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Critical coupling of surface plasmons in graphene attenuated total reflection geometry

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We study the optical response of an attenuated total reflection (ATR) structure in Otto configuration with graphene sheet, paying especial attention to the occurrence of total absorption. Our results show that due to excitation of surface plasmons on the graphene sheet, two different conditions of total absorption may occur. At these conditions, the energy loss of the surface plasmon by radiation is equal to its energy loss by absorption into the graphene sheet. We give necessary conditions on ATR parameters for the existence of total absorption.

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The localization provided by surface plasmons (SPs) is very attractive for many applications such as data storage, microscopy, light generation or biophotonics [1,2]. Apart from the well known SPs supported by an insulator–metal interface, long living SPs can be supported by graphene – a 2 D sheet of carbon atoms organized in a honeycomb lattice – from terahertz up to mid-infrared frequencies [3]. High confinement, relative low loss, and the ability of tuning the SP spectrum through electrical or chemical modification of the carrier density, makes the graphene a promising plasmonic alternative material to noble metals at long wavelengths [4,5]. Phase-coupling techniques which give the photon the additional propagation constant increase needed to achieve SP excitation have been extensively used. One of the most popular coupling techniques is based on the use of attenuated total reflection (ATR) which requires the introduction of a second surface, usually the base of a prism, as shown in Fig. 1 for the Otto configuration [6,7]. The excitation of SPs causes a pronounced minimum in the reflectivity which may reach zero value (total absorption condition) for optimized ATR structures [6,8].

In this letter, we report the main results of our theoretical study about the total absorption phenomenon in an ATR system in Otto configuration with graphene monolayer. By applying energy conservation in a finite-size region, we demonstrate that critical coupling in which the incident radiation is totally absorbed is achieved when the energy loss of the SP by radiation into the prism is equal to its energy loss by absorption into the graphene monolayer. This result is in accord with those obtained in Ref. [9] by applying a different method and for a metallic ATR structure. In addition, it is found that the reflection coefficient can have two zeros for two different angles of incidence and thicknesses of the vacuum layer (or chemical potentials on the graphene monolayer). In [10], it was reported that the reflectivity of an ATR system in Otto configuration may have two zeros, but only one of them is caused by excitation of SPs. In contrast, we show that the two zeros found here are due to the excitation of SPs on the graphene monolayer. Furthermore, we give necessary conditions on ATR parameters for the existence of total absorption. The Gaussian system of units is used and an $\exp(-i\omega t)$ time-dependence is implicit throughout the paper, with ω as the angular frequency, t as the time, and $i=\sqrt{-1}$.

Fig. 1 shows the Otto–ATR structure. Medium 2 is vacuum in contact with two nonmagnetic dielectric materials ($\mu_1=\mu_3=1$) with real and positive electric permittivities (ε_1, ε_3). A SP can be excited along the graphene monolayer located at interface 2–3 when the incident plane wave reaches the base of the prism (interface 1–2) with an angle θ greater than the critical angle of total reflection. To illustrate this coupling mechanism, we study the electromagnetic response of the ATR structure when excited by a plane wave (plane wave scattering problem, or reflectivity problem). On the other hand, this coupling is reciprocal, *i.e.*, the SP propagating by the graphene monolayer in $+x$ direction ra-

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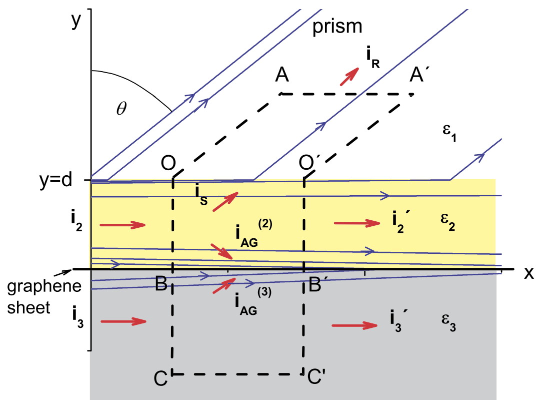

