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Dynamically tunable broadband terahertz modulation based on monolayer graphene metamaterials

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Abstract. Dynamically tunable cut wire and split ring resonators (SRRs) based on monolayer graphene metamaterials are presented in terahertz regime. As the Fermi level of the graphene pattern increasing, the resonance frequency presents blue shift and higher intensity. Two resonant peaks that can be modulated dynamically in the range of 2.4-3.4THz and 4.1-5.8THz appear. The monolayer graphene metamaterials realize dynamically broadband terahertz modulation with a minimum modulation depth 63.9% at 2.74THz, and the highest modulation depth 93.3% at 3.4THz.

1. Introduction

Graphene is a one-atom-thick material composed of carbon atoms with ultra-high carrier mobility up to $1 \times 10^6 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ at 15K and $2 \times 10^5 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ at room temperature[1, 2]. The Density of States of graphene is extremely low because of the one-atom-thick nature, so it is easy to modulate the Fermi level of graphene with electrostatic field or chemical doping. The Plasmon resonance magnitude of graphene is also weak because of poor carrier concentration in graphene[3]. Metamaterial can improve the interaction between light and matters, is helpful to improve the light control ability of graphene[4]. Here we demonstrate an electrostatically tunable graphene metamaterial employing cut wire and split ring resonators (SRRs) by structure the graphene on the single-crystal quartz substrate to realize modulate of the incident illumination dynamically.

2. Simulation and Discussion

Single cell of the graphene modulator composed by a cut wire and a split-ring resonator is shown in Figure 1. Monolayer graphene was transferred to the 300 μm single quartz and shaped with lithograph. We consider normal incidence with electric field parallel to the SRR gap. As the thickness of graphene is 0.34nm, which is much smaller than the horizontal size, graphene can be consider as a two-dimensional surface with no depth. The electrical property of graphene can be described with the surface conductivity according to the Kubo formula at THz region[5]:

$$\sigma(\omega) = \frac{ie^2 E_F}{\pi \hbar^2 (\omega + i\Gamma)} \quad (1)$$



Where e is elementary charge, i is the imaginary unit, $\hbar = h/2\pi$ is the reduced Planck's constant, $\Gamma = 1/\tau$ is the carrier scattering rate, ω is the incident radiation angular frequency and E_F is the Fermi level of graphene. We use COMSOL Multiphysics to performance the numerical simulations. The surface current boundary condition is used to model the unit cell.

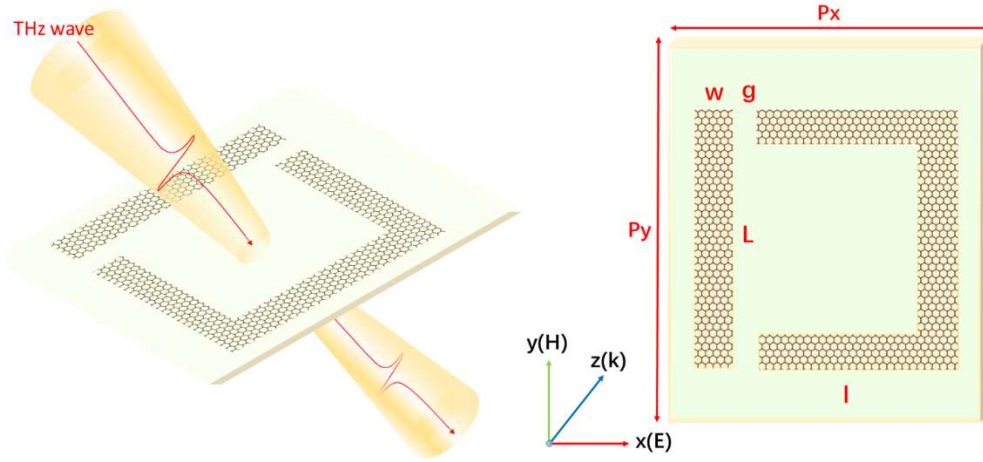


Figure 1. Schematic of the light interacting with graphene SRRs, the electric field E is along the x -axis, the incident light is propagating along the z -axis, the cut wire width $w=0.5\mu\text{m}$, the length $L=3\mu\text{m}$, the gap between the cut wire and SRR is $g=0.25\mu\text{m}$, the SRR width is $l=2\mu\text{m}$, the cell period length $P_x=3.65\mu\text{m}$, $P_y=3.65\mu\text{m}$.

Figure 2 presents the extinction spectrum with $E_F=0.4\text{eV}$ and the electric field distribution at resonance frequencies. The extinction in the transmission $1-T/T_0$ is used to characterize the controllability of light. Two obvious resonant peaks at 2.79THz and 4.74THz are obtained. The lower frequency is the LC resonant peak and the higher is the dipolar mode resonant peak. These two kinds of resonance modes enhance both absorption and reflection of light.

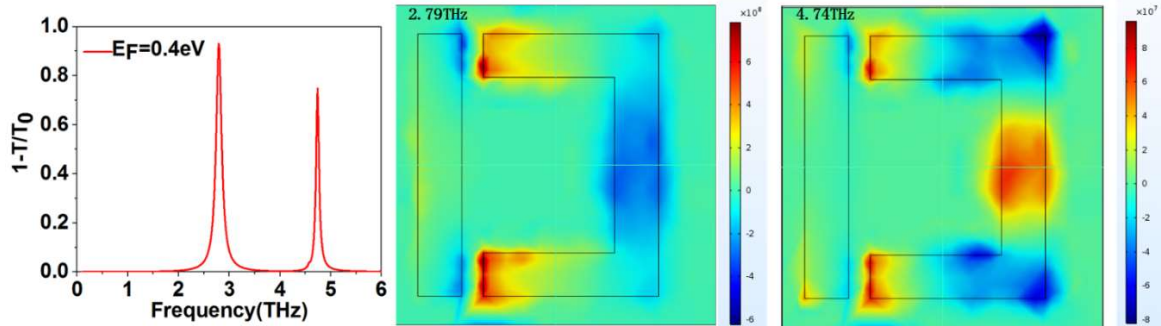


Figure 2. Extinction ($1-T/T_0$) spectrum in transmission of the graphene SRRs, ($E_F=0.4\text{eV}$, 300K , $\tau=5\text{ps}$) and distributions of normalized z -component of electric field E_z at 2.79THz , 4.74THz .

