Terahertz Rectification by Noncentrosymmetric Plasmonic Metasurface

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***Abstract*—The plasmon modes lacking the inversion symmetry can be excited by terahertz radiation on a noncentrosymmetric plasmonic metasurface formed by a two-dimensional electron system gated by a metal grating with an asymmetric unit cell. Excitation of the noncentrosymmetric plasmon mode leads to the terahertz rectification by generating a plasmon-photogalvanic current in the two-dimensional electron system. Strong terahertz photogalvanic response of the noncentrosymmetric plasmonic metasurface was predicted theoretically and demonstrated experimentally.**

I. Introduction

In natural material crystals without the crystallographic centrosymmetry, DC electric current can by generated under the action of optical illumination. This phenomenon is commonly referred to as the photogalvanic effect [1]. Generally, the absence of the inversion symmetry in a natural crystal yields the asymmetry in the electronic response while the optical field may be symmetric or even homogeneous. Photogalvanic DC response can be exhibited by an artificial noncentrosymmetric microperiodic structure with two-dimensional electron system (2DES) due to asymmetric electronic response [2]. The photocurrent can be excited also in a centrosymmetric 2DES, including graphene, by obliquely incident electromagnetic wave due to the photon drag effect [3].

The purpose of this paper is to show that the photogalvanic current can be excited in a homogeneous 2DES gated by the metal double-grating with an asymmetric unit cell (Fig. 1) if the normally incident terahertz (THz) radiation excites noncentrosymmetric plasmon modes triggering the plasmon drag in 2DES, while the electronic response of 2DES remains centrosymmetric.

II. Differential Plasmon Drag in 2DES

Let us assume that the external THz wave of frequency ω with the electric field polarized across the double-grating metal strips (the x-direction) in the plane of 2DES is incident from vacuum at the normal direction upon the metal double-grating plane. The DC photocurrent density generated due to the ponderomotive nonlinearities in a homogeneous 2D electron system by normally incident THz wave can be described by the equation [4]

$$j_x = -\frac{1}{L}\frac{e\tau}{2m\omega}\int_{-L/2}^{L/2} \mathrm{Im}\left[\sigma(\omega)\tilde{E}_x^{*}\frac{\partial}{\partial x}\tilde{E}_x\right], \qquad (1)$$

where $\sigma(\omega) = e^2 N_{2D}\tau/[m(1-i\omega\tau)]$ is the dynamic Drude conductivity of 2DES with $-e$ and m being the electron charge ($e > 0$) and effective mass, N_{2D} is the sheet electron density, τ is the characteristic electron scattering time, $\tilde{E}_x$ is the x-component of the near electric field induced in the 2DES, and $L = w_1 + s_1 + w_2 + s_2$ is the grating-gate period. One can re-write Eq. (1) in the Fourier representation as [5]

$$j_x = -\frac{e\tau}{2m\omega}\mathrm{Re}[\sigma(\omega)]\sum_{p>0} q_p\left(|\tilde{E}_{x,p}|^2 - |\tilde{E}_{x,-p}|^2\right), \qquad (2)$$

where $q_p = 2p\pi/L$ and $\tilde{E}_{x,p}$ are the amplitudes of the Fourier harmonics of the complex-valued electric field $\tilde{E}_x$ in 2DES. It is seen from Eq. (2) that the net DC photocurrent results from the differential plasmonic drag by the oppositely travelling Fourier harmonics of the electric field in 2DES. The non-zero differential plasmon drag current appears only for a noncentrosymmetric field in 2DES where $|\tilde{E}_{x,p}|^2 \neq |\tilde{E}_{x,-p}|^2$. The sign of the photocurrent is determined solely by the asymmetry of the electric field (because all other quantities entering Eq. (2) are positive), being reversed for the mirror reflection of the near field $|\tilde{E}_{x,p}|^2 \rightarrow |\tilde{E}_{x,-p}|^2$. Therefore, this effect can be termed the plasmon-photogalvanic effect because it is totally determined by the noncentrosymmetry of the near electric field in 2DES. It is worth noting that the noncentrosymmetric plasmonic drag is allowed even for the normal incidence of THz wave upon the 2DES despite the lack of the in-plane component of the photon wavevector in the incoming THz wave. This becomes possible due to an asymmetric profile of the plasmonic field with non-zero in-plane component of the reduced plasmon wavevector.

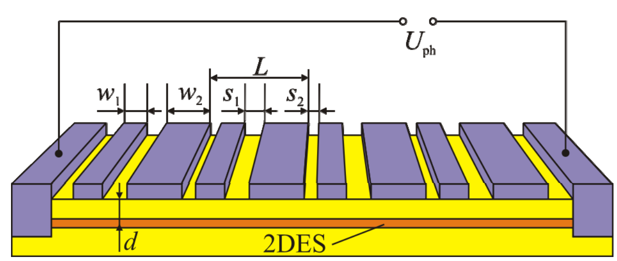

Fig. 1. Two-dimensional electron system gated by the periodic metal double-grating with period $L = w_1 + w_2 + s_1 + s_2$. The double-grating gate is formed by two sub-gratings of metal strips of different width (w_1 and $w_2 \neq w_1$). An asymmetric unit cell of the double-grating gate is formed by the lateral shift of one sub-grating in respect to the other so that $s_1 \neq s_2$. The double-grating gate is separated from a homogeneous 2DES by a barrier layer of thickness d. Terahertz radiation is incident from the top and generates the plasmon-photogalvanic current which induces the photovoltage U_{ph} between the open side contacts.

