A terahertz modulator based on double-layer graphene

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Terahertz electromagnetic spectrum has long been recognized as an important region for scientific research. A new efficient broadband modulator for terahertz waves at room temperature can be realized using double layer graphene. The modulator is mainly composed by graphene-Al_2O_3-graphene three layers structure, with the carrier density of graphene modified by bias voltage, the absorption can be modulated quickly. The plane wave scattering and absorption by electric biased graphene are studied by the equivalent circuit method. This simplified equivalent circuit has good transportability, which is easy to calculate. The graphene based THz modulator has advantages like low cost, excellent tunability and easy to control, thus promising for THz system applications.

1. Introduction

With the rapid development of wireless communication technology, the contradiction between the high-speed communication service and the limited spectrum resources has been more prominent. Terahertz wireless communication transmission rate can reach 1~10Gb/s, which has advantages like rich band resource, wide bandwidth, difficult to detect and strong anti-jamming capability. It has become one of the hottest areas of wireless communications research at present [1-3]. In recently years, variety of methods and structures has been proposed to design miniature high-performance terahertz communication devices, e.g. terahertz sources [1,2], modulators [4].

Graphene, a 2D material, has attracted a lot of attention since it first deposited on dielectric through exfoliation in 2004 [5]. This material has lots of unique properties, such as extraordinary carrier transport properties and linear band-structure, which represent a great potential in electromagnetic applications [6]. In particular unlike conventional metals, its chemical potential can be tuned by electrostatic or chemical doping. The unique combination of outstanding transport properties and excellent electrical properties has attracted strong interest in its use in modulators [7]. Electrical control THz transmittance type modulator was recently demonstrated in graphene-SiO_2-Si configuration, which is a remarkable result since the active device basically consists of an atom-thick graphene [7,8]. Recently the double layer graphene structure is proposed [9], which consist of two graphene sheets separated by an insulating. By this structure the electronic properties can be tuned without any metal gate.

In this paper, we proposed a modulator based on double layer graphene. Due to a metal film in the bottom the THz beam would transmission through the modulator twice, and the study exhibits that the double layer graphene modulator has better performance than monolayer graphene modulator. The relationship between gate voltage V_g and the conductivity of double layer graphene separated by a thin Al_2O_3 layer is investigated and used to modulation the THz wave transmission. A simplified equivalent circuit is used to calculate the absorption, as a result the modulation depth *MD* was up to 95% with an insertion loss about 1.2dB in comparison with a modulator based single layer graphene with a modulation depth of 64% [8]. The proposed modulator has also shown good capacity of temperature tolerance, and has a board working band. These results make contributions to the development of THz wave modulators and novel THz devices.

2. The equivalent circuit and device design

The graphene sheet is modeled as a thin two-dimension surface characterized by an anisotropic surface conductivity $\bar{\bar{\sigma}}$ [10], the conductivity can be expressed as $\bar{\bar{\sigma}} = \begin{bmatrix} \sigma_L & \sigma_T \\ \sigma_T & \sigma_L \end{bmatrix}$, where σ_L is the longitudinal conductivity, and σ_T is the transverse conductivity, where T=300K, and Γ=0.11meV. Assuming a plane wave incidence on the graphene sheet, the equivalent circuit of graphene deposed on a substrate can be deduced as a four port network [11], shown in Fig. 1a. Port 1 and port 3 are the input and output port of TE waves, respectively. Port 2 and port 4 are for the TM waves. Where $Y_i^{TE} = \dfrac{k_i}{\omega\mu_0}$, $Y_i^{TM} = \dfrac{\omega\varepsilon_i\varepsilon_0}{k_i}$, k_i means the wave number, i represents the air or media, and $Y_\sigma^{TE/TM} = \sigma_L$, $Y_C^{TE} = \dfrac{\sigma_T^2}{Y_{air}^{TM} + Y_{media}^{TM} + \sigma_L}$, $Y_C^{TM} = \dfrac{\sigma_T^2}{Y_{air}^{TE} + Y_{media}^{TE} + \sigma_L}$.

In absence of magnetic field and frequency below 1THz, the σ_T could be regard as 0, so $Y_C^{TE/TM} = 0$. In a special case, when the THz beam normally incident into the

graphene, the $Y_i^{TM} = Y_i^{TE}$, so the equivalent circuit can be simplified as a two port network shown in Fig. 1b.
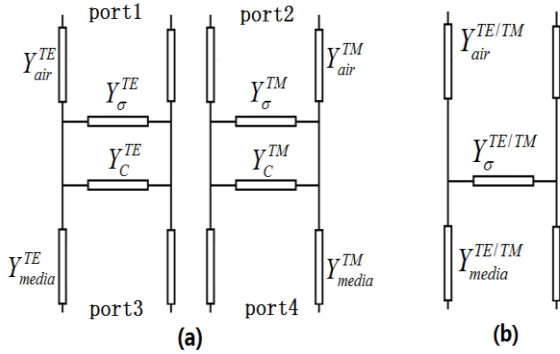

Fig. 1. (a) The equivalent circuit for graphene sheet. (b) Simplified equivalent circuit for graphene with a THz beam normally incidence.

