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Propagation and collision of photorefractive screening solitons

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We investigate experimentally propagation and collision of photorefractive screening solitons. We demonstrate soliton formation, self-bending and phase-sensitive collision which results in energy exchange, soliton fusion and birth of new solitons.

Spatial optical solitons in photorefractive materials have attracted much attention recently because they can be created and manipulated with very low laser power [1], [2]. The most interesting, from the practical point of view, there are so-called screening solitons. In this case, the optical beam propagates in photorefractive crystal biased with external DC electric field. The presence of the optical beam in the crystal leads to photo-excitation of electric charges, their migration and subsequent trapping by the defects. In a steady-state spatial distribution of charges leads to screening of the externally applied electric field which decreases in illuminated area of the crystal. The electric field modifies the index of refraction via the Pockels effect in such a way that the beam becomes self-trapped and propagates in a form of a spatial soliton [3]–[6]. It has been suggested that spatial solitons could be used in all-optical switching [7]. The concept of application of spatial solitons in all-optical switching is based on the fact that soliton form optical waveguides in nonlinear medium which can be used to guide additional signal beam. In fact, this idea has been recently demonstrated experimentally also in the case of photorefractive solitons [8]. Apart from single waveguides also such important optical elements as *X*- and *Y*-junctions can be realized with spatial solitons. These structures involve two or more intersecting waveguides and they can be formed by colliding two or more solitons [9]–[11].

In this work, we study experimentally properties of screening photorefractive solitons in strontium niobate crystal. We demonstrate both characteristic features of individual solitons as well as their interaction (collision). The latter aspect is particularly interesting as material response of the DC biased photorefractive crystal to the propagating light beam can be approximately modelled as saturable nonlinearity [5]. Therefore, soliton collision has inelastic character reflected in emission of radiation as well as strong dependence on relative phase of solitons [12] – [14].

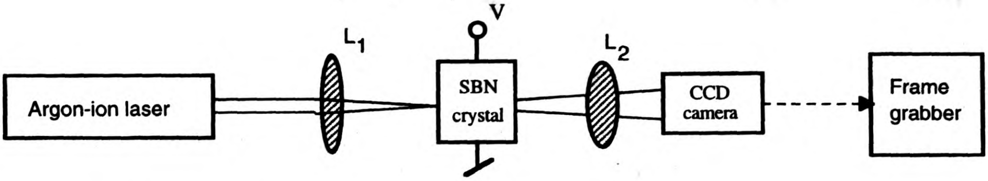

Fig. 1. Experimental setup

The experimental setup used in our studies is shown schematically in Fig. 1. Optical beam derived from an argon-ion laser ($\lambda = 514.5$ nm) was focused into $13-15$ μ spot on the a-face of the SBN:60 photorefractive crystal (5 mm^3 cube). Additionally crystal was illuminated by an incoherent background beam co-propagating with the signal beam in order to control the degree of saturation of nonlinear refractive index change. The exit as well as side faces of the crystal could be imaged with the CCD camera and processed with a frame grabber software. In this way we were able to record both, intensity profile of the out-coming beam and its trajectory inside the crystal. A DC electric field (of 3.5 kV) necessary for soliton formation was applied to the crystal by two silver-painted electrodes on its c-faces.

Initially we propagated only a single beam through the crystal. We found that indeed solitons were formed. For input power of approximately 5 μW and background uniform illumination of $1-5$ mW generated solitons were almost circular with the diameter of approximately 10 microns. Formation of the solitons was also confirmed by side-view observation of the beam trajectory which is shown in Fig. 2. In the first case (Fig. 2**a**), the biasing field is turned off. This corresponds to just linear propagation and results in diffraction of the beam. When the DC field is present diffraction is averted and this leads to self-trapping of the beam (Fig. 2**b**). Since the photorefractive effect is relatively slow (its speed depends on light intensity), the process of soliton formation can be easily observed in real time. We demonstrate it in Fig. 3. The sequence of frames shown there depicts intensity profile of the outgoing beam at the exit face of the crystal in various stages of the soliton formation process. Initially output beam is wide and of low intensity (diffraction only). As the refractive index change builds up beam experiences strong self-focusing until the steady state is reached when the beam propagates as soliton. The whole process displayed in Fig. 3 takes approximately 20 seconds. This graph also clearly shows that the position of the beam changes as it experiences focusing. This is the so-called self-bending effect. The light-induced refractive index change actually consists of two contributions: local and nonlocal. The first one is responsible for soliton formation while the latter, which is roughly proportional to spatial derivative of beam intensity, leads to bending of the beam trajectory. As a result, beam propagates along

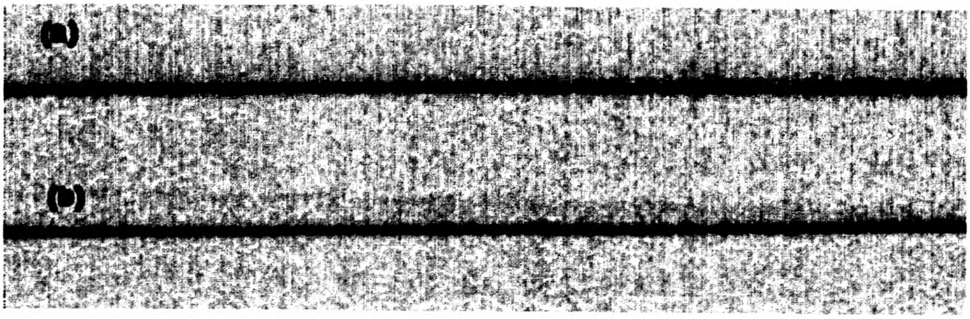

Fig. 2. Trajectory of the focused optical beam in photorefractive crystal: a — linear propagation (diffraction), b — self-trapping

