Observation of incoherently coupled photorefractive spatial soliton pairs

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We report what is to our knowledge the first observation of incoherently coupled photorefractive spatial soliton pairs.

There has been a growth of interest in optical spatial solitons since the first observation of self-trapping of light. Recently a new type of soliton, the photorefractive spatial soliton,[1–3] was predicted and successfully observed. Photorefractive solitons differ from traditional Kerr-type solitons. For example, they exhibit stable self-trapping in two transverse dimensions and can exist at microwatt power levels. Thus they are potentially useful in applications such as all-optical beam switching and steering, in optical interconnects, and in implementing nonlinear-optical devices. At present, three generic types of photorefractive soliton have been observed: quasi-steady-state solitons,[1,4] steady-state screening solitons,[2,3,5–8] and photovoltaic solitons.[9] Attention has been paid to soliton-induced waveguides in bulk photorefractive media.[10]

In this Letter we report what is to our knowledge the first observation of incoherently coupled photorefractive soliton pairs. These soliton pairs involve photorefractive screening solitons that exist in the steady state.[2,3] As recently predicted,[11] a coupled pair of screening solitons can be generated, provided that the two beams share the same polarization and wavelength and are mutually incoherent. When two such beams propagate collinearly in a biased photorefractive crystal, they experience a refractive-index modulation that is induced by both beams.[11] The combined intensity distribution creates an effective waveguide that guides both beams in it, forming a coupled soliton pair. A soliton pair can involve two solitons of the same or different forms, i.e., bright–bright, dark–dark, or bright–dark. Soliton pairing was previously proposed for Kerr nonlinear systems, and an observation of a bright–dark spatial soliton pair in a focusing Kerr medium was reported in which the two beams were of different colors.[12]

For photorefractive screening solitons, the theory predicts a unique relation among the soliton width, the trapping voltage, and the intensity ratio (the ratio of the soliton peak irradiance to the sum of the equivalent dark irradiance and a uniform background irradiance).[2,3] This relation has been confirmed experimentally for both bright and dark one-dimensional solitons.[7,8] A large deviation from this condition proves unfavorable for soliton propagation. For instance, an optical beam diffracts if the trapping voltage is not high enough (at a particular intensity ratio), whereas it breaks up into multiple filaments if the applied voltage is too high. This relation is illustrated in Fig. 1 for bright solitons; the soliton width is in normalized units $\Delta\xi = \Delta x k n_b (r_{\text{eff}} V/l)^{1/2}$ as a function of u_0, the square root of the intensity ratio. Here Δx is the FWHM in actual units, $k = 2\pi n_b/\lambda$, λ is the free-space wavelength, n_b is the unperturbed refractive index, r_{eff} is the electro-optic coefficient [r_{33} for strontium barium niobate (SBN:61) in our experimental configuration], V is the applied voltage, and l is the distance between the two electrodes.[2,3] In our case, two mutually incoherent beams of the same size can form a pair, provided that their total intensity ratio and width match the curve of Fig. 1. However, once they are decoupled (i.e., one beam is blocked), each beam alone cannot be sustained as a soliton under the same experimental condition. This happens because the coupled pair corresponds to point A on the existence curve of Fig. 1, whereas each beam alone moves to point B. This entails a large deviation from the curve, and each component by itself no longer behaves as a soliton. Similar results have also been obtained in our numerical simulations.

The experiments are performed with a cw argon-ion laser operating at 488 nm. The laser beam is collimated and split by a polarizing beam splitter. The ordinarily polarized beam is used as uniform background

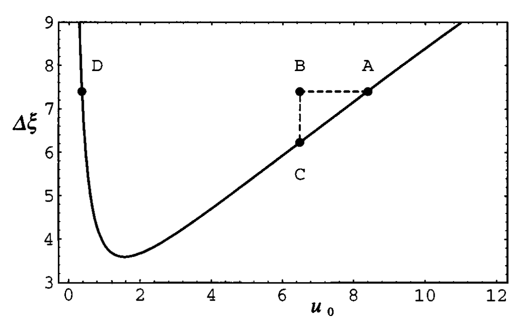

Fig. 1. Theoretical plot of the normalized soliton width $\Delta\xi$ versus the square root of the intensity ratio u_0. Points A, B, and C correspond to the experimental conditions discussed in the text.

