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Electrically tunable terahertz metamaterials based on graphene stacks array

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A B S T R A C T

With the ability of tuning chemical potential via gate voltage, the permittivity of graphene stack can be dynamically adjusted over a wide range. In this paper, we design electrically tunable metamaterials based on the graphene/Al_2O_3 stacks array, which can achieve a good modulation of resonant frequency and peak value in terahertz region. Due to the enlargement of plasmonic resonance response and the broaden distribution of electric field, our proposed structures perform a better tunability compared with traditional metamaterials loaded monolayer graphene. Since the dipole-dipole coupling between adjacent stacks strengthens immensely as reduces the filling factor of array, the modulated capacity could be further improved. It is found that for oblique incidence, the transmission property is also sensitive to the chemical potential of graphene as well as the polarization direction of incident terahertz wave. These results could be very instructive for the potential applications in voltage-sensitive devices, tunable sensors and photovoltaic switches.

1. Introduction

In the last decade, the researches of metamaterial (MM) has rapidly progressed among both scientific and engineering communities owing to its manifest exotic electromagnetic phenomenons which are not ordinarily encountered in the nature, such as negative permittivity and permeability [1–3], negative refractive index [4] and so on. Although the operating frequencies of MMs can be effectively modulated by reconstructing the geometries or modifying the supporting substrates, it is difficult to change the physical structure after fabrication [5–7]. To over come this issue and realize a large dynamic tunability of the structure-fixing MMs in the terahertz (THz) region, some practical methods have been put forward through combining the MMs to nonlinear composite materials [8–10]. These methods can improve the multi-band tunability of MMs remarkably with some especial modulated mechanisms, and offset the deficiency of devices' non-tunability by controlling the properties of composite with external conditions such as temperature and stress [11,12]. However, the impurity doping of composite and asymmetrical distribution of the conductive particles could apparently affect the nonlinear response, leading to the instability of working performance [13].

Since its discovery in 2004, graphene, a single two-dimensional plane of carbon atoms arranged in a honeycomb lattice, has raised much concern due to its unique atomic thickness, electrical, and thermal properties [14,15]. Especially, graphene has been found to support surface plasmons at THz frequency ranges and to show lower Ohmic loss compared to conventional

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noble metal [16,17], and its conductivity can be tuned under electric/magnetic biasing or chemical doping [18]. Thus, these excellent metal-like characteristics make graphene be promising for the design of tunable MMs and other relative devices. For instance, He et al. realized a tunable near-IR MM by embedding monolayer graphene between the metal structure and polyimide substrate, which achieved an apparent modulation of transmission owing to adjusting the chemical potential of graphene [19]. Zhang et al. designed a dynamically tunable THz absorber via patterning the monolayer graphene into a periodic split-ring array and then coating on the top surface of MM, made it possible to electrically shift the absorption peak [20]. However, it is still generally believed that graphene does not conduct well enough to replace metals and achieve a wide range of tunability in MMs, since the monolayer graphene inlaid in the MM is too thin to sustain an intense resonance [21].

In this paper, we propose electrically tunable THz MMs based on a pair of graphene/Al_2O_3 stacks (GSMM) and graphene/Al_2O_3 stacks array (GSAMM) in sequence. The extinction ratio as well as the resonant response of this multi-layer structure are verified to be sensitive to the graphene layer number and the filling factor of array. On one hand, the resonant frequency and peak value of GSMM and GSAMM can be adjusted observably through applying gate voltage between metal film and substrate. On the other hand, the filling factor of graphene stacks array is further optimized to improve the tunability. In addition, for the oblique incidence of THz wave with thirty degrees to the GSAMM, we realize a good switching-adjustment characteristic.

2. Analysis of graphene stacks array

To prove that the feasibility of our proposed tunable THz MMs based on graphene/Al_2O_3 stacks, we firstly analyze the complex conductivity model of monolayer graphene. In general, the monolayer graphene is electrically modeled either as a 2D infinitesimally thin conductive layer by the complex surface conductivity σ_g, or as a 3D actual medium by the permittivity ε_g [22]. The relationship between each other is $\varepsilon_g = 1 + j\sigma_g/\omega\varepsilon_0 h_g$, where ω is the angular frequency, ε_0 is the permittivity of air, and h_g is the thickness of graphene. Here, σ_g can be calculated as $\sigma_g = \sigma_{\mathrm{intra}}(\omega) + \sigma_{\mathrm{inter}}(\omega)$, which contains two contributed portions [23–25]: $\sigma_{\mathrm{intra}}(\omega)$ represents absorption due to intraband electron-photon scattering, while $\sigma_{\mathrm{inter}}(\omega)$ is caused by interband electron transition process. Their expressions are given by Ref. [24].

$$\sigma_{\mathrm{intra}}(\omega) = j\frac{q^2}{\pi\hbar(\hbar\omega + j\Gamma_c)}\left[\mu_c + 2k_BT\ln\left(e^{-\mu_c/k_BT} + 1\right)\right], \tag{1}$$

$$\sigma_{\mathrm{inter}}(\omega) = j\frac{q^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - (\hbar\omega + j\Gamma_c)}{2|\mu_c| + (\hbar\omega + j\Gamma_c)}\right], \tag{2}$$

Where q is the charge of electron, $\hbar$ is the reduced planck constant, k_B is the Boltzman constant, and μ_c is the chemical potential of graphene. Γ_c represents the damping constant which can be defined as $\Gamma_c = q\hbar v_f^2/\mu\mu_c$, where v_f (~$c/300$ m/s) is

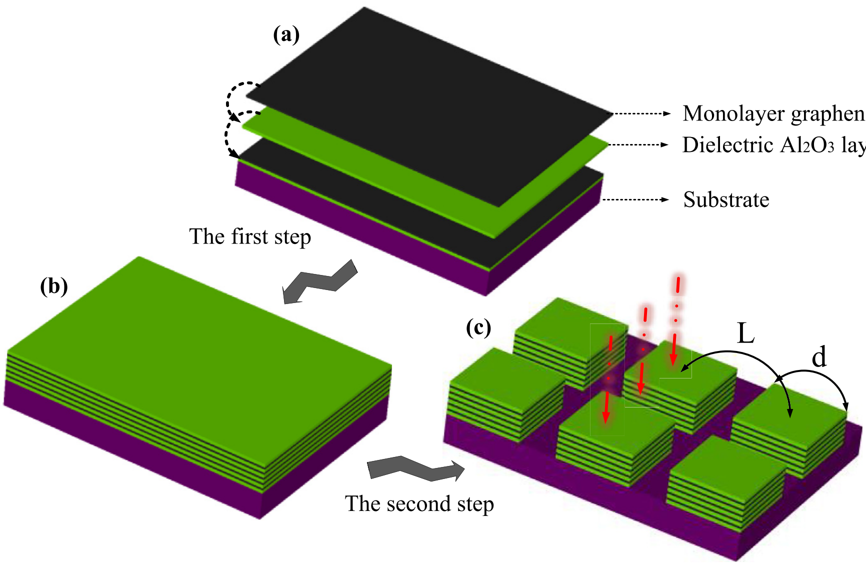

Fig. 1. Fabrication processes of the graphene stacks array: (a) Coat dielectric layer and monolayer graphene by turns. (b) unpatterned multilayer structure. (c) patterned graphene stacks array. *d* is the diameter of unit stack and *L* is the distance between adjacent stacks.