Switching between positive and negative group delay of the optical pulse reflection from layer structures with a Graphene sheet

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In this paper, we investigate the propagation of the light pulse reflected from the layer system with a graphene layer. We show a tunable transition between positive and negative group delay of the optical pulse reflection in such a layered system controlled by the properties of the graphene layer, and reveal two mechanisms to control the propagation properties of the light reflected from such systems. It is demonstrated that the reflected group delays are greatly tunable from positive and negative values in both mechanisms of resonances and the excitations of the surface plasmon resonances, which are adjusted by tuning the Fermi energy and temperature of the graphene layer. Our results are helpful to control the pulse propagations and are useful for design of graphene-based optical devices.

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I. INTRODUCTION

Controlling the group delay (or group velocity) of a light pulse has been extensively studied in both theories and experiments for many years [1–4]. When group velocity is much smaller than the speed of light c in vacuum, it often refers to slow light with a large value of group delay. The large positive group delay has potential applications in realizing optical delay lines [5] and a high-efficiency memory for optical pulses [5]. The approaches for realizing this delay have been widely investigated in various circumstances, such as ensembles of warm atoms (i.e. Rb and Cs) in vapor cells [5], photonic crystal waveguides [5], and multiple quantum wells [6]. Meanwhile, when group velocity is possible to be much larger than c or even becomes negative, it may be called as fast light with a very small or negative group delay. It should be emphasized that this group delay do not violate causality or special relativity because group velocity is not regarded as a signal velocity [2]. It has been observed in different systems including left-handed media [10], the samples of GaP:N [11], quantum wells [12], double-Lorentzian fiber grating [13], weakly absorbing slabs [14], atomic media [15], and ruby [16]. Furthermore, in some system or media, such as fibers [17, 18], semiconducting waveguides [19, 20], nonlinear wave-mixing processes [21], solids at room temperature [22, 23], and gain slabs [24], the two types of group delay can be demonstrated simultaneously. Recently, with the emergence of new materials, controlling the group delay in other structures and media are receiving more and more attention.

Graphene, a one-atom-thick allotrope of carbon, is focused extensively in materials science and condensed-matter physics [25, 26]. It has linear dispersion relation of electronic states characterized by conical and valence bands joined together at Fermi level (the so called Dirac point), and the Fermi level can be controlled by application of external or magnetic fields [27–33]. Due to the tunability, graphene shows many potential applications in graphene-based nano-electronic and optoelectronic devices [27, 34]. Several research papers have been focused on the manipulation of the light propagation in the system with graphene by controlling the conductivity of graphene. In 2015, Hao et al. revealed that graphene exhibits much stronger slow light capability than other materials [35], and a large delay-bandwidth product has been obtained in graphene-based waveguide. Meanwhile, Lu et al. designed a kind of plasmonic structure consisting of a monolayer graphene to slow down and trap the light in the mid-infrared region [36]. Shi et al. found that the plasmonic modes in the graphene nanostructure can be confined to a special size that is hundreds of times smaller than their corresponding wavelength in vacuum [37]. Li et al. investigated the graphene ribbon waveguide and achieved an outstanding plasmonically induced transparency window with a group time up to 0.28ps [38]. On the other hand, in 2014 [39], Jiang et al. investigated the negative group delay of the TE-polarized beam reflected from a Fabry-Perot cavity with the insertion of the graphene. Next year, they found that a fast pulse reflection can take place from the graphene covered lossless dielectric slab [40]. It is possible to realize the large positive and negative group delay in the same structure with the help of the graphene layer. In addition, the Otto configuration combined with graphene have been investigated, and the transverse magnetic surface plasmons [41], perfect terahertz absorption [42], and surface modes of transverse electric polarization [43, 44] have been proved and studied in succession in such a configuration.

