Incoherently coupled dark–bright photorefractive solitons

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We report the observation of incoherently coupled dark–bright spatial soliton pairs in a biased bulk photorefractive crystal. When such a pair is decoupled, the dark component evolves into a triplet structure, whereas the bright one decays into a self-defocusing beam. © 1996 Optical Society of America

There has been a steady increase of interest in spatial solitons over the past three decades. Optical spatial solitons provide a means of controlling light by light[1] and are thus potentially useful in developing all-optical switching devices. Research in this field has included soliton formation, soliton-induced waveguides, soliton interactions, and coupled soliton pairs. Thus far, soliton pairs have been studied in nonlinear Kerr media, including coupled dark–bright pairs.[2] A coupled dark–bright spatial soliton pair was observed by use of two beams of different wavelengths.[3] In the past, generating a coupled pair of the same wavelength posed a challenge, especially when the two soliton beams are sharing the same polarization. Also, because both dark and bright solitons induce a waveguide that can guide another beam within it, it is hard to distinguish a coupled dark–bright soliton pair from a bright beam that is guided by the waveguide induced by the dark soliton without affecting the dark component. This subtlety arises because for a coupled soliton pair the refractive-index modulation is created by both beams, and each beam alone cannot form a soliton under the same conditions, whereas for a beam guided by a soliton-induced waveguide, the index modulation is set by only the soliton, which is unchanged if the guided beam is removed.

Recently, a new class of solitons, photorefractive spatial solitons,[4] was discovered. These solitons exhibit stable self-trapping in both transverse dimensions and can be observed even at microwatt power levels.[5] Photorefractive solitons were observed in biased photorefractive crystals in both quasi-steady-state[5] and steady-state[6] as well as in photovoltaic media.[7] Steady-state (screening) solitons[6,8–10] form when a beam passes through a properly biased photorefractive crystal. The refractive-index change can have a self-focusing (or self-defocusing) effect on the optical beam. Bright or dark screening solitons can be generated, depending on the polarity of the applied field with respect to the crystalline axes.[6,11–13] For one-dimensional screening solitons, the theory predicts a unique relationship (a soliton existence curve) among the soliton width, applied field, and intensity ratio, i.e., the ratio of the peak soliton intensity to the sum of the dark irradiance and a uniform background.[8–10] This relationship is different for bright and dark solitons and has been experimentally verified.[12,13] A large deviation of the experimental parameters from the soliton existence curve proves unfavorable for soliton propagation. For instance, an optical beam diffracts if the applied voltage is not high enough (at a particular intensity ratio), whereas it breaks up into multiple filaments if the voltage is too high.[12,13] Recent studies have investigated photorefractive vector solitons[14] and incoherently coupled photorefractive soliton pairs.[15,16]

Here we report what is to our knowledge the first observation of an incoherently coupled dark–bright photorefractive spatial soliton pair. As recently predicted,[15] an incoherently coupled soliton pair can propagate in a biased photorefractive crystal if the pairing beams experience roughly the same refractive index and electro-optic coefficient. The pair involves two steady-state screening solitons[8–10] propagating collinearly and experiencing a refractive-index modulation induced by both beams. The coupled soliton pair can have dark–bright as well as bright–bright and dark–dark realizations. A stable dark–bright photorefractive pair can be realized only with a self-defocusing nonlinearity and when the peak intensity of dark component is higher than that of the bright.[15] Earlier,[16] we demonstrated coupling and decoupling between two bright screening solitons.

An incoherently coupled dark–bright photorefractive soliton pair can be intuitively understood from Fig. 1, which shows a superposition of the intensities of a dark-notch-bearing beam, a bright beam, and a uniform background illumination beam. I_d, I_b, and I_{bg} are the peak intensities of the dark, bright, and background beams, respectively. We account for a possible grayness of the dark beam by permitting a nonzero intensity I_{d0} at the center of the dark notch (here the soliton is almost black; $I_{d0} \ll I_d$). Because these three beams are all mutually incoherent (i.e., their interference pattern varies

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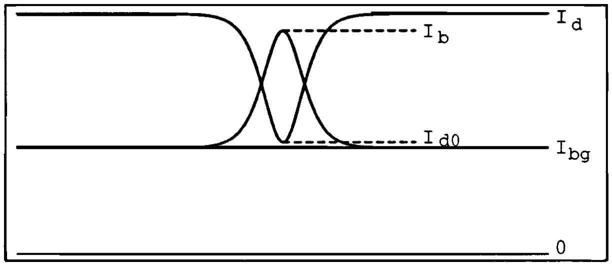

Fig. 1. Superposition of the intensities of a dark-notch-bearing beam I_d, a bright beam I_b, and a uniform-background beam I_{bg}. I_d, I_b, and I_{d0} are measured from I_{bg}.

