Terahertz tunable optical dual-functional slow light reflector based on gold-graphene metamaterials

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Abstract
Tunable terahertz optical dual-functional slow light reflector based on gold-graphene metamaterials has been designed and the proposed structure can achieve a good optical reflection effect and slow light effect. The tunable function can be dynamically controlled by applying a voltage to the gold and it can achieve a good effect for selecting reflection band. In more detail, the gold in this device can enable us to dynamically tune the Fermi level of graphene, thus this device can achieve a good tunable effect. Compared with other structures, the graphene monolayer in this structure is simpler and forms a complete band distribution, laying a solid foundation for the subsequent implementation of the device. Through the derivation and analysis of the optical equivalent-cavity coupled mode theory, the theoretical fitting transmission and reflection of this device can be obtained, and they are in good agreement with the numerical results. Furthermore, the slow light effect of this device has been analyzed and it is found that this device has a better slow light performance. This investigation is expected to provide a theoretical basis for the realization of tunable slow light reflectors.

1. Introduction

Graphene, which started at a torn monolayer of carbon atoms with a benzene ring structure, opens a new platform [1, 2]. It adds many potential applications for various applications, such as photodetectors [3, 4], modulators [5, 6], sensors [7, 8] and so on [9–12]. The researchers initially did not believe that the atomic monolayer structure could exist independently in the nature or laboratory, but the experimental facts broke this uncertainty. After that, researchers have carried out a lot of investigations on this new carbon monolayer [13–17], and people find that the graphene monolayer has excellent conductivity and ductility. These unique characteristics create some excellent electronic and optical properties, and then graphene can provide a deep foundation for its application in various functional devices [18–22].

In recent years, terahertz technology has been developed rapidly, and it shows a wide range of potential applications in the fields of communication, detection and energy [23–26]. In particular, many materials and biomolecules have characteristic absorbance in the absorption spectra in terahertz band. The energy of terahertz wave is low and thus the damage caused by light source is very small. Moreover, the artificial micro/nano metamaterial can well fit the characteristics of terahertz band, which provides an excellent structural foundation for terahertz technology. In particular, the researchers have found that there is an overlapping region between graphene and terahertz. Graphene has metal-like properties in the terahertz band [27, 28], which enables graphene to conduct propagating surface plasmon wave in terahertz band. This property is also used in various optical graphene-based devices, such as slow light device [18], filter [29], sensor [8], and so on [30–33].
In this paper, we have designed a tunable terahertz optical dual-functional slow light reflector based on gold-graphene metamaterials. We have used a gold-graphene hybrid metamaterial structure to achieve a good optical reflection and slow light effect. The gold in this device can enable us to dynamically tune the Fermi level of graphene, thus this device can achieve a tunable effect. Compared with other structures, this structure is simple. Moreover, the graphene monolayer in our device is a complete band distribution, laying a solid foundation for the subsequent implementation of the device. By changing the Fermi level modulated by voltage, we can dynamically select the reflective frequency band for this device, which makes it possible to realize an excellent reflector. Based on the derivation and analysis of the equivalent coupled mode theory (CMT), the theoretical fitting transmission and reflection data of this device are obtained, and the theoretical fitting data are in good agreement with the numerical results. The consistency of theoretical fitting and numerical simulation can verify that the equivalent CMT is a good analysis method for this structure. Furthermore, we have analyzed the slow light effect of the structure and found that this designed structure also has a better slow light performance. The maximum group refractive index is 245, which is better than the general slow light device. This investigation is expected to provide a theoretical basis for the realization of tunable slow light reflectors.

