

Conference paper
UDC 621.315.592
DOI: <https://doi.org/10.18721/JPM.191.110>

Hybridization between the plasmonic modes of a graphene square screened by a metal gate and the Fabry–Pérot resonances in barrier layer

K.V. Mashinsky ¹✉, V.V. Popov ¹, D.V. Fateev ^{1,2}

¹Kotelnikov Institute of Radio Engineering and Electronics of the RAS (Saratov Branch), Saratov, Russia

²Saratov State University, Saratov, Russia

✉ konstantin-m92@yandex.ru

Abstract. Hybridization of fundamental and higher plasmonic modes of a graphene square screened by a metal back gate with the Fabry–Pérot resonances in barrier layer is predicted. We show that the absorption cross-section of higher plasmon modes in a screened graphene square is greater than that in the unscreened structure by an order of magnitude.

Keywords: graphene, plasmon, Fabry–Pérot resonance, terahertz

Funding: This study was funded by Russian Science Foundation grant number 22-19-00611-П.

Citation: Mashinsky K.V., Popov V.V., Fateev D.V., Hybridization between the plasmonic modes of a graphene square screened by a metal gate and the Fabry–Pérot resonances in the barrier layer, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 19 (1.1) (2026) 64–68. DOI: <https://doi.org/10.18721/JPM.191.110>

This is an open access article under the CC BY-NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>)

Конференционная статья
УДК 621.315.592
DOI: <https://doi.org/10.18721/JPM.191.110>

Гибридизация между плазмонными модами графенового квадрата, экранированного металлическим затвором, и резонансами Фабри–Перо в барьерном слое

К.В. Машинский ¹✉, В.В. Попов ¹, Д.В. Фатеев ^{1,2}

¹Саратовский филиал Института радиотехники и электроники им. В.А. Котельникова РАН, г. Саратов, Россия

²Саратовский государственный университет, г. Саратов, Россия

✉ konstantin-m92@yandex.ru

Аннотация. Предсказана гибридизация основной и высших плазмонных мод графенового квадрата, экранированного нижним металлическим затвором, с резонансами Фабри–Перо в барьерном слое. Показано, что сечение поглощения высших плазмонных мод в экранированном графене возрастает на порядок величины по сравнению с соответствующими значениями в неэкранированной структуре.

Ключевые слова: графен, плазмон, резонанс Фабри–Перо, терагерц

Финансирование: Исследование поддержано Российским научным фондом (проект № 22-19-00611-П).

Ссылка при цитировании: Машинский К.В., Попов В.В., Фатеев Д.В. Гибридизация между плазмонными модами графенового квадрата, экранированного металлическим затвором, и резонансами Фабри–Перо в барьерном слое // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2026. Т. 19. № 1.1. С. 64–68. DOI: <https://doi.org/10.18721/JPM.191.110>

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (<https://creativecommons.org/licenses/by-nc/4.0/>)

Introduction

Unique properties of graphene, such as a gapless linear energy spectrum [1] and high electron mobility at room temperature [2], become particularly evident when exciting terahertz (THz) plasmons [3] in graphene nanostructures. Plasmons in graphene exhibit strong electric field localization and open up a range of new nonlinear effects [3]. It is possible to create THz-emitting devices based on plasmons in active graphene [4] using charge carrier inversion in graphene [5] and the emergence of drift instabilities [6].

All of this makes the study of THz plasmons in graphene promising for development of detectors, sensors and amplifiers of THz waves [3].

Only a few plasmonic effects have been discovered in spatially confined two-dimensional (2D) electron systems. In particular, the electromagnetic retardation leads to a decrease in the resonant frequencies of plasmonic excitations in 2D electron stripes [7]. It has also been proposed to use edge plasmons in confined graphene structures to achieve stronger localization of the THz field below the diffraction limit [8]. The lowest plasmonic modes in square 2D electron systems placed in an external magnetic field were studied experimentally and theoretically in [9].

For the theoretical description of plasmonic effects in transistor graphene structures, the quasi-electrostatic approach is typically used [10, 11], making it possible to estimate both the frequencies of plasmonic resonances and the possibility of their electrical tuning. However, within the quasi-electrostatic approximation, it is impossible neither to describe the retardation effects of electromagnetic fields, nor to solve problems of the excitation of 2D plasmons by electromagnetic waves and the emission of electromagnetic waves by 2D plasmons.

