Weak plasmon modes in periodic structures for terahertz detection and amplification

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Abstract. Weak plasmon modes in periodic structures with a two-dimensional electron gas without an inversion center are studied theoretically. The asymmetry of the electric field and Fourier harmonics of weak plasmon modes can lead to the excitation of a travelling plasmon by an electromagnetic wave normally incident on the structure and to the appearance of nonlinear effects leading to the rectification of the incident radiation. The low radiation damping of weak plasmon modes can be used to increase the efficiency of terahertz plasmon amplifiers.

1. Introduction
Plasma waves (plasmons) and plasmon resonances in two-dimensional electron gas (2DEG) of solid-state structures attract wide interest of researchers due to their promising properties. The strong localization of the plasmon field near the 2DEG surface and the strong deceleration of the plasmon in comparison with the electromagnetic (EM) wave make it possible to increase the interaction of the EM fields with matter. The frequencies of plasmons in modern materials fall into the terahertz range, which, together with the picosecond relaxation time of plasmons, makes it possible to observe plasmon resonances at room temperature. It is important that the classical nature of plasmons removes some of the quantum limitations characteristic of the terahertz range. For the excitation of plasmons, effective decelerating systems are needed that match the momentum and energy of EM waves and plasmons.

The aim of the paper is to review the obtained results on using weak plasmon modes in periodical structures including new results of THz lasing with weak modes.

2. Discussions
Standard systems for exciting plasmons are short-period gratings, in which the harmonics of the scattered EM field receive momentum determined by reciprocal grating vectors. The electric field of the incident wave creates a strong dipole moment in the parts of the grating, which leads to the excitation of charge oscillations in the 2DEG. However, among all the eigenmodes of plasmons in spatially symmetric grating structures, along with modes with a large dipole moment (strong modes), there is the same number of eigenmodes with a zero dipole moment. Such weak modes are characterized by a symmetric spatial charge distribution in the plasmon resonator and an antisymmetric field distribution. The incident EM wave cannot create a charge distribution in a symmetric plasmon...
resonator, which is typical for weak modes. Therefore, the excitation of such "weak" plasmon modes by an incident EM wave is impossible in symmetric systems. However, weak modes can be excited in spatially asymmetric systems, in which the spatial field distribution in weak modes transforms from antisymmetric (in a symmetric system) to asymmetric (in a system without an inversion center). This report is devoted to the identification and discussion of the properties and features of the excitation of such weak plasmon modes.

Such weak modes can be excited, for example, in periodic structures in which the spatial symmetry is broken by a direct current flowing in the 2DEG [1]. Another example of a periodic structure without an inversion center, in which the excitation of weak plasmon modes is possible, is a structure with a 2DEG and a dual grating gate (figure 1). The nested gate subgratings are located in the same plane, have different gate widths, and are offset relative to each other in the grating plane to create asymmetry of the unit cell of the periodic structure. Such a double grating with an asymmetric unit cell can be located above one or several parallel sheets of 2DEG.

Excitation of weak plasmon modes due to the introducing the asymmetry into the structure leads to a doubling of the number of plasmon resonances in the spectrum [1]. Additional resonances of weak plasmon modes have a composition of Fourier harmonics different from strong modes. Due to spatial distribution of electric field in plasmon mode (figure 2) its' amplitudes of the dominant counterpropagating Fourier harmonics of weak plasmon modes are not equal to each other, while for strong plasmon modes such amplitudes are the same [2]. This feature of weak modes leads to the possibility of exciting a traveling plasma wave in 2DEG at normal incidence of an EM wave on the system [3]. Due to this property of weak modes, there is a transfer of EM energy and momentum by a traveling plasmon in 2DEG. Since, in the general case, the response of 2DEG to the acting electric field is nonlinear, then along with the excitation of a traveling plasmon, nonlinear quadratic effects will arise, such as rectification of the incident EM wave [4], for example, the effect of dragging of charge carriers in 2DEG by a plasmon. The asymmetric distribution of the plasmon field in the plasmon resonator, which is characteristic of the excitation of weak plasmon modes, leads to the appearance of the plasmon ratchet effect.

The indicated properties of weak plasmon modes also have disadvantages associated with weak conversion of the incident wave energy into a weak plasmon mode. Therefore, to enhance the effects on weak plasmon modes, the properties of the anti-crossing mode are used, in which strong and weak plasmon modes are excited simultaneously. In the anti-crossing mode, both modes are hybrid and have the property of good conversion of the incident wave energy into a plasmon, which is characteristic of strong modes, and the property of asymmetry of weak modes. For example, in the anti-crossing mode, it is possible to direct up to 70% of the incident wave power into a unidirectionally traveling plasma wave.

The possibility of controlling the excitation of weak modes by applying a constant voltage between the gate electrodes and 2DEG looks interesting and promising. On the one hand, using a constant
voltage, it is possible to change the density of charge carriers in the 2DEG under the gate electrode, and, accordingly, the resonance frequency of plasmons, which makes it possible to switch to the anti-crossing mode of plasmon modes. On the other hand, by switching between different weak modes of different orders under different gate electrodes, one can electrically choose the direction of propagation of the traveling plasma wave [5].

Another interesting property of the excitation of weak plasmon modes is their low radiative damping, and, depending on the asymmetry of the structure, the radiative damping of weak modes can be rearranged over a wide range. The most promising application of weak radiative damping is possible in structures allowing amplification of plasma oscillations [6]. The amplification mechanisms can be both drift instabilities and radiative recombination of charge carriers, for example, in graphene or cadmium-mercury-tellurium structures. Since the amplification in the active medium must compensate for the dissipative losses in the system and the radiation losses, the use of weak plasmon modes with small (sometimes almost zero) radiative damping makes it possible to significantly reduce the wave amplification thresholds [7].

3. Conclusions
This paper reviews studies of weak plasmon modes in structures without an inversion center. The use of weak modes for the plasmon detection of THz radiation, for the excitation of a unidirectionally traveling plasmon, and for lowering the plasmon threshold of THz radiation generation in structures with active graphene is considered.

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