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Topological Features of Bright Vector Solitons in Ring Resonators with Normal Dispersion

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Abstract: Experiments and simulations of unusual bright vector solitons in Kerr ring resonators with normal dispersion displaying a phase defect with a phase jump of π in one of the linear polarization components are presented.   2024 The Author(s)

The emergence of temporal cavity solitons (TCS) in passive resonators [1] has attracted huge interest in the past decade due to their features and potential applications, ranging from massive optical communications, laser ranging, frequency standards and spectroscopy [2, 3]. Group velocity dispersion is used to counterbalance the focusing or defocusing effects of the Kerr nonlinearity. In general bright TCS are observed in the regimes of anomalous dispersion while dark solitons are more easily found with normal dispersion. The situation becomes more complex when fields of two orthogonal polarizations are simultaneously present in the optical cavity. For example regimes of dark-bright TCS have been predicted and observed in [4]. Here we demonstrate both experimentally and theoretically the existence of unusual topological bright-bright vector solitons in ring resonators in regimes of normal dispersion when considering the circular polarization components. These kind of solitons have been named 'faticons' [5]. We demonstrate the topological character of bright faticons by showing that one of the linear polarization components displays a phase defect corresponding to a discontinuous phase jump of π .

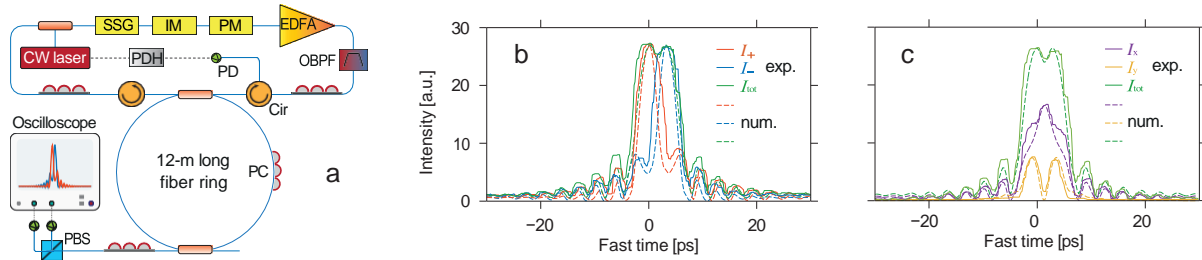


Fig. 1. (a) Experimental setup. (b) Experimental intensity profile of the vector soliton detected in the \pm polarisation basis compared with simulation results. (c) Same as (b) but for the x/y polarisation basis.

Experiment. Our experimental setup is depicted in Fig. 1a. The ring resonator comprises a 12 m long segment of optical fibre. At the driving wavelength of 1552.4 nm, the fibre features a normal group velocity dispersion. The resonator includes a 90/10 coupler to inject the coherent driving field into the cavity, and a 99/1 tap coupler to monitor the intracavity dynamics. The resonator has a round trip time of 57 ns. To control the detuning of our Kerr resonator, the wavelength of the driving laser is actively stabilised to coincide with a cavity resonance using the Pound–Drever–Hall technique implemented on a counter-propagating replica of the initial cw laser. The polarisation setting of our experiments is primarily controlled by three polarisation controllers (PCs). Initially, the polarisation state of the pulsed driving is carefully adjusted at the input of the resonator to predominantly excite one of the principal modes of the cavity, e.g. E_x . Finally, at the resonator's output port, additional polarisation controllers, in conjunction with polarizing-beam-splitters (PBS), are used to split the output field either in terms of the x/y linear polarization basis or the \pm circular polarization basis.