A clear advantage of the finite-difference time-domain (FDTD) method is its applicability for analyzing the plasmonic effects in complex structures containing the resonators of various geometric shapes [12, 13]. However, FDTD calculations were unable to explain experimental data on 2D plasmon resonances in graphene nanoribbons [14]. The intrinsic problem of the FDTD method arises from large differences in the scales of subwavelength plasmonic elements and of the entire structure, the latter typically significantly exceeds the wavelength of the electromagnetic wave.

In this paper, we study the hybridization of fundamental and higher plasmon modes of a graphene square screened by a metal back gate with the Fabry–Pérot resonances in the barrier layer by using a self-consistent electromagnetic approach.

Materials and Methods

The structure consists of a graphene square with a side $w = 1 \mu\text{m}$ separated from the metal back gate by a barrier layer of boron nitride of thickness d with a dielectric constant $\epsilon_2 = 4.5$ (Fig. 1, *a*). The metal gate is located on the surface of the dielectric medium with a dielectric constant $\epsilon_3 = 4.5$. A plane monochromatic THz wave with the electric field polarized along one side of the graphene square is normally incident onto graphene from free space ($\epsilon_1 = 1$). The Fermi energy of charge carriers in graphene is 150 meV, its momentum scattering time is 2 ps which corresponds to carrier mobility about $10^7 \text{ cm}^2/\text{V}\cdot\text{s}$ at room temperature [15].

The study was conducted within the framework of the self-consistent electromagnetic approach based on the integral equation method [16, 17]. This approach includes several steps. First, Maxwell's equations and electromagnetic boundary conditions are Fourier transformed. In the next step, the integral equations for the components of oscillating current densities in x - and y -directions in graphene are formulated. Third, these integral equations are solved using the Galerkin method, which transforms the system of two integral equations into an infinite system of linear algebraic equations for the coefficients of the current density expansion over the Legendre polynomials. Finally, the infinite system of linear algebraic equations is truncated to achieve the desired level of the solution convergence and numerically solved. The calculated coefficients of the current density expansion make it possible to calculate the absorption cross-section of the structure, determine the electromagnetic fields in any point of the structure, and find the spatial distribution of charge density oscillations in graphene. To evaluate the efficiency of plasmon excitation in graphene, the absorption cross-section (as the ratio of the average absorbed power

