Polarization Multistability of Cavity Polaritons

N. A. Gippius,[1,2] I. A. Shelykh,[3] D. D. Solnyshkov,[1] S. S. Gavrilov,[1,4] Yuri G. Rubo,[5] A. V. Kavokin,[6,7] S. G. Tikhodeev,[2] and G. Malpuech[1]

[1]*LASMEA, CNRS, Université Blaise Pascal, 24 av. des Landais, 63177 Aubière, France*
[2]*A. M. Prokhorov General Physics Institute, RAS, Russia*
[3]*ICCMP, Universidade de Brasilia, 70904-970 Brasilia DF, Brazil*
[4]*Institute of Solid State Physics, RAS, Russia*
[5]*Centro de Investigación en Energía, Universidad Nacional Autónoma de México, Temixco, Morelos 62580, Mexico*
[6]*School of Physics & Astronomy, University of Southampton, SO17 1BJ, Southampton, United Kingdom*
[7]*Physics Faculty, University of Rome II, 1, via della Ricerca Scientifica, 00133, Roma, Italy*

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New effects of polarization multistability and polarization hysteresis in a coherently driven polariton system in a semiconductor microcavity are predicted and theoretically analyzed. The multistability arises due to polarization-dependent polariton-polariton interactions and can be revealed in polarization resolved photoluminescence experiments. The pumping power required to observe this effect is 4 orders of magnitude lower than the characteristic pumping power in conventional bistable optical systems.

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Introduction.—Cavity polaritons are elementary excitations of semiconductor microcavities with extremely small effective mass m^* ranging from 10^{-4} to 10^{-5} of the free electron mass [1]. In the low density limit they behave as weakly interacting bosons and their Bose-Einstein condensation (BEC) has been recently claimed [2]. Under resonant excitation two main mechanisms of optical nonlinearity have been identified, the polariton parametric scattering [3–8] and bistability of the polariton system [9–12]. These two mechanisms often coexist since both of them are induced by polariton-polariton interaction [10,11]. Another mechanism of nonlinearity is related to the change of the exciton oscillator strength [13].

An important peculiarity of the cavity polaritons is related to their polarization or pseudospin degree of freedom. Polaritons have two possible spin projections on the structure growth axis, ± 1, corresponding to the right and left circular polarizations of the counterpart photons. In case of nonzero in-plane wave vector ($k \neq 0$) these two components are mixed by TE-TM splitting [14]. The mixing of the $k = 0$ states appears due to the polariton-polariton interaction, which depends on the spin orientation. Namely, the interaction of polaritons in triplet configuration (parallel spin projections on the structure growth axis) is different from that of polaritons in singlet configuration (antiparallel spin projections). The spin-dependent polariton coupling strongly affects the predicted superfluid properties of the polariton system [15,16] and leads to remarkable nonlinear effects in polariton spin relaxation, such as self-induced Larmor precession and inversion of the linear polarization during the scattering act [17].

In this Letter we show that the interplay between the nonlinearity caused by the polariton-polariton interactions and the polarization dependence of these interactions results in a remarkable *multistability* of a driven polariton system, contrary to the usual optical *bistability* in the spinless nonlinear case. We consider the ground state ($k = 0$) polariton mode having a finite lifetime which is coherently pumped at normal incidence to the microcavity plane by a *cw* laser of variable intensity, frequency, and polarization. We calculate the resulting intensity and polarization of the polariton field and show that, for a given polarization of the pump and depending on the history of the pumping process, the polariton polarization can, in general, take three different values. For instance, a linearly polarized laser can result in a strongly right circularly, strongly left circularly, or in a linearly polarized polariton state. The whole system is therefore not simply bistable but multistable. It allows the realization of a multichannel optical switch sensitive not only to the pump intensity but also to its polarization. It is worth noting that this conversion from linear to circular polarization arises without any TE-TM splitting [18] and represents a new nonlinear effect.

