Physics Letters A 376 (2012) 2151–2156

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Dynamics of polaritons in semiconductor microcavities near instability thresholds

Peng-Bin He [a,b,*]

[a] CFTC, Universidade de Lisboa, Avenida Professor Gama Pinto 2, Lisboa 1649-003, Portugal
[b] College of Physics and Microelectronics Science, Key Laboratory for Micro-Nano Physics and Technology of Hunan Province, Hunan University, Changsha 410082, PR China

ARTICLE INFO

Article history:
Received 19 December 2011
Received in revised form 13 April 2012
Accepted 24 April 2012
Available online 14 May 2012
Communicated by A.R. Bishop

Keywords:
Nonlinear optical systems
Optical parametric oscillators
Polaritons

ABSTRACT

A theoretical study is presented on the dynamics of polaritons in semiconductor microcavities near parametric instability thresholds. With upward or downward ramp of optical pump, different instability modes emerge in parameter space defined by damping and detuning. According to these modes, stationary short-wave, stationary periodic, oscillatory periodic, and oscillatory uniform parametric instabilities are distinguished. By multiple scale expansion, the dynamics near threshold can be described by a critical mode with a slowly varying amplitude for the last three instabilities. Furthermore, it is found that the evolutions of their amplitudes are governed by real or complex Ginzburg–Landau equations.
© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Polaritons in the semiconductor microcavity form a strongly nonequilibrium system with cubic nonlinearity, which is of fundamental importance and application promise [1]. Cavity polaritons are coupled modes of cavity photons and excitons. The photonic component ensures easy adjustability and detection, while the excitonic component provides a strong interaction between polaritons. These unique features make some interesting phenomena possible, such as polariton Bose–Einstein condensation [2–4] and superfluid [5,6], optical bistability [7], soliton [8–10] and vortex excitations [11,12], parametric amplification and oscillation [13–17], etc.

In the semiconductor microcavity, parametric oscillation is a process that generates coherent signal and idler modes from a pair of pumping polaritons. Comparing with the optical counterpart, polariton parametric oscillator possesses much richer dynamics due to the cubic nonlinearity. There have some experimental and theoretic investigations on this aspect. For example, observation of parametric oscillation has been reported [13–15]. A classical model was proposed to treat the amplifier and oscillator unitively [16]. The threshold behavior was discussed on the basis of three-mode theory [17].

As nonequilibrium dissipative systems, polaritons in semiconductor microcavity can be used to study pattern formation outside of equilibrium [18]. With lower energy pump, there exist ground states (trivial or inhomogeneous stationary solutions). If increasing pump, possible instabilities lead to a variety of pattern formation. The dynamics of the patterns close to the instability threshold can be separated into a fast component (with the temporal and spatial scales set by the critical frequency and wave number respectively) and an envelope that varies slowly in space and time. This can be done by multiple scale expansion. In general, the solution near threshold is a plane-wave critical mode with a slowly varying amplitude. The amplitude satisfies nonlinear partial differential equations. This perturbation method has been used to analyze the parametric conversion process and nonlinear behavior near parametric threshold in optical parametric oscillators [19–21]. Enlightened by the similarity between optical and polariton parametric oscillators, we apply multiple scale expansion on the cavity polariton system to study the dynamics near instability thresholds.

In this Letter, two kinds of pump-like modes, mono-mode and bistable mode, are analyzed. By stability analysis, different instabilities are classified in parameter plane. The lower and upper thresholds are obtained. The neutral stability surfaces are illuminated simply. Applying multiple scale expansion near the instability thresholds, three kinds of signal–idler pairs and their amplitude equations are introduced as the solutions and solvability condition of a hierarchy of equations.

2. Pump-like mode

Considering the spatially homogeneous pump $\mathcal{E}_p e^{-i\omega_p t}$, the polariton behavior in semiconductor cavity is described by the dimensionless equations [5,8,11],

* Correspondence to: College of Physics and Microelectronics Science, Key Laboratory for Micro-Nano Physics and Technology of Hunan Province, Hunan University, Changsha 410082, PR China.
E-mail address: pbhe1026@yahoo.com.cn.

