Optical analog of the Aharonov-Bohm interferometer

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We propose a novel spin-optronic device based on the interference of polaritonic waves traveling in opposite directions and gaining topological Berry phase. It is governed by the ratio of the TE-TM and Zeeman splittings, which can be used to control the output intensity. Due to the peculiar orientation of the TE-TM effective magnetic field for polaritons, there is no analogue of the Aharonov-Casher phaseshift existing for electrons.

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The problem of the spin dynamics is one of the most interesting in mesoscopic physics. The investigations in this field are stimulated by the possibility of creation of nanodevices, where the spins of the single particles could be precisely manipulated and controlled. The first device of this type, namely spin transistor, was proposed in early 90’s in the pioneer work of Datta and Das \[1\], who used an analogy between the precession of the electron spin provided by Rashba spin-orbit interaction (SOI) and the rotation of the polarization plane of light in optically anisotropic media.

However, the experimental realization of the spin transistor proposed by Datta and Das turned out to be quite complicated, due to the extremely low efficiency of spin injection from ferromagnetic to semiconductor materials. It was then proposed to use mesoscopic gated Aharonov-Bohm (AB) rings as a possible basis of various spintronic devices such as spin transistors \[2,3\], spin filters \[4,5,6\], and quantum splitters \[4\]. The conductance of such structures depends both on the magnetic and the electric fields applied perpendicular to the interface of the structure. The magnetic field provides the AB phaseshift between the waves propagating in the clockwise and anticlockwise directions thus resulting in the oscillations of the conductance.

The electric field applied perpendicular to the plane of the ring also affects the conductance. It has a two-fold effect. First, it changes the carrier wavenumber thus leading to conductance oscillations analogical to those observed in the Fabry-Perot resonator. Second, it induces the Rashba SOI and creates the dynamical phaseshift between the waves propagating within the ring. It consists of Aharonov-Casher (AC) phaseshift, arising from different values of the wavenumbers for the waves propagating in opposite directions \[3,4\], and a Berry (geometric) phase term \[2\], accumulated during the adiabatic evolution of the electron’s spin in the inhomogeneous effective magnetic field created by Rashba SOI and external magnetic field perpendicular to the structure’s interface. As a result, the conductance of the mesoscopic ring exhibits oscillations \[8\] as a function of the perpendicular electric field.

It was recently proposed that in the domain of mesoscopic optics the controllable manipulation of the spin of excitons and exciton-polaritons can provide a basis for the construction of optoelectronic devices of the new generation, called spin-optronic devices \[9\]. The first element of this type, polarization-controlled optical gate, was recently realized experimentally \[10\].

Exciton polaritons are the elementary excitations of semiconductor microcavities in the strong coupling regime. Being a mixture of quantum well (QW) excitons and cavity photons, they possess a number of peculiar properties distinguishing them from other quasi-particles in mesoscopic systems. An important property of cavity polaritons is their (pseudo)spin \[11\], inherited from the spins of QW exciton and cavity photon and directly connected with the polarization of emitted photons. If one is able to control the spin of cavity polaritons, one can therefore control the polarization of emitted light, which can be used in optical information transfer.

The analog of Rashba SOI in microcavities is provided by the longitudinal-transverse splitting (TE-TM splitting) of the polariton mode. It is well known that due to the long-range exchange interaction between the electron and the hole, for excitons having non-zero in-plane wavevectors the states with dipole moment oriented along and perpendicular to the wavevector are slightly different in energy \[12\]. In microcavities, the splitting of longitudinal and transverse polariton states is amplified due to the exciton coupling with the cavity mode \[13\] and can reach values of about 1 meV.

TE-TM splitting results in the appearance of an effective magnetic field provoking the rotation of polariton
FIG. 1: (color online) Orientation of the effective magnetic fields provided by Rashba SOI (full arrows) and TE-TM (dashed arrows) splitting in the reciprocal space pseudospin. It is oriented in the plane of the microcavity and makes a double angle with the $x$-axis in the reciprocal space,

$$\tilde{B}_{LT}(k) \sim e_x \cos(2\phi) + e_y \sin(2\phi)$$ (1)

This is different from the orientation of the effective magnetic field provided by Rashba SOI (see Fig. 1), which makes a single angle with $y$-axis,

$$\tilde{B}_{SOI}(k) \sim e_x \sin(\phi) - e_y \cos(\phi)$$ (2)

This peculiar orientation of $\tilde{B}_{LT}$ results in different interference patterns for electrons and polaritons in ring interferometers, leading in particular to the absence of AC phaseshift for polaritons, as we shall see below [14].

