Photorefractive Solitons

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Invited Paper

***Abstract*—We present a review of recent works on spatial optical solitons in photorefractive media. We discuss fundamental properties of screening solitons and their interaction.**

***Index Terms*—Photorefractive materials, photorefractive nonlinearity, spatial solitons.**

I. Introduction

IT HAS been known for more than three decades that an optical beam can induce strong changes of the refractive index in certain electrooptic materials [1]. When discovered in the 1960s, this so-called *photorefractive (PR) effect* was originally considered undesirable, since it led to scattering and deformation of collimated light beams. However, it was soon realized that photorefractivity was a novel nonlinear mechanism with enormous potential applications in holography [2]. Since that time, PR nonlinear optics has enjoyed constant interest with activities including optical phase conjugation, optical signal processing, and optical storage [3].

The physics of the PR effect can be summarized using the widely accepted basic band transport model [4]. In the simplest case, this model assumes the existence of the donor and trapping centers located inside the energy band gap. The presence of a nonuniform light beam excites charge carriers, say electrons, from the donor centers, while in the conduction band these electrons move either by means of diffusion and/or drift due to external or internal electric field. After migrating, the electrons are trapped on the acceptor sites. In the steady state, this process leads to charge separation inside the crystal (trapped electrons leave behind ionized donors) and a resulting space charge electric field. Since the crystal is electrooptic, the presence of the nonuniform electric field results in a modulation of its refractive index. The strength of this effect (i.e., refractive index change) is independent of the light intensity and is determined only by material parameters such as the electrooptic coefficients and the concentration of donor and acceptor centers. The most commonly used PR materials are inorganics such as lithium niobate, barium titanate, bismuth silicon oxide, and strontium barium niobate [4]. Also, a strong PR effect has been demonstrated in polymers [5].

A few years ago, it was suggested that PR materials could also be used to form and support optical spatial solitons [6], [7]. A bright optical spatial soliton represents an optical beam propagating in the medium without changing its profile. To create such solitons, the medium has to exhibit a self-focusing effect. Then, the presence of the optical beam will lead to an increase of the refractive index in the center of the beam and subsequent trapping of the beam inside a self-induced waveguide. In standard nonlinear materials, the nonlinearity is usually rather weak and, therefore, high light intensity is required to achieve appreciable self-focusing and the creation of solitons. PR media are exceptional in this respect since the large refractive index change can be obtained with optical powers in microwatts.

Two basic types of spatial solitons can exist in the PR medium, depending on whether the soliton formation process requires the presence of the external electric field or not. In the former case, we deal with the so-called *screening solitons*, which will be considered here in great detail. The second type, the *photovoltaic solitons*, will be briefly discussed in Section VII. Screening solitons are formed when an optical beam propagates in the PR crystal biased with an external direct current (dc) electric field [8]–[12]. The presence of the beam leads to photo-excitation of electric charges, their migration and subsequent trapping by acceptor centers. The distribution of photo-excited charges induces a space-charge electric field which screens out the external field. The effective spatially varying electric field modulates the refractive index of the medium in such a way that the beam becomes self-trapped by a locally increased index of refraction and may propagate as a spatial soliton [13].

A unique feature of the PR nonlinearity is its ability to exhibit either self-focusing or self-defocusing in the same crystal by a simple reversal of the polarity of the biasing field. Hence, the same crystal can be used to study either bright or dark solitons. In addition, since this nonlinearity is wavelength sensitive, it is possible to generate solitons using one wavelength (and low optical power) and then use the soliton-supported channels to guide another, much stronger. optical beam of a different wavelength.

The ease of their formation and manipulation using very low laser power, as well as their stability and robustness, makes screening solitons very attractive for practical applications. Because of their accessibility, screening solitons have also become a very useful tool in experimental verification of many theoretical predictions of general soliton theory, in particular soliton collision.

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Here, we present a brief overview of recent advances in the field of screening spatial solitons in PR media.

II. Theoretical Model

The two-dimensional (2-D) analysis of the formation, stability and nonlinear evolution of the $(2+1)D$ soliton-type structures in PR media is crucial for a complete understanding of collisional properties of these solitons due to special features of the PR nonlinearity. The theory of PR solitons is based on the physics of the PR effect in biased electrooptic crystals. PR materials respond to the presence of the optical field by a nonlinear change in the refractive index Δn that is both an anisotropic and nonlocal function of the light intensity. The anisotropy does not allow radially symmetric soliton solutions, thereby requiring an explicit treatment of both transverse coordinates [14]–[16]. The nonlocality is another feature of the PR response that makes it significantly different from typical nonlinear optical media, where the nonlinear refractive index change is a local function of the light intensity. This local response, in the simplest case of an ideal Kerr-type medium $\Delta n \propto |E|^2$, where $|E|^2$ is the light intensity, results in the canonical nonlinear Schrödinger equation for the amplitude of light propagating in the medium [17]. A more realistic model results in the appearance of higher order nonlinearities which are an indication of the saturable (but still local) character of the nonlinearity [18]. In contrast, in PR media, the change in the refractive index is proportional to the amplitude of the static electric field induced by the optical beam. As will be shown below, finding the material response therefore requires solving an elliptical-type equation for the electrostatic potential with a source term due to the light-induced generation of mobile carriers [19], [20].

