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EXCITATION OF SURFACE PLASMON-POLARITONS BY ATTENUATED TOTAL REFLECTION IN GRAPHENE-BASED METASURFACE

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In this work we theoretically analyze the electromagnetic behavior of graphene-based metasurface, consisting on arranged array of graphene stripes, under attenuated total reflection conditions. We investigate surface plasmon-polaritons excitation at terahertz and sub-terahertz frequencies. We show that surface plasmon-polaritons may be excited in the metasurface for some orientation with respect to incident wave plane. Effectivity of surface plasmon-polaritons excitation depends on graphene chemical potential and graphene stripes width. We believe that our results open a new road for graphene metasurface based terahertz devices, such as modulators.

Keywords: *graphene, metasurface, terahertz.*

Introduction

Plasmonics is a modern branch of photonics that studies the localization conditions of electromagnetic fields on scales of the order of the wavelength and smaller than the wavelength. Currently, research in the field of plasmonics is developing quite rapidly, since this area has great potential for development, and an increasing number of researchers are joining it. Plasmon structures are already widely used in nanolasers and biosensors. The discovery of graphene production caused a huge stir in the scientific world. Graphene was mathematically modeled in the last century, but it was not possible to get it in practice until 2004 [1]. Due to the vastness of its properties, including electromagnetic ones, graphene has been widely developed in many fields of science, including plasmonics [2–7].

Recently, the study of metasurfaces, two-dimensional analogs of metamaterials, has also attracted great interest in modern physics. Metasurfaces, like metamaterials, allow you to control the properties of radiation, but at the same time they have much lower absorption [8]. An important feature of such surfaces is their compatibility with modern planar technologies used in modern electronics, while retaining most of the properties inherent in three-dimensional metamaterials.

In this paper, an attempt is made to combine all three scientific directions to further study their properties in more detail.

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1. Theoretical background

Plasmon excitation in graphene-based metasurfaces was studied using Otto geometry [9]. This method is based on the principle of total internal reflection. At the angle of incidence of the exciting wave $\theta > \theta_{\text{crit}}$ (θ_{crit} is the critical angle of total internal reflection), photons from a semi-infinite prism tunnel through the air gap and excite plasmons on a metasurface located on a semi-infinite dielectric (Fig. 1).

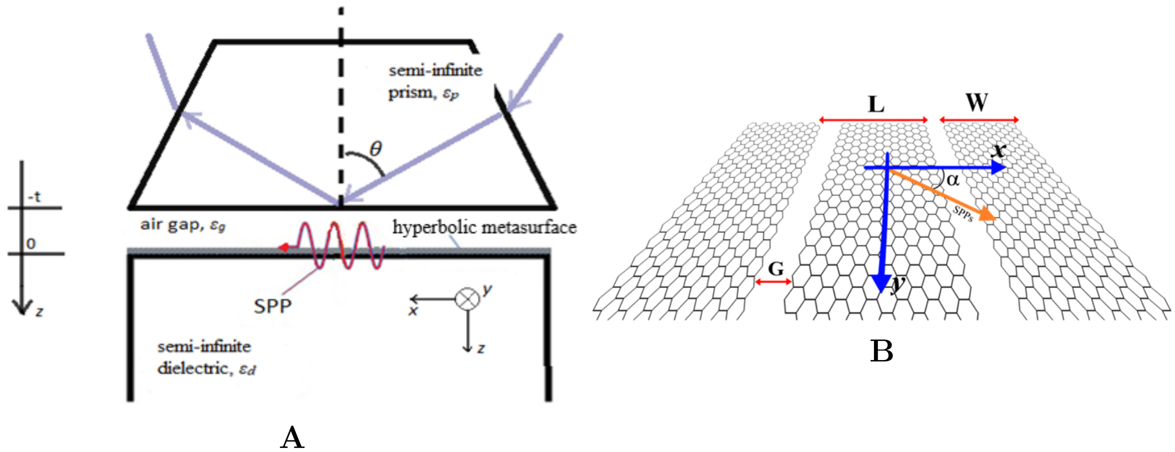

Fig. 1. Cross-section of surface plasmon excitation in graphene-based metasurface using Otto geometry and scheme of graphene-based metaurfece with propagation direction of SPPs

By solving a system of Maxwell's equations with corresponding boundary conditions at each interface (semi-infinite prism — air gap and air gap — metasurface — semi-infinite dielectric), we can calculate the reflection coefficients of an electromagnetic wave from a given structure, which can be used to conclude how much of the energy of the incident wave is transferred to the excitation of surface plasmons.

