Instability-induced formation and nonequilibrium dynamics of phase defects in polariton condensates

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ABSTRACT

We study, theoretically and numerically, the onset and development of modulational instability in an incoherently pumped spatially homogeneous polariton condensate. Within the framework of mean-field theory, we identify regimes of modulational instability in two cases: (1) strong feedback between the condensate and reservoir, which may occur in scalar condensates, and (2) parametric scattering in the presence of polariton splitting in spinor condensates. In both cases we investigate the instability-induced textures in space and time including nonequilibrium dynamics of phase dislocations and vortices. In particular we discuss the mechanism of vortex destabilization and formation of spiraling waves. We also identify the presence of topological defects, which take the form of half-vortex pairs in the spinor case, giving an “eyelet” structure in intensity and dipole-type structure in the spin polarization. In the modulational domain, we observe formation of the phase defect process of condensate formation from an initially spatially incoherent low-density state. In analogy to the Kibble-Zurek-type scaling for nonequilibrium phase transitions, we find that the defect density scales with the pumping rate.
I. INTRODUCTION

The formation of complex spatiotemporal patterns and textures is a particularly intriguing phenomenon occurring in a diverse range of physical systems [1, 2]. The patterns commonly arise in nonlinear dissipative systems driven far from equilibrium. Among examples of such systems, exciton-polaritons in semiconductor microcavities have emerged as a hybrid light-matter system with strongly nonlinear properties. Effects such as Bose-Einstein condensation [3–5], superfluidity [6–8], and the formation of solitons [9–13] have been well documented in the literature [14, 15].

A particularly important nonlinear effect in the context of pattern formation in microcavities is the parametric scattering of resonantly excited polaritons in planar semiconductor microcavities [16–19]. The pair scattering of pairs of polaritons to different states in reciprocal space allows a homogeneous polariton field to spontaneously break translational symmetry. This effect enables the formation of ordered hexagonal/triangular lattices, predicted theoretically [20–22] and observed experimentally [23] under different excitation conditions, as well as lattices of breathing solitons [24].

Under nonresonant/coherent excitation, vortex lattices were predicted to occur in harmonic traps [26, 27] and later observed in experiments involving multiple excitation spots [27]. The formation of multilobed [28] and vortex-antivortex patterns [29] under ring-shaped excitation, as well as sunflower ripples [30] excited by a narrow pump spot, have also been reported. In these examples, the translational symmetry of the system is already broken by the chosen shape of the pump spot and/or the presence of a gradient in the potential of polaritons (as in, for example, the case of harmonic traps [41]).

In this work we consider the possibility of spontaneous breaking of translational symmetry and pattern formation in planar microcavities excited by a spatially homogeneous incoherent pump. The pumping creates a reservoir of "hot" exciton-like polaritons, which form a polariton condensate through a stimulated scattering process. The translational symmetry breaking is triggered by linear instability of the homogeneous condensate to spatial modulations, and the nonlinear evolution of the unstable state leads to formation of spatial patterns. We consider two different mechanisms of such modulational instability (MI) in this system. The first one arises when the polariton condensate has a strong feedback effect on the reservoir, in the form of reservoir depletion due to stimulated scattering of reservoir excitons into polaritons. In this case, while polariton-polariton interactions are repulsive, the essentially saturable nature of exciton-polariton interactions may lead to effectively attractive nonlinearity for sufficiently low pump powers [31]. This effective focusing nonlinearity in the system naturally leads to MI of a spatially homogeneous state, which was established in several previous studies for both quasi-1D and 2D geometry [15, 26, 31–35].

Modulational instability is also known in spin-1 Bose-Einstein condensates of ultracold atoms due to parametric coupling [36–39] and nonlinear interactions between spin components [40], as well as in 1D exciton-polariton condensates with a spin (polarization) degree of freedom [41]. Although polariton systems are nonconservative and nonequilibrium, the two-component spin degree of freedom of polaritons does allow a second mechanism of MI, which works also in the defocusing regime where a strong condensate-reservoir feedback is unnecessary. A circularly polarized excitation splits the energy of the \( \sigma^+ \) and \( \sigma^- \) states due to anisotropic interactions [42, 43] occurring between the spin-polarized reservoir and condensed polaritons. This splitting sets the foundation for a parametric scattering process as polaritons in an initially homogeneous state with wave vector \( \mathbf{k} = 0 \) on the upper spin-split branch can now scatter to degenerate nonzero wave vector states on the lower branch, reminiscent of experiments under resonant excitation in triple microcavities [44] or experiments in one-dimensional polariton systems [45]. While such a scattering process is not strictly allowed in isotropic cavities as it would violate spin conservation, the presence of sample anisotropy, which typically causes an additional linear polarization splitting and hybridization of the \( \sigma^+ \) and \( \sigma^- \) branches, relaxes this limitation.