The modulator proposed here is mainly composed by graphene-Al$_2$O$_3$-graphene three layer structure. The three layer structure is deposited on a SiO$_2$ substrate. The main difference between the reflective structure and transmittance structure is a metal film beneath the SiO$_2$ layer as shown in Fig. 2a. The metal film covers the entire backside of the modulator, acting as a reflector. Due to this metal film, when the THz beam reach the metal film, it would have total reflection and then transmission through the double layer graphene again. Therefore the reflective structure has a better modulation depth and large loss compared with the transmittance structure. Each graphene sheet is connected to a metal contact, a bias voltage V_g can be applied through these contacts, thus one graphene sheet sever as a gate for another graphene. Due to the gate voltage V_g, an excess electron density in the top graphene sheet and hole density in the bottom graphene sheet is obtained. The electron density and hole density are almost equal if the graphene is undoped, but the Fermi levels in each graphene have different signs. Meanwhile the relationship between electric field and Fermi energy is derived by [11]:

$$\frac{\varepsilon_0 \pi \hbar^2 v_F^2}{e} E_0 = \int_0^\infty \varepsilon \left[fd(\varepsilon) - fd(\varepsilon + 2\mu_c) \right] d\varepsilon \quad (1)$$

The calculated results are compared with the results calculated by fresnel transfer matrices [9], as show in Fig. 3. It shows the transmittance of THz beam transmitted through single graphene sheet, from the figure we can see that the calculation results are equal by the two methods, which proves the validity of this equivalent circuit in this model.

In order to calculate the absorption of this modulator, a simplified equivalent circuit is used here. Assuming a THz beam normally impinging on this modulator, the equivalent circuit of this structure can be established as shown in Fig. 2b, where Y_{Al2O3} and Y_{SiO2} are the characteristic admittances of Al$_2$O$_3$ media and SiO$_2$ media. According to the to the impedance transformation of

transmission line theory [12], the admittances in this circuit could simplify to a tunable parameter Y_{final}, which is a graphene conductivity related parameter, as shown in Fig. 2c. Through the simplified equivalent circuit of modulator, the reflection coefficient can be calculated as:
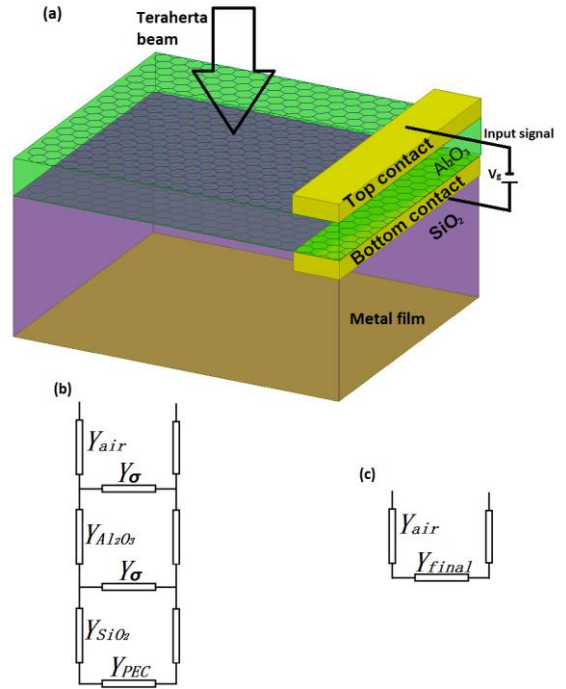
$$\Gamma = \frac{Y_{air} - Y_{final}}{Y_{air} + Y_{final}} \quad (2)$$

Fig. 2.(a) Schematic of the graphene based terahertz modulation, using the graphene sheets of 1.2cm×1.2cm separated by an Al$_2$O$_3$ layer. (b) The equivalent Circuit of the modulator. (c) The simplified equivalent circuit after impedance transformation.
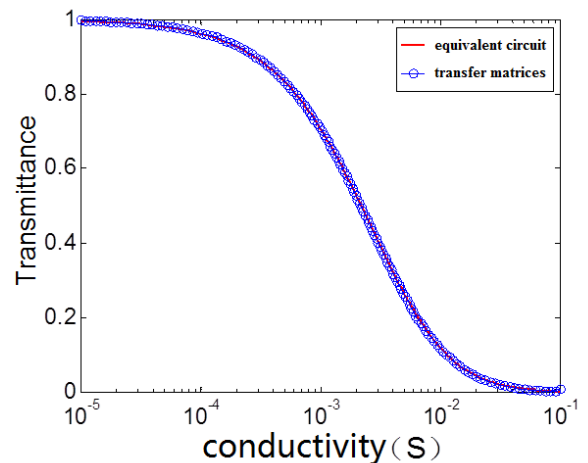

Fig. 3. Transmittance as a function of graphene conductivity by the equivalent circuit and fresnel transfer matrices.

