Dual-frequency on–off modulation and slow light analysis based on dual plasmon-induced transparency in terahertz patterned graphene metamaterial

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Abstract

A dual-frequency on–off modulator with considerable modulation depth (MD) and relatively low insertion loss (IL) is performed with patterned monolayer graphene metamaterial. Destructive interference in this structure gives rise to the dual plasmon-induced transparency (DPIT) phenomenon. The coupled mode theory, confirmed by simulated values, is comprehensively introduced to expound the physical mechanism of the DPIT effect. In addition, the influences of the Fermi level on the DPIT transmission spectrum and the carrier mobility of graphene on the on–off modulation are researched. It is found that the dual-frequency on–off modulator exhibits remarkable modulation performance on both switches and is easier to fabricate in operation than other multi-layer graphene-based modulators. In the ‘on1/off1’ state, the MD and IL are 93%, 0.32 dB, respectively. In the ‘on2/off2’ state, the MD and IL are 85%, 0.25 dB, separately. Moreover, the property of slow light reflected by the group index is analyzed. It exhibits that the group index of the proposed structure with multi-channel can reach 358. Thus, the proposed structure stretches the versatile applications in multi-function modulators and multi-channel slow light devices at the terahertz band.

1. Introduction

Graphene, a novel and tunable two-dimensional (2D) material [1], has sparked increased attention of researchers due to its impressive performance in mobility [2], thermal conductivity [3], and optical transparency [4]. Further research shows that graphene can cause strong interaction with terahertz wave owing to its intraband transitions, and has myriad applications in detecting and imaging [5, 6]. The surface conductivity of graphene can be actively modulated over a broad range through chemical or electrostatic doping. Thus, graphene becomes the most promising candidate in the fields of electronics and photonics. Besides, graphene with metallic response can support the propagation of surface plasmons and enhance light-graphene interaction. Compared to conventional materials plasmons, graphene plasmons own some desirable properties in the mid-infrared and terahertz band, such as more flexible turnability, much stronger locality, and relatively lower propagation losses. Recently, various groups have conducted extensive research on graphene plasmonics, from theoretical analysis to experimental operation [7, 8]. Thus, many practical applications have been triggered, such as optical filtering [9], sensing [10], modulation [11–14], and other interesting phenomena, such as Fano resonance [15, 16] and plasmon induced transparency [17].

Plasmon-induced transparency (PIT), as an analog of electromagnetically induced transparency (EIT), is a transparent effect caused by the destructive interference between radiation modes in a unit cell of metamaterial [18, 19]. In general, the PIT effect can slow down the propagation velocity of photons and has broad applications around the domain of slow light [20, 21]. Besides, the transmission spectrum of PIT has
a well-defined transparency window, in which it offers an approach to obtain a modulator with desirable modulation performance. In 2015, Bai et al achieved the MD of 63% based on high-resistivity silicon and gold resonators by utilizing the PIT effect [22]. In 2018, Wang et al achieved a liquid crystal (LC) modulator with PIT metamaterial, which had the MD of more than 90% and the IL of less than 0.5 dB [23]. In 2020, Zhang et al designed a multilayer graphene metamaterial with the MD of 83.3% and the IL of 7.2% [24]. However, the limited MD and notable IL make them difficult to realize high-performance modulators.

In this paper, a terahertz dual-frequency on–off modulator with high-performance based on monolayer graphene metamaterial is proposed. The unit cell of the graphene pattern includes a continuous graphene wire acted as a dark radiation mode, and a cross-shaped graphene array worked as two bright radiation modes. The destructive interference between three radiation modes can cause an obvious DPIT effect. Remarkably, the DPIT effect, with two transparent channels, is different from the single-peak PIT effect and is suitable for practical applications. The coupled mode theory (CMT) is introduced to expound the physical mechanism of the three radiation modes and calculate the theoretical transmittance of the DPIT effect. The theoretical values are keeping abreast of the simulated values derived from the finite difference time domain (FDTD) method. The proposed dual-frequency on–off modulator possesses some distinguished properties. Firstly, compared to most metal waveguide structures [25, 26], our structure is more convenient to modulate the Fermi level of graphene by changing the gate voltage instead of modifying the physical structure. Secondly, different from multilayer graphene structures, our structure is very simple and easy to fabricate in operation. Importantly, the on–off modulator possesses dual-frequency modulation, and both switches exhibit remarkable modulation performance on MD and IL. Moreover, the performance of slow light with multi-channel in this system can reach 358, which is superior to other slow-light devices [27, 28]. Thus, the proposed structure will diversify the designs for dual-frequency on–off modulators and multi-channel slow light devices.