Motivated by these studies, we have theoretically considered the light reflected from the layer configuration.
that incorporates graphene. Two mechanisms that realize the group delay of the reflected pulse to be control from positive to negative values, or vise versa, are demonstrated. The first is related to resonances occurred when the incident angle is smaller than the total internal reflection angle. The second one is related to the excitation of surface plasmon happened when the incident angle is larger than the total internal reflection angle. Both of cases lead to a distinct variation of the group delays of the reflected light pulse, and it can be controlled by adjusting the Fermi energy and the temperature of the graphene sheet. Moreover, the structural parameters such as the position of the graphene layer and angle of incidence can also provide an effective method to control the reflected light pulse. Our results may have potential application in graphene-based optical technologies and information processing.

II. MODEL AND CALCULATION

Let a light pulse with a carrier frequency $\omega$ inside the dielectric medium $\varepsilon_1$ be incident on the slab system containing a graphene layer. As shown in Fig. 1(a), the graphene layer is placed inside the dielectric medium $\varepsilon_2$ with a distance $d$ to the interface between dielectric media $\varepsilon_1$ and $\varepsilon_2$, and $\theta$ is the incident angle of light. Here it should be emphasized that since $\varepsilon_1 > \varepsilon_2$, when the total internal reflection occurs, in this sense, the structure can be seen as Otto configuration similar to that in Ref. [46]. The surface conductivity $\sigma$ of graphene is usually given by Kubo formula. In the low temperature limit $k_B T \ll E_F$ and the zero collision rate ($\tau^{-1} = 0$), the surface conductivity can be expressed as:

$$\sigma = \sigma_{\text{Intra}} + \sigma_{\text{Inter}},$$

where $\sigma_{\text{Intra}} = \frac{2e^2}{\hbar} k_B T \ln \left( \cosh \frac{2E_F}{k_B T} \right)$ is the intraband electron transition contribution, and $\sigma_{\text{Inter}} = \sigma_0 + \sigma_2 \arctan \left( \frac{\omega - 2E_F}{\hbar k_B T} \right) - \frac{\sigma_2}{2} \ln \left( \frac{\hbar \omega + 2E_F}{\hbar \omega - 2E_F} \right)$ is the interband electron transition contribution. Here $\sigma_0 = \frac{e^2}{\hbar}$, $\varepsilon$ is the permittivity of medium 1, and $\sigma_2$ is the permittivity of medium 2 (air or vacuum). In addition, it requires $\varepsilon_1 > \varepsilon_2$, so the total internal reflection can occur when the angle of incidence is larger than the critical angle. $\theta$ and $d$ denote the incident angle and gap between the medium 1 and graphene, respectively, and $\sigma$ represents the conductivity of graphene. The effects of (b) the Fermi energy $E_F$ and (c) temperature $T$ on the optical conductivities of the graphene sheet, with $T = 300K$ and $E_F = 0.2eV$, respectively.

FIG. 1. (color online) (a) Schematic diagram of the layered-structure with graphene. Here $\varepsilon_1$ is the permittivity of medium 1, and $\varepsilon_2$ is the permittivity of medium 2 (air or vacuum). On the other hand, it can be seen as a thin layer with effective dielectric constant $47 \, 48$. For our purposes, using one of these methods is only for theoretical convenience and the same results are expected by another method. Here we treat graphene as a zero-thickness layer. According to the Maxwell’s equation and the boundary conditions,
the reflection coefficient \( r \) for TM-polarization is given by

\[
r = \frac{r_{12} + r_\sigma e^{i2kz_1d}}{1 + r_{12}r_\sigma e^{i2kz_1d}},
\]

where \( r_{12} = \frac{\varepsilon_2k_{12} - \varepsilon_1k_{2}}{\varepsilon_2k_{12} + \varepsilon_1k_{2}} \) is Fresnel reflection coefficient between \( \varepsilon_1 \) and \( \varepsilon_2 \), \( r_\sigma = \frac{\varepsilon_2k_{12} - \varepsilon_1k_{2}}{\varepsilon_2k_{12} + \varepsilon_1k_{2}} \) is the Fresnel reflection coefficient for the interface of a graphene layer inside \( \varepsilon_2 \), \( \varepsilon_0 \) is the permittivity of vacuum, and \( k_{jz} = (k_0^2\varepsilon_j - k_0^2) \) \( j = 1, 2 \) is the \( z \) component of the wave vector inside the \( j \)th medium with \( k_j = k_0\sqrt{\varepsilon_j} \sin \theta \) and \( k_0 = \frac{\omega}{c} \). For the narrow-spectrum incident pulse, i.e., \( \Delta \omega \ll \omega \) (\( \Delta \omega \) is the spectrum width), the group delay of the reflected pulse can be calculated by (40)

