Terahertz electro-optical multi-functional modulator and its coupling mechanisms based on upper-layer double graphene ribbons and lower-layer a graphene strip

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Abstract

A terahertz multifunction modulator composed of upper-layer double graphene ribbons and lower-layer a graphene strip, which can generate a Fano resonance produced by hybrid between a broad mode and a narrow mode, is proposed to realize electro-optical switch and filtering function. The electric field distribution, hybrid theory, and quantum level theory are all employed to explain the Fano resonance, whose transmission spectra are fitted by coupled mode theory. In comparison to other graphene-based terahertz modulators, the amplitude modulation degree can reach 99.57%, meaning an excellent electro-optical switch can be realized. Moreover, the extinction ratio of Fano resonance can reach 99.70%, demonstrating an unparalleled electro-optical filter is implemented. Finally, variations in the lateral and longitudinal lengths of the lower-layer a graphene strip enable excellent dual-band, triple-band filters. Thus, this work provides a new way to implement terahertz multi-function modulators.

1. Introduction

Recently, metamaterials which offer great advantages in manipulating electromagnetic waves have been widely studied. In general, a synthetic material providing electromagnetic properties not found in nature is called a metamaterial, which has potential applications in invisibility cloaking, miniaturized antennas, and negative refraction [1–6]. Metamaterials can be used not only in communication systems, but also in biosensing and imaging systems. Especially in the terahertz band, the metamaterials have become a new candidate for regulating terahertz waves owing to the fact that the existing terahertz devices cannot meet the actual needs. Terahertz metamaterials composed of noble metals and semiconductors are easy to manufacture, high efficiency, and low loss, so they are rapidly developing in research fields such as perfect absorbers [7], modulators [8], sensors [9], and polarization converters [10]. However, the large loss of metal and medium and static regulation seriously hinder the development of terahertz metamaterials. Graphene [11], due to its low loss, strong plasmon local ability, dynamic tunability, and long carrier relaxation time, has become a research hotspot in the terahertz metamaterials. In particular, the discovery of graphene surface plasmons (SPPs) further promotes the development of graphene-based terahertz devices [12–18]. In 2012, Sensale-Rodriguez et al achieved 16% amplitude modulation by controlling the in-band transition of single-layer graphene [19]. 2015 witnesses that Liu et al combined graphene nanoribbons with metal complementary structures to obtain a modulation degree of 60% [20]. In 2016, Rusen Yan et al realized a 90% amplitude modulation degree based on cross graphene [21]. These graphene-based terahertz...
metamaterials can only achieve amplitude modulation with a low modulation degree. However, the terahertz metamaterial based on Fano resonance can not only achieve an amplitude modulation with a 99.57% modulation degree, but also a frequency modulation with a 99.70% extinction ratio.

In this paper, a terahertz multifunction modulator composed of upper-layer double graphene ribbons and lower-layer a graphene strip, which can generate a Fano resonance produced by hybrid between a broad mode and a narrow mode, is proposed to realize electro-optical switch and filtering function. The electric field distribution, hybrid theory, and quantum level theory are all employed to explain the Fano resonance, whose transmission spectra are fitted by coupled mode theory (CMT). The proposed terahertz metamaterials can only achieve amplitude modulation with a low modulation degree. However, the terahertz metamaterial possesses such merits. Firstly, compared to terahertz metamaterials composed of metals and semiconductors, the dynamic tunability of the proposed metamaterials is a huge advantage. Secondly, graphene ribbons and graphene strips, which can be grown by chemical vapor deposition (CVD) [22], are easier to implement than other patterned graphene. Importantly, the terahertz modulator can implement both amplitude and frequency modulation. In comparison to other graphene-based terahertz modulators [19–21], the amplitude modulation degree can reach 99.57%, meaning an excellent electro-optical switch can be realized, which is not available in other double-layered graphene system based on modulation of surface plasmons [23, 24]. Moreover, the extinction ratio of Fano resonance can reach 99.70%, demonstrating an unparalleled electro-optical filter is implemented. Finally, variations in the lateral and longitudinal lengths of the lower-layer a graphene strip enable excellent dual-band, triple-band filters. Thus, this work provides a new way to implement terahertz multi-function modulators.

