Two dimensional vectorial localized structures in optical cavities

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Localized structures in lasers and in optical cavities containing nonlinear optical materials are being intensively studied [1–4] because of two main reasons. On the one hand complex spatio-temporal dynamics is often dominated by these particle-like objects. Secondly, the ability to control, create and erase these objects opens the way to new technological developments, including parallel information processing. We are here concerned with two dimensional localized objects in the transverse plane of an optical cavity. Generally speaking they are named cavity solitons and they can take the form of vortices or bright or dark dissipative spatial solitons.

Most studies of localized structures in optical systems consider light with a fixed polarization. However, the vectorial degree of freedom of light leads to a very interesting phenomenology associated with a space and time dependent polarization [5]. Such degree of freedom is also relevant from the point of view of information encoding and processing. We address here the question of new types of localized structures emerging from polarization nonlinear dynamics.

A visualization of vectorial localized structures can be given in terms of isolated zeroes or peaks of either of the two independent polarization components of the electric field. Situations of hole-hole, peak-hole or peak-peak in a given polarization background can be envisaged. A proper classification [6] of these objects depends on the reference states preferred by a particular system. We consider here three different systems which give relevant examples of possible vectorial localized structures and of their dynamics.

Broad Area Lasers

The interaction of the two polarization components of light in rotationally symmetric large aperture lasers can be described, close to threshold, by the Vector Complex Ginzburg Landau Equation (VCGLE) [7]. The VCGLE can be written as coupled equations for the two circularly polarized components $A_\pm$ of the slowly varying part of the vector complex field:

$$\partial_t A_\pm = A_\pm + (1+i\alpha)\nabla^2 A_\pm - (1+i\beta)(|A_\pm|^2 + \gamma|A_\mp|^2)A_\pm . \tag{1}$$

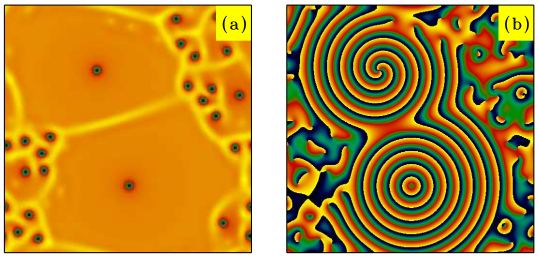

FIG. 1. Frozen field configuration: (a) $|A_+|^2$, (b) ϕ_g ($\gamma = 0.1$, $\alpha = 0.2$, and $\beta = 2$).

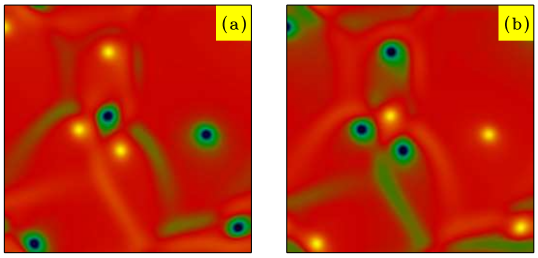

FIG. 2. Instantaneous configuration for $\gamma = 0.8$. (a) $|A_+|^2$, (b) $|A_-|^2$. Bright (dark) spots correspond to maximum (minimum) intensity.

The parameters α and β are associated with the strength of diffraction and detuning respectively and the condition $1 + \alpha\beta > 1$ is always satisfied. For the coupling parameter $\gamma < 1$, as considered here, homogeneous linearly polarized solutions in an arbitrary direction are preferred. In this background it is natural to look for localized structures of vortex type as isolated zeros of A_+ and/or A_- [4]. Charges $n_\pm$ are associated with the change of the phases $\phi_\pm$ of $A_\pm$ around those zeroes. We call *vectorial defect* a zero that is present in both components of the field at the same point. A vectorial defect can be of *argument* type ($n_+ = n_- = 1$)

or of *director* type ($n_+ = -n_- = 1$). They are identified, respectively, by a two-armed spiral or a target pattern of the global phase $\phi_g = \phi_+ + \phi_-$ (Fig. 1). A *mixed defect* is a zero present only in one component of the field. Vectorial defects are stable in a range of parameters. Within this range they freeze the dynamics creating exclusion islands with mixed defects concentrated at their borders. Vectorial defects loose their stability either by an unbinding of the zeroes of the two fields or by an instability of the phase spirals. This leads to a dynamical state in which $A_\pm$ are highly anticorrelated. This state is dominated by mixed defects characterized as a localized bound state of a zero of one component and a peak of the opposite circularly polarized component. These localized objects move on a linearly polarized background (Fig. 2).

Vectorial self-defocusing Kerr Resonators

Consider a ring cavity filled with an isotropic Kerr medium and driven by an external linearly polarized input field. This can be described by coupled driven and damped Non Linear Schrödinger Equations for the two circularly polarized components $A_\pm$ of the slowly varying part of the vector complex field. In a mean field approximation they become [5]

$$\partial A_\pm = -(1-i\theta)A_\pm + ia\nabla^2 A_\pm + A_0 - i[\alpha|A_\pm|^2 + (\alpha+\beta)|A_\mp|^2]A_\pm, \tag{2}$$

where A_0 is the input field, and θ is the cavity detuning. A stripe pattern orthogonally polarized to the input field occurs close to threshold. For higher values of A_0 the system prefers either of two equivalent homogeneous states which are close to circularly polarized states. Polarized localized structures are here visualized as a hole of A_+ (A_-) in the background of a circularly positive (negative) polarized state together with a peak of A_- (A_+) (Figs. 3 and 4) . These structures are related to domain walls separating the two equivalent homogeneous circularly polarized states. They are stable for $A_{0,m} < A_0 < A_{0,M}$ within the range in which homogeneous states are stable. For $A_0 < A_{0,m}$ a circular spot of one polarization, in the background of the opposite one, grows and leads to a labirynthine pattern. For $A_{0,M} < A_0$ the system, after switching-on A_0, evolves in a self-similar way to a final homogeneous state. The situation is reminiscent of what has been described for vectorial intracavity Second Harmonic Generation [3].

