Photorefractive SOLITONS

BRUNO CROSIGNANI and GREG SALAMO

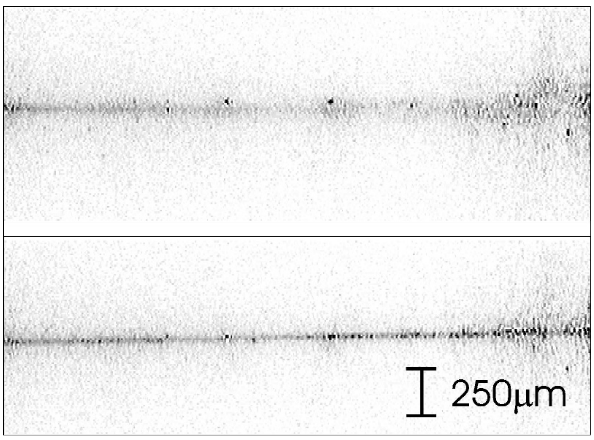
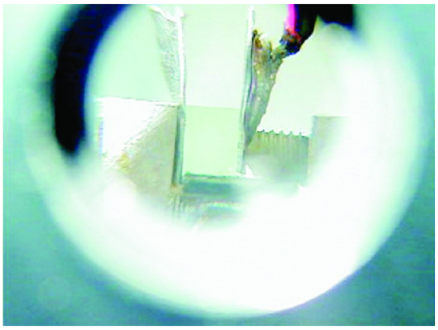


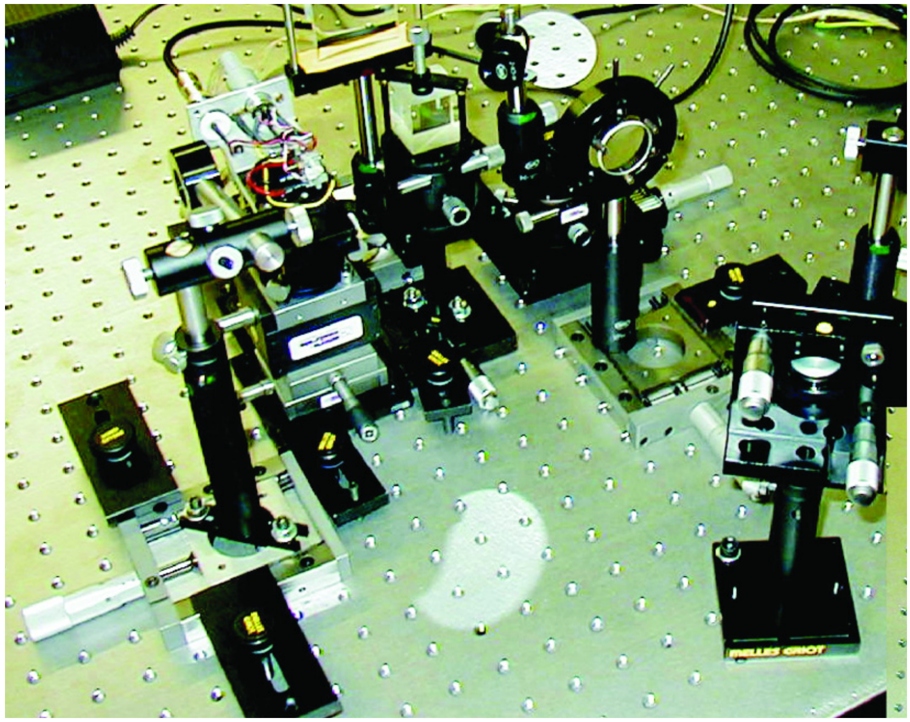
Figure 1. PR soliton. Naturally diffracting visible laser beam in a sample of KLTN (*top*). When an external voltage is applied to the crystal, the screening nonlinearity is activated and propagation occurs without diffraction (*bottom*).