2. Graphene Fano system

As shown in figure 1(a), the proposed metamaterial consists of upper-layer double graphene ribbons (UDGRs) on top of the silicon substrate attached by lower-layer a graphene strip (LGS). All geometric parameters are shown in the caption of figure 1. In the system, according to the Kubo formula, the conductivity $\sigma$ of single-layer graphene can be easily achieved as $[25, 26]$:

$$\sigma(\omega, E_f, \tau, T) = \frac{2e^2}{\pi \hbar^2} \left[ \frac{1}{(\omega + i\tau - 1)^2} \int_0^{+\infty} \frac{\eta f_d(\varepsilon) - \eta f_d(-\varepsilon)}{\partial \varepsilon} d\varepsilon \right] $$

$$- \int_0^{+\infty} \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega + i\tau - 1)^2 - 4\varepsilon^2} \varepsilon d\varepsilon = \sigma_{\text{intra}} + \sigma_{\text{inter}}$$

(1)

Here, $\omega$, $\tau$, $e$, $\hbar$, $E_f$, $\varepsilon$ and $T$ are the angular frequency of the incident light, the carrier relaxation time, the electron charge, the reduced Planck constant, the Fermi level, the dielectric of graphene, and the system temperature (300 K), respectively. The Fermi–Dirac distribution is indicated as $f_d(\varepsilon) = 1/[1 + e^{(\varepsilon - E_f)/k_B T}]$, with $k_B$ being the Boltzmann constant. Besides, $\sigma_{\text{inter}}(\omega)$ and $\sigma_{\text{intra}}(\omega)$ are intraband electron photon scattering and direct interband photon transitions, respectively, which can be obtained as:

$$\sigma_{\text{intra}} = \frac{2ie^2k_B T}{\pi \hbar^2(\omega + i\tau - 1)} \text{ln} \left[ 2 \cosh \left( \frac{E_f}{2k_B T} \right) \right]$$

(2)

$$\sigma_{\text{inter}} = \frac{ie^2(\omega + i\tau - 1)}{4\pi k_B T} \int_0^{+\infty} G(\xi) \frac{d\xi}{\hbar^2(\omega + i\tau - 1)^2 - \xi^2}$$

(3)

where $G(\xi) = \sinh(\xi)/[\cosh(E_f/k_B T) + \cosh(\xi)]$, in which $\xi = \varepsilon/k_B T$. The frequency band in the terahertz range ($k_B T \ll 2E_f$), $\sigma_{\text{intra}}(\omega)$ can be ignored, so $\sigma_{\text{inter}}(\omega)$ is regarded as the main contribution of $\sigma$. 

Figure 1. (a) An unit schematic of the proposed metasurface. (b) Schematic of the UDGRs and the LGS. The structure parameters are as follows: $L_x = L_y = 4.0 \mu m$, $L_z = 3.0 \mu m$, $L_3 = 1.5 \mu m$, and $d = 0.3 \mu m$. 

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Therefore, $\sigma$ can be obtained as follows:

$$\sigma_G = \frac{i e^2 E_i}{\pi h^2 (\omega + i \tau)^{-1}}. \quad (4)$$

Here, the graphene mobility is $\tau = \mu E_f / (e v_F^2)$, with $v_F = 10^6$ m s$^{-1}$ being the Fermi velocity. The $x$-polarized plane wave is chosen as the excitation source, whose intensity is weak. In this case, the nonlinear effect of graphene has little effect, so it is ignored. Moreover, the dispersion of the plasmon wave propagating on graphene is expressed as:

$$\varepsilon_1 \sqrt{\beta^2 - \varepsilon_1 k_0^2} + \varepsilon_2 \sqrt{\beta^2 - \varepsilon_2 k_0^2} = -\frac{i \sigma}{\omega \varepsilon_0}. \quad (5)$$

Where $k_0$, $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_0$ are the wave vector of the $x$-polarized light, the relative permittivity of air and silicon, and the vacuum permittivity, respectively.

