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Polariton multistability and fast linear-to-circular polarization conversion in planar microcavities with lowered symmetry

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The multistability of cavity-polariton systems with lowered symmetry (e.g., in laterally strained microcavities) allows implementing a few picoseconds long switching from linear to almost circular polarization of the cavity transmission under a resonant linearly polarized optical pump with slowly changing intensity. This effect has been observed in a high-Q GaAs microcavity using spectrally narrow 70 ps long pump pulses. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4773523]

Exciton polaritons in quantum well microcavities are promising candidates for use in a new generation of micrometer-and-picosecond scale optic devices owing to the unique combination of properties borrowed from photons and excitons. These composite bosons form due to strong exciton-photon coupling[1] and inherit a very small effective mass and macroscopic coherence length from cavity photons and a large interaction rate from excitons. Their properties can be controlled and probed by convenient optical means, for polaritons tunnel through Bragg mirrors by turning into photons with the same statistics. A pump with circular σ^+ or σ^- polarization excites polaritons with $J_z = +1$ or $J_z = -1$, respectively,[2] J_z being the projection of the total angular momentum along the normal $0z$ to the cavity plane (xy).

The repulsive interaction between polaritons with coincident J_z leads to the blue-shift of their resonance energy. Even at moderate excitation powers, the blue-shift can be several times larger than the spectral linewidth of a polariton state.[3] So, if a coherent pump is applied *above* the resonance, a positive feedback loop between the amplitude and effective resonance energy of the driven mode can appear in a certain transitional range of amplitudes, which implies bistability of the optical response of a cavity.[3,4] At the same time, polaritons with opposite J_z attract each other only slightly.[5] As a result, polariton systems driven by elliptically polarized light can exhibit a multistable behavior with up to four stability branches (each of the σ^+ and σ^- components of the cavity field can be either in "up" or "down" state). This leads to the possibility of sharp transitions between the branches and a strong hysteresis in the response under a pump with varying intensity or polarization.[6] Switchings between discrete stability branches have been proposed as a base for memory elements[7] and logic gates.[8]

The multistability in cavity-polariton systems has recently been observed under continuous-wave (cw) excitation conditions.[9–11] In the cw regime, a 2D polariton system is influenced by a long-lived excitonic reservoir that partially levels the $\sigma^\pm$ polariton energies and thus reduces the difference in the $\sigma^\pm$ switch-up thresholds.[10,12] In fact, the cw experiments left open the question concerning the possibility of fast polarization switchings on a timescale comparable to the lifetime of polaritons.

In this letter, we show that the multistability of the cavity-polariton systems excited with short (70 ps long) light pulses can provide linear-to-circular and circular-to-linear polarization conversions due to varying pump power within 30 ps long time intervals. These transitions are ensured in systems with energy-split lower polariton (LP) levels with orthogonal linear polarizations.[13]

In the approximation neglecting all "incoherent" effects in a resonantly driven polariton system,[12] its dynamics can be considered within a mean-field approach based on the Gross-Pitaevskii equations. For a single LP mode characterized by a zero in-plane wave vector ($\mathbf{k} = 0$), they can be written in the $\sigma^\pm$ basis ($\hbar = 1$):[6]

$$i\frac{d}{dt}\begin{pmatrix}\psi_+\\ \psi_-\end{pmatrix} = \left[(\omega_0 - i\gamma)\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \frac{\delta}{2}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}\right]\begin{pmatrix}\psi_+\\ \psi_-\end{pmatrix} + \begin{pmatrix}(V_1|\psi_+|^2 + V_2|\psi_-|^2)\psi_+\\ (V_2|\psi_+|^2 + V_1|\psi_-|^2)\psi_-\end{pmatrix} + \begin{pmatrix}\mathcal{E}_+(t)\\ \mathcal{E}_-(t)\end{pmatrix}e^{-i\omega_p t}. \quad (1)$$

Here $\mathcal{E}_\pm$ are the $\sigma^\pm$ amplitudes of the pump wave with a frequency ω_p close to the LP branch (the upper branch states are neglected); $V_{1,2}$ are the polariton-polariton interaction constants, ω_0 and γ are the frequency and decay rate of polaritons in a degenerate system, and δ is the splitting between the linearly polarized eigenstates. Such splitting at $\mathbf{k} = 0$ is often observed in partially disordered cavities due to lowered symmetry, but it also can be introduced manually[14] by applying a lateral stress along one of the structure axes.