A graphene-based hyperbolic metasurface was chosen as the surface on which plasmons are excited. Such a metasurface has a number of unique properties, such as the radiation pattern of a point dipole placed on such a surface, the hyperbolic form of the isofrequency contour, and the Purcell effect [10].

Such a metasurface can be obtained by using a lattice of graphene strips. The conductivity tensor of such a surface has the following form [10; 11]:

$$\hat{\sigma} = \begin{pmatrix} \sigma_{xx}^{\text{eff}} & 0 \\ 0 & \sigma_{yy}^{\text{eff}} \end{pmatrix}.$$

The components of such a tensor can be calculated using the following formulas:

$$\sigma_{xx}^{\text{eff}} = \frac{L\sigma\sigma_c}{W\sigma_c + G\sigma}, \quad \sigma_{yy}^{\text{eff}} = \sigma\frac{W}{L},$$

where G is the gap width between the strips, W is the width of the strips, L is the lattice period, σ is the graphene conductivity; $\sigma_c = -i\omega\epsilon_0 L\pi \ln[\csc(\pi G/L)]$ is the effective conductivity associated with the near-field interaction between adjacent graphene strips. Also in this paper, we consider the situation in the absence of an external magnetic field $B = 0$, from which we can conclude that the conductivity of graphene in this paper is equal to [12]:

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}},$$

where

$$\sigma_{\text{intra}} = \frac{2ie^2k_BT}{\hbar^2\pi(\omega+i\Gamma)} \ln\left[2\cosh\left(\frac{\mu_{ch}}{2k_BT}\right)\right],$$

$$\sigma_{\text{inter}} = \frac{e^2}{4\hbar\pi}\left[\frac{\pi}{2} + \arctan\left(\frac{\hbar\omega-2\mu_{ch}}{2k_BT}\right) - \frac{i}{2}\ln\frac{(\hbar\omega+2\mu_{ch})^2}{(\hbar\omega-2\mu_{ch})^2-(2k_BT)^2}\right],$$

2. Results and discussions

The following values of the structure parameters were used to calculate the reflection coefficients: $\varepsilon_p = 12$, $\varepsilon_g = 1$, $\varepsilon_d = 4$, $T = 300$ K, $\mu_{ch} = 0.2$–0.8 eV, $\Gamma = 0.11$ eV, $t = 2$ μm, $L = 100$ nm.

Due to the large number of parameters, we will further investigate an excitation of SPPs numerically. First, let us consider a metasurface with gaphene stripe width $W = 75$ nm and graphene chemical potential $\mu_{ch} = 0.8$ eV, oriented at small angle $\alpha = \pi/9$ with respect to the incident light plane. Results of frequency and incident angle dependence of the reflectance is shown in Fig. 2. One can see the region with small values of reflectance which correspond to the incident angle values up to approximately 35 degrees. For the higher incident angles the total internal reflectance should occur because of satisfying the relation of $\theta > \theta_{\text{crit}} = \arcsin[(\epsilon_d/\epsilon_p)^{1/2}] \approx 35.3$ degrees for chosen prism and dielectric. But we can see an attenuation of total internal reflection at low frequencies (below approximately 2 THz) in the incident angle range 37 deg $< \theta <$ 80 deg corresponding to SPPs excitation in graphene metasurface. This angular range decreases with increase of frequency.