By considering the stability of the steady states of the system to weak perturbations, we find the zones of MI in the two different regimes. In the scalar case, where MI is derived from the condensate-reservoir feedback, we find that the homogeneous state breaks its translational symmetry and forms a turbulent state of phase dislocations, i.e., vortices. Unlike the previously studied cases, vortices do not form as the result of thermal fluctuations [46] or scattering on disorder [47]. Rather, the spatial fragmentation of the initially homogeneous condensate due to the development of MI creates multiple
interference between polaron flows generated by the randomly distributed sources, which leads to the
development of multiple phase dislocations, similar to the scenario previously considered for multiple
pump spots [48] and highly inhomogeneous trapped polaron condensates [26, 49].

In the case of modulational stability background, we show that multiple phase singularities can appear
as a result of mean-field evolution of an initial white noise state, which mimics a precondensate state
lacking spatial and phase coherence. Remarkably, formation of multiple vortices in this scenario seems
to be analogous to, but not the same as, the Kibble-Zurek mechanism, which acts during the quench
through a phase transition to the Bose-Einstein condensation (BEC) [50, 51]. Indeed, the latter
describes the formation of boundary defects between different domains of condensate which develop
an independent phase rather than inheriting it from the neighboring spatial domains [52, 53].

We stress that the process of defect formation during nonequilibrium condensation of exciton-
polaritons does not follow the scenario of the Kibble-Zurek mechanism [53, 54, 55]. The main difference
is that in the latter, it is assumed that the system is initially in thermal equilibrium, and is driven out of
equilibrium only in the vicinity of the phase transition [56, 57]. The process is divided into three phases,
corresponding to adiabatic-impulse-adiabatic evolution. In nonequilibrium condensation, the system is
far from equilibrium at the outset, and the transition to the quasiequilibrium (condensed) state occurs
only after crossing the critical point.

Nevertheless, the Kibble-Zurek mechanism and the defect formation in nonequilibrium systems have
much in common. In both cases, defects are created due to symmetry breaking in separate parts of
the system which cannot communicate in a finite time. In both cases, there is a competition of two time
scales existing in the system, which results in the same algebraic forms of power-law scalings for the
number of defects and their characteristic creation time [54]. In the polaron condensation case, the
quench time is replaced by the time scale of the formation of the condensate, which is controlled by
the external pumping rate. We refer the reader to Sec. IV of Ref. [54] for the detailed description of
the process.

Regardless of the mechanism of the vortex formation, either as the result of the MI development or as
a result of transition to BEC, we show that the presence of the incoherent reservoir affects
substantially both stability of vortices and their collective dynamics even for the case of a stable
homogeneous background. As a consequence, the vortices can lose their radial symmetry and
develop either into spatially localized rotating phase dislocations or into nonlocalized spiraling waves.

A similar situation occurs in the spinor case, although multiple branches of modulational instability
and stable solutions are present. Defects in the spin polarization of the condensate may appear even in the
modulationaly stable regime. Such structures move randomly in the microcavity plane and are
composed of half-vortex [58] half-antivortex pairs [59], exhibiting an associated dipole-type spin
texture. We predict that the density of vortices grows with increasing pump power similarly to the
Kibble-Zurek scaling behavior.

The paper is organized as follows. In Sec. II, we describe the mathematical model of a semiconductor
microcavity operating in the strong-coupling regime under the incoherent homogeneous optical pump
of a circular polarization. Then, in Sec. III, we study the stability and collective dynamics of phase
dislocations in a single-component polaron condensate. Here the dynamics is mostly affected by the
modulational instability originating from the strong feedback between the condensate and reservoir. In
Sec. IV, we report a numerical analysis of the condensate dynamics in the presence of polarization
splitting in spinor condensates. In Sec. IV, we study the defect formation and the scaling laws for their
density in analogy to the Kibble-Zurek mechanism.

II. THEORETICAL MODEL

III. NONEQUILIBRIUM DYNAMICS IN THE SCALAR CASE

IV. NONEQUILIBRIUM DYNAMICS IN THE SPINOR CASE

V. CONCLUSIONS

ACKNOWLEDGMENTS

APPENDICES

SUPPLEMENTAL MATERIAL

CLICK TO EXPAND

REFERENCES

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