

Optical vortex solitons: experiment versus theory

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We present a brief overview of recent experimental and theoretical results on optical vortex solitons (in particular, those recently obtained at the Australian National University). Special attention is paid to a direct comparison between the experimental data on the structure and motion of vortex solitons created as localized structures in a diffracting Gaussian beam and the theory based on the generalized nonlinear Schrödinger equation. We also analyze, for the first time to our knowledge, the effect of strong nonlinearity saturation on the transverse (or snake-type) instability of a dark-soliton stripe and show that saturation leads to a drastic suppression of the instability. © 1997 Optical Society of America [S0740-3224/97/00511-4]

1. INTRODUCTION

Spatiotemporal evolution of light in nonlinear media and stable propagation of optical solitons have been subjects of considerable theoretical and experimental research in nonlinear optics during past years. Spatially localized solutions of nonlinear propagation equations in defocusing media are dark solitons, which correspond to an intensity dip within a uniform background. Temporal dark solitons described by the $(1 + 1)$ -dimensional (one temporal and one spatial) nonlinear Schrödinger (NLS) equation have been predicted theoretically¹ and subsequently have been observed in optical fibers.² The spatial analog of these dark solitons were also observed experimentally as spatial dark-stripe solitary waves in a bulk nonlinear medium.³ Despite strong similarities between dark stripes and their temporal relatives, the stripe differs from the $(1 + 1)$ -dimensional soliton in that it is unconstrained in $(2 + 1)$ spatial dimensions, whereas the temporal soliton is confined by the fiber in higher transverse dimensions. Linear stability analysis developed for a defocusing Kerr medium⁴ shows that a spatial dark-soliton stripe is unstable to transverse (long-wavelength) modulations. The effects produced by this transverse modulational (or snake-type) instability have been observed experimentally, and it is well established that in the strongly nonlinear regime the instability leads to the generation of pairs of optical vortex solitons with alternating polarities, either as isolated spots spawned from the edges of the dark-soliton stripes⁵ or as a sequence of vortex solitons as the result of the stripe decay.⁶⁻⁸ The instability of the dark-soliton-stripe beams and subsequent vortex generation have been investigated both numerically^{9,10} and by means of the asymptotic analytical theory.¹¹

Optical vortex solitons are stable stationary structures that exist in a defocusing bulk nonlinear optical medium

on a uniform background. Vortex soliton solutions of the $(2 + 1)$ -dimensional cubic NLS equation were introduced and analyzed in the pioneering paper by Pitaevskii¹² as topological excitations within superfluids. In the context of nonlinear optics, they were theoretically suggested by Snyder *et al.*,¹³ and experimental observations of optical vortex solitons have been reported by several groups^{3,14-16} for different optical materials. In experiments, however, vortex solitons are of finite total energy, are necessarily nonuniform, and are often created in materials that exhibit saturating or diffusive nonlinearities. Vortex motion is observed to be strongly dependent on the inhomogeneities in the background field. In contrast, the theory of optical vortex soliton motion, often in a search for a precedent in fluid dynamics, has assumed a cubic nonlinearity and a background of constant amplitude (analogous to fluid incompressibility) and has been unable to capture a number of obvious features of vortex dynamics, e.g., the drift and rotation of a vortex around a beam—effects that also exist for linear propagation but which become dependent on light intensity in the nonlinear regime. Understanding this dynamics is important for any future application of vortex solitons.

In this paper we present an overview of the experimental results on the generation and dynamics of optical vortex solitons (basically those obtained at the Laser Physics Centre, Australian National University) and compare them with the recent analytical results based on the generalized NLS equation that takes into account a background beam of finite extent and non-Kerr nonlinearity. We start our consideration by introducing the model (Section 2) and then analyzing, for the first time to our knowledge, the transverse instability of a dark-soliton stripe in a defocusing (e.g., saturable) non-Kerr medium (Section 3). Then, in Section 4, we describe several reported demonstrations of optical vortex solitons that are generated

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