

The Non-linear Optical Spin Hall Effect and Long-Range Spin Transport in Polariton Lasers

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(Dated: April 25, 2012)

We report on the experimental observation of the non-linear analogue of the optical spin Hall effect under highly non-resonant circularly polarized excitation of an exciton polariton condensate in a GaAs/AlGaAs microcavity. The circularly polarized polariton condensates propagate over macroscopic distances while the collective condensate spins coherently precess around an effective magnetic field in the sample plane performing up to four complete revolutions.

Semiconductor microcavities in the strong coupling regime are excellent candidates for designing novel “spinoptronic” devices due to their strong optical non-linearity, unusual polarization properties and fast spin-dynamics. The first steps towards the fabrication of spin-based switching have been recently demonstrated [1–3]. An important goal for the development of integrated devices is coherent spin transport. Being neutrally charged, exciton-polaritons have a significantly smaller scattering cross section with atomic cores, than electrons in a metal. Frictionless flow, which is one of the characteristics of a superfluid, has been recently demonstrated in polaritons [4]. Fabrication of high finesse microcavities has allowed ballistic polariton propagation and long-range order extending over macroscopic distances far beyond the excitation area [5]. Here we show the coherent transport of the spin vector in propagating polariton condensates. We observe ballistic propagation of spin polarized polaritons over distances of a few hundred microns. The observed non-dissipative long-range spin transport is caused by mass transport of exciton-polaritons which distinguishes the phenomenon we observe from spin superfluidity reported for ^3He [6], where the spin transport is decoupled from the mass transport.

The polarization state of exciton-polaritons can be described within the pseudospin formalism [7]. Polaritons possess a spin with two possible projections on the structural growth axis of the microcavity. The polarization of the emitted light gives direct access to the pseudospin state, which is fully characterized by the 4 component Stokes vector $\vec{s} = (s_0, s_x, s_y, s_z)$. Here s_0 is the total degree of polarization and $s_{x,y,z} = (I_{H,D,\circ} - I_{V,A,\circ})/I_{tot}$. $I_{H,D,\circ}$ and $I_{V,A,\circ}$ are the measured intensities in the horizontal and vertical, diagonal and anti diagonal and the two circular polarization components and I_{tot} is the total emission intensity. The transverse electric and magnetic mode splitting in the microcavity acts as a direc-

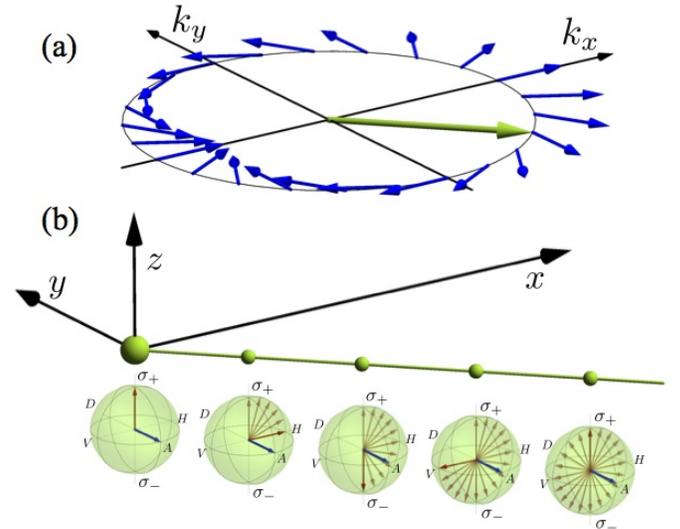


FIG. 1. Polaritons experience an effective magnetic field that depends on their in-plane k -vector. The effective magnetic field (blue arrows) is plotted at each point on a ring in the momentum space (a). (b) A polariton injected at the center of the excitation spot with an initial spin $\sigma_z = +1$ (marked by red arrows) and moving outwards (along the green vector) experiences a spin precession along the effective magnetic field (shown by the blue arrow in (a)). The precession of the pseudospin vector in the Poincaré sphere at points where $\vec{x} \cdot \vec{k} = \pi/2, \pi, 3\pi/2, 2\pi$ is shown.

tionally dependent effective magnetic field (FIG. 1 (a)), which causes the precession of the pseudospin for polaritons (FIG. 1 (b)). This phenomenon being the optical analogue of the spin Hall [8] effect was first predicted by Kavokin and coworkers for resonant Rayleigh scattering [9] and was experimentally observed in a semiconductor microcavity in the strong coupling regime [10] and a purely photonic cavity [11] under resonant injection of

polaritons and photons. In this Letter we demonstrate the non linear optical spin Hall effect occurring by the formation of a polariton ring condensate in momentum space from incoherently injected polaritons.

