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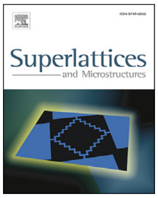

Spontaneous spin bifurcations in a Bose-Einstein condensate of indirect excitons

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ABSTRACT

In this paper, we theoretically study the spin dynamics of a spatially trapped Bose-Einstein condensate of indirect excitons (IXs). A spontaneous parity-symmetry breaking spin bifurcation for bright excitons is reported under non-resonant linearly polarized pumping. Above a certain pumping amplitude, condensation for bright excitons spontaneously and stochastically adopts one of two spin-polarized configurations S_z depending on initial occupations. This phenomenon of spontaneous spin bifurcations is attributed to the small energy splitting and difference in dissipation rates between bright and dark excitons in IX systems. The considered systems thus have potential applications in spin memories, spin switches and to simulate spin interactions in condensed lattices.

1. Introduction

An exciton is a quasiparticle consisting of an electron bound to a hole in a semiconductor. Due to their bosonic nature, excitons are expected to allow for a Bose-Einstein condensate (BEC) at low temperatures [1,2]. However, experimental observation of BEC of excitons has remained a challenge because the lifetime of ordinary excitons is too short to allow cooling to low temperature in a regular semiconductor. Indirect excitons (IXs), bound pairs of electrons and holes in spatially separated quantum well (QW) layers, have two primary advantages over ordinary excitons in bulk systems, *i.e.*, long lifetime and short exciton cooling time [3,4]. The long lifetime results from the reduced overlap of electron and hole wavefunctions leading to a radiative lifetime three orders of magnitude longer than that of ordinary direct excitons. The short exciton cooling time is caused by enhanced scattering of the exciton with acoustic phonons in the quantum well due to the relaxation of momentum conservation along the growth direction. The long lifetime and the fast cooling rate of indirect excitons allow their cooling beyond the temperature of quantum degeneracy [5].

An important feature of the condensing bosons in QWs is the spin degree of freedom, which is directly related to the polarization of absorbed or emitted light and can lead to novel phenomena. The spin structure of exciton-polaritons, the mixed light-exciton quasiparticles in semiconductor microcavities, has been widely studied in the past years [6]. An exciton-polariton has a two-component spin degree of freedom which was shown to lead to exciting phenomena such as polarization multistability [7,8], the optical spin Hall effect [9,10] and spin analogy of the Meissner effect [11]. In contrast to polariton, an IX has a four-component spin degree of freedom. The spin structure of IXs was only recently explored and found to be very rich [12–16]. The IX spin lifetime can be as long as their lifetime and IX spin propagation over several microns has been reported

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[17]. The existence of IXs in a compact solid-state system in principle allows on-chip spintronic devices with current nano-patterning technologies [18]. The short spin dephasing of IXs [19] can be also expected to allow spintronic devices with smaller error correction overheads and increased computational efficiency. Very recently, the two-component polariton condensates were experimentally reported to show a spontaneous symmetry-breaking bifurcation in their polarization state under nonresonant pumping [20], analogous to the weak lasing regime [21]. Therefore, a clearly intriguing problem is to explore whether the four-component IX condensates can show a similar spontaneous symmetry-breaking bifurcation under nonresonant pumping.

2. Formalism

In zinc-blend semiconductor QWs (e.g. GaAs/AlGaAs system), the lowest energy excitons are formed by electrons with spin projection on the QWs growth axis of ±1/2 and heavy holes with quasi-spin (sum of spin and orbital momentum) projection in the same direction of ±3/2 [14]. Therefore, IXs inherit four possible spin projections, as a sum of electron spin and heavy hole quasi-spin, on the growth axis of ±1 and ±2. Bright excitons with spin projections ±1 can be coupled to light while dark excitons with spin projections ±2 are optically prohibited. For IXs, bright and dark states are usually nearly degenerate, while there may be some splitting between them due to the short and long-range exchange interactions. We present simulations of IXs with consideration of the spin structure using Gross-Pitaevskii type equations. We consider that IXs are confined in electrostatic or laser light traps so that a highly degenerate IX gas can be achieved in the trap center [22,23]. Both linearly polarized optical and electric pumping are utilized to create the trapped IXs condensate via nonresonant excitation of electron-hole plasma. In order to avoid the spin-flip scattering of condensate caused by the exciton reservoir, specific excitation geometry is considered to induce the spatial separation of condensate and pumped exciton reservoir (*i.e.* the excitation beam can be shaped into a separated four-spot pattern). The order parameter of the IX condensate is a four-component complex vector $(\varphi_{+1},\quad \varphi_{-1},\quad \varphi_{+2},\quad \varphi_{-2})$, and evolves according to the following equations [12,14]:

