Terahertz amplification by electron beam excited graphene surface plasmon polaritons in a planar structure

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Abstract: A novel physical mechanism for development of Terahertz amplifier with plannar structure is presented in this paper. The theoretical analysis study and numerical calculations have been carried out, the significant results show that 12.69 *dB* per 1 *mm* length can be obtained. In principle, the mechanism is quite similar to that of space charge theory.

Keywords: Electron beam, Surface plasmon polaritons, Amplifier, Terahertz, Planar structure

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I. Introduction

Although the generation of Terahertz (THz) has been successfully developed by using graphene Surface Plasmon Polaritons excited by electron beam [1-4], the THz amplification is still a big challenge till now. A novel physical mechanism is presented to solve this problem by using graphene SPPs excitation. The theoretical study shows that when the velocity of the electron beam is a little bit higher than the phase velocity of SPPs waves, the energy of electron can be transformed to SPPs wave to amplify them. In principle, this is similar to space charge wave theory which used in traveling wave device for a long time [5-9].

II. Theoretical formula

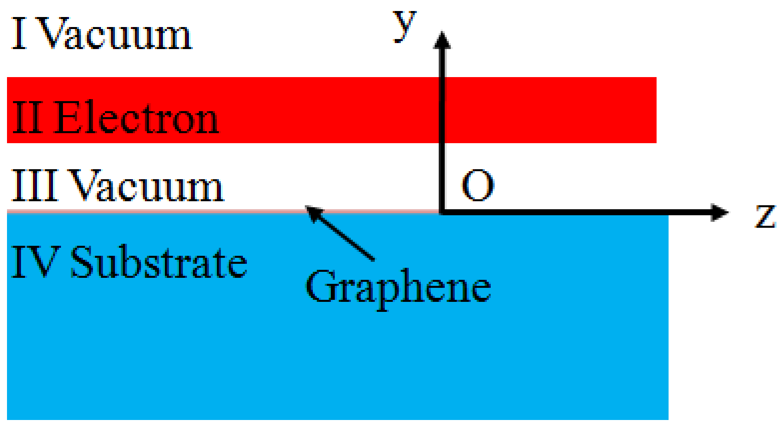


Fig. 1 Planar Schematic

Solving the homogeneous Helmholtz equation together with the boundary conditions, the E_z component of the fields in region I and III can be obtained. And then all the other field components can be obtained by Maxwell's equations. The factor $e^{-j\omega t}$ is neglected.

In the region I:

$$E_z^I = A_1 e^{-k_1(y-y_0-h)} e^{jk_z z} \tag{1}$$

$$H_x^I = -\frac{j\omega\varepsilon_0}{k_1} A_1 e^{-k_1(y-y_0-h)} e^{jk_z z} \tag{2}$$

Where:

$$k_1 = \sqrt{-k_0^2 + k_z^2}$$

In the region II:

$$E_z^{II} = [A_2 e^{-k_2(y-y_0)} + A_3 e^{k_2(y-y_0-h)}] e^{jk_z z} \tag{3}$$

$$H_x^{II} = -\frac{j\omega\varepsilon_0}{k_2} [A_2 e^{-k_2(y-y_0)} - A_3 e^{k_2(y-y_0-h)}] e^{jk_z z} \tag{4}$$

Where $k_2 = \sqrt{\alpha(-k_0^2 + k_z^2)},\ \alpha = 1 - \frac{\omega_{pe}^2}{(\omega - k_z v)^2} \quad \omega_{pe}^2 = \frac{\rho_0 e}{\varepsilon_0 m},\ \rho_0 = \frac{J}{u_0}$

In the region III:

$$E_z^{III} = [A_4 e^{-k_3 y} + A_5 e^{k_3(y-y_0)}] e^{jk_z z} \tag{5}$$

$$H_x^{III} = -\frac{j\omega\varepsilon_0}{k_3}[A_4 e^{-k_3 y} - A_5 e^{k_3(y-y_0)}] e^{jk_z z} \tag{6}$$

In the region IV:

$$E_z^{IV} = A_6 e^{k_4 y} e^{jk_z z} \tag{7}$$

$$H_x^{IV} = \frac{j\omega\varepsilon_0\varepsilon_4}{k_4} A_6 e^{k_4 y} e^{jk_z z} \tag{8}$$

Where： $k_4 = \sqrt{-\varepsilon_4 k_0^2 + k_z^2}$

The monolayer graphene is also considered as a conductive surface with conductivity σ_g, [10, 11]

$$\sigma_g = \frac{je^2 k_B T}{\pi\hbar^2(\omega + j/\tau)}\{\frac{\mu_c}{k_B T} + 2\ln[\exp(-\mu_c / k_B T) + 1]\} \tag{9}$$

j is the imaginary unit , T is temperature, k_B is Boltzmann constant, τ is relaxation time, and μ_c is chemical potential.