We use a $5\lambda/4$ AlGaAs/GaAs microcavity with a Rabi splitting of ~ 9 meV and a cavity photon lifetime of ~ 9 ps [12]. A circularly polarized continuous wave excitation was tuned to a reflection minimum of the Bragg mirror outside the high reflectivity region and focused to a $\sim 5 \mu\text{m}$ diameter spot through a 0.2 NA objective. All experiments were performed at ~ 7 K using a cold finger cryostat. The excitation laser was intensity modulated using an acousto optic modulator at 10 kHz with a 5% duty cycle to reduce sample heating. The emission was spectrally separated from the excitation laser and imaged onto a water-cooled CCD or sent to a 300 mm imaging spectrometer. Calibrated waveplates and a polarizer were positioned in the detection path to analyse the polarization.

When the sample is excited with a sufficiently small excitation spot, ($\lesssim 10 \mu\text{m}$), the repulsive interaction causes a strong blueshift of the condensate and radial ballistic propagation of condensed polaritons out of the excitation spot. FIG. 2 shows the energy-resolved emission of a cross section through the excitation spot for below (a) and above (b) threshold power. The far-field emission forms a ring above the threshold in reciprocal space (inset in FIG. 2 (b)). The collected emission spectra at different distances from the excitation area show a superlinear increase (c) and a rapidly dropping linewidth (d) at the photoluminescence threshold as far as $300 \mu\text{m}$ away from the excitation spot. These features are characteristic for lasing, condensation and buildup of coherence.

In reference [13] we showed that the spin of the excitation laser is conserved to a certain degree under non resonant circularly polarized excitation, whilst the phase correlation between the spin up and spin down polaritons is lost. We utilize this phenomenon to non-resonantly form polariton condensates with a collective spin state and study their long-range spin transport. The transverse electric and the transverse magnetic photon mode splitting causes the rotation of the spin as the polaritons propagate through the sample, due to the optical spin Hall effect [9]. FIG. 3 (a) shows the integrated emission mapped in the near field. The linear components of the Stokes vector (s_x and s_y) exhibit a cartwheel pattern (FIG. 3 (b) and FIG. 3 (c)). The circular component (FIG. 3 (d)) reveals up to four revolutions of the pseudospin around the effective magnetic field within the polariton lifetime and a circular symmetric ring pattern.

To demonstrate the non-linearity of the effect the same measurement was performed below the threshold. Here polaritons are evenly distributed in k -space and therefore experience different effective magnetic fields. Fig. 3 (h) depicts the intensity below threshold. The Stokes components s_x , s_y and s_z are displayed in FIG. 3 (i),(j) and

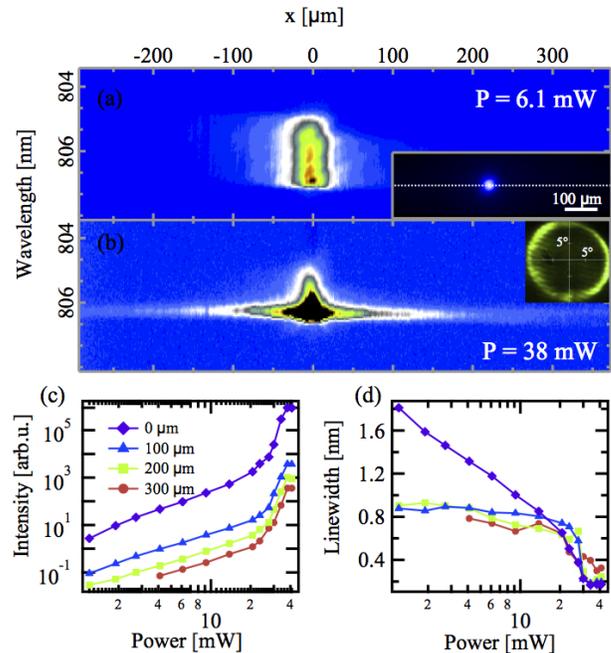


FIG. 2. Energy resolved emission of a cross section through the image of the spot (inset in a) below (a) and above threshold (b). The inset in (b) shows the far field emission above threshold. (c) Emission intensity at various distances from the excitation spot show a superlinear increase at a threshold of about 25 mW. (d) The linewidth as a function of power rapidly drops at the threshold (color legend in (c)).