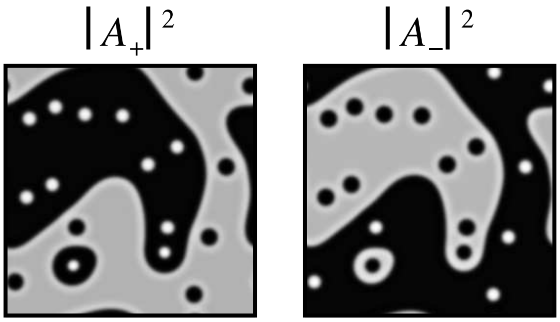

FIG. 3. Field intensities $|A_\pm|^2$ in the range of existence of localized structures $A_{0,m} < A_0 < A_{0,M}$.

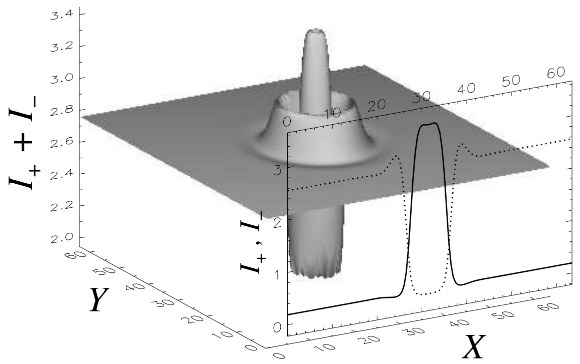

FIG. 4. Total field intensity ($|A_+|^2 + |A_-|^2$) of a localized structure and transverse profile of the intensities $|A_+|^2$ (solid line) and $|A_-|^2$ (dotted line).

Type II Degenerate Optical Parametric Oscillator

A Type II degenerate OPO, for which the pump is not resonant with the cavity, can be described by the following equations for the signal A_x and the idler A_y. These are two orthogonally and linearly polarized complex fields.

$$\partial_t A_x = -(1+i\Delta)A_x + ia\nabla^2 A_x + \mu A_y^* + \sigma|A_y|^2 A_x \tag{3}$$

$$\partial_t A_y = -(1+i\Delta)A_y + ia\nabla^2 A_y + \mu A_x^* + \sigma|A_x|^2 A_y \tag{4}$$

The parametric coupling coefficient μ and the nonlinear coupling coefficient σ depend on phase mismatch and they are generally complex. We consider a situation of negative detuning $\Delta < 0$ for which preferred states are traveling waves of A_x and A_y in an arbitrary direction, with the same amplitude and frequency but with opposite phase and wavenumber. Localized structures occur in this background as isolated zeroes of the two fields A_x and A_y. Due to the parametric coupling these defects occur simultaneously for the two fields (Fig. 5) and with opposite charge, $n_1 = \pm 1$ and $n_2 = \mp 1$, for each field. Note that they do not correspond to isolated zeroes of the circularly polarized components of the vector field. These localized structures are spontaneously formed when switching-on the pump field. After a transient dynamics, in absence of walk-off [8], they are stable and their number is conserved for very long times (Fig. 6). One of these objects can be isolated and stabilized by choosing a beam size smaller than the wavelength of the traveling wave selected in the background. These structures are spontaneously formed vectorial dark spatial solitons of a different nature than the bright structures discussed for degenerate Type I OPO [2] or the dark structures for non-degenerate Type I OPO [9]. They are also different from the dark solitons which can be stabilized in a degenerate Type I OPO by imposing the structure in the pump beam [10] or by the walk-off [11].

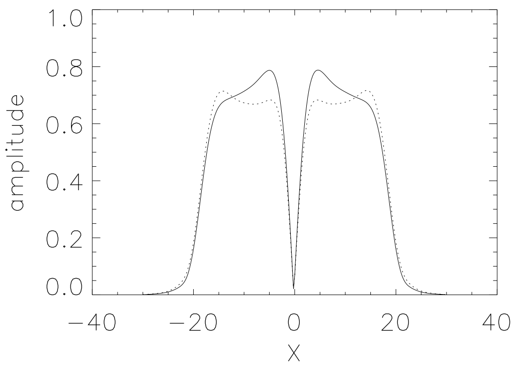

FIG. 5. Transverse amplitude profile (solid line $|A_x|$, dotted line $|A_y|$ across the center of a vectorial dark soliton at perfect phase-matching ($\mu = 1.5, \sigma = -1.5$, other parameters $\Delta = -0.2, a = 2$).

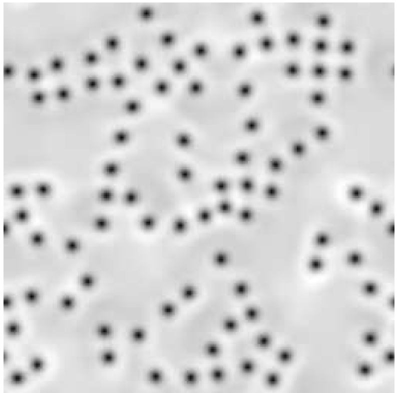

FIG. 6. Instantaneous configuration of $|A_x|$; dark spots correspond to minimum intensity ($\Delta = -0.25$, $a = 1$, other parameters as in fig. 5).

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