Spin Textures of Exciton-Polaritons in a Tunable Microcavity with Large TE-TM Splitting

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(Received 9 March 2015; published 8 December 2015)

We report an extended family of spin textures of zero-dimensional exciton-polaritons spatially confined in tunable open microcavity structures. The transverse-electric–transverse-magnetic (TE-TM) splitting, which is enhanced in the open cavity structures, leads to polariton eigenstates carrying quantized spin vortices. Depending on the strength and anisotropy of the cavity confining potential and of the TE-TM induced splitting, which can be tuned via the excitonic or photonic fractions, the exciton-polariton emissions exhibit either spin-vortex-like patterns or linear polarization, in good agreement with theoretical modeling.

DOI: 10.1103/PhysRevLett.115.246401 PACS numbers: 71.36.+c, 42.55.Sa, 71.70.Ej, 78.55.Cr

Another notable characteristic of semiconductor microcavities is the transverse-electric–transverse-magnetic (TE-TM) splitting [19], which defines two nondegenerate polarization directions relative to the in-plane wave vector [20]. In optical microcavities, TE-TM splitting enables the observation of interesting optical phenomena including the optical spin-Hall effect [21], magnetic-monopole-like half solitons [22], spinor condensate with half-quantum circulation [23], and possibly topological insulators [24–26].

In this Letter we demonstrate the controlled realization of polaritonic spin vortices in an open-access microcavity with a tunable texture, where a top concave mirror creates a zero-dimensional confinement potential for polaritons. The large TE-TM splitting in the open cavity, which consists of two Bragg mirrors separated by an air gap, defines the polariton eigenstates described by an extended family of spin vortices and textures. We also observe polariton emissions showing both spin-vortex-like patterns as well as linearly polarized states depending on the strength and anisotropy of the polariton eigenstates in the cavity, should be distinguished from vortices reported in extended BECs and superfluids, which are collective states arising from interparticle interactions [27,28].

The open microcavity system consists of planar bottom distributed Bragg reflectors (DBR) and a concave top DBR.
where $\varphi_{s l}(\theta)$ is the azimuthal part of the polariton wave function with $s = \pm 1$ corresponding to polaritons associated with $\sigma^\pm$ polarized light, $C(r)$ is the radial part of the normalized Laguerre-Gauss mode with $l = \pm 1$, and $\theta$ and $r$ are angular and radial coordinates. The total angular momentum can be defined for each $\varphi_{s l}(\theta)$ as $J = l + s$, being $J = -2$, 0 or +2. Using degenerate perturbation theory and including the TE-TM splitting term, one obtains the following new eigenmodes [29]:

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\begin{align*}
\psi_1(r, \theta) &= \frac{1}{\sqrt{2}} C(r)(\varphi_{11}(\theta) + \varphi_{-11}(\theta + \pi)), \\
\psi_2(r, \theta) &= \frac{1}{\sqrt{2}} C(r)(\varphi_{11}(\theta) + \varphi_{-11}(\theta)), \\
\psi_3(r, \theta) &= \frac{1}{\sqrt{2}} C(r)(\varphi_{11}(\theta) + \varphi_{-11}(\theta - \pi)), \\
\psi_4(r, \theta) &= \frac{1}{\sqrt{2}} C(r)(\varphi_{1-1}(\theta) + \varphi_{-1-1}(\theta)),
\end{align*}
\]