0375-9601/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physleta.2012.04.057

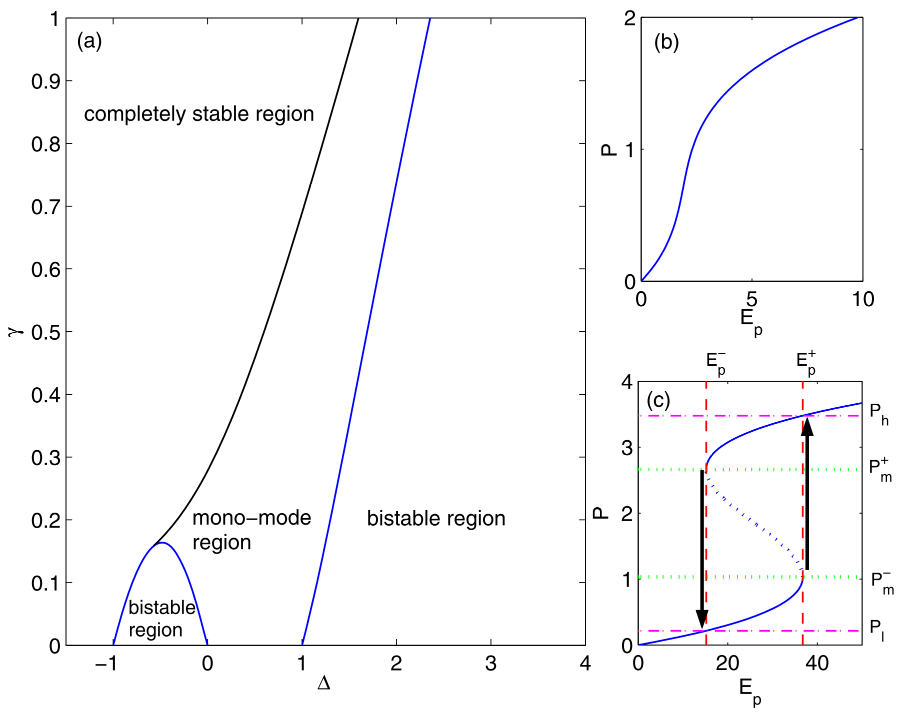

Fig. 1. (Color online.) (a) Mono-mode and bistable regions. (b) Mono-mode. Here, $\Delta = 1.6017$ and $\gamma = 0.6558$. (c) Bi-stability. Here, $\Delta = 3.0789$ and $\gamma = 0.6818$. The bistable state exists between E_p^+ and E_p^- which are denoted by the vertical dashed lines. The middle dotted branch is unstable. The horizontal dotted lines denote P_m^+ and P_m^-. The horizontal dash-dotted lines denote P_h and P_l.

$$i\partial_t E + \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E + (i\gamma + \Delta)E + \psi = i\mathcal{E}_p,$$
$$i\partial_t \psi + (i\gamma + \Delta)\psi + E = |\psi|^2\psi. \quad (1)$$

Here, the spatial and temporal coordinates are rescaled by $\sqrt{v/(2k_z\Omega_R)}$ and $1/\Omega_R$ respectively, where Ω_R is the Rabi frequency, v is the light speed in the semiconductor, and k_z is the quantized photon momentum along the growth direction. The photon and exciton fields are normalized by $\sqrt{\Omega_R/g}$ with g being the interaction constant between excitons. γ are the damping constants normalized to Ω_R. $\Delta = (\omega_p - \omega_r)/\Omega_R$ represents the detuning of the pumping frequency ω_p from the identical resonance frequency of exciton and cavity ω_r. The squared amplitude of external pump is normalized by Ω_R^3/g. The photon and exciton fields are described as $\mathcal{E} = Ee^{-i\omega_p t}$ and $\Psi = \psi e^{-i\omega_p t}$.

