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# Spin-current resonances in a magnetically inhomogeneous 2D conducting system

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The high-frequency transport in a two-dimensional conducting ring having an inhomogeneous collinear magnetic structure has been considered in the hydrodynamic approximation. It is shown that the frequency dependence on the radial electric conductivity of the ring exhibits resonances corresponding to new hybrid oscillations in such systems. The oscillation frequencies are essentially dependent on the applied electromagnetic field and the spin state of the system.



## 1. Introduction

Spin accumulation in conducting nanosystems remains a problem of continuous keen interest [1]. Its dynamic aspect was investigated for the first time in [2]. In a conductor with inhomogeneous magnetic properties a nonequilibrium spin concentration generates forces acting on the spin components of the carriers and exciting coupled spin-current oscillations (we call them a "spin pendulum"). In this study we consider the possibility of spin-current resonances in a two-dimensional conducting ring in a non-quantizing magnetic field. As an example, the above effects are examined in a nondegenerate electron system on the liquid helium surface (*ESLH*) and in two-dimensional semiconducting heterostructures. Magnetic inhomogeneity of these systems can be induced in various ways, for example, by introducing nonequilibrium concentrations of magnetic impurities, applying spatially inhomogeneous magnetic fields or inhomogeneous electrostatic gate fields commonly used in experiments on heterostructures [3]. Experimental observation of resonances investigated in the article is the way to reveal of previously predicted by us [2] "spin pendulum" oscillations of the conductor spin system, and study effects associated with them.

For the experimental realization of the predicted effects, one can use materials which are widely used in experiments with 2D electronic conductors in heterostructures [4] based on GaAs and *ESLH*. The problem is only in the creation of the spatial inhomogeneity of the spin polarization conductor by methods suggested above.

Previously we investigated closely the transport and the spin-electric effect in the *ESLH* employing the quasi-equilibrium approximation [5], i.e., in external electromagnetic fields whose frequencies were low enough to permit the spin diffusion to form the equilibrium electron distribution under the influence of the forces of the inhomogeneous magnetic field acting on the spins. It was shown that within the range used the longitudinal and lateral electrical resistances in the magnetic field were determined not only by the momentum-loss scattering of electrons, but also by the electron–electron collisions generally dominant in the *ESLH* [6] and important in low-dimensional semiconducting structures [7]. This study is concerned with the transport properties of the mentioned inhomogeneous systems at relatively high frequencies of the external field. It is shown that new resonances can be formed involving the spin degree of freedom. The conditions of their observation have been studied.

## 2. Two-liquid hydrodynamics of conducting spin systems

The description of conducting systems possessing the spin degree of freedom in the two-liquid hydrodynamic approximation was substantiated in [2]. A similar approach was employed earlier in [8]. For simplicity, we consider a system with collinear magnetization. To put it differently, the system is an incoherent mixture of "spin-up" and "spin-down" states, i.e., two electron spin components. The hydrodynamic approximation is valid when the momentum–conservation collisions in the electron system (normal

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collisions) dominate over other possible ones [9]. We assume that the inequality $\nu_{ee} \gg \nu$ ($\nu_{ee}$ is the frequency of electron–electron collisions, $\nu$ is the frequency of electron collisions with possible structure imperfections) is obeyed and the mean free path is $l_{ee} \ll L$ and $\nu_{ee} \gg \omega$, where $L$ and $\omega$ are the characteristic lengths and frequencies of the problem, respectively. This condition holds true in the *ESLH* [6] and heterostructures [10].

In the *ESLH* currents are generated in a noncontact way by applying an AC electric potential to the electrodes located near the *ESLH*. The same technique is applicable for low-dimensional heterostructures. In this case the polarized charges $\rho_e$ induced by the electrodes in the electron system or the corresponding polarization currents related to the charges according to the continuity equation $div\boldsymbol{j}_e = -\partial\rho_e/\partial t$ can be taken as pre-assigned parameters.

