TOTAL POLARISATION CONVERSION IN TWO-DIMENSIONAL ELECTRON SYSTEM UNDER CYCLOTRON POLARITON RESONANCE CONDITIONS

V. V. Popov*, T. V. Teperik

Saratov Division of the Institute of Radio Engineering and Electronics,
Russian Academy of Sciences, 410019 Saratov, Russia

*) e-mail: popov@ire.san.ru, Fax: 7(8452)519104

The polarisation conversion of a linear polarized electromagnetic wave incident onto a two-dimensional (2D) electron system at an angle $\theta$ is theoretically studied. We consider the 2D system located at the interface between two dielectric media with different dielectric constants. An external dc magnetic field is assumed to be directed along the normal to the 2D electron layer. In such a configuration the cyclotron-polaritons (CPs) in 2D electron system can be excited with the frequencies in the vicinity of the cyclotron frequency. Under the CPs excitation the resonance polarisation conversion of electromagnetic wave greatly increases in the system. In the absence of the electron scattering in 2D system, the polarisation conversion reaches 100% at a certain value of the angle of incidence $\theta > \theta_R$, where $\theta_R$ is the total reflection angle. Extremely high polarisation conversion takes place in a quite wide range of variation of the angle of incidence. High polarisation conversion efficiency (above 80%) remains when the actual electron scattering in the 2D system on GaAs is taken into account. The considered phenomena may be taken up in polarisation spectroscopy of 2D electron systems.

It is well known that optical-activity effects, which are optical rotation and polarisation conversion, take place in the systems which possess no mirror planes of symmetry. Just such a system is two-dimensional (2D) electron plasma layer in an external magnetic field. The conversion of the polarisation of an electromagnetic wave (EW) shined onto magnetoactive 2D electron system is usually small [1-3] because in this case the region of interaction of EW with the polarisation active medium is small. However, the effect may increase substantially (resonantly) when the external EW excites eigen-oscillations in the 2D system.

The resonant Faraday effect arising in a system of 2D electron disks as result of the
excitation of edge magnetoplasmons was observed in [4]. The results obtained in [4] show that the effect becomes several times stronger under magnetoplasma resonance conditions. At the same time, the power of the polarisation-converted wave in the experiments [4] remains comparatively low (less than 10% of the power of the incident wave). The smallness of the resonance effect in this case is most likely due to the mismatch of the distributions of the field of the external (uniform in the plane of the 2D system) EW and the field of nonuniform edge magnetoplasmons, as a result of which the excitation efficiency of the latter decreases substantially.

The resonant polarisation conversion of an electromagnetic wave which is associated with the excitation of uniform transverse plasma oscillations of electrons in a thin semiconductor film has been studied in [5]. The magnitude of the effect is proportional to a small parameter $d/\lambda$, where $d$ is the film thickness and $\lambda$ is the EW wavelength. Naturally, this lowers the efficiency of resonant polarisation conversion in thin layers.

The limitations due to a small thickness of the electron layer, in principle, do not arise if the external EW excites in-plane eigen-oscillations in the layer. There are two types of in-plane collective excitations in a homogeneous 2D electron system. They are well known surface magnetoplasmon-polaritons (MPPs) and cyclotron-polaritons (CPs) [6]. In [7] it is shown that when the MPPs are excited in a 2D electron system by an external EW in an attenuated total reflection (ATR) geometry, almost complete conversion of the incident $p(s)$-polarised wave into a wave with $s(p)$-polarisation is possible. However, according to [7], total polarisation conversion occurs in the limit of weak coupling of the external EW with 2D electron system. In this case, two resonance conditions, corresponding to excitation of the both MPPs and cyclotron oscillations in 2D electron layer must be fulfilled at the same time. It is clear that these conditions lead to very stringent requirements on the parameters of a possible experiment on the observation of total polarisation conversion. Moreover, dissipation of the energy of the EW due to electron scattering in a real 2D system can lead to almost complete distraction of a weak coupling of the external EW with the oscillations of a 2D electron plasma in the ATR geometry.

