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Magnetic-field induced bistability in a quasi-one-dimensional semiconductor microcavity

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ABSTRACT

We theoretically study the magnetic-field induced bistability in a quasi-one-dimensional semiconductor microcavity. A critical magnetic field is obtained, and the bistability appears if a magnetic field is greater than the critical value. For a positive energy detuning of the pump from the bare exciton polaritons, one bistability loop first emerges, then it divides into two loops, and finally one of them vanishes with the increasing magnetic field. This phenomenon originates from the magnetic-field modulated interactions for opposite spins. In the variational process, there are two important effects: one is a logic gate with a small variation of the excitation laser, and the other is a spin texture like skyrmion and this texture is periodic if the energy detuning varies periodically in real space, which is useful for designing the spin-dependent optoelectronic devices.

1. Introduction

Exciton polaritons (EPs) are quasiparticles which arise from the strong coupling between excitons and cavity photons in a semiconductor microcavity. This kind of quasiparticles is very particular, for instance, the effective mass is extremely small and there exists nonlinear interaction between EPs, which originate from the properties of photons and excitons, respectively. When the semiconductor microcavity is fabricated to form a quasi-one-dimensional (QOD) structure, EPs can propagate in one direction, while the confinement of the other direction leads to a splitting of energy levels. In this structure, there are many appealing phenomena [1–5], and they are important to comprehend the QOD exciton–polariton condensate.

In a microcavity, the interaction constants are dependent on the spins of EPs [6–8], precisely speaking, the interaction with parallel spins is several times greater than that with antiparallel spins. Moreover, EPs with parallel spins repel each other, while the attraction always exists with opposite spins. These features result in a lot of appealing spin textures, such as the half-vortices [9–11] and half-solitons [12–15].

The interaction between EPs can bring nonlinear effects, and bistability [16] and multistability [17] are examples. In the bistability loop, the density is determined not only by the pump, but by its initial value, so this phenomenon is suitable to be used as switches [18,19] and logic circuits [20]. In addition, different kinds of solitons can be found in the bistability region [21–23]. Bistability emerges in the previous study with proper parameters, while we will discuss the variation of bistability with an external magnetic field, which has not been considered so far.

In this paper, we investigate the magnetic-field induced bistability of EPs with spin-dependent interactions in a QOD semiconductor microcavity. We find that the energy detuning of the pump from the bare EPs plays a key role in the bistability, and there is a spin texture like skyrmion [24–27] with proper parameters, i.e., a finite region with reversing the spin in the background of aligned spins. The paper is organized as follows: In Section 2, using the Gross–Pitaevskii equations, we discuss the distribution of EPs with opposite spins in real space. In Section 3, the analytical and numerical results are obtained and discussed. Finally, the conclusion of this work is given in Section 4.

2. Model and formulation

In a QOD semiconductor microcavity, we take fully into account the loss, supplement, and interactions between EPs with parallel and antiparallel spins. An external magnetic field is applied to the plane of the microcavity, and there will be the Zeeman splitting for opposite spins. Then the Gross–Pitaevskii equations for two spin components are written as [4]

$$i\hbar\frac{\partial}{\partial t}\phi_\sigma = -\frac{\hbar^2}{2m}\frac{\partial^2\phi_\sigma}{\partial x^2} + \alpha_1|\phi_\sigma|^2\phi_\sigma + \alpha_2|\phi_{\bar\sigma}|^2\phi_\sigma - \frac{i\hbar}{2\tau}\phi_\sigma - (\delta + \frac{1}{2}\eta_\sigma\Omega_z)\phi_\sigma + P_\sigma, \tag{1}$$

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where ϕ_σ is the order parameter of EPs with spin σ ($=\uparrow$ or $\downarrow$), and $\bar{\sigma}$ represents the spin opposite to σ. $\eta_\uparrow = 1$ and $\eta_\downarrow = -1$. m and τ denote the effective mass and lifetime of EPs, respectively. α_1 (α_2) labels the interaction constant between EPs with parallel (antiparallel) spins. δ is the energy detuning of the pump from the bare EPs. Ω_z describes the Zeeman energy induced by a magnetic field, which is treated as a single parameter here. The term P_σ denotes the optical pumping, which supplements EPs continuously and keeps the system in the steady state.

In the microcavity, the distribution of EPs is along one direction x, and affected by many factors, such as the pump, interactions, and Zeeman energy. The density of EPs with spin σ is expressed as $n_\sigma = |\phi_\sigma|^2$. For the linearly polarized pump, the densities are the same for opposite spins without Zeeman splitting, i.e., $n_\uparrow = n_\downarrow$. If a magnetic field is applied, the situation is different, and the densities may be unequal for opposite spins. Hence the polarization degree is necessary to describe this case, which is defined as

$$\chi = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}. \tag{2}$$

Using this polarization degree, we can discuss many interesting phenomena and their possible applications.

3. Results and discussion

The applied laser is linearly polarized ($P_\uparrow = P_\downarrow = P$) and perpendicular to the plane of the microcavity. Throughout the calculations in this work, the parameters are chosen from the typical GaAs/AlGaAs microcavity and experimentally accessible. $\alpha_1 = 1.2 \times 10^{-3}$ meV µm, $\alpha_2 = -0.2\alpha_1$, $\tau = 15$ ps [5].