The rigorous model of PR solitons involves the so-called Kukhtarev's equations [21] which govern the physics of the PR effect. Here, for the sake of simplicity, we will use phenomenological approach as in [22].

Let us consider the propagation of an optical beam with an amplitude $A(x, y, z)\exp(ik_0 z)$ in an externally biased PR medium, where k_0 is a wave vector and $A(x, y, z)$ represents the slowly varying amplitude of the beam. We assume that the beam propagates along the z axis and the biasing field is applied along the x axis. An additional uniform, broad beam provides the background illumination. We will first consider the effect of light intensity on the refractive index change of the PR crystal. Keeping in mind that the biased crystal can be treated as an electrical circuit, one can write the following steady-state relations for the electric field in the crystal $\vec{E}(x, y)$ and current density $\vec{j}(x, y)$ [22]:

$$\vec{j} = \sigma \vec{E} \tag{1a}$$

$$\operatorname{div} \vec{j} = 0 \tag{1b}$$

where σ is the photoconductivity of the medium. The first of these equation represents Ohm's law, while the second is the continuity equation. In typical PR crystals, for diffusion and drift lengths much smaller than the beam's size, the photoconductivity is proportional to the total light intensity $\sigma \propto I + I_0$, where $I = |A|^2$ and I_0 denotes background (or dark) light intensity.

Introducing the electrostatic potential $\varphi(x, y)$ by

$$\vec{E}(x, y) = \vec{E}_0 - \nabla\varphi \tag{2}$$

where $\vec{E}_0$ denotes the value of uniform externally applied field, the continuity equation yields

$$\nabla^2\varphi + \nabla\varphi \cdot \nabla \ln(I + I_0) = E_0 \frac{\partial}{\partial x} \ln(I + I_0). \tag{3}$$

The spatially varying dc electric field modulates the refractive index of the crystal via the electrooptic effect

$$\Delta n = \hat{r}_{\text{eff}} \left(\frac{\partial \varphi}{\partial x} - E_0 \right) \tag{4}$$

where $\hat{r}_{\text{eff}}$ is the effective electrooptic tensor. This refractive index change is then used in the wave-equation, which in the slowly varying amplitude approximation reads

$$\left[\frac{\partial}{\partial z} - \frac{i}{2} \nabla^2 \right] A(\vec{r}) = i\gamma \left(\frac{\partial \varphi}{\partial x} - E_0 \right) A(\vec{r}) \tag{5}$$

where γ is a material parameter.

In the one-dimensional (1-D) case, i.e., when considering the propagation of a narrow stripe beam across the PR crystal, the electrostatic potential and light intensity will depend on a single transverse coordinate only. Then (3) is easily solved, leading to the nonlinear index change in the form

$$\Delta n \propto \frac{I_0}{I + I_0}. \tag{6}$$

Substituting Δn into the wave equation, one obtains the following dimensionless equation:

$$i \frac{\partial u}{\partial z} + \frac{1}{2} \frac{\partial^2 u}{\partial x^2} - \frac{u}{|u|^2 + 1} = 0 \tag{7}$$

where the beam's amplitude has been normalized to the background intensity $(u(x, z) = A(x, z)/\sqrt{I_0})$.

This is the well-known nonlinear Schrödinger equation with a saturable nonlinearity. The saturation is due to the fact that the maximum index change in the PR crystal is determined solely by the value of the biasing field (not light intensity) and is largest when the external field is completely screened out by the space charge field. From (3), it is evident that the sign of the index change depends on the polarity of the biasing field. Hence, just by flipping the direction of the dc field, the same crystal will exhibit either a self-focusing or self-defocusing nonlinearity. This is a very useful property, since it allows the formation of either bright or dark spatial solitons using exactly the same nonlinear medium.