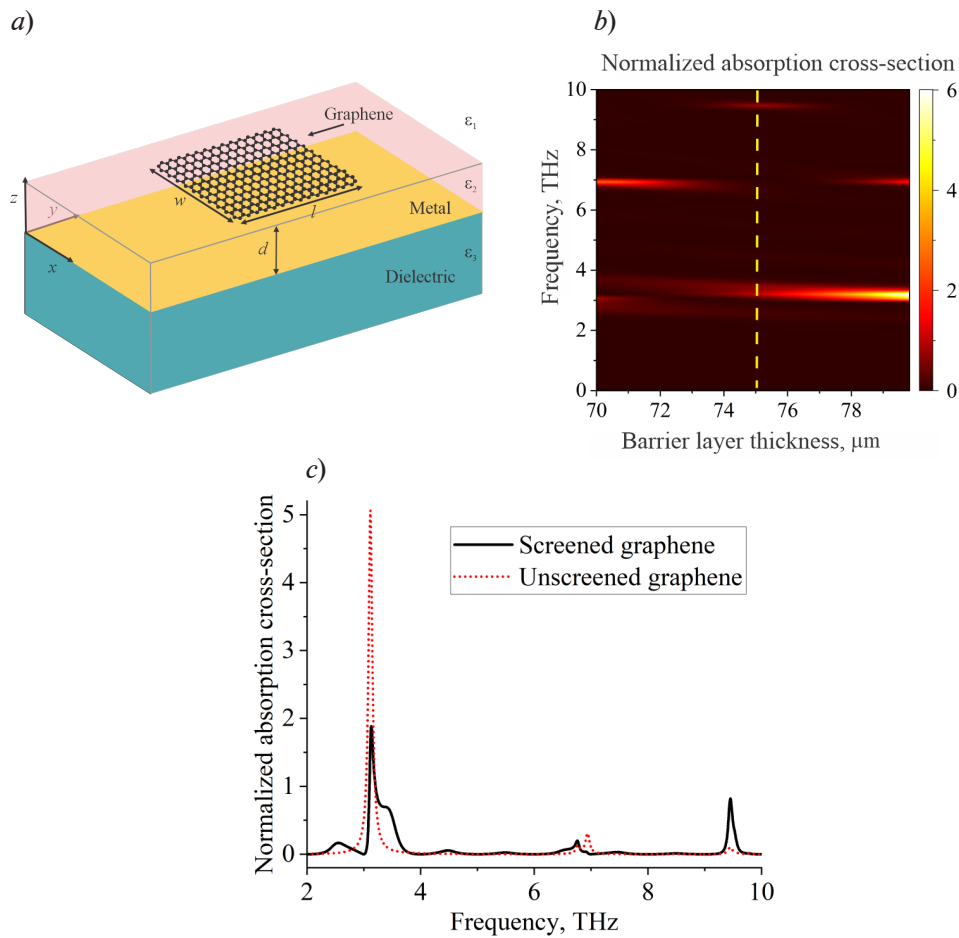


Fig. 1. Studied structure (a); absorption cross-section (normalized to the geometric area of graphene square) spectra as a function of barrier layer thickness (b); normalized absorption cross-section of unscreened graphene (red dotted line) and screened graphene with barrier layer thickness $d = 75 \mu\text{m}$ (black solid line; the third resonance amplification mode at a frequency of 9.5 THz) (c)

to the average energy flux density of the incident wave), normalized to the area of graphene, is used in the work.

Results and Discussion

The dependence of calculated normalized absorption cross-section spectra on barrier layer thickness demonstrates the fundamental plasmon resonance with large dipole moment (at a frequency of about 3 THz) and the series of higher plasmon resonances with smaller dipole moment (at frequencies of about 7 THz and 9.5 THz) (Fig. 1, b) [18]. Due to the smaller dipole moment of higher plasmon modes, they are much more weakly coupled to the external THz wave. Using a structure with a thick dielectric barrier whose thickness is comparable to the wavelength of THz wave, it is possible to observe Fabry–Pérot resonances in the barrier layer at frequencies $\omega = \pi(2m - 1) / (2\sqrt{\epsilon_0\mu_0\epsilon_2d})$, here m is an integer. Fig. 1, b shows the Fabry–Pérot resonances in the dielectric barrier layer due to their interaction with plasmon resonances. The frequencies of plasmon resonances do not depend on d for such distances between the graphene and the metal screen, since the plasmon wavelength is significantly shorter than d . The cross-section of the absorption spectrum of Fig. 1, b at $d = 75 \mu\text{m}$ is shown in Fig. 1, c (black solid line). Fig. 1, c (black solid line) also shows the main plasmon resonance (3 THz) and two higher resonances at frequencies at 7 and 9.5 THz, as well as a set of Fabry–Pérot resonances. Hybridization of plasmon resonances and Fabry–Pérot resonances occurs if the barrier layer thickness is comparable with the wavelength of incident THz wave in medium 2. In the constructive interference regime, more power of incident THz wave is converted into plasmons in the graphene, increasing the plasmon absorption cross-section. This plasmon ‘pumping’ effect significantly increases the efficiency of



interaction of THz radiation not only with the fundamental but also with higher plasmon modes (Fig. 1, *c* (black solid line)). The interference of plasmon modes in the graphene layer and Fabry–Pérot modes in the barrier layer allows selective enhancement of higher plasmon modes and, thus, a significant increase in the localization of the plasmon electric field. The absorption cross-section of high plasmon modes in screened graphene square is increased by an order of magnitude compared to that in the unscreened structure (Fig. 1, *c* (red dotted line)).

The Fabry–Pérot resonances of electromagnetic wave in the barrier layer can be used not only to enhance but also to weaken parasitic plasmonic resonances, for example, to create narrow-band radiation sources.

Conclusion

In this work, we predict hybridization between the fundamental and higher plasmonic modes of a graphene square screened by a metal back gate and the Fabry–Pérot resonances in the barrier layer. The anticrossing effect of plasmon and Fabry–Pérot resonances makes it possible to create structures which may enhance or weaken any plasmon resonance, especially the higher ones.

Acknowledgments

This study was funded by the Russian Science Foundation, Grant # 22-19-00611-П.