The boundary conditions can be written as

$$\begin{aligned} &E_z^{I} = E_z^{II},\ H_x^{II} - H_x^{I} = 0 \\ &E_z^{II} = E_z^{III},\ H_x^{III} - H_x^{II} = 0 \\ &E_z^{IV} = E_z^{III},\ H_x^{IV} - H_x^{III} = \sigma_{g1} E_z^{III} \end{aligned} \tag{10}$$

Submitting the electromagnetic fields into the above boundary conditions, the dispersion relation can be obtained:

$$\frac{\dfrac{1}{k_3} + \dfrac{\varepsilon_4}{k_4} - \dfrac{\sigma_g}{j\omega\varepsilon_0}}{\dfrac{1}{k_3} - \dfrac{\varepsilon_4}{k_4} + \dfrac{\sigma_g}{j\omega\varepsilon_0}} e^{k_3 y_0} = \frac{1-M_2}{1+M_2} e^{-k_3 y_0} \tag{11}$$

Where $$M_1 = \frac{k_1 - k_2}{k_2 + k_1} e^{-k_2 h},\quad M_2 = \frac{k_3}{k_2} \frac{(1 - M_1 e^{-k_2 h})}{1 + M_1 e^{-k_2 h}}$$

III. Results

The permittivity of dielectric substrate is $\varepsilon_s = 2.1$. For the grapheme sheet, $T = 300K$, $\tau = 1.2\,ps$, and chemical potential $\mu_c = 0.2eV$. The current density of electron beam is 200*A/cm*^{2}, and its velocity is 0.1c. At the frequency 4.506 *THz*, the wavevector of graphene SPPs is $k_z = 9.42537 \times 10^5 - i1460.8\,rad/m$. The theoretical value of gain is：

$$\begin{aligned} G &= 20\log\{\exp[\mathrm{Im}(k_z L)]\} \\ &= 8.686\,\mathrm{Im}(k_z L) \end{aligned} \tag{12}$$

If the interaction length is 1mm, the gain can reach 12.69 *dB*.

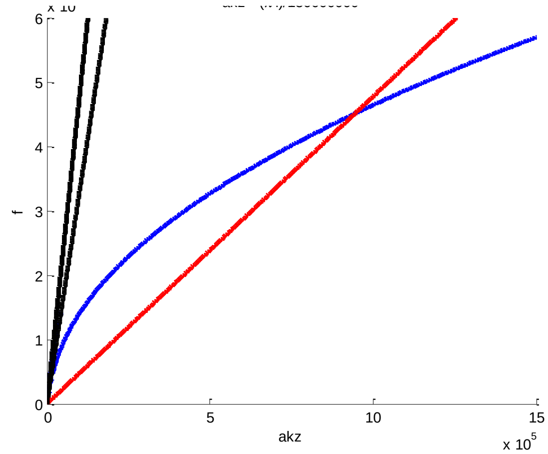
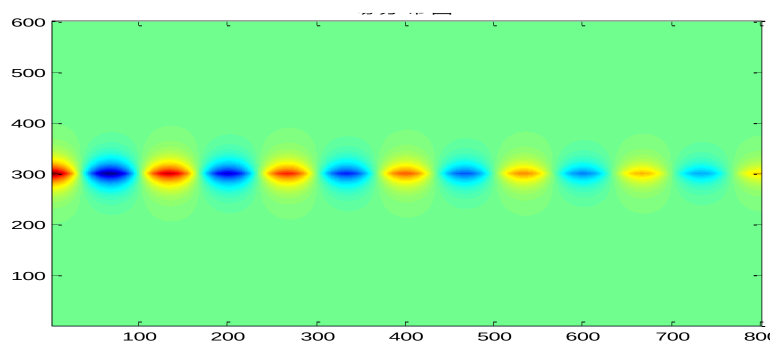
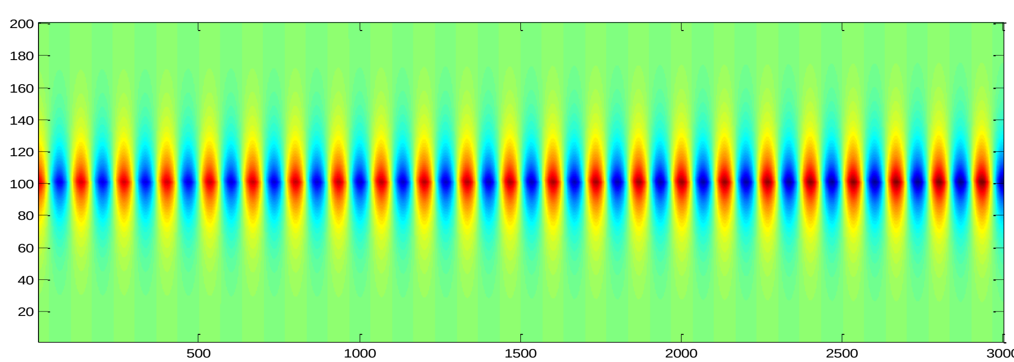