2. Structural design and theoretical analysis

The geometric structure diagram of the graphene metamaterial with dual-frequency on-off modulation and slow light application is shown in figure 1(a). The unit cell of the proposed structure composes of a continuous graphene wire, and a graphene ribbon with a pair of same size graphene chips distributed on the left and right sides symmetrically. The thickness of the doped silicon (Si) is 0.19 μm, in which a monolayer graphene pattern is sandwiched into 0.15 μm and separated from the substrate by a 10 nm-thick SiO₂ layer. The red arrow, as an excitation source, indicates the incident plane wave propagating along the negative y-direction. Besides, a metal electrode is mounted between the metal pad and the graphene layer to modulate the Fermi level and the carrier concentration of the entire graphene. In the simulations, the effective area is divided into Ye cells, and the mesh step is uniformly set to 0.1 μm [29]. The periodic boundary conditions are chosen in the x and z directions, and perfectly matched layers are applied in y directions.

The top view of the proposed unit cell structure is presented in figure 1(b). For clarity of description, the continuous graphene wire is named CW, and the other three graphene ribbons are labeled SRRL, SRRM, and SRRR from left to right. In this unit cell, the SRRL, SRRR, and SRRM act as two bright radiation modes, which are strongly coupled with the incident polarization plane wave. By contrast, as a dark radiation mode, the CW barely couples with incident polarization plane wave, but can be indirectly excited by the SRRL, SRRR, and SRRM.

In this simulation, graphene is modeled as a two-dimensional surface conductivity layer without thickness [30, 31]. The complex surface conductivity of monolayer graphene includes intraband and interband transitions processes based on the Kubo formula as below [32, 33]:

\[
\sigma(\omega, E_F, \tau, T) = \sigma^{\text{intra}} + \sigma^{\text{inter}} = \frac{2e^2k_B T}{\pi\hbar^2} \frac{i}{\omega + i\tau^{-1}} \ln \left[ 2 \cosh \left( \frac{E_F}{2k_B T} \right) \right],
\]

\[
+ \frac{e^2}{4\hbar^2} \left[ \frac{1}{2} + \frac{1}{\pi} \arctan \left( \frac{\hbar \omega - 2E_F}{2k_B T} \right) - \frac{i}{2\pi} \ln \frac{(\hbar \omega + 2E_F)^2}{(\hbar \omega - 2E_F)^2 + 4(k_B T)^2} \right],
\]

(1)

where, \(\sigma^{\text{intra}}\) is the intraband transitions, \(\sigma^{\text{inter}}\) is interband transitions. \(e, k_B, \hbar, \omega, E_F, \tau, T\) and \(T\) are the electron charge, the Boltzmann’s constant, the Planck’s constant, the photon angular frequency, the Fermi level of graphene, the carrier relaxation time, and the room temperature (300 K), separately. According to the Pauli exclusion principle [34], the contribution of \(\sigma^{\text{inter}}\) is negligible compared to \(\sigma^{\text{intra}}\) in the low terahertz band. The Kubo equation can be further simplified into a Drude-like model when the Fermi level
satisfies the formula of $E_F \gg (\hbar \omega, k_B T)$ [35]:

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

Where, carrier relaxation time $\tau = \mu E_F/(e\nu_F^2)$. In this work, $\nu_F$ (Fermi velocity) is fixed to $10^6$ m s$^{-1}$ $\mu$ (carrier mobility of graphene) varies from 1.0 m$^2$ Vs$^{-1}$ to 2.5 m$^2$ Vs$^{-1}$.

