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Active graphene plasmonic grating for terahertz beam scanning device

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ABSTRACT

We have proposed an electrically controllable terahertz (THz) beam scanning device based on asymmetric graphene plasmonic grating. It is proved that the dispersion relation of surface plasmon waves can be efficiently manipulated on the periodic metal–dielectric–graphene plasmonic structure by an external bias voltage, and thus the derivation angle of the THz beam can be actively tuned. The numerical results show that the radiation angle of THz waves through this device can be tuned from $-18°$ to $18°$ with the bias changing from 53.5 mV into 368.8 mV at the operating frequency of 0.5 THz. This electrically active beam scanning device has important application in the THz imaging, radar and communication systems.

1. Introduction

Terahertz (THz) techniques in imaging, radar and communication systems have been greatly developed in recent years. To realize these application systems, THz functional devices, such as THz modulators [1], filters [2], splitters [3], isolators [4] and polarizers [5], are indispensable. Among them, active directional beaming and beam scanning devices [6–8] can control the propagation direction of light in the free space, which are the core device in the above application systems, and thus are in highly demand. However, THz directional beaming devices have been rarely reported up to now, and their performances are still limited [9]. One problem is most of the device cannot be feasibly controlled by the electrical or optical means, so the beam direction cannot be active controlled and fast scanned. Another deficiency is that the deviation angle of the device is generally no more than 10° leading a very small scanning range in the space. Therefore, active beam scanning devices with large scanning angle range are still very desirable in THz frequency region.

Graphene has recently attracted intense attention of the research community due to its extraordinary mechanical, electronic and optical properties [10,11]. Being a monolayer of carbon atoms tightly packed in a two-dimensional honeycomb lattice, monolayer graphene has interesting prospects as a plasmonic material. Furthermore, the dielectric properties of graphene can be dynamically tuned by chemical or electrostatic changes [12–14], which manipulate the effective refractive index and transmission property of the surface plasmon polaritons (SPPs) on the graphene plasmonic devices in the optical and THz regime.

In this work, utilizing a periodically asymmetric graphene plasmonic grating structure, we realize to an active beam scanning device for THz waves. It is proved that the dispersion relation of surface plasmon waves can be efficiently manipulated on the periodic metal– dielectric–graphene plasmonic structure by an external bias voltage, and thus the derivation angle of the beam is manipulated by the external bias between the graphene and the metal substrate. The numerical results show that, when the external voltage bias changes from 53.5 mV into 368.8 mV, the radiation angle can be scanned in a large angle range from $-18°$ to $18°$.

2. Theory and structure model

2.1. THz property of graphene

The surface conductivity of a monolayer graphene film can be calculated by the Kubo formalism. The expression for conductivity (σ) [15,16] is

$$\sigma = \frac{e^2(\omega + i\tau^{-1})}{i\pi\hbar^2}\left[\frac{1}{(\omega + i\tau^{-1})^2}\int_0^\infty \varepsilon\left(\frac{\partial F(\varepsilon)}{\partial \varepsilon} - \frac{\partial(-\varepsilon)}{\partial \varepsilon}\right)d\varepsilon - \int_0^\infty \frac{F(-\varepsilon) - F(\varepsilon)}{(\omega + i\tau^{-1})^2 - 4(\varepsilon/\hbar)^2}d\varepsilon\right] = \sigma^{intra} + \sigma^{inter} \quad (1)$$

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where $F(\varepsilon) = \{1 + \exp[(\varepsilon - \mu_c)/K_B T]\}^{-1}$ is the Fermi–Dirac distribution, e is the electron charge, ω is the radian frequency, μ_c is the chemical potential, $\tau = 10^{-13}$ s is the relaxation time, K_B is the Boltzmann constant, $\hbar$ is the reduced Planck's constant, T is the Kelvin's temperature. In Eq. (1), the first term represents the contribution of intraband electron–photon scattering and the second term arises from the contribution due to the direct interband electron transitions. When $\mu_c \gg K_B T$, Eq. (1) simplifies as a form with the intraband contribution

$$\sigma^{intra} = \frac{ie^2 \mu_c}{\pi \hbar^2 (\omega + i\tau^{-1})} \tag{2}$$

and the interband contribution

$$\sigma^{inter} = \frac{e^2}{4\hbar^2}\left[1 + \frac{i}{\pi}\ \ln\ \frac{\hbar(\omega + i\tau^{-1}) - 2\mu_c}{\hbar(\omega + i\tau^{-1}) + 2\mu_c}\right] \tag{3}$$

In the following discussions, $T = 300$ K ($K_B T = 26$ meV), and it is easy to match the conduction of $\mu_c \gg K_B T$. In Eqs. (2) and (3), e and $\hbar$ are constants, μ_c and τ are the characteristic values of graphene. Then we can calculate the conductivity of the graphene with the corresponding ω at THz regime. The conductivity of the graphene with different chemical potential is calculated in the THz frequency range by Eqs. (1)–(3), as shown in Fig. 1. The conductivity of graphene increases as the chemical potential varying from 0.1 to 0.4 eV, which indicates the conductivity of graphene can be effectively controlled by changing the chemical potential. As can be seen from Fig. 1, the monolayer graphene presents its properties similar to metal in the THz band. The absorption is relatively small [15]. Therefore, the absorption of the graphene can be ignored. Meanwhile, the nonlinearity such as saturable absorption effect [25,26] occurs under high-intensity electromagnetic field, but the intensity of THz source is generally low at present. Thus the nonlinear effect of graphene can be ignored in the THz band in our following discussion.

