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Two-dimensional electron gas in the regime of strong light-matter coupling: Dynamical conductivity and all-optical measurements of Rashba and Dresselhaus coupling

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A nonperturbative interaction of an electronic system with a laser field can substantially modify its physical properties. In particular, in two-dimensional (2D) materials with a lack of inversion symmetry, the achievement of a regime of strong light-matter coupling allows direct optical tuning of the strength of the Rashba spin-orbit interaction (SOI). Capitalizing on these results, we build a theory of the dynamical conductivity of a 2D electron gas with both Rashba and Dresselhaus SOIs coupled to an off-resonant high-frequency electromagnetic wave. We argue that strong light-matter coupling modifies qualitatively the dispersion of the electrons and can be used as a powerful tool to probe and manipulate the coupling strengths and adjust the frequency range where optical conductivity is essentially nonzero.

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\textbf{Introduction.} Since the appearance of the pioneering works on spintronics, followed by unprecedented research progress in the field [1], there has been tremendous interest in studying spin-orbit coupled systems. This is mainly motivated by the possibility to use spin-orbit interactions (SOIs) for the design of prospective nanoelectronic devices [2] where the spin of a system can be manipulated without application of an external magnetic field. In two-dimensional (2D) electronic systems, SOIs can be provided either by a lack of inversion symmetry of the crystalline lattice itself (the so-called Dresselhaus term [3]) or structural asymmetry of the quantum well (the Rashba term [4]). While the strength of the Dresselhaus term is determined exclusively by the material and geometry of the structure, the strength of the Rashba term can be tuned by application of a gate voltage, which opens a way for the design of various spintronic components including Datta-Das spin field-effect transistors [5].

Meanwhile, the search for alternative ways to manipulate spin-orbit coupling still attracts considerable attention. It was recently proposed that the latter can be achieved by coupling of a 2D electron system with a strong off-resonant electromagnetic field (dressing field) [6], when no real absorption of the wave takes place but the spectrum of the system is changed. This corresponds to the so-called regime of strong light-matter coupling. The resulting dispersion renormalization was recently studied for the electrons in bulk semiconductors [7,8], quantum wells [9–12], and graphene [13–19]. The dressing field also has a profound impact on the transport properties of low-dimensional electronic structures. In particular, it leads to an increase of dc conductivity of a two-dimensional electron gas (2DEG) and suppresses the effect of weak localization [12]. The oscillating behavior of conductivity and its strong anisotropy also have been predicted for monolayer graphene dressed by linearly polarized light [19] and three-dimensional topological insulators [20]. Moreover, in graphene, a time-periodic circularly polarized field gives rise to a dynamical gap opening and the resulting photocurrent can flow without any applied bias voltage [21].

In this Rapid Communication we investigate the effect of electromagnetic dressing on the transport properties of 2DEG with both Rashba and Dresselhaus SOIs in a quantum well grown in the [001] direction. Interestingly, the trade-off between Rashba and Dresselhaus couplings leads to a finite-frequency response with spectral features that are significantly different from those of a pure Rashba or Dresselhaus system [22]. The plasmon spectrum in Rashba-Dresselhaus systems also changes dramatically [23,24]. Thus, coupling to a strong off-resonant field opens possible ways of controlling the charge and spin current response of the system, providing also a tool to extract the Rashba and Dresselhaus couplings in all-optical measurements.

\textit{Model.} We consider a spin-orbit coupled 2DEG in which the electrons are restricted to move within a plane perpendicular to the $\hat{z}$ axis irradiated by an external electromagnetic wave propagating perpendicular to the interface, $E = E_0 \cos \Omega t$, where $E_0 = |E_0|$ is an amplitude of the wave and $\Omega$ is frequency. Periodic time dependence is characterized by a symmetry operation that corresponds to a translation by a period of a driving field, and Floquet quasienergies [25–27] describe the total phase shifts the quantum system picks up, evolving over a period. As long as the frequency of the irradiating field is far from the resonant frequencies of electronic interband transitions, so that interband absorption does not happen, and is high enough to satisfy a condition $\Omega \tau \gg 1$ (where $\tau$ stands for the relaxation time of a bare Hamiltonian) the problem can be mapped to an effective time-independent model in which the parameters of the undriven Hamiltonian are renormalized by the field. In our further discussion we focus on the linearly polarized dressing field only, $E_0 = -E_0 \hat{x}$.