III. NONCENTROSYMMETRIC PLASMON MODES

Noncentrosymmetric plasmon modes can be excited in 2DES using the metal double-grating-gate coupler with a noncentrosymmetric unit cell [6] irradiated by incoming THz wave (Fig. 1). A particular case of the gated plasmon excitation in a homogeneous 2DES is considered in this paper. (In principle, the plasmons in the ungated parts of 2DES can also be excited. However, the frequencies of the ungated plasmons greatly exceed those of the gated plasmons so that the gated and ungated plasmons can be considered independently.) The wavelength of the gated plasmons excited under a metal strip of the double-grating gate is determined by the width of a respective strip (either w_1 or w_2). The plasmons excited under different metal strips couple forming a collective plasmon mode distributed over the entire area of 2DES. Because the period of the structure is much shorter than THz wavelength, the entire structure can be considered as a planar plasmonic metasurface. Different collective plasmonmodes of such metasurface can interact with each other exhibiting the bright and subradiant modes in the regions of the mode repelled crossings.

Away from the repelled-crossing regions, the normally incident THz radiation excites the plasmon modes with the electric field confined under the strips of either one or another sub-grating. Therefore, the profiles of the plasmon modes remain highly symmetric in the x-direction relative to the center of the respective strip and, hence, the amplitudes of the oppositely travelling Fourier harmonics are almost equal in this case. However, the plasmon modes become strongly noncentrosymmetric (with strongly different amplitudes of the oppositely travelling Fourier harmonics of the plasmonic field) in the repelled-crossing regime due to the cross-dephasing of the two coupled plasmon modes in this regime.

IV. PLASMON-PHOTOGALVANIC CURRENT AND RESPONSIVITY

Enhanced difference in the amplitudes of the oppositely travelling Fourier harmonics in the repelled-crossing regime causes corresponding peaks in the photocurrent due to the differential plasmon drag, Eq. (2). The relative current responsivity is defined as a ratio between the photocurrent density and the energy flux in the incident THz wave.

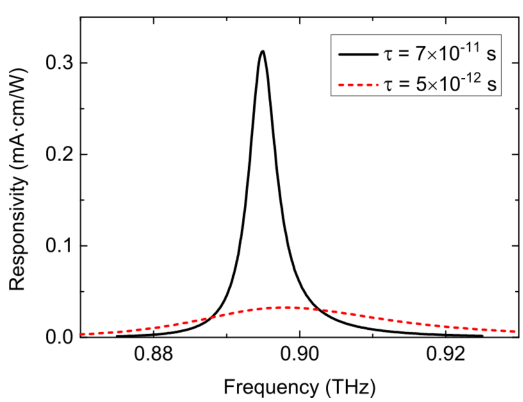

Fig. 2. Responsivity peak of the plasmon-photogalvanic current in the repelled crossing of the plasmon modes in the structure with s_1 = 1 μm, s_2 = 2 μm w_1 = 2 μm, and w_2 = 1.1 μm for two different values of the electron scattering time.

The responsivity peak at the repelled crossing of the plasmon modes with the electric-field distributions of different parities under the metal strips of different sub-gratings is shown in Fig. 2 for two different values of the electron scattering time. For the electron scattering time $\tau = 5\times10^{-12}$ s, the relative responsivity reaches 30 μA·cm/W, which yields the responsivity 150 mA/W for the device area of 20×20 μm^2. This corresponds to the device voltage responsivity 15 kV/W or the 2DES resistance about 100 kΩ. Such strong THz photogalvanic response of the noncentrosymmetric planar plasmonic crystal was demonstrated experimentally [7].

V. SUMMARY

In summary, it has been shown that the plasmon-photogalvanic current can be excited on the plasmonic metasurface with an asymmetric unit cell via the differential plasmon drag of free carriers in 2DES by noncentrosymmetric plasmonic field. A strong asymmetry of the plasmon field arises due to the resonant coupling of different plasmon modes excited on the plasmonic metasurface. Although this analysis is limited to considering the coupling and mixing between the screened plasmon modes, the results have a more general value because they provide a symmetry criteria which can also be applicable for building a strongly asymmetric plasmonic field in a polymodal planar plasmonic crystals supporting both screened and unscreened plasmon modes and incorporating a spatially periodic 2DES. Resonant excitation of the plasmonic field with a strong asymmetry gives a key to understanding the origin of ultra-strong THz plasmon-photogalvanic effects in 2DES.

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