Fig. 2 The dispersion curve

In the case of no electron beams, $k_z = 943069 \times 10^5 + 27266.74i \ rad/m$, n=9.983. The Contour map of SPPs wave propagation are given in Figure 3.



a. Without electron beam



b. With electron beam

Fig. 3 Contour map of SPPs wave propagation

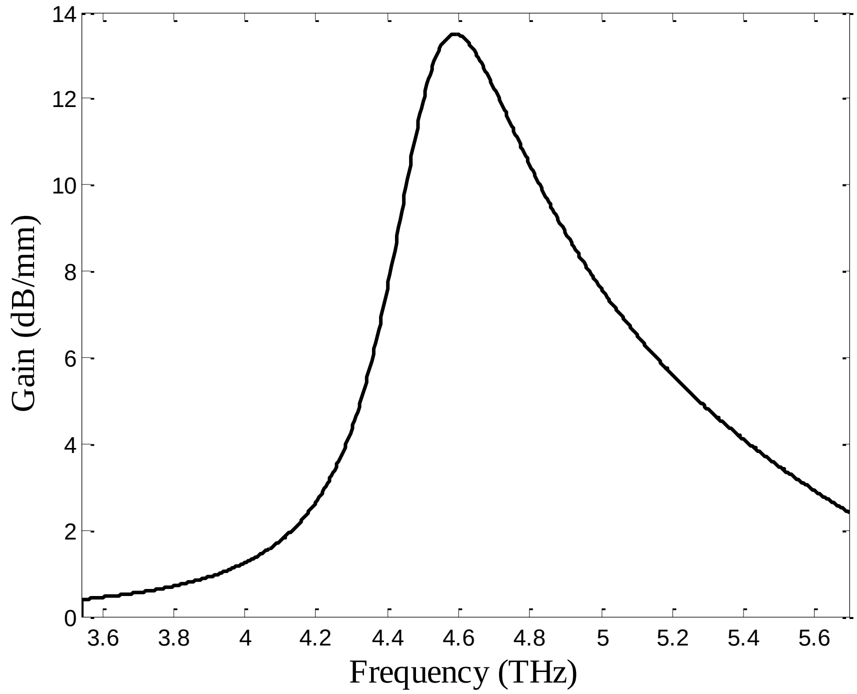


Fig. 4 The Gain vs Frequency

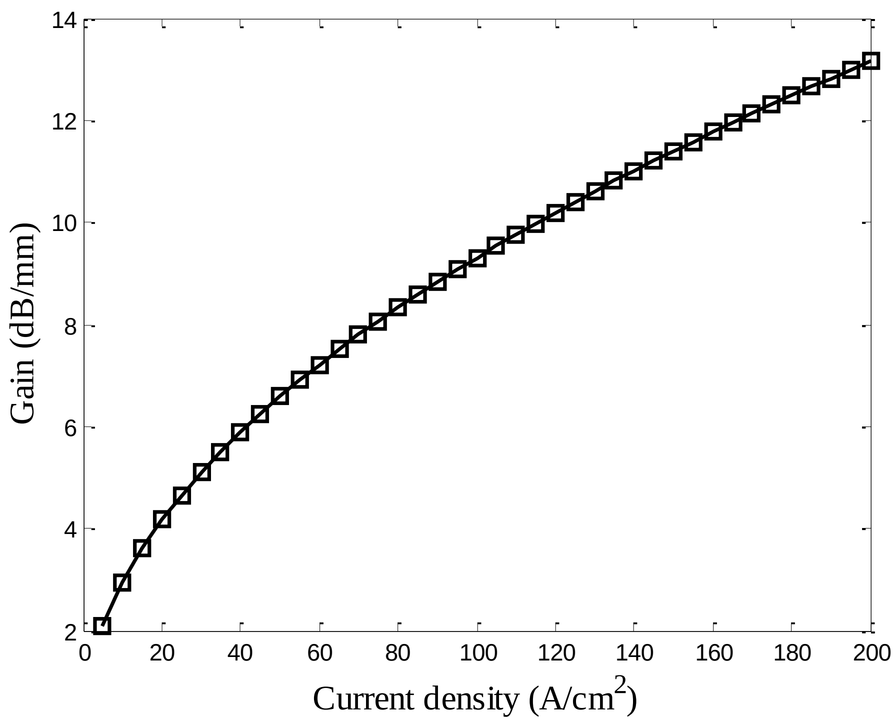


Fig. 5 The Gain vs current density

IV. Conclusions

Theoretical study and numerical calculation have been carried out for THz amplification by means of graphene SPPs excited by electron beam. The results show that when the velocity of the electron beam is slightly faster than the phase velocity of the graphene SPPs, the energy of electron beam can be transformed to SPPs wave to amplify them. In principle, the mechanism is quite similar to the space charge wave theory which has been used for traveling wave amplifier devices for a long time.

The results obtained in this Manuscript, 12.69 *dB* for 1 *mm* length is significant and attractive, comparing with the papers appeared in references [12-16].

References

[1] Shenggang Liu, Chao Zhang, Min Hu, et al. “Coherent and tunable terahertz radiation from graphene surface plasmon polaritons excited by an electron beam”. *Applied Physics Letters*, 104, 201104, (2014)

[2] Gong Sen, Zhao Tao, Matthew Sanderson, et al. “Transformation of surface plasmon polaritons to radiation in graphene in terahertz regime”. *Appl. Phys*. Lett, 106, 223107 (2015)

[3] Tao Zhao, Sen Gong, Min Hu, et al. “Coherent and Tunable Terahertz Radiation from Graphene Surface Plasmon Polarirons Excited by Cyclotron Electron Beam”. *Scientific Reports* 5:16059 (2015)

[4] Shenggang Liu, Min Hu, Renbin Zhong, et al. “Electron beam excitation of surface plasmon polaritons and transformation into electromagnetic radiation”. *TST*, 8, 2, 69-84 (2015)

