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Polariton physics/Physique des polaritons

Soliton physics with semiconductor exciton–polaritons in confined systems

Physique des solitons avec des polaritons excitoniques semiconducteurs dans des systèmes confinés

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ABSTRACT

In the past decade, there has been a significant progress in the study of non-linear polariton phenomena in semiconductor microcavities. One of the key features of non-linear systems is the emergence of solitons. The complexity and the inherently strong nonlinearity of the polariton system made it a perfect sandpit for observing solitonic effects in half-light half-matter environment. This review focuses on the theory and the latest experimental elucidating physics as well as potential applications of conservative and dissipative solitons in exciton–polariton systems.

RÉSUMÉ

Au cours de la dernière décennie s'est opéré un progrès significatif dans l'étude des phénomènes non linéaires de polaritons dans des microcavités à semiconducteurs. Un des phénomènes caractéristiques des systèmes non linéaires est l'émergence de solitons. La complexité et la forte non-linéarité inhérente au système de polaritons en fait un parfait terrain de jeu pour observer des effets solitoniques dans un environnement mi-lumière mi-matière. Cet article passe en revue la théorie et les tout derniers développements physiques expérimentaux ainsi que des applications potentielles des solitons conservatifs et dissipatifs dans les systèmes de polaritons excitoniques.

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1. Introduction

Solitons are non-spreading self-localised wavepackets. The first soliton has been described by John Scott Russell in 1834 [1], who observed an isolated non-spreading water wave moving across the Union canal near Edinburgh. With the development of high power pulsed lasers in 1970–1980's, it became possible to investigate optical solitons through the formation of non-diffracting beams and non-dispersing pulses of light propagating in bulk materials or optical fibres with a $\chi^{(3)}$ nonlinearity [2]. Picosecond pulse narrowing and splitting of the initial pulse into several peaks with increasing pulse power has been observed in 1980 in optical fibres with anomalous group velocity dispersion [3,4], which is essential for soliton formation in the case of positive (self-focusing) nonlinearity. Soliton phenomena in single-mode fibres and in many other systems can be described using nonlinear Schrödinger equations, which has become a paradigm model in soliton physics.

Matter wave solitons have been demonstrated in the clouds of Bose-condensed atoms placed in a magnetic trap. The interactions between atoms were tuned from repulsive to attractive via Feshbach resonance which cancels the dispersive spreading induced by the kinetic energy of atoms [5]. Multiple matter-wave solitons were observed bouncing in the trap and interacting amongst themselves repulsively [6]. It was also possible to observe bright solitons with condensates consisting of repulsively interacting atoms by altering the sign of the matter wave dispersion using optical lattice potentials [7]. Similarly, solitonic effects with light beams have been observed in nonlinear materials with periodic spatial modulation [8].

Self-localised structures existing in a dissipative system with an external supply of energy are often called *dissipative solitons* [9,10]. The balance between dispersion and nonlinearity for the dissipative solitons is also accompanied by the loss-gain balance. Dissipative solitons in optical resonators have been observed, e.g., in the vertical cavity surface emitting semiconductor lasers (VCSELs) operating in the bistable regime [11,12]. VCSEL solitons can be switched on/off using an external writing pulse, which makes them potentially suitable for applications in optical information processing.

Microcavity polaritons, which arise from strong exciton–photon coupling in semiconductor microcavities, attracted significant interest in the last decade [13–16]. The excitonic component in the polariton wavefunctions leads to strong repulsive polariton–polariton interactions and hence to a strong de-focusing nonlinearity. In fact, the interaction energy between two polaritons confined in 1-μm^2 area was measured in the range of 2–10 μeV [17], implying $\chi^{(3)}$ polariton nonlinearity to be two to three orders of magnitude higher than nonlinearity in VCSELs operating in the weak-coupling regime [18], bringing down the threshold powers required for observation of bistability, parametric wave mixing, and soliton formation. The two-dimensional nature of the polariton system allows one to address particular polariton states in energy–momentum space using external laser sources of relatively weak optical power, whereas the giant optical nonlinearity and fast ps response time of the polariton system are favourable to the development of polariton devices with applications in all-optical signal processing and switching [19,20].

Non-equilibrium polariton Bose condensates have been observed under non-resonant (above band gap) pumping [21,22], where it was suggested that polariton–polariton scattering plays an essential role in the convergence to the condensate state. One of the most remarkable properties of the interacting polaritons is the superfluid-like behaviour [23]. In the case when a polariton condensate flowing with a finite momentum interacts with a defect, suppression of polariton backscattering is observed, which is attributed to the renormalisation of the condensate excitation spectrum from parabolic to sonic-like due to polariton–polariton interactions at high particle density. While condensation is characterised by localisation of the polariton density in momentum space and formation of an extended state in real space, the soliton formation is associated with the localisation in real space and spectral broadening in momentum space.

In what follows, we will discuss the theory and experimental results on conservative and dissipative polariton solitons in planar polaritonic superfluids [24,25], in modulated polaritonic microcavity waveguides (microwires) [26], in slab waveguides [27] and in two-dimensional microcavity lattice potentials [28]. A particular emphasis will be paid to the role of the polariton polarisation (pseudo-spin) and formation of the so-called vector polariton solitons in both conservative [29] and dissipative [30] systems. Here, the spin-dependent anisotropy in the polariton–polariton interaction is important, and can lead to the vector solitons, whose polarisation oscillates rapidly in time and space.

2. Theory of exciton–polariton solitons in microcavities

2.1. Model equations

Non-propagating (zero momentum) modes in an ideal planar microcavity can be represented using the basis of circular polarizations $\sigma_\pm$, which couple with the ±1-spin excitons inside the quantum wells. Similarly, the propagating (non-zero momentum) modes occupied by moving bright solitons can be represented by a TE mode, where the non-zero electric field component is parallel to the mirrors and perpendicular to the momentum, and a quasi-TM mode, with a dominant electric field component aligned with the momentum and a small component perpendicular to the mirrors. The quasi-TM mode is directly associated with the small momentum-dependent energy splitting between the two modes, which becomes zero for the zero-momentum case.

The equations for the photonic modal amplitudes $E_{x,y}$ in the TE–TM representation are [30]:

$$\partial_t E_{x,y} - \mathrm{i}d(1\pm\alpha)\nabla^2 E_{x,y} + (\gamma_\mathrm{p} - \mathrm{i}\delta_\mathrm{p})E_{x,y} = \mathrm{i}\,\Omega_\mathrm{R}\psi_{x,y} + (a\pm b)E_\mathrm{p}\,\mathrm{e}^{\mathrm{i}k_\mathrm{p}x} \quad (1)$$

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