With the graphene pattern structure is located between the substrate Si and SiO$_2$, the Maxwell equations and electromagnetic field boundary conditions can be used to solve the dispersion relationship. The dispersion relationship can be expressed as [36]:

$$\begin{align*}
\sqrt{\beta^2 - \epsilon_{Si}\beta_0^2} + \sqrt{\beta^2 - \epsilon_{SiO_2}\beta_0^2} = \frac{i\sigma_g}{\omega \epsilon_0},
\end{align*} \quad (3)$$

Here, $\beta$ is the propagation constant; $\beta_0$ is the wave vector of the incident light; $\epsilon_0$ is the dielectric constant of vacuum; $\epsilon_{SiO_2} = 3.9$ is the relative dielectric constant of SiO$_2$, and the relative dielectric constant of Si is 11.9 [37]. Moreover, the effective refractive index can be expressed as: $n_{eff} = \beta/k_0$.

Besides, the $E_F$ of graphene can be modulated dynamically by adjusting the gate voltage $V_g$, which can be expressed as [38]:

$$E_F = \hbar \nu_F (\pi \epsilon_0 \epsilon_{SiO_2} V_g/e d_{gs})^{1/2}, \quad (4)$$

where, $d_{gs}$ is the thickness of SiO$_2$ layer.

Figure 2(a) presents the dependence of the transmittance on frequency for the DPIT effect. As a plane-polarized wave propagating along the negative direction of the $y$-axis is shone to the graphene arrays perpendicularly, a prominent DPIT effect (black curve) is observed. Wherein, the CW as a dark radiation mode can generate a narrow discrete spectrum (grey curve). The SRRL, SRRR, and SRRM as two bright radiation modes can form two broad continuum spectra (red curve, verdant curve, respectively). For thoroughly figure out the intrinsic operation mechanism of the DPIT effect caused by graphene arrays, the electric field strength distributions of dip1, dip2, and dip3 are shown in figures 2(b)–(d), respectively. As displayed in figure 2(b), the electric field strength is mainly localized at the SRRL, SRRR, and CW, indicating that the CW is indirectly excited by the SRRL and SRRR (bright radiation mode 1). Therefore,
Figure 2. (a) The simulated transmittance profile of the DPIT effect when the $E_F$ and the carrier mobility are set to 1.0 eV and 1.0 m$^2$ Vs$^{-1}$, respectively. Here, (b)–(d) denote the resonance dips of the DPIT effect, which are labeled dip1(2.59 THz), dip2(4.85 THz), dip3(6.26 THz). (b)–(d) The calculated electric field strength distributions in the x-direction of the unit cell at dip1, dip2, dip3, respectively.

Figure 3. (a) Equivalent CMT model of the bright-dark-bright radiation modes. (b) Fitting of FDTD numerical simulations and CMT theoretical calculations on transmittance vs frequency, Here, $E_F$ is set to 1.0 eV, carrier mobility is set to 1.0 m$^2$ Vs$^{-1}$. dip1 is formed by the interaction between dark radiation mode and bright radiation mode 1. In figure 2(c), the electric field strength is located on the CW, SRRL, SRRR, and the SRRM (bright radiation mode 2), which shows that the resonance of three radiation modes will generate dip2. During the formation of dip1 and dip2, the CW is excited, and the degree of excitation is quite weak. Figure 2(d) shows that the electric field strength is distributed throughout the element at 6.26 THz, implying that the resonance of the bright-dark-bright radiation modes will produce dip3. Thus, the destructive interference between the two bright and one dark radiation modes can generate a significant DPIT curve.

