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Guided plasmon–polaritons in a planar Bragg microresonator with two-dimesional electron system

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Abstract. We present the results of theoretical investigation of the plasmon–polaritons formed due to the interaction of two-dimensional plasmons in a planar Bragg microresonator with guided modes of dielectric substrate slab. A conclusion is made that guided plasmon–polaritons may be taken up for the development of controllable guided wave THz frequency filters and modulators.

Introduction

Recently, the interaction of dipole electron excitations in two-dimensional (2D) electron systems with electromagnetic (EM) cavity modes have been extensively studied. Particularly, the exciton–phonon coupling in cavity-embedded quantum wells has received the bulk of attention. The exciton–phonon coupling results in the anticrossing between excitonic states and the resonator confined photon modes which gives birth to the cavity-polaritons [1–4]. The cited papers are devoted to radiative exciton–polaritons. Radiative exciton–polariton dispersion has been measured from angle-resolved photoluminescence experiments [3, 4].

Plasma oscillations in 2D electron systems (2D plasmons) are nonradiative electron dipole excitations [5]. Hence they can not couple to EM radiation through one-phonon absorption or emission processes. To couple 2D plasmons to EM wave a lateral diffraction grating with periodicity $L \ll \lambda$, where λ is the EM wavelength, is formed on the top surface of the structure [5]. The grating couples transverse EM wave to longitudinal plasma oscillations with in-plane wavevectors $k_\parallel = 2\pi m/L$ ($m = 1, 2, 3\ldots$). In fact, such a grating makes up an open Bragg resonator for 2D plasma oscillations. The theory of EM emission from 2D plasmons in semiconductor heterostructure with planar metal grating was developed in [6–8].

In a plane-parallel dielectric substrate slab the EM field confinement takes place for guided modes with in-plane wavevectors from the interval $\omega/c < k_\parallel < \omega\sqrt{\varepsilon_s}/c$, where c is the light velocity, ω is the angular frequency of EM wave, ε_s is the dielectric constant of the substrate medium. In this paper we present a theoretical investigation of the polaritons formed due to the interaction of 2D plasmons in a planar Bragg resonator with EM guided modes of dielectric substrate slab.

1. Guided plasmon–polariton dispersion

The structure under consideration involves a plane-parallel dielectric slab of thickness d (semi-insulating GaAs in actual semiconductor heterostructures) with 2D electron system on one of its faces. Planar grating with periodicity L consists of perfectly conducting strips of width w and it is separated from 2D electron system by dielectric interlayer of thickness δ

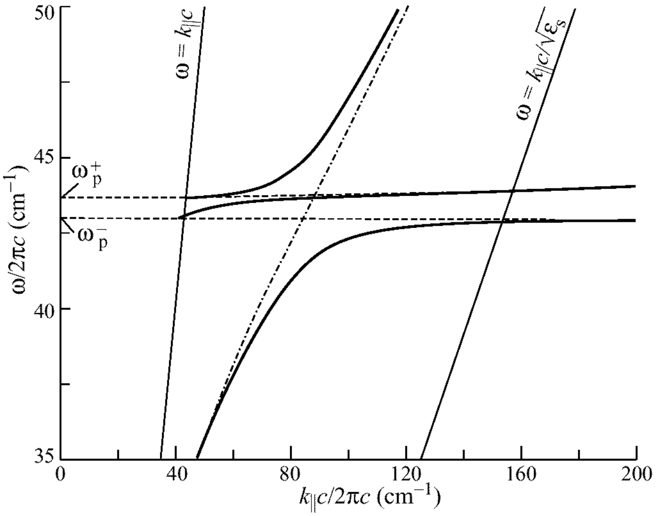

Fig. 1. Guided plasmon-polariton dispersion in the structure with parameters $N_{2\text{D}} = 6.7 \times 10^{11}$ cm^{-2}, $\varepsilon_s = 12.8$, $d = 3.5 \times 10^{-3}$ cm, $\delta = 8 \times 10^{-6}$ cm, $L = 8.7 \times 10^{-5}$ cm, and $w/L = 0.9$ in the case of $1/\tau = 0$.

(wide band gap semiconductor AlGaAs). The in-plane wavevector of polariton excitations studied in this paper is aligned with the direction of the grating periodicity.

The theoretical results given below are obtained through a straightforward extension of our previously published theory [8] to the case of finite thickness of the structure substrate. Similarly to [6–8], 2D electron plasma is described by the areal conductivity $\sigma_{2\text{D}}$ in a local approximation (the Drude model) with the areal density of electrons $N_{2\text{D}}$ and a phenomenological electron relaxation time τ. The parameters used in the calculations are typical of that for 2D electron systems in GaAs/AlGaAs heterostructures. We assume that the substrate dielectric constant ε_s is equal to that of the interlayer.

Figure 1 shows the region of interaction of the fundamental (lowest in the frequency) 2D plasma oscillations with the fundamental EM guided TM-mode of the dielectric substrate slab for the case where there is no electron scattering in the 2D system ($1/\tau = 0$). Dispersion of the fundamental TM-mode is given in Fig. 1 by dash-dotted line. Dashed lines in Fig. 1 mark dispersions of the fundamental 2D plasma eigen-oscillations in a planar Bragg resonator on a semi-infinite substrate. It is known [8] that 2D plasma eigen-oscillations with wavevector $k_\| = 0$, which corresponds to the center of the first Brillouin zone in the reduced band scheme of the Bragg resonator, split up into doublets. One mode in a doublet is radiative while the other is nonradiative. The frequencies of the fundamental nonradiative and rediative modes are denoted in Fig. 1 as ω_p^+ and ω_p^- respectively. The electric fields of different plasma oscillations in the doublet have symmetry of different parities in relation to the centers of the grating slits. The nonradiative mode possesses nodes of the longitudinal electric field at the centers of the grating slits while the radiative one exhibits antinodes of that there.

