Transformation of surface plasmon polaritons to radiation in graphene in terahertz regime

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Abstract
We demonstrate a concept that allows direct excitation of surface plasmon polaritons (SPPs) by a moving electron bunch above a single layer graphene sheet deposited on a dielectric substrate without any additional coupling requirements. We show that if the two-dimensional current in the graphene is dominated by the third order nonlinear effect when the surface electric field exceeds a moderate strength of $\sim 5\text{kV/cm}$, the SPP mode can cross the light line although the group velocity remains much smaller than the speed of light. This effect gives rise to direct transformation of SPPs into radiation. The underlying mechanism of the crossing of the SPP dispersion into the light line is the energy shift of charged particles in the nonlinear regime and the finite transport scattering time in graphene. Both the energy and lifetime of the SPPs increase with the field intensity. The radiation intensity and frequency can be tuned with an AC bias.

Keywords
terahertz, graphene, radiation, polaritons, regime, plasmon, transformation, surface

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Transformation of surface plasmon polaritons to radiation in graphene in terahertz regime

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We demonstrate a concept that allows direct excitation of surface plasmon polaritons (SPPs) by a moving electron bunch above a single layer graphene sheet deposited on a dielectric substrate without any additional coupling requirements. We show that if the two-dimensional current in the graphene is dominated by the third order nonlinear effect when the surface electric field exceeds a moderate strength of \(~5\text{kV/cm}\), the SPP mode can cross the light line although the group velocity remains much smaller than the speed of light. This effect gives rise to direct transformation of SPPs into radiation. The underlying mechanism of the crossing of the SPP dispersion into the light line is the energy shift of charged particles in the nonlinear regime and the finite transport scattering time in graphene. Both the energy and lifetime of the SPPs increase with the field intensity. The radiation intensity and frequency can be tuned with an AC bias.

Graphene has some exceptional electronic, mechanical, and optical properties.1–5 Because the plasmon frequency in graphene lies in the terahertz frequency regime and is found to be tunable, intense research has been carried out to search for graphene based radiation sources, detectors, and modulators,6–11 especially in the terahertz region. Recent experimental and theoretical works have shown that graphene can support surface plasmon polaritons (SPPs).12–17 Due to the unique properties of graphene including high mobility and universal conductance, there can be a significant enhancement of light radiation from graphene SPPs. The enhancement can be up to two orders of magnitude when a graphene sheet is deposited on a periodic dielectric substrate. Graphene SPPs are particularly useful at low frequency as the plasmon frequency of graphene with favourable charge carrier concentration lies in the 1–50 THz frequency regime. This makes graphene an ideal candidate for developing low frequency light radiation sources such as terahertz emitters. For a uniform graphene structure, the SPP modes lie below the light dispersion line of the dielectrics. Therefore, the direct conversion of SPPs to light is impossible. The key challenge in graphene photonics and plasmonics is enabling SPPs to be excited by an incident field. The two most commonly used techniques involve using a prism to allow for wavevector matching, or introducing a periodic microstructure either directly in the graphene sheet or in the substrate dielectrics to cause band folding. The band folding of the SPP dispersion under a periodic potential brings the SPP mode at large \(q\) back into the first Brillouin zone. Thus, the SPP mode crosses the light line, and SPP-light coupling becomes possible.18 This technique requires precise control of the periodicity.

Recently, Bludov et al.19 considered nonlinear transverse electric (TE)-polarized surface polaritons on graphene. They included the nonlinear dielectric function of the substrate in the SPP calculation and found that the system can support and stabilize nonlinear TE plasmon polaritons. The results rely on a strong nonlinear dielectric as a substrate. On the other hand, it has been shown that graphene is a strong nonlinear material.20–24 The required threshold field for graphene to exhibit the nonlinear effect is rather moderate in the order of a few kV/cm. Gorbach recently derived an amplitude equation for nonlinear transverse magnetic (TM) and TE surface plasmon waves supported by graphene.25 Significant nonlinear optical interactions at the few photon levels in graphene have been realized.26 Therefore, it is reasonable to believe that with a certain substrate, graphene will enter the nonlinear regime first, while the dielectric substrate remains as a linear system.

