Theory of Incoherent Optical Solitons: Beyond the Mean-Field Approximation

Sergey A. Ponomarenko (T-4), N.M. Litchinitser (University of Michigan, Ann Arbor), and E. Poutrina and G.P. Agrawal (The Institute of Optics, Rochester); ***sergeyp@lanl.gov***

The behavior of fluctuating fields coupled via a nonlinear interaction is a rich and challenging subject that is of considerable interest in the areas of physics as diverse as hydrodynamic turbulence and theory of phase transitions. In the domain of optics, the interest in this topic has recently been reinforced by the ground-breaking experiments on the generation of solitons using partially coherent and even nearly incoherent, thermal-like sources of light [1].

In general, theoretical description of nonlinearly coupled statistical fields in terms of appropriate correlation functions is a formidable task because one has to deal with an infinite hierarchy of evolution equations for the correlation functions of all orders. In certain cases, however, the use of the mean-field approximation (MFA), which amounts to neglecting any effects associated with the fourth- and higher-order field correlations, can be justified. Indeed, the MFA has been quite successful in understanding phase transitions, Bose-Einstein condensation, and statistical wave propagation in nonlinear optical media. In the optical context, the MFA can be justified when the response time of a nonlinear medium is much longer than a typical correlation time associated with phase fluctuations across the wave front. Within the framework of the mean-field approximation, the nonlinear refractive index of the medium is assumed to depend only on the average intensity of an optical beam. This crucial assumption has made it possible to put forward several equivalent formulations of the mean-field theory of partially coherent solitons.

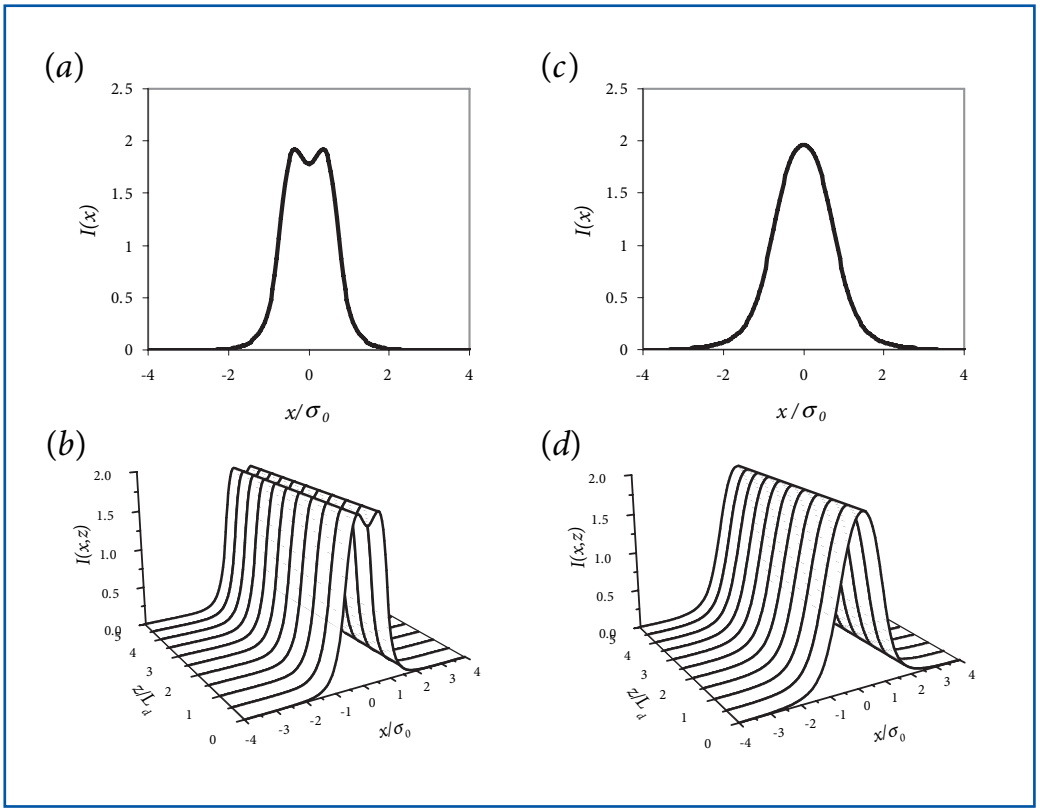

Figure 1— ***Intensity profile (a) and its evolution (b) for a two-mode partially coherent soliton in the medium with the threshold-type nonlinearity predicted by the mean-field theory. Curves (c) and (d) show the corresponding results obtained using our theory.***