Although the potential equation (3) has been derived using a simple phenomenological approach, it is essentially the same as the one derived rigorously by Zozulya *et al.* from Kukhtarev's model [23], [24]

$$\nabla^2\varphi + \nabla\varphi \cdot \nabla \ln(I + I_0) = E_0 \frac{\partial}{\partial x} \ln(I + I_0) + \frac{k_B T}{e} \cdot \left\{ \nabla^2 \ln(I + I_0) + [\nabla \ln(I + I_0)]^2 \right\} \tag{8}$$

where k_B is the Boltzman constant, T is temperature and e denotes the electron charge. Clearly, the difference between (3) and (8) is the appearance of two additional terms with the factor $k_B T/e$. These terms, which account for a diffusion of photoexcited charges, lead to an asymmetric contribution to the refractive index which causes solitons to bend during propagation. This self-bending effect is often neglected, since it is only important for very narrow beams [25], [26].

The system of (8) and (5) has been widely used to study the formation and interaction of optical screening solitons as it provides rather faithful account of the effect of PR nonlinearity. In particular, it accurately represents the anisotropic nature of this nonlinearity and its consequence on the interaction of solitons.

Unfortunately, this system of equations is nonintegrable and therefore has to be solved numerically. Typically, the potential equation is solved using a finite difference method. The resulting index distribution is then used in the propagation equation which is solved either by a fast Fourier method or a Cranck–Nicolson scheme [27]. In looking for stationary soliton solutions, the iteration procedure of Petviashvili is commonly employed [28], [29].

III. Soliton Formation

The first experimental observation of the spatial PR solitons was reported by Segev *et al.* [7] using a strontium barium niobate (SBN) PR crystal. By applying an external voltage (few hundred volts per centimeter), a clear focusing of the beam and soliton formation was observed. However, the solitons observed in this particular experiment were of transient nature (so called “quasisteady state”) and existed only within a narrow temporal window before the screening of the external field actually took place. In 1994, Stepanov’s group [8] reported the first observation of steady-state screening solitons in PR barium titanium oxide (BTO). This crystal possesses significantly weaker electrooptic properties than SBN and therefore a much higher electric field (a few kilovolts per centimeter) had to be used to create solitons. In Fig. 1, we reproduce the plot from [8]. It shows evident narrowing (expanding) of the output beam as positive (negative) voltage is applied to the crystal. In the same year, Shih *et al.* [11] demonstrated the formation and propagation of steady-state screening bright spatial solitons in SBN crystal. Due to the extremely high value of electrooptic coefficient, the nonlinearity was high enough to allow for the creation of very narrow (less than 10 μm in diameter) solitons.

As the screening involves the transport of charge carriers, the timescale of the process equals that of the usual PR effect—from milliseconds to seconds, depending on the particular material and light intensity [4]. The dynamics of soliton formation have been studied numerically in [23], [30], [111], [112]. It has been shown that the steady state is reached after several stages of focusing and defocusing. Indeed, this behavior has been fully confirmed in experimental observations [31].

Since their first experimental observation, PR solitons have been the subject of very intense experimental and theoretical studies. They have been observed not only in commonly used noncentrosymmetric PR crystals such as BTO [32], BSO [33], [34], [113], potassium niobate [35], [114], [36], and SBN, but also in biased semiconductors [37], [115], [38] and even centrosymmetric crystals [39]. These studies resulted in the observation of a great variety of interesting features. They include such effects as the formation of dark spatial solitons [40]–[42], self-bending of solitons [25], [26], soliton propagation in optically active crystal [34], [113], [43], [44], demonstration of waveguiding properties of spatial solitons [45], [116]–[118], or modulational instability of planar wave fronts in PR crystals [46], [47]. As an example, in Fig. 2 we show the experimentally observed modulational instability of a wide Gaussian beam in a PR crystal in the regime of strong self-focusing [47]. Modulational instability constitutes one of the most fundamental effects associated with wave propagation in nonlinear media. It signifies the exponential growth of a weak perturbation of the amplitude of the wave as it propagates. The gain leads to amplification of sidebands, which breaks up the otherwise uniform wave front and generates fine localized structures (filamentation) [48]. Thus, it may act as a precursor for the formation of bright spatial solitons. The four graphs in Fig. 2 display light intensity distribution at the exit facet of the PR SBN crystal for few values of the biasing field. As Fig. 2 shows, an increase of the nonlinearity, which is achieved here by applying a higher biasing field, leads to the break-up of the smooth beam and formation of spatial solitons.