For $k_\| \neq 0$ a plasmon electric field amplitude distribution does not possess the symmetry with a definite parity in relation to the centers of the grating slits. Therefore, strictly speaking, the both plasma oscillations in the doublet experience radiative damping when their wavevector values fall into the interval $0 < k_\| < \omega/c$. However, the radiative damping of "nonradiative" mode remains several orders of magnitude weaker than that of the "radiative" one since the inequality $\omega/c \ll 2\pi/L$ (i.e. $L \ll \lambda$) is fulfilled. For the same reason, the plasma modes practically conserve definite parities of the symmetry of the electric field amplitude distributions in the interval of $k_\parallel$ shown in Fig. 1.

All modes become nonradiative in the region of the dispersion plane to the right from the light line $\omega = k_\parallel c$ in Fig. 1. In the sector between the light lines $\omega = k_\parallel c$ and $\omega = k_\parallel c/\sqrt{\varepsilon_s}$, the confinement of polariton fields in the transverse direction arises from the total internal reflection of EM wave in the plane-parallel dielectric substrate slab. The electric fields of the guided modes decay with distance from the structure faces whereas inside the substrate a transverse standing wave is formed. When $k_\parallel > \omega\sqrt{\varepsilon_s}/c$, there are only nonradiative 2D plasma oscillations with the electric fields decaying from 2D electron system survive in the structure.

One can see from Fig. 1 that well away from the interaction region the polariton dispersion merges into the dispersion of an uncoupled plasma or EM mode. In the interaction region the EM guided mode demonstrates the anticrossing with the plasmon doublet. As the wavevector increases the lowermost polariton mode transforms from photonlike mode into plasmonlike one. On the contrary, the uppermost polariton mode transforms from plasmonlike mode into photonlike one. The third mode retains its plasmon character at any wavevector value. But the parity of symmetry of the electric field distribution for this mode is reversed with increasing $k_\parallel$.

2. Guided plasmon–polariton resonance

Dispersion and attenuation of guided plasmon–polaritons in the vicinity of the fundamental plasmon doublet at finite electron relaxation in 2D system are shown in Fig. 2 which represent a typical single-resonance behaviour of the system with a full width at half maximum of the attenuation resonance curves of $\Delta\omega = 1/\tau$ in spite of the fact that there

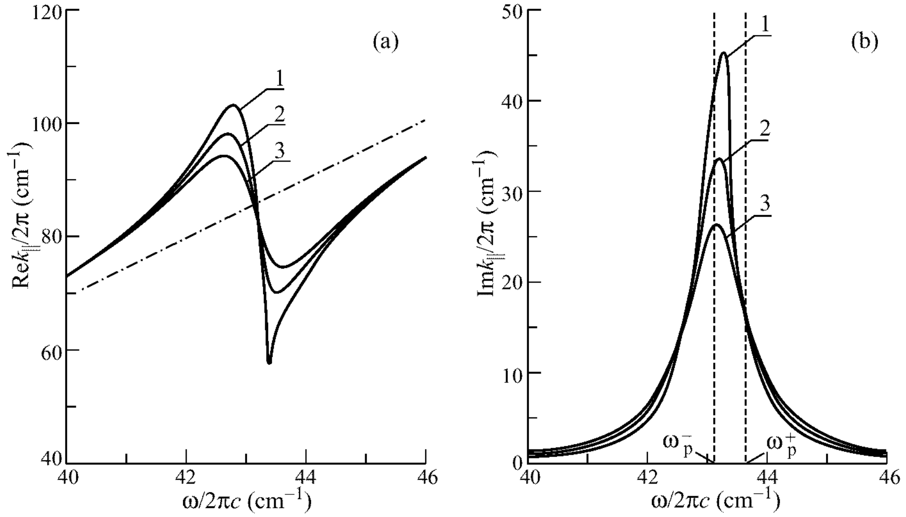

Fig. 2. Dispersion (a) and attenuation (b) of guided plasmon–polaritons for various values of 2D electron relaxation time $\tau = 6.5$ (10^{-12} s) (curves 1), $\tau = 5$ (curves 2) and $\tau = 4$ (curves 3). The other parameters of the structure are the same as in Fig. 1. Dashed-dotted line in Fig. 2(a) marks the dispersion of the fundamental TM-mode of the substrate slab.

are two plasmon eigen-modes with different frequencies in the plasmon doublet. The point here is that the upper plasmon mode in the doublet does not virtually couple to a long-wavelength EM substrate quided mode due to its peculiar electric field distribution parity mentioned above. Hence this mode does not essentially affect the plasmon–polariton resonance curve shape.

The frequency of the fundamental guided plasmon–polariton resonance practically coincides with the frequency ω_p^- of the lower fundamental 2D plasmon mode in the doublet. Clearly this frequency varies with the areal electron density in the 2D system. Culculations show that guided plasmon–polariton attenuation at the resonance may be as great as 50 dB/λ while it is under 0.5 dB/λ away from the resonance. This offers possibilities for the development of controllable guided wave THz frequency filters and modulators.

Acknowledgements

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