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Complete optical absorption in graphene by using nano-gratings to excite graphene surface plasmons

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ABSTRACT

Optical absorption enhancements of graphene by exciting graphene surface plasmon waves using nano-gratings are studied. Based on temporal coupled mode theory, we show that the electron relaxation time of graphene and the geometry of the device play crucial roles in determine the absorption rate, and complete optical absorption is possible by adjusting the geometric parameters of the device to match the electron relaxation time of graphene. Moreover, the absorption spectrums can be dynamically tuned by varying the Fermi energy of graphene. Our study could benefit the development of graphene based photonic and optoelectronic devices, such as infrared photodetectors and bolometers.

1. Introduction

Over the past decade, graphene has attracted tremendous research interest owing to its extraordinary electronic and optical properties. As a single layer of carbon atoms closely arranged in honeycomb lattice, graphene exhibits remarkably high absorption rate defined by the fine structure constant $\pi\alpha$ ($\approx$2.3%). However, such absorption rate is still insufficient in a variety of graphene based photonic and optoelectronic applications, and enhancement of the rate up to 100% is greatly desired. Recently, graphene has been found to support surface plasmons whose intense optical fields can be explored to enhance light-graphene interactions [1–4]. By patterning graphene into nano-structures to excite graphene plasmons, the absorption rate of graphene are significantly improved and even complete optical absorption is reported to be possible [5–8]. Another effective route of graphene plasmon excitations is to introduce nano scatters (nano-tips, nano-particles and nano-gratings) in the vicinity of graphene [9–15]. This approach does not require the pattering of graphene and hence preserves its high mobility. It has been demonstrated that the approach is promising to increase the absorption rate of graphene, but systematic studies of the underlying physical mechanism and the condition to achieve complete optical absorption still lack.

In this paper, we investigate optical absorption enhancements in graphene by introducing nano-gratings to excite graphene surface plasmons. We first show that the absorption rate can be well described within the temporal coupled mode theory, a simple phenomenological model which only requires two parameters to predict the resonant absorption rate. We then show that one parameter only relates to the electron relaxation time of graphene and the other parameter connects with the geometric structure of the device. Complete absorption condition is reached when the two parameters are equal. Furthermore, it is demonstrated that the absorption spectrums can be tuned by varying the Fermi energy of graphene and the grating period.

2. Device configuration and theoretical description

The device under study is shown in Fig. 1(a) and (b). The graphene is placed on the top of the substrate whose bottom is deposited with metal as a back reflector, and a dielectric layer is sandwiched between the graphene and the metal grating. The metal grating, dielectric spacer and graphene form a capacitor where the grating and graphene serves as the two electrodes. Hence, the Fermi energy of graphene can be dynamically tuned by applying a voltage between the metal grating and the graphene.

Another function of the metal grating is to excite the graphene surface plasmonic wave. Because the wavevectors between a graphene plasmonic wave and an incident TM wave are in huge mismatch, they cannot couple to each other unless to introduce the grating to compensate the mismatch. Specifically, when a TM wave with angular frequency ω vertically incidents on the grating, its nth diffraction order will gain an extra wavevector $2n\pi/l$ with n being an integer and l the grating period. Then, the nth order

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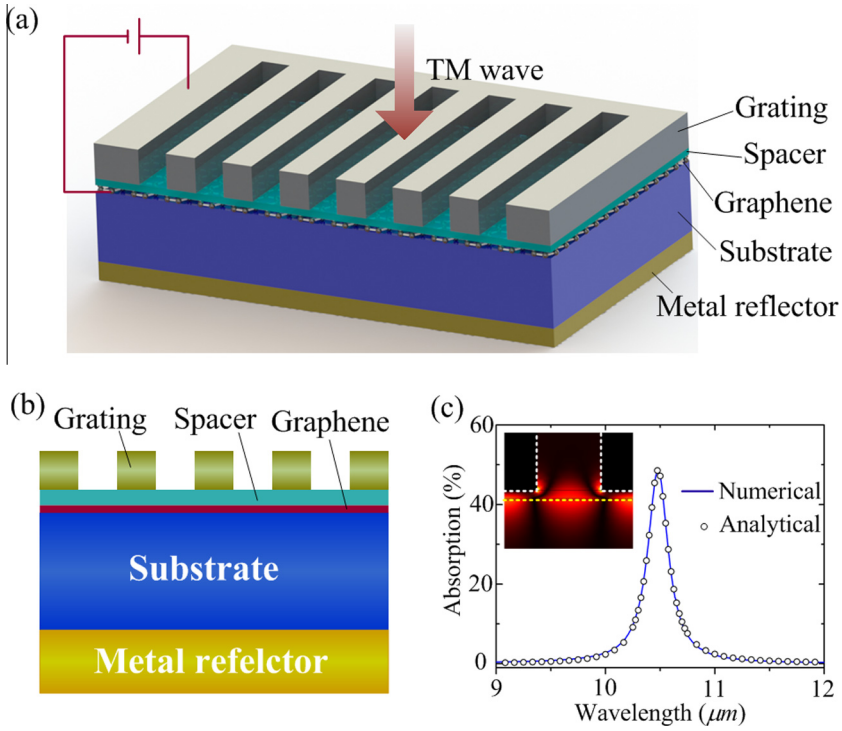

