Broadband Terahertz Transmission Modulation Based on Hybrid Graphene-Metal Metamaterial

Lan-Ju Liang, Zhang Zhang, Xin Yan, Xin Ding, De-Quan Wei, Qi-Li Yang, Zhen-Hua Li, and Jian-Quan Yao

Abstract—A novel patterned metamaterial, composed of graphene layer and metal periodic array of split ring resonators (SRRs) and cross-shaped resonators (CSRs), with broadband terahertz (THz) wave modulation was proposed and theoretically studied. It demonstrated that a broad passband high transmission of over 96.1% in the frequency range from 1.02 THz to 1.66 THz and two narrow band resonance frequencies \( f_1 \) and \( f_2 \) could be generated. The modulation depth of transmission was 29.2% when the graphene layer was covered on the metal metamaterial surface, and the modulation depth could be further increased by increasing the Fermi energy of graphene layer and reached approximately 79.5% at 1.0 eV in a broadband THz frequency range. The resonance frequencies of \( f_1 \) and \( f_2 \) were blue-shifted, and their modulation depths reached about 63.2% and 18%, respectively. These results show that the ultrathin graphene-metal metamaterial exhibits potential to achieve high-performance active THz devices and may offer widespread applications.

Index Terms—Graphene, metamaterial, modulator, terahertz.

1. Introduction

A metamaterial, consisting of a two-dimensional patterned metal structure, has been proposed and studied recently, whose electromagnetic properties are determined by subwavelength resonant elements. It is a promising material for engineering novel devices, such as reflection devices, biosensors, tunable filters, and polarization modulators due to the unique optical physics and control of incident electromagnetic waves. In recent years, terahertz (THz) waves have attracted increasing interests for its promising future in applications of communications, military radar, biology, and medical sciences. Many kinds of THz devices have been proposed to exploit potential applications especially for active modulators. However, the complicated manufacturing and lower modulation efficiency have been constraints on the developments of metamaterials to obtain tunable performance devices in practical applications operated at THz frequencies.

Graphene, a single-layer with hexagonally arranged carbon atoms, has attracted much attention due to its excellent properties such as high carrier mobility and charge carrier densities, which offers a superior solution to the modulation device. On the basis of graphene structure, active THz modulators were proposed and characterized over the past several years. Li et al. proposed a graphene metamaterial hybrid structure and the modulation depth of transmission was 29.0% in the frequencies from 0.6 THz to 0.9 THz. Li et al. proposed a graphene-silicon hybrid metamaterial and the modulation depth of transmission was 61% at the 0.67 THz. For current THz modulators, there are still many shortcomings, such as small modulation depth and narrowband width. Therefore, performance characteristics of tunable devices should be further improved for practical applications in THz technology.

In this paper, we numerically investigated on the transmission modulation devices in the THz range based on a hybrid graphene metamaterial deposed on the flexible substrate by using finite integration time domain (FITD). Although, some researches have studied the graphene-modulated split ring resonators (SRRs) devices, the active modulation characteristics of the hybrid structure of the graphene-metal metamaterial are still needed studying extensively. In our designed structure, the metal metamaterial is covered with...
graphene layer, leading to a flat band in transmission. Meanwhile, graphene allows the control on voltage-modulated surface plasmon at the interface, which can tune the transmission characteristics of incident waves at THz frequencies. By varying graphene’s Fermi energy \( E_F \) levels, the flat-band transmission decreases from 68.0\% to 19.7\%, and the resonance frequencies are also changed. When \( E_F = 1.0 \) eV, the transmission modulation depth reaches 79.5\% in broadband THz frequencies, ranging from 1.05 THz to 1.65 THz. Moreover, the modulation depths are 63.2\% and 18.0\% for the resonance frequencies \( f_1 \) and \( f_2 \), respectively. This proposed hybrid graphene metamaterial presents better features compared with conventional THz modulation because of its flat-broadband range and large range modulation.