The absorption of graphene is composed by two processes: intraband transitions and interband transition, which is closely related with the conductivity $\sigma(\omega)=\sigma_{intra}(\omega)+\sigma_{inter}(\omega)$ [6], where ω is the angular frequency. In terahertz region, the $\sigma_{inter}(\omega)$ is much less than $\sigma_{intra}(\omega)$, so $\sigma(\omega)\approx\sigma_{intera}(\omega)$, which is sensitive to Fermi energies. The relationship between electric bias and conductivity is depicted in Fig. 4a. It can be seen that the conductivity σ varies obviously with the change of electric field E_0. The conductivity is nearly zero without any electric bias, and the conductivity increases with the rising of $|E_0|$. Therefore the modulator can be designed according to the characteristics of different conductivity with bias voltage. The calculation of absorption is used the simplified equivalent circuit, shown in Fig. 4b. The absorption has a max value at $\sigma(\omega)\approx6mS$ in the single layer graphene case. As for the double layer graphene, the max absorption has left shift, which means a smaller conductivity can cause a max absorption. As we could see single layer graphene can only provide limited absorption in relative small conductivity. In order to get a higher modulation depth with a relative small conductivity, double layer graphene is used in this configuration.
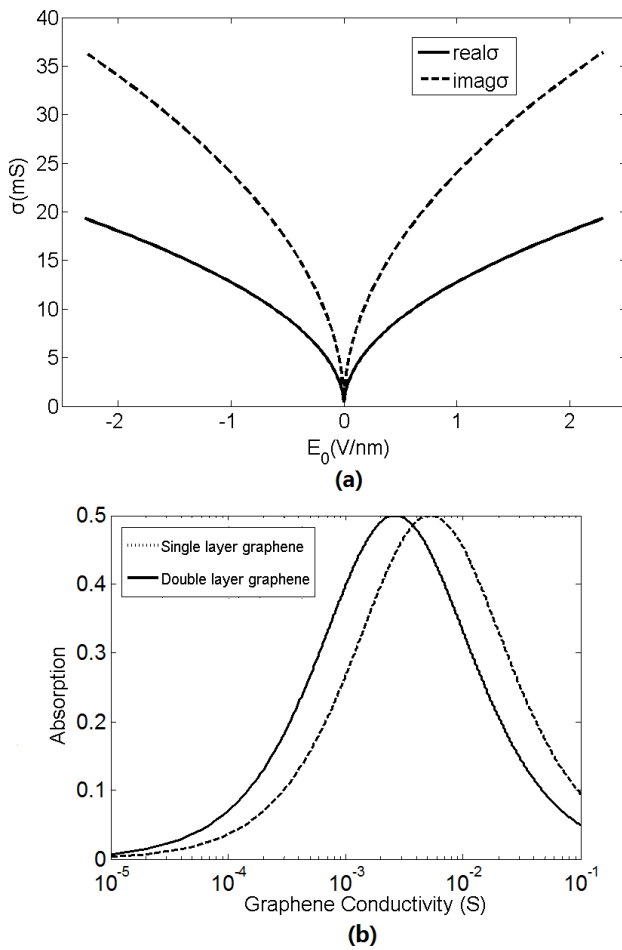
3. Results

Variation of the Fermi energies results in the change of the real and imaginary parts of graphene conductivity, the Fermi energies in turn is related with some parameters, such as bias voltage and the thickness of Al_2O_3 layer. Here we utilize two graphene sheets about 1.2cm×1.2cm separated by an Al_2O_3 layer which has a thickness of 100nm. The graphene-Al_2O_3-graphene is placed on the top of SiO_2 substrates with a 190μm thickness. Since the same mobilities and symmetric band structure, each graphene sheet contributes equally to the modulator. Without any bias the Fermi level of graphene sheets are at Dirac point, where introducing a minimum insert loss or attenuation. As the increasing of the bias voltage, the charge density will increase, so does the transmission loss.