The system we consider in the present paper is an optical ring interferometer placed in the external magnetic field perpendicular to its interface (fig. 2). The polaritons are injected in the ingoing lead by a laser beam, propagate in the ring and leave it by the outgoing lead, where their output intensity is detected. To make the polaritons propagate along a desirable path, one needs to engineer a corresponding confinement potential, which can be achieved by variation of the cavity width [15], putting metallic stripes on the surface of the cavity [16] or applying a stress [17]. The other option is to produce the waveguide structure by lithography, as in the case of micropillar cavities [18]. The narrow waveguide for polaritons has its own TE-TM splitting, which is inversely proportional to waveguide dimensions [19] and which can dominate over the cavity splitting (for a waveguide of 1$\mu$m width this splitting can be as high as 1-2 meV [20]).

To calculate the intensity of the outgoing beam, we consider the polariton states inside 1D ring, and take into account the TE-TM splitting (of both origins) and the Zeeman splitting, the latter provided by an external magnetic field perpendicular to the cavity plane. With such geometry the averaging of the full Hamiltonian to 1D is valid since the energy splitting between two successive confined TE modes is orders of magnitude larger than the TE-TM splitting. The corresponding Hamiltonian in the basis of circular polarized states reads [21]

$$\tilde{H} = \begin{pmatrix} H_0(k) + \Delta_Z(B) & \frac{1}{2}e^{2i\phi}\Delta_{LT}(k) \cr \frac{1}{2}e^{-2i\phi}\Delta_{LT}(k) & H_0(k) - \frac{\Delta_Z(B)}{2} \end{pmatrix}$$ (3)

where $\tilde{k} = -ia^{-1}d/d\phi$, $a$ is the radius of the ring, $H_0(\tilde{k})$ is the bare polariton dispersion, $\Delta_{LT}(k)$ and $\Delta_Z(B)$ are the TE-TM and the Zeeman splittings respectively.

In our further consideration we use the effective mass approximation, $H_0(\tilde{k}) = \hbar^2 k^2 / 2m_{eff}$ and assume the longitudinal-transverse splitting to be $k$-independent in the region of wavenumbers under study. The solution of the Schroedinger equation with Hamiltonian (4) can be expressed as (compare with a solution for electrons [22])
\[ \Psi_+(\phi) = \frac{1}{\sqrt{1 + \xi^2}} \left( -\xi e^{i\phi} e^{-i\phi} \right) e^{ik_+ a \phi} \] (4)

\[ \Psi_- (\phi) = \frac{1}{\sqrt{1 + \xi^2}} \left( e^{i\phi} \xi e^{-i\phi} \right) e^{ik_- a \phi} \] (5)

where the normalization factor reads

\[ \xi = \frac{\Delta_{LT}/2\Delta_Z}{1 + (\Delta_{LT}/2\Delta_Z)^2 + 1} \] (6)

and wavenumbers \( k_{\pm} \) can be straightforwardly found from the characteristic equation of the Hamiltonian (3).

The eigenstates of the Hamiltonian (3) are elliptically polarized. Their pseudospin makes an angle \( \theta = \arctan(\Delta_{LT}/\Delta_Z) \) with \( z \)-axis. In the limit of weak Zeeman splitting the polarization is linear (\( \theta = 0 \)), and in the opposite limit it changes to circular (\( \theta = \pi/2 \)).

The outgoing intensity can be found by decomposing the states of ingoing and outgoing beams \( \Psi_{in,out} \) by eigenstates of the Hamiltonian (3) in the entrance and exit points (i.e. for \( \phi = 0 \) and \( \phi = \pi \) respectively):

\[ \Psi_{in,out} = \frac{1}{\sqrt{1 + |\xi|^2}} \left[ A_{in,out}^+ \left( \frac{\xi}{1} \right) + A_{in,out}^- \left( -\frac{1}{\xi} \right) \right] \] (7)

where the outgoing amplitudes \( A_{out}^\pm \) can be found as a sum of all terms corresponding to the propagation between the ingoing and outgoing leads. For a given spin orientation, the waves traveling in the clockwise and anticlockwise directions obtain a different Berry phase. Indeed, the direction of the effective magnetic field, consisting of the in-plane TE-TM field and \( z \)-directed real field, changes along the polariton trajectory and follows a cone-shaped path (see Fig. 3). In the adiabatic approximation the polariton pseudospin follows the direction of this field and the corresponding geometric phase can be found as a half of the solid angle covered by it [2],

\[ \theta_B = \pm \pi \left( 1 - \frac{\Delta_Z}{\sqrt{\Delta_Z^2 + \Delta_{LT}^2}} \right) \] (8)

where the sign corresponds to the propagation direction.