In the present work the phenomenon of the resonant polarisation conversion of EW which excites the CPs in a 2D electron system is studied theoretically. Since the CPs are
radiative oscillations, they can be excited by the incidence of the external EW directly onto the surface of a 2D system without using any additional devices (like the ATR structures). In this situation the CPs in a 2D system are strongly coupled to the incident EW, greatly expanding the possibilities of observing the phenomena considered below.

In the structure considered here, the 2D electron layer is located in the $x - y$ plane in the interface of two media with dielectric constance $\varepsilon_1$ and $\varepsilon_2$. Static magnetic field $\vec{B}_0$ is directed along the $z$ axis. One can solve the whole magneto-optical problem in the structure shown in Fig.1 starting from the Maxwell equations with boundary conditions at the interface of the media which take into account the response of the magnetoactive 2D electron plasma. We describe the 2D electron plasma in a simplest local Drude model for conductivity tensor

$$\hat{\sigma} = \begin{pmatrix} \sigma_\perp & \sigma_\times \\ -\sigma_\times & \sigma_\perp \end{pmatrix}$$

with the components

$$\sigma_\perp = \sigma_0 \frac{1 - i\omega\tau}{(\omega_c\tau)^2 + (1 - i\omega\tau)^2}, \quad \sigma_\times = -\sigma_0 \frac{\omega_c\tau}{(\omega_c\tau)^2 + (1 - i\omega\tau)^2},$$

(1)

where $\omega$ is the angular frequency of the EW, $\omega_c = |e|B_0/cm^* = \omega_c = |e|B_0/cm^*$ is the cyclotron frequency, $\sigma_0 = e^2N_s\tau/m^*$ is the conductivity of the 2D electron system in the absence of an external magnetic field, $e$ and $m^*$ are, respectively, the charge and effective mass of electron, $N_s$ is the surface electron density, $\tau$ is the phenomenological relaxation time of the electron momentum in 2D system.

Let us assume that the EW incident onto 2D system from medium 1 (see Fig.1) at an angle $\theta$ to the $z$ axis has a linear $p$-polarisation so that the electric vector of the wave resides in the plane of incidence ($x - z$ plane). Then we can introduce the magneto-optical complex coefficients for electric fields:

$$r_{pp} = \frac{E_p^{(r)}}{E_p^{(i)}}, \quad r_{sp} = \frac{E_s^{(r)}}{E_p^{(i)}}, \quad t_{pp} = \frac{E_p^{(t)}}{E_p^{(i)}}, \quad t_{sp} = \frac{E_s^{(t)}}{E_p^{(i)}},$$

(2)

where superscripts $i$, $r$, and $t$ refer to the incident, reflected, and transmitted waves, respectively, and the subscripts $p$ and $s$ correspond to waves with $p$ and $s$ polarisation (in the latter case the electric field vector of the EW is perpendicular to the plane of incidence).
We can also introduce the power conversion coefficients as ratios of the components of the energy flux vectors normal to the plane of the 2D system:

\[
R_{pp} = \frac{P_{p}^{(r)}}{P_{p}^{(i)}}, \quad R_{sp} = \frac{P_{sp}^{(r)}}{P_{p}^{(i)}}, \quad T_{pp} = \frac{P_{p}^{(t)}}{P_{p}^{(i)}}, \quad T_{sp} = \frac{P_{sp}^{(t)}}{P_{p}^{(i)}} \tag{3}
\]

The meanings of subscripts and superscripts in (3) are the same as in (2). The quantities \(r_{sp}, t_{sp}, R_{sp},\) and \(T_{sp}\) are obviously the polarisation conversion coefficients.

Since the procedure of the solution of the electromagnetic problem is quite standard, although rather cumbersome, we do not present here explicit over lengthy expressions for magneto-optical and power conversion coefficients.