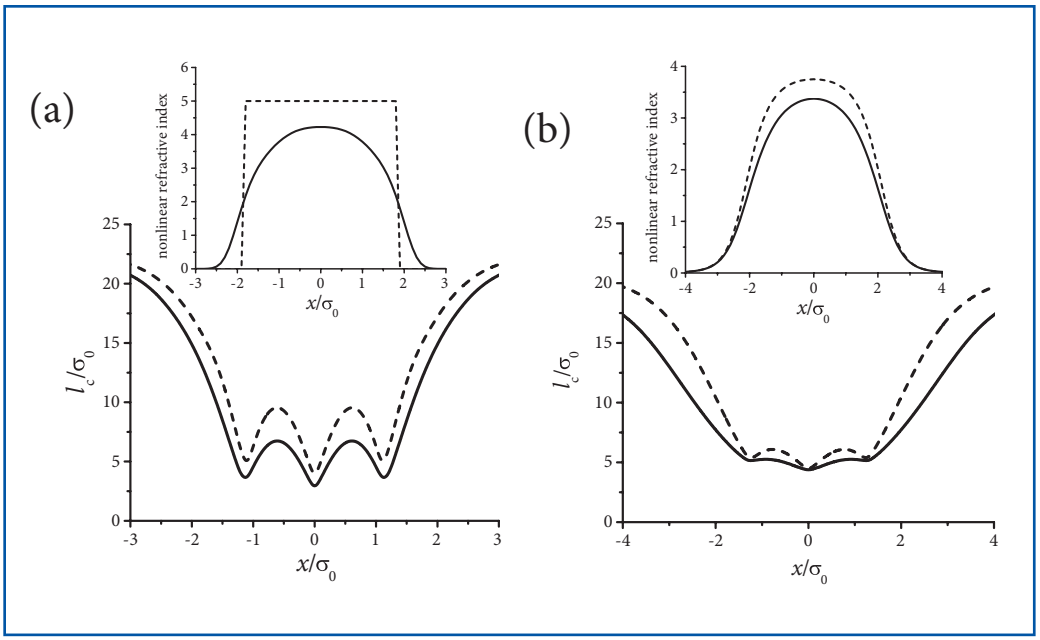

Figure 2— ***Spatial coherence length as a function of normalized transverse coordinate for the four-mode solitons generated by thermal (solid line) and laser-like (dashed line) sources in (a) threshold-type and (b) photorefractive nonlinear media. The insets show the averaged nonlinear refractive indices.***

However, the mean-field theory of partially coherent solitons does not take into account intensity fluctuations of the source generating such solitons. Consequently, some of the predictions of the mean-field theory concerning white-light solitons, produced by thermal-like sources with large intensity fluctuations, can be questionable. Thus, it is important to determine how intensity fluctuations in the source plane affect the salient properties of the optical solitons generated by partially coherent sources. We have recently formulated the first theory of partially coherent optical solitons that goes beyond the mean-field approximation [2]. In our approach, we argue that the nonlinear response to a fluctuating optical field of a slow-responding medium, whose response time is much longer than a typical correlation time associated with phase fluctuations of the field, can be characterized by the time-averaged nonlinear refractive index. This approach generalizes the previously developed mean-field theory of partially coherent spatial solitons and is capable of taking into account the contribution of source intensity fluctuations to the nonlinear response of the medium. For this reason, the new theory is expected to provide a more accurate quantitative description of the white-light solitons generated in a recent experiment [1] compared with that provided by the mean-field theory. We demonstrate that the intensity profiles and spatial coherence lengths of the solitons generated by fluctuating, quasi-monochromatic laser light and those produced by spectrally filtered thermal light can be qualitatively and quantitatively different. The results are displayed in Figs. 1 and 2 for the two types of nonlinear media: thresholding nonlinearity and photorefractive nonlinearity.

[1] M. Mitchell and M. Segev, *Nature* **387**, 880 (1997).
[2] S.A. Ponomarenko, N.M. Litchinitser, and G.P. Agrawal, *Phys. Rev. E* **70**, 015603(R) (2004).