The story has it that, when Schwinger learned of the Feynman diagrams, he remarked that quantum electrodynamics had been brought to the masses. A similar statement could be applied to photorefractive (PR) solitons. In fact, among the family of known optical self-trapped waves, PR solitons are of an altogether peculiar nature: they are the consequence of an extended buildup in time of optical nonlinearity. As a consequence, although the generation of a spatial soliton in conventional nonlinear media requires the use of high optical powers and sophisticated experimental techniques, its observation in PR media requires a few milliwatts of continuous-wave laser power and accessible experimental apparatus. In other words, the discovery that PR crystals support spatial nonlinear waves[1] has profoundly altered the rules of the game and has rapidly shifted attention from soliton generation physics to the rich realm of soliton phenomenology.[2] This circumstance has produced the involvement of a relatively large number of experimental groups, making the topic a field in its own right.[3]

Spatial solitons are a consequence of the strong beam nonlinearity that emerges in PR samples of electro-optic crystals that host a small concentration of deep donor and acceptor impurities. In a typical configuration, donors that far outnumber acceptors can be ionized in the presence of a light beam of suitable wavelength (typically visible) that would otherwise pass undisturbed in a pure sample. Corresponding electrons are promoted to the conduction band of the crystal in which they are free to move under the combined influence of diffusion and of an electrostatic field, until they recombine with a donor, previously ionized by light or by the presence of an acceptor. Since the ionized donors remain in a fixed position, the process inevitably leads to a separation between ion and electron charges and to the onset of an electric field (space-charge field). This field, in turn, through the electro-optic effect, induces a variation of the refractive index, which changes the propagation of the very beam that has generated it and gives rise to self-action.

PR solitons are continuous-wave visible, micrometer-sized beams that propagate without undergoing diffraction (see Fig. 1). As for other types of optical soliton, they occur through an exact balance between natural beam diffraction and material supported self-focusing. However, as opposed to nonlinearities based on electronic polarizability, such as the Kerr nonlinearity, that lead to local nonlinear refractive-index variations $\delta n(I)$, here the dependence of δn on intensity I turns out to be much more complicated because it is characterized by both spatial and temporal nonlocality. This means that δn at point $\mathbf{r}$ and time t depends on the values $I(\mathbf{r}', t')$ at points $\mathbf{r}'$ in the vicinity of $\mathbf{r}$ at time $t' < t$. Among the consequences, which range from self-trapping of incoherent light to the support of needle solitons, is the prevention of a straightforward interpretation of the soliton as the mode of the waveguide it generates. Whereas the lack of spatial nonlocality is associated with the variation scales introduced by charge diffusion, time nonlocality, which leads to a characteristic buildup of self-action, is a consequence of the fact that the small fraction of light absorbed by the crystal donors at a given time acts on the propagation of all the light that arrives at subsequent times. Thus PR solitons are not instantaneous but require that the space-charge field reach the steady-state





self-trapping distribution, a process that occurs in a finite time during which energy is delivered to the system. This accounts both for the low power required to observe the effect and for its slow response time (typically of the order of seconds for milliwatt solitons).

Since their first prediction,[1] PR solitons have been observed (see Fig. 2 for a typical setup) in different crystals, in different structural phases, supported by different types of effective nonlinearity, as slabs and needles, in the form of dark or bright beams, as scalar or vector, single or multicomponent structures, and even resulting from spatiotemporal incoherent illumination.[4]

There is no indication that solitons can be observed in any PR sample, since the effective nonlinear interaction depends on a number of material parameters, among which the most important is perhaps lattice geometry. It is fair to say that the family of more widely used uniaxial samples support a more or less similar phenomenology, such as SBN, $LiNbO_3$, $KNbO_3$, and $BaTiO_3$. Solitons are also observed in BSO and BGO, in semiconductor InP, and in paraelectric KLTN, and this testifies to their more general nature.