Next, CMT is used for theoretical mechanism research in the proposed structure of bright-dark-bright radiation modes [39, 40]. As shown in figure 3(a), the elements $A_1$, $A_2$, and $A_3$ denote three resonators (bright, dark, and bright radiation modes, separately), where the superscripts ‘in’ and ‘out’ separately indicate the inflow and outflow radiation waves, the subscripts ‘+’ and ‘−’ respectively imply the propagation direction of the radiation waves. $\gamma_{in}$ and $\gamma_{on}$ ($n = 1, 2, 3$) are the inherent loss coefficient and external loss coefficient of the nth mode. $\mu_{nm}$ ($m = 1, 2, 3, m \neq n$) is the mutual coupling coefficient among the three radiation modes.
In order to explore the influence of the calculations, and the black line indicates the simulated values. It is found that the simulated values fit well with the theoretical values, laying a solid foundation for subsequent analysis. As illustrated in figure 4(b), as the $E_F$ increases from 0.6 eV to 1.2 eV at an interval of 0.2, the DPIT curves reveal a blue-shift trend. Moreover, the evolution of transmittance vs. frequency at different Fermi levels by theoretical calculations are shown in figure 4(c). The increasing $E_F$ leads to a blue-shift of the DPIT curves, which coincides with figure 4(b).

3. Results and discussion

In order to explore the influence of $E_F$ on the DPIT phenomenon, we obtain its theoretical transmittance by CMT, and its simulated transmittance through FDTD. The transmittance spectra of the fitting between FDTD and CMT vs. frequency are shown in figure 4(a). The red circles represent the theoretical calculations, and the black line indicates the simulated values. It is found that the simulated values fit well with the theoretical values, laying a solid foundation for subsequent analysis. As illustrated in figure 4(b), as the $E_F$ increases from 0.6 eV to 1.2 eV at an interval of 0.2, the DPIT curves reveal a blue-shift trend. Moreover, the evolution of transmittance vs. frequency at different Fermi levels by theoretical calculations are shown in figure 4(c). The increasing $E_F$ leads to a blue-shift of the DPIT curves, which coincides with figure 4(b).
Figure 4. (a) Transmittance spectra vs frequency obtained by CMT calculations and FDTD simulations at different Fermi levels. (b) The dependence of $E_F$ on the frequency of the center of the dips and peaks. (c) Evolution of transmittance vs frequency at different Fermi levels.

Figure 5. The dual-frequency on–off modulation of the transmittance spectra when the $E_F$ is respectively set to 0.6 eV (dark dots) and 0.8 eV (red dots). Here the carrier mobility is 1.0 m$^2$/Vs$^{-1}$.

It is worth noting that the on-off modulation based on the DPIT effect can be achieved at frequencies of 2.32 THz, 3.81 THz, 4.41 THz, and 5.01 THz, as illustrated in figure 5. As we all know, one critical factor for the modulator is the MD: $MD = \frac{|T_{top} - T_{dip}|}{T_{top}} \times 100\%$. The other is $IL$, which is the optical loss when the light intensity is maximized: $IL = -10\log(T_{top})$. In the simulations, $T_{top}$ is the maximum transmittance, and $T_{dip}$ is the minimum transmittance.

Through the above analysis, it is found that the requirement of high-performance modulation cannot be met due to the limited MD and notable IL at the frequencies of 2.32 THz and 3.81 THz. However, at 4.41 THz, a high transmittance corresponding to the transmission peak represents the ‘on’ state, and a low transmittance corresponding to the transmission dip denotes the ‘off’ state. The MD is calculated to be about 79%, and the IL is 0.7 dB. Similarly, we can obtain the ‘on’ state and the ‘off’ state at 5.01 THz. The MD is computed to be about 62%, and the IL is 0.5 dB. Thus, a high-performance on–off modulator is achieved with two different frequencies.
Furthermore, the impact of carrier mobility on the proposed modulator is discussed when the $E_F$ is fixed at 0.6 eV and 0.8 eV. As shown in figure 6(a), with the increases of the carrier mobility, the range of modulation frequency appears a red-shift slightly. It is shown that the modulator is insensitive to carrier mobility. Moreover, the 3 dB bandwidth of DPIT becomes narrower, leading the expected MD and IL. In figure 6(b), as the carrier mobility increases, the MDs of the 'on$_1$/off$_1$' state and 'on$_2$/off$_2$' state show upward trends. When the carrier mobility increases to 2.5 m$^2$/Vs$^{-1}$, the MDs of 'on$_1$/off$_1$' state and 'on$_2$/off$_2$' state can reach 93% and 85%, separately. While in figure 6(c), it is observed that the ILs in the 'on$_1$/off$_1$' state and 'on$_2$/off$_2$' state decrease as the carrier mobility increases, reaching the values of 0.32 dB and 0.25 dB, respectively. Here, to illustrate the outstanding of our modulator, some graphene-based modulators are compared, as listed in table 1. Obviously, the proposed on-off modulator has dual-frequency and high-quality modulation performance.