\[
\tau_r = \frac{d\phi_r(\omega)}{d\omega},
\]

where \( \phi_r \) is the phase of the reflection coefficient. In our calculation, without loss of generality, we assume \( \varepsilon_1 = 2.25 \) and \( \varepsilon_2 = 1 \) for vacuum (or air). This means that the Brewster angle \( \theta_B \) of the system is \( \theta_B = 33.69^\circ \), and the critical angle \( \theta_c \) of total reflection is \( \theta_c = 41.8^\circ \).

III. NUMERICAL RESULTS AND DISCUSSIONS

First we consider the case of normal incidence, and the results presented here can be extended to the angles of incidence \( \theta < \theta_c \). In Fig. 2, we show the typical properties of light pulse reflected from the layered system containing a graphene layer for different values of \( d \) (\( d = 30 \mu m, 40 \mu m \) and \( 90 \mu m \)) in the case of normal incidence. It is clear that the reflection dips in Fig. 2(a) are observed as a result of the structural resonance. For convenience, we use \( \omega_{R,j} \) to denote the resonant frequencies with \( j = 1, 2, 3 \cdots \). In Fig. 2(b), we compare the magnitudes of Fresnel reflection coefficients \( |r_{12}| \) and \( |r_\sigma| \). In our calculation, \( |r_{12}| = 0.2 \) for normal incidence, whereas \( |r_\sigma| \) decreases with the increase of frequency. Thus there is a critical frequency \( \omega_c \) which makes \( |r_{12}(\omega_c)| = |r_\sigma(\omega_c)| \), see Fig. 2(b). From Fig. 2, when \( |r_{12}(\omega_{R,j})| > |r_\sigma(\omega_{R,j})| \), the changes of phase with frequency for these resonances are abnormally dispersive and the corresponding group delays are negative. When \( |r_{12}(\omega_{R,j})| < |r_\sigma(\omega_{R,j})| \), the situation is totally reversed. For examples, in the case of \( d = 30 \mu m \), all resonances are in the region of \( |r_{12}(\omega_{R,j})| > |r_\sigma(\omega_{R,j})| \), therefore the group delays of the reflected light pulse are negative near resonances. In the case of \( d = 40 \mu m \), one of resonances moves to the region of \( |r_{12}| < |r_\sigma| \), thus the corresponding group delay becomes positive. As \( d \) increases, there are more numbers of resonances moving into the region of \( |r_{12}| < |r_\sigma| \); for instance, there are two resonances satisfying this condition in the plots for \( d = 90 \mu m \). For a fixed graphene-based layered structure, \( \varepsilon_1, \varepsilon_2 \) and \( d \) are usually fixed and cannot be changed. However, it is expected that we can change \( r_\sigma \) by controlling the Fermi energy and temperature, thus the propagation of light reflection is automatically manipulated.

From the above discussion on Fig. 2, it is observed that the critical frequency \( \omega_c \) at which the condition of \( |r_{12}(\omega_c)| = |r_\sigma(\omega_c)| \) holds is very important for implementing the transition of phases and group delays near the corresponding resonances. Since \( r_{12} \) is a constant, one can change \( r_\sigma \) by adjusting the Fermi energy and temperature. In Fig. 3(a), we show that an increase in the value of \( E_F \) greatly shifts the curve for \( |r_\sigma| \) to the higher-frequency region. Thus the value of \( \omega_c \) in the system increases linearly with \( E_F \), see the inset in Fig 3(a). Therefore, the reflected group delays near the frequencies of resonances change their signs as \( E_F \) increases in Fig.
FIG. 3. (color online) Effects of the Fermi energy \( E_F \) on (a) \(|r_\sigma|\) and (b) group delays \( \tau_r \). Inset in (a) shows the dependence of the critical frequency \( \omega_c \) on the value of \( E_F \). Insets in (b) show the detail dependence of \( \tau_r \) on \( E_F \) at frequencies \( \omega/2\pi = 2.60 \text{THz}, 5.92 \text{THz}, 9.25 \text{THz}, \) and 12.60THz near each resonance, indicated by the vertical dash lines from left to right. The other parameters are \( \theta = 0^\circ \), \( d = 45 \mu \text{m} \), and \( T = 300 \text{K} \).