2. Structure and theoretical model

As shown in figure 1, the tunable optical plasmonic dual-functional slow light reflector is made of three materials. They are respectively graphene, gold (Palik [34]) and silicon substrate (the relative permittivity is 11.9). It is set to an infinite length in the $y$-direction comparing with the $xy$-direction of this device, and then we can use two-dimensional simulation for reducing simulation time. Thus, we perform the finite difference time domain (FDTD) simulations with periodic boundary conditions at $x$ direction and a perfect matched layer boundary condition at $z$ direction, respectively. Their distribution in each period is shown in figure 1(b) and the specific structural parameters are reflected in the captions. These parameters are invariant in this study. The light source is located at terahertz band and the ambient temperature is a room temperature ($E_F \gg \hbar \omega$, $k_B T$) [28], thus the graphene monolayer conductivity can be described as:

$$\sigma_g = \frac{ie^2 E_F}{\pi \hbar^2 (\omega + i \tau^{-1})},$$

(1)

here, $e$, $E_F$, $k_B$, $\omega$, $\tau$, respectively, are the elementary charge, Fermi level, Boltzmann constant, reduced Planck constant, angular frequency, carrier relaxation time. Moreover, it should be mentioned that the carrier relaxation time could satisfy the following equation: $\tau = \frac{\mu E_F}{(e v_F^2)}$ [35, 36], the carrier mobility $\mu$ and Fermi velocity $v_F$ respectively are 1.00 m$^2$ (V s)$^{-1}$ and 10$^8$ m s$^{-1}$.

The light source is projected from the top of the structure, i.e., the negative direction of the $z$-axis, as shown by the arrow in figure 1(a). The FDTD method is used to simulate the optical properties of the structure. The optical spectra of the structure are shown in figure 2(a) when the Fermi level is equal to 0.6 eV. The black line, red line and blue line are respectively the transmission, reflection, absorption spectra of this tunable optical plasmonic dual-functional slow light reflector. Figures 2(b)–(d) respectively show the cross-section of electric field distribution at resonant frequency. It can be seen that the energy localized by graphene and gold is very small at the two resonant frequencies of transmission or reflection, which can be attributed to the excellent reflection performance of the structure. And also, it can be seen that the reflection is almost 100% at this time.

Between the two reflection peaks, all of the energy is transmitted and localized between the structures due to the resonance between graphene and metal, as shown in figures 2(a) and (c). Compared with the electric field distributions and spectra at the reflection peaks, the structure at the reflection dip can absorb about 22% of the energy of the light source. If the device is used as a reflector and a transmitter, this part of energy is lost. However, if it is used as an absorption device, the absorption coefficient is not very high at this time, and some follow-up works are needed. Considering the characteristics of this structure, this structure has incomparable properties in terms of reflection performance. The device can be regarded as a good optical reflector due to the nearly 100% reflection efficiency.

In addition, due to the advantages of graphene, it is easy to tune the reflection frequency band of this structure by external voltage. The device can tune the reflection frequency band without changing any geometric parameters, so it can achieve an excellent tunable effect by using the circuit, and then it can be used for the practical functions such as communication. The modulation relationship between voltage and graphene is as follows [11, 37]:

$$E_F = \hbar v_F \left(\frac{\pi \varepsilon_0 \varepsilon_{sub} V_V}{d_{sub} e}\right)^{1/2}.$$ 

(2)
Figure 1. (a) The tunable optical plasmonic dual-functional slow light reflector. (b) The front view of one unit of the periodic device. The structural parameters are: $L = 3000 \text{ nm}$, $H = 200 \text{ nm}$, $l_g = 2200 \text{ nm}$, $l_{Au} = 2000 \text{ nm}$, $h = 100 \text{ nm}$.

Figure 2. (a) The transmission/reflection/absorption spectra of the tunable optical plasmonic dual-functional slow light reflector with Fermi level $E_F = 0.6 \text{ eV}$. (b)–(d) The electric field distribution of resonant dips and peak, (b) dip1 of resonant frequency $= 8.67 \text{ THz}$, (c) peak of resonant frequency $= 10.62 \text{ THz}$, (d) dip2 of resonant frequency $= 12.37 \text{ THz}$.

Here, $\varepsilon_0$, $\varepsilon_d$, $V_g$, $d_{sub}$ are respectively the relative dielectric constant of air and dielectric, voltage, distance between graphene and electrode. From this equation, we can tune the Fermi level of graphene by changing the bias voltage between graphene and electrode. Moreover, because each periodic unit of the designed device has a metal structure. The gold acts as an electrode to regulate the Fermi level of graphene, and it is also a structural material. It can resonate with graphene, and the gold and graphene can together tune the transmission and reflection efficiency. Moreover, the length of graphene monolayer in $y$-direction is much longer than that in $x$-direction, and thus it can be regarded as infinite and a two-dimensional simulation. Compared with the graphene-based discontinuous pattern, our design can tune the applied voltage of graphene more easily, and thus it can be realized more easily in manufacturing.