with eigenenergies: $E_1 = E_0 + 2\beta/\sigma^2$, $E_2 = E_3 = E_0$, and $E_4 = E_0 - 2\beta/\sigma^2$, where $E_0$ is the energy of the LG$_{00}$ mode, $\beta = \hbar^2/(m_{TE} - 1/m_{TM})/4$ is a parameter related to the TE-TM splitting [$n_{TE(TM)}$ are the lower-polariton masses in the TE(TM) polarizations], and $\sigma$ is the parameter defining the size of the modes [29]. The structure of the new eigenmodes, being spin vortices as illustrated in Fig. 1, can be understood by observing that the TE-TM splitting lifts the degeneracy by coherently combining the $J = 0$ wave functions ($\varphi_{11}$ and $\varphi_{-11}$) to form new eigenstates, while leaving the energy of the two $J = \pm 2$ modes unaffected. For the $J = \pm 2$ modes any linear combination of $\varphi_{11}$ and $\varphi_{-11}$ is a suitable eigenmode in the presence of TE-TM splitting. Similarly to the case of spin vortices in planar two-dimensional cavities [11], here we obtain that the splitting between the new eigenmodes is linearly dependent on $\beta$.

To investigate the properties of spin vortices, low temperature photoluminescence (PL) measurements were carried out (details in Ref. [29]). In the first set of measurements, a concave mirror with a radius of curvature (ROC) of 20 $\mu$m was employed and the mirror separation was $\sim 1$ $\mu$m. The cavity is detuned so that polaritons in the FEM modes have a photonic fraction of $\sim 64\%$. Below the condensation threshold, the spectrum associated with
the FEM displays two broad features, as shown in Fig. 2(a). With increase of pump power, condensation occurs and the linewidths drop sharply due to an increase of temporal coherence. Three well-resolved modes labeled by i, ii, and iii are now revealed in Fig. 2(b). Energy resolved images, coherence. Three well-resolved modes labeled by i, ii, and iii are now revealed in Fig. 2(b). Energy resolved images, for each mode in the horizontal-vertical (0° and 90°) basis, diagonal (±45°) basis, and circular (σ+ and σ−) basis, and the associated Stokes parameters, S1, S2, and S3, are calculated for each pixel of the image [29]. The linear polarization angle ϕ, defined as 2ϕ = arctan(S2/S1), is mapped out for each mode in the middle panels of Figs. 2(c), 2(d), and 2(e). As the circular polarization degree (S3) is low for all the three modes [29], the linear polarization vectors characterize well the spin textures.

All three modes display quantized pseudospin currents characterized by a 2π rotation of ϕ around the mode cores, with a high linear polarization degree $\sqrt{S_1^2 + S_2^2} \sim 0.95$ being exhibited. For both modes i and iii, ϕ changes nearly linearly with the real space azimuthal angle θ, corresponding to the rotation of the vector of linear polarization clockwise around the mode center, which indicates a corotating relation between θ and ϕ, as indicated by the right panels of Figs. 2(c) and 2(e). At θ = 0°, we observe ϕ = −90° (horizontal polarization) for mode i and ϕ = 0° (vertical polarization) for mode iii [0° is defined as vertical, see the middle panel of Fig. 2(c)], showing they are azimuthal and radial spin vortices corresponding to the TE and TM eigenmodes $\psi_1$ and $\psi_3$ in Fig. 1, respectively. By contrast, mode ii is a spin antivortex displaying the opposite pseudospin vector rotation with respect to i and iii, with ϕ and θ counterrotating [right panel Fig. 2(d)]. Its hyperbolic-like polarization pattern results from the coherent combination, with any initial phase difference, of J = ±2 states with different polarizations (modes $\psi_2$ and $\psi_3$ in Fig. 1 correspond to the case with a phase difference of 0 or π). The energy splitting of 0.56 meV observed between modes i and iii, along with $\sigma = 0.65 \mu m$ obtained from the actual sizes of the spin vortices, indicates a TE-TM splitting factor $\beta = 0.06 \text{ meV } \mu m^2$ [29], a value ~3 times larger than that reported in monolithic micro-cavities [21,22,29,31]. The large value of $\beta$ mainly arises from the phase shifts due to reflections at the air gap interfaces in the open cavity system. Possible reasons for the unequal energy spacing between modes i, ii, and iii are discussed in Ref. [29].