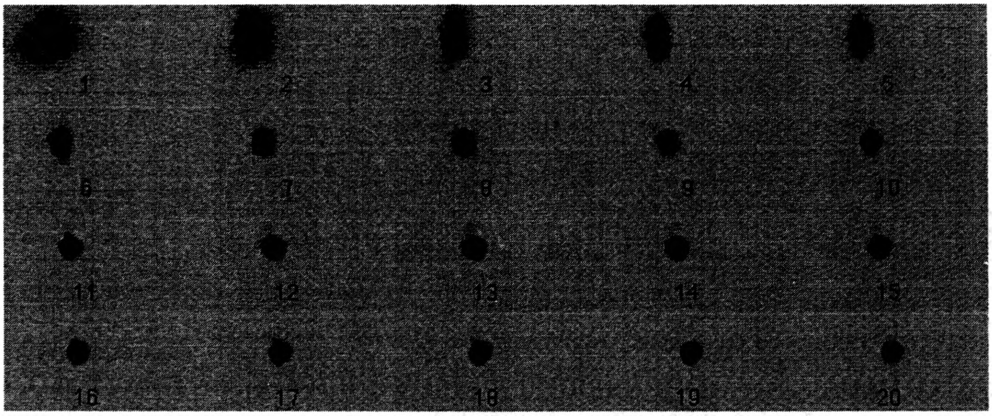

Fig. 3. Intensity profile of the optical beam observed on the exit face of the crystal during subsequent stages of the soliton formation process

parabolic trajectory [15], [16]. In our experiments the self-bending of the solitons as large as 50 μ over 5 mm propagation distance has been easily observed.

In the next step, we modified our experimental system in order to allow two optical beams simultaneously propagate and intersect inside the crystal. This arrangement (which is actually Mach–Zender interferometer) was used to study collision of two solitons. We found that in the most cases two solitons emerged from the collision. However, the interaction of beams after resulted in the energy exchange – after the collision one of the solitons could be stronger than the other. The energy transfer between solitons could be altered by varying a relative phase of the two solitons. We also found that in some cases, when solitons were approximately in-phase they would fuse forming a single beam. This behaviour agrees with results of theoretical studies of interaction of solitons in saturable nonlinear media [12] – [14]. One of the most interesting conclusions of these theoretical works states that collision of two solitons in saturable medium can result in a "birth" of new solitons [14]. Indeed, we observed this effect in our experiments. To this end we increased slightly the initial angle between both beams (approx. 2 degrees). In this case collision of two beams resulted in the appearance of three distinctive solitary beams (see Fig. 4). Due to strong energy transfer, the power (and intensity) carried by respective solitons were significantly different. As the soliton on the far left carries least power it has distinctively elliptic profile (property which is in agreement with theory [17]). The formation of three solitons in the process of soliton collision has been explained in [14] by formation of the pseudo-linear interference fringes and their subsequent evolution in the separate solitons. Varying the relative phase of both incident beams we could form either two or three distinctive fringes which could later evolve into separate solitons. Additionally varying the relative phase effects the position of the interference fringes and subsequently final position of the formed solitons which is nothing else than so-called soliton steering.

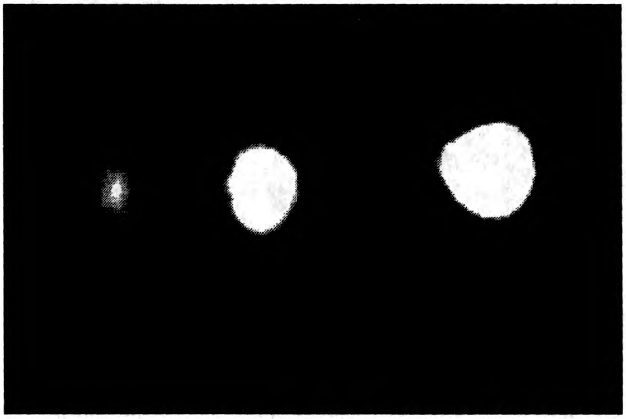

Fig. 4. Collision-induced "birth" of new soliton

The waveguide structures formed by colliding solitons could be used to guide and steer an external signal beam. This property was easily demonstrated in our experiments by blocking one of the intersecting beams (after the soliton structure was formed). As was mentioned earlier, due to the slow time response of the photorefractive crystal the modulation of the refractive index persists for some time after the light is turned off. During that time the remaining beam serves as an external signal beam. Propagating through soliton-induced structure results in redistribution of the beam power among existing waveguide channels and was manifested (in the case depicted in Fig. 4) by the presence of three distinctive bright spots corresponding to three separate waveguides.

In summary, we investigated propagation and collision of the screening solitons in photorefractive strontium niobate crystal. We demonstrated soliton self-bending, phase-controlled soliton fussion and steering, as well as collision-induced formation of new soliton.

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