With proper pump intensity, the polariton field simply oscillates with the same frequency and wave vector as pump. Under the spatially homogeneous pump ($k_p = 0$), these modes are determined by

$$(i\gamma + \Delta)E_0 + \psi_0 = i\mathcal{E}_p,$$
$$(i\gamma + \Delta)\psi_0 + E_0 = |\psi_0|^2\psi_0. \quad (2)$$

Considering the structure of this equation, the phase factor of ψ_0 can be incorporated into the pumping term by transformation. And that, only $|\psi_0|^2$ is considered as the density of pump-like polariton. So, it is reasonable to assume that ψ_0 is real ($\psi_0 = p$). By eliminating E_0 from Eqs. (2), one can get a cubic equation about the square modulus of ψ_0, $(\gamma^2 + \Delta^2)P^3 - 2\Delta(\gamma^2 + \Delta^2 - 1)P^2 + [(\gamma^2 + \Delta^2 + 1)^2 - 4\Delta^2]P - E_p = 0$, where $P = p^2$, and $E_p = |\mathcal{E}_p|^2$. The type of the roots determines the properties of pump-like modes. By algebraic analysis and considering P and E_p are positive, one can find that three real roots exist in regions $\Sigma_0 > 0$, $E_p^- < E_p < E_p^+$ and $-1 < \Delta < 0$ or $\Delta > 1$, where $E_p^\pm = (f \pm 2\sqrt{\Sigma_0^3})/[27(\gamma^2 + \Delta^2)^2]$, with $\Sigma_0 = \Delta^2(\gamma^2 + \Delta^2 - 1)^2 - 3\gamma^2(\gamma^2 + \Delta^2 + 1)^2$ and $f = 2\Delta(\gamma^2 + \Delta^2 - 1)[\Delta^2(\gamma^2 + \Delta^2 - 1)^2 + 9\gamma^2(\gamma^2 + \Delta^2 + 1)^2]$. Otherwise, there exists one real root. The one real root corresponds to a mono-mode excited by pump (shown in Fig. 1(b)), while, the three real roots represent the bistable state (shown in Fig. 1(c)). The regions of these states in Δ–γ plane are shown in Fig. 1(a).

As depicted in Fig. 1(c), these three real roots form a hysteretic loop. It has been verified experimentally that the system is in the bistable state here [7,17]. The turning points of the hysteretic loop are $P_m^\pm = [2\Delta(\Delta^2 + \gamma^2 - 1) \pm \sqrt{\Sigma_0}]/[3(\Delta^2 + \gamma^2)]$, which can be obtained by $\frac{dE_p}{dP} = 0$. The intermediate part between P_m^- and P_m^+ is unstable, named as single-mode instability [5,17]. Therefore, when $E_p^- < E_p < E_p^+$ (or $P_l < P < P_h$), the multiple states excited by pump in zeroth-order system must be considered. The hysteretic loop starts at P_l and ends at P_h, where $P_{h,l} = 2[\Delta(\Delta^2 + \gamma^2 - 1) \pm \sqrt{\Sigma_0}]/[3(\Delta^2 + \gamma^2)]$. With upward ramp of pump, the polariton density jumps from P_m^- to P_h at $E_p = E_p^+$, while from P_m^+ to P_l at $E_p = E_p^-$ for downward ramp, as shown by the arrows in Fig. 1(c).

3. Parametric threshold and neutral stability surface

3.1. Stability analysis

With upward or downward ramp of pump, the pump-like mode will be destroyed possibly. By linear stability analysis, the instability thresholds and the unstable modes can be well studied. Meanwhile, the completely stable region and different kinds of parametric instabilities can be distinguished.

Assuming $E = E_0 + E'$, and $\psi = \psi_0 + \psi'$, where E' and ψ' are responses for small perturbation, it can be obtained by linearization that

$$\frac{\partial \mathbf{V}'}{\partial t} + \hat{L}\mathbf{V}' = 0, \quad (3)$$

where

Download English Version:

https://daneshyari.com/en/article/8206462

Download Persian Version:

https://daneshyari.com/article/8206462

Daneshyari.com