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illumination[6–8] covering the entire crystal, and the extraordinarily polarized beam is split into two soliton-forming beams. These two beams are made mutually incoherent at the input face of the crystal by having their optical path difference greatly exceed the coherence length of the laser. Thus no stationary interference gratings can form within a time scale comparable with the response time of the crystal. The two beams are cylindrically focused (narrow in x and almost uniform in y, which define the transverse plane) onto the crystal input face and propagate collinearly (along z, the longitudinal direction) through the crystal. One-dimensional solitons are generated by application of an appropriate (magnitude and polarity) dc field parallel to the crystalline c axis.[8] The input–output beams are monitored by a CCD camera.

The first experiment involves two bright beams of nearly the same input size (FWHM 9 μm, ± 1 μm) and of the same peak intensity of ~ 120 mW/cm^2 [Fig. 2(a)]. Without the external field, each beam diffracts to ~ 52 μm [Fig. 2(b)] after 5-mm propagation. When both beams are on, the peak intensity ratio between the sum of the two bright beams and the uniform background beam is 84 ± 20%. The error is because the beams are not exactly uniform in y: they are cylindrically focused Gaussian beams rather than ideal one-dimensional beams. By application of a positive voltage of $V = 2150$ V between $l = 4.5$ mm, the output beams are trapped to form a steady-state coupled soliton pair. This corresponds to point A on the soliton curve of Fig. 1. In this case, the requirements for the trapping voltage are rather strict. A 5% increase (or decrease) in the applied voltage causes a soliton breakup (or decay into a diffracting beam). Figure 2(c) shows photographs of each beam taken immediately (less than 0.1 s) after its pairing beam has been turned off. We observe that both beams are trapped to their initial input size. Since the two collinear beams have the same frequency and polarization, we distinguish between them in the output by blocking one beam with a mechanical shutter and sampling the other within a time interval (0.1 s) much shorter than the dielectric relaxation time (response time) of the crystal, which is ~ 1 s in our experiments. This permits viewing each soliton beam separately, because the refractive-index modulation created by both soliton beams remains unaffected by the rapid change in the intensity within such a short time interval. Figure 2(c) is obtained by this method. When the two beams are decoupled, i.e., one of the beams stays blocked, the remaining beam can no longer preserve its soliton properties. Instead, it exhibits strong self-bending toward the crystalline c axis and is severely distorted in the transverse plane. Eventually, the beam breaks up. Figure 2(d) shows a photograph of each beam taken after its pairing beam has been blocked for a time (5 min) much longer than the crystal response time. Although each beam is still focused to a certain degree, it is by no means a soliton. Note that the photographs of Fig. 2 and of Fig. 4 below are centered at the same location; thus the shift of the output beams is due to self-bending effects.[6,13] The transition from a coupled pair to the case of one beam alone shifts the operating point from A to B in Fig. 1. This implies that the applied voltage of 2150 V is too high for the remaining beam to form a soliton on its own. However, by readjustment of the applied voltage down to 1200 V (without a change in its intensity), each beam can then be trapped to form a single soliton without the need of the other. This corresponds to point C on the soliton existence curve of Fig. 1. A single beam can also be self-trapped by readjustment of the intensity ratio while the voltage is kept unchanged, which moves the operating point to A or D on the existence curve.

The above experimental observations are then compared with numerical simulations. The two coupled evolution equations[11] are solved by beam-propagation methods. For completeness, beam self-bending effects[13] have been included in our simulations. The parameters used correspond to those of the experiments: the input FWHM of each beam is 9.9 μm, the trapping voltage is 2150 V (over 4.5 mm), and the total intensity ratio is 84, where the two input beams are of equal intensity. The electro-optic coefficient is 280 pm/V. Figure 3(a) depicts each component of such a soliton pair under these conditions. The pair propagates unchanged and smoothly self-bends by 22.9 μm after 5 mm of propagation. When one of the beams is turned off (for the same voltage), each beam does not maintain a constant width while propagating; instead, it experiences considerable oscillation in its width as illustrated in Fig. 3(b). In this case, its self-bending reaches 31.5 μm. These simulations agree well with experimental observations.