Although PR solitons are a consequence of beam self-action mediated by the PR effect, the effective soliton-supporting nonlinearity can change considerably from configuration to configuration. The most widely documented and implemented configuration leads to screening solitons, which occur when an extraordinary polarized laser beam is launched in a zero-cut uniaxial sample, biased along the optical axis. As the beam propagates and diffracts within the sample, it gives rise to mobile charge in its path that drifts in the applied field. This leads to a charge separation that effectively screens the external field along the beam trajectory. For an appropriate electro-optic response, this static field modulation gives rise to a self-lensing effect and ultimately leads to a soliton that, generally transient, can be rendered steady state by a homogeneous illumination of the sample. In some conditions, such as for the reduced system leading to slab solitons, this interaction leads to an effective saturated Kerr nonlinearity. A slightly different situation is encountered in PR samples with a strong photovoltaic response in which solitons arise even without an external bias. It turns out, however, that this behavior also leads to a similar saturated Kerr nonlinearity (for slab beams), in which the role played by the external field is now played by the so-called photovoltaic field. A somewhat different situation occurs for configurations that involve paraelectric PR samples. These are crystals that are in all similar to standard noncentrosymmetric samples, except that they are kept above their Curie temperature and are thus in their high-symmetry centrosymmetric phase. Apart from a slightly modified version of screening solitons, which, in the reduced slab case, again lead to a saturated Kerr-like nonlinearity, the higher symmetry supports an entirely different effective nonlinearity that is due to charge diffusion. In unbiased samples photogenerated charge diffuses from the beam trajectory to dark regions, leading to a generally small asymmetric space-charge field, responsible, in noncentrosymmetric

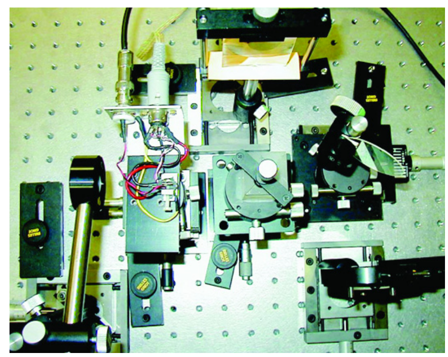


Figure 2. PR soliton setup (*center photograph*). Beams are launched onto the biased PR sample through a cylindrical lens for slab solitons, through a spherical lens for needles, and recombined with the background beam. Close-ups of beam launch and detection (*bottom right*) and of the sample (*top left*).

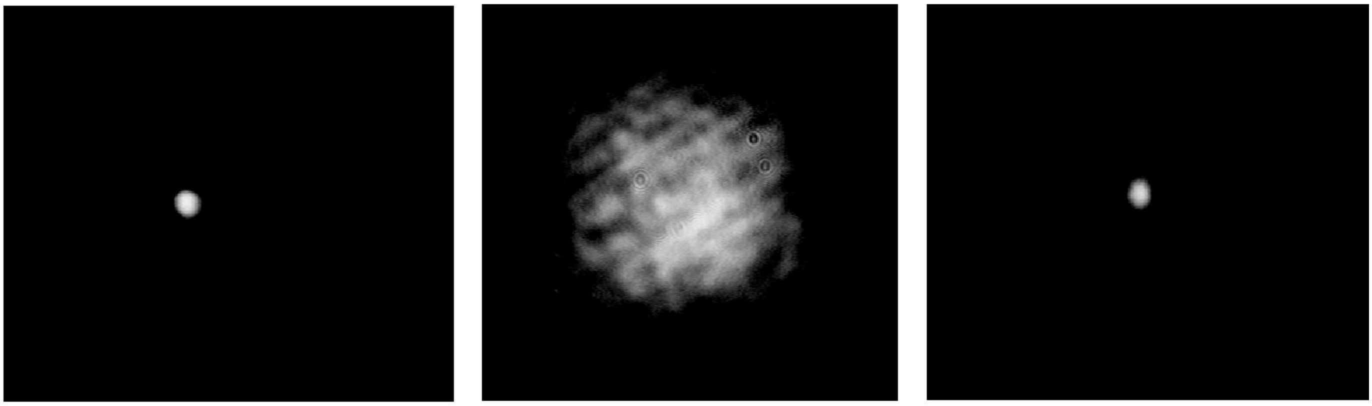


Figure 3. On-axis photographs of a PR needle soliton. Input focused beam distribution (*left*), natural diffracting beam after 6.4-mm propagation in a sample of KLTN (*center*), self-trapped beam distribution (*right*).