\textit{Effective time-independent Hamiltonian.} We start our analysis with the Hamiltonian of a spin-orbit coupled 2DEG,

$$H = \frac{p_x^2 + p_y^2}{2m} + \alpha(p_y \sigma_z - p_z \sigma_y) + \beta(p_x \sigma_z - p_z \sigma_x), \quad (1)$$

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where $\sigma_\| = (\sigma_x, \sigma_y, \sigma_z)$ is a vector of Pauli matrices acting in spin space, and constants $\alpha$ and $\beta$ characterize the strengths of Rashba and Dresselhaus couplings, respectively. This Hamiltonian describes, for example, an InAs-based quantum well grown in the [001] direction [28]. The eigenstates of this Hamiltonian are purely determined by the electron momentum $p = (p_x, p_y)$ and chirality of the spin branches. In the presence of an external electromagnetic field the Hamiltonian acquires a time-dependent term via a canonical replacement $\hat{p} \rightarrow \hat{p} - e\hat{A}(t)/c$, which originates from a minimal coupling to the field, where $\hat{A}(t) = -c \int_0^t \hat{E}(t') dt'$. (here, $c$ is the speed of light).

Performing unitary transformation with a matrix,

$$
U(t) = \frac{1}{\sqrt{2}} e^{-i\frac{\gamma \hat{E} \cdot \hat{p}}{\hbar c} t} \begin{pmatrix} e^{-i\cos \Omega t} & e^{i\sin \Omega t} \sin 2\Omega t \\
- e^{-i\sin \Omega t} & e^{i\cos \Omega t} \end{pmatrix},
$$

where $\gamma = eE_0\sqrt{\alpha^2 + \beta^2/(\hbar \Omega^2)}$ is dimensionless field-matter coupling and $\tan \xi = \beta/\alpha$, and keeping zeroth-order harmonics [29] in the Floquet expansion only (which is possible for off-resonant external fields), we can reduce the problem to an effective time-independent Hamiltonian that resembles a bare Hamiltonian with effective anisotropic Rashba and Dresselhaus couplings renormalized by the field,

$$
\hat{H} = \frac{p_x^2 + p_y^2}{2m} + (\alpha_x p_x + \beta_x p_y)\sigma_x - (\alpha_x p_x + \beta_y p_y)\sigma_y,
$$

where Rashba

$$
\alpha_x = \alpha \left[ 1 - \frac{\alpha^2 - \beta^2}{\alpha^2 + \beta^2} (1 - J_0(2\gamma)) \right], \quad \alpha_y = \alpha, \quad (4)
$$

and Dresselhaus-type couplings

$$
\beta_x = \beta \left[ 1 + \frac{\alpha^2 - \beta^2}{\alpha^2 + \beta^2} (1 - J_0(2\gamma)) \right], \quad \beta_y = \beta. \quad (5)
$$

In expressions (4) and (5), $J_0(2\gamma)$ is the zeroth-order Bessel function of the first kind. Thus, the off-resonant electromagnetic field provides a versatile tool to tune the spin-orbit coupled system picks up an extra term determined by the Kubo formula. For a probing field of frequency $\omega$ it can be evaluated as follows.

$$
\sigma_{ab}(\omega) = \frac{1}{\hbar \omega} \int_0^\infty dt (\langle \hat{J}_a(t) \hat{J}_b(0) \rangle) e^{i(\omega+i\delta)t}, \quad (9)
$$

where $\delta$ is a positive infinitesimal constant introduced to guarantee the convergence of the integral. The angular brackets stand for quantum and thermal averaging.

With the help of the Hamiltonian $\hat{H}$ we can estimate the current operators,

$$
\hat{j} = \nabla_p \hat{H} = -\frac{e}{m} \begin{pmatrix} p_x \\
p_y \end{pmatrix} - e\sigma_x \begin{pmatrix} \beta_x \\
\alpha_x \end{pmatrix} + e\sigma_y \begin{pmatrix} \alpha_y \\
\beta_y \end{pmatrix}.
$$

FIG. 1. The proposed renormalization of the dispersion relation $\varepsilon_{p+}$ is illustrated schematically: The upper surface corresponds to 2DEG with both Rashba and Dresselhaus SOIs with no external field, and the lowest one results from renormalization by field with (4) and (5). To make the effect of renormalization more pronounced in (6) we put $2m = 1, \beta/\alpha = 12/15$, and $\gamma = 0.2$. 