According to [5], the following linearized system of hydrodynamic equations can be written down:

$$i\omega(\rho_{e\sigma} + \delta\rho_\sigma) + div\rho_\sigma \boldsymbol{u}_\sigma = -\nu_s \Pi^*(\mu_\sigma - \mu_{-\sigma}) \tag{1}$$

$$(i\omega + \nu)m\boldsymbol{u}_\sigma - e\frac{[\boldsymbol{u}_\sigma \boldsymbol{H}]}{c} + \nabla(\mu_\sigma + e\varphi) = -m\frac{\rho_{-\sigma}}{\rho}\nu_{ee}(\boldsymbol{u}_\sigma - \boldsymbol{u}_{-\sigma}) \tag{2}$$

$$\sum_\sigma \delta\rho_\sigma = 0 \tag{3}$$

$$\Pi^{*-1} = \sum_\sigma \Pi_\sigma^{-1} \tag{4}$$

This system is for a "good" conductor [5] in which the departure from electric neutrality is related only to the polarization charges providing in the first approximation a steady potential along the conductor; $\varphi$ is the next approximation to the potential induced by the flowing current. We have $\delta\rho_{e\sigma} = 0$ when the current source is connected directly. It is convenient to choose the spin components of the polarization charge in the equilibrium form: $\rho_{e\sigma} = \Pi_\sigma \rho_e/\Pi$, $\Pi = \sum_\sigma \Pi_\sigma$ (however, the total density of the component $\rho_{e\sigma} + \delta\rho_\sigma$ can be far from equilibrium). In Eqs. (1)–(4) $\omega$ is the frequency of the applied electric field, $\delta\rho_\sigma$ is the non-equilibrium addition to the density of the electrons with the spin projections $\sigma$ onto the chosen direction, $\rho_\sigma$ is the equilibrium density which is assumed to be spatially inhomogeneous due to the applied nonuniform electric and magnetic fields and nonequilibrium concentrations of magnetic impurities; $\nu_s$ is the frequency of the spin-flip processes, $\delta\mu_\sigma$ is the nonequilibrium addition to the chemical potential of the spin component in the ESLH case when the momentum distribution of electrons can be considered classical; $\delta\mu_\sigma = T(\delta\rho_\sigma/\rho_\sigma)$, $T$ is the temperature; $\Pi_\sigma$ is the density of states of the spin component at the Fermi surface; $\boldsymbol{u}_\sigma = \boldsymbol{j}_\sigma/\rho_\sigma$ is the drift velocity, $\boldsymbol{H}$ is the magnetic field component perpendicular to the two-dimensional plane, $\nu$ is the frequency of momentum-loss collisions of electrons, $\nu_{ee}$ is the frequency of electron–electron collisions (see the description [11] of the processes of scattering in spin-polarized transport). It is found [5] that at relatively low frequencies the drift velocities of spin components can differ significantly even when the drift approximation is applicable.

At frequencies exceeding the inverse time of spin diffusion within the boundaries of the sample the rate variations in spin components are negligible. In this case it is convenient to multiply Eq. (2) by $\rho_\sigma$ and sum it over $\sigma$:

$$(i\omega + \nu)m\boldsymbol{j} + \sum_\sigma \rho_\sigma \nabla\mu_\sigma + \rho e\nabla\varphi - \frac{e}{c}[\boldsymbol{j}\boldsymbol{H}] = 0 \tag{5}$$

Here $\rho_0 = \sum_\sigma \rho_{0\sigma}$ is the total equilibrium charge density, $\boldsymbol{j} = \rho_0\boldsymbol{u}$ is the total electron flow. On summation the right-hand side of Eq. (2) loses the term describing the mutual friction of the electron components.

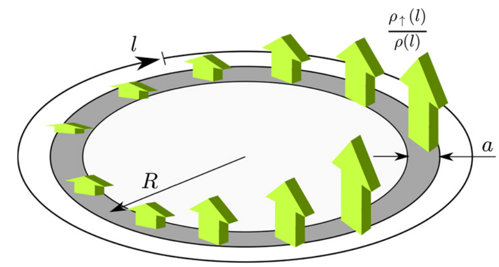


**Fig. 1.** Scheme of the proposed experiment: 2D magnetically inhomogeneous conducting ring with the width $a$ and radius $R$. The annular geometry of the proposed experiment is fundamentally important for considered effect, because this allows current to flow in the direction perpendicular to the applied electric field direction.