When the two bright beams are of different sizes, the coupling behavior becomes even more evident. Figure 4 shows the experimental results from a 12- and a 7-μm beam of nearly the same peak intensity. When both beams are on, the total intensity ratio with respect to the background irradiance is approximately

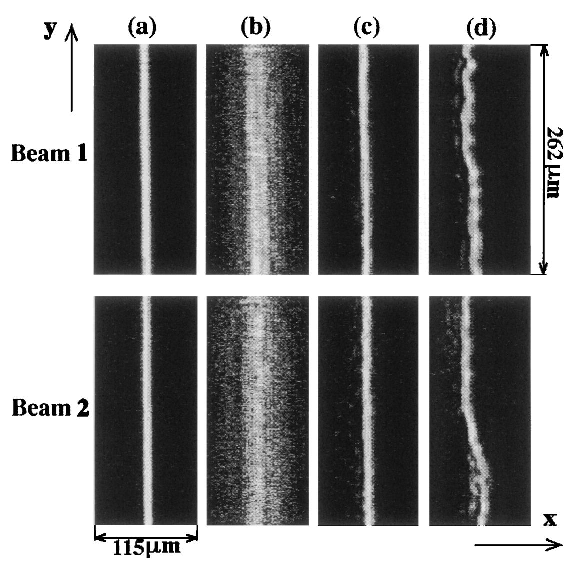

Fig. 2. Experimental results showing coupling of two bright solitons of the same size. Photographs are taken at the (a) input and (b)–(d) the output faces of the crystal: (a) input, (b) normal diffraction, (c) coupled output, (d) decoupled output.

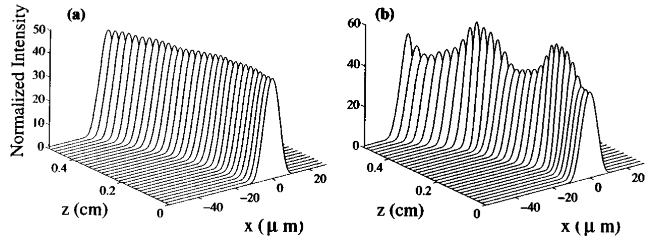

Fig. 3. Numerical simulations corresponding to Fig. 2. (a) One of the beams from a coupled pair, (b) one of the beams when the two beams are decoupled.

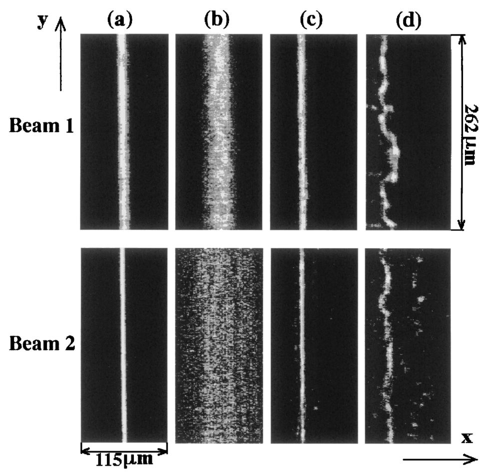

Fig. 4. Coupling of two bright solitons of different sizes (from experiments). (a)–(d) Same as in Fig. 2.

68 (±20%). At $V = 2600$ V, mutual self-trapping is observed. Interestingly, the two beams seem to be trapped at different sizes. Figure 4(c) shows a photograph of each beam taken immediately (less than 0.1 s) after its pairing beam has been turned off, and Fig. 4(d) show the same beams after the pairing beam has been blocked for 5 min and the crystal has reached steady state again. In the case of one beam alone, each beam eventually breaks up and becomes twisted, with much stronger self-bending. Although our experiments indicate that two beams of different sizes can exhibit mutual self-trapping, the numerical simulations for these experimental conditions show that the two beams no longer behave as a soliton pair as for the case of equal beam width. Instead, the FWHM of the coupled pair undergoes cycles of expansions and contractions (±2 μm). At a particular voltage, both beams nearly recover at the output their initial widths, which is what we observe in experiments. However, at this point we cannot say whether the expansion–contraction cycles exist in the experiments, since the calculated variation in the beam width is rather small.