Because the polaritons generated by this structure are only attached to the surface of graphene monolayer, we can approximate using the propagation constant of plasmonic wave in the infinite graphene monolayer to analyze this propagation constant in our structure. Therefore, we can easily obtain the approximate propagation constants of plasmonic wave in this structure:

$$\beta = k_0 \sqrt{\varepsilon_{Si} - \left( \frac{2}{\eta_0 \sigma_g} \right)^2},$$  \hspace{1cm} (3)

here, $k_0$, $\varepsilon_{Si}$, $\sigma_g$, and $\eta_0$ are wave numbers in free space, relative dielectric constant of silicon, graphene conductivity, and intrinsic impedance in free space, respectively. We can easily get the effective refractive
index by the relationship between the effective refractive index and the propagation constant: \( n_{\text{eff}} = \beta / k_0 \). The real and imaginary parts of effective refractive index against frequency are shown in figures 3(a) and (b) in different Fermi level.

Through the definition of internal loss quality factor: \( Q_i = \text{Re}(n_{\text{eff}})/\text{Im}(n_{\text{eff}}) \), we can get the value of internal loss factor, which is very helpful for the data of coupling theory and numerical analysis. Moreover, we also need to find the total quality factor, and it can be obtained from the full width of half maximum at each resonance: \( Q_t = f/\Delta f \). The relationship between effective total and internal quality loss factor for different Fermi level is shown in figure 3(c). Figure 3(d) shows the values of resonant frequency of dips and peak for different Fermi level. From the figures, we can see that as an increase of Fermi level, the imaginary and real parts of effective refractive index would decrease. The internal loss quality factor also increases with the increase of Fermi level, but the total quality factor shows a different trend. The quality factor at resonant dip of lower frequency will decrease with the increase of Fermi level, and the quality factor at resonant dip of higher frequency will increase with the increase of Fermi level.

3. Simulation and discussions

As mentioned above, we can use the CMT \([38, 39]\) to analyze the simulation data of this structure. The two dips at the resonant window can be regarded as two coupled cavities (\( S_1 \) and \( S_2 \)). We can assume that the electric field of excited plasmonic wave in this structure has a harmonic time dependence: \( E(r, t) = E(\tau) e^{-i\omega t} \). If we respectively express \( s_1 \) and \( s_2 \) as the complex amplitudes of the optical modes (\( S_1 \) and \( S_2 \)). Therefore, the mode analysis of the two optical equivalent cavities can be described by the following formula:

\[
\left( \begin{array}{cc} \gamma_1 & -i\mu_{12} \\ -i\mu_{21} & \gamma_2 \end{array} \right) \left( \begin{array}{c} s_1 \\ s_2 \end{array} \right) = \left( \begin{array}{cc} -\gamma_1^{1/2} & 0 \\ 0 & -\gamma_2^{1/2} \end{array} \right) \left( \begin{array}{c} s_{1\text{in}}^{\text{in}} + s_{1\text{out}}^{\text{out}} \\ s_{2\text{in}}^{\text{in}} + s_{2\text{out}}^{\text{out}} \end{array} \right). \tag{4}
\]

Here, \( \gamma_n = i(\omega - \omega_n) - \gamma_0 n \) and \( \gamma_0 = \gamma_0 n \) (\( n = 1, 2 \)) representing the two optical modes, \( \omega \) is the angular frequency of incident source, \( \omega_n \) is the resonant angle frequency of the \( n \)th optical mode, \( s_n \) represents the incident or outgoing wave of \( n \)th mode (where, the superscript \( \text{in} \) represents the incident wave, \( \text{out} \) represents the outgoing wave, the subscript \( + \) represents the positive propagating wave, and \( - \) represents the negative propagating wave, respectively). Moreover, \( \gamma_0 = \omega_n/(2Q_{\text{out}}) \) is the external loss and \( \gamma_0 = \omega_n/(2Q_{\text{in}}) \) is the
(a) and (b) The transmission and reflection performance of this tunable optical plasmonic dual-functional slow light reflector. The red dot line shows the CMT calculation data. The blue solid line shows the FDTD simulation value. The Fermi levels are 0.6, 0.7, 0.8, 0.9 and 1.0 (eV), respectively.

