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Terahertz lasing in open plane-parallel metal-dielectric resonator with graphene

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Abstract. Terahertz amplification and lasing regimes in open plane-parallel metal-dielectric resonator with population inverted (active) graphene are studied theoretically. Terahertz lasing arises at the Fabry—Perot resonance in the open-side metal-dielectric substrate of graphene in the vicinity of the reststrahlen band edge of GaAs superstrate due to photon-phonon interaction in GaAs.

Keywords: terahertz, lasing, graphene, inversion, Fabry—Perot resonance

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Терагерцовая лазерная генерация в открытом плоскопараллельном металлодиэлектрическом резонаторе с графеном

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Аннотация. Теоретически исследованы режимы усиления и генерации терагерцового излучения в открытом плоскопараллельном резонаторе с графеном с инверсной населенностью. Терагерцовая генерация возникает на частоте резонанса Фабри-Перо в металлизированной только с одной стороны подложке графена вблизи края полосы остаточных фононных лучей в покровном GaAs слое вследствие фотон-фононного взаимодействия в GaAs.

Ключевые слова: терагерц, лазер, графен, инверсия, Фабри-Перо резонанс

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Introduction

Terahertz (THz) lasers are in demand for THz imaging systems, medical diagnostics, and monitoring systems [1]. Graphene, being a natural two-dimensional material with unique properties such as a zero band gap and linear energy spectrum of charge carriers originally synthesized in [2, 3], can become a possible candidate for creating miniature THz lasers.

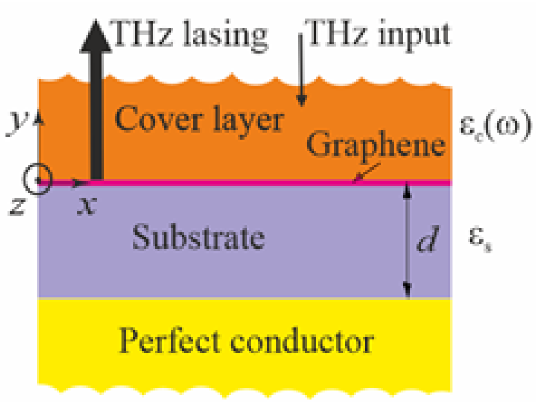

Fig. 1. Structure under consideration

In this paper, we theoretically study the THz amplification and lasing regimes in open parallel-plane metal-dielectric resonator with population inverted (active) graphene. The structure under consideration is schematically shown in Fig. 1. Graphene is deposited on a dielectric hBN substrate of thickness *d* screened by ideal conductor at the bottom, which forms a one-side perfect mirror of the Fabry—Perot resonator. No second mirror exists on the other side of the hBN substrate, so that the Fabry—Perot resonator is partially open. Graphene is covered with semi-infinite (in our theoretical model) GaAs superstrate. We consider that THz wave with TEM polarization incident normally upon graphene from inside GaAs cover layer and reflects back being amplified due to its interaction with active graphene. The inverted carrier distribution in graphene is assumed to be created by optical illumination [4]. We show that THz lasing arises at the Fabry—Perot resonance in the hBN substrate in the vicinity of the reststrahlen band edge of GaAs superstrate due to photon-phonon interaction in GaAs.

Materials and methods

Solving the Maxwell equations with conventional electromagnetic boundary conditions in the graphene plane and on the perfect conductor plane, we obtain the power reflection coefficient of the incident TEM wave:

$$R = \left| \frac{Y_{\text{ch}} - Y_{\text{load}}}{Y_{\text{ch}} + Y_{\text{load}}} \right|^2, \tag{1}$$

where Y_{ch} and Y_{load} are the characteristic admittance of the incident TEM mode in GaAs and the admittance of the terminal load (including graphene and dielectric substrate screened by the perfect conductor), respectively. These admittances are defined as

$$Y_{\text{ch}} = \frac{k_{\text{yc}}}{\omega\mu_0}, \; Y_{\text{load}} = \sigma(\omega) + i\frac{k_{\text{ys}}}{\omega\mu_0} ctg\left(k_{\text{ys}} d\right), \tag{2}$$

where ω and m_0 are the angular frequency and magnetic constant, respectively, $\sigma(\omega)$ is the dynamic conductivity of active graphene [5], and