The proposed graphene Fano system is simulated by the finite-difference time-domain (FDTD) method, which is a full-wave numerical simulation of the transmission spectra. In the simulations, periodic boundary conditions (PBC) are applied in the $x$ and $y$ directions, and perfectly matched layers (PML) are imposed along the negative $z$-axis direction of the system. The $x$-polarized plane waves are shone perpendicularly along the negative $z$-axis. Besides, the mesh sizes in the proposed system and simulation time are set to 0.1 $\mu$m and 10 000 fs, respectively.

3. Simulation results and theoretical models

To clearly interpret the physical insights of Fano resonance, the transmission spectra of only upper-layer and dual-layer structures are researched, as shown in figure 2(a). When the $x$-polarized light acts as an excitation source, a red Lorenz curve is directly produced by the UDGRs. The electric field is mainly localized at the inner edges of the UDGRs, which is caused by coupling between the graphene ribbons, as shown in figure 2(c). In this case, electric field of the upper-layer structure is evenly distributed. When the LGS is introduced the system, uniform electric field of the upper-layer structure is broken owing to round trip coupling between the UDGRs and the LGS. The extremely strong electric fields are localized at the inner edges of the UDGRs and on the surface of the LGS, generating a blue Fano curve with a resonance peak of 74.7%.

To further explain the underlying mechanism of the Fano resonance, firstly hybrid theory is employed, as shown in figure 3(a). A broad superradiant mode is excited by the UDGRs, and a narrow subradiant mode is excited by the LGS. As a result, two new energy levels are generated by near-field coupling between the superradiant mode and the subradiant mode, which are the low-frequency mode $|\omega_1\rangle$ at 3.93 THz and high-frequency mode $|\omega_2\rangle$ at 5.86 THz. Meanwhile, the coupled mode theory is also used to reveal the mechanism, as shown in figure 3(b). $A_1$ and $A_2$ are superradiation mode and subradiation mode
respectively, which are analogous to two mutually coupled resonators. The $A_{\text{in}}/A_{\text{out}}$ are the incident light traveling toward or backward the hypothetical resonators of the superradiant or subradiant. And the $A_\pm$ express two different propagating directions of the incident light. $a_1$, $a_2$, $\mu_1$, and $\mu_2$ are the amplitudes and coupling coefficients of two resonators, respectively; $\gamma_{01}$, $\gamma_{02}$, $\gamma_1$, and $\gamma_2$ are inter-loss and intra-loss of two resonators, respectively. The relationship between the two resonators is expressed as:

$$\begin{pmatrix} \gamma_1 & -i\mu_2 \\ -i\mu_1 & \gamma_2 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} -\gamma_{01}/2 & 0 \\ 0 & -\gamma_{02}/2 \end{pmatrix} \begin{pmatrix} a_{1\text{in}} + A_{1\text{in}}^\text{out} \\ A_{1\text{in}}^\text{in} + A_{2\text{in}}^\text{in} \end{pmatrix}. \tag{6}$$

