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Controlled spin pattern formation in multistable cavity-polariton systems

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Cavity polaritons are composite bosons originating due to the strong coupling of confined quasi-two-dimensional excitons and cavity photons. Their lifetime is very small ($\tau \sim 10{-}50$ ps in GaAs-based cavities), however, they can form long-lived macroscopically occupied states under coherent optical excitation. Such states are considered as highly nonequilibrium Bose condensates obeying the generalized Gross–Pitaevskii equation with dissipation and external driving. The right- and left-circular polarization components ($\sigma^{\pm}$) of the optical field correspond to the spin-up ($J_z = +1$) and spin-down ($J_z = -1$) components of the polariton fluid. Polaritons with parallel spins repel each other; the interaction between polaritons with anti-parallel spins is comparatively weak. The nonlinearity makes the optical response *multistable* [1, 2]. Switches between different steady-state branches occur as sharp jumps in the cavity field near certain critical values of the pump parameters [3]. These jumps proceed on the scale of several τ which is much shorter than a typical duration of controlled switches in lasers.

In this Letter we show that multistability can also manifest itself in spin pattern formation. Namely, the spin-up and spin-down polaritons can be dynamically separated in the cavity plane under linearly polarized (spin-symmetric) optical excitation. As a result, the circular polarization of the emitted light is spatially modulated within the wave front. Previously, the only way to implement spin patterning in laterally homogeneous cavities was to vary the pump intensity [4]; otherwise, the dominant spin state was found to spread throughout the pumped spot [5]. Here we propose to control the polariton spin by varying the pump polarization direction that becomes a very important governing parameter in anisotropic microcavities [6, 7].

The spinor Gross–Pitaevskii equation reads:

$$i\hbar\frac{\partial\psi_{\pm}}{\partial t} = \left(E - i\gamma + V\psi_{\pm}^{*}\psi_{\pm}\right)\psi_{\pm} + \frac{g}{2}\psi_{\mp} + f_{\pm}e^{-i\frac{E_p}{\hbar}t}. \quad (1)$$

The two-component macroscopic wavefunction $\psi_{\pm}$ depends on time and spatial coordinates in a two-dimensional active cavity layer. The choice of $V = 1$ determines the units of ψ and pump amplitude f; in particular, $|\psi_{\pm}|^2$ have the dimension of energy and represent the blue shifts of the $\sigma^{\pm}$ resonances. In the general case, energy $E = E(-i\hbar\nabla)$ implies the dispersion law common for both spin components; γ is the decay rate. The eigenstates at $\psi_{\pm} \to 0$ are polarized linearly in the x and y directions so long as $\psi_{\pm} = (\psi_x \mp i\psi_y)/\sqrt{2}$ by definition, and $g \equiv E_x - E_y$ is the splitting between them. Such anisotropy (lifted x/y degeneracy) may come from a lateral stress along one of the main axes x, y.

We show that the anisotropy results in a finite right or left circular polarization of the cavity field depending on the pump polarization direction. Hence, the latter parameter predetermines which of the spin-up and spin-down components is amplified on reaching the bistability threshold. On the other hand, the same effect of the x/y splitting also reveals itself as spin coupling and as such makes the amplified spin component suppress the other. This stabilizes the states with high circular polarizations. In what follows we consider the pump source with spatially varying polarization direction and investigate the resulting spin distributions of the cavity field.

Let the pump source have the following form in polar coordinates (r, ϕ):

$$f_{\pm}(r,\phi,t) = f\exp\left[-\frac{(r-R)^2}{2a^2} \mp im\phi - i\frac{E_p}{\hbar}t\right]. \quad (2)$$

The pump profile has the shape of a ring of radius $R = 40$ μm and thickness $a \approx 3$ μm. Integer numbers $-m$ and $+m$ correspond to the angular momenta of the σ^+ and σ^- polarization components, respectively. Similar distributions can be implemented with the use of the Laguerre–Gauss beams [8]. Thus, the pump has strictly linear yet angle-dependent polarization. The angle between the polarization direction and the x axis equals $m\phi$.

Fig. 1 represents the cases of $m = 2, 3, 4$ slightly above the threshold pump density. At larger m, the ten-

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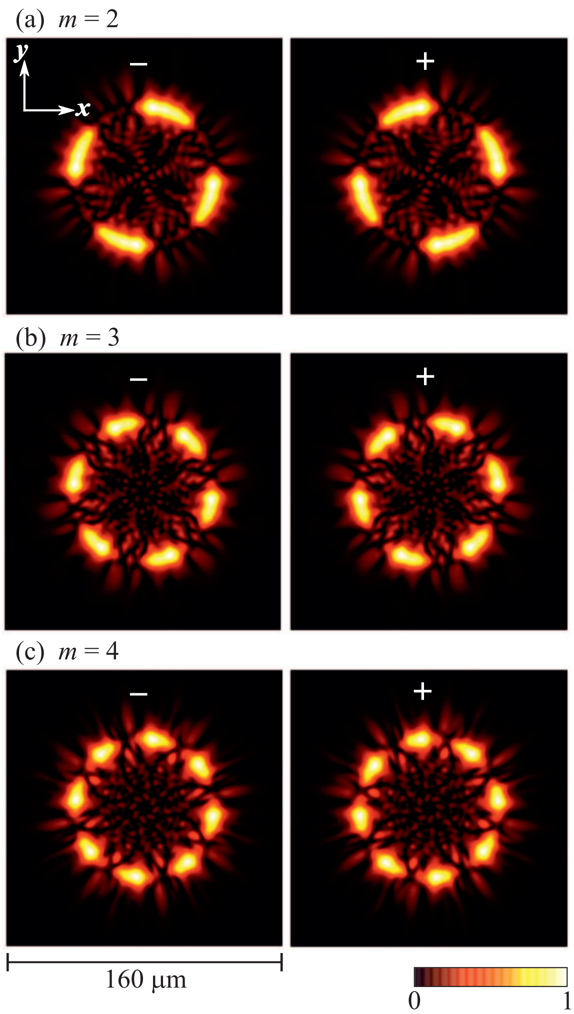

Fig. 1. (Color online) Steady-state distributions of $|\psi_-(x,y)|^2$ (left side) and $|\psi_+(x,y)|^2$ (right side) for $W/W_{\rm thr} \approx 1.5$ and $m = 2$ (a), $m = 3$ (b), and $m = 4$ (c). In each panel, $|\psi_\pm|^2$ are normalized to unity

dency of the high-energy states with a given spin to spread in all directions due to their free flow counteracts the spin separating mechanism. Nevertheless it is clearly seen that the opposite-spin regions remain separated even when their sizes are reduced to several microns at $m = 4$. Here the radial flux of polaritons becomes especially noticeable in spite of the sharp decrease of the pump intensity in the radial direction.

To summarize, in this work we have predicted a novel mechanism of spin pattern formation in semiconductor microcavities with strong exciton-photon coupling. Unlike spin textures in non-resonantly excited Bose–Einstein condensates (e.g., [9]), it does not require a specially prepared potential landscape. Controlled spatial separation of opposite-spin polaritons results in the output light whose circular polarization is modulated within the wave front. In view of very fast optical switches in polariton systems, this effect may find use in the field of information encoding and transmission.

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