(k) respectively. In case of a linearly polarized excitation laser the ring condensate is randomly polarized within the excitation area [13, 14] and no spin pattern was observed. Theoretically, the spatial dynamics of polariton condensates is described by a Gross-Pitaevskii type equation for the polariton field [15], which should be coupled to a reservoir of hot excitons that are excited by the non-resonant pump [16]. The Gross-Pitaevskii equation is generalized to include the polarization degree of freedom [17] of polariton condensates:

$$\begin{aligned}
 i\hbar \frac{d\Psi_{\sigma}(x,t)}{dt} = & \left(-\frac{\hbar^2}{2m} \nabla^2 - i\hbar \frac{\gamma}{2} + \alpha |\Psi_{\sigma}(x,t)|^2 \right. \\
 & + (g_R + i\hbar \frac{\tau}{2}) n_{\sigma}(x,t) + \hbar G P_{\sigma}(x,t) + V(x) \Big) \Psi_{\sigma}(x,t) \\
 & + \frac{\Delta_{LT}}{k_{LT}^2} \left(i \frac{\partial}{\partial x} + \sigma \frac{\partial}{\partial y} \right)^2 \Psi_{-\sigma}(x,t) \quad (1)
 \end{aligned}$$

$\Psi_{\sigma}(x,t)$ represents the mean field of polaritons, with $\sigma = \pm$ representing the spin of polaritons. We approximate the polariton dispersion as parabolic, with effective mass m , which is valid since the observed energies and in-plane wavevectors in the experiment lie in the parabolic part of the dispersion. γ represents the polariton decay rate. α is the polariton-polariton interaction strength,