It is well known [6] that the magnitudes of wave vector \(k_x\) of the CPs in the plane of 2D system lie in the range \(0 < k_x < \omega \sqrt{\max(\varepsilon_1, \varepsilon_2)/c}.\) An external EW incident at an angle \(\theta\) excites in the 2D system force oscillations with longitudinal wave vector \(k_x = \omega \sqrt{\varepsilon_1} \sin \theta/c.\) In order to be able to investigate the entire range of variation of the CP wave vector values, we assume \(\varepsilon_1 > \varepsilon_2.\) It is obvious that for \(\theta > \theta_R,\) where \(\theta_R = \sin^{-1}(\varepsilon_2/\varepsilon_1)^{1/2},\) the regime of total internal reflection of the EW from the media interface takes place.

The most interesting is the behaviour of polarisation conversion coefficient \(R_{sp}\) at the CP resonance. The corresponding curves for the case where there is no electron scattering in the 2D system \((1/\tau = 0)\) are presented in Fig.2. The remaining parameters used in the calculations are characteristic for GaAs/AlGaAs heterostructures with a 2D electron gas. The choice of values of the dc magnetic field that correspond to the results presented is dictated by the condition of resonant excitation of the CPs \(\omega \sim \omega_c [6].\) It follows from Fig.2 that \(R_{sp}\) increases substantially in the total internal reflection region and reaches unity at a certain angle of incidence \(\theta > \theta_R.\) For comparison, we indicate that far from resonant values of the dc magnetic field the calculations give a polarisation conversion coefficient \(R_{sp}\) less than \(10^{-3}\) for any angle of incidence. At resonance (Fig.2) the extremely high polarisation conversion coefficient remains in a quite wide range of variation of the angle of incidence of the EW. This is explained by the comparatively weak dependence of the CP frequency on the in-plane wave vector \(k_x = (\omega \sqrt{\varepsilon_1}/c) \sin \theta [6].\) As it is evident from Fig.2, polarisation conversion is quenched for \(\theta = \theta_R\) and \(\theta = \pi/2.\) The physical explanation
for this fact is that in the both cases the total electric field at the 2D electron layer is perpendicular to the 2D system plane [8]. Therefore, the external EW does not interact with in-plane excitations of 2D system at these angles.

In Fig.3 the dark tone indicates \( \omega - \theta \) regions in which the polarisation conversion coefficient \( R_{sp} > 0.99 \) for various values of the surface electron density in 2D system. The figure also shows the CP dispersion curves \( \omega[k_z(\theta)] \) for the same values of the surface density. For a low electron density the total polarisation conversion occurs near the cyclotron-polariton frequency \( (\omega \simeq \omega_c) \) for any angle of incidence of the EW. This corresponds to the case of weak coupling when the external wave induces comparatively low electric currents in the 2D system. As the electron density increases, the coupling of the external EW to the 2D system grows, and the frequency range in which almost total polarisation conversion occurs broadens. Under strong coupling the total polarisation conversion occurs at resonant frequencies different from the CP eigen-frequencies.

The state of polarisation of reflected wave may be determined from the ratio of the magneto-optical complex reflection coefficients (2) \( r_{sp}/r_{pp} = (|r_{sp}|/|r_{pp}|) \exp(i\delta) \). The magneto-optical rotation angle \( \psi \) and ellipticity \( \varepsilon \) of reflected wave are calculated by the formulas [9]:

\[
\begin{align*}
\text{tg}2\psi & = \text{tg}2\varphi \cos \delta, \\
\sin 2\varepsilon & = \sin 2\varphi \sin \delta,
\end{align*}
\]

where \( \varphi = \text{tg}^{-1}(|r_{sp}|/|r_{pp}|) \). In Fig.4 the rotation angle and ellipticity are shown in the frequency range across the CP magneto-optical resonance in the total reflection regime. In the absence of the electron scattering in 2D system the ellipticity becomes zero at the resonance and the rotation angle reaches the values of \( \pm \pi/2 \). These correspond to the total polarisation conversion conditions. The rotation angle experiences a jump of \( \pi \) and the handedness of elliptical polarisation reverses its sign at the resonance. The electron scattering in a real 2D electron system leads to a gradual but still very steep transition of the rotation angle from positive to negative values across the resonance (see Fig.4).