## 3. Spin-current and combined spin–cyclotron resonances

Consider a two-dimensional conducting ring with the radius $R$ and width $a$ (see Fig. 1). The ring is connected, directly or in a noncontact way, to an AC current source along its outer and inner boundaries. Apart from the mentioned small parameters of the problem, we take into account the geometric small parameter $a \ll 2\pi R = L$ which normally corresponds to the experimental conditions on the ESLH. The properties of the conductor and the magnetic field are assumed to be homogeneous along the radial coordinate $r$.

Note that in the main approximation with respect to the geometric small parameter the polarization charge density $\rho_{e\sigma}$ can be taken as an odd function of the $r$-coordinate ($-a/2 < r < a/2$). Therefore, on averaging the sought-for values over $r$ the term for polarization charges drops out of Eq. (1). Assuming equal drift velocities for the spin components (see above) we have $\boldsymbol{j}_\sigma = \rho_\sigma\boldsymbol{u} = \boldsymbol{j}\rho_\sigma/\rho$. Averaged Eq. (1) gives:

$$\delta\rho_\sigma = -(i\omega + \nu_s)^{-1} j_l \frac{d}{dl}\left(\frac{\rho_\sigma}{\rho}\right). \tag{6}$$

Here $l$ is the coordinate along the ring. The equation takes into account the absence of a current flow through the sample boundaries on a noncontact connection. In the case of direct connection equation (6) is also valid if densities of the in- and out-currents at the same $l$ are equal to each other. The latter may be provided by the homogeneity of the lead-in and the lead-out when the resistivity of the material of the contacting leads is much higher than that of the ring. $j_l$ is the $l$-projection of the width-averaged total electron flow in the ring. It is $l$-independent by virtue of electric neutrality (result of $\sigma$-summed Eq. (1) and Eq. (3)). Henceforward the notation of averaging is omitted since we use only $r$-averaged quantities (except for Eq. (12)).

Averaging Eq. (5) over $r$ we obtain in the $r$- and $l$-projections:

$$(i\omega + \nu)mj_r + \frac{e}{a}\rho\big[\varphi(a/2) - \varphi(-a/2)\big] + \frac{eH}{c}j_l = 0 \tag{7}$$

$$(i\omega + \nu)mj_l - \sum_\sigma \rho_\sigma \frac{d}{dl}\left[(i\omega + \nu_s)^{-1}\Pi_\sigma^{-1}\frac{dj_l(\rho_\sigma/\rho)}{dl}\right] + e\rho\frac{d\varphi}{dl} - \frac{eH}{c}j_r = 0 \tag{8}$$

According to Eqs. (4) and (6), $\mu_\sigma$ in Eqs. (7) and (8) is expressed in terms of the flows. The $l$-independent parameter $j_l$ in the second term of Eq. (8) is kept under the derivative sign for using the equation in the next section. The term for the pressure difference at the ring edges is omitted from Eq. (7): according to estimation, this quantity is lower in parameter $a \ll L$ than the other contributions to the potential $\varphi$. After dividing both sides of Eq. (8) by $\rho$ and performing integration over $l$ within the boundaries of the ring we obtain:

$$(i\omega+\nu)\langle m/\rho\rangle j_l - j_l\left\langle \sum_\sigma \rho^{-1}\rho_\sigma (i\omega+\nu_s)^{-1}\frac{d}{dl}\left[\Pi_\sigma^{-1}\frac{d\rho_\sigma}{dl}\right]\right\rangle - \frac{e}{c} j_r \langle H/\rho\rangle = 0 \quad (9)$$

$$\langle A\rangle = L^{-1}\oint A dl$$

This equation describes the forced oscillations of the oscillator ("spin pendulum" [2]) whose eigenfrequency is

$$\omega_s^2 = \langle m/\rho\rangle^{-1}\sum_\sigma\left\langle \Pi_\sigma^{-1}\left[\frac{d}{dl}\left(\frac{\rho_\sigma}{\rho}\right)\right]^2\right\rangle \quad (10)$$

$\nu$ and $\nu_s$ are the frequencies responsible for the oscillation damping and the term $ej_r\langle H/\rho\rangle/c$ is the driving force.