Fig. 1. Schematic of the investigated device (a) and its side view (b). The comparison between the numerical absorption spectrum and the analytical one (c). The inset in (c) is norm of the electric field of the excited graphene surface plasmon mode. The white dashed lines represent the boundaries of the grating, and the yellow dashed line is the position of the graphene. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

graphene plasmonic wave can be excited by the diffraction order provided Re $[q(\omega)] = 2n\pi/l$, where $q(\omega)$ is the dispersion relation of the plasmonic wave with q being its wavevector. Typically, the wavevector of a graphene plasmonic wave is an order higher than that of the TM wave [4], which requires the grating period l to be very small so that $2n\pi/l$ is large enough to compensate the mismatch.

The interaction between the TM wave and the device can be modeled by the temporal coupled mode theory [15], which show that the absorption rate A is given by

$$A = \frac{4\gamma_0\gamma_1}{(\omega-\omega_a)^2+(\gamma_0+\gamma_1)^2}. \quad (1)$$

Here, ω_a is the resonant frequency of the device, γ_0 is the intrinsic loss rate of the device, and γ_1 is the coupling rate of the device with the TM wave. The equation shows that at resonant frequency (i.e., $\omega = \omega_a$), complete absorption is possible (i.e., $A = 100\%$) if $\gamma_0 = \gamma_1$ is fulfilled, and this is the so called critical coupling condition. It is worth noting that the metal back reflector in Fig. 1 is critical for achieving complete absorption. If there is no such reflector, the form of Eq. (1) should be modified and the maximum absorption rate is no longer 100% but 50% [15].

In the follows, we will calculate the absorption spectrum numerically to reveal how the intrinsic loss rate γ_0 and the coupling rate γ_1 relate to the device parameters. In the numerical simulations, the intraband surface conductivity of graphene are given by the Drude model,

$$\sigma(\omega) = \frac{2e^2T}{\pi\hbar}\frac{i}{\omega+i\tau^{-1}}\log\left[2\cosh\left(\frac{E_f}{2K_BT}\right)\right]. \quad (2)$$

In Eq. (2), e is the elementary charge, $\hbar$ is the reduced Plank constant, E_f is the Fermi energy, τ is the electron relaxation time, $T = 300$ K is the temperature. The interband part of the conductivity is negligible in what our study concerns.

We first compare the numerical result with the analytical one given by Eq. (1) to demonstrate the validity of the temporal coupled mode theory. The parameters of the device are set as follows, the period, height and filling factor of the grating are 150 nm, 100 nm and 0.5, respectively. The thickness and refractive index of the dielectric spacer are 20 nm and 1.5. The Fermi energy and the electron relaxation time of the graphene are 0.4 eV and 0.3 ps. The thickness and refractive index of the substrate are 500 nm and 1.5. The metals of the grating and the back reflector are taken as perfect metals. The numerical absorption spectrum calculated by finite element method using COMSOL is shown in Fig. 1(c). An absorption peak is observed at the free space wavelength of about 10.5 μm, which corresponds to the excitation of the first order graphene surface plasmonic mode, and the mode pattern is shown in the inset. We also calculated the absorption spectrum using Eq. (1) by setting $\gamma_0 = 1.67$ THz, $\gamma_1 = 0.28$ THz, and plot the result in Fig. 1(c). It is clear that the analytical spectrum is in good agreement with the numerical one, signifying the behavior of the device can be well described by temporal coupled mode theory.

3. Results and discussion

Because the electron relaxation time of graphene represents the average time needed for electrons to dissipate their energy, thus it should have connections with the intrinsic loss rate γ_0. To confirm this idea, we calculate the absorption spectrum numerically by varying the relaxation time from 0.05 to 4 ps while keeping other parameters of the device unchanged. Fig. 2(a) shows the spectrums for $0.05\text{ ps} < \tau < 0.4$ ps, where the resonant absorption rate increases from 38% at $\tau = 0.05$ ps to 100% at $\tau = 0.4$ ps, and the bandwidth becomes narrower as τ grows. The spectrums for $0.4\text{ ps} < \tau < 4$ ps are displayed in Fig. 2(b). Compared with Fig. 2(a), the resonant absorption rate drops now with the increase