In Fig. 1b we compare the experimental and simulation results of a bright vector soliton, the faticon, in the circular \pm -polarization basis. In Fig. 1c we compare the experimental and simulation results of the same

soliton but in the linear x / y polarization basis. The experiment/simulation agreement is spectacular. The numerical simulations have been performed by using two coupled Lugiato-Lefever equations with normal dispersion [6],

$$\partial_t E_{\pm} = S - (1 + i\theta)E_{\pm} + i(|E_{\pm}|^2 + B|E_{\mp}|^2)E_{\pm} - i\partial^2 E_{\pm}, \quad (1)$$

where $E_{\pm}(\tau, t)$ are the slowly varying amplitudes of the two circular polarization components of the field, S is the amplitude of the linear input field, θ is the input pump detuning to its near nearest cavity resonance and B is the cross coupling coefficient that has been measured to be 1.8 for our experiment. Here, τ and t are the ‘fast time’ and ‘slow time’ variables describing the evolution over a single round trip, and many round trips of the cavity respectively. Fig 1c appears to show that the E_y linear polarization component corresponds to a dark soliton. The question addressed here is whether this entity is a gray soliton or a topological dark soliton.

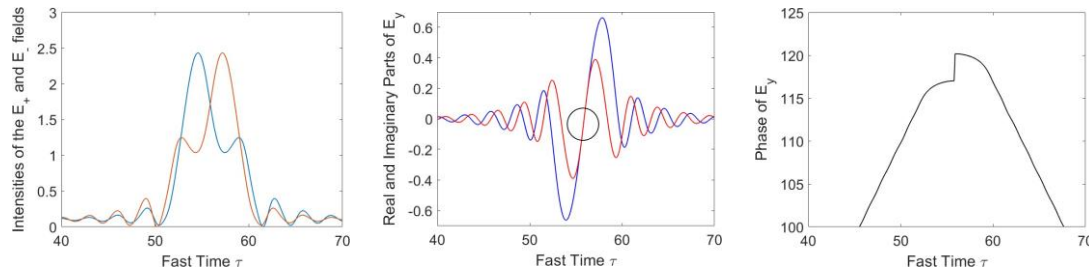


Fig. 2. Left panel: intensity profile of the vector soliton in the $+/-$ polarisation basis. Central panel: real and imaginary parts of E_y linear polarization component of the vector soliton. The black circle shows where the real and imaginary parts of E_y are simultaneously equal to zero. Right panel: phase profile of E_y linear polarization component of the vector soliton displaying the π phase jump.

Simulations. The question about the topological nature of the faticons is not purely academical. Bright solitons in the Nonlinear Schrödinger Equation and in the Lugiato-Lefever equation with anomalous dispersion are notoriously non-topological. Topological defects are not only more stable against perturbations, but cannot be untangled easily because of finite phase jumps. To characterise the topological feature of the faticon displayed in Fig. 1, we show the result of numerical simulations of the coupled Lugiato-Lefever equations in Fig. 2. On the left hand side one can see the intensity profile of the bright vector soliton, the faticon, in the circular $+ / -$ polarisation basis. In the central and right panels we show the real/imaginary parts and the phase of the linear polarization component $E_y = i(E_- - E_+) / 2$ across the soliton profile, respectively. These quantities are readily available in numerical simulations but are, of course, difficult to measure directly in experiments. The black circle in the central panel of Fig. 2 shows that the real and imaginary parts of E_y are simultaneously equal to zero where the intensities of the E_{\pm} are equal (see the left panel of Fig. 2). This means that the intensity profile of the linear polarization component E_y presents an exact zero defect singularity at its center. It is not a gray soliton. The phase profile in the right panel of Fig. 2 demonstrates that in the position of the defect there is a phase jump of π , i.e. a topological phase defect singularity, a key difference with previous vector solitons in this system [6].

Through comparisons of numerical simulations and experimental results we demonstrate that faticons have the surprising feature of being simultaneously a bright-bright vector solitons in the $+ / -$ circular polarization components and bright-dark vector solitons in the linear x/y polarization components. The topological defect character of the faticon can lead to a long-awaited experimental observation of defect-mediated turbulence [7, 8] in passive optical systems.

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