2. Computational Methods

The structure design of metamaterial and the full wave numerical simulations are performed by commercial finite element package computer simulation technology (CST) microwave studio. Fig. 1 (a) shows the schematic of the proposed hybrid graphene-metal metamaterial deposited on top of \( SiO_2 / Si \). The thicknesses of \( SiO_2 \) and Si layers are 300 nm and 1 \( \mu \)m, respectively. In our simulation, \( SiO_2 \) is considered as a nondispersive dielectric with a relative permittivity \( \varepsilon_{SiO_2} = 3.9 \). The bottom layer is polyimide film, and the thickness of polyimide is 30 \( \mu \)m, as shown in Fig. 1 (b). The dielectric constant and loss tangent of polyimide are 3.10 and 0.05, respectively. The designed metal structure is composed of SRRs and cross-shaped resonators (CSRs), the thickness of the metal structure is 200 nm. The geometrical parameters are as follows: \( P = 120 \) \( \mu \)m, \( w_1 = 5 \) \( \mu \)m, \( w_2 = 6 \) \( \mu \)m, \( d = 6 \) \( \mu \)m, \( L = 90 \) \( \mu \)m, and \( L_2 = 40 \) \( \mu \)m, as shown in Fig. 1 (c). All the simulation results are calculated by using the frequency domain solver, and the unit-cell boundary conditions in the \( x-y \) plane and flouquet ports in the \( z \) direction are adopted for the designed structure.

\[ \Delta \omega = \left( \text{Im}(\sigma_g(\omega)) - i \text{Re}(\sigma_g(\omega)) \right) \int \frac{|E|^2 dS}{W_0} \]  

where \( \sigma_g(\omega) \) is graphene conductivity, \( S \) denotes the graphene covering layer area, \( E_{\text{En}} \) is the electric field in the plane of graphene, \( W_0 = 2 \int |E|^2 dV \) is the stored electromagnetic energy of the metamaterial uncovered with graphene. From (3), we know that the resonance frequency shift of \( \text{Re}(\Delta \omega) \) is determined by \( \text{Im}(\sigma_g(\omega)) \), and it is blue-shifted for \( \text{Im}(\sigma_g(\omega)) < 0 \). In addition, the transmission of the graphene-metamaterial can be written in terms of materials’ impedances as follows:

\[ t_{\text{meta}}(\omega) = \left| \frac{2Z_{\text{meta}}(\omega) + Z_0}{Z_{\text{meta}}(\omega) + Z_0 + Z_{\text{sub}} + Z_{\text{sub}}/2Z_{\text{sub}}} \right| \]  

where \( Z_0 = 377 \) \( \Omega \) and \( Z_{\text{sub}} = Z_0/\mu_{\text{sub}} \) are the vacuum and substrate impedances, respectively, and \( Z_{\text{meta}}(\omega) \) is the complex impedance of the graphene-metamaterial layer. According to (1), graphene’s surface conductivity can be controlled by varying its \( E_F \), thereby changing the impedance and transmission efficiency of the metamaterial. Thus, the transmission amplitude can be modulated through the hybrid graphene-metal metamaterial with different \( E_F \) levels.