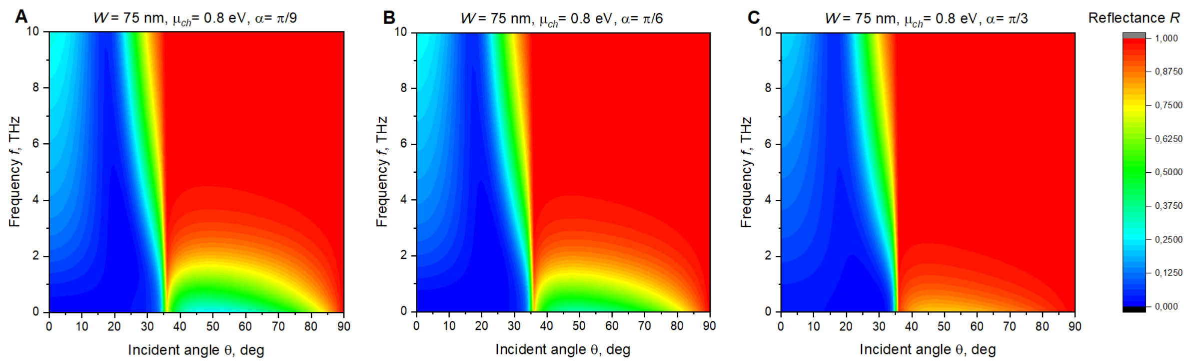

Fig. 2. Reflectance as a function of frequency f and incident angle θ for a TM-polarized incident wave incident wave at a fixed metasurface orientation angle $\alpha = \pi/9$ (A), $\pi/6$ (B) and $\pi/3$ (C). $W = 75$ nm, $\mu_{ch} = 0.8$ eV

Now, let us investigate an impact of metasurface orientation on SPPs excitation. For this reason, we will fix a frequency at $f = 1$ THz and calculate reflectance diagram in $\alpha - \theta$ parameters. Results of calculations are shown in Fig. 3. One can see, that the diagram is symmetric with response to the metasurface orientation angle $\alpha = 45$ degrees.

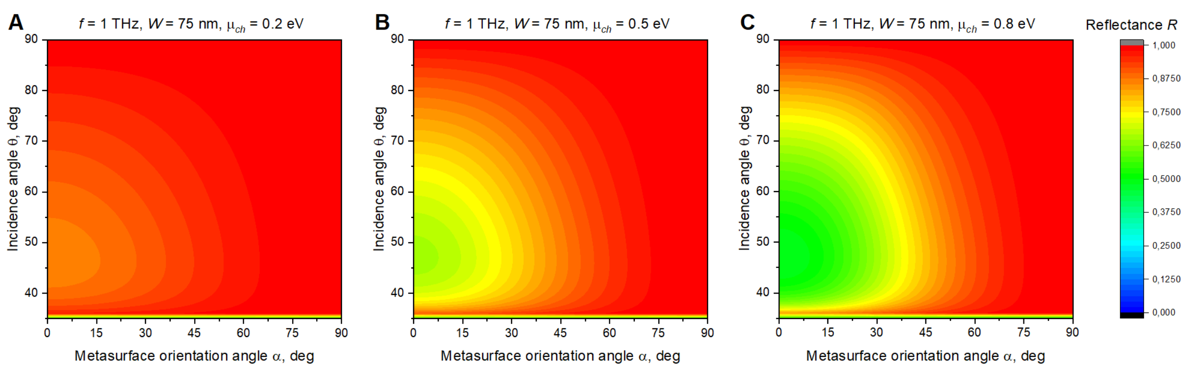

Fig. 3. Reflectance as a function of metasurface orientation angle α and incident angle θ for a TM-polarized incident wave for $f = 1$ THz, $W = 75$ nm and chemical potential values: $\mu_{ch} = 0.8$ eV (A), $\mu_{ch} = 0.5$ eV (B) and $\mu_{ch} = 0.2$ eV (C)

Fig. 3 shows the diagrams for different graphene chemical potential values. One can see, that for lower chemical potentials the excitation of SPPs is less effective and may be observed for narrower range of incident angles.