3(b), and the light pulses at different carrier frequencies can be manipulated from negative to positive group delay reflection by simply adjusting the value \( E_F \), see the inset in Fig. 3(b).

The effect of temperature on light reflection in such systems is very subtle because temperature only controls the transition part of conductivity \( \sigma \) near the \( 2E_F \). From Fig. 1(c), it is seen that changing temperature has more distinct effect on the real part of \( \sigma \), which represents the absorption of the graphene layer. Of course, there are significant changes in the imaginary part of \( \sigma \) near the frequencies close to \( 2E_F \). In Fig. 4, we show the effect of the temperature \( T \) on the light reflection in this system. Similar to the case of Fig. 3, the curve of \( r_\sigma \) is shifted by changing \( T \), but the critical value of \( \omega_c \) is not linear with \( T \). The dependence of the reflected group delays on \( T \) is very sensitive when the resonance of the system happens around the frequency satisfying the equation \( |r_{12}(\omega_c)| = |r_\sigma(\omega_c)| \), see Fig. 4(b). Another interesting feature is that, at the extremely low temperature, the group delay of the reflected light pulse shows the sharp change near \( 2E_F \).

FIG. 4. (color online) Effects of temperature \( T \) on the values of (a) \(|r_\sigma|\) and (b) \( \tau_r \). Here we take \( T = 100 \text{K}, 800 \text{K}, 1200 \text{K}, \) and 1500K as examples. Inset in (a) shows the dependence of the critical frequency \( \omega_c \) on temperatures \( T \). Inset in (b) displays the behavior of the group delay as a function of \( T \) at frequency \( \omega/2\pi = 5.94 \text{THz} \), which is denoted by the vertical dash line in (b). Other parameters are \( \theta = 0^\circ \), \( d = 45 \mu \text{m} \), and \( E_F = 0.34 \text{eV} \).

FIG. 5. The critical frequency \( \omega_c \) as a function of the incident angle \( \theta \) for the case of \( E_F = 0.2 \text{eV} \) and \( T = 300 \text{K} \). Inset shows the detail near the Brewster angle \( \theta_B \).

Now we extend the above results into the cases of inclined incidence. When the angle of incidence is \( \theta < \theta_c \), the above results can be readily obtained even for the cases of inclined incidence. Based on the above condi-
tion $|r_{12}(\omega_c)| = |r_\sigma(\omega_c)|$, we illustrate the dependence of the critical frequency $\omega_c$ on incident angle in Fig. 5. From Fig. 5, we see that the critical frequency $\omega_c$ increases before the Brewster angle $\theta_B$. Near $\theta_B$ there are two values of $\omega_c$ satisfying the above condition. This is not surprising since $r_\sigma$ is not a monotonic function of frequency. For certain angles, there are two regions satisfying $|r_{12}| < |r_\sigma|$. For example, as illustrated in Fig. 5, there may be only one point of intersection between $|r_{12}|$ and $|r_\sigma|$ for angles $\theta \in [0, 33.413^\circ)$ and $\theta \in (33.95^\circ, \theta_c)$ or two points of such intersection for angles $\theta \in (33.413^\circ, 33.63^\circ)$ and $\theta \in (33.749^\circ, 33.95^\circ)$, and even no point of such intersection for angles between $33.63^\circ$ and $33.749^\circ$. Therefore, by choosing the interesting frequency region and adjusting the Fermi energy and temperature, we can naturally manipulate the group delays in such systems.