We can obtain from Eq. (9)

$$j_l = -(i\omega+\nu_s)\frac{e}{c} j_r \frac{\langle H/\rho\rangle}{\langle m/\rho\rangle(o^2-\omega_s^2)}$$
$$o^2 = -(i\omega+\nu_s)(i\omega+\nu) \quad (11)$$

It is clear that the $l$-component of the polarization current can be neglected on account of the parameter $a \ll L$ and the component $j_r$ is taken equal to the polarization current:

$$j_r = j_{er} = -i\omega\int_{-a/2}^{r}\rho_e dr' \quad (12)$$

In the case of a noncontact connection $j_r$ is the source-allowed input current. By substituting Eq. (11) into Eq. (7), dividing the obtained equation by $\rho$ and integrating it with respect to $l$ we can find the electrical resistance of the ring, i.e., the correlation between the mean voltage in the ring $U = \langle\varphi(-a/2)\rangle - \langle\varphi(a/2)\rangle$ and the current $ej_r$:

$$U = (ej_r)\frac{a}{e^2}\langle m/\rho\rangle(i\omega+\nu)\frac{(o^2-\omega_s^2-\Omega'^2)}{(o^2-\omega_s^2)}$$
$$\Omega'^2 = \Omega^2(i\omega+\nu_s)/(i\omega+\nu) \quad (13)$$

where the cyclotron frequency is $\Omega = |e|\langle H/\rho\rangle/c\langle m/\rho\rangle$.

It follows from Eqs. (11) and (13) that when scattering is absent and $\omega=\omega_s$, we get the resonance with singularities of the current along the ring and its resistance, while at $\omega=\Omega+\omega_s$ we get the resonance with the singularity in the conductivity of the ring (zero resistance). The first resonance occurs at the frequency of the "spin pendulum". In [2] this kind of oscillations was excited by a variable magnetic flux through the ring section. In our case they are excited by the Lorentz force acting on the current in the radius direction. At $\omega=\Omega+\omega_s$ we have a combined resonance in which the cyclotron resonance oscillations [12] are coupled with the first-type eigenmodes. When the magnetic properties of the ring are homogeneous, the combined oscillations turn into cyclotron ones. Note that a combined oscillation cannot exist as a pure eigenmode in the ring analyzed: we get $j_r=0$ when the current source is disconnected. This is due to the electric neutrality requirements. However, a such type oscillations are possible if the ring edges, are short-circuited $r=\pm a/2$.

It is interesting to discuss the prerequisites to the formation of the above resonances. In the *ESLH* an inhomogeneous magnetic field can induce the inhomogeneity of the equilibrium spin polarization: $\rho_\sigma/\rho = \exp(\sigma\mu_B H_t/2T)/2\cosh(\mu_B H_t/2T)$ where, in contrast to the foregoing formulas, $H_t$ is the total magnetic field strength rather than its perpendicular component; $\mu_B$ is the Bohr magneton, $T$ is the temperature, $\sigma=\pm1$. Then $\omega_s \sim \mu_B H_t\delta/(mT)^{1/2}L$ at $\mu_B H_t < T$, where $\delta$ is the relative variation of the magnetic field in the ring. The highest frequency attainable

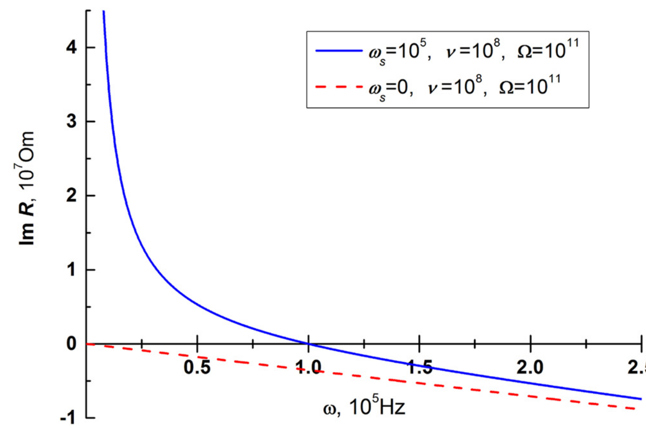


**Fig. 2.** The imaginary part of resistance $R=U/aej_r$ in the case of strong relaxation $\nu \gg \omega_s$ (ESLH). The distinction between the blue (solid line) and red (dashed line) curves demonstrates the role of magnetic nonuniformity. $\rho=10^{12}$ cm$^{-2}$, $m=0.64\cdot10^{-28}$ g, $\nu_s \ll 10^8$ Hz.