Qualitatively, the multistability can be understood as follows. We consider that the cavity is illuminated by laser light at normal incidence at the frequency above the bottom of the lowest polariton branch (LPB). At low pumping, the pump is not in resonance with the polariton eigenstate, so the population of the driven mode remains low. At higher pumping, polariton-polariton interactions lead to the blueshift of the LPB, so that it approaches the pump laser frequency. At resonance, the population jumps up abruptly. If the pumping power is then decreased, the population of the polariton mode jumps down back, but at a lower threshold. As a result the typical *S*-shape dependence of the intracavity field on the pumping intensity appears as Fig. 1 shows, which means the formation of a hysteresis cycle. The additional polarization degree of freedom makes this picture much more complex and rich.

Coherent polarization evolution.—We therefore consider the scheme previously described where a microcavity

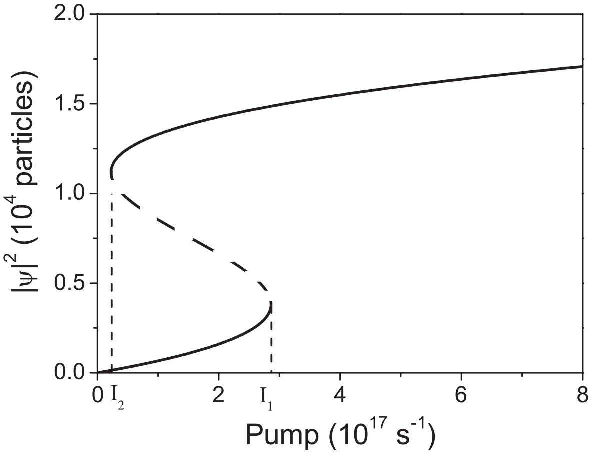

FIG. 1. The polariton population $|\psi_\sigma|^2$ versus pumping intensity $|p_\sigma|^2$ for the circularly polarized pump ($\sigma = \pm 1$). Dashed line shows the unstable region. I_1 and I_2 mark two jumps in population caused by the increase and decrease of the pumping intensity, respectively.

is pumped by laser light perpendicular to the cavity plane ($k = 0$), with spatially uniform and slowly changing with time intensity p_σ and frequency ω near the bottom of the LPB, where $\sigma = \pm 1$ is the circular polarization index. We neglect the nonparabolicity of the polariton dispersion and the wave vector dependence of exciton and photon fractions. These approximations are well justified since the effects we discuss are taking place in a narrow energy and wave vector range close to the polariton ground state at $k = 0$ with the eigenfrequency ω_0.

The $k = 0$ polariton wave function ψ_σ satisfies the driven spinor Gross-Pitaevskii equation [15,19], which in the quasistationary case can be written as (we set $\hbar = 1$)

$$\left[\omega_0 - \omega - \frac{i}{\tau} + \alpha_1|\psi_\sigma|^2 + \alpha_2|\psi_{-\sigma}|^2\right]\psi_\sigma + \frac{p_\sigma}{\sqrt{4\tau}} = 0, \tag{1}$$

where the number of the particles in the system with spin σ is $N_\sigma = |\psi_\sigma|^2$, τ is the polariton lifetime, $\alpha_{1(2)}$ is the matrix element of polariton-polariton interaction in the triplet(singlet) configuration, respectively. The exchange interaction is suppressed for polaritons in the singlet configuration since it involves split-off dark excitons as intermediate states. As a result, there is an attraction between polaritons of opposite spin, $\alpha_2 < 0$, and polariton-polariton interaction is strongly anisotropic $|\alpha_2| \ll \alpha_1$ [20].

At thermodynamic equilibrium the polariton BEC leads to the formation of the linearly polarized condensate, which minimizes the free energy of the system [15]. In the case of *cw* driven system the situation is qualitatively different. The polariton system is intrinsically out of equilibrium and its state is now defined by the pump. The parameters of the driven mode, however, are not uniquely defined. E.g., with a linearly polarized pump the polariton system can change its polarization either to the left or to the right circular, increasing thus the blueshift and entering into resonance with the pump. The left- and right-circular polarizations can appear in this case with equal probabilities.