much faster than the response time of the crystal), the nonlinear response of the medium is determined by the intensity superposition only. In a particular choice of $I_d > I_b$, the total intensity pattern is of a dark notch that is rather broad (much wider than each of its bright and dark components) and has an effective ratio between the peak intensity and the intensity at the center of the notch of $u_{\infty\text{eff}}^2 = (I_d - I_b - I_{d0})/(I_{\text{bg}} + I_b + I_{d0})$. This dark notch can be self-trapped at an appropriate applied field, as with ordinary dark (or gray) photorefractive screening solitons.[9,10] When the bright component is blocked ($I_b = 0$), $u_{\infty\text{eff}}$ increases to $\approx (I_d/I_{\text{bg}})^{1/2}$ because $I_{d0} \ll I_d$, whereas I_b is close to I_d. For dark (or gray) solitons, however, larger u_∞ means that a lower field is required because the nonlinearity is too high to support a fundamental dark soliton of the same width.[10] If the applied field is not adjusted accordingly, the dark notch evolves into a higher-order dark soliton when the input notch is broad enough or breaks up owing to transverse instabilities if the input notch is too narrow.[12]

The experimental setup is similar to that of Ref. 12. A cw argon-ion laser beam (488 nm) is collimated and split by a polarizing beam splitter. The ordinarily polarized beam is used as uniform background illumination to mimic the dark irradiance,[6,10] and the extraordinarily polarized beam is split into two soliton-forming beams. One of these two beams illuminates a $\lambda/4$ step mirror, which generates on reflection a narrow dark notch.[12] The dark notch is then imaged onto the input face of a SBN:61 crystal with the dark-notch-bearing beam covering the entire input face. The other beam (the bright component) is cylindrically focused to nearly the same width at the input as the dark notch (narrow in x and nearly uniform in y, $x-y$ being the transverse plane). We make the dark and bright input beams mutually incoherent by having their optical path difference greatly exceed the coherence length of the laser. A coupled dark–bright soliton pair forms when an appropriate (in magnitude and polarity) dc field is applied in the x direction ($\|c$ axis). The beams at the input–output faces of the crystal are monitored by a CCD camera.

First, we generate a coupled dark–bright soliton pair (Fig. 2). The peak intensity of the dark beam (I_d) is made slightly larger than the sum of the peak intensity of the bright beam (I_b) and I_{d0}, resulting in a small dip ($\sim$36 μm FWHM) in the combined intensity ($I_d/I_{\text{bg}} = 1.197$, $I_b/I_{\text{bg}} = 1.088$, and $I_{d0}/I_{\text{bg}} = 0.026$; thus $u_{\infty\text{eff}} \approx 0.198$). The width of the dark notch is 14 μm, and that of the bright beam is 11 μm [Fig. 2(a)]. Without the external field, each beam diffracts after 5 mm of propagation in the crystal [Fig. 2(b)]. By applying a voltage of -400 V between the two electrodes, which are 4.5 mm apart, we observe that the output beams are coupled into a steady-state fundamental dark–bright soliton pair. We monitor the bright and the dark components of the soliton pair separately by blocking one and sampling the other within a time interval of 0.1 s, so that the index modulation induced by the coupled pair cannot respond in such a short time to the change because of the blocking of one beam.[16] The dielectric relaxation time of the crystal is 3 s in our experiments. Figure 2(c) shows photographs of the output dark and bright components taken immediately (<0.1 s) after the pairing beam is blocked. In this way we distinguish between the components even though they have the same frequency and polarization.

Next, we show that each of the two beams cannot maintain the form of a fundamental soliton when they are decoupled, i.e., when one of the beams is blocked and a new steady state is reached. Figures 3(a) and 3(b) show photographs of the dark and the bright beams, respectively, taken after the pairing beam is blocked for a much longer time (1 min) than the crystal response time. Because the polarity of the applied voltage is not appropriate for the bright soliton,[10] the bright beam alone diffracts and experiences self-defocusing [Fig. 3(b)]. In the case of a dark beam alone, the applied voltage is too high to maintain the fundamental dark soliton: when the bright beam is blocked $u_{\infty\text{eff}}$ increases to 1.068, for which the nonlinearity is too high. Instead, the dark beam evolves into a triple-soliton structure [Fig. 3(a)] when the bright beam is absent and all other conditions are unchanged. Interestingly, as we unblock the bright beam, we observe guidance of the bright beam into

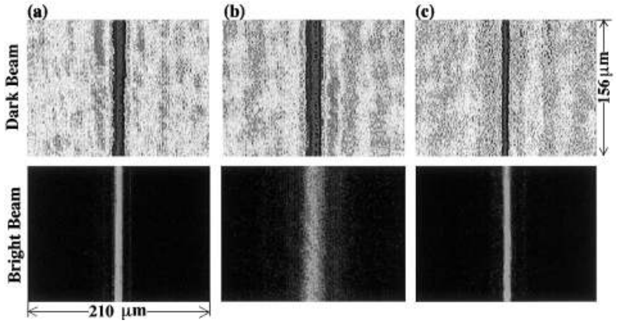

Fig. 2. Photographs showing a coupled fundamental dark–bright soliton pair: (a) input, (b) output (normal diffraction), and (c) output coupled soliton pair.