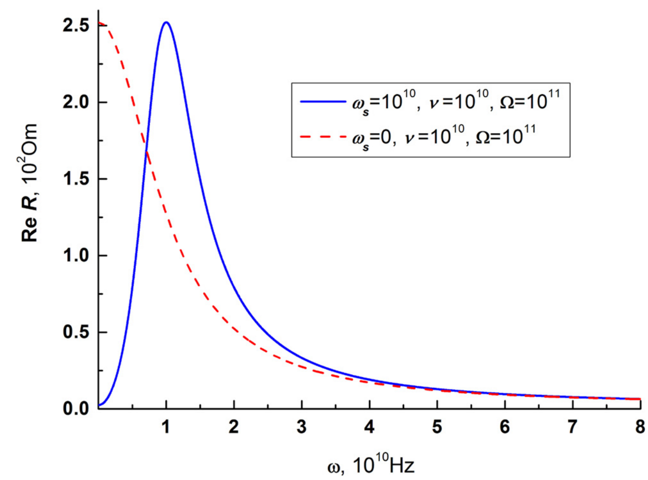


**Fig. 3.** The real part of resistance. The parameters are typical for 2D heterostructures; $\rho=10^{12}$ cm$^{-2}$, $m=0.64\cdot10^{-28}$ g, $\nu_s \ll 10^8$ Hz.

at $T=1$ K, $\mu_B H_t \sim T$, $\delta\sim1$, $L\sim1$ cm is of the order of $10^6$ Hz, which is about two orders of magnitude lower than the relaxation frequency $\nu$ at this temperature [6]. It is therefore impossible to observe in full the above discussed resonances in the *ESLH*, but the imaginary part of electrical resistance demonstrates a "combined resonance": $\mathrm{Im}\,R=0$ at $\nu_s \ll \omega_s$ (see Fig. 2).

In semiconducting heterostructures the spin polarization inhomogeneity can be induced by a nonuniform field of gates. In the case of degenerate electron statistics, $\omega_s \approx v_F\delta/L$ ($v_F$ is the Fermi velocity) and the ratio between $\omega$ and $\nu$ is determined by the correlation between the size of the ring and the mean free path with respect to momentum-loss collisions. Fig. 3 illustrates the effect of current attenuation along the ring at $\omega<\omega_s$, which suppresses magnetoresistance at decreasing frequency. The reason is that the current-produced spin nonuniformity accumulates and retards the current.

## 4. Plasma oscillations

In the previous section we considered the electric neutrality of a good conductor assuming that the condition $\omega \ll \omega_p$ ($\omega_p$ is the plasma frequency) is obeyed. On discarding this assumption, Eq. (3) should be replaced by the Poisson equation or an equivalent expression accounting for the nonequilibrium addition to the potential inside the ring:

$$\varphi(r,\alpha) = e \int\limits_{-a/2}^{a/2} \int\limits_{0}^{2\pi} \delta\rho(r',\alpha') \frac{r'dr'd\alpha'}{|\mathbf{r}'-\mathbf{r}|}, \quad \delta\rho = \sum_\sigma \delta\rho_\sigma \tag{14}$$

where $\alpha$ is the polar angle.

Plasma oscillations along the ring can be excited by applying AC current at the ring edges. This can be done in different ways: i) by providing nonuniform ($l$-dependent) densities of spin components or the total electron density; or ii) by inducing the inhomogeneous input current $ej_r$, as a result of angle variation of the leads resistances at direct current injection or due to different distances between ring and the exiting electrodes on noncontact current feed. At last, it is possible to make a ring of a variable width.

Using Eq. (16) we can obtain the width-averaged potential of the ring:

$$\varphi = eaK\delta\rho, \quad K \cong \frac{2^{3/2}}{\varepsilon}\left[3 + 2.5\ln 2 + \ln\left(\frac{2R}{a}\right)\right] \tag{15}$$

Here we disregard the weak dependence $K(r')$ and use the value at $r'=0$; $\varepsilon$ is the dielectrical permittivity of the ring determined by the bound electrons.