In this letter, we demonstrate a mechanism that can bring the SPP mode above the light line without the requirement of structural modification. It has been shown that under a moderate electric field strength of a few kV/cm, the third order conductivity in graphene exceeds the linear conductivity. Both the interband and intraband conductivities depend strongly on the amplitude and frequency of the electrical field. We shall show that the combination of the nonlinear surface current and a finite relaxation time can lift the long wavelength SPP mode above the light line of the dielectric, making the SPP-radiation transformation immediately possible in the absence of any other zone-folding or diffraction mechanism. This result is of significance in understanding the high field electronic transport and SPP excitation in graphene.

Let us consider a graphene sheet grown on dielectrics with a dielectric constant \(\epsilon_d\). Above the graphene is a different type of dielectric with dielectric constant \(\epsilon_1\). The model system is shown schematically in Fig. 1. The intraband conductivity can be obtained by solving the Boltzmann equation...
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FIG. 1. The structure considered when calculation SPP dispersion relations. A layer of graphene is sandwiched between two dielectrics.

Here, \( f \) is the distribution function in the presence of an applied field, \( f_0 \) is the equilibrium distribution function, which is taken to be the Fermi-Dirac distribution function,

\[
f_0^+ = \left[ 1 + \exp \left( \frac{\mu - E}{k_BT} \right) \right]^{-1}.
\]

Here, \( \pm \) indicates the conduction and valence band, \( \mu \) is the chemical potential, and \( T \) is the absolute temperature. The linear conductivity is given as

\[
\sigma_1 = \frac{4\sigma_0}{\pi} \frac{1}{\gamma - i\omega} \left\{ \mu + 2k_BT \ln \left[ 1 + \exp \left( -\frac{\mu}{k_BT} \right) \right] \right\} = \frac{4\sigma_0}{\pi} \frac{1}{\gamma - i\omega} f_1,
\]

where \( \sigma_0 = e^2/h \) and \( \gamma = \hbar/\tau \) is the relaxation rate. The second order current is zero in uniform systems. The third order conductivity can be written as

\[
\sigma_3 = \frac{3}{4} \phi^2 E_0^2 \left( \frac{\gamma^2 - 6\omega^2}{\gamma^2 - 6\omega^2 + 15}\omega I_1 \right),
\]

where \( \phi = e\hbar v_F \approx 2 \times 10^8 \text{ eV}^2 / \text{cm/V} \), \( E_0 \) is the amplitude of the electric field on graphene, and

\[
I_1 = \int_0^\infty dp \left( 1 \frac{\partial f_0}{\partial p} - \frac{\partial^2 f_0}{\partial p^2} - p \frac{\partial^3 f_0}{\partial p^3} \right).
\]

where \( f_0 = f_0^+ - f_0^- \). Fig. 2 shows the frequency dependent conductivity ratio \( \sigma_3/\sigma_1 \) in the 0–2 THz region. The nonlinear effect increases with decreasing chemical potential and initially increases then decreases as a function of frequency (cf. Fig. 2). A negative real component of the conductivity has been observed in other graphene structures in both the linear and nonlinear regimes. This property has been proposed for amplification of terahertz radiation.\(^{22,27,28}\) The most interesting nonlinear effect is that the imaginary part for \( \sigma_3 \) is entirely negative. This makes the excitation of a TE SPP mode in graphene possible. We found that the negative imaginary part of the conductivity is necessary for the TM SPP mode to cross the light line. For a field amplitude greater than 5 kV/cm, the conductivity is dominated by the nonlinear term.

By using Maxwell’s equations and the appropriate boundary conditions, we arrive at the general dispersion relations for the TM and TE modes

\[
\frac{\epsilon_1}{\kappa_1(3\omega)} + \frac{\epsilon_2}{\kappa_2(3\omega)} + \frac{4i\omega}{3\omega} \sigma_3(3\omega) = 0.
\]
increasing the field also increases the damping of the SPPs, allowing the dispersion to lie within the light cone but also the relaxation rate is 2.6 meV.

In Fig. 3, the nonlinear SPP mode for complex $\omega$ is shown. Compared to the linear mode, the dispersion of the nonlinear mode shifts vertically. Due to this vertical shift, the dispersion relation also lies within the light cone; however, increasing the field also increases the damping of the SPPs, making this method of excitation completely infeasible. For complex $q$, we found that increasing the electric field causes the dispersion relation to also lie within the light cone but also the decay rate decreases with increasing electric field. For sufficiently high fields ($E \approx 5 \text{kV/cm}$), the ratio $\text{Im}(\omega)/\text{Re}(\omega) < 1$ as can be seen in Fig. 4. In the linear regime, apart from the fact that the SPP mode is far away from the light line, this ratio is much greater than 1 in the small $q$ region. In the nonlinear regime, the ratio can be smaller than 1 in the small $q$ region, where the SPP mode is above the light line.