The parameters of the studied system are as follows: $\hbar\gamma = 0.08$ meV, $\hbar\delta = 0.05$ meV, $\hbar(\omega_p - \omega_0) = 0.28$ meV. In the calculations, we take $V_1 = 1$ (so that $\hbar|\psi|^2$ has the dimension of energy) and $V_2 = 0$. The Cartesian basis (xy) is defined according to unitary transformation rule $\begin{pmatrix}\psi_x\\ \psi_y\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ i & -i\end{pmatrix}\begin{pmatrix}\psi_+\\ \psi_-\end{pmatrix}$; the eigenstates are polarized along the x and y axes, and for the sake of definiteness we assume $\delta = \omega_x - \omega_y > 0$.

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Under constant pumping, intra-cavity field oscillates at pump frequency. Substituting $\psi_\pm(t) \to \psi_\pm e^{-i\omega_p t}$ into Eq. (1) leads to the equation for steady-state amplitudes.[6,15] In Fig. 1, the steady-state response diagrams are drawn for the pump wave with almost linear polarization ($\rho_p^{(\mathbf{x},\mathbf{y})} = (|\mathcal{E}_\mathbf{x}^2| - |\mathcal{E}_\mathbf{y}^2|)/(|\mathcal{E}_\mathbf{x}^2| + |\mathcal{E}_\mathbf{y}^2|) = \pm 0.99$). The cases of x and y pump polarization directions appear drastically different from each other. In the former case, that corresponds to exciting of the upper split-off eigenstate ($\rho_p^{(\mathbf{x},\mathbf{y})} = +0.99$), the cavity field and, hence, the cavity transmission signal attain a very high degree of circular polarization $\rho_{\rm tr}^{(+,-)} = (|\psi_+^2| - |\psi_-^2|)/(|\psi_+^2| + |\psi_-^2|)$ in a wide range of pump powers, so that a strong polarization conversion under varying pump is expected. By contrast, if $\rho_p^{(\mathbf{x},\mathbf{y})} = -0.99$, then the jump in the cavity-field intensity is unlikely to be accompanied by any change in its polarization. The sensitivity of multistability conditions to the pump polarization direction has also been revealed in a recent theoretical study,[13] where the steady-state output light polarization as function of the pump polarization at a constant pump power was analyzed. In particular, it was shown that the output field can have either σ^+ or σ^- polarization in response to a linearly polarized pump, which corresponds to intermediate pump powers ($I_p \approx 0.4$) in our Fig. 1(a).

The diagrams in Fig. 1 show only the steady-state attractors of the phase trajectory. Below, we consider the *dynamics* of the polarization conversion studied both experimentally and numerically based on Eq. (1); a qualitative discussion of this effect is placed at the close.

Experimentally, we have performed time- and polarization-resolved measurements of the cavity transmission. The GaAs/AlAs microcavity has quality factor $Q \approx 7 \times 10^3$, Rabi splitting $\hbar\Omega \approx 10.5$ meV, and photon-exciton mismatch $\hbar(\omega_c - \omega_x) \approx -5$ meV. The sample is kept at $T = 2$ K. It is excited by optical pulses generated by a mode-locked Ti:Sapphire laser with a repetition rate of 8 MHz and pulse duration of 70 ps; the pump is focused onto a 30 μm wide spot on the sample and is orthogonal to the cavity surface. The transmission signal is detected by a streak-camera with spatial and time resolutions of 5 μm and 6 ps, respectively; the signal is collected from the $5 \times 15\ \mu\mathrm{m}^2$ area at the spot center. Other parameters of the system, such as γ, δ, and $\omega_p - \omega_0$, approximately equal the model parameters listed above.