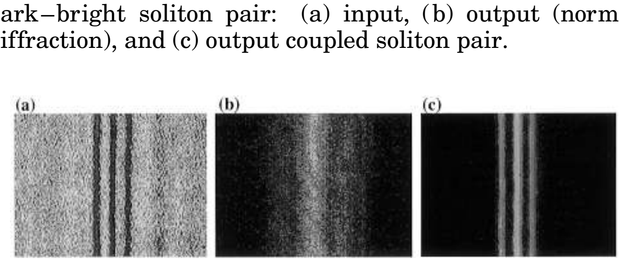

Fig. 3. Photographs showing (a) the output dark and (b) the bright beams when the pair is decoupled. (c) Bright beam guided in the triple-soliton induced waveguide.

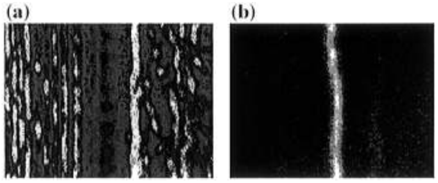

Fig. 4. Photographs showing the unstable output (a) dark and (b) bright components.

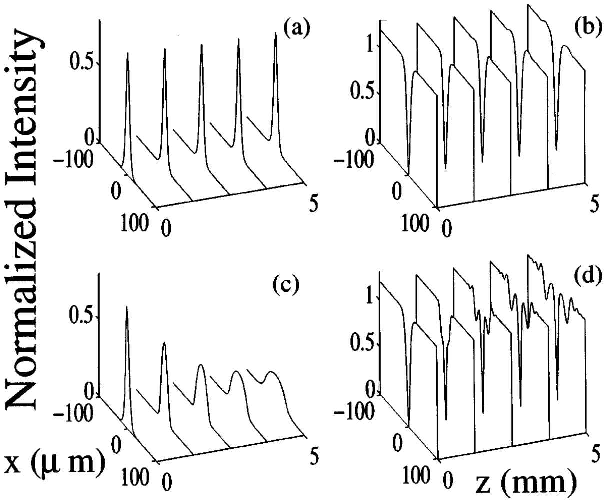

Fig. 5. Numerical results showing the propagation of (a) the bright and (b) the dark components of a coupled soliton pair. (c), (d) Corresponding propagation when the pairing component is absent.

the triple-channel waveguide induced by the high-order dark soliton [Fig. 3(c)]. This waveguide persists for a few seconds before the bright beam is defocused by the bias field. Eventually, a fundamental dark soliton is retrieved without the bright beam when the voltage is readjusted to −250 V.

Finally, we set the peak intensity of the bright beam higher than that of the dark beam, obtaining a small peak in the total intensity ($I_d/I_b = 0.82$). At a negative bias, the beams cannot form a coupled soliton pair because the combined intensity induces an antiguide.[10,15] We then reverse the polarity of the applied field so that it favors trapping of bright solitons (analogous to coupling dark and bright solitons in a self-focusing medium[3]). However, with positive voltage the two beams become unstable and cannot form a soliton pair: Their intensity pattern is distorted by strong transverse modulation instability.[13] Figure 4 shows the dark and the bright components taken in the same way as for Fig. 2(c).

We compare the experimental observations with numerical simulations. The two coupled evolution equations[15] are solved by use of beam-propagation methods. The parameters used are close to those of the experiment: a 5-mm-long SBN crystal, $r_{33} = 280$ pm/V, $\lambda = 488$ nm, and $V = -400$ V (over 4.5 mm). The input intensity FWHM of both the bright beam and the dark notch is 14 μm. For these parameters, we find a bright–dark pair at $I_d/I_{\mathrm{bg}} = 1.2$ and $I_b/I_{\mathrm{bg}} = 0.8$. Figures 5(a) and 5(b) depict the intensity profiles of the bright–dark components when they propagate in the crystal as a coupled pair. When the pairing beam is absent, the bright beam self-defocuses [Fig. 5(c)], while the dark component evolves into a dark triplet [Fig. 5(d)]. The small difference between the I_b/I_{bg} values used in the experiment is attributed to the small residual grayness in the dark beam of the experiment on reflection from the step mirror. This implies that the phase of the dark component does not undergo an ideal π phase jump. Overall, the experimental and theoretical results are in good agreement.

In conclusion, we have demonstrated a steady-state coupled dark–bright spatial soliton pair in a biased photorefractive crystal.

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