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Harmonics radiation of graphene surface plasmon polaritons in terahertz regime

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ABSTRACT

This letter presents an approach to extract terahertz radiation from surface plasmon polaritons excited in the surface of a uniform graphene structure by an electron beam. A sidewall configuration is proposed to lift the surface plasmon mode to be close to the light line, so that some of its harmonics have chances to go above the light line and become radiative. The harmonics are considered to be excited by a train of periodic electron bunches. The physical mechanism in this scheme is analyzed with three-dimensional theory, and the harmonics excitation and radiation are demonstrated through numerical calculations. The results show that this technique could be an alternative to transform the surface plasmon polaritons into radiation.

1. Introduction

There is current interest in the research on applications of graphene due to its exceptional electronic, mechanical, and optical properties [1–7], especially, developing graphene-based devices in terahertz regime is attractive for the time being since the finding that the surface plasmon polaritons (SPPs) supported by a graphene sheet could be tuned in terahertz regime by adjusting external gate voltage or chemical doping [8–11]. Recently, it is actively attempted to extract terahertz radiation from the graphene SPPs driven by an electron beam [12–14] in virtue of the fact that it could be a promising method in developing a coherent and tunable terahertz radiation source. As is known, the SPP modes are nonradiative and usually they are tightly combined along the surface of a uniform graphene structure, challenges therefore exist in converting the SPPs to radiative electromagnetic waves. One approach based on the band folding has been developed [12,13,15,16]. They suggested a system composed of a graphene sheet deposited on a precisely designed periodic dielectric substrate, where the band folding of the SPP dispersion under a periodic potential brings the SPP mode back into the first Brillion zone, resulting in that the SPP mode crosses the light line and becomes radiative. Another technique employing the nonlinear effect of the conductivity was proposed in Ref. [14]. The authors addressed that if the current in the graphene is dominated by the third order nonlinear effect when the surface electric field exceeds a threshold of ∼5 kV/cm, there is possibility for the SPP mode to cross the light line, and this effect gives rise to direct transformation of SPPs into radiation.

In this letter, a sidewall structure is proposed to upshift the SPP mode to be close to the light line, so that it is possible for harmonics of the SPPs to go above the light line and radiate. The physical mechanism is analyzed with three-dimensional theory, and the numerical results show that this technique could be an alternative to transform the SPPs into radiation.

2. Theory of sidewall structure

We consider a three-dimensional Cartesian coordinate as shown in Fig. 1. An infinitely thin electron beam with velocity v_0 moves in the z direction in the vacuum over a graphene sheet located on a dielectric substrate, which is assumed to occupy the entire space below the graphene sheet. Sidewalls assumed to be made of perfect conductor are placed in the x direction, and the width of the gap between the sidewalls is chosen as $w = 100$ μm. Considering the fact that the width of an electron beam can be generated in several tens of micrometers, this value is feasible for the electron beam to travel through the system. The conductivity of graphene has been widely studied, and the intraband conductivity which

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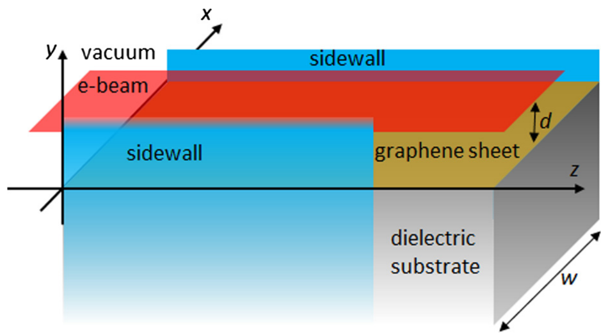

Fig. 1. Schematic of graphene-based radiation structure driven by an electron beam.

dominates the low frequency process of graphene SPP is given as [1,12,17]

$$\sigma_g = \frac{je^2 K_B T}{\pi \hbar^2(\omega + j\tau^{-1})}\left[\frac{\mu_c}{K_B T} + 2\ln(e^{-\frac{\mu_c}{K_B T}} + 1)\right], \quad (1)$$

where T is temperature, K_B is Boltzmann constant, τ is relaxation time, and μ_c is chemical potential. We choose $\mu_c = 0.15$ eV, $\tau = 0.5$ ps, and $T = 300$ K for all numerical calculations in this paper [12]. It has been known that the real part of the equivalent permittivity becomes negative when graphene dynamical intraband conductivity has a positive imaginary part, resulting in the possibility of generation of the SPPs in graphene.

We first discuss the dispersion relation in absence of electron beam. The most general modes with zero electric field in the x direction ($E_x = 0$) is focused in this paper, and the time dependence $e^{-j\omega t}$ is assumed for all field components. Considering the sidewall boundaries, the x-directed magnetic field in such a configuration can be expressed as

$$H_{1,x}(x, y, z) = B_1 \sin(k_x x) e^{jk_{1,y} y} e^{jk_z z}, \quad (2)$$

in the vacuum region, and

$$H_{2,x}(x, y, z) = B_2 \sin(k_x x) e^{-jk_{2,y} y} e^{jk_z z}, \quad (3)$$

in the dielectric region, respectively. Here $k_{1,y} = \sqrt{\omega^2/c^2 - k_x^2 - k_z^2}$, $k_{2,y} = \sqrt{\varepsilon_r \omega^2/c^2 - k_x^2 - k_z^2}$, $k_x = n\pi/w$, $n = 1, 2, 3, \ldots$, ε_r is permittivity of the dielectric substrate, and $c = 1/\sqrt{\varepsilon_0 \mu_0}$ is the velocity in the vacuum. The z-directed electric fields can be worked out through the Maxwell equations, and they are written as

$$E_{1,z}(x, y, z) = \frac{\omega \mu_0 k_{1,y}}{\frac{\omega^2}{c^2} - k_x^2} B_1 \sin(k_x x) e^{jk_{1,y} y} e^{jk_z z}, \quad (4)$$

$$E_{2,z}(x, y, z) = -\frac{\omega \mu_0 k_{2,y}}{\varepsilon_r \frac{\omega^2}{c^2} - k_x^2} B_1 \sin(k_x x) e^{jk_{1,y} y} e^{jk_z z}. \quad (5)$$