One sees that \( \theta_B \) depends on the TE-TM and Zeeman splittings and changes from zero for \( \Delta_{LT} \ll \Delta_Z \) to \( \pi \) for \( \Delta_{LT} \gg \Delta_Z \). It differs by a factor of 2 (coming from Eq. (11)) from the geometric phase for electrons in the gated AB ring with Rashba SOI.

Considering only the processes with no more than one round trip inside the ring, one has for outgoing amplitudes

\[ \frac{A_{out}^\pm}{\sqrt{A_{in}^\pm}} = e^{-T/\tau} e^{i\pi k_{\pm} a} \cos(2\theta_B) + \sqrt{2} e^{-T/\tau} e^{i\pi k_{\pm} a} \cos(6\theta_B) \] (9)

where \( \tau \) is the polariton lifetime, \( T = \pi a/\sqrt{m_e e f} /\sqrt{2E} \) is the propagation time from ingoing to outgoing lead, \( e \) is the probability amplitude for a polariton traveling along one of the arms of the ring to quit the ring through the outgoing lead, \( r \) is the amplitude of transition into the other arm (see fig. 2). The formulae (7) and (9) allow to determine the intensity of the outgoing beam. It depends on the Berry phase \( \theta_B \), which thus plays a role of the AB phase of electronic ring interferometers. The difference of the device we propose from the classical electronic AB interferometer is that it needs the presence of the magnetic field and not just of the vector potential in the region of the particle propagation. It should also be noted that due to the peculiar orientation of the TE-TM splitting for polaritons, there is no analogue of the AC phaseshift present for electrons in a ring with Rashba SOI. Indeed, for the electrons the AC phaseshift arises due to the distinct wavenumbers for the particles traveling clockwise and anticlockwise inside the ring, as for them the mutual orientation of the spin and effective magnetic field provided by Rashba SOI is different. On the contrary, for polaritons the inversion of the propagation direction does not change the direction of the effective magnetic field provided by TE-TM splitting (see Fig. 1), and thus the AC phaseshift is absent.
The Berry phase can be modulated by tuning the intensity of TE-TM splitting, e.g., by variation of the detuning between the exciton and photon modes inside the ring (which can be achieved e.g. by variation of stress forming the ring interferometer) or by tuning the external magnetic field. The dependence of the intensity of the beam on $\theta_B$ is shown at Fig. 3. One sees that the intensity is maximal for $\theta_B = 0, \pi$ and in the region between these two points reveals a local maximum at $\theta_B = \pi/2$.

To check the results of our analytical theory, we have performed a simulation of the structure we propose using coupled Gross-Pitaevskii equations for excitons and Schröedinger equations for photons taking into account their polarization \[24\]. In this simulation we studied pulse propagation through the ring interferometer of $16 \mu m$ diameter without magnetic field as well as under a field of 35 Tesla causing an exciton Zeeman splitting of 2 meV. This value can be sufficiently reduced by the use of dilute semi-magnetic cavities \[25\] or by choosing a different material system (e.g. CdSe/ZnSe \[26\]).

The results of our simulations are shown in Figure 4. All images show spatial distribution of the emission intensity, which is directly proportional to the local density of polaritons. The top two panels (a,b) show the initial stage of the pulse propagation through the ring waveguide at time $t=15$ ps after the excitation. The bottom two panels (c,d) show the final stage of the pulse propagation ($t=30$ ps), when the two beams interfere at the outgoing lead connection point. Without magnetic field (left column – panels a,c) the interference is constructive, and the output into the outgoing lead has the highest value. Under a certain magnetic field (right column - panels b,d) the interference is destructive and a dark spot is visible instead of a bright one. This result corresponds to the predictions of the analytical theory and demonstrates that such a waveguide can indeed operate as an optical interferometer.

In conclusion, we have proposed an optical analog of the spin-interference device based on a mesoscopic ring interferometer. We demonstrated that the Berry phase provided by the TE-TM and Zeeman splittings for polaritons plays a role of AB phase for electrons and leads to a variation of the intensity of the outgoing beam. On the other hand there is no analogue of the corresponding Aharonov-Casher effect because of the peculiar symmetry of the TE-TM splitting. This system allows to solve the main difficulties occurring in electronic systems such as the low efficiency of spin injection from a ferromagnet to a semiconductor system. The effect we propose cannot be observed for bare cavity photons, but is specific of strongly coupled exciton-polaritons because it requires a finite Zeeman splitting. The use of exciton-polaritons is also highly advantageous with respect to the bare excitons \[27\], since the mean free path of exciton-polaritons is much longer due to their photon component.

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