It is evident from Eqs. (8), (15) and the continuity equation $i\omega\delta\rho + dj_l/dl = 0$ that the forced plasma oscillations of electron density in a homogeneous ring can be written as:

$$\delta\rho = -j_{r1}\Omega\sin\alpha/R\left(\omega^2 - \omega_p^2 - i\omega\nu\right) \tag{16}$$

where the plasma frequency is $\omega_p = (e^2\rho dK/mR^2)^{1/2}$. Here we assume that the oscillations are excited by the inhomogeneity $j_r = j_{r0} + j_{r1}\cos\alpha$. The potential difference between the ring edges can be written as $U = U_0 + U_1\sin\alpha$. Then $U_1$ of Eq. (7) can be obtained as

$$U_1 = (ej_{r1})ae^{-2}\frac{m}{\rho}(i\omega+\nu)\frac{\omega^2-\omega_p^2-i\omega\nu-\Omega^2}{\omega^2-\omega_p^2-i\omega\nu} \tag{17}$$

In the absence of attenuation at zero voltage we observe the magnetoplasma resonance at $\omega^2 = \omega_p^2 + \Omega^2$ [13].

To analyze the importance of the spin effects in a magnetically inhomogeneous ring we assume that only the quantity $\rho_\sigma = \rho_{0\sigma} + \sigma\rho_1\cos\alpha$ is dependent on the $l$-coordinate. Allowance for other inhomogeneous quantities is quite simple though it involves too cumbersome formalism. For simplicity, we assume that the inequality $\rho_1 \ll \rho_{\sigma 0}$ is obeyed and takes into account only the zero and first harmonics in the $\alpha$-dependences of the sought-for magnitudes. Then Eqs. (7), (8) and (15) give $U = U_0 + U_1\cos\alpha$:

$$U_0 = (ej_r)ae^{-2}\frac{m}{\rho}(i\omega+\nu)\left[1 - \Omega'^2\frac{(o^2-\omega_p'^2)+C}{(o^2-\omega_s^2)(o^2-\omega_p'^2)-B^2/2}\right] \tag{18}$$

$$U_1 = -(ej_r)ae^{-2}\frac{m}{\rho}\Omega'^2(i\omega+\nu)\frac{[(o^2-\omega_p'^2)+C]B}{(o^2-\omega_s^2)(o^2-\omega_p'^2)-B^2/2} \tag{19}$$

where $C=0$ in this model. $\omega_s^2 = (2m\rho R^2)^{-1}\sum_\sigma \Pi_\sigma^{-1}\rho_1^2$, $\omega_p'^2 = \omega_p^2 + (m\rho R^2)^{-1}\sum_\sigma \Pi_\sigma^{-1}\rho_{\sigma 0}^2$, $B = (m\rho R^2)^{-1}\rho_1\sum_\sigma \Pi_\sigma^{-1}\sigma\rho_{\sigma 0}$.

Thus, if the "spin pendulum" and plasma resonances have essentially different frequencies ($\omega_s \ll \omega_p$ that is the case of a "good conductivity"), then for $\omega \ll \omega_p$ the difference between Eqs. (18) and (13) is not higher than $(\omega_s/\omega_p)^2$. Specifically, the combined resonance (see the previous section) is shifted about $B^2/\omega_p^2$. As a result of the pressure of the inhomogeneous electron density the plasma frequency increases slightly in the case of "good conductivity". In this case the magnetoplasma resonance is closely similar

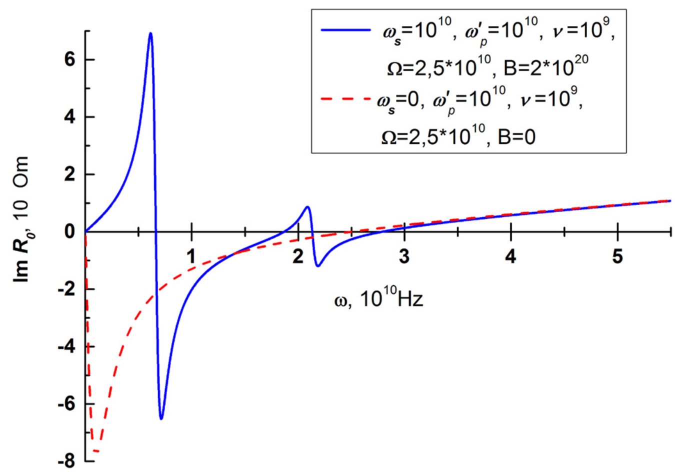


**Fig. 4.** The imaginary part of resistance in a nanowide ring; $\rho = 10^{12}$ cm$^{-2}$, $m = 0.64\cdot 10^{-28}$ g, $\nu_s \ll 10^8$ Hz.

to that described by Eq. (17) (the only difference is that the oscillations are forced by the inhomogeneity of the magnetic structure rather than an inhomogeneous current).