3. Results and Discussion

3.1 Broad Flat-Band Transmission of the Designed Metal Metamaterial

First, in order to clarify the modulation mechanism of the hybrid metamaterial structure, we investigated the
transmissions of the designed metal metamaterial (sold line), SRRs (dash line), and CSRs (dot line) using CST Microwave Studio without graphene layer of three structures, as shown in Fig. 2 (a). When the polarization of the incident THz waves was perpendicular to the gap-bearing side of SRRs, a flat region emerged as a wide passband with a transmission efficiency over 96.1% from 1.02 THz to 1.66 THz, and two resonance frequencies were generated at 0.71 THz and 1.90 THz, respectively. From the transmission spectra of the SRRs (dash line) and CSRs (dot line) structure and the surface current distributions at \( f_1 \) and \( f_2 \), it can be seen that the strong surface current distributions in two side lengths of SRRs at \( f_1 \) demonstrated an enhanced dipolar coupling, which is closely related to the polarization of the incident waves. To verify this polarization dependent effect, the according electric field distributions along different directions (\( E_x \) and \( E_y \)) are also presented in Figs. 2 (d) and (e). It is clearly seen that the electric field distributions change largely with the polarization of the incident waves transforming from x- to y-direction. On the other hand, the electric field distributions at \( f_2 \) are similar with that at \( f_1 \), indicating the same dipolar resonance due to the anisotropic electric field distribution (not shown here). It is worthy note that there is no evidenced inductance-capacitance (LC) resonance which will drive the circulating surface currents in the SRRs loop as reported in other research works. This may be interpreted by the SRRs-CSRs coupling effect. It can be seen from Figs. 2 (b) and (c) that the surface currents also appear in the CSRs structure, the interactions of higher mode resonances for SRRs and the dipolar resonance for CSRs produce a mixed-mode resonance, which would prevent the formation of circulating currents in the SRRs structure, resulting in the decrease, even elimination of LC resonance mode.

3.2 Graphene-Metal Hybrid Metamaterial

We also characterized the THz transmission spectra of the designed hybrid metamaterial graphene, as shown in Fig. 3. The broadband transmission decreased from 96.1% to 68.0%, and the flat-transmission bandwidth decreased from 1.10 THz to 1.62 THz when the monolayer graphene was transferred on the metamaterial surface. The THz transmission at \( f_1 \) increased from 0 to 40% (\( \Delta T^1 = 0 \)) and showed a strong redshift in the resonant region from 0.71 THz to 0.59 THz (\( \Delta f = 0.12 \) THz), while that at \( f_2 \) increased from 10% to 27% (\( \Delta T^2 = 17% \)) and showed no obvious resonant frequency shifts.

From the above analysis, we know that \( f_1 \) is a dipole oscillator model for SRRs. This resonance frequency \( f_1 \) can be determined by \( f \approx 1/4\pi d \sqrt{\varepsilon_{ave}} \), where \( \sqrt{\varepsilon_{ave}} \) is the average permittivity of the surrounding medium and \( d \) is the length of the SRRs arm. When the graphene layer was deposited on the surface of metamaterial, the \( \sqrt{\varepsilon_{ave}} \) was increased, which resulted in the redshift of the resonance \( f_1 \). Furthermore, the change in transmission was determined on \( Z_{matt} (\omega) \) according to (4). When graphene layer was deposited on the metamaterial surface, \( Z_{matt} (\omega) \) was increased, resulting in the transmission of graphene metamaterial changing. The simulation results showed that the proposed hybrid ultrathin graphene metamaterial device can modulate the resonance frequency and transmission in the THz frequencies.

3.3 Hybrid Graphene-Metal Metamaterial with Different Fermi Levels

In order to further study the characteristics of the hybrid graphene metamaterial, the THz transmission spectra under
various Fermi levels of graphene were studied. The carrier concentration \( n \) corresponds to the Fermi energy of graphene, thus we can obtain:

\[
E_F = \hbar \gamma \sqrt{\frac{n}{m^*}} \tag{5}
\]

where \( \gamma \) is Fermi velocity (\( 1.1 \times 10^6 \) m/s in graphene). On the other hand, the biased voltage would induce the change of carrier concentration as:

\[
n \approx V_c e_0 / e t_s \tag{6}
\]

where \( e_0 \) and \( e \) are the permittivities of vacuum and silicon dioxide, respectively, \( t_s \) is the thickness of silicon dioxide, and \( e \) is electron charge. Then, based on (5) and (6), we obtain:

\[
E_F = \mu \sqrt{\frac{\pi e_0 V_c}{e t_s}}. \tag{7}
\]

