Incoherent vector vortex-mode solitons in self-focusing nonlinear media

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We suggest a novel type of composite spatial optical soliton created by a coherent vortex beam guiding a partially incoherent light beam in a self-focusing nonlinear medium. We show that the incoherence of the guided mode may enhance, rather than suppress, the vortex azimuthal instability, and we also demonstrate strong destabilization of dipole-mode solitons by partially incoherent light. © 2004 Optical Society of America

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Optical vortices are associated with phase dislocations of diffracting coherent optical beams.[1] When optical vortices propagate in self-defocusing nonlinear media, a vortex core with a phase dislocation becomes self-trapped, and the resultant stationary singular beam is known as an optical vortex soliton.[2,3] However, in self-focusing nonlinear media, optical vortices can exist as ringlike optical beams that carry a phase singularity,[4] which are known to be unstable and decay into several fundamental optical solitons.[3,5]

If a vortex-carrying beam is partially coherent, the phase front topology is not well defined, and statistics are required for quantifying the phase. However, such a partially incoherent vortex beam can be stabilized in a self-focusing nonlinear medium when the degree of spatial incoherence exceeds a certain threshold value, as was recently demonstrated theoretically and experimentally.[6]

Waveguides induced by optical vortices in both linear and nonlinear regimes are of special interest because this type of waveguide is robust and can be made reconfigurable.[7–9] Moreover, vortex-induced waveguides can guide large-amplitude beams beyond the applicability limits of linear guided-wave theory, and, together with a guided beam, they can form a vortex-mode vector soliton or its dipole-mode generalization.[10–12] Recent theoretical studies, including rigorous stability analysis,[12] suggested that the stable propagation of spatial vortexlike stationary structures in a self-focusing medium may become possible in the presence of a large-amplitude guided beam.

The main purpose of this Letter is twofold. First we demonstrate, for the first time to our knowledge, that the initially coherent vortex beam can guide partially incoherent light in a self-focusing nonlinear medium and be stabilized by it against azimuthal instability, creating a novel type of stable incoherent soliton. Second, we demonstrate that in some cases the incoherence of the guided beam may even enhance, rather than suppress, the vortex azimuthal instability.

We consider the mutually incoherent interaction of two optical beams propagating in a self-focusing saturable nonlinear medium described by the coupled equations

$$i\frac{\partial u}{\partial z} + \Delta_\perp u + F(I_{\text{tot}})u = 0\,,$$
$$i\frac{\partial v}{\partial z} + \Delta_\perp v + F(I_{\text{tot}})v = 0\,, \qquad (1)$$

where u and v are the dimensionless amplitudes of two fields, $F(I) = I/(1+\sigma I)$, where σ characterizes the nonlinearity saturation effect, and $I_{\text{tot}} = |u|^2 + |v|^2$ is the total beam intensity. Spatial coordinate z is the propagation direction of the beams, and $\Delta_\perp$ stands for the transversal part of the Laplace operator. The model [Eqs. (1)] describes the interaction of two mutually incoherent beams in photorefractive nonlinear media when both the anisotropy of a nonlinear response and diffusion effects are neglected. Different types of composite vector soliton in such a model have been predicted theoretically and were observed experimentally in photorefractive crystals.[10–12]

We consider the case when one of the beams, say u, carries a spatially localized, initially coherent optical vortex of the form $u(r,\phi;z) = u(r)\exp(i\phi)\exp(i\beta_1 z)$, where β_1 is the vortex propagation constant, vortex amplitude function $u(r)$ vanishes for $r \to \infty$, and r and ϕ are the radius and the phase, respectively, in cylindrical coordinates.

When the second field, v, is also coherent, it can be written in the form $v(r,z) = v(r)\exp(i\beta_2 z)$, where $v(r)$ is the beam's amplitude and β_2 is the second

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propagation constant. However, when field v is generated by a partially incoherent source this simple presentation is no longer valid, and we study the beam propagation numerically by employing the coherent density approach.[13] This approach is based on the fact that partially incoherent field v is represented by a superposition of mutually incoherent components v_j tilted with respect to the z axis at various angles in such a way that $I_v = \sum_j |v_j|^2$, where $|v_j|^2 = G(j\vartheta)I_v$, and

$$G(\theta) = (\pi\theta_0)^{-1/2}\exp(-\theta^2/\theta_0^2) \quad (2)$$

is the angular power spectrum. Thus the coherence of a partially incoherent light beam is determined by the parameter θ_0; i.e., less coherence means larger θ_0. Here $j\vartheta$ is the angle at which the jth beam in the component v is tilted with respect to the z axis. For our numerical simulations we used a set of 1681 mutually incoherent beams, all initially tilted at different angles.