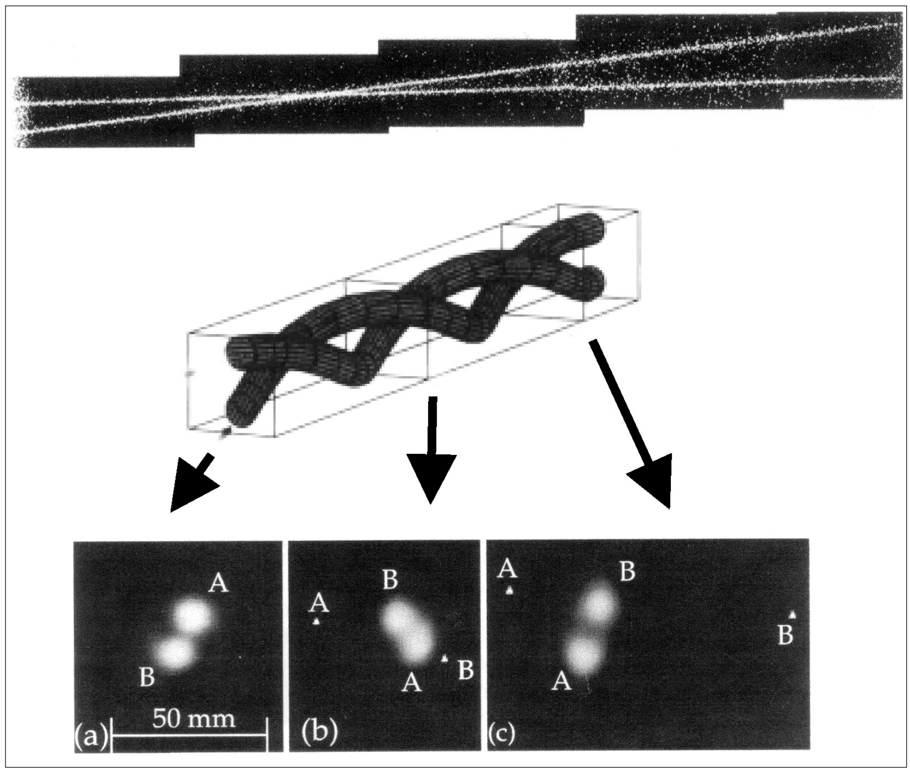


Figure 4. PR soliton interaction. Incoherent collision (*top*) and soliton spiraling (*center and bottom*).

samples, for asymmetric soliton self-bending. In contrast, with paraelectrics this leads to an observable self-lensing effect that represents a higher-order logarithmic-type nonlinearity. Although no solitons have thus far been observed because of such diffusion, for sample temperatures in close proximity to the Curie temperature, diffusion has been shown to give rise to self-trapping by seeding a specific domain pattern. Given the highly nonperturbative nature of this process, however, no effective nonlinearity has yet been formulated.

Apart from their relative ease of observation, PR solitons are important because they also occur in two transverse dimensions in the form of needle solitons (see Fig. 3). If, in the standard screening configuration, instead of launching a diffracting one-dimensional beam of laser light, a two-dimensional mode, such as a laser TEM_{00} mode, is launched, self-trapping occurs, leading to a nondiffracting, almost circular symmetric needle. This apparently fortuitous effect, in an all but circular symmetric physical system, has puzzled researchers in the field. The key to understanding needles can be found in their profoundly anisotropic and nonlocal nature, of which a mere extension of the saturated Kerr effective nonlinearity, valid for the slab case, is at most an oversimplification for the needle case.

Even by limiting our attention to screening solitons, we are faced with an extraordinarily rich phenomenology. First, screening solitons in their standard or photovoltaic versions results as both bright beams and dark solitary waves, according to the sign of the self-lensing effect that, in turn, depends on the sign of the electro-optic response. For needle configurations, this leads to the observation of a variety of vortex solitons. Second, the saturated nature of the effective nonlinearity, coupled to the slow response time of optical self-action, allows the trapping of beams composed of different optical modes, whether they be polarization components or more general spatial modes.

