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Excitation of plasmon modes localized at the edge of a graphene rectangle by teraherz wave

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Abstract. Excitation of edge plasmon modes in a graphene rectangle by an incident electromagnetic wave is predicted. The problem is solved using a self-consistent electromagnetic approach based on the method of integral equations developed by the authors. It is found that the frequencies of edge plasmon resonances depend on both the width and length of graphene rectangle. For a graphene rectangle having the aspect ratio of 1 micron by 200 microns, the frequencies of edge plasmon resonances lie in terahertz frequency range

Keywords: edge plasmon, terahertz, graphene

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Возбуждение терагерцовой волной плазмонных мод, локализованных на краю графенового прямоугольника

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Аннотация. Предсказано возбуждение падающей электромагнитной волной краевых плазмонных мод в графеновом прямоугольнике. Задача о возбуждении плазмонов решена с помощью разработанного авторами самосогласованного электродинамического подхода, основанного на методе интегральных уравнений. Обнаружено, что частоты краевых плазмонов зависят как от ширины графенового прямоугольника, так и от его длины. Для прямоугольника с аспектным соотношением сторон 1 микрон на 200 микрон частоты резонансов краевых плазмонов лежат в терагерцовом диапазоне частот.

Ключевые слова: краевой плазмон, терагерц, графен

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Introduction

Plasmons in graphene structures are considered as promising platform for planar terahertz optoelectronics [1,2]. Advantages of plasmons in graphene include field localization at lengths shorter than the electromagnetic wavelength [3], nonlinear properties useful for terahertz detection [4, 5], as well as the possibility of their amplification [6, 7].

Theoretical studies of plasmon effects are commonly conducted in the assumption that the graphene structure is uniform and infinitely long in the direction perpendicular to the plasmon wave vector [8, 9]. Different types of plasmon modes in two-dimensional (2D) electron systems have been studied under this assumption: single-layer plasmons [10], screened plasmons [11, 12], "gate proximity" plasmons [11], and oblique plasmons in graphene nanoribbon array [13].

Consideration of full three-dimensional plasmonic problems, in which a 2D plasmonic cavity is confined in two perpendicular directions, made it possible to reveal edge plasmon modes [14]. Using the near-field optical microscopy for excitation and imaging plasmons in disk-shaped and rectangular graphene nanocavities, strong interaction of edge [15, 16] and sheet plasmon modes [14] was experimentally observed. Edge plasmon is viewed as a tool for stronger localization of terahertz (THz) field below the diffraction limit [17].

In this work, we predict the excitation of plasmonic modes localized near the edge of a graphene rectangle by a normally incident THz electromagnetic wave.

Structure and Methods

We solve the problem of the incidence of an electromagnetic wave on a rectangular graphene cavity (Fig. 1, *a*). A graphene rectangle lies on a flat interface between two media with different dielectric constants; the length of the rectangle is $l = 200$ μm, and its width is $w = 1$ μm. A linearly polarized wave of THz frequency is normally incident on the plane of the interface between two media, scatters by a graphene rectangle and excites plasmon modes in it. The electric field vector of the incident wave is polarized along the short side of the rectangle w.

The problem is solved using a rigorous electromagnetic approach based on the integral equation method [18]. The main steps of the electromagnetic approach include:

(i) Fourier transformation of the Maxwell equations and electromagnetic boundary conditions;

(ii) formulation of the integral equations for the components of oscillating current densities in graphene;

(iii) solving the integral equations using the Galerkin procedure by expanding the current density components into series over the orthogonal Legendre polynomials;

(iv) transforming the system of integral equations into an infinite system of linear algebraic equations for the expansion coefficients of current densities;

(v) truncating the infinite system of linear algebraic equations for reaching the desired convergence of its solution and then solving it numerically.

The calculated expansion coefficients of current densities make it possible to determine the electromagnetic fields at any point of the structure under consideration, calculate the absorption cross section of the structure, and find the spatial distributions of charge density oscillations over the graphene rectangle.