Figure 1 compares the propagation of two-component composite beams in two cases. In the first case, shown in the upper two rows of Fig. 1, self-trapped vortex u and beam v that it guides are both coherent. In general, such a composite beam demonstrates three different ways in which it could have evolved (see, e.g., Ref. 12). When the amplitude of guided beam v is small, vortex u decays as it does in the scalar case.[5] For an intermediate value of the vortex amplitude, the vortex is still unstable, but it evolves into a structure with a rotating dipole component, known as a dipole-mode vector soliton.[11] Finally, for relatively large amplitude of the guided beam both the coherent and the partially incoherent vector-mode soliton become stable; see Fig. 1.

The mutual interaction between the vortex beam and the mode that it guides has the character of mutual attraction, and it is expected to provide an effective physical mechanism for stabilizing the vortex beam in a self-focusing nonlinear medium. Indeed, it is well known that a scalar self-trapped vortex beam becomes unstable in a self-focusing nonlinear medium owing to the effect of azimuthal modulational instability. In this case the vortex splits into fundamental beams that fly off the main vortex ring.[5] Bright solitons, however, are known to be stable in such media. As was demonstrated for two-dimensional vortex solitons, mutual attraction of the components in a two-component system may lead to a counterbalance of the vortex instability by the bright component if the amplitude of the latter is large enough.[12]

We studied the effect of partial incoherence of a guided mode on vortex stabilization. As was mentioned above, for an intermediate value of the guided-mode amplitude the vortex structure does not survive and, instead, the vortex is transformed into a dipole-mode soliton.[11] An example of such an evolution is presented in Fig. 2 (upper two rows). Because of the initial phase dislocation carried by the vortex, the resultant dipole rotates during its propagation. However, we can observe that, when the vortex guides partially incoherent light, the resultant dipole soliton becomes more unstable and, in particular, the instability of the vortex beam is enhanced by the incoherence of the guided mode, as shown in Fig. 2 (lower two rows). The filaments no longer form a rotating dipole-mode vector soliton but rather fly off the main vortex ring.

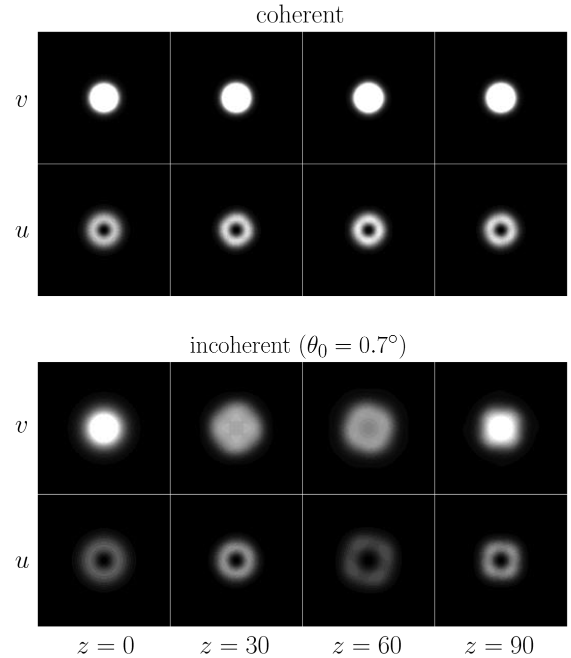

Fig. 1. Propagation of the vortex-mode two-component composite soliton with $\beta_1 = 1.0$. Top, coherent guided mode with $\beta_2 = 1.5$. Bottom, the same for a partially incoherent guided mode (at $\theta_0 = 0.7$); both beams have the same power as in the coherent case described above.

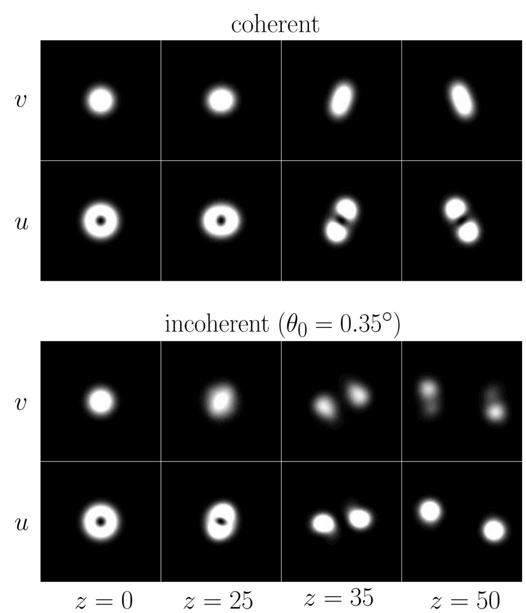

Fig. 2. Comparison of the unstable propagation of coherent and partially incoherent vortex-mode solitons. Top, coherent vortex at $\beta_1 = 1.0$ and coherent guided mode at $\beta_2 = 1.45$. The vortex-mode soliton evolves into a rotating dipole-mode soliton. Bottom, the same for the partially incoherent guided mode (at $\theta_0 = 0.35$); the vortex decays into two separate beams.

