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Polarization-dependent solitons in the strong coupling regime of semiconductor microcavities

Y. Fu [a], W.L. Zhang [a,b,*], X.M. Wu [a]

[a] *Key Laboratory of Optical Fiber Sensing & Communications (Education Ministry of China), University of Electronic Science & Technology of China, Chengdu 611731, China*

[b] *State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yatsen University, Guangzhou, 510275, China*

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ABSTRACT

This paper studies the influence of polarization on formation of vectorial polariton soliton in semiconductor microcavities through numerical simulations. It is found that the polariton solution greatly depends on the polarization of both the pump and exciting fields. By properly choosing the pump and exciting field polarization, bright–bright or bright–dark vectorial polariton solitons can be formed. Especially, when the input conditions of pump or exciting field of the two opposite polarizations are slightly asymmetric, an interesting phenomenon that the dark solitons transform into bright solitons occurs in the branch of soliton solutions.

1. Introduction

Cavity polaritons are half-matter half-light quasi-particles arising from the strong coupling between excitons and photons. Polaritons can be operated all-optically with fast response speed thanks to their photonic characteristics, meanwhile, excitonic characteristics of polariton induce strong nonlinear effect [1–11]. Thus, studies on fast nonlinear phenomenon of polariton in quantum well semiconductor microcavities are very attractive recently [5,12], particularly, in areas of low threshold bistability, parametric wave mixing and Bose–Einstein condensation [9,12–17].

Thanks to the observation of low-threshold bistability, polarization multistability and parametric scattering of polaritons, the necessary foundations for the realization of half-light half-matter solitons can be prepared [1,12–15]. In the past few years, since polariton solitons can form the movable binary elements, which are useful for future high-speed and low-power optical information processing and parallel processing, many researchers devote much energy to the dark and bright polariton solitons in semiconductor microcavities [10,15]. Recently, a part of researchers began to take into account the polarization characteristics when studying the formation of polariton solitons [2,4]. However, detailed relationship between polarizations of the pump/exciting field and the generated solitons still needs to be further uncovered.

As we know, two possible spins of light, i.e., right circular polarized (RCP) and left circular polarized (LCP) light, are supported inside microcavities, which introduce additional degree of freedoms to flexibly form solitons. For example, pump and exciting fields with different degree of polarizations would give birth to variety kinds of polariton solitons [10,11,18–20]. In our paper, the formation rule and dependence of polariton soliton on polarization characteristics of the pump and exciting fields are considered. Through diverse combinations of pump and exciting fields with specified degree of polarization, bright–bright, bright–dark vectorial solitons [2–4,15,21] are formed. Particularly, in the LCP mode, branches of soliton solutions which have step changes with the increase of pump intensity are found, corresponding to

* Corresponding author. Key Laboratory of Optical Fiber Sensing & Communications (Education Ministry of China), University of Electronic Science & Technology of China, Chengdu 611731, China. Tel.: +86 18981839359.

E-mail address: wl_zhang@uestc.edu.cn (W.L. Zhang).

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Table 1
Typical simulation values.

Parameters	Symbols	Values
Photon decay rate	γ_p	0.1
Exciton decay rate	γ_c	0.1
Exciton–exciton interaction constant	η	−0.1
Vacuum speed of light	c	3×10^8 m/s
Refractive index	n	3.5
Pump frequency	ω_{in}	6.4×10^7 Hz
Wave number	k_{in}	1.7
Rabi frequency	Ω	$\hbar\Omega = 2.5$ meV
Normalized frequency detuning	δ	−0.05
Transverse coordinate	x	Variable
Time	t	Variable
Photonic field	E	Variable
Excitonic field	ψ	Variable
Pump field	E_{in}	Variable
Exciting field	F	Variable

the transformation between dark and bright solitons when pump/exciting condition changes.

2. Theoretical model

The Gross–Pitaevskii model [1,4,22,23] has been well used to reflect coupling and dynamics of the exciton–polariton systems. As shown in Eqs. (1) and (2) [1,2,4,12,20,21], there are two dimensionless equations that depict the excitonic and photonic components of polariton fields.

$$\partial_t E_{1,2} = i(\partial_x^2 + 2ik_{in}\partial_x - k_{in}^2)E_{1,2} - (\gamma_p - i\delta)E_{1,2} + i\psi_{1,2} + E_{in1,in2} + F_{1,2} \quad (1)$$

$$\partial_t \psi_{1,2} = iE_{1,2} - (\gamma_e - i\delta)\psi_{1,2} - i(|\psi_{1,2}|^2 + \eta|\psi_{2,1}|^2)\psi_{1,2} \quad (2)$$