It is worth noting that the angle tan $\theta = p_y/p_x$, while for a system doped up to $E_F > 0$ and a concentration of charge carriers $n$,

$$
E_F = \frac{\pi n \hbar^2}{m} - m(\alpha_x^2 + \alpha_y^2 + \beta_x^2 + \beta_y^2) / 2
$$

It is well grown in the [001] direction [28]. The eigenstates of this Hamiltonian are purely determined by the electron momentum $p = (p_x, p_y)$ and chirality of the spin branches. In the presence of an external electromagnetic field the Hamiltonian acquires a time-dependent term via a canonical replacement $\hat{p} \rightarrow \hat{p} - e\hat{A}(t)/c$, which originates from a minimal coupling to the field, where $\hat{A}(t) = -c \int_0^t \hat{E}(t') dt'$ (here, $c$ is the speed of light).

Performing unitary transformation with a matrix,

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U(t) = \frac{1}{\sqrt{2}} e^{-i\frac{\gamma \hat{E} \cdot \hat{p}}{\hbar c} t} \begin{pmatrix} e^{-i\cos \Omega t} & e^{i\sin \Omega t} \sin 2\Omega t \\
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where $\gamma = eE_0\sqrt{\alpha^2 + \beta^2/(\hbar \Omega^2)}$ is dimensionless field-matter coupling and $\tan \xi = \beta/\alpha$, and keeping zeroth-order harmonics [29] in the Floquet expansion only (which is possible for off-resonant external fields), we can reduce the problem to an effective time-independent Hamiltonian that resembles a bare Hamiltonian with effective anisotropic Rashba and Dresselhaus couplings renormalized by the field,

$$
\hat{H} = \frac{p_x^2 + p_y^2}{2m} + (\alpha_x p_x + \beta_x p_y)\sigma_x - (\alpha_x p_x + \beta_y p_y)\sigma_y,
$$

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$$

In expressions (4) and (5), $J_0(2\gamma)$ is the zeroth-order Bessel function of the first kind. Thus, the off-resonant electromagnetic field provides a versatile tool to tune the corresponding spin-orbit strengths. One can easily verify that the dispersion relations of dressed electrons and corresponding eigenstates (see Fig. 1 to observe renormalization due to an external field) of the Hamiltonian $\hat{H}$ are determined by

$$
\varepsilon_{p\|} = \frac{p_x^2}{2m} + \lambda p \Delta(\theta), \quad \langle \hat{p}_\| \rangle = \frac{1}{\sqrt{2}} \left( \lambda e^{-i\Phi} \right),
$$

where $\tan \Phi = (\alpha_x \cos \theta + \beta_x \sin \theta)/(\alpha_x \sin \theta + \beta_x \cos \theta)$, the chirality index is denoted by $\lambda = \pm 1$, and the anisotropic spin splitting is defined by

$$
\Delta(\theta) = \sqrt{(\alpha_x \cos \theta + \beta_x \sin \theta)^2 + (\alpha_x \sin \theta + \beta_x \cos \theta)^2}.
$$

It is worth noting that the angle $\tan \theta = p_y/p_x$, while for a system doped up to $E_F > 0$ and a concentration of charge carriers $n$,

$$
E_F = \frac{\pi n \hbar^2}{m} - m(\alpha_x^2 + \alpha_y^2 + \beta_x^2 + \beta_y^2) / 2
$$
without loss of generality, in the following we assume $\omega > 0$, and after quite straightforward algebra we obtain [29]

$$\text{Re} \, \sigma_{\alpha \beta}(\omega) = \frac{e^2 (\alpha_\alpha \alpha_\beta - \beta_\beta \beta_\alpha) \omega}{4 \pi \hbar^2} \int \frac{d^2 p}{\Delta^2(\theta)} \times \left( \begin{array}{cc} \sin^2 \theta & -\sin \theta \cos \theta \\ -\sin \theta \cos \theta & \cos^2 \theta \end{array} \right) \times \delta(\epsilon_{p+} - \epsilon_{p-} - \hbar \omega).$$  \hspace{1cm} (11)

Expression (11) clearly manifests that the conductivity due to spin-orbit coupling disappears for $|\alpha| = |\beta|$. In fact, in this case a delicate interplay between the Dresselhaus and Rashba couplings leads to a momentum-independent conductivity, which determines the integration area $\omega = \omega_0$ and $\omega = \omega_b$.