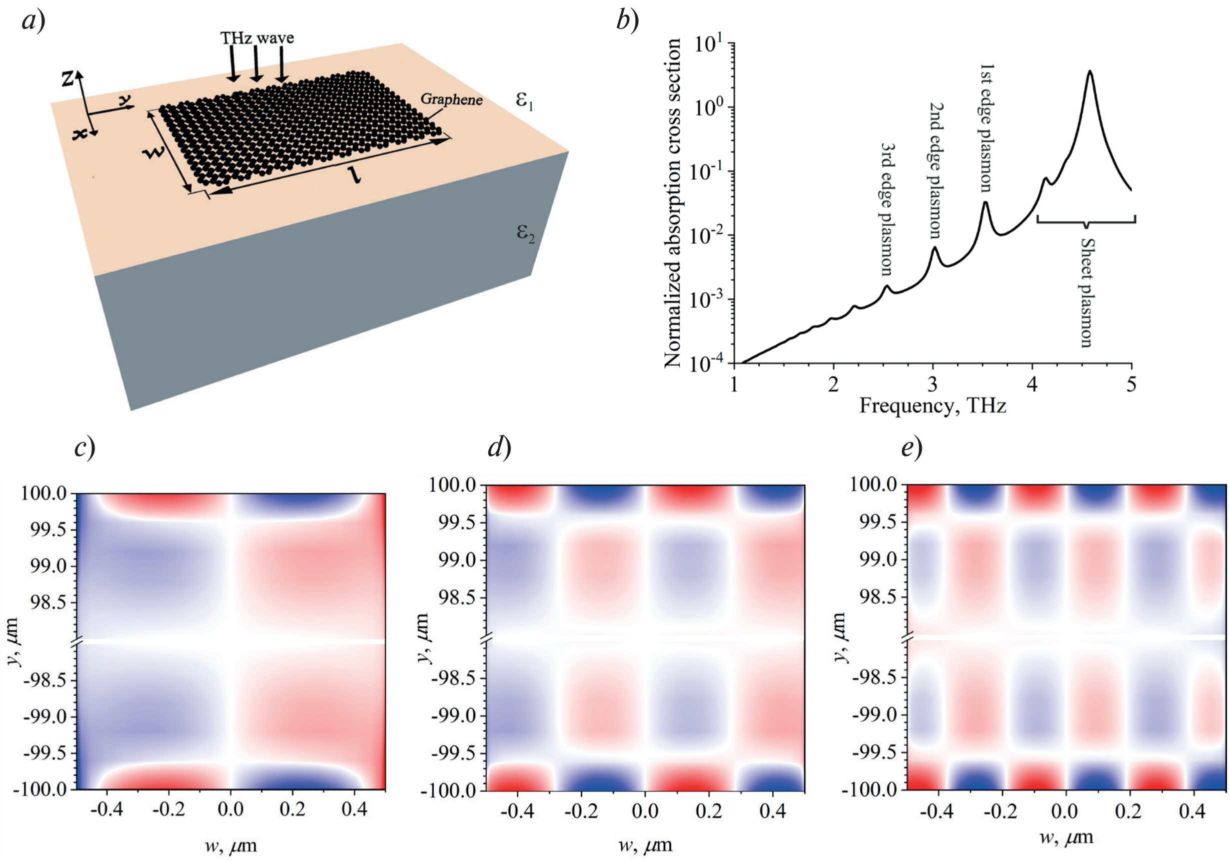

Fig. 1. Schematic view of the studied structure (*a*). Spectrum of absorption cross-section normalized to the geometric area of graphene rectangle for w = 1 μm and l = 200 μm (*b*). The instantaneous spatial distributions of the oscillating charge density over the area of graphene rectangle in the plasmon resonances excited at frequencies of 3.6 THz (*c*), 3.1 THz (*d*), and 2.5 THz (*e*). Red color in panels (*c*), (*d*), and (*e*) indicates a positive sign of the oscillating charge density, and blue indicates a negative sign. Considerable middle parts of the vertical axes y in panels *c*, *d*, and *e* are omitted to visually show the effects at the edges of graphene rectangle. Parameters of graphene: Fermi energy of charge carries is 150 meV and the momentum relaxation time of charge carriers in graphene is 2 ps

Results and Discussion

The calculated spectrum of the absorption cross section of graphene rectangle demonstrates a series of different resonances (Fig. 1, *b*). Resonance at frequency 4.6. THz corresponds to the excitation of the fundamental *sheet* dipole plasmon mode with charge density oscillations across the length of the graphene rectangle. This fundamental plasmon mode is distributed almost homogeneously along the length of graphene rectangle. For long rectangles with length $l > 50w$, additional resonances are revealed at frequencies below the fundamental *sheet* plasmon mode frequency (Fig. 1, *b*). Instantaneous spatial distributions of the oscillating charge density in these plasmon modes in graphene rectangle are plotted in Figs. 1, *c*, *d*, *e*. As seen in Figs. 1, *c*, *d*, and *e*, the charge oscillations in these plasmon modes are strongly localized near the longitudinal edges of graphene rectangle in crucial contrast from the well-known fundamental *sheet* plasmon mode in which the charge oscillations exist over the entire area of graphene cavity. The profiles of the charge carrier distributions in these modes correspond to the bright plasmon modes because have strong dipole moments due to odd numbers of nodes across the length of graphene rectangle. The wave number of the *edge* plasmon mode excited at frequency 3.6 THz is close to the value of $k_x = \pi/w$, the wave number of the *edge* plasmon mode excited at frequency 3.1 THz is close to $3\pi/w$, and for the *edge* plasmon mode excited at frequency 2.5 THz its wave number corresponds to $5\pi/w$. The dependence of the resonance frequencies these *edge* plasmon modes on their wave numbers are typical for the backward waves characterized by anomalous dispersion.

Conclusion

In this work, we predict the *edge* plasmon modes in graphene rectangular cavity which can be excited by incident THz electromagnetic wave. The frequencies of *edge* plasmon modes fall within THz frequency range in elongate graphene rectangles with micron width. The frequencies of the *edge* plasmon modes reside below the frequency of the fundamental *sheet* dipole plasmon mode in long graphene rectangles with a length approximately 50 times longer than the width of graphene rectangle.

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