Figure 2 shows measured signal intensities and polarizations in the case of pumping of the lower LP eigenstate ($\rho_p^{(\mathbf{x},\mathbf{y})} \approx -1$). The signal exhibits a well pronounced threshold behavior typical of bistable systems. It increases sharply with respect to the driving force at $t = -20$ ps for $W = 2.5\,W_{\rm thr}$ and at $t = -40$ ps for $W = 5\,W_{\rm thr}$ [Fig. 2(a)], W being the peak pump density, and $W_{\rm thr} \approx 500\ \mathrm{kW/cm^2}$ the conventional "threshold" value. Expectedly, the stronger the pump, the earlier occurs the switch-up,[12] but in either case no polarization switching is observed, which is in agreement with the steady-state estimate [Fig. 1(d)].

The opposite case of $\rho_p^{(\mathbf{x},\mathbf{y})} \approx +1$ is shown in Fig. 3, which represents both measured and calculated data. The pump is set a little above the threshold ($W = 1.3\,W_{\rm thr}$), and the signal reaches its maximum 30 ps after the peak pump intensity has been gone through. As expected in accordance with Figs. 1(a)–1(c), the switch-up of the signal intensity is accompanied by (i) the jump in circular polarization up to $\rho_{\rm tr}^{(+,-)} \approx 0.9$ and (ii) the jump in the "diagonal" linear polarization $\rho_{\rm tr}^{(\mathbf{x}\pm\mathbf{y})}$. This transition takes approximately 30 ps in both the experiment and modeling.

According to Fig. 1(a), a further increase in the pump power should result in the second (circular-to-linear) polarization transition. It is evidenced in Fig. 4 drawn for $W = 5\,W_{\rm thr}$. The system tends to proceed to the state with high circular polarization at $t \approx -30$ ps, but eventually it comes to the new state with linear polarization well before the pump reaches its peak magnitude. Now, the $\sigma^\pm$ attractors have a much smaller impact on the system dynamics, which is not surprising in view of a very rapidly changing pump power. This impact is, however, clearly seen in Fig. 4: the π_y component of the signal exhibits more than an order-of-magnitude growth within the short time intervals during

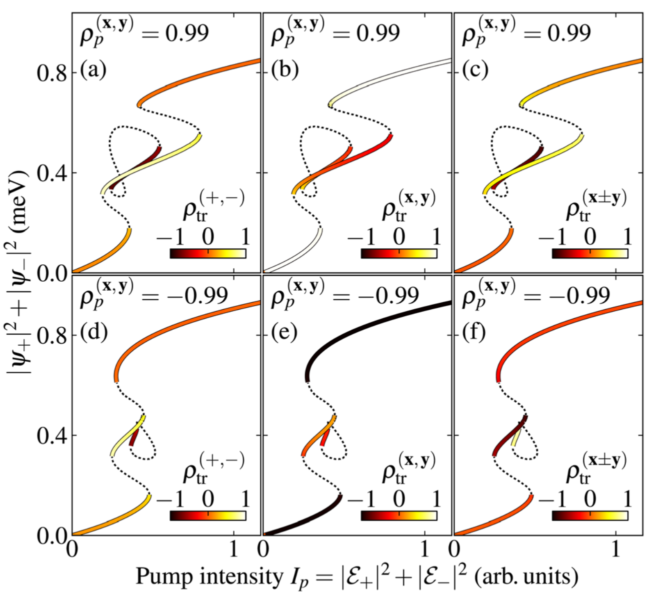

FIG. 1. Steady-state response to the pump wave characterized by the degree of circular polarization $\rho_p^{(+,-)} = 0.15$ and degree of linear polarization $|\rho_p^{(\mathbf{x},\mathbf{y})}| \approx 0.99$, the polarization axis being parallel to that of the upper ((a)–(c)) and lower ((d)–(f)) split-off LP eigenstates ($0x$ and $0y$, respectively). Degrees of polarization of intra-cavity field (and thereby of the transmission signal) in the circular ($\sigma^\pm$) and two Cartesian [($\mathbf{x}$, $\mathbf{y}$) and ($\mathbf{x}+\mathbf{y}$, $\mathbf{x}-\mathbf{y}$)] bases are shown by colors. Asymptotically unstable solutions are shown by dashed lines.