These results paint an interesting picture about the effect of the electric field on the dispersion relations. Despite the inclusion of a finite relaxation rate causing the dispersion curve to deviate from the light line in the low frequency limit, an increase in the incident field is found to fix this and allow for excitation. When the relaxation rate is not included, increasing the field does not cause the SPP dispersion curve to cross into the light cones, the effect only occurs when a finite relaxation rate is included. Our finding here is that the interplay of the nonlinear conductivity and the finite relaxation can give rise to the unexpected possibility that SPPs can be directly transformed into radiation inside the light cone without any additional structural modification for momentum matching.

We shall now consider excitation of the nonlinear SPPs by an electron bunch moving with velocity $u_0$ above the graphene sheet. This corresponds to an excitation at the working point where the electron beam line intersects with the nonlinear SPP dispersion relation (cf. Fig. 3). The components of the electromagnetic field of the bunch oscillating at $3\omega$ are given as

$$E_z = -\frac{eK_c}{6\omega_0} e^{i\kappa_c(y-y_0)} e^{ik_cz},$$
$$H_y = -\frac{1}{2} e^{i\kappa_c(y-y_0)} e^{ik_cz},$$

where $\kappa_c = \sqrt{k_0^2 - k_z^2}$, $k_z = 3\omega/u_0$ and $y_0$ is the position of the electron bunch. By using the boundary conditions at $y=0$,

$$E_z^+ + E_z^- = E_z^{II}, H_y^+ - (H_y^+ + H_y^0) = \sigma_3(E_z^{II} + E_0).$$

In the boundary equation, the $H$ field discontinuity is determined by the total current $j(3\omega)$, which is in response to the total surface field $(E_z^{II} + E_0)$. The total field is the linear combination a large AC bias field $E_0$ and the emitted field. The emitted field is much smaller than $E_0$ for the entire frequency region, except at resonance. Therefore, we shall only retain the $E_0$ dependence in the nonlinear conductivity. We obtain the emitted field amplitude

$$A_1 = \left(\frac{i2Ke_0}{\kappa_2} + 1\right) e^{i\kappa_c y_0} + \frac{e^{i\kappa_c y_0} + \sigma_3 E_0}{i3\omega_0 \sqrt{\kappa_1 \kappa_2}} - \sigma_3 E_0,$$
$$A_2 = A_1 - \frac{eK_c}{6\omega_0} e^{i\kappa_c y_0}.$$

Fig. 5 shows that the radiation field is directly transformed from the nonlinear SPP. The radiation spectrum is a sharply peaked function centered around the frequency as determined by the working point (the intersection) of the electron beam and the SPP dispersion. For the beam speed of 0.42 c, the peak frequency is 0.39 THz. The peak height is predominantly determined by the nonlinear field $E_0$, as the second term in the numerator in $A_1$ is much stronger than the field of the probing electron beam. The radiation amplitude
The SPP can be transformed into radiation.

When excited by an electron beam moving at speed faster than the light in the dielectrics, the SPP mode has a higher phase velocity than the phase velocity of the light in the dielectrics. Therefore, it may not be practical than that on the air side. The radiation is strongly localized near the interface. Hence, the propagation in the dielectric side is more efficient than that on the air side. The radiation is strongly localized near the interface. Therefore, it may not be practical to use this mechanism for developing emitters. To reduce the attenuation, a stronger field would be required.

In conclusion, we have shown that it is possible for the SPP dispersion to cross the light line in a graphene on top of a periodic structure, the SPP energy in the second band after zone folding increases as \( q \). The SPP energy decreases with \( q \), and the peak height was also found to increase with the beam energy.

It should be pointed out that although direct transformation of SPPs to radiation is possible in the current model, the propagation of the SPP generated radiation is restricted by the heavy attenuation along the direction perpendicular to the interface. The propagation in the dielectric side is more efficient than that on the air side. The radiation is strongly localized near the interface. Therefore, it may not be practical to use this mechanism for developing emitters. To reduce the attenuation, a stronger field would be required.

In conclusion, we have shown that it is possible for the SPP dispersion to cross the light line in a graphene on top of dielectrics. Due to a nonlinear current in the graphene, the SPP mode has a higher phase velocity than the phase velocity of the light in the dielectrics. When excited by an electron beam moving at speed faster that the light in the dielectrics, the SPP can be transformed into radiation.

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