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The two peaks in Figs. 2 and 3 correspond to electronic excitations involving states with allowed wave vectors exactly at $\omega_a = \hbar \Omega_+ (\Delta_+)$ and $\omega_b = \hbar \Omega_- (\Delta_+)$ (featured in the inset to the Fig. 2), provided $\omega_- < \omega_a < \omega_b < \omega_+$. This is in huge contrast to the results of a pure Rashba or Dresselhaus system for which $\text{Re} \sigma_{xx}(\omega) = e^2/(16\pi \hbar)$, and $\text{Re} \sigma_{xy}(\omega) = e^2/(16\pi \hbar) J_0(2\gamma)$, in the finite frequency range determined by $|\omega - 2 \omega_a m^2 a^2 + 2m E_F| \lesssim 2ma^2$.

One can also observe that the lower peak of the components of the conductivity tensor $\text{Re} \sigma_{ab}(\omega)$ at $\omega = \omega_a$ moves towards $\omega_-$ with an increase of $\gamma$ (see Fig. 2). This effect becomes even more pronounced when the ratio $\beta/\alpha$ grows. Interestingly, $\text{Re} \sigma_{xx}(\omega)$ reaches maximal value in the absence of a dressing field and becomes suppressed with an increase of $\gamma$. This is in contrast to the behavior of $\text{Re} \sigma_{xy}(\omega)$, which is shown to take the lowest value in the absence of the field and gains a maximum value at $\omega_-$ with increasing $\gamma$ (not shown).

Contrary to a pure Rashba or Dresselhaus material, in which it requires a circularly polarized field [34], in a biased two-dimensional electron gas the presence of both couplings leads to the emergence of Hall-type conductivity of the charge carriers, even in the absence of an external magnetic field [35] (see also Ref. [29]). Results presented in Fig. 2 show that the Hall-type conductivity is also quite sensitive to the dressing field. The off-diagonal components of the frequency-dependent conductivity tensor can be accessed, e.g., via measurements of the Faraday rotation angle, which for sufficiently thin films is proportional to $\sigma_{xy}(\omega)$ (see, e.g., Ref. [36]).

It should be noted that the modification of the dynamical conductivity by a dressing field allows for an experimental determination of the relative strength of the spin-orbit coupling $\beta/\alpha$. The current methods include photocurrent measurements [28,37] or optical monitoring of electron spin precession [38], or persistent charge and spin current measurements in a mesoscopic ring [39]. We propose to extract $\alpha$ and $\beta$ from spectroscopic experiments in the pump-probe regime. Based on the theory developed in this Rapid Communication, one can show that

$$E_F = \left( p_0^2 - \sqrt{p_0^2 - A m^2} \right)/\left(4m\right),$$

$$|\alpha^2 - \beta^2| = \frac{B}{8m E_F J_0(2\gamma)},$$

and

$$\alpha^2 + \beta^2 = \frac{A J_0(2\gamma)}{2m E_F J_0(2\gamma)} + 2 \sqrt{\frac{A^2 J_0^2(2\gamma) + 8B^2 (1 - J_0^2(2\gamma))}{32m E_F J_0(2\gamma)}},$$

where $p_0 = \sqrt{2\pi n \hbar^2}$ is the Fermi momentum of a spin-degenerate two-dimensional electron gas, $A = \hbar^2 (\omega_+ - \omega_0 + \omega_0 \omega_+)$, and $B = \hbar^2 \sqrt{\omega_- \omega_+ \omega_0 \omega_+}$. The parameters $\omega_\pm$, $\omega_0$, and $\omega_b$ can be extracted implicitly from the experimentally measured dynamical conductivity curves for various light-matter coupling parameters $\gamma$ (Fig. 3).

Conclusions and outlook. In this Rapid Communication we have provided a systematic and self-contained analysis of the transport properties of a dressed 2D electron system with simultaneous Rashba and Dresselhaus SOIs. We showed that strong light-matter coupling leads to renormalization of the spectrum of the system, which results in a dramatic modification of the dynamical conductivity of a system. In particular, we demonstrated that the frequency range where the conductivity is essentially nonzero can be tuned by properly adjusting the parameters of the dressing field. Moreover, we proposed a way to define independently the constants of Rashba and Dresselhaus SOIs in all-optical measurements.

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