Fig. 4 (a) shows the transmission spectra of the bare metamaterial and hybrid graphene metamaterial with various \( E_F \) levels. The transmittance of the bare metamaterial approaches 96.1%. When the metamaterial was covered with graphene layer, the broadband average transmission decreased from 68.1% to 19.7% with the graphene \( E_F \) from 0.3 eV to 1.0 eV. In addition, the flat-band transmission exhibited little change in bandwidth but the flat band blue-shifted to higher frequencies in the band location. Table 1 shows a detailed description of the transmission performance for different graphene chemical potentials. To demonstrate the flat property of the passband, the transmission ripple was also calculated. In the flat-band region, the ratio of the difference between the maximum and minimum transmissions to the maximum transmission is referred as transmission ripple. It is found that the ripple decreased from 5% to 3% in a broadband THz frequency range, and the flat characteristic becomes much better with the increase of the \( E_F \) level. When the \( E_F = 1.0 \) eV, the transmission is 19.7%. Therefore, the simulation results demonstrate that this hybrid graphene metamaterial can realize on-to-off switching responses of the THz waves. Both the resonance frequencies \( f_1 \) and \( f_2 \) blue-shifted with the increase of \( E_F \). Fig. 4 (b) reveals the resonance frequency with different \( E_F \) levels with simulated data. The straight lines show the exponential fits to the simulation data. The fitting functions for \( f_1 \) and \( f_2 \) are described by \( f_1 = 1.60 - 1.01 e^{-E_F/0.29} \) and \( f_2 = 2.35 - 0.33 e^{-E_F/0.40} \), respectively. The resonance frequencies \( f_1 \) and \( f_2 \) are 1.58 THz and 2.33 THz at 1.0 eV, respectively.

The modulation depths of resonance frequency and transmission are defined as \( f_{\text{mod}} = \Delta f / f_{\text{max}} \) and \( T_{\text{mod}} = \Delta T / T_{\text{max}} \), respectively. Note that to define the modulation depth of transmission strictly, the transmission of the bare metamaterial and graphene-metamaterial at different Fermi energy, \( T_{\text{max}} \) and \( T \) respectively, are adopted as the average values in the range from 1.05 THz to 1.65 THz. Therefore, from Table 1, the transmission modulation depth \( (\Delta T / T_{\text{max}}) \) achieves 79.5%, and that of the resonance frequencies \( f_1 \) and \( f_2 \) are 63.2% and 18.0%, respectively with an applied Fermi energy of 1.0 eV.

![Fig. 4. Modulated results of the metamaterial under different graphene \( E_F \): (a) THz transmission spectra and (b) resonance frequencies \( f_1 \) and \( f_2 \).](image)

<table>
<thead>
<tr>
<th>Table 1: Transmission properties with different ( E_F ) levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi energy of graphene (eV)</td>
</tr>
<tr>
<td>No graphene</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.7</td>
</tr>
<tr>
<td>1.0</td>
</tr>
</tbody>
</table>
Fig. 5 shows the real and imaginary conductivities change of graphene by continuously adjusting $E_F$. It shows that the real and imaginary conductivity of graphene was increased with increasing $E_F$ level.

Additionally, the resonance frequency shift of $\text{Re}(\Delta \omega)$ was determined by $\text{Im}(\sigma_j(\omega))$ from (3). And $\text{Im}(\sigma_j(\omega))$ is negative in the frequency range from 0.4 THz to 2.8 THz with different graphene $E_F$. Therefore, the resonance frequencies of $f_1$ and $f_2$ were blue-shifted by increasing $E_F$. The modulation depth of the resonance frequency $f_1$ was larger than that of $f_2$ because of the larger change in $\text{Im}(\sigma_j(\omega))$ for the same change in $E_F$.

The modulation depth of the resonance frequency $f_1$ was larger than that of $f_2$ because of the larger change in $\text{Im}(\sigma_j(\omega))$ for the same change in $E_F$. According to the resistor-inductance-capacitance (RLC)-series electrical circuit, the bare metamaterial impedance can be directly written as $Z_{\text{meta}}(\omega) = R + i\omega L + 1/(i\omega C_g)$ (3). The capacitance can be expressed as $C_g = C + (\sigma_j/\omega)(W_0/L_0)$ when the monolayer graphene was layered on top of the metamaterial, where $C$ is the capacitance of the bare metamaterial, $\sigma$ is the graphene layer conductivity, and $W_0/L_0$ is the effective aspect ratio of the conducting graphene (3). The conductivity of graphene layer was increased with increasing $E_F$, thereby enhancing the $C_g$ and decreasing the $Z_{\text{meta}}(\omega)$ of the hybrid graphene metamaterial. Simultaneously, the transmission amplitude of the proposed structure can be dynamically controlled according to (4). On the other hand, the graphene layer manifests ‘metallic’ properties more obviously with increasing $E_F$, and the transmission efficiency decreases in broad frequencies.