$$i\frac{d\varphi_{+1}}{dt}=\frac{i}{2}(P+W_1-\mathit{\Gamma}-S)\varphi_{+1}-\left(\frac{i}{2}\gamma_{bd}-\varepsilon_{bd}\right)\varphi_{+1}+\left[\alpha_1|\varphi_{+1}|^2+\alpha_2|\varphi_{-1}|^2\right]\varphi_{+1}+\alpha_3\left[|\varphi_{+2}|^2+|\varphi_{-2}|^2\right]\varphi_{+1} + \alpha_4(\varphi_{-1})^*\varphi_{+2}\varphi_{-2} \tag{1}$$

$$i\frac{d\varphi_{-1}}{dt}=\frac{i}{2}(P+W_1-\mathit{\Gamma}-S)\varphi_{-1}-\left(\frac{i}{2}\gamma_{bd}-\varepsilon_{bd}\right)\varphi_{-1}+\left[\alpha_1|\varphi_{-1}|^2+\alpha_2|\varphi_{+1}|^2\right]\varphi_{-1}+\alpha_3\left[|\varphi_{+2}|^2+|\varphi_{-2}|^2\right]\varphi_{-1} + \alpha_4(\varphi_{+1})^*\varphi_{+2}\varphi_{-2} \tag{2}$$

$$i\frac{d\varphi_{+2}}{dt}=\frac{i}{2}(W_2-\mathit{\Gamma}-S)\varphi_{+2}+\left(\frac{i}{2}\gamma_{bd}-\varepsilon_{bd}\right)\varphi_{+2}+\left[\alpha_1|\varphi_{+2}|^2+\alpha_2|\varphi_{-2}|^2\right]\varphi_{+2}+\alpha_3\left[|\varphi_{+1}|^2+|\varphi_{-1}|^2\right]\varphi_{+2} + \alpha_4(\varphi_{-2})^*\varphi_{+1}\varphi_{-1} \tag{3}$$

$$\frac{d\varphi_{-2}}{dt}=\frac{i}{2}(W_2-\mathit{\Gamma}-S)\varphi_{-2}+\left(\frac{i}{2}\gamma_{bd}-\varepsilon_{bd}\right)\varphi_{+2}+\left[\alpha_1|\varphi_{-2}|^2+\alpha_2|\varphi_{+2}|^2\right]\varphi_{-2}+\alpha_3\left[|\varphi_{+1}|^2+|\varphi_{-1}|^2\right]\varphi_{-2} + \alpha_4(\varphi_{+2})^*\varphi_{+1}\varphi_{-1} \tag{4}$$

where $S=\eta_{sb}(|\varphi_{+1}|^2+|\varphi_{-1}|^2)+\eta_{sd}(|\varphi_{+2}|^2+|\varphi_{-2}|^2)$ represents gain saturation [24] with coefficient η_{sb} and η_{sd} for bright and dark IXs. P is the incoherent incoming scattering rate for external optical pumping of bright excitons, W_1 and W_2 are incoherent incoming scattering rate for external electric pumping of bright and dark excitons, respectively. $\mathit{\Gamma}$ is the average dissipation rate of IXs. $2\gamma_{bd}$ and $2\varepsilon_{bd}$ are dissipative and energy differences between bright and dark excitons. $\alpha_1, \alpha_2, \alpha_3$ and α_4 are exciton interaction constants [12]. Unless otherwise specified, the parameters used for the simulations are as follows: $\mathit{\Gamma}=0.2\ \ \mathrm{ns}^{-1},\ \eta_{sb}=\eta_{sd}=5\ \ \mathrm{ns}^{-1}\ ,\ \gamma_{bd}=0.5\ \ \mathrm{ns}^{-1},\ \varepsilon_{bd}=0.5\ \ \mathrm{ns}^{-1},\ \alpha_1=5\ \ \mathrm{ns}^{-1},\ \alpha_2=4\ \ \mathrm{ns}^{-1},\ \alpha_3=\alpha_1,\ \alpha_4=0.6\ \ \mathrm{ns}^{-1}$. Without loss of generality, we assume $W=W_1=W_1$ in our calculations. The optical pumping intensity is characterized by $\chi_P=(P-2\gamma_{bd})/2\varepsilon_{bd}$ which is the ratio of effective dissipation rate difference between dark and bright excitons to energy difference. The ratio χ_p plays an important role in determining spontaneous spin bifurcations.

The complex order parameter for condensate bright components $(\varphi_{+1},\quad \varphi_{-1})$ can be directly detected by measuring the photoluminescence (PL) spectra. The polarization resolved PL provides the information about the components of condensate pseudospin vector:

$$S_x=(\varphi^*_{-1}\varphi_{+1}+\varphi^*_{+1}\varphi_{-1})\Big/\left(|\varphi_{+1}|^2+|\varphi_{-1}|^2\right) \tag{5}$$

$$S_y=i(\varphi^*_{-1}\varphi_{+1}-\varphi^*_{+1}\varphi_{-1})\Big/\left(|\varphi_{+1}|^2+|\varphi_{-1}|^2\right) \tag{6}$$

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