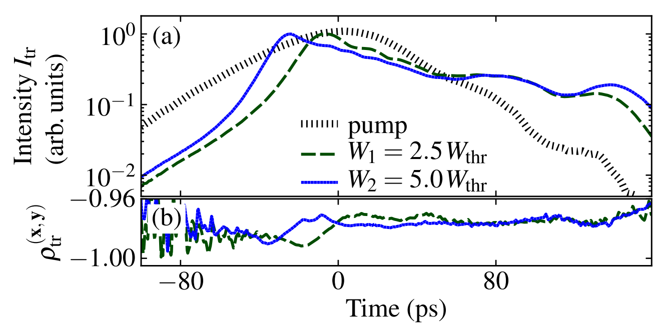

FIG. 2. Time dependences of the intensities (a) and degrees of linear polarization (b) of the transmission signal in the case of exciting of the *lower* split-off LP eigenstate ($\rho_p^{(\mathbf{x},\mathbf{y})} \approx -1$). Solid and dashed lines correspond to different peak pump intensities W. Dotted line in panel (a) represents the pulse shape.

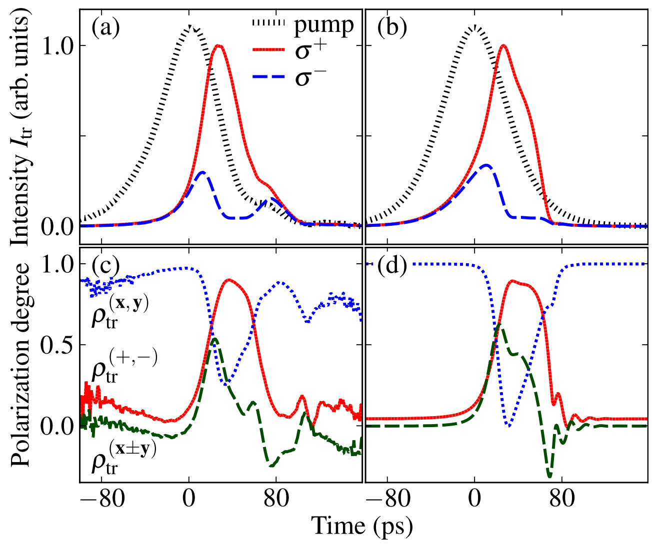

FIG. 3. Intensities of the $\sigma^{\pm}$ components ((a) and (b)) and degrees of polarization ((c) and (d)) of the transmission signal in the case of exciting of the *upper* split-off LP eigenstate ($\rho_p^{(\mathbf{x},\mathbf{y})} \approx +1$) at $W = 1.3\,W_{\text{thr}}$ (*slightly* above the threshold). Dotted lines in panels ((a) and (b)) show the pulse shape. Left ((a) and (c)) and right ((b) and (d)) panels represent measured and calculated data, respectively.

which the system is attracted by the intermediate branch of stability.

At the back front of pump pulses, the modeled system always shows a sharp reverse transition to the low-field state. By contrast, the measured signal does not show any sharp drop in intensity, decreasing with time nearly in the same manner as the driving force. This discrepancy seems to originate from partial filling of the long-lived exciton states due to spatial inhomogeneity of exciton potential and/or the scattering of polaritons by acoustic phonons. These "reservoir" states grow when the pump is strong and afterwards scatter back to the $\mathbf{k} = 0$ mode long after the driving force has decreased.[12] Note, however, that even purely coherent one-mode model (1) provides a good qualitative description of