### 4. Conclusions

In conclusion, we have designed a novel ultrathin THz modulator based on hybrid graphene-metal metamaterial. The proposed metamaterial structure exhibited a flat broad passband transmission response in THz frequencies. The modulation depth of transmission was 29.2% when graphene was layered on the metamaterial, meanwhile that of 79.5% was achieved through adjusting the graphene’s $E_F$ to 1.0 eV in a broadband THz frequency range. The modulation depths of resonance frequencies $f_1$ and $f_2$ were 63.2% and 18.0%, respectively. These results demonstrate that this kind of ultrathin hybrid graphene metamaterial enables effective manipulation of THz waves, and this new modulator may offer widespread applications in the wireless communications, imaging systems, biomedical sensing, and so on.

### References


Lan-Ju Liang was born in Shandong Province in 1979. She received the B.S. degree from the University of Yili Normal China, Yili in 2002 and the M.S. degree from the University QuFu Normal, Qufu in 2005. She received her Ph.D. degree from the Nanjing University, Nanjing in 2014. Now she is currently a professor with the Department of Opto-Electronic Engineering, Zaozhuang University, Zaozhuang. Her research interests include terahertz devices, metamaterial, graphene and photonic crystal.

Zhang Zhang was born in 1990. He received the B.S. degree from Wuhan Institute of Technology, Wuhan in 2013 and the M.S. degree from Yunnan University (YNU), Kunming in 2016, both in material physics. He is currently pursuing the Ph.D. degree with the School of Precision Instrument and Opto-Electronics Engineering, Tianjin University, Tianjin. His research interests include terahertz technology, metamaterials, and graphene surface plasmon.

Xin Yan was born in 1977. He received the B.S. degree from the University of Yili Normal China, Yili in 2002 and the M.S. degree from Zhengzhou University, Zhengzhou in 2008. He is currently pursuing the Ph.D. degree with the School of Precision Instrument and Opto-Electronics Engineering, Tianjin University. And he is also an associate professor with the Department of Opto-Electronic Engineering, Zaozhuang University. His research interests include terahertz technology, metamaterials, and graphene.

Xin Ding was born in 1972. He received the Ph.D. degree from Tianjin University in 2000. Now he is a professor with the College of Precision Instrument and Opto-Electronics Engineering, Tianjin University. His current research interests include terahertz devices and laser.

De-Quan Wei was born in 1964. He received the B.S. degree from the Liaocheng University, Liaocheng in 1985. Now he is currently a professor with the Department of Opto-Electronic Engineering, Zaozhuang University. His research interests include terahertz devices and metamaterial.

Qi-Li Yang was born in 1981. She received the B.S. degree from the Liaocheng University in 2004 and the M.S. degree from China University of Mining and Technology, Beijing in 2007. Now she is currently a lecturer with the Department of Opto-Electronic Engineering, Zaozhuang University. Her research interests include micro-nano devices and THz technology.

Zhen-Hua Li was born in 1987. He received the B.S. degree from Shandong University, Weihai in 2006 and the M.S. degree from Korea University of Technology and Education, Cheonan-si in 2009. Now he is currently an assistant professor with the Department of Opto-Electronic Engineering, Zaozhuang University. His research interests include micro-nano devices and semiconductor.

Jian-Quan Yao was born in 1939. He received the M.S. degree from the Tianjin University in 1965. He is currently an Academician with the Chinese Academy of Sciences and a professor with the College of Precision Instrument and Opto-Electronics Engineering, Tianjin University. His current research interests include terahertz sources, terahertz devices, metamaterials, and laser.