Fig. 1. (Color online.) Schematic illustration of the ATR geometry. The graphene sheet is located at $y = 0$ interface, between media 2 and 3. Closed region where energy conservation is applied (dashed line). Lines of Poynting vector flux are plotted (blue lines) for $\omega/c = 0.025$ μm^{-1} and thickness $d = 0.026\lambda$. $\varepsilon_1 = 16$, $\varepsilon_2 = 1$, $\varepsilon_3 = 3.9$ and graphene parameters are $\mu_c = 0.35$ eV, $\gamma = 0.1$ meV and $T = 300$ K.

diates away from the vacuum layer in the form of a beam that progresses at an angle θ in the prism region, as shows Fig. 1. This fact leads to radiation losses which are expressed as an increase of the imaginary part of the SP propagation constant. To obtain all the propagation characteristics of SPs in the ATR system, we study the non-trivial solutions to the boundary value problem in the absence of incident fields (guided-wave eigenvalue problem, or eigenmode problem).

For p polarization the magnetic field of the electromagnetic eigenmodes is parallel to the z axis, $\mathbf{H} = e^{i\alpha x} h(y)\mathbf{z}$, where α is the propagation constant of the ATR eigenmodes and

$$h(y) = \begin{cases} r_1 e^{i\beta^{(1)} y} & y > d, \\ \left[r_2 e^{i\beta^{(2)} y} + t_1 e^{-i\beta^{(2)} y}\right] & 0 < y < d, \\ t_2 e^{-i\beta^{(3)} y} & y < 0. \end{cases} \quad (1)$$

Here, r_j and t_j $(j = 1, 2)$ are complex magnitudes, and $\beta^{(j)} = \sqrt{k_0^2 \varepsilon_j - \alpha^2}$ $(j = 1, 2, 3)$ is the component in the y direction of the wave vector in each of the media, $k_0 = \omega/c$ is the modulus of the photon wave vector in vacuum, ω is the angular frequency and c is the vacuum speed of light. The electric fields $\mathbf{E} = e^{i\alpha x}\mathbf{e}(y)$ are easily written also as functions of r_j and t_j by means of a Maxwell curl equation, where

$$\mathbf{e}(y) = \begin{cases} \frac{r_1}{k_0\varepsilon_1}[-\beta^{(1)}\mathbf{x} + \alpha\mathbf{y}]e^{i\beta^{(1)} y} & y > 0, \\ \frac{1}{k_0\varepsilon_2}[-\beta^{(2)}(t_1 e^{i\beta^{(2)} y} - r_2 e^{-i\beta^{(2)} y})\mathbf{x} & \\ \quad + \alpha(t_1 e^{i\beta^{(2)} y} + r_2 e^{-i\beta^{(2)} y})\mathbf{y}] & 0 < y < d, \\ \frac{t_2}{k_0\varepsilon_3}[\beta^{(3)}\mathbf{x} + \alpha\mathbf{y}]e^{-i\beta^{(3)} y} & y < 0. \end{cases} \quad (2)$$

There are two types of boundary conditions which must fulfill the solutions given by Eqs. (1) and (2), boundary conditions at $y = \pm\infty$ and boundary conditions at interfaces $y = 0$ and $y = d$. The former requires either outgoing waves at infinity or exponentially decaying waves at infinity, depending on the values of α and $k_0\sqrt{\varepsilon_j}$ [12]. The boundary conditions at $y = d$ require the continuity of the tangential components of the electric field and the magnetic field. The boundary conditions at $y = 0$ require the tangential component of the electric field to be continuous and the tangential component of the magnetic field to be discontinuous across the interface by an amount whose magnitude is equal to the magnitude of the surface current density on graphene sheet [5,11]. Applying these conditions in Eqs. (1) and (2) we obtain a homogeneous system for the four unknown coefficients r_j and t_j $(j = 1, 2)$ [5]. The dispersion equation for the propagation constant α can be obtained by requiring the determinant D of this system to be zero, a condition that can be written as

$$D = (Z_1 + Z_2)\left(Z_2 + Z_3 W_2^+\right) + (Z_1 - Z_2)\left(Z_2 - Z_3 W_2^-\right) e^{i2\beta^{(2)} d} = 0, \quad (3)$$