$$k_{\text{yc}} = \sqrt{\varepsilon_{\text{c}}(\omega)}\frac{\omega}{c}, \; k_{\text{ys}} = \sqrt{\varepsilon_{\text{s}}}\frac{\omega}{c}, \tag{3}$$

are the normal-to-graphene-plane components of the wavevector of TEM mode in the graphene cover layer (GaAs) and in the substrate, respectively, with *c* being the speed of light, $\varepsilon_c = 4.5$ is the dielectric constant of the substrate (hBN), and

$$\varepsilon_c(\omega) = \varepsilon_\infty \frac{\omega_{LO}^2 - \omega^2}{\omega_{TO}^2 - \omega^2}, \tag{4}$$

is the dielectric function of GaAs [6], where $\omega_{LO} = 2\pi\cdot 8.76$ THz and $\omega_{TO} = 2\pi\cdot 8.05$ THz are the longitudinal (LO) and transverse (TO) optical phonon frequencies in GaAs, which are the high frequency and the low frequency edges of the reststrahlen band, respectively, and ε_∞ is the dielectric constant at an infinite frequency.

Results and discussion

Let us first analyze the possibility of lasing in open plane-parallel metal-dielectric resonator with graphene but without superstrate. In Fig. 2, *a* we present reflection spectrum in the structure with $\varepsilon_c = 1$ for the quasi-Fermi energy value in graphene 35 meV, the mean free time of the charge carriers in graphene 0.3 ps, and charge carriers temperature 300 K. One can see a series of peaks corresponding to the Fabry—Perot resonances in the substrate. The incident wave is amplified due to interaction with active graphene but no lasing occurs. The absence of lasing in such structure can be explained as follows. According to Eq. (1), to obtain lasing regime one needs to realize matching of the characteristic admittance of the incident TEM mode in vacuum $Y_{ch} = Y_0 \approx 2.65$ mS and the admittance of the terminal load Y_{load}. The free-space admittance Y_0 is a real valued quantity, hence, the total admittance matching $Y_0 + Y_{load} = 0$ can be fulfilled only at the Fabry—Perot resonances in the substrate, where the admittance of the terminal load becomes also the real-valued quantity $Y_{load}(\omega_{res}) = \mathrm{Re}\sigma(\omega_{res})$. However, the free-space admittance is far greater than the graphene conductivity in THz frequency range, hence the sum of the free-space admittance and the admittance of the terminal load at the Fabry—Perot resonances in the desired THz frequency range is always positive $Y_0 + \mathrm{Re}\sigma(\omega_{res}) > 0$ (as can be seen from Fig. 2, *b*).

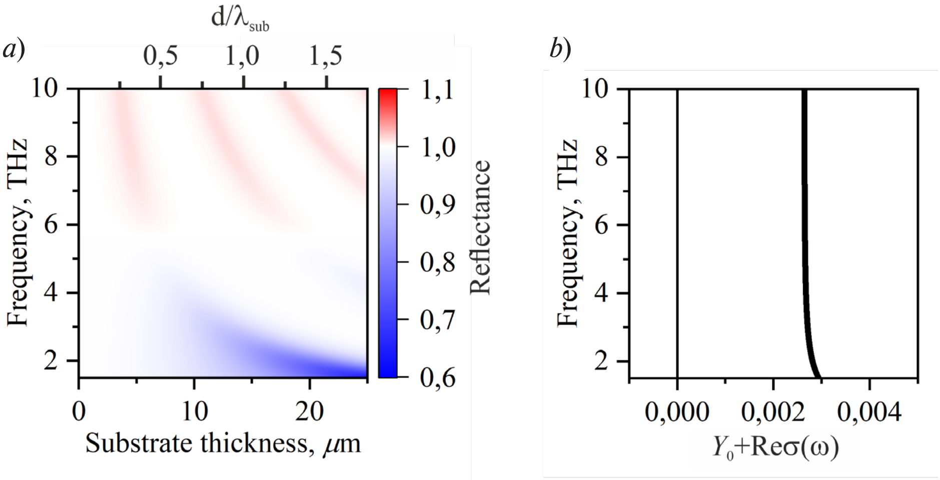

Fig. 2. Reflection spectrum in dependence on frequency and the substrate thickness d/λ_{sub}, where λ_{sub} is the wavelength of the TEM wave in the substrate, in the structure with $\varepsilon_c = 1$ (*a*). The sum of the free-space admittance and the admittance of the terminal load at the Fabry—Perot resonances, $Y_0 + \mathrm{Re}\sigma(\omega)$, in dependence on frequency for the structure with $\varepsilon_c = 1$ (*b*)