Lastly, we discuss the case of total internal reflection (i.e., $\theta > \theta_c$). In this situation, the layered structure may be seen as an Otto structure. It is known that the effective dielectric constant of the graphene layer can be given by $\varepsilon_\sigma = 1 + i\sigma/\omega\varepsilon_0 d_g$, where $d_g = 0.5\text{nm}$ is the thickness of graphene sheet [51]. Thus $\text{Re}[\varepsilon_\sigma] < 0$ if $\text{Im}[\sigma] > \omega\varepsilon_0 d_g$. In this sense, the graphene layer can be considered as the suitable alternative to a metal. It is well known that the surface plasmon can be excited at a metal-dielectric interface, and there is the counterintuitive dispersion effect in the Otto configuration with metals [51]. When the graphene layer displays the properties of a metal, it is expected that the light reflection in graphene-based Otto structures may also be manipulated through the excitation of surface plasmon resonances.

In Fig. 6(a), we show the typical excitation of surface plasmon resonance (SPR) in such graphene-based Otto systems. There exists an optimal angle to excite the SPR for a fixed value of thickness $d$. For example, in the case of $d = 300\mu\text{m}$, the optimal excitation of SPR is located at the angle around $63.93^\circ$ denoted by the vertical dashed line in Fig. 6(a). This optimal angle decreases along the dispersive curve of the ideal surface plasmon, see the inset of Fig. 6(a), as the value of $d$ increases. In Fig. 6(b), we show the physical properties of light reflection, its phase shift and group delay before and after the optimal angle of the SPR. It is clear that the pulse reflection suffers the transition from positive to negative group delay. Similarly, there exists an optimal thickness $d$ for a certain angle of incidence. As shown in Fig. 7(a), in the case of $\theta = 60^\circ$, the optimal thickness $d$ is around $368\mu\text{m}$. Near the excitation frequency of the SPR, it is clearly seen that the reflected group delay is tunable by adjusting the thickness $d$, see Fig. 7(b).

Furthermore, as discussed in the cases of resonance, the Fermi energy and the temperature may also significantly affect on the properties of light reflection in the cases of SPR excitations. Thus the reflected group delays are tunable by controlling the values $E_F$ and $T$. In Fig. 8(a), we show the linear relation of the SPR frequency vs the Fermi energy, and the group delays show different behaviors as $E_F$ changes. There also exists a transition value of $E_F$, which may lead to the changes of group delay from positive to negative values near the SPR frequency, see the right part of Fig. 8(a). It can be seen that the effect of $E_F$ on the SPR frequency is similar to the previously discussed resonant situations. However only one optimal $E_F$ exists when other parameters (like temperature, thickness $d$ and angle) are unchanged. There are similar effects of temperature $T$ on the SPR frequency and group delays. Of course, the effect of temperature on the SPR frequency is not linear, see Fig. 8(b).

**IV. SUMMARY**

We have presented the tunable transition effect of light pulse reflection in a layer system which contains a graphene layer. It is shown that there are two mechanisms to control the properties of light pulse reflection. When the angle of incidence is less than the critical angle of total reflection, the reflected group delay can be greatly tuned near the frequencies of resonances where the magnitudes of the Fresnel reflection coefficients satisfy certain conditions. In the case of total reflection, the optimal excitation of the SPR is the critical value to adjust the properties of pulse reflection in such Otto systems. It is demonstrated that the reflected group delays are controllable and tunable by adjusting the Fermi
FIG. 7. (color online) (a) The existence of the optimal thickness for the excitation of the SPR. (b) The behavior of the group delay $\tau_r$ as a function of thickness $d$ at frequency $\omega/2\pi = 0.5847$THz with $\theta = 60^\circ$. Other parameters are the same in Fig. 6.

FIG. 8. (color online) (Left) Dependence of the function $|r|$ on (a) the Fermi energy $E_F$ and (b) temperature $T$. (Right) The corresponding reflected group delays as functions of frequencies under different values of $E_F$ and $T$. Here $T = 300$K in (a) and $E_F = 0.2$eV in (b), and other parameters are $\theta = 60^\circ$ and $d = 350$µm.

energy and temperature of the graphene sheet. The reflected group delays can also manipulate via changing the structural parameters including the position of the graphene layer and the angle of incidence. These results are useful to understand the fundamental physics underlying graphene-based light-matter interactions, and they may have potential applications in graphene-based optical signal processing and optical sensing.

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