Several issues merit discussion. First, the coupled soliton pair is observed in steady state and is stable. As has been noted, the soliton pair exhibits the properties of steady-state photorefractive screening solitons, which are stable against small perturbations, especially in the region of high intensity ratios.[8] When the intensity ratio is reduced to <3, we cannot observe any stable soliton pairs. This is in agreement with recent experimental observations[8] and theoretical predictions[2,3] of photorefractive one-dimensional bright solitons, since in this intensity range the solitons behave as Kerr solitons, which are unstable in bulk media. Second, when one of the pairing beam is turned off, the other beam suffers more from self-bending. We can see that the beam bending is stronger in Fig. 4(d) than in Fig. 2(d). This is because the self-bending that is due to the diffusion field is enhanced by the applied field, which is larger in the experiment of Fig. 4. Third, although there is good agreement between experiments and numerical simulations, the experimental situation is much more complicated than the (1 + 1)-dimensional modeling. For instance, the breakup of the decoupled beams shown in Figs. 2(d) and 4(d) is accompanied by transverse modulation instability, which is not included in the present model.

In conclusion, we have shown that two mutually incoherent beams of the same polarization and wavelength can form a coupled steady-state spatial soliton pair in a biased photorefractive medium under steady-state conditions. Current experiments are aimed toward observation of dark–dark and bright–dark coupled photorefractive soliton pairs.

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References

1. M. Segev, B. Crosignani, A. Yariv, and B. Fischer, Phys. Rev. Lett. **68,** 923 (1992).
2. M. Segev, G. C. Valley, B. Crosignani, P. DiPorto, and A. Yariv, Phys. Rev. Lett. **73,** 3211 (1994); J. Opt. Soc. Am. B **13,** 709 (1996).
3. D. N. Christodoulides and M. I. Carvalho, J. Opt. Soc. Am. B **12,** 1628 (1995).
4. G. Duree, J. L. Shultz, G. Salamo, M. Segev, A. Yariv, B. Crosignani, P. DiPorto, E. Sharp, and R. Neurgaonkar, Phys. Rev. Lett. **71,** 533 (1993); **74,** 1978 (1995).
5. Steady-state self-focusing in photorefractive media was first observed by M. D. Iturbe-Castillo, P. A. Marquez-Aguilar, J. J. Sanchez-Mondragon, S. Stepanov, and V. Vysloukh, Appl. Phys. Lett. **64,** 408 (1994).
6. M. Shih, M. Segev, G. C. Valley, G. Salamo, B. Crosignani, and P. DiPorto, Electron. Lett. **31,** 826 (1995); Opt. Lett. **21,** 324 (1996).
7. Z. Chen, M. Mitchell, M. Shih, M. Segev, M. Garrett, and G. C. Valley, Opt. Lett. **21,** 629 (1996); **21,** 716 (1996).
8. K. Kos, H. Ming, G. Salamo, M. Shih, M. Segev, and G. C. Valley, Phys. Rev. E **153,** R4330 (1996).
9. M. Taya, M. Bashaw, M. M. Fejer, M. Segev, and G. C. Valley, Phys. Rev. A **52,** 3095 (1995).
10. M. Shin, M. Segev, and G. Salamo, Opt. Lett. **21,** 931 (1996).
11. D. N. Christodoulides, S. R. Singh, M. I. Carvalho, and M. Segev, Appl. Phys. Lett. **68,** 1763 (1996).
12. M. Shalaby and A. J. Barthelemy, IEEE J. Quantum Electron. **28,** 2736 (1992).
13. M. I. Carvalho, S. R. Singh, and D. N. Christodoulides, Opt. Commun. **120,** 311 (1995).