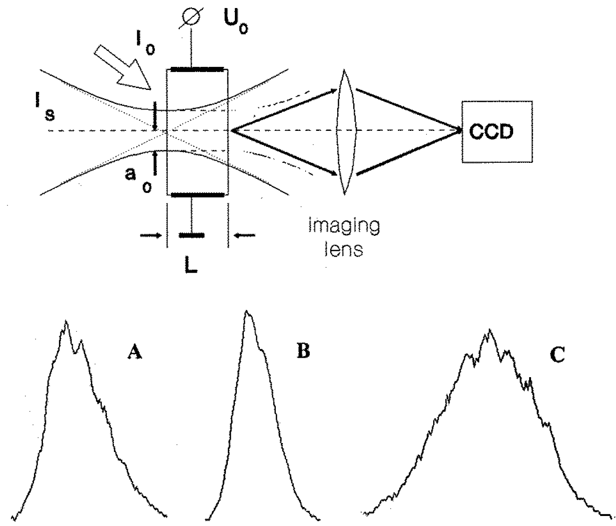

Fig. 1. (Top) Experimental scheme used to observe bright spatial soliton in PR BTO crystal. (Bottom) Output light profiles observed for different external dc voltages applied to BTO sample: (a) 0 V, (b) +2.5 kV, and (c) −2.5 kV. (Figure taken from [8].)

IV. Interaction of Photorefractive Solitons

The tremendous interest in solitons has been stimulated by soliton collisional properties. Right from the advent of soliton physics, it became apparent that in many aspects solitons behave like particles. They are robust objects displaying “forces” when interacting. The nature of the forces exerted by coherently interacting solitons has been discussed in the literature for both temporal [49], [119] and spatial [50], [51] solitons .

It is well known from the classical investigations of Zakharov and Shabat [52], [120] that solitons governed by integrable

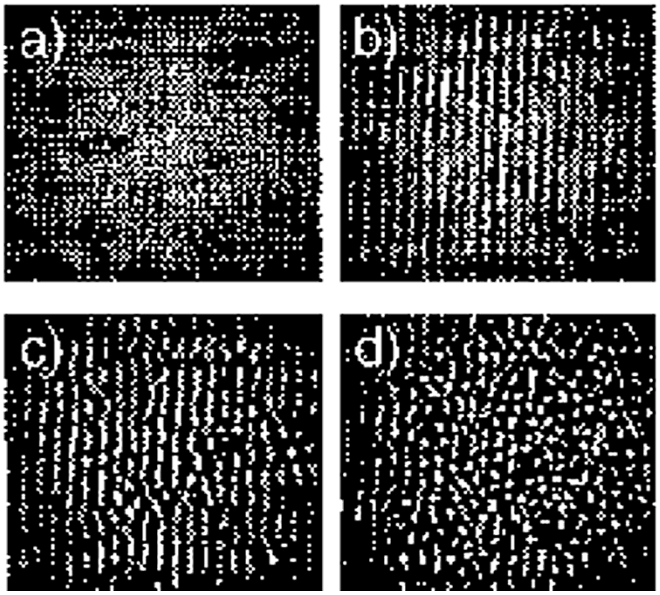

Fig. 2. Modulational instability of wide radially symmetric Gaussian beam propagating in biased SBN crystal: output near-field intensity distribution for: (a) 0, (b) 600, (c) 1200, and (d) 1500 V, which show the central 0.8×0.8 mm^2 region of the beam. (Figure taken from [47].)

models, such as 1-D spatial solitons in a cubic nonlinear (Kerr) media, behave as elastic particle-like objects during a collision. They remain unperturbed, completely preserving their identities and form. However, the collision of solitons propagating in non-Kerr materials may be drastically different. Non-integrable models, such as those describing saturable nonlinear media, lead to inelastic collisions, as reflected in the emission of radiation, as well as a strong dependence of the outcome of the collision on the relative phase of the solitons [53], [121]. In particular, it has been predicted that solitons can annihilate each other, fuse, or give birth to new solitons when colliding in nonlinear materials exhibiting saturation. This kind of behavior is rather generic, being independent of the particular mathematical models for the specific nonlinear medium [54]. However, since the PR solitons can be very easily realized, they are obvious primary candidates for experimental studies of soliton–soliton interactions. In recent years, research efforts resulted in the demonstration of many generic collisional effects, including ones previously predicted theoretically (but never observed), as well as completely novel ones, and also those specific for PR nonlinearity.