We also observe spin textures for polaritons condensed into higher order LG-associated modes, when these are tuned into resonance with the exciton. Similar to the LG0±1 case, TE-TM splitting also mixes modes in the second excited manifold (SEM) like, for example, LG10 and LG02 modes [38]. As illustrated in Fig. 3(a), the modes formed are quasi-spin-vortices labeled as type A and B. The polarization vectors exhibit radial (A) or azimuthal (B) spin vortex character in the inner core and azimuthal (A) or radial (B) spin vortex character in the outer ring, connected by transient elliptically polarized states. Such quasi-spin-vortices were experimentally observed as shown in Figs. 3(b) and 3(c), with a change of linear polarization angle of π between the inner core and outer ring. Here above condensation threshold four spectrally resolved condensates are observed and for simplicity we show polarization patterns only for two of them, which fully demonstrate the principle illustrated in Fig. 3(a). The imperfection of the mode spatial profile and the linearlike
The polarization vector of the inner core in Fig. 3(c) compared to 3(a) are most likely due to the slightly elliptical shape of the top concave mirror.

If the concave top mirror has a sufficiently strong ellipticity which perturbs the harmonic confinement potential along the two orthogonal directions with strength \(a\) (see Ref. [29] for details) it may induce Mathieu-Gauss (MG) modes [39,40] which are characterized by linear polarized orthogonal double-lobe profiles [see Fig. 4(d)]. The eigenmodes of the cavity arise from the competition between the asymmetry of the mirror and the strength of the TE-TM splitting: either spin vortices or linear polarized states will be formed depending on which term dominates. In order to achieve condensation in MG modes the TE-TM splitting can be reduced by tuning the energy of the condensed modes closer to the exciton, and by using mirrors with smaller ROC, where the confinement potential is stronger and the spatial anisotropy is more pronounced.

From these considerations a concave mirror with a ROC of 7 µm is chosen, and a photon fraction of 41% employed. Figure 4(a) shows the spectrum of the polariton condensate associated with the FEM, where the low energy modes ii and iii are preferentially selected above threshold, leading to significantly larger intensity than mode i. Nontrivial differences, compared to the spin vortices in Fig. 2, are found in the mode spatial profiles and polarization patterns, as shown in Figs. 4(b) and 4(c) for mode ii and iii. Instead of being spin vortices or antivortices, modes ii and iii clearly show MG-like orthogonal double-lobe profiles (left panels) with vertical (ii) and horizontal (iii) linear polarization (right panels). The simulated intensity distribution and polarization maps of one of the eigenstates confined in an elliptical potential are shown in Fig. 4(d) for decreasing TE-TM splitting factors. Theoretically, it is seen that smaller TE-TM splitting leads to the MG mode being the eigenstates of the system as the ellipticity term has greater influence. Importantly, for the same ROC = 7 µm mirror, we can recover the vortexlike spin textures for all three modes similar to those shown in Fig. 2 by doubling the photonic fraction up to 82%, as shown in the Supplemental Material [29].
1.02 meV. This demonstrates the advantages of the tunability of the open cavities in permitting the degree of the light and matter fractions of the cavity polaritons to be varied but also in allowing flexible manipulation of the polarization textures.

In summary, we have demonstrated polariton emission exhibiting spin vortices and more elaborate spin textures in a tunable microcavity system with lateral confinement. These spin textures can be described as orthogonal eigenstates on the higher order Poincaré sphere (HOPS) [41]. This might lead to a new type of cavity quantum electrodynamics by manipulating the vector states on the HOPS involving both the OAM and polarization (pseudoospin) degrees of freedom, since the excitonic part of the polaritons can be dynamically manipulated with external magnetic field or fast Stark pulses [42,43].

We acknowledge support by EPSRC Grant No. EP/J007544, ERC Advanced Grant EXCIPOL, and the Leverhulme Trust.

Note added.—Recently, spin vortex phenomena in polariton micropillars coupled in a hexagonal pattern were reported in Ref. [44].

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