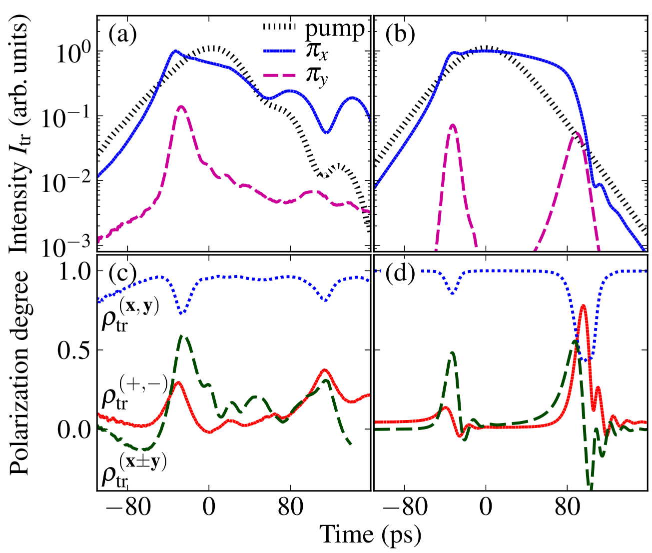

FIG. 4. Intensities recorded in the linear polarization ($\pi_{x,y}$) components ((a) and (b)) and degrees of polarization ((c) and (d)) of the transmission signal in the case of exciting of the *upper* split-off LP eigenstate ($\rho_p^{(\mathbf{x},\mathbf{y})} \approx +1$) at $W = 5\,W_{\text{thr}}$ (*significantly* above the threshold). Left ((a) and (c)) and right ((b) and (d)) panels represent measured and calculated data, respectively.

the polarization switchings observed in the range of increasing transmission intensity.

Thus, both the experiment and numeric modeling conform to the multistability diagrams shown in Fig. 1. Each of the diagrams allows the $\sigma^{\pm}$ components of the cavity field to be switched-up individually or in combination, giving rise to the four stability branches. The intermediate stability branches with high circular polarizations are "screened out" and become inaccessible in the case of exciting of the lower split-off eigenstate; by contrast, they are rather wide when exciting the upper one, so that the output polarization can be made circular even when the pump field polarization is almost linear. To understand the physical source of the difference, one should analyze the phases of the field components.

Let us consider first the simplest case of a bistable one-component polariton oscillator[3,4] whose steady-state amplitudes ψ obey the equation $(\omega_p - \omega_0 - V|\psi|^2 + i\gamma)\psi = \mathcal{E}$. Let $\psi = \bar{\psi}e^{i\phi}$ and $\mathcal{E} = \bar{\mathcal{E}}e^{i\chi}$. The phase of ψ with respect to the driving force $[\phi - \chi = \arg(\mathcal{E}^*\psi)]$ satisfies the relations

$$\tan(\phi - \chi) = -\frac{\gamma}{\omega_p - \omega_0 - V|\bar{\psi}|^2}, \quad \sin(\phi - \chi) < 0. \quad (2)$$

The bistability area exists if $\omega_p - \omega_0 > \sqrt{3}\gamma$ (see Ref. 3). The transition from the lower to the upper stability branch is accompanied by the jump in intensity $\Delta(V|\bar{\psi}|^2) \gtrsim (2/3)\sqrt{(\omega_p - \omega_0)^2 - 3\gamma^2}$ and hence by the phase shift $\Delta\phi$ within the interval $-\pi < \Delta\phi \lesssim -\arctan\sqrt{(\omega_p - \omega_0)^2 - 3\gamma^2}/2\gamma$.