This diverse family of experimentally accessible soliton beams has allowed PR optics to become the playground for a number of studies that have considerably extended our understanding of nonlinear science. In particular, it has permitted the observation of phenomena that might have seemed mere theoretical concoctions only a decade ago, along with the discovery of totally new and unexpected features that accompany the emergence of solitons and their interaction. We recall the observation of coherent and incoherent soliton collisions, the conservation of soliton angular momentum giving rise to soliton spiraling (Fig. 4), soliton fusion and birth, and even a soliton phenomenon never even hinted at in previous experimental and theoretical studies, which is the interaction between solitons of different dimensionality, that is, between a needle soliton and a slab soliton.[5]

From a theoretical point of view, the complexity of the PR effect makes the description of nonlinear beam propagation extremely challenging, especially if one wishes to include the inherently anisotropic character of the whole process. The model, based on the classical rate-equation approach, in its time-independent version involves the nontrivial and generally formidable interplay between a transverse electrostatic problem and a coupled parabolic optical wave equation. For the screening configuration, one can provide a relatively simple and yet effective theoretical description in one-dimensional geometry, that is, when dealing with a slab soliton. The problem becomes much more involved in two-dimensional geometry, that is, when one generates a needle. Here, anisotropy and nonlocality play a major role, and even numerical studies face considerable difficulties.

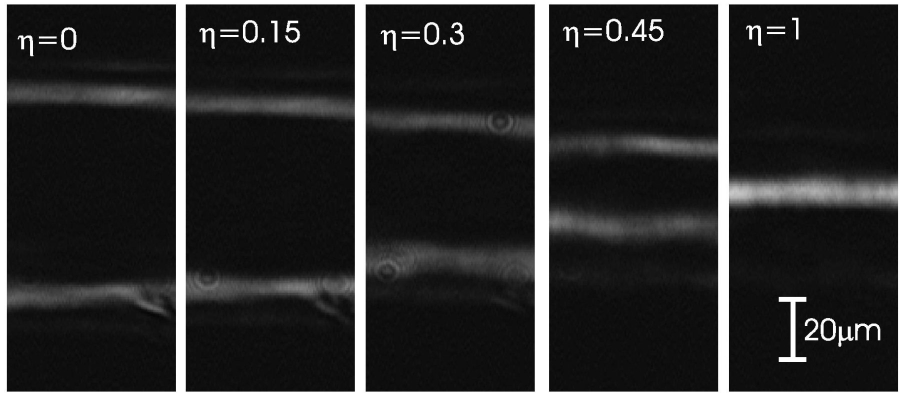


Figure 5. Electroholography of a PR soliton. By applying different voltages to the sample where a slab soliton was previously formed, light was routed electro-optically, as the transverse beam photographs of the output face show (η being the ratio between the applied and the soliton voltage).[7]

As far as applications are concerned, PR solitons are still in their infancy. Their one basic implementation is considered beam steering and beam manipulation. In particular, a PR soliton can guide a second infrared signal beam. The signal, being of longer wavelength and thus not photoactive, is passively accompanied by the soliton through the sample without undergoing diffraction. Soliton reconfigurability makes this particularly promising, especially in more complicated schemes that have been demonstrated, such as soliton-based directional couplers, and second-harmonic generation enhancers. Some applications are hampered by the generally slow PR optical response (unless intense laser pulses are used), and a more realistic approach is based on the use of nondynamic guiding structures. These structures can be obtained by soliton fixing.[6] Another strategy is based on electroholography of a soliton, with which one can obtain beam steering and manipulation without charge displacement, but simply through the readout of a deposited soliton in a paraelectric, where the quadratic electro-optic response allows for nontrivial pattern modulation (see Fig. 5).

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Bruno Crosignani, Dipartimento di Fisica, Università dell'Aquila, L'Aquila, Italy and INFM-Roma 1, Rome, Italy, can be reached by e-mail at bcross@caltech.edu. Greg Salamo, Physics Department, University of Arkansas-Fayetteville, Arkansas.