\[ Q_{o} = 1/Q_{tn} + 1/Q_{in} \]

\[ \mu_{12} (\mu_{21}) \] is the coupling coefficient between the two modes. Moreover, the incident and outgoing waves in the two optical modes also should meet the following relationship according to the conservation of energy:

\[ S_{in}^2 + S_{out}^1 = S_{out}^2 + S_{in}^1 e^{i\varphi} \]

\[ S_{in}^1 - S_{out}^2 = S_{out}^1 - S_{in}^2 e^{i\varphi} (n = 1, 2) \]

Here, \( \varphi \) is phase change between the two optical plasmonic modes. Combining the equations (2)–(4) and assuming that the excitation source only incident from the positive direction (i.e., \( S_{in}^2 = 0 \)), we can receive the transmission (reflection) coefficient about this system:

\[ t = \frac{S_{out}^2}{S_{in}^1} = e^{i\varphi} + \left( \gamma_{1} \gamma_{2} e^{i\varphi} + \gamma_{1} \gamma_{2} e^{i\varphi} + (\gamma_{1} \gamma_{2})^{1/2} e^{i\varphi} \chi_1 + (\gamma_{1} \gamma_{2})^{1/2} \chi_2 \right) (\gamma_{1} \gamma_{2} - \chi_1 \chi_2)^{-1} \]

\[ r = \frac{S_{out}^1}{S_{in}^1} = e^{i\varphi} + \left( \gamma_{1} \gamma_{2} e^{i\varphi} + (\gamma_{1} \gamma_{2})^{1/2} \chi_1 e^{i\varphi} + (\gamma_{1} \gamma_{2})^{1/2} \chi_2 e^{i\varphi} \right) (\gamma_{1} \gamma_{2} - \chi_1 \chi_2)^{-1} \]

From figure 4, we can see that the resonant frequency has a blue shift as an increase of Fermi level of graphene monolayer, which can be attributed to the demand higher energy caused by the increase of Fermi
level. Moreover, with the increase of the Fermi level of graphene, the reflection efficiency increases to 98%, which provides an excellent basis for the device as an optical tunable reflector.

Due to the dispersion properties of the gold and graphene, this structure can also be used as a slow light device. According to the transmission coefficient obtained from the CMT in this system, the theoretical phase change can be obtained: $\theta = \text{arg}(t)$. According to this complex phase, we can obtain the group refractive index [40–42]:

$$n_g = \frac{c}{\rho} \frac{dk}{d\omega} - \frac{c}{H} \frac{d\theta}{d\omega},$$

where $c$ is the light speed in vacuum, $H$ is the thickness of the whole device (0.2 $\mu$m), and $\theta$ is the phase.

From figure 5, we can see the evolution between group refractive index and phase against frequency at different Fermi level. We can see that the group refractive index and phase change dramatically at the resonant window due to the dispersion of plasmonic wave. Moreover, it can be seen from the figure that the peak value of group refractive index will increase with the increase of Fermi level, and the frequency position will also have blue shift.

4. Conclusion

In conclusion, we have constructed a novel graphene hybrid gold terahertz structure, and the proposed structure can achieve a good optical reflection effect and slow light effect. The structure of this device can realize a plasmonic resonant window, and we can dynamically control this plasmonic resonant window by applying a voltage. The special structure of this device makes it easier to adjust the Fermi level of graphene monolayer, and it can achieve a good effect for selecting reflection band. Through the derivation and analysis of the optical equivalent-cavity CMT, the theoretical fitting transmission and reflection of this device can be obtained, and they are in good agreement with the numerical results. The consistency of theoretical fitting and numerical simulation can verify that this optical equivalent-cavity CMT can analyze this system very well. Through the transmission coefficient, we can get the phase change of this device, and then we can get the effective group index. It is found that this device has an excellent slow light performance. The maximum group index can reach to 245, and it is better than many general slow light devices. This research is expected to provide a theoretical basis for the realization of tunable high-performance slow light reflectors.
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