \times \exp\left(- \frac{0.129 - 1.5 \times 10^{-4}T}{k_B T}\right) \tag{4}$$

k_B is the Boltzmann constant.

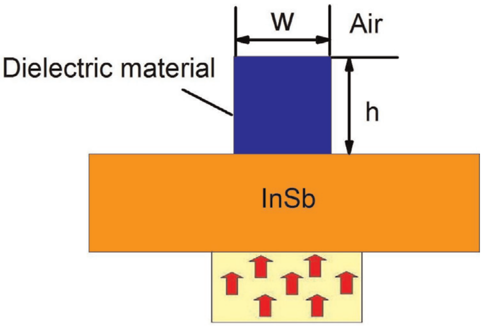

Fig. 1. The sketch of DLSPs waveguide structure, a dielectric stripe is deposited on the InSb substrate layer, the width and length of dielectric stripe is w and h with the values of both 100 μm.

The mode area can be defined as the ratio of the total mode energy and peak energy density, which can be given by [15]

$$A_m = \frac{W_m}{\max\{W(r)\}} = \frac{1}{\max\{W(r)\}}\int_{-\infty}^{+\infty} W(r)d^2r \tag{5}$$

where W_m and W(r) are the electromagnetic energy and energy density, respectively. $W(r)$ is calculated by the formula:

$$W(r) = \frac{1}{2}\left(\frac{d(\varepsilon(r)\omega)}{d\omega}|E(r)|^2 + \mu_0|H(r)|^2\right) \tag{6}$$

A_0 is the normalized diffraction-limited area and calculated by $\lambda^2/4$. The normalized effective mode area is A_m/A_0. The effective index n_eff and propagation length L can be defined by $n_\mathrm{eff} = \mathrm{Re}(\beta)/k_0$ and $L = \frac{\lambda}{4\pi \mathrm{Im}(N_{ef})}$, respectively.

The modulation depth (Mod) can be defined as

$$\mathrm{Mod} = \frac{x_\mathrm{max} - x_\mathrm{min}}{x_\mathrm{max}} \tag{7}$$

Here x stands for n_eff, L and A_m/A_0, respectively. The figure of merits (FoM) of the propagation mode is defined as

$$\mathrm{FoM} = \frac{L}{\sqrt{A_m}} \tag{8}$$

3. Results and discussions

The real part of the effective index (Re(n_eff)) and propagation length (L_spp) of the modes versus temperature for different kinds of dielectric stripes are shown in Fig. 2. The width and thickness of the dielectric stripe are both 100 μm. The numerical results have been obtained from the FEM software package-COMSOL MULTIPHYSICS 4.0. The dielectric stripe materials are SiO_2, Al_2O_3, and Si, respectively. Because temperature changes in a wide range, i.e. 300–600 K, the refractive index of the dielectric stripe changes significantly. Therefore, the thermo-optic effect has been taken into account in the simulation. The thermo-optic coefficients of SiO_2, Al_2O_3 and Si are 1×10^{-5}/K, 4.7×10^{-5}/K and 1.8×10^{-4}/K, respectively [39,40].

It can be found from Fig. 2 that as the refractive index of dielectric stripe increases, the value of Re(n_eff) increases, the propagation length decreases, which means that the propagation modes can be better confined in the dielectric stripe. In addition, Fig. 2 also shows that the influences of temperature on the propagation properties. As the temperature increases, the value of Re(n_eff) decreases, the propagation length increases. The reasons are shown in the following. As the temperature increases, the carrier concentration of InSb increases, resulting into the enhancement of the dielectric constant of InSb at higher temperature. For instance, the dielectric constants of InSb are $-8.25 \times 10^1 + 2.62 \times 10^1 i$, $-1.18 \times 10^3 + 7.16 \times 10^2 i$, and $-2.10 \times 10^3 + 1.69 \times 10^3 i$ at the temperatures of 300 K, 500 K, and 600 K, respectively. Thus, InSb layer shows better "metallic" properties at higher temperature. Consequently, much less modes penetrates into the substrate layer, leading into the value of the effective indices of propagation modes decreasing.

Fig. 3 shows the modulation depth of the DLSPs waveguides versus temperature for different kinds of dielectric stripes. The modulation depth has been defined by using the Eq. (7), and x stands for n_eff. It can be found from Fig. 3 that the modulation depth of Re(n_eff) and L_SPP increase with the increase of temperature, resulting from the value of the effective index of hybrid modes decrease at higher temperature. Furthermore, with the permittivity of the dielectric stripe increases, the modulation depth of the L_SPP increases, i.e. the value of Si stripe is much larger