When the pump is homogeneous in real space, the term of kinetic energy in Eq. (1) can be neglected without any spatial potential. Then we discuss the effect of a magnetic field on the densities of EPs using the following equation which can be derived from Eq. (1),

$$\left[(\alpha_1 n_\sigma + \alpha_2 n_{\bar{\sigma}} - \frac{1}{2}\eta_\sigma \Omega_z - \delta)^2 + \frac{\hbar^2}{4\tau^2}\right] n_\sigma = |P_\sigma|^2. \tag{3}$$

From Eq. (3), we can obtain the variation of n_σ with the pump P_σ, and there may exist bistability. As known, bistability results from the nonlinear interaction, but only the interaction may not lead to bistability. Thus the proper parameters in Eq. (3) are necessary to discuss this phenomenon.

If the bistability appears, the turning points meet the equation $\partial P_\sigma / \partial n_\sigma = 0$, so we can get an analytic expression for the turning points from Eq. (3),

$$\left(3\alpha_1^2 - 4\alpha_2^2 + \frac{\alpha_2^4}{\alpha_1^2}\right) n_\sigma^2 + 2A_\sigma \frac{2\alpha_1^2 - \alpha_2^2}{\alpha_1} n_\sigma + A_\sigma^2 + \frac{\hbar^2}{4\tau^2} = 0, \tag{4}$$

where

$$A_\sigma = \frac{\alpha_2 - \alpha_1}{\alpha_1}\delta - \eta_\sigma \frac{\alpha_1 + \alpha_2}{2\alpha_1}\Omega_z. \tag{5}$$

We can see that $n_\uparrow$ and $n_\downarrow$ are coupled, and they should be self-consistent in Eq. (3). Eq. (4) is a quadratic equation, and the discriminant is expressed as,

$$\Delta_\sigma = A_\sigma^2 \alpha_1^2 - \frac{\hbar^2}{4\tau^2}\left(3\alpha_1^2 - 4\alpha_2^2 + \frac{\alpha_2^4}{\alpha_1^2}\right). \tag{6}$$

If the bistable behavior appears, there are solutions of Eq. (4), so we have $\Delta_\sigma \geq 0$. Besides, n_σ is a positive real number, then the term A_σ should be smaller than zero. Therefore, we obtain the condition of bistability,

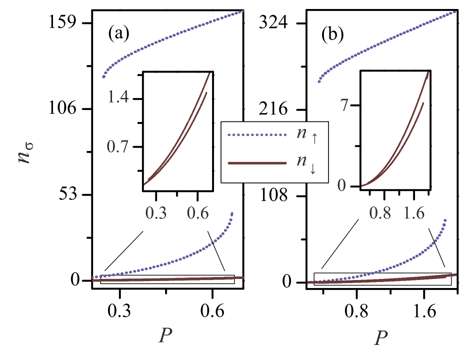

Fig. 1. (Color online.) The density n_σ varying with the pump P for different magnetic fields. $\Omega_z = 0.7$ meV and 1 meV in (a) and (b), respectively. The insets in (a) and (b) are the bistability loop for EPs with spin $\downarrow$, $\delta = -0.2$ meV in both panels.

$$A_\sigma \leq -\frac{\hbar}{2\tau\alpha_1}\sqrt{3\alpha_1^2 - 4\alpha_2^2 + \frac{\alpha_2^4}{\alpha_1^2}}. \tag{7}$$

The right side of Eq. (7) is a constant here, and we should discuss the term A_σ.

In this situation, whether the bistable behavior emerges depends on the parameters δ and Ω_z. When the energy detuning δ is smaller than zero, we have a critical Zeeman energy Ω_c which can be used to judge whether there is bistability, and $\Omega_c \approx -3\delta + 0.09$ meV with the above parameters. If $\Omega_z \leq \Omega_c$, there is no bistability for both spins, and n_σ is monodrome as P_σ varies. When $\Omega_z > \Omega_c$, there are bistability loops for opposite spins, that is, the lower and upper states appear for each spin, as shown in Fig. 1(a). The value of n_σ depends on both its initial condition and P_σ in this region. Besides, $n_\uparrow$ is always larger than $n_\downarrow$ even when $n_\uparrow$ is in the lower state.

As the magnetic field goes up, the difference of densities between the lower and upper states increases for each spin, and the turning points at the beginning and end of the bistability loop, as well as their difference, become large by comparing Fig. 1(a) and 1(b). The turning points are the same for opposite spins with a fixed Zeeman energy because $n_\uparrow$ and $n_\downarrow$ are coupled, for instance, they are at $P = 0.25$ and $P = 0.66$, respectively, in Fig. 1(a). If we can judge that there is bistability for one spin, the other exists certainly in the same region, thus we can only discuss this phenomenon for one spin with Eq. (7).

When the energy detuning δ is zero, we have the critical Zeeman energy $\Omega_c \approx 0.09$ meV. The variation of the bistability loops with the magnetic field is similar to the case $\delta < 0$. There is only one bistability loop for each spin with the increasing Ω_z, and the bistability of EPs with spin $\downarrow$ is induced by that of spin $\uparrow$.

Finally, we discuss the case $\delta > 0$, and this situation may be different from the above cases. From Eq. (7), we get the critical Zeeman energy $\Omega_c \approx -3\delta + 0.09$ meV for EPs with spin $\uparrow$, the bistability emerges for $\Omega_z > \Omega_c$. For spin $\downarrow$, the critical Zeeman energy is expressed as $\Omega_c \approx 3\delta - 0.09$ meV, which is different from the EPs with spin $\uparrow$. We can see that there are two critical Zeeman energies, and bistability takes place if one of them is met, so this case is more complex.

If $\Omega_z = 0$, we get $n_\uparrow = n_\downarrow$, and the critical Zeeman energies are the same for different spins. Thus there is only one bistability loop for each spin with $\delta > 0$, and the loops are coincident for opposite spins. As $\Omega_z \neq 0$, the critical Zeeman energy can be used to discuss the bistability, and the magnetic field will play an important role, as shown in Fig. 2.