Graphene is a one-atom-thick two-dimensional material, so it has very low Density of States, the surface conductivity of graphene closely related to the carrier's concentration. Unlike the traditional metals, the carrier concentration of graphene is influenced by the Fermi level E_F and can be modulated by gating or chemical doping. With the Fermi level E_F changing from 0.1eV to 0.9eV , the extinction spectrum is shown in Figure 3.

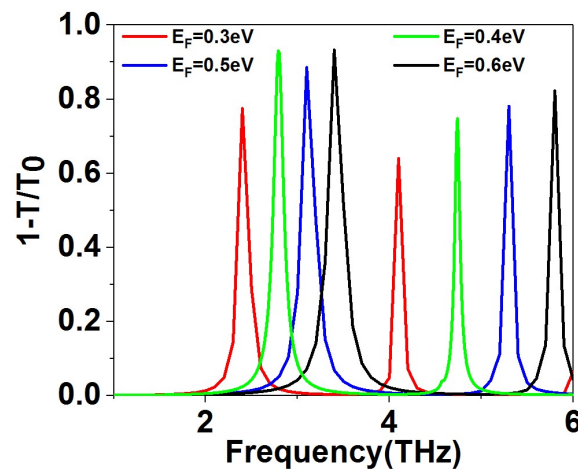


Figure 3. The extinction spectra of graphene with Fermi level arrange from 0.3eV to 0.6eV. The highest modulation depth is 93.3% at 3.4THz when $E_F=0.6\text{eV}$.

Approximately 13% of the light can penetrate the single-crystal quartz, that is accord with the calculated value of the Fresnel formula between 1THz to 6THz. With higher E_F , the extinction in transmission has a blue shift and stronger intensity. But at the resonant peak at 2.74THz with $E_F=0.4$ is an exception. The excitation in transmission reaches up to 93.3% at 3.4THz when $E_F=0.6\text{eV}$. When $E_F=0.3\text{eV}$, the excitation in transmission at 4.1THz is 63.9%. With the Fermi level of the graphene SRRs increases from 0.3eV to 0.6eV, the resonance frequencies can be tuned from 2.4THz to 3.4THz and 4.1THz to 5.8THz, realized broadband modulation with single metamaterials structure.

Besides the material characteristic the geometric dimensioning also play a significant role in enhancing the interaction between graphene and light. We consider the Fermi level $E_F=0.4\text{eV}$ and the momentum relaxation time $\tau=5\text{ps}$. The resonance frequencies show a blue shift with the cut wire length and the SRR width become narrower as shown in Figure 4. Gap width hardly affects the resonance, but the cut wire and SRR's width can significantly change the resonance effects. By adjusting the geometry of the graphene structure, we can get a suitable resonance frequency within a predetermined range.

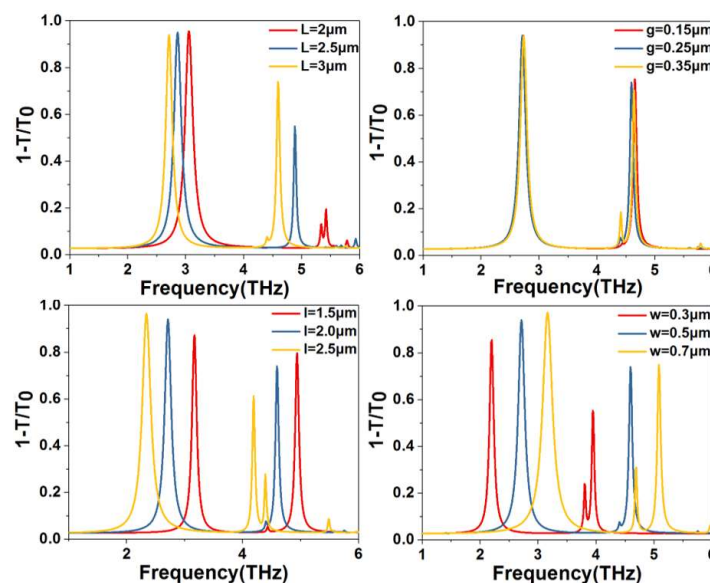


Figure 4. The extinction spectra of graphene SRRs with different geometric dimensions.

3. Conclusion

Benefit from the tunable surface conductivity of graphene, metamaterials fabricated with graphene can realized broadband light modulation more efficient. With the cut wire and SRR composite structure, the interaction between light and graphene is greatly enhanced. Two kinds of resonant peaks appear simultaneously, LC resonance at low frequency and electric dipolar resonance at high frequency respectively. With the Fermi level of graphene changing from 0.3eV to 0.6eV, light between 2.4-3.4THz and 4.1-5.8THz can hardly penetrate the SRRs structure. The modulation depth exceeds 63.9% at all resonant peaks and the highest modulation depth reaches 93.3% at 3.4THz.

The monolayer graphene CSRRs can be used to manufacture an electric field tunable broadband optical modulator in terahertz regime. This work could be helpful to the guide the development of transparent terahertz devices such as detectors, modulators.

Acknowledgements

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