Equation (1) can be used to relate the number of polaritons $N = |\psi_{+1}|^2 + |\psi_{-1}|^2$ and the degree of circular polarization $\rho_c = (|\psi_{+1}|^2 - |\psi_{-1}|^2)/N$ with the pump intensity $I = |p_{+1}|^2 + |p_{-1}|^2$ and the pump polarization degree $\rho_p = (|p_{+1}|^2 - |p_{-1}|^2)/I$. Namely,

$$\begin{aligned} I/4\tau = [&\Omega^2 + \tau^{-2} + (\alpha_1 - \alpha_2)(1 - \rho_c^2)\Omega N \\ &+ (1/4)(\alpha_1 - \alpha_2)^2(1 - \rho_c^2)N^2]N, \end{aligned} \tag{2}$$

$$\rho_p I/4\tau = [\Omega^2 + \tau^{-2} - (1/4)(\alpha_1 - \alpha_2)^2(1 - \rho_c^2)N^2]\rho_c N, \tag{3}$$

where $\Omega = \omega - \omega_0 - \alpha_1 N$.

It follows from Eqs. (2) and (3) that only for the pump with a pure circular polarization, $\rho_p = \pm 1$, the polarizations of the polariton system and the pump coincide. In this case the present spinor model can be reduced to the scalar model [10,11]. For elliptical pumping the polarizations of the polariton system and of the laser are different due to the different blue shifts for right and left circular-polarized components. Because of the effect of the self-induced Larmor precession [17] the polarization ellipse of the driven mode is rotated with respect to the polarization ellipse of the pump by some angle which depends on the pump intensity. Moreover, in this regime even the signs of circular polarization degrees of the polaritons and the pump can be different, as we show in the next subsection.

Multistability and hysteresis.—The population $|\psi_{\pm 1}|^2$ as a function of the pump intensity $|p_{\pm 1}|^2$ for the case of fully circular-polarized excitation (when the polarization of the driven mode coincides with that of the pump) is shown in Fig. 1. The energy of the laser ω is chosen above the energy of the bare polariton state, $\omega - \omega_0 = 3$ meV, so that the curve shows the classical S shape. Here and below, we use $\alpha_1 = 6xE_b a_B^2/S$, where $a_B = 100$ Å is the two dimensional exciton Bohr radius, $E_b = 8$ meV is the exciton binding energy, $x = 1/4$ is the squared exciton fraction, and $S = 100$ μm^2 is the laser spot area. The polariton life-time is $\tau = 2$ ps. These parameters are typical for a GaAlAs microcavity. We have denoted by I_1 and I_2 the laser intensities corresponding to the bending points of the S-shaped curve taking place with the increase and decrease of pumping intensity, respectively.

The evolution of the internal polarization can be conveniently illustrated and understood considering the case $\alpha_2 = 0$, when Eqs. (1) for two values of σ are simply decoupled and the two circular components evolve independently [21]. The change of ρ_c with the total pump intensity is shown in Fig. 2(a) for the elliptically polarized pump with $\rho_p = 0.2$, so that σ^+ component slightly exceeds σ^- one. As the intensity of the pump increases, the