In a spinor system described by Eq. (1), the difference between ϕ_+ and ϕ_- makes possible a direct spin-flip transition between the σ^+ and σ^- components as long as the low-field eigenstates are split due to any reason ($\delta \neq 0$). Namely, if differences $\psi_{\pm} - \chi$ were imposed from the outside, intensities $I_{\pm} = \psi_{\pm}^*\psi_{\pm}$ would obey the equation

$$\frac{d\sqrt{I_{\pm}}}{dt} = -\gamma_0\sqrt{I_{\pm}} + \frac{\delta}{2}\sin(\phi_{\mp} - \phi_{\pm})\sqrt{I_{\mp}} + \bar{\mathcal{E}}_{\pm}\sin(\chi_{\pm} - \phi_{\pm}). \quad (3)$$

If the pump excites the upper eigenstate, so that $\chi_+ - \chi_- = 0$ and $\delta = \omega_x - \omega_y > 0$, then, according to the above consideration, $\sin(\phi_- - \phi_+)$ takes positive (negative) values due to the switch-up of the σ^+ (σ^-) component.[16] After either of the $\sigma^{\pm}$ switch-ups, the δ-term in Eq. (3) causes the spin-flip transition from the not-switched-up component to the switched-up one. Thereby the "minor" component decays and is prevented from being switched-up in its turn. Accordingly, the steady-state diagram in Figs. 1(a)–1(c) exhibits a wide region where only one of the $\sigma^{\pm}$ components is found in the high-field state. Note that $\sin(\phi_- - \phi_+)$ equals $\rho_{tr}^{(\mathbf{x}\pm\mathbf{y})} = (I_{\mathbf{x}+\mathbf{y}} - I_{\mathbf{x}-\mathbf{y}})/(I_{\mathbf{x}+\mathbf{y}} + I_{\mathbf{x}-\mathbf{y}})$, the latter is explicitly shown in Fig. 1(c). Within each of the two stability branches with high circular polarizations [Figs. 1(a)–1(c)], $\rho_{tr}^{(+,-)}$ and $\rho_{tr}^{(\mathbf{x}\pm\mathbf{y})}$ have the same sign if $\rho_p^{(\mathbf{x},\mathbf{y})} > 0$. In both the experiment and modeling shown in Fig. 3, the peak of $\rho_{tr}^{(\mathbf{x}\pm\mathbf{y})}$

appears 10–20 ps earlier than the maximum circular polarization. Thus, reaching the largest $\rho_{\rm tr}^{(+,-)}$ is indeed involved by the jump in the $\sigma^{\pm}$ phase shift that, according to our qualitative analysis, opens the spin-flip transition channel. In the case of a comparatively large pump intensity (Fig. 4), this peculiarity is not observed; on the other hand, in this case $\phi_+ - \phi_-$ changes so rapidly that Eq. (3) becomes invalid.

The situation appears completely opposite if the pump excites the lower split-off LP eigenstate, which is provided by $\delta = \omega_x - \omega_y > 0$ and $\chi_+ - \chi_- = \pm\pi$, so that all the spin-flip transitions are reversed. Now, the switched-up σ^+ or σ^- component "pumps" the not-switched-up one thereby helping it to reach its own switch-up threshold. As a result, the intermediate steady-state branches with high circular polarizations of intra-cavity field shrink away for small $\rho_p^{(+,-)}$ [Figs. 1(d)–1(f)] and are completely absent in the case of exactly linearly polarized excitation (not shown). If yet present, they exhibit opposite signs of $\rho_{\rm tr}^{(+,-)}$ and $\rho_{\rm tr}^{(\mathbf{x}\pm\mathbf{y})}$ for $\rho_p^{(\mathbf{x},\mathbf{y})} < 0$.

In the limiting case $\rho_p^{(\mathbf{x},\mathbf{y})} = 1$, the two circularly polarized branches have the same intensities, and which of the two corresponds to the actual state attained by the switched-up system is determined spontaneously by fluctuations occurring during instability development.