V. Coherent Soliton Interaction

It is also well known that in the case of homogeneous self-focusing media, the interaction force depends on the relative phase of the solitons. When two solitons are in-phase, the total light intensity in the area between the beams increases. This, in turn, results in a local increase of the refractive index, which effectively attracts both beams. Exactly the opposite situation arises when the solitons are out-of-phase. Then, the light intensity drops in the interaction region and so does the refractive index. This results in the beams moving away from each other, which indicates a repulsive force. Phase-sensitive interactions of spatial PR solitons have been demonstrated by several groups [55]–[60]. In particular, [59] presents an experimental evidence of phase-controlled energy exchange and the "birth" of bright PR solitons. In this experiment, two mutually coherent beams propagated at a small angle so the trajectories of the resulting solitons intersected inside the PR crystal. It was shown that collisions occurring at a large angle are basically elastic; solitons are unaffected by the interaction. However, for small interaction angles ($< 1^\circ$), the outcome of the collision depends strongly on the relative phase of the solitons. In particular, in-phase solitons tend to collapse into a single beam while out-of-phase solitons clearly repel. For intermediate values of the relative phase, the soliton interaction leads to energy exchange. By changing the relative phase by π, the direction of the energy transfer process can be reversed. After setting the intersection angle to $\approx 0.8^\circ$ and relative phase to zero, the collision of two solitons was shown to result in the formation of three solitons. This soliton birth effect, although predicted theoretically quite some time ago in studies of the so-called Gaussons, i.e., solutions of the nonlinear Schrödinger equation with logarithmic nonlinearity [61], [122], has been only recently observed experimentally.

It is worth noting that the reverse process to soliton birth, namely annihilation of the solitons, has also been observed [62]. Here, the simultaneous collision of three solitons resulted in only two outgoing solitons.

Recently, similar collisional properties of coherent solitons (i.e., energy exchange and soliton birth) have been observed in planar PR waveguides [63].

As mentioned earlier, the spatial solitons behave like particles exhibiting forces during the mutual interaction. In Fig. 3, we illustrate this effect in case of two closely placed, nonintersecting, coherent solitons. The pictures show time sequence of the light intensity distribution at the exit face of the 5-mm-long SBN crystal. Initially, only a single beam is present in the medium and forms a spatial soliton. The first frame in the Fig. 3 depicts the moment when the second beam was launched. This beam gradually forms a soliton which interacts with the already existing soliton. As a result of the interaction, solitons exchange energy and their trajectories display spatial and temporal rotatation.

Among various observations of effects associated with coherent interaction of PR solitons, it is worth mentioning recent experiments by DelRe *et al.* who demonstrated intrinsically inhomogeneous interaction forces in collision of solitons of different dimensionalities [64].

VI. Interaction of Incoherent Solitons

In typical isotropic self-focusing media, mutually incoherent solitons always attract each other. This is because the total light intensity always increases in the region where the beams overlap. This leads to an increase of the refractive index and subsequent attraction of the solitons. Recently, Shih *et al.* and Shih and Segev [65], [66] have studied incoherent soliton interactions in PR media in the regime where the physics is quite similar to that pertaining to saturable Kerr media [53], [121]. They demonstrated the fusion of two incoherent solitons [66].

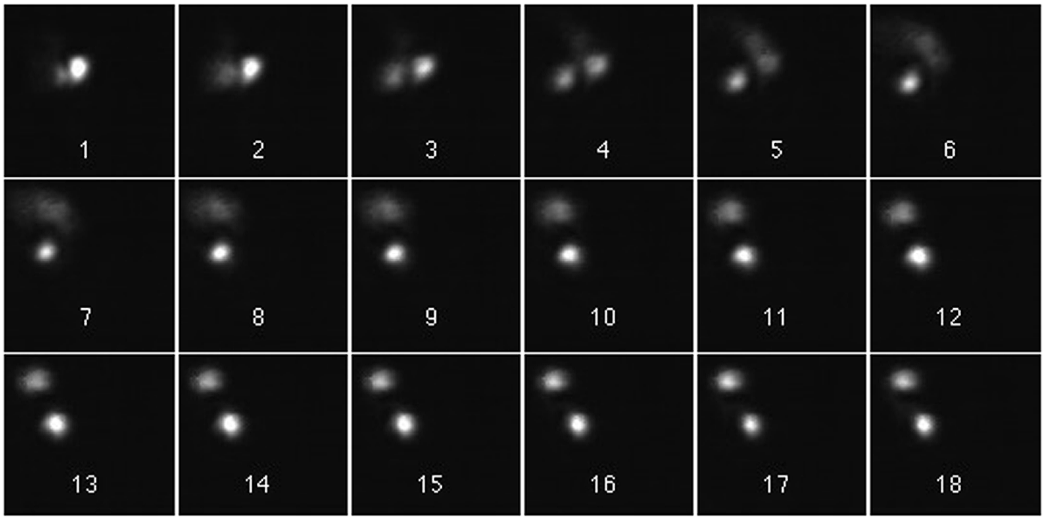

Fig. 3. Experimentally observed dynamic rotation of coherently interacting screening solitons propagating in 5-mm-long SBN crystal biased with 3-kV dc field. Each frame corresponds to a 0.5-s time step. As the solitons interact, they experience mutual spatial (and temporal) rotation. (Figure taken from [60].)

