Experimental observation of spatial soliton interactions

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We report the experimental observation of interaction forces between two fundamental spatial optical solitons in a nonlinear glass waveguide. Both attraction and repulsion were observed, depending on the relative phase between the solitons.

Spatial optical solitons are self-trapped optical beams that propagate without changing their spatial shape because of the competing effects of diffraction and self-focusing in a nonlinear medium.[1] Self-trapped beams are known to be unstable in bulk media and often lead to catastrophic self-focusing. They are stable, however, when diffraction is limited to one spatial dimension, such as in planar optical waveguides. The spatial soliton is described by the nonlinear Schrödinger equation[2] and is completely analogous to the temporal soliton in optical fibers. Bright spatial solitons, which can be obtained in materials with a positive nonlinear refractive index, have recently been reported in multimode CS_2 waveguides[3] and single-mode glass waveguides.[4,5] We note that dark spatial solitons, which are possible in materials with a negative nonlinear refractive index, have been reported recently.[6] However, in this Letter we limit our discussion to bright solitons.

One of the attractive features of solitons is their particlelike behavior. In particular, solitons tend to interact in a way that mimics interactions between massive particles. Such interactions between optical solitons were studied theoretically[7,8] and have been experimentally observed in the temporal domain.[9] Interactions between self-trapped beams were observed in a cell of liquid CS_2.[10] Here we report the experimental observation of interactions between two-dimensional spatial solitons in a single-mode planar waveguide. Spatial solitons are particularly attractive for studies of soliton interactions because the interaction effects are observed in the most straightforward way.

When two fundamental solitons are launched parallel to each other they can attract or repel each other, depending on the relative phase $\delta\phi$ between them.[7,8] The interaction is initially attractive for $|\delta\phi| < \pi/2$ and repulsive for $\pi/2 < |\delta\phi| < 3\pi/2$. The case $\delta\phi = 0$ is special; the two solitons are then bound, and they evolve periodically around each other. In all other cases, the two solitions will eventually separate. The strength of the interaction depends on the initial soliton separation and decreases as the separation is increased. Figure 1 shows numerical simulations of the two limiting cases with relative phases of 0 and π rad.

The interaction between solitons can be understood qualitatively by considering the perturbation that one soliton exerts on the other. Consider a solition that without perturbation propagates along the axis. A second in-phase soliton next to it perturbs the background refractive index so that effectively the first solition rides on an index gradient that increases toward the perturbing soliton. This gradient causes the soliton to bend toward the perturbing neighbor. When the two solitons are out of phase, they interfere to cancel the field at the center point between them. Now each soliton rides on an index gradient that increases away from the other soliton, which causes them to move away from each other.

The experimental setup is shown schematically in Fig. 2. The excitation source in our experiment was a colliding-pulse mode-locked dye laser and copper-vapor-laser-pumped dye amplifier system.[11] The laser system produced 100-fsec pulses with energies of several microjoules at a repetition rate of 8.6 kHz and a wavelength of 620 nm. The laser output was spatially filtered and split into two equal-intensity beams. The intensity of the beams was controlled by using a variable attenuator wheel. The temporal delay of one of

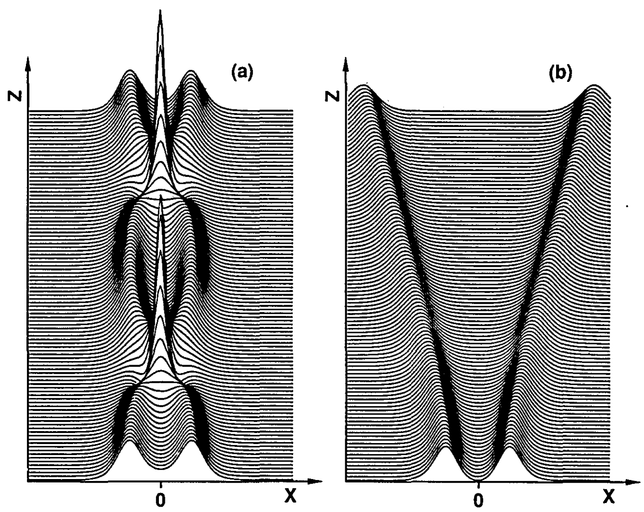

Fig. 1. Simulation of soliton interactions showing the spatial intensity profile in the transverse direction as a function of the propagation distance z. Two fundamental solitons are launched in parallel along the z axis. The relative phase is (a) 0, which results in attraction, and (b) π, which results in repulsion.