Fig. 5 shows the reflectance power versus frequency with different gate voltages V_g. When the modulator is unbiased (V_g=0), the maximum reflectance power is about 0.75 so the insert loss is ~1.2dB. The insert loss is mainly caused by multi-transmitting through graphene sheets. Due to the large absorption of graphene with a high Fermi level, the reflectance power decreases very fast. Here we set the low voltage of modulation signal as 0V (ON state, for signal "1"), and the high voltage as 10V (OFF state, for signal "0"), therefore the modulation depth can be defined as $MD=(R(0V)-R(10V))/R(0V)$, Where $R(0V)$ means the reflectance power with gate voltage of 0V, so does the $R(10V)$. Due to the $R(10V)$ is very small compared to $R(0V)$, the modulation depth was calculated to be more than 95% in the working band (580GHz ~612GHz). These results excellent agrees the analysis in section 2, indicates that terahertz transmission in graphene closely relate with the Fermi level. In the working band the graphene conductivity changes slightly with the change of frequency, so the transmission coefficient or absorption coefficient would remain almost the same value in this region, if without the SiO_2 substrate. But due to the cavity oscillation, the SiO_2 substrate also has influence on the performance, which makes the curve of reflectance power just as Fig. 5.

Fig. 4. (a) Graphene conductivity as a function of applied electrostatic bias E_0, (b) The relationship between the energy absorption and graphene conductivity, for T=300K, f=600GHz.
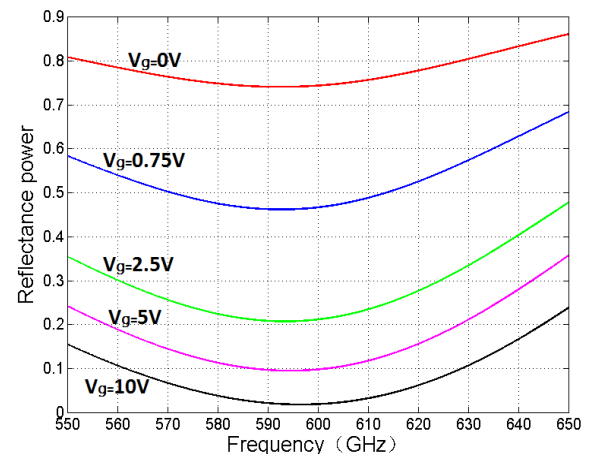

Fig. 5. Reflectance power versus frequency with different gate voltages.

The modulator would have a good performance with a low modulation speed. However with the rising of modulation speed the response time of this modulator should take into account. Equivalent circuit method is adopted to estimate the RC time constant. The resistance R is calculated by half of the inverse of the graphene conductance averaged over the voltage bias V_g. The capacitance of this modulator is calculated by parallel plate capacitor model. Finally the RC time constant is found to be ~0.115ms. The 3dB bandwidth is calculated to be ~13KHz by the RC time constant. The relationship between the normalized amplitude modulation magnitude and the modulation frequency is shown in Fig. 6. From the figure we can see that when the modulation frequency is below 1KHz the modulator works very well, then it would get worse with the increasing of modulation frequency. Although other uncertainties may affect operates of modulator at high speed, here considered the modulator bandwidth primarily determined by the RC time constant is reasonable and feasible. Therefore as long as the frequency of input signal is below the modulation bandwidth, the modulator could operate very well.
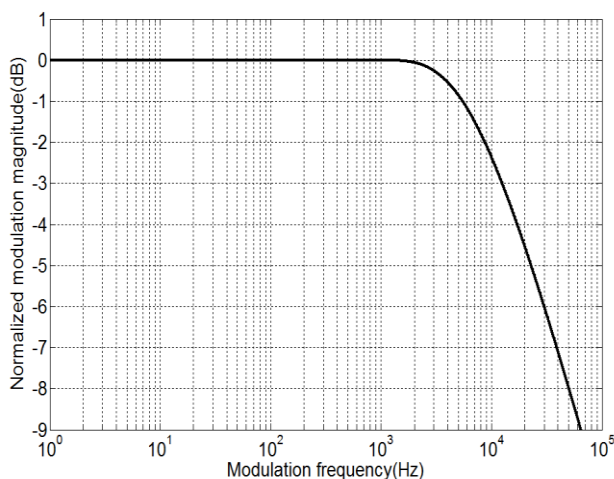

Fig. 6. The relationship between normalized modulation magnitude and the modulation frequency.

4. Conclusion and outlook

This paper has demonstrated an extraordinary control over terahertz transmittance and absorption achieved by a double-layer graphene structure. With the simplified equivalent circuit, the calculation of scattering and absorption would be much easier for terahertz waves. Therefore it shows an enormous potential of graphene as an active material in manipulating the terahertz waves.

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