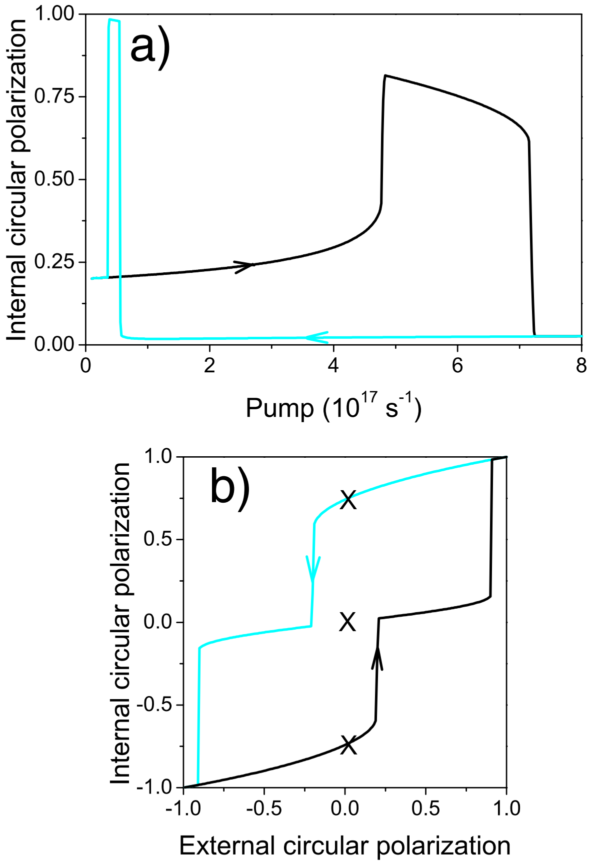

FIG. 2 (color online). (a) Circular polarization degree of the driven mode versus external pumping intensity for slightly elliptical pump ($\rho_p = 0.2$). Arrows show the direction in which the pump intensity is changed. (b) Circular polarization degree of the driven mode ρ_c versus circular polarization degree of the pump ρ_p. Arrows show the direction in which the pump polarization degree is changed. The pump intensity is just above I_1. Crosses mark the stable points at $\rho_p = 0$.

solution moves along the lower branch of the S curve for both σ^+ and σ^- components. However, the σ^+ component, since it dominates, reaches the threshold intensity I_1 first. The corresponding intensity of the polariton field jumps abruptly to the upper branch. At the same time, the intensity of the σ^- pump has not yet reached the I_1 bending point. So, the jump of the total polariton density is accompanied by a jump of the circular polarization degree. If the intensity of pump increases further, the intensity of the σ^- mode also reaches I_1. The polariton population increases again, but this now results in an abrupt decrease of the circular polarization degree of the driven mode. If we now reduce the intensity, the reversed process takes place at the pumping intensity I_2 so that hysteresis in both the occupation and polarization power dependencies appear.

Figure 2(b) shows another interesting configuration, where the laser intensity I is kept constant in the domain $I > I_1$ and $I_1 > I/2 > I_2$. The cyan line shows the change of the circular polarization degree of the driven mode ρ_c induced by the laser initially polarized σ^+ and whose polarization is progressively rotated towards the σ^- polarization. One can observe a weak decrease of ρ_c, which, however, remains quite high even when the pumping is linearly polarized. This is due to the fact that the σ^+ component remains on the upper branch of the S curve whereas the σ^- stays on the lower branch. Then there are two jumps of polarization corresponding to the jumps of σ^+ and σ^- components of the polariton population, and finally the polarization becomes fully σ^-. The black line shows the evolution of ρ_c with the inverse change of the pump polarization. The stable points corresponding to full linear polarization of the laser are marked with crosses in Fig. 2(b). One can see that the internal polarization can be either nearly σ^+, either nearly σ^-, or fully linear. The latter case is in fact degenerate. There can be two stable driven mode occupations N for the same value of the external laser intensity I.

Figure 3 shows the functional dependence between σ^+ and σ^- components of the polariton population and the intensity and polarization of pump calculated accounting for the coupling between polaritons with opposite spins described by $\alpha_2 = -0.1\alpha_1$. This value of α_2 corresponds to recent estimations of Ref. [20]. The circular polarization degree of the pump laser is represented by the color of the surface of solution and the intensity of the pump is on the vertical z axis. The linear part of the polarization of the laser is kept aligned along x direction.