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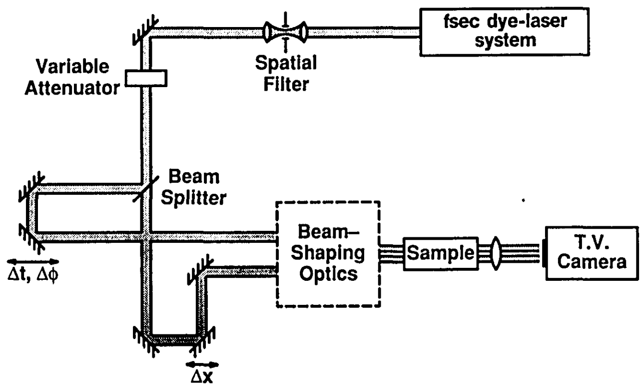

Fig. 2. Experimental setup for launching two parallel spatial solitons.

the beams could be varied by changing the path length. A piezoelectric transducer permitted fine adjustment of the path length and hence the relative phase between the two pulses. The distance between the parallel beams could be adjusted by translating a mirror. The two beams were shaped by an optical system that focused the beams into the planar waveguide but kept them parallel in the waveguide plane. In that plane the input beams were 22 μm wide (FWHM). The optical system consisted of a cylindrical lens, which focused the two incident beams individually to yield a side-by-side pair of highly elliptical beams, and a demagnifying telescope, consisting of a spherical lens and a microscope objective, which relayed the pair of cylindrically focused beams to the entrance face of the waveguide. The 5-mm-long ion-exchange waveguide was the same one used in our earlier experiments.[4] It was formed by potassium–sodium ion exchange in Schott B270 glass. The waveguide layer that was formed was approximately 3–4 μm thick with an index step of $\Delta n = 0.007$. The spatial profile of the light emerging from the output side of the guide was observed by imaging onto a television camera. We note that our experiment measures a spatial profile that is an average over the different spatial profiles that correspond to different intensities within the pulse temporal profile. Related temporal averaging effects have been observed in a number of all-optical switching experiments, including measurements of 100-fsec switching in dual-core fiber nonlinear couplers[12,13] and of picosecond switching in a birefringent fiber rocking filter.[14] In the present study the highest-intensity portions of the pulse, which correspond to best spatial soliton propagation, are weighted most heavily in the average; therefore we still expect to observe the essential features characteristic of soliton interactions.

Figure 3 shows an example of our data. The light distribution at the input to the waveguide is shown in Fig. 3a. The two beams are launched parallel to each other and are spaced by 45 μm (approximately twice the FWHM). The power is adjusted so that each beam by itself forms the narrowest output distribution. Our previous experiments showed that this happens when the peak power is approximately 1.5 times the fundamental soliton power.[4] The peak power was then 360 kW. In Fig. 3b we show the output distribution when the two beams are displaced in time so that they do not interact. The intensity distribution is then generated by the (incoherent) sum of two independent solitons. Note that the separation of the two peaks in the output spatial profile is the same as for the input. The less-complete extinction of the intensity between the two peaks in Fig. 3b compared with that of the input intensity described in Fig. 3a is a result of the temporal averaging inherent in our experiments. When the timing is adjusted so that the two beams coincide in the waveguide, the two solitons interact. The separation between the solitons changes as a function of the relative phase between them. Figures 3c and 3d show the two extreme cases observed. In the case of attractive interaction (Fig. 3d), the two beams partially coalesce. When they repel (Fig. 3c), the distance between them increases by a factor of 1.7, from 45 to 76 μm. The dependence of the output separation as a function of the relative phase of the inputs is a clear indication of soliton interactions.

The interaction between the solitons is expected to decrease in strength as the initial separation between them is increased. We have tested this expectation by repeating our experiments with an initial soliton separation of 55 μm. Our data, shown in Fig. 4, indeed indicate diminished interaction effects compared with the data of Fig. 3. For the attractive case (Fig. 4d) the output solitons are separated by 32 μm, equal to 58% of