Following the method addressed in Ref. [12], the monolayer graphene is assumed to be atomically thin, then it is considered as a conductive surface with conductivity σ_g. Thus, the boundary conditions at $y = 0$ are written as

$$E_{1,z}(x, 0, z) = E_{2,z}(x, 0, z), \quad (6)$$

$$\boldsymbol{e}_y \times \left(H_{1,x}(x, 0, z)\boldsymbol{e}_x - H_{2,x}(x, 0, z)\boldsymbol{e}_x\right) = \sigma_g E_{1,z}(x, 0, z)\boldsymbol{e}_z. \quad (7)$$

Substituting field expressions into the above boundary conditions, the dispersion relation between frequency ω and axial wave number k_z for the SPP modes can be directly derived as

$$\frac{\omega \mu_0 \sigma_g}{\varepsilon_0 \mu_0 \omega^2 - k_x^2} + \frac{\varepsilon_r \varepsilon_0 \mu_0 \omega^2 - k_x^2}{(\varepsilon_0 \mu_0 \omega^2 - k_x^2) k_{2,y}} + \frac{1}{k_{1,y}} = 0. \quad (8)$$

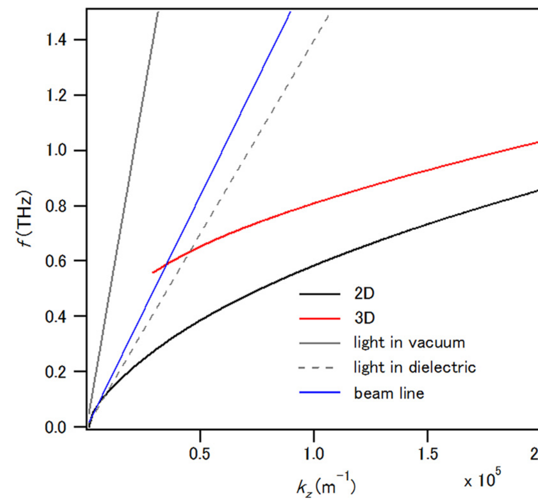

Fig. 2. Dispersion relations for surface plasmon polaritons calculated with 2D and 3D equations.

When $w \to \infty$, we have $k_x = 0$, and the equation becomes

$$\frac{\sigma_g}{\varepsilon_0 \omega} + \frac{\varepsilon_r}{k_{2,y}} + \frac{1}{k_{1,y}} = 0, \quad (9)$$

which has been known as the two-dimensional dispersion equation established elsewhere [12]. With choosing the permittivity of the substrate as $\varepsilon_r = 11.7$, Eqs. (8) and (9) can be numerically solved and the fundamental modes ($n = 1$) are given as Fig. 2. The light line in vacuum $\omega = ck_z$, in dielectric $\omega = k_z c/\varepsilon_r$, and the electron beam line $\omega = k_z c\beta$ are also plotted for comparison. Here $\beta = v_0/c$ is the Lorentz factor, and $\beta = 0.35$ is adopted in this calculation. Comparing with the two-dimensional result, the three-dimensional dispersion curve is lifted due to the sidewalls. There is an end point for the three-dimensional dispersion curve, which indicates the cutoff frequency induced by the sidewalls, and the cutoff frequency is about 0.56 THz. From the intersection point of the electron beam line with the dispersion curve we know that the SPPs can be excited with a frequency of 0.59 THz. The threshold for Cherenkov radiation to occur in this configuration can be worked out as $\omega > ck_x\sqrt{1/(\varepsilon_r - 1/\beta^2)}$ by the radiation condition $k_{2,y} > 0$. Thus, the threshold for a beam with $\beta = 0.35$ is obtained as 0.8 THz, which is higher than the frequency of SPPs, resulting in that the excited SPP mode cannot radiate though it crosses the light line in dielectric. However, we note that some of the second or higher order harmonics of the SPP mode can exceed the threshold and consequently become radiative. Next, we discuss the excitation of SPP harmonics and demonstrate the radiation phenomenon.

3. Harmonics radiation

In all radiation sources using an intense electron beam, the mechanism leading to superradiance is beam bunching [18–24]. The spectral intensity of the radiation will be enhanced at the bunching frequency and its harmonics. A prebunched electron beam can certainly be employed to drive the system to excite the harmonics of SPPs. On the other hand, an initially continuous beam in this configuration could be bunched by the interaction with the irradiative SPPs when proper conditions are satisfied and reach beam bunching, and the repetition frequency of the periodic bunches will be same as that of the irradiative SPP mode. In order to demonstrate the properties of harmonic radiation more clearly, we avoid the problem of bunching from an initially continuous beam. Instead, a train of bunches is generated to drive the system. We consider the idealized case in which periodic line charges