The proximity of spin and plasma frequencies and, hence, a quite intensive interference of the above oscillations are possible only for nanoscale width rings, when: $\varepsilon\Pi^{-1} \approx e^2a$, ($\Pi = \rho/T$ in the *ESLH*). In this case with scattering disregarded ($\nu = \nu_s = 0$), the mean electrical resistance of the ring is imaginary, and according to Eq. (18) it has two "spikes" in frequency dependence determined by the equation $(\omega^2-\omega_s^2)(\omega^2-\omega_p^2) = B^2/2$ and is zero at two frequencies of the combined resonance: $(\omega^2-\omega_s^2-\Omega^2)(\omega^2-\omega_p^2) = B^2/2 + C$ (see Fig. 4). Note that the frequency of the plasma resonance is shifted even when the magnetic structure of the ring is homogeneous ($\rho_1 = 0$). In the case of the *ESLH* $\omega_p'^2 - \omega_p^2 = T/mR^2$ (Maxwell statistics), which corresponds to the state equation of the ideal gas and it is independent of the magnetic field value. In the case of quantum statistics ($T \ll \Delta$, $\Delta$ being the spin splitting of spectrum) the shift of the resonance frequency is dependent on the magnetic field. Really, the density of states of a two-dimensional system is considered to be $\sigma$-independent: $\Pi_\sigma = m/2\pi\hbar^2$ for a quadratic isotropic spectrum and, when at $\Delta \ll \varepsilon_F$, the magnitude $\sum_\sigma \rho_{\sigma 0}^2$ increases with increasing $H$ as $\Delta^2$ and the addition is of the order of $(\mu_B H_t\Pi_\sigma)^2/4$). Since $L \gg l_{ee}$ is assumed throughout this consideration, the electron pressure must be taken into account.

Naturally, to perform further calculations in Eqs. (18)–(19) we need to specify our model. Thus, in the ESLH case, in the sake of simplicity let us assume that the inhomogeneous spin state is induced only by the inhomogeneity of that component of the magnetic field which is parallel to the conducting surface: $H_t^2 = H^2 + H_\parallel^2$, $H_\parallel^2 = H_0 + H_1\cos\alpha$. Then $\omega_s^2 = (\mu_B H_t)^2/8TmR^2$, $B = 0$.

In the case of the degenerated statistics (e.g. for semiconducting heterostructures) it seems reasonable to induce the spatial inhomogeneity of the magnetic structure applying an inhomogeneous electric gate potential, $V = V_0 + V_1\cos\alpha$, $V_1 \ll V_0$. The resulting inhomogeneity of the electron density is an additional factor responsible for excitation of plasma oscillations and we have $\rho = \rho_0 - \Pi V_1\cos\alpha$, $C = B\Pi V_1/2\rho_0$, $\omega_s^2 = [V_1(\rho_{\sigma 0} - \rho_{-\sigma 0})]^2/2\pi\hbar^2\rho_0^3R^2$.

Since this consideration is restricted to only two harmonics in the $\alpha$-dependence of the nonequilibrium density, it is impossible to examine resonances of the next series of plasma oscillations (the frequency of the nearest resonance is $\omega_{p1} = 2\omega_p[1 - 2^{5/2}/3K]^{1/2}$). It is obviously that next resonances are less pronounced as to compare with the discussed above in the measure of the small parameter $\rho_{\sigma 1}/\rho_{\sigma 0} \ll 1$.

In conclusion, we have discussed the high-frequency transport phenomena in a two-dimensional conducting rings with the magnetically inhomogeneous structure. It has been predicted an existence of a number of resonances in a.c. conductivity which are due to a new type hybrid oscillations of carriers caused by the interrelated "spin pendulum", cyclotron and plasma oscillations. The effect of current flow blocking due to spin inhomogeneity has been predicted.

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