REFERENCES

1. Otsuji T., Boubanga Tombet S.A., Satou A., Fukidome H., Suemitsu M., Sano E., Popov V., Ryzhii M., Ryzhii V., Graphene-based devices in terahertz science and technology, *Journal of Physics D: Applied Physics*. 45 (30) (2012) 303001.
2. Mayorov A.S., Gorbachev R.V., Morozov S.V., Britnell L., Jalil R., Ponomarenko L.A., Blake P., Novoselov K.S., Watanabe K., Taniguchi T., Geim A.K., Micrometer-scale ballistic transport in encapsulated graphene at room temperature, *Nano Letters*. 11 (6) (2011) 2396–2399.
3. Han J.W., Progress of terahertz nonlinearities on graphene plasmonic structures, *Current Applied Physics*. 74 (2025) 44–53.
4. Boubanga Tombet S., Knap W., Yadav D., Satou A., But D.B., Popov V.V., Gorbenko I.V., Kachorovskii V., Otsuji T., Room-Temperature Amplification of Terahertz Radiation by Grating-Gate Graphene Structures, *Physical Review X*. 10 (3) (2020) 31004.
5. Ryzhii V., Negative dynamic conductivity of graphene with optical pumping, *Journal of Applied Physics*. 101 (8) (2007) 083114.
6. Moiseenko I.M., Fateev D.V., Popov V.V., Dissipative drift instability of plasmons in a single-layer graphene, *Physical Review B*. 109 (4) (2024) L041401.
7. Kukushkin I.V., Muravev V.M., Smet J.H., Hauser M., Dietsche W., Von Klitzing K., Collective excitations in two-dimensional electron stripes: Transport and optical detection of resonant microwave absorption, *Physical Review B*. 73 (2006) 113310.
8. Nikitin A.Y., Guinea F., García-Vidal F.J., Martín-Moreno L., Edge and waveguide terahertz surface plasmon modes in graphene microribbons, *Physical Review B*. 84 (2011) 161407(R).
9. Zarezin A.M., Mylnikov D., Petrov A.S., Svintsov D., Gusikhin P.A., Kukushkin I.V., Muravev V.M., Plasmons in a square of two-dimensional electrons, *Physical Review B*. 107 (2023) 075414.
10. Rakheja S., Sengupta P., Gate-voltage tunability of plasmons in single-layer graphene structures - Analytical description, impact of interface states, and concepts for terahertz devices, *IEEE Transactions on Nanotechnology*. 15 (2016) 113.
11. Ryzhii V., Ryzhii M., Shur M.S., Mitin V., Satou A., Otsuji T., Resonant plasmonic terahertz detection in graphene split-gate field-effect transistors with lateral p-n junctions, *Journal of Physics D: Applied Physics*. 49 (2016) 315103.
12. Zhou F., Wang Y., Zhang X., Wang J., Liu Z., Luo X., Zhang Z., Gao E., Dynamically adjustable plasmon-induced transparency and switching application based on bilayer graphene metamaterials, *Journal of Physics D: Applied Physics*. 54 (2021) 054002.
13. Lorente-Crespo M., Ballesteros G.C., Mateo-Segura C., García-Meca C., Edge-plasmon whispering-gallery modes in nanoholes, *Physical Review Applied*. 13 (2020) 1.

14. Zhao W., Zhao S., Li H., Wang S., Zhang S., Huang K., Qiu H., Chen J., Li Z., Luo Y., Gao P., Wang Y., Bao W., Gao P., Bai X., Wang J., Nanoimaging of low-loss plasmonic waveguide modes in a graphene nanoribbon. *Nano Letters*, 21 (7) (2021) 3106–3111.

15. Domaretskiy D., Wu Z., Nguyenet V.H., Hayward N., Babich I., Li X., Nguyen E., Barrier J., Indykiewicz K., Wang W., Gorbachev R.V., Xin N., Watanabe K., Taniguchi T., Hague L., Fal'ko V.I., Grigorieva I.V., Ponomarenko L.A., Berdyugin A.I., Geim A.K., Proximity screening greatly enhances electronic quality of graphene, *Nature*. 644 (2025) 646–651.

16. Mashinsky K.V., Popov V.V., Fateed D.V., Complete electromagnetic consideration of plasmon mode excitation in graphene rectangles by incident terahertz wave, *Scientific Reports*. 14 (2024) 7546.

17. Fateev D.V., Polischuk O.V., Mashinsky K.V., Calculation plasmon resonances in the structure of a graphene rectangular resonator located above a homogeneous graphene sheet, *RENSIT*. 18 (1) (2026) 115–122.

18. Polischuk O.V., Fateed D.V., Popov V.V., Terahertz plasmon modes excitation in a graphene square microcavity, *RENSIT*. 16 (3) (2024) 367–372.

THE AUTHORS

MASHINSKY Konstantin V.

konstantin-m92@yandex.ru

ORCID: 0000-0002-0724-6391

POPOV Vyacheslav V.

popov_slava@yahoo.co.uk

ORCID: 0000-0003-1303-6443

FATEEV Denis V.

fateevdv@yandex.ru

ORCID: 0000-0003-1406-5385

Received 15.12.2025. Approved after reviewing 23.03.2026. Accepted 24.03.2026.