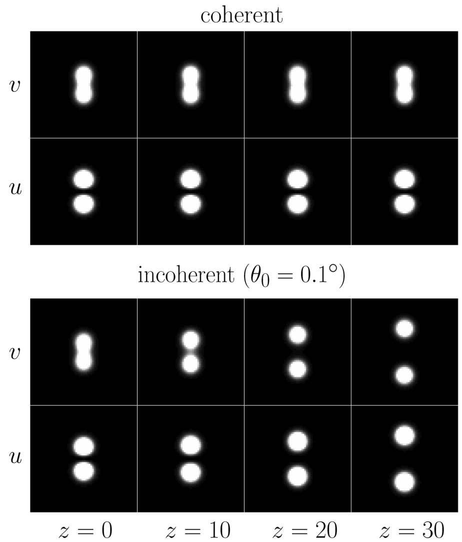

Fig. 3. Propagation of the dipole-mode vector solitons with coherent and incoherent fundamental beams. The initial profile of the beams corresponds to a solitary solution with propagation constants $\beta_1 = 1.0$ for the dipole and $\beta_2 = 1.15$ for the fundamental component. Top, the evolution of the fundamental; bottom, that of the dipole. Although the degree of incoherence is not very high ($\theta_0 = 0.1°$), it is enough to destabilize the soliton and leads to the soliton's decay.

We believe that this type of enhanced instability can be illustrated by a simple physical argument. Indeed, the incoherent fundamental beam can be thought of as many beams that have different momenta in the transverse plane; these momenta, pointing away from the center of the beam, add to the momentum of the vortex beam that decays faster than for the coherent case.

The situation is quite different when the soliton is stable in the coherent case. Here the incoherence of the fundamental guided mode seems to have a weak effect on the propagation of the vortex soliton, and it destabilizes the composite soliton only quite near the stability threshold and only when the incoherence is rather strong. Therefore the vortex-mode solitons with an incoherent fundamental mode normally show no sign of instability in a relatively broad range of the system parameters (Fig. 1).

Thus, partial incoherence destabilizes the rotating dipole-mode vector soliton that develops from the azimuthal instability of the vortex. It also has a destabilizing effect on the dipole-mode vector solitons, which are stable in the coherent case. We simulated the propagation of such solitons, varying the degree of coherence of field v; an example is presented in Fig. 3. The figure shows the propagation of the dipole-mode soliton with an entirely coherent fundamental component and the propagation of a soliton whose fundamental component is mildly incoherent ($\theta_0 = 0.1°$). The fundamental and the dipole components have equal power in both cases. It can be seen that the soliton with the incoherent fundamental component decays, whereas the coherent one remains stable.

In conclusion, we have introduced a novel type of composite spatial soliton consisting of a vortex guiding copropagating partially incoherent light. The vortex beam, known to be unstable in a self-focusing nonlinear medium, can be stabilized by a large-amplitude guided mode above a certain value of its incoherence, whereas for a low-amplitude bright component the incoherence may even enhance, rather than suppress, the instability.

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References

1. See M. S. Soskin and M. V. Vasnetsov, in *Progress in Optics*, E. Wolf, ed. (Elsevier, Amsterdam, 2001), Vol. 42, pp. 219–276.
2. G. A. Swartzlander and C. Law, Phys. Rev. Lett. **69,** 2503 (1992).
3. See, e.g., Yu. S. Kivshar and G. P. Agrawal, *Optical Solitons: From Fibers to Photonic Crystals* (Academic, San Diego, Calif., 2003), Chap. 8.
4. Such beams were suggested by V. I. Kruglov and R. A. Vlasov, Phys. Lett. A **111,** 401 (1985).
5. W. J. Firth and D. V. Skryabin, Phys. Rev. Lett. **79,** 2450 (1997).
6. C. C. Jeng, M. Shih, K. Motzek, and Yu. Kivshar, Phys. Rev. Lett. **94,** 043904 (2004).
7. A. P. Sheppard and M. Haelterman, Opt. Lett. **19,** 859 (1993).
8. C. T. Law, X. Zhang, and G. A. Swartzlander, Jr., Opt. Lett. **25,** 55 (2000).
9. A. H. Carlsson, J. N. Malmberg, D. Anderson, M. Lisak, E. A. Ostrovskaya, T. J. Alexander, and Yu. S. Kivshar, Opt. Lett. **25,** 660 (2000).
10. Z. H. Musslimani, M. Segev, D. N. Christodoulides, and M. Soljacic, Phys. Rev. Lett. **84,** 1164 (2000).
11. J. J. García-Ripoll, V. M. Pérez-García, E. A. Ostrovskaya, and Yu. S. Kivshar, Phys. Rev. Lett. **85,** 82 (2000).
12. J. Yang and D. E. Pelinovsky, Phys. Rev. E **67,** 016608 (2003).
13. See, e.g., D. N. Christodoulides, T. H. Coskun, M. Mitchell, and M. Segev, Phys. Rev. Lett. **78,** 646 (1997).