It turns out that in PR media, it is possible to achieve both attractive and repulsive forces between mutually incoherent solitons. It was pointed out some time ago [23] that the nonlinear response of a PR crystal to a single optical beam is strongly anisotropic. First, the optical lens induced by the beam is astigmatic [67], [123], which results in a typically elliptical intensity profile of the steady-state solitons. Second, and more important, as far as the soliton interaction is concerned, the asymptotic behavior of the light induced refractive index change is drastically different along the two principal transverse directions [23]. In the direction perpendicular to the direction of the applied field, the refractive index reaches its peak value in the center of the beam and then monotonically decays to zero. The situation is different along the direction of the applied field. Away from the center of the beam, the refractive index first decreases then changes sign and monotonically approaches zero. Far from the center of the beam, the index actually increases with light intensity, indicating self-defocusing.

Such substantially different asymptotics lead to a nonstandard interaction of two nearby solitons, which depends dramatically on their location and separation [68]. Numerical simulations of this effect are shown in Fig. 4. For beams propagating in the plane perpendicular to the direction of the applied field, the refractive index change always increases in the region between beams [Fig. 4(c)], which indicates their attraction. For beams located along the direction of the applied field, the refractive index change depends on their separation. For closely placed beams, the index increases in the overlapping region and the beams attract [Fig. 4(a)]. On the other hand, for large separation, the refractive index actually decreases in the overlapping region, leading to the repulsion of solitons [Fig. 4(b)]. Interestingly, for the input beams separated along both the x and y axes, a clear rotation of solitons is observed, as shown in Fig. 4(d). As the solitons interact, they not only increase their separation distance, but also experience spiraling about the center of the beams. It should be emphasized that the spiraling motion is due to the anisotropy of the potential created by the two beams and occurs even though they are launched in parallel. Fig. 5 illustrates experimentally observed anomalous interaction of two incoherent solitons. In this case, the biasing field of 2 kV/cm was applied along horizontal direction while beams were initially propagating in parallel. Two closely placed beam experienced attraction and subsequent fusion [Fig. 5(a)], while beams separated by more than 40 μm clearly repel [Fig. 5(b)]. Similar behavior (with weaker repulsion) is observed for even larger separation [60 μm, Fig. 5(c)]. It should be added that, in the same experiment, the mutual rotation of two beams separated along both the x and y axes was observed.

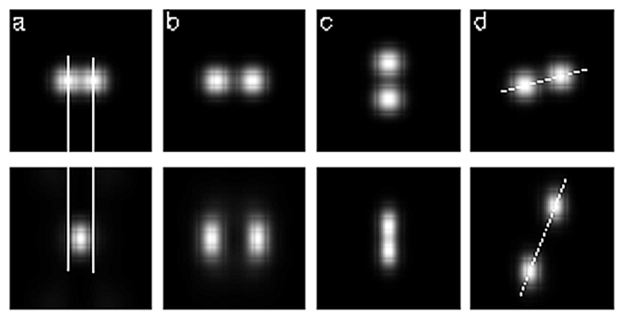

Fig. 4. Numerical calculations of propagation of two initially parallel incoherent solitons, for initial separation of: (a) $d_x = 3.8$, (b) $d_x = 5.3$, and (c) $d_y = 5.3$. In (d), $d_x = 5$ and $d_y = 1.5$. Top row: input beams. Bottom row: output beams. (Figure taken from [68].)

Some time ago, it was predicted that a pair of spatial solitons in a self-focusing medium should spiral around each other if their mutual attraction can counter-balance the divergence of their trajectories [51]. The first experimental observation of this effect in a PR crystal was reported by Shih *et al.* [69]. The spiraling of 270° over a distance of 10 mm has been observed. It is worth mentioning that numerical simulation of soliton interaction in PR crystals indicate that soliton spiraling is possible only over a limited distance. This is due to the anisotropy of PR nonlinearity, which leads to the nontrivial topology of soliton trajectories when the beams are launched slanted to the direction of external field [70]. Numerical simulations reveal that initially skewed beams exhibit complicated motion in propagation. Typi-