As the layer number of graphene increases, its electromagnetic property tend to the graphite, and thus its steerable properties will be receded. The steerable dielectric properties of monolayer graphene are more outstanding than the bilayer graphene and the multilayers graphene. In our work, we control the beaming direction by manipulating the effective refractive index of the graphene plasmonics, so in order to get a better manipulation, we select monolayer graphene to design the device.

2.2. Device structure

The proposed THz beam scanning device is shown in Fig. 2. Fig. 2(a) and (b) shows a single and a double-side structure with the same geometry parameters, respectively. A silica grating with $t = 100$ μm thickness is fabricated on the Ag substrate with a slit of $w = 100$ μm width in the middle. The monolayer graphene covers on the top of the silica grating. Thus, the metal-film, silica layer and monolayer graphene formed a metal–dielectric–graphene grating structure. All the grating grids have the uniform geometry with the period of $d = 440$ μm, the fill factor of $f = 0.5$, and the distance between the slit and the nearest grid $g = 220$ μm. Electric gate array structures are applied on the metal-film as the back electrode and the graphene as the front electrode, independently on the left-side grids and right-side, thus the bias at different side can be controlled independently.

For this metal–dielectric–graphene structure, the μ_c of graphene can be controlled by the bias V_g applied between the metal and the graphene, which follows [17]:

$$\mu_c = \hbar \cdot v_F \sqrt{\frac{4\pi n}{g}} \tag{4}$$

where $v_F = 10^6$ m/s is the Fermi velocity of the graphene, $g = 4$ is the degeneracy factor, n is the carrier density in the system and can be taken as [18]

$$n = 7.2 \times \frac{t}{300}\frac{\varepsilon_d}{3.9}V_g \tag{5}$$

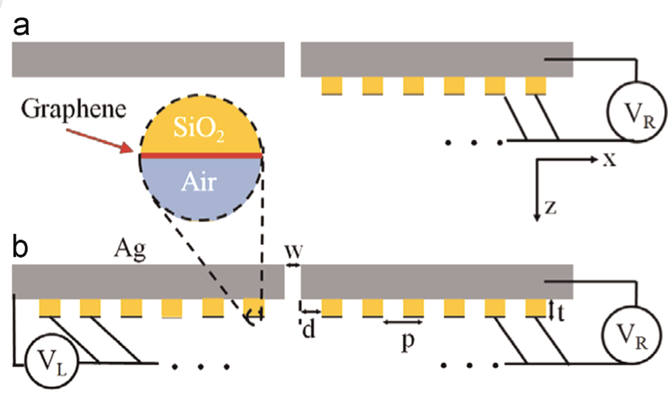

Fig. 2. Schematic diagram of the (a) single-side and (b) double-side THz beam scanning device.

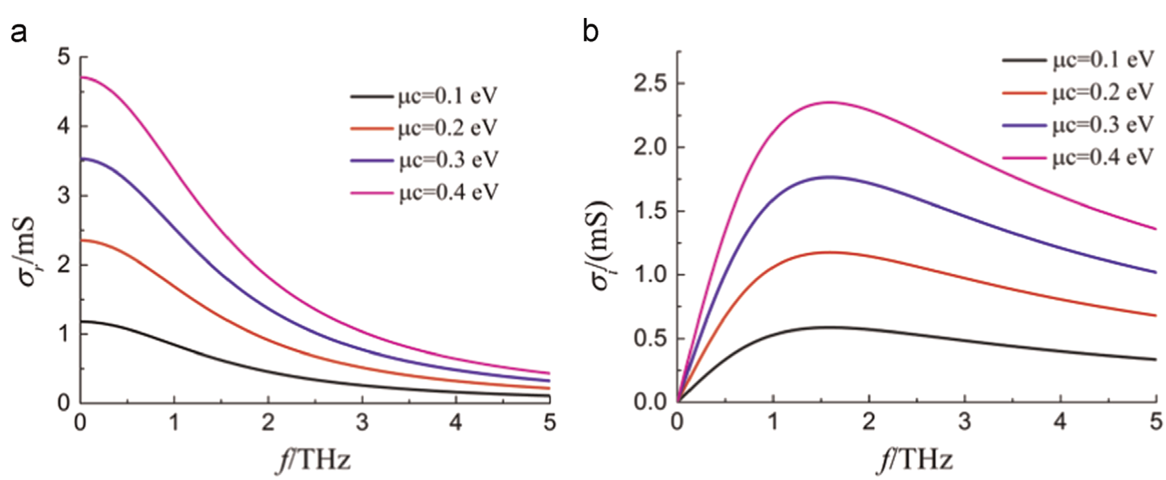

Fig. 1. Real (a) and imaginary (b) parts of conductivity of monolayer graphene with different chemical potentials $\mu_c = 0.1$–0.4 eV in the THz regime.