[5] Liu Shenggang , Li Hongfu , Wang Wenxiang, et al. Introduction to microwave electronics, Beijing: National Defense Industry Press (1985) (In Chinese)

[6] Pierce J R. “Theory of the beam-type traveling-wave tube”[J]. *Proceedings of the IRE*, 35(2): 111-123 (1947)

[7] Kompfner R. Proceedings of the IRE, 35, 2, 124-127 (1947);

[8] Liu Shenggang. “The relativistic space charge wave theory”. *Chinese Journal of Electronics*, 18(4)， 6-11 (1990) (In Chinese)

[9] Liu Shenggang. “Space-charge wave theory of free electron lasers”. *International Journal of Electronics*, 72, 1, 161-180 (1992) (In Chinese)

[10] Hwang, E. & Sarma, S. “Dielectric function, screening, and plasmons in two-dimensional graphene”. *Phys. Rev*.

B. 75, 205418 (2007).

[11] Wang, B., Zhang, X., Yuan, X. & Teng, J. "Optical coupling of surface plasmons between graphene sheets. Appl." *Phys. Lett*. 100, 131111 (2012).

[12] Israel De Leon and Pierre Berini. "Amplification of long-range surface plasmons by a dipolar gain medium". *Nature. Photonics*. 4, 382-387 (2010)

[13] Malte C. Gather, Klaus Meerholz, Norbert Danz, et al. "Net optical gain in a plasmonic waveguide embedded in a fluorescent polymer". *Nature. Photonics*. 4, 457-461 (2010)

[14] Pierre Berini and Israel De Leon. "Surface plasmon－polariton amplifiers and lasers". *Nature. Photonics*. 6, 16-24 (2012)

[15] Yuya Takatsuka, Kazuhiro Takahagi, Eiichi Sano, et al. "Gain enhancement in graphene terahertz amplifiers with resonant structures". *Journal of Applied Physics*, 112, 033103 (2012)

[16] Alexander A. Dubinov, Vladimir Ya. Aleshkin, Maxim Ryzhii1, et al. "Terahertz Laser with Optically Pumped Graphene Layers and Fabri–Perot Resonator". *Applied Physics Express* 2, 092301 (2009)