Where $\gamma_{1(2)} = (i\omega - i\omega_{1(2)}) - (\gamma_{01(2)} - \gamma_{01(2)})$. The incident light passing through $A_1$ and $A_2$, the coupling relationship of the system can be obtained according to the conservation of energy:

$$A_{1\text{in}}^\text{in} = A_{1\text{in}}^\text{out} e^{i\phi}, A_{1\text{in}}^\text{in} = A_{2\text{in}}^\text{out} e^{-i\phi}, \tag{7}$$

$$A_{1\text{in}}^\text{in} = A_{1\text{in}}^\text{out} a_{1\gamma_1}, A_{2\text{in}}^\text{out} = A_{2\text{in}}^\text{in} = b\gamma_{02}/2, \tag{8}$$

where $\phi = \text{Re}(\beta)d$ is the phase difference between two resonators. So the transmission coefficient of this system is expressed as:

$$t = \frac{A_{2\text{in}}^\text{out}}{A_{1\text{in}}^\text{in}} = e^{i\phi} + [\gamma_{01}\gamma_2 e^{i\phi} + \gamma_{02}\gamma_1 + (\gamma_{01}\gamma_{02})^{1/2}(\chi_1 e^{i\phi} + \chi_2) \cdot (\gamma_1\gamma_2 = \chi_1\chi_2)^{-1}, \tag{9}$$

Here, $\chi_{1(2)} = i\mu_{1(2)} + (\gamma_{01(2)}\gamma_{02(1)})^{1/2}$. Thus, the transmittance of the system is $T = t^2$.

Furthermore, the physical insight of the Fano resonance can also be explained by the three-level EIT system. The Fano system involves a superradiant state $|1\rangle$ and a subradiant state $|2\rangle$. A dipole-allowed transition $|2\rangle \rightarrow |1\rangle$ is defined as $|0\rangle \rightarrow |1\rangle$ (here, $|0\rangle$ is ground state), which is similar to the superradiant mode excited in the UDGRs. $|0\rangle \rightarrow |2\rangle$ indicates a dipole-forbidden transition, which is similar to the subradiant mode excited in the LGS. $|1\rangle \rightarrow |2\rangle$ shows coupling between the superradiation mode and the subradiation mode. Therefore, destructive interference between two optical path $|0\rangle \rightarrow |1\rangle$ and $|0\rangle \rightarrow |1\rangle \rightarrow |2\rangle \rightarrow |1\rangle$, producing an obvious Fano resonance.

The Fano transmission spectra of numerical simulation are fitted by CMT, as shown in figures 4(a)–(d). With the increase of graphene (UDGRs and LGS) Fermi level in a step of 0.3 eV, the Fano curve has an obvious blue-shift meaning an excellent modulation function. The extinction ratio of the left transmission spectrum can reach 99.7% in the range of 0.6 eV to 1.2 eV, indicating the Fano system can realize unparalleled single-band filter. Moreover, Electro-opticalal switch can also be implemented by the Fano system, as shown in figure 4(e). When the graphene Fermi level is 0.6 eV, the transmission amplitude $B_0$ at 4.2 THz is 70%, meaning transmission loss is 30%; when the graphene Fermi level is 1.2 eV, the transmission amplitude $B_1$ at 4.2 THz is 0.3%. Thus, considering 30% insertion loss, modulation degree MD of amplitude at 4.2 THz can be obtained by:

$$\text{MD} = \left| \frac{B_0 - B_1}{B_0} \right| \times 100\% = 99.57\%, \tag{10}$$

which means the electro-optical switch can be realized. The ‘on’ state is set as transmittance of 70%; the ‘off’ state is set as transmittance of 0.3%. Additionally, a detector which only monitors light waves with a
frequency of 4.2 THz is established at the exit of the Fano system. Therefore, two buttons of $E_f = 0.6 \text{ eV}$ and $E_f = 1.2 \text{ eV}$ can implement switch of on/off state. Figure 4(d) shows three-dimensional modulation diagram, which reflects the filtering and switch mechanism. It is worth mentioning that graphene mobility observed from the experimental data is basically independent of temperature $T$, which indicates that the graphene mobility is still limited by the scattering of impurities at 300 K, so it can be significantly increased to 10 m$^2$Vs$^{-1}$ [29, 30]. By applying the gate voltage, the observed graphene carrier concentration is as high as $4 \times 10^{18}$ m$^{-2}$, which means $E_f = 1.17 \text{ eV}$ [31, 32]. Therefore, we reasonably assume that the Fermi energy $E_f$ can be dynamically adjusted from 0.6 eV to 1.2 eV in the Fano system.