In addition, another vital optical property of the proposed structure is explored. Slow light has the ability to enhance light–matter interaction, which can be used in the fields of optical buffers and tunable switches [44]. The performance of the slow light effect can be directly reflected by the group index, making the study on the group index quite necessary, which is expressed as:

$$n_g = \frac{c}{\lambda} \frac{d\theta}{d\omega}.$$  

(16)

Here, $c$ indicates the speed of light in vacuum. $\lambda = 0.2$ μm represents the thickness of the Si. $\theta$ is the phase of transmission. The phase shift can be calculated from the transmittance supplied by equation (11).

**Table 1.** Comparisons between graphene-based modulators.

| Reference/year | Material structure                  | Modulation type | Modulation depth | Insertion loss | Modulation band |
|---------------|-----------------------------------|-----------------|-----------------|----------------|-----------------|
| [41]/2016     | Hybrid graphene/metal stacked      | Single-frequency| 90%             | Less than 0.5 dB| Terahertz       |
| [42]/2017     | Graphene split-ring resonator      | Single-frequency| 98.9%           | 0.83 dB        | Terahertz       |
| [24]/2020     | Multi-layer patterned graphene    | Single-frequency| 83.3%           | 7.2%           | Terahertz       |
| [43]/2019     | Double-layer graphene             | Single-frequency| 21.3 dB         | 0.1 dB         | Mid-infrared    |
| This work     | Single-layer patterned graphene   | Dual-frequency  | 'on$_1$/off$_1$' state 93% | 'on$_1$/off$_1$' state 0.32 dB | Terahertz       |
|               |                                   |                 | 'on$_2$/off$_2$' state 85% | 'on$_2$/off$_2$' state 0.25 dB | Terahertz       |

Figure 6. (a) The active dual-frequency on-off modulation of the transmittance spectra as the carrier mobility changes from 1.0 m$^2$/Vs$^{-1}$ to 2.5 m$^2$/Vs$^{-1}$, (b) Dependence of the MD on carrier mobility in the 'on$_1$/off$_1$' state and 'on$_2$/off$_2$' state, (c) Dependence of the IL on carrier mobility in the 'on$_1$/off$_1$' state and 'on$_2$/off$_2$' state.
The changes in the group index and phase shift of monolayer graphene with frequency at different Fermi levels are displayed in figures 7(a)–(d). It is obviously noticed that the phase shift drops sharply at three resonance frequencies, leading to the alter of the group index. The group index reaches a maximum of 358 when $E_F$ is set to 1.2 eV, showing terrific applications in slow light devices.

4. Conclusion

In summary, we numerically and theoretically study the DPIT transmittance of the bright-dark-bright radiation modes in the terahertz field. The simulated values are fit well with theoretical values. The impact of the $E_F$ on the DPIT effect is scientifically analyzed. Remarkably, the proposed structure can realize a dual-frequency on–off modulator by utilizing the DPIT effect. Research shows that the structure displays a remarkable modulation performance on both switches by actively controlling the carrier mobility of graphene. In the ‘on1/off1’ state, the MD and IL are 93%, 0.32 dB, respectively. In the ‘on2/off2’ state, the MD and IL are 85%, 0.25 dB, separately. Furthermore, the performance of slow light in this structure, directly reflected by the group index, is analyzed at different Fermi levels. The results show that the group index with multi-channel can reach 358. The proposed structure may open up new avenues for terahertz modulation and sensing technology, and lay a solid foundation for the research of graphene metamaterials.

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Conflict of interest

The authors declare that they have no competing interests.

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