where $Z_j = \frac{\beta^{(j)}}{\varepsilon_j}$, $W_2^\pm = 1 \pm \frac{4\pi\sigma}{ck_0} Z_2$ and σ is the conductivity of the graphene sheet given by the Kubo formula [11]. It should be noted that the eigenvalue α is complex-valued, where Imα is the spatial decay rate and it represents the total damping of the eigenmode. In addition to SPs, there also exist eigenmodes having $|\mathrm{Re}\,\alpha| < k_0$. In this case, the field inside the vacuum layer propagates along x direction bouncing between the two boundaries at $y = 0$ and at $y = d$ before it loses most of its energy by refraction, *i.e.*, by radiation into the semi-infinite regions above $(y > d)$ and below $(y < 0)$ the vacuum layer. In this paper we confine our attention to just SPs which are evanescent waves in the vacuum layer and in the semi-infinite region $y < 0$.

Since Eq. (3) gives two complex solutions differing in sign (for propagation along $\pm x$), we have chosen the one with $\mathrm{Re}\,\alpha > 0$. For conventional media, in this case dielectric media 1, 2 and 3, the physically correct Riemann sheet gives $\mathrm{Im}\,\alpha \geq 0$ [12].

After calculating α, we obtain the field amplitudes r_2, t_1, and t_2 in Eq. (1) as a function of r_1. As both the magnetic and the electric SP fields depend on x axis in the form $e^{i\alpha x}$, the time-averaged Poynting vector thus reads

$$\langle\mathbf{S}\rangle = \frac{c}{8\pi}\,\mathrm{Re}\left(\mathbf{E} \times \mathbf{H}^*\right) = e^{-2\mathrm{Im}\alpha x}\mathbf{s}(y), \quad (4)$$

where the asterisk denotes the complex conjugate and $\mathbf{s}(y) = \mathbf{e}(y) \times \mathbf{z}h^*(y)$. In the second equality in Eq. (4) we have taken into account that α is a complex number. According with Eq. (4), surface plasmons are attenuated as propagate along $+x$ direction. The attenuation is due by two damping processes, namely, energy radiation and energy absorption. This means that, as the SP propagates along the graphene sheet, part of the energy it carries can be radiated into the prism and the other part is absorbed in the graphene sheet. In the proximity of the graphene surface, the lines of Poynting vector flux are almost parallel to the x-axis. Due to absorption losses in the graphene sheet, a small number of lines finish on this surface, as can be seen in Fig. 1, where we have plotted the lines of Poynting vector for $\omega/c = 0.025$ μm^{-1} and for a thickness $d = 0.026\lambda$ ($\lambda = 2\pi\, c/\omega$ is the photon wavelength). The presence of surface 1–2 at the base of the prism is manifested in the existence of current lines that emerge from the surface in region $y > d$ in the form of radiation flow. The density of these lines along the propagation direction decreases as a consequence of the decrease in the power density carried by the SP. These lines can be verified to form an angle θ with the y-axis given by the relation $\omega/c\,\sqrt{\varepsilon_1}\sin\theta = \mathrm{Re}\,\alpha$.

In considering the energy balance in the region $OAA'O'B'C'CB$ of Fig. 1, lines OA and $O'A'$ are taken to be parallel to the radiation direction. As a consequence, the energy flows i_1 through the line OA and i_1' through the line $O'A'$ are equal to zero. The total incident energy flow reaching the region $CBOA$ has two parts: the flow i_3 through the line CB in the lower medium 3 and the incident energy flow i_2 through the line BO in the medium 2. One part $i_{ag}^{(2)}$ of the incident energy flow i_2 is absorbed by the graphene sheet and another part i_s is transmitted to the medium 1 through the line OO'. A third part i_2' is transmitted through the line $O'B'$. Taking into account Eq. (4), we can see that this part is $i_2' = i_2\, e^{-2\,\mathrm{Im}\,\alpha\, X}$, where X is the length of the segment AA'.

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