In figure 5, based on the electric field enhancement effect of the subradiation mode, the geometric parameters of the LGS are changed to explore the evolution of Fano resonance. With the increase of the lateral length $L_1$, the Fano curve is remarkable red-shifted. Meanwhile, the dual-band of the Fano curve gradually evolves into triple-band with transmittance of about 0, demonstrating an outstanding triple-band filter function is realized, as shown in figures 5(a)–(c). The phenomenon is similar to Rayleigh-type anomalies in photonics crystal slabs. As the lateral length $L_1$ increases, the LGS generates dual subradiant states $|2a\rangle$ and $|2s\rangle$. Consequently, destructive interference among dipole-allowed transition $|0\rangle\rightarrow|1\rangle$ and two optical paths $|0\rangle\rightarrow|1\rangle\rightarrow|2a\rangle\rightarrow|1\rangle$ and $|0\rangle\rightarrow|1\rangle\rightarrow|2s\rangle\rightarrow|1\rangle$, producing a triple-band system. From figures 5(d)–(f), as the longitudinal length $L_2$ increases from 0.5 µm to 2.5 µm, a symmetrical dual-band with transmittance of about 0 evolves into a single one owing to the blue-shifted of the right transmission dip, which promotes to the degeneration of transparent window. To sum up, the proposed Fano system can effectively customize single-band, dual-band, and triple-band filters according to actual demand.
Figure 6. (a) Existence of splitting three energy levels when two resonance modes are coupled to each other. (b–g) Electric field distribution of three resonance bands in a triple-band system.

To gain a deeper understanding of the formation mechanism of the triple-band system, the hybrid energy diagram and the electric field distribution of three bands are shown in figure 6. Here, three bands of the triple-band system are indicated as ‘band1, band2, and band3’. When there is only the UDGRs in the triple-band system, the weak electric field is confined to the surface of the graphene ribbons, which is enhanced at the inner edge of graphene ribbons due to the coupling between them. When there is only the LGS in the triple-band system, extremely strong electric field is localized on the surface of the graphene strip and its surrounding. As a result, three new energy levels are generated by near-field enhance between the weak electric field in the UDGRs and extremely strong electric field in the LGS, which are a low-frequency mode at 2.13 THz, a middle-frequency mode at 4.44 THz, and high-frequency mode at 5.88 THz, as shown in figures 6(a)–(g). Here, this hybrid process is similar to the molecular orbital energy levels of HF. In figures 6(b)–(c), part of the UDGRs is enhanced by the lower-layer electric field localized around the LGS, which leads to formation of band1. In figures 6(d)–(e), the electric field in both the UDGRs and LGS is enhanced by strong coupling between the UDGRs and the LGS, generating the band2. The increment in the lateral length $L_1$ of the LGS enhances the inductance of the lower-layer structure, which weakens the electric field strength of the entire system, as shown in figures 6(f)–(g). Thus, greatly weak electric field is bound to the UDGRs and the LGS, forming the band3.

4. Conclusions

In short, we have simulated and fitted the Fano resonance generated by hybrid between the UDGRs and the LGS. Electric field distribution, hybrid theory, coupled mode theory, and quantum level theory are all employed to explain the physical origin of Fano resonance. Research shows that excellent single-band filters with an extinction ratio of 99.70% and electro-optical switch can be achieved by dynamically modulating the Fermi levels. In addition, the variation of the lateral and longitudinal distances of the LGS can implement dual-band and triple-band filters. Thus, this work lays a solid theoretical foundation for the realization of single-band, dual-band, triple-band filters and electro-optical switch.

Competing interests

The authors declare that they have no competing interests.

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