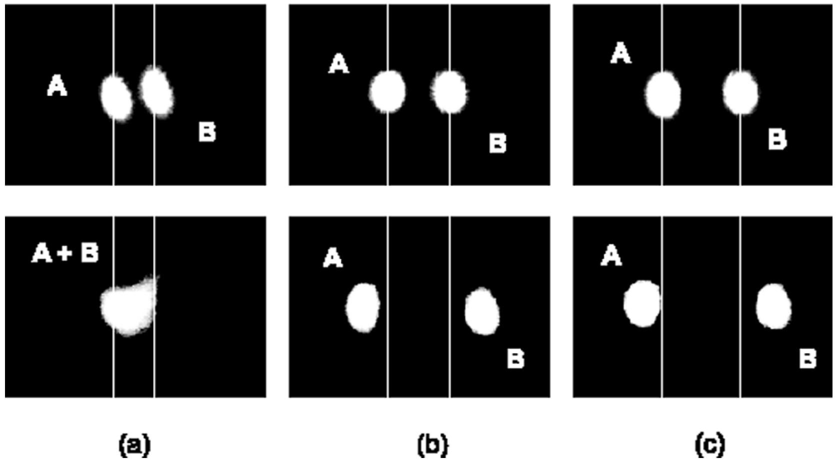

Fig. 5. Experimental observation of separation-dependent interaction of incoherent solitons. The x axis (direction of the applied field) is horizontal. (a) Fusion for close separation. (b) and (c) Repulsion of well-separated solitons. (Figure taken from [31].)

cally, they exhibit some rotation combined with oscillations and end up either flying apart or fusing.

VII. Variety of Solitons in Photorefractive Media

PR nonlinearity not only allows for the realization of spatial solitons using very low optical power, but also offers a unique opportunity to create many different types of solitons, such as dark solitons.

Dark spatial solitons require negative nonlinearity—or self-defocusing. As was mentioned earlier, in PR media, either type of nonlinearity (positive or negative) can be easily achieved by choosing appropriate polarization of the biasing field.[1] Then dark solitons in the form of the intensity dip on the otherwise constant background can be formed. 1-D dark screening solitons have been observed in biased BTO and SBN crystals [40], [41]. Also, the formation of 2-D dark solitons (soliton vortices) has been reported in [71] and [72]. It is well known that 1-D dark solitons are, in principle, unstable in two dimensions and are subject to transverse instability. This has been demonstrated in the case of PR dark solitons by Mamaev *et al.* [73]. The dark soliton stripes break upon propagation and individual vortices are formed. A vortex soliton, being a topological object, is stable in typical self-defocusing Kerr-type media. On the other hand, it appears that in an anisotropic nonlinear medium, such as a biased PR crystal, vortex soliton propagates stably only over a finite distance. Further propagation leads to its destruction [74].

Screening optical solitons are formed when a PR medium is biased with a dc electric field. However, solitons can be also formed in unbiased PR crystals, namely those that exhibit a photovoltaic effect, i.e., a generation of a dc current in a media illuminated by a light beam in the absence of an external field and spatial inhomogeneity [75], [76]. This current and subsequent trapping of charge carriers gives rise to a space charge field which induces a refractive index modulation via the Pockels effect. Recently, dark [77], [124], [125] and bright [78] photovoltaic spatial solitons have been observed using nominally pure lithium niobate and copper-doped potassium–niobium–strontium–barium niobate crystals.

Among recent advances in the field of optical solitons, demonstration of the formation of incoherent [80], [81], [126], [138]–[140] and multicomponent (or vector) spatial solitons [82]–[86], [127]–[129] have attracted strong attention. The notion of incoherent solitons is particularly important as it opens the possibility of using light sources with degraded or poor coherence in soliton-based all-optical signal processing. In the light beam generated by an incoherent light source, there is no correlation between light emitted from two different points. This results in some level of randomness (or partial correlation) in the phase across the beam. As a result, a partially coherent beam spreads faster than its coherent counterpart of the same width. Additionally, the intensity distribution across the beam exhibits a speckled structure, which prevents the "standard" uniform self-focusing observed in instantaneous nonlinear media as the beam tends to form filaments. It turns out, however, that self-focusing and soliton formation are still possible, provided the nonlinear medium is inertial and responds much slower than the time scale characterizing the random phase variation. In such cases, the medium will respond to the time averaged intensity, which—being a smooth function of the spatial variables—will induce a smooth waveguide-like structure trapping the beam. In fact, the experiments with incoherent solitons have been conducted using a PR nonlinearity [80]–[81], [126].

The so-called multicomponent solitons or vector solitons are formed when two or more mutually incoherent beams co-propagate in nonlinear medium [82]–[86], [127]–[129]. Then, the vector solitons can be viewed as composite states where one of the components induces an effective waveguide that supports other components as the guided modes of different orders. The physics of the soliton-induced waveguides applied for a two-component (bimodal) system lead to the idea of the so-called multipole spatial vector solitons [87]. One of the simplest type of such vector soliton involves mutual co propagation of the fundamental and the dipole-mode components [88]–[91]. The two lobes of the dipole-mode component have a relative phase difference of π and tend to repel each other. The repulsion of out-of-phase lobes of the dipole beam is overcome by

[1]As commonly used PR crystals are ferroelectrics, the use of the reversed polarity has to be conducted with care so the applied field does not exceed the coercive field as this may cause depoling of the crystal or reversal of its polarization axis

the presence of the fundamental beam which provides a stabilizing factor leading to formation of a new object: dipole mode vector soliton [89]. This soliton is a very robust, albeit complex, object. It may preserve its structural integrity in collisions with other soliton beams, or display more complicated dynamics that involve the internal degrees of freedom such as internal oscillations or rotation [92].