Here, values and definitions of the parameters used in the simulation are given in Table 1, which are based on typical values of GaAs/InGaAs quantum well microcavity lasers [1,2,4–6,12]. In the equations, E represents the photonic field and ψ represents the excitonic field. Subscript 1 corresponds to the RCP mode meanwhile subscript 2 corresponds to the LCP mode. The separate dimensionless parameters t, x and k_{in} are normalized to $1/\Omega$, x_0 $(= \sqrt{c^2/2n^2\omega_{in}\Omega})$ and $1/x_0$; $\gamma_{p,c}$ and δ are normalized to Ω. Nonlinear terms in Eq. (2) are $|\psi_{1,2}|^2\psi_{1,2}$ and $\eta|\psi_{1,2}|^2\psi_{1,2}$, representing interactions in the same and opposite directions, respectively. In the simulation, a modified 4th-order Runge–Kutta method [4,24] is applied to solve the equations numerically. In detail, there are two variables in Eqs. (1) and (2), namely time and space, and they are not correlative, so that the Runge–Kutta method can be used on time simulation, meanwhile, in the process of using Runge–Kutta method, the Euler method is used for spacial simulation.

It is known that soliton solutions can be found in bistable region; therefore once the bistable region is determined, solitons could be triggered by intruding external exciting field [15,17].

In our discussion, the polarization degree of pump and exciting fields are defined as $\rho_1 = (|E_{in1}|^2 - |E_{in2}|^2) / (|E_{in1}|^2 + |E_{in2}|^2)$ [2] and $\rho_2 = (|F_1|^2 - |F_2|^2)/(|F_1|^2 + |F_2|^2)$ respectively.

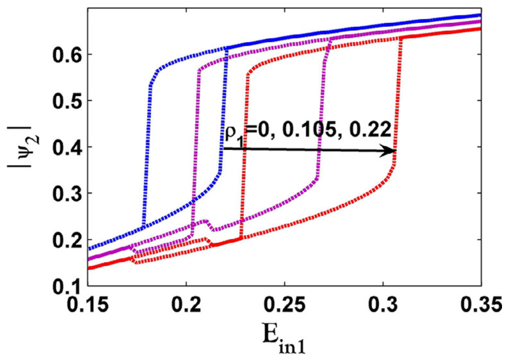

Fig. 1. The bistable loops of the LCP mode in different input polarization conditions. The transverse coordinate shows the maxima of the output exciting fields in LCP mode at the end of simulation time, and the longitudinal coordinate shows the pump intensity, E_{in1}. In addition, $k_{in} = 0$ and $\delta = -0.05$.

3. Simulation results

Fig. 1 shows the bistable characteristics of the exciton intensity versus pump intensity for different values of ρ_1. In the analysis, E_{in1} varies increasingly and decreasingly between 0.15 and 0.35. For $\rho_1 = 0$, both ψ_1 and ψ_2 have the same anticlockwise bistable loops. When ρ_1 increases, less component of LCP pump light is injected, thus, the bistable region of ψ_2 becomes wider and moves to larger value of E_{in1}, which is illustrated by the dashed curves in Fig. 1. Besides, in the bistable loops of ψ_2, a small-scale clockwise bistability is also observed, which is caused by interaction between the two polarization modes (i.e., the bistability of the RCP mode will cause a reverse change of the LCP mode).

Beside the polarization of pump field, polarization degree of the exciting field also influences formation of solitons. This means that various vectorial polariton solitons can be formed through combination of the pump and exciting field with different polarization degrees. In Fig. 2, soliton solutions are given for $\rho_1 = 0$, and ρ_2 changes from 0 to 1. The left (right) column corresponds to the RCP (LCP) polarization. Since $\rho_1 = 0$, all the bistable loops are the same in Fig. 2 (a)–(f), which is shown by the red dotted curves. The solid curves, namely, the soliton branches, are plotted by connecting peak (dip) values of bright (dark) solitons at the end of simulation time. When ρ_2 is close to zero, the two polarization modes are nearly equally triggered, therefore, similar bright soliton branches are obtained in both polarization directions, which are shown by Fig. 2 (a) and (b). With ρ_2 increasing, intensity of exciting field in the LCP direction becomes weaker and weaker, so that bright solitons can only be triggered in the RCP direction. Correspondingly, dark solitons appear in the LCP direction, which is passively caused by the bright solitons due to cross nonlinear interaction [2].

Fig. 3 shows examples of spatiotemporal trajectories of soliton formation for a fixed pump polarization and two different polarizations of the exciting field (i.e., $\rho_2 = 0.6$ and 0). It is observed that lunching of the exciting field causes temporal and spacial fluctuation, which evolves to an