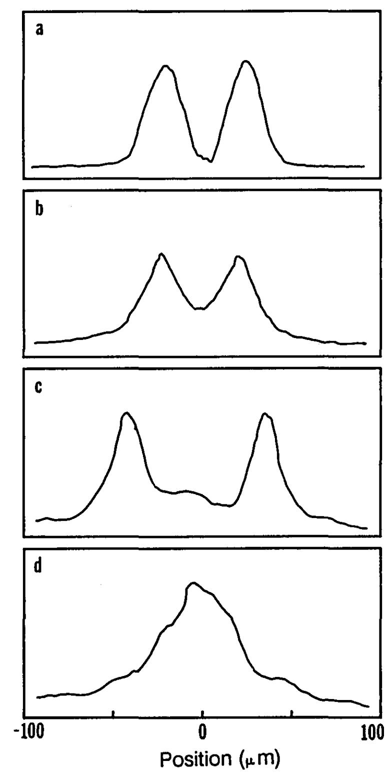

Fig. 3. Soliton interactions for two 22-μm FWHM solitons separated by 45 μm. The vertical scales are the same for plots b–d. a, Light distribution at the input of the waveguide; b, output light distribution when the two beams do not overlap in time; c, interacting solitons with π relative phase; d, interacting solitons with 0 relative phase.

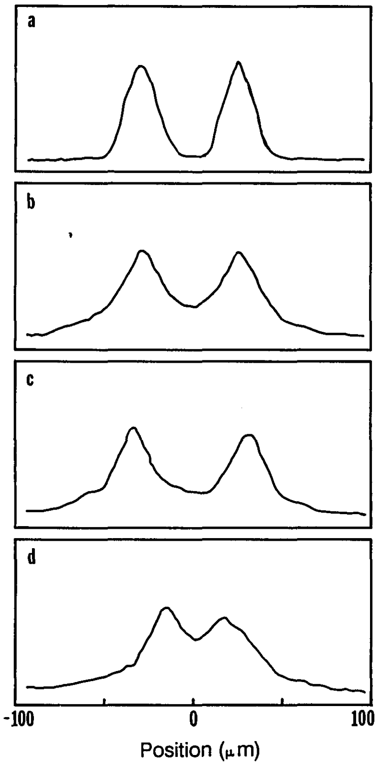

Fig. 4. Same as in Fig. 3 for an initial soliton separation of 55 μm.

the input separation, but the individual solitons are still distinct. In the repulsive case the output solitons are separated by 66 μm, a 20% increase over the input separation. Thus the interaction is clearly reduced compared with that of Fig. 3, where a 70% increase in separation is observed.

From Ref. 8, two identical in-phase solitons with an input amplitude distribution of

$$A(z) = A_0 \operatorname{sech}\left(\frac{x - x_0}{w}\right) + A_0 \operatorname{sech}\left(\frac{x + x_0}{w}\right), \tag{1}$$

where $A_0 = (1/kw)(n_0/n_2)^{1/2}$ for spatial solitons,[1,2,4] oscillate with a period of

$$z_p = \frac{2z_0 \sinh(2x_0/w)\cosh(x_0/w)}{2x_0/w + \sinh(2x_0/w)}. \tag{2}$$

In Eqs. (1) and (2), A_0 and w are, respectively, the amplitude and a measure of the width of the individual fundamental solitons, $2x_0$ is their initial separation, n_2 and k are the nonlinear refractive index and the wave vector, respectively, and $z_0 = \pi^2 n_0 w^2/\lambda$ is the usual soliton period. We note that the soliton period is a factor of π larger than the confocal parameter $b = \pi w^2/\lambda$. For the conditions of our experiment, $w = 22$ μm/1.76 = 12.5 μm, $n_0 = 1.5$, and $\lambda = 0.62$ μm, the oscillation period for two solitons initially separated by $2x_0 = 45$ μm, corresponding to the data in Fig. 3, is calculated from Eq. (2) to be approximately 19 mm, and the two solitons are expected to coalesce in half that distance, i.e., in approximately 9.5 mm. We observe partial coalescence in 5 mm. For an initial separation of $2x_0 = 55$ μm, Eq. (2) predicts a coalescence distance of 15 mm. The data of Fig. 4d show approximately a twofold reduction in soliton separation in the 5-mm sample length. In both cases the observed interactions are somewhat larger than expected from the simple theoretical expressions in Refs. 7–9. We should stress, however, that the simple theory does not take into account a number of important experimental effects, including the averaging over different intensities present with the pulse temporal profile that is inherent to our measurements, the non-sech profile of the input beam, and the temporal reshaping of our 100-fsec pulse owing to a combination of self-phase modulation and dispersion. It is worth noting that there is no theory currently available that treats spatial self-focusing that occurs simultaneously with temporal self-phase-modulation and dispersion. Experimentally we do indeed observe significant spectral broadening of pulses that emerge from the waveguide. With these differences in mind, however, the agreement of the simple theory with experiment is not unreasonable.

In summary, we have demonstrated both attractive and repulsive interactions between spatial optical solitons in a single-mode planar waveguide. The strength of the interaction decreases with increasing soliton separation, as expected.

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