Recently, the generalization of the dipole-mode vector soliton has been proposed by Carmon *et al.*. In this, so-called propeller soliton [93], the dipole component exhibits continuous rotation as soliton propagates. In the subsequent publication, the same group theoretically analyzed various scenarios of the collisions of such solitons, which result in the exchange of angular momentum [94].

It is worth noting that a PR nonlinearity being essentially nonlocal also enables the formation of a stable single component soliton with nontrivial structure. Mamaev *et al.* have shown [95] that two parallel out-of-phase beams located along the direction of the biasing dc field may form a bound state and propagate as a single-component dipole soliton.

VIII. Application of Photorefractive Solitons

The fact that spatial solitons actually form waveguides in the nonlinear medium provides unique a opportunity to use them for all-optical switching. They can form reconfigurable guiding channels which can then guide other optical beams [96]. This so-called light-guiding-light concept to guide, direct and manipulate light by light itself offers potential for application in photonic devices. This concept is based on the ability to implement logic operations by allowing solitons to collide in a nonlinear medium [97], [130]–[132], as well as on the possibility of soliton induced waveguides being used to guide and switch additional beams [98]–[99], [133]. For instance, a simple elastic collision of two solitons creates a waveguide X-junction while fusion of two or more (N) solitons forms a 1-to-N beam splitter. The guiding properties of PR solitons and their use in optical circuitry have been studied quite extensively. A few groups demonstrated the formation of X- and Y-junctions [100]–[102], [134] and waveguide couplers [103]. Some time ago, Lan *et al.* showed that a soliton-induced optical waveguide could be used for an efficient second harmonic generation [104]. The same group recently demonstrated the use of a soliton-induced channel waveguide to create an efficient optical parametric oscillator [105].

Although the PR nonlinearity is very strong, it is also rather slow, with typical response times ranging from milliseconds to fractions of a second[2] [106]. Hence, it cannot be used to create very fast reconfigurable waveguide channels and switches. On the other hand, unlike other nonlinear media where the perturbation of the refractive index perturbation exists only as long as the soliton that induces it, the index perturbation associated with PR solitons can be made permanent. This so-called *soliton fixing effect* relies on a local domain reversal in ferroelectric PR crystals [107]. This is a very useful property, as it allows us to form complex, passive, low-loss waveguide structures, such as multiport splitters or beam combiners, which can be used to control other optical beams even after the soliton beams are turned off. These waveguide structures can be easily created by soliton collisions. Recently, a few fixed fundamental waveguide geometries— including X- and Y-junctions—were realized experimentally [108], [135].

As we mentioned earlier, under typical circumstances the screening solitons cannot form fast optical switches. However, as DelRe *et al.* demonstrated recently, one can actually perform dynamic soliton-based switching in centrosymmetric PR crystals using electroholography [109]. In this particular case, the spatial solitons are used to create the basic waveguide structure which is then employed to guide signal beams of different, nonPR wavelength (typically infrared). Hence, at this wavelength, the soliton-formed waveguide structure remain stable even at a high power level. By varying the external biasing field, the waveguide structure can be modified via the electrooptic effect, leading to fast (limited by the capacitive charging times only and not by PR response) changes of the propagating properties of the signal beams. DelRe *et al.* demonstrated this dynamic switching concept using a paraelectric potassium–lithium–tantalate niobate crystal.

[2]Photorefractive semiconductors, such as CdZnTe [38], offer a faster response time in microseconds. In addition, the response time of the photorefractive process can be substantially shortened using intense laser pulses.

IX. Summary

We presented a brief overview of the recent developments in the field of PR solitons. In a relatively short period, this topic has attracted enormous interest, and the rapid progress that has been achieved in both theory and experiments has led to a much deeper understanding of soliton phenomena. These advances obtained in a specific area of nonlinear optical physics have, however, proven generally applicable to many other fields [110], [136], [137]. Solitons exist in nonlinear systems in many areas of science including such diverse fields as mechanics, optics, gravity, elementary particle physics, and quantum physics. The majority of properties discovered so far for PR solitons appear to be universal for all solitons, irrespective of the particular nonlinear physical system. Therefore, the exceptional accessibility of PR solitons and advances in their study make them a very useful tool to experimentally verify theoretical predictions that improve our general understanding of nonlinear dynamic systems.

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