The effect of electron scattering in 2D system on the CP assisted polarisation conversion is demonstrated in Fig.5. It is evident that if the coupling between external EW and the CPs in the 2D system is weak (low electron density), the electron scattering...
suppresses the polarisation conversion effect almost completely like in the case of MPP assisted polarisation conversion in ATR geometry. At the same time, a high polarisation conversion efficiency at CP resonance remains even in the presence of the electron scattering if the electron density in the 2D system is high. Because of that the CP assisted polarisation conversion at high electron densities in 2D system is much more profitable from the practical point of view as compared to MPP assisted one.

Note that the solution of the problem of the incidence of an s-polarized wave onto a 2D electron system gives the same values for the polarisation conversion coefficients \( R_{ps} = R_{sp} \) in the total reflection regime. This attests to a reciprocal character of the polarisation conversion process for \( \theta \geq \theta_R \).

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References

[1] R.F.O’Connell, G.Wallace, Phys. Rev. B., 26 (1982) 2231.

[2] V.A.Volkov and S.A.Mikhailov, JETP Lett., 41 (1985) 476.

[3] V.A.Volkov, D.V.Galchenkov, L.A.Galchenkov et al., JETP Lett., 43 (1986) 326.

[4] L.A.Galchenkov, I.M.Grodnenskii, M.V.Kostovetskii et al., Fiz. Tekh. Poluprovodn., 22 (1988) 1196 [Sov. Phys. Semicond., 22 (1988) 757].

[5] M.I.Bakunov and S.I.Zhukov, Pis’ma Zh. Tekh. Fiz., 16, 1 (1990) 69 [Sov. Tech. Phys. Lett., 16 (1990) 30].

[6] V.V.Popov, T.V.Teperik, and G.M.Tsymbalov, JETP Lett., 68 (1998) 210.

[7] Yu.A.Kosevich, Solid State Commun., 104 (1997) 321.

[8] V.V.Popov and T.V.Teperik, JETP Lett., 70 (1999) 254.

[9] M.Born and E.Wolf, Principles of Optics (6th edn). Oxford: Pergamon Press, 1980.
Figure captions.

Fig.1. The structure under consideration and coordinate system. $\varepsilon_1$ and $\varepsilon_2$ are dielectric constants of the media.

Fig.2. Coefficient of conversion of the polarisation in the reflected wave vs the angle of incidence: a) $N_s = 2 \times 10^{12} \text{ cm}^{-2}$; $B_0$ (kG): 44 (1), 45 (2), 46 (3), 46.5 (4), 47 (5); b) $B_0 = 46$ kG; $N_s(10^{12} \text{ cm}^{-2})$: 0.8 (1), 0.9 (2), 1 (3), 2 (4), 3 (5). $\omega/2\pi c = 60 \text{ cm}^{-1}$, $\varepsilon_1 = 12.8$, $\varepsilon_2 = 1$.

Fig.3. Regions of the parameters $\omega - \theta$ with the polarisation conversion efficiency $R_{sp} > 0.99$ and dispersion curves for cyclotron-polaritons for $\varepsilon_1 = 12.8$, $\varepsilon_2 = 1$, $B_0 = 46$ kG, and $N_s(10^{12} \text{ cm}^{-2})$: 0.2 (1), 1 (2), 2 (3), 3 (4).

Fig.4. Rotation angle (solid curves) and ellipticity (dashed curves) of the reflected wave vs frequency across the CP resonance with no electron scattering (curves 1) and with electron scattering (curves 2, $\tau = 10^{-12}$ s) in 2D system.

Fig.5. Curves 1 and 3 correspond to the case when there is no electron scattering in the 2D system ($1/\tau = 0$); curves 2 and 4 correspond to $1/\tau = 10^{11}$ s$^{-1}$. Curves 1 and 2: $N_s = 2 \times 10^{12} \text{ cm}^{-2}$, $B_0 = 46$ kG; curves 3 and 4: $N_s = 2 \times 10^{11} \text{ cm}^{-2}$, $B_0 = 45.3$ kG. All other parameters are the same as in Fig.2.