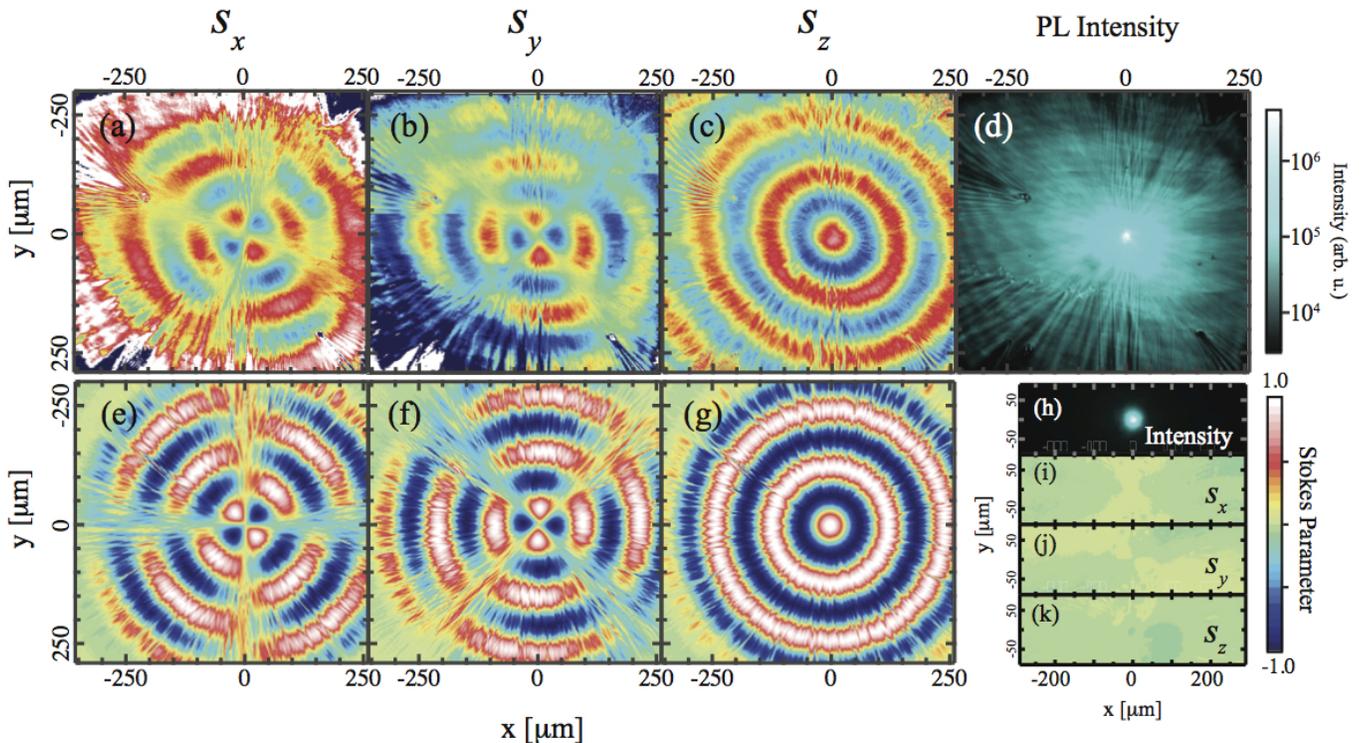


FIG. 3. (a) Experimental data (a-c) and numerical simulations (e-g) of the Stokes parameters of the emission of a polariton condensate non-resonantly excited with circularly polarized laser at $2 \times P_{thr}$, s_x (a,e) s_y (b,f) s_z (c,g). (d) Emission intensity on a logarithmic color scale. Below the P_{thr} the effect cannot be observed, due to the broad k -space distribution (h-k).

which was assumed spin independent for simplicity (the interactions between polaritons with opposite spins are much weaker [18]. $n_\sigma(x, t)$ is the density of the hot exciton reservoir, which may be polarized depending on the pump polarization but is assumed incoherent. g_R represents the effect of repulsive interactions between the reservoir and polaritons (also assumed negligible for oppositely polarized spins) and r is the condensation rate, representing the process where hot excitons condense into polaritons. An additional pump-induced shift is described by the interaction constant G where $P_\sigma(x, t)$ is the spatial pump distribution [16]. $V(x)$ represents the static disorder potential typical in semiconductor microcavities, which is chosen as a random Gaussian correlated potential [10]. The last term represents the presence of longitudinal-transverse splitting of the polariton modes [9, 19], which is assumed to increase with the square of the in-plane wavevector (parabolic approximation). Δ_{LT} defines the longitudinal-transverse splitting at $k = k_{LT}$. The evolution of the hot exciton density is given by the rate equation:

$$\frac{dn_\sigma(x, t)}{dt} = (-\Gamma + \Psi + r|\Psi_\sigma(x, t)|^2)n_\sigma(x, t) + P_\sigma(x, t), \quad (2)$$

where Γ is the reservoir decay rate. We consider a circularly polarized continuous wave pump. Starting from

a random initial condition the time evolution of the system can be calculated numerically until a steady state is reached, which is independent of the initial condition. FIG. 3(e)-(f) show the distribution of the calculated Stokes vectors in space [20].

Although we have included a disorder potential in our theoretical model, the Rayleigh scattering of polaritons with disorder is not necessary for the observation of the multiple rings and cartwheel structure of the polarization in space. This is in contrast to the original demonstration of the optical spin Hall effect [9–11] where Rayleigh scattering was required to populate a ring in reciprocal space. In our case, polaritons condense at the laser spot position with a blue-shifted energy due to their interactions with uncondensed hot excitons. While these hot excitons experience a limited diffusion, polaritons ballistically fly away from the laser spot, converting this interaction energy into kinetic energy. The kinetic energy is characterized by the non-zero wavevector of polaritons, which due to the circular symmetry of the excitation corresponds to a ring in reciprocal space.

The disorder potential does however have a noticeable effect on the fine structure of the polarization in space. Without disorder, similar calculations reveal smooth rings with perfect circular symmetry in the s_z distribution (and smooth profiles with order 2 rotational

symmetry in the s_x and s_y distributions). The addition of disorder gives the rings a noticeable texture and breaks the perfect circular symmetry (leaving only approximately symmetrical distributions). The observed texture is similar to that recorded experimentally. Although this indicates that a small amount of scattering with disorder is present, it is clear that we are in a regime of weak scattering or it would not be possible to observe such clear polarization patterns over such distances.

In conclusion we have experimentally demonstrated the non-linear optical spin Hall effect in a polariton condensate, with remarkable agreement with the theoretical prediction. The non-resonant circular excitation allows the excitation of a ring in reciprocal space without the need for large amounts of disorder. Polariton spins propagate ballistically over a $300\ \mu\text{m}$ distance with minimal scattering and minimal loss of spin information. This record confirms the great potential of semiconductor microcavities for the fabrication of spinoptonic devices.