According to the recent theoretical predictions,[6,15] the same effect of a strong linear-to-circular ($\pi - \sigma$) polarization conversion at $\rho_p^{(+,-)} \approx 0$ may also be caused by an attraction between cross-circularly polarized polaritons ($V_2 < 0$) even in spatially isotropic systems ($\delta = 0$). In spite of the similarity, this mechanism is essentially different from that considered in our study since it does not depend on polarization directions (and thus on the *sign* of $\rho_p^{(\mathbf{x},\mathbf{y})}$) according to Eq. (1). Numerical estimations show that in the studied system $-0.15 < V_2/V_1 < 0.3$, for only within this interval the responses at $\rho_p^{(\mathbf{x},\mathbf{y})} = -0.99$ and $\rho_p^{(\mathbf{x},\mathbf{y})} = +0.99$ appear to be qualitatively distinct from each other and correspond to those observed in the experiment. Note that whilst it is hardly possible to control the V_2 constant by any means, the splitting δ between the LP levels can be governed by applying lateral stress or using special microcavity structures with manually engineered exciton or photon potential.

To summarize, we have proposed and demonstrated experimentally an ultra-fast all-optical way to convert light polarization from linear to almost circular, based on the nonlinear properties of strongly coupled quantum well microcavities. Although the proposed method is currently far from being implemented in ready-to-use switching devices due to very low temperatures required for its operation, it has the potential advantage of compactness and an extremely high speed of conversion. The temperature requirement can be reduced in modern wide-band-gap semiconductor heterostructures with large exciton-photon coupling strengths.

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[1]C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. **69**, 3314 (1992).
[2]I. A. Shelykh, A. V. Kavokin, and G. Malpuech, Phys. Status Solidi B **242**, 2271 (2005).
[3]A. Baas, J. P. Karr, H. Eleuch, and E. Giacobino, Phys. Rev. A **69**, 023809 (2004).
[4]N. A. Gippius, S. G. Tikhodeev, V. D. Kulakovskii, D. N. Krizhanovskii, and A. I. Tartakovskii, EPL **67**, 997 (2004).
[5]P. Renucci, T. Amand, X. Marie, P. Senellart, J. Bloch, B. Sermage, and K. V. Kavokin, Phys. Rev. B **72**, 075317 (2005).
[6]N. A. Gippius, I. A. Shelykh, D. D. Solnyshkov, S. S. Gavrilov, Y. G. Rubo, A. V. Kavokin, S. G. Tikhodeev, and G. Malpuech, Phys. Rev. Lett. **98**, 236401 (2007).
[7]I. A. Shelykh, T. C. H. Liew, and A. V. Kavokin, Phys. Rev. Lett. **100**, 116401 (2008).
[8]T. C. H. Liew, A. V. Kavokin, and I. A. Shelykh, Phys. Rev. Lett. **101**, 016402 (2008).
[9]T. K. Paraïso, M. Wouters, Y. Léger, F. Morier-Genoud, and B. Deveaud-Plédran, Nature Mater. **9**, 655 (2010).
[10]D. Sarkar, S. S. Gavrilov, M. Sich, J. H. Quilter, R. A. Bradley, N. A. Gippius, K. Guda, V. D. Kulakovskii, M. S. Skolnick, and D. N. Krizhanovskii, Phys. Rev. Lett. **105**, 216402 (2010).
[11]C. Adrados, A. Amo, T. C. H. Liew, R. Hivet, R. Houdré, E. Giacobino, A. V. Kavokin, and A. Bramati, Phys. Rev. Lett. **105**, 216403 (2010).
[12]S. S. Gavrilov, A. S. Brichkin, A. A. Demenev, A. A. Dorodnyy, S. I. Novikov, V. D. Kulakovskii, S. G. Tikhodeev, and N. A. Gippius, Phys. Rev. B **85**, 075319 (2012).
[13]Ö. Bozat, I. G. Savenko, and I. A. Shelykh, Phys. Rev. B **86**, 035413 (2012).
[14]R. B. Balili, D. W. Snoke, L. Pfeiffer, and K. West, Appl. Phys. Lett. **88**, 031110 (2006).
[15]S. S. Gavrilov, N. A. Gippius, S. G. Tikhodeev, and V. D. Kulakovskii, JETP **110**, 825 (2010).
[16]Although switch-up of one of the $\sigma^{\pm}$ components affects the phase of the other, this additional change does not alter the estimated signs of $\sin(\phi_- - \phi_+)$.