Now, let us analyze the impact of graphene stripes width on the effectivity of SPPs excitation by attenuated total internal reflection method. Fig. 4 shows the color maps of reflectance for different graphene width stripes ($W = 75$ nm, 50 nm and 25 nm). One can see, that for smaller graphene stripes width the SPPs excitation is less effective.

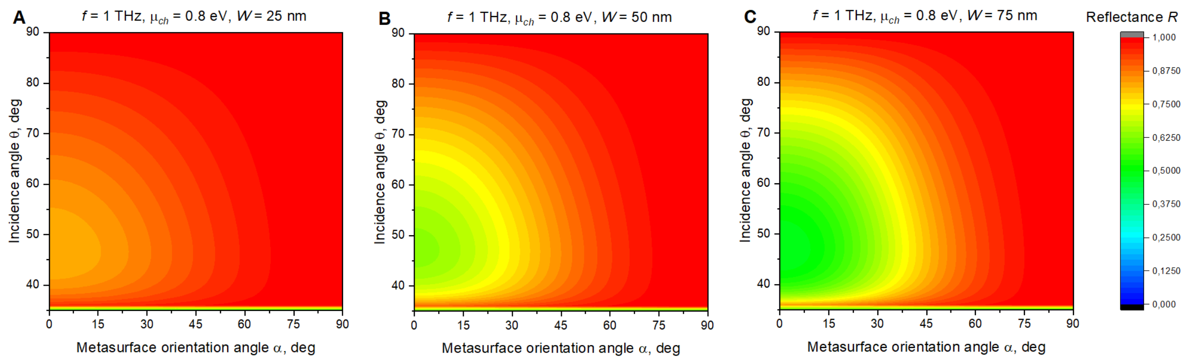

Fig. 4. Reflectance as a function of metasurface orientation angle α and incident angle θ for a TM-polarized incident wave for $f = 1$ THz, $\mu_{ch} = 0.2$ eV and graphene stripe width values: $W = 75$ nm (A), $W = 50$ nm (B) and $W = 25$ nm (C). Colors were rescaled to 0.5-1 range for clarity

From the obtained color maps, we can conclude that excitation of SPPs in graphene-based metasurface may be observed at THz frequencies and it strongly depends on graphene chemical potential, which may be tuned, for example, by gate voltage. While for chemical potential $\mu_{ch} = 0.8$ eV reflectance may decrease in minimum up to approximately 0.45, for $\mu_{ch} = 0.2$ eV at the same metasurface orientation and incidence angle this value is just 0.86. SPPs excitation also depends crucially on graphene stripes width.

Conclusion

For conclusions, our investigation has shown that graphene-based hyperbolic metasurface is a good candidate for THs plasmonics. SPPs excitation may be observed just for some orientation of metasurface with respect to the incident wave plane. It become less effective for smaller graphene chemical potentials and narrower graphene stripe width.

The possibility to significantly tune reflectance by change of graphene chemical potential may open a perspective to use the proposed structure as possible candidate for THz modulator.

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ВОЗБУЖДЕНИЕ ПОВЕРХНОСТНЫХ ПЛАЗМОН-ПОЛЯРИТОНОВ В МЕТАПОВЕРХНОСТИ НА ОСНОВЕ ГРАФЕНА МЕТОДОМ НАРУШЕННОГО ПОЛНОГО ВНУТРЕННЕГО ОТРАЖЕНИЯ

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Теоретически анализируется электромагнитное поведение метаповерхности на основе графена, состоящей из упорядоченного массива графеновых полос, в условиях нарушенного полного внутреннего отражения. Исследовано возбуждение поверхностных плазмон-поляритонов на терагерцовых и субтерагерцовых частотах. Показано, что поверхностные плазмон-поляритоны могут возбуждаться в метаповерхности для некоторой ориентации полос графена относительно плоскости падающей волны. Эффективность возбуждения поверхностных плазмон-поляритонов зависит от химического потенциала графена и ширины полос. Авторы считают, что полученные результаты открывают новые пути развития для терагерцовых устройств на основе графеновой метаповерхности, таких как модуляторы.

Ключевые слова: *графен, метаповерхность, терагерцовый диапазон частот.*

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