The green areas correspond to nearly linearly polarized pumping. If the intensity of the pump increases, while its polarization is kept linear, the system follows the black

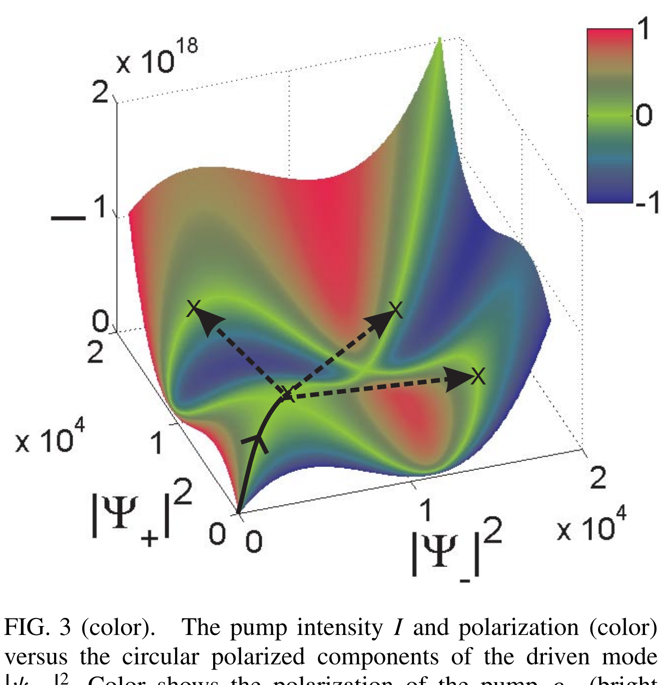

FIG. 3 (color). The pump intensity I and polarization (color) versus the circular polarized components of the driven mode $|\psi_{\pm 1}|^2$. Color shows the polarization of the pump ρ_p (bright green corresponds to linear polarization). The crosses mark the four stable points for the driven mode corresponding to the same linearly polarized pump intensity. Arrows show the three possible jumps in case if the pump intensity is slightly increased.

solid line and black arrows shown in the Fig. 3. One can see that from the critical point at the end of the solid black line the system can jump into three possible stable points (shown by crosses). One of them corresponds to the linearly polarized state and two others to nearly right- and left-circularly polarized states. The stability of the states was verified using the standard linearization procedure as it is done in [11]. The choice of the final state by the system is random and is triggered by fluctuations.

Note also that the jump of the system to the circularly polarized final state induces a redshift of the cross-circular component because of the negative sign of α_2. The red shift drives this component out of resonance with the pump, which leads to stronger polarization of the final state. The positive feedback in polarization of the polariton system would not take place for the case $\alpha_2 = 0$, where only a linearly polarized driven mode would be formed. Experimentally, we expect this effect to have a key impact on the polarization measurements performed with resonantly excited microcavities. It will result in a random sign of the observed polariton polarization changing from one experiment to another.

It should be noted that polarization multistability and chaos in nonlinear optical systems have been studied for more than 30 years (see, e.g., [22]). A general phenomenological description of polarization bistability can be found in [23]. A number of intriguing nonlinear effects have been predicted and observed in different systems, including four-wave mixing in anisotropic crystals [24,25], magnetic cavities [26], and vertical cavity surface emitting lasers [27]. However, in the systems investigated previously extremely high powers (10 $\mathrm{MW/cm^2}$ [22]) are required for observation of polarization multistability effects linked to optical nonlinearities. The advantage of the microcavities is that in the strong coupling regime the nonlinear threshold corresponds to much lower pumping powers (e.g., 650 $\mathrm{W/cm^2}$ [28]) which opens the way to realization of low threshold polarization switches. Potential applications in polariton optical devices with use of polarization squeezing and entanglement effects can be foreseen. These phenomena have been already studied in atomic ensembles placed in optical cavities [29]. Multistable systems can also have chaotic dynamics (for the particular system it is a subject of current research), and in this case microcavities could be used for data encryption and transmission using the chaotic communication method. Therefore the low threshold multistable system here described could be used for practical realization of new applications like data encryption and communication [30].

Conclusions.—We have analyzed the polarization of the spinor polariton system pumped by a *cw* laser of variable polarization at $k = 0$ by solving the polarization-dependent Gross-Pitaevskii equation. We have shown that for a given polarization of the pumping laser the polariton polarization can take three different values. For instance at linear pumping the resulting polariton state can be right circularly, left circularly, or linearly polarized. In realistic cases, the intensity and polarization of the driven mode are random. The transitions between different states are triggered by the fluctuations of the intensity and polarization of the pump.

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