Now, let discuss the possibility of the lasing regime in open plane-parallel metal dielectric resonator with graphene covered by GaAs superstrate, taking into account the photon-phonon interaction in GaAs. Fig. 3, *a* shows the reflection resonances corresponding to the Fabry—Perot resonances in hBN substrate. In the vicinity of the high frequency edge of GaAs phonon reststrahlen band $\omega \geq \omega_{LO}$ (at about 8.8 THz) the dielectric function of the GaAs becomes very small (but positive) leading to drastic decrease of the characteristic admittance $Y_{ch} = \sqrt{\varepsilon_c(\omega)}\,Y_0$. Hence, the THz lasing condition, $Y_{ch} + Y_{load} = 0$, can be fulfilled (see Fig. 3, *b*). Because of this, one can see the high quality resonances corresponding to THz lasing in Fig. 3, *a*, which occur near the high frequency edge of GaAs reststrahlen band (at frequency about 8.8 THz).

We also note that THz lasing emerge at the Fabry—Perot resonances for the substrate thickness values nearly equal to $d = (2n - 1)\cdot\lambda_{sub}/4$, where λ_{sub} is the wavelength of the TEM wave in the substrate and n is the integer. Hence, graphene is located in the vicinity of the antinode of the standing wave in the substrate.

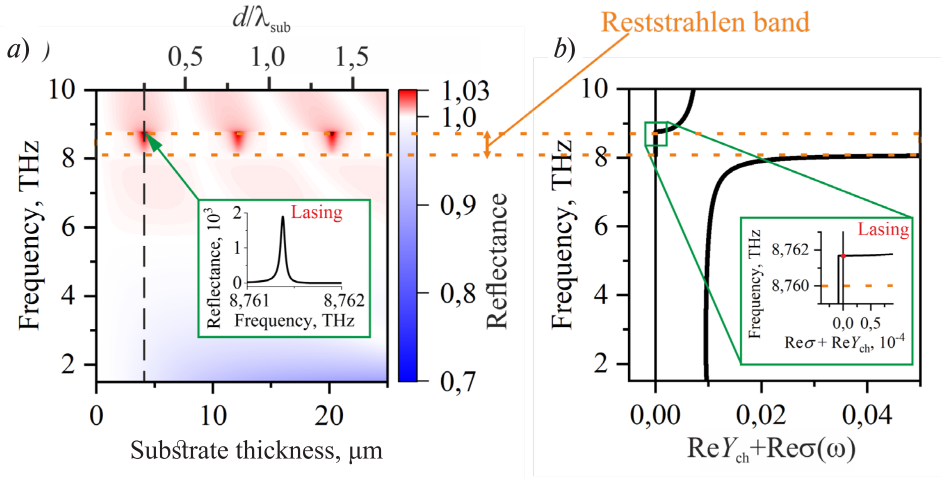

Fig. 3. Reflection spectrum in dependence on frequency and the substrate thickness for the structure with graphene covered by semi-infinite GaAs. The inset represents the cross-section of the raster map for $d = 4.2$ mm (corresponding to THz lasing) (*a*). The sum of the characteristics admittance and the admittance of the terminal load at the Fabry—Perot resonances, $\mathrm{Re}\,Y_{ch} + \mathrm{Re}\sigma(\omega)$, in dependence on frequency for the structure with graphene covered by semi-infinite GaAs. The inset represents the frequency range in the vicinity of the high frequency edge of GaAs reststrahlen band indicating (by red point) the THz lasing condition (*b*)

Conclusion

Terahertz amplification and lasing in open plane-parallel metal-dielectric resonator with population inverted are studied theoretically. Terahertz lasing arises at the Fabry—Perot resonances in the substrate in the vicinity of the reststrahlen band edge of GaAs superstrate due to sharp decrease of the characteristic admittance of GaAs.

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