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- [1] P. G. Lagoudakis, P. G. Savvidis, J. J. Baumberg, D. M. Whittaker, P. R. Eastham, M. S. Skolnick, and J. S. Roberts, *Physical Review B* **65**, 161310 (2002).
- [2] A. Amo, T. C. H. Liew, C. Adrados, R. Houdré, E. Giacobino, A. V. Kavokin, and A. Bramati, *Nature Photonics* **4**, 361 (2010).
- [3] C. Adrados, T. C. H. Liew, A. Amo, M. D. Martín, D. Sanvitto, C. Antón, E. Giacobino, A. Kavokin, A. Bramati, and L. Viña, *Physical Review Letters* **107**, 146402 (2011).
- [4] A. Amo, J. Lefrere, S. Pigeon, C. Adrados, C. Ciuti, I. Carusotto, R. Houdre, E. Giacobino, and A. Bramati, *Nat Phys* **5**, 805 (2009).
- [5] E. Wertz, L. Ferrier, D. D. Solnyshkov, R. Johne, D. Sanvitto, A. Lemaître, I. Sagnes, R. Grousson, A. V. Kavokin, P. Senellart, G. Malpuech, and J. Bloch, *Nature Physics* **6**, 860 (2010).
- [6] A. S. Borovik-Romanov, Y. M. Bun'kov, V. V. Dmitriev, and Y. M. Mukharskii, *JETP Lett.* **40**, 1033 (1984).
- [7] K. V. Kavokin, I. A. Shelykh, A. V. Kavokin, G. Malpuech, and P. Bigenwald, *Physical Review Letters* **92**, 017401 (2004).
- [8] M. Dyakonov and V. Perel, *Physics Letters A* **35**, 459 (1971).
- [9] A. Kavokin, G. Malpuech, and M. Glazov, *Physical Review Letters* **95**, 136601 (2005).
- [10] C. Leyder, M. Romanelli, J. P. Karr, E. Giacobino, T. C. H. Liew, M. M. Glazov, A. V. Kavokin, G. Malpuech, and A. Bramati, *Nature Physics* **3**, 628 (2007).
- [11] M. Maragkou, C. E. Richards, T. Ostatnický, A. J. D. Grundy, J. Zajac, M. Hugues, W. Langbein, and P. G. Lagoudakis, *Optics Letters* **36**, 1095 (2011).
- [12] G. Tosi, G. Christmann, N. G. Berloff, P. Tsotsis, T. Gao, Z. Hatzopoulos, P. G. Savvidis, and J. J. Baumberg, *Nature Physics* **8**, 190 (2012).
- [13] H. Ohadi, unpublished.
- [14] J. J. Baumberg, A. V. Kavokin, S. Christopoulos, A. J. D. Grundy, R. Butté, G. Christmann, D. D. Solnyshkov, G. Malpuech, G. Baldassarri Höger von Högersthal, E. Feltn, J. Carlin, and N. Grandjean, *Physical Review Letters* **101**, 136409 (2008).
- [15] I. Carusotto and C. Ciuti, *Physical Review Letters* **93**, 166401 (2004).
- [16] M. Wouters and I. Carusotto, *Physical Review Letters* **99**, 140402 (2007).
- [17] I. A. Shelykh, Y. G. Rubo, G. Malpuech, D. D. Solnyshkov, and A. Kavokin, *Physical Review Letters* **97**, 066402 (2006).
- [18] C. Ciuti, V. Savona, C. Piermarocchi, A. Quattropani, and P. Schwendimann, *Physical Review B* **58**, 7926 (1998).
- [19] G. Panzarini, L. C. Andreani, A. Armitage, D. Baxter, M. S. Skolnick, V. N. Astratov, J. S. Roberts, A. V. Kavokin, M. R. Vladimirova, and M. A. Kaliteevski, *Physical Review B* **59**, 5082 (1999).
- [20] Parameters: $m = 7 \times 10^{-5}$ of the free electron mass, $\Delta_{LT} = 0.05\ \text{meV}$, $k_{LT} = 2.05\ \mu\text{m}^{-1}$, $\alpha = 2.4\ \mu\text{eV}\ \mu\text{m}^2$, $\gamma = 0.2\ \text{ps}^{-1}$, $\Gamma = 10\gamma$, $\hbar r = 0.1\ \text{meV}\ \mu\text{m}^{-2}$, $G = 0.03\ \mu\text{m}^2$. The disorder potential was generated with $0.05\ \text{meV}$ root mean squared amplitude and $1.5\ \mu\text{m}$ correlation length. The pump intensity was chosen to match the experimentally measured blueshift of the polariton condensate.