Observation of Two-Dimensional Bright Photovoltaic Spatial Solitons

W. L. She
State Key Laboratory of Ultrafast Laser Spectroscopy, Zhongshan University, Guangzhou, China

K. K. Lee and W. K. Lee
Department of Physics and Materials Science & Technology Research Center, The Chinese University of Hong Kong, Shatin, Hong Kong, China

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We have observed two-dimensional bright photovoltaic photorefractive spatial soliton for the first time in a Cu:KNSBN $K_{0.25}Na_{0.75}Sr_{1.5}Ba_{0.5}Nb_5O_{15}$ crystal. Characteristics of the observed spatial soliton are explained by an equivalent electric field induced by the background irradiance.

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In recent years, photorefractive spatial soliton (SS) has attracted much attention. So far, three types of SS's have been predicted and observed, namely, quasi-steady-state SS [1–8], screening SS [9–12], and photovoltaic (PV) SS [13–16]. Quasi-steady-state SS can form within a time window after the formation of photorefractive grating and before significant screening of the applied electric field. Screening SS is a steady-state phenomenon which is a result of nonuniform screening of the applied electric field by photoexcited charge carriers. Formation of quasi-steady-state and screening SS's require, respectively, positive and negative perturbations of the refractive index. PV SS is also a steady-state phenomenon which is a result of refractive index perturbation due to PV current and requires a material of large PV effect. The observed quasi-steady-state SS's are two-dimensional, while screening SS's can be one or two dimensional [12,17]. It has been predicted that one-dimensional, bright and dark, PV SS's can exist [16]. Whether this type of SS is one- or two-dimensional is still not clear. However, to the best of our knowledge, only one-dimensional dark PV SS has been observed [14]. It has also been predicted that a screening PV SS may exist but has not been observed [18].

Bright PV SS can form if perturbation Δn of the crystal refractive index, due to PV current (or PV space-charge field), is positive. Unfortunately, single crystals of $LiNbO_3$ in which a number of SS investigations have been carried out have a large PV coefficient but the perturbation is negative [14]. Recently we found a PV space-charge field of 28 kV/cm in Cu:KNSBN using 400 mW 488 nm radiation of 2.5 mm beam diameter. Its $r_{33} = 200 \times 10^{-12}$ m/V is $\sim$6.3 times that of $LiNbO_3$. We also found, by using interferometry, that the perturbation of the refractive index in Cu:KNSBN was *positive*. These results led us to discover bright PV SS in this crystal.

Theories have predicted that the optimal condition for the formation of a PV SS is that the intensity of dark irradiance I_d is roughly the same as that of the signal beam I_s [16]. In practice, $I_d \ll I_s$. Experimental studies therefore make use of a background laser light (o ray) of intensity I_b to enhance the dark irradiance so that its intensity is of the same order as I_s [14]. In the previous theoretical studies of PV SS's, the dark or background irradiance was treated as a constant [16]. Let K_p^e be the PV coefficient of the signal beam (e ray), γ_R the charge carrier recombination rate, N_A the density of the acceptor, e the electron charge, and μ the mobility of the charge carrier. For $I_b \gg I_d$, and the crystalline c axis along the x direction, the open circuit space-charge field due to PV effect alone is given by

$$E_{\mathrm{sc}}(x) = -\frac{I_s(x)/I_b}{1 + I_s(x)/I_b} E_p , \qquad (1)$$

where $E_p = K_p^e \gamma_R N_A / e\mu$. In our experiment, the signal beam was normally an e ray while the background light was an o ray. If the diameters of the signal and background beams are comparable, the space-charge fields induced by the beams are of the same order. We found that $K_p^o/K_p^e \approx 0.4$, where K_p^o is the PV coefficient of the o ray. When the diameter of the background beam is much larger than that of the signal beam, I_b can be treated as uniform and thus induces a uniform space-charge field E_o (equivalent field). Let N_D, N_D^+, n, ε_o, and ε_r be the donor concentration, ionized donor concentration, charge carrier concentration, permittivity of free space, and relative permittivity of the crystal, respectively. When the crystal is open circuit, the modified space-charge field can be found by using the Kukhtarev equation [19],

$$E_{\mathrm{sc}}(x) = \frac{1}{1 + I_s(x)/I_b} E_o - \frac{I_s(x)/I_b}{1 + I_s(x)/I_b} E_p , \qquad (2)$$

where $E_o = -(K_p^o/K_p^e)E_p$ and approximations N_D, N_D^+, $N_A \gg n$, and $|(\varepsilon_o \varepsilon_r / e N_A)\partial E_{\mathrm{sc}}/\partial x| \ll 1$ have been used. For $K_p^o/K_p^e > 0$, theory has shown that E_o increases the width of a PV SS [18]. In this Letter, we report on the observation of *bright* PV SS, observed for the first time to our knowledge. The PV SS observed by us is also different from the observed dark PV SS [14] in that it is two dimensional. We also discuss effects of E_o on a PV SS.

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The experiment was carried out by using a Coherent Innova 300 argon ion laser in all line multimode operation. A prism was used to select a certain wavelength. Unless otherwise stated, the wavelength used was 488 nm. The laser beam was split by a beam splitter to one strong beam and one weak beam. The weak (signal) beam was allowed to pass through a polarization rotator, a Glan-Thompson prism, and a convex lens of 10.4 cm focal length. It entered a single domain Cu:KNSBN crystal of dimensions $6 \times 6 \times 6$ mm^3 through a crystalline *a* face. The crystal was supported by a polished fused silica plate such that its *c* axis was in a horizontal plane. The strong (background) beam passed through a polarization rotator, a Glan-Thompson prism, and a telescope such that it was a collimated beam of diameter ~2.5 mm. The background beam was made to propagate in the same direction as that of the signal beam using a beam splitter. The signal beam was an *e* ray while the background beam was an *o* ray. The signal beam waist was at a distance 5.5 mm from the input face on which the spot size of the beam was ~ 32 μm (FWHM). The laser output was fixed, while I_s and I_b were varied by using the polarization rotators. The beam profile of the SS was obtained by using an imaging system similar to that described in Ref. [3]. The background beam was blocked from entering the CCD camera by a polarizer in front of the camera lens.

The signal beam entered the crystal at an incident angle of 5° [20]. With I_b set at 8 W/cm^2, a stable SS along both transverse directions was observed for I_s between 3 and 62 W/cm^2. For I_s below 3 W/cm^2, it was not possible to study the SS because the polarization rotator did not give pure enough *e* ray. For $I_s > 100$ W/cm^2, self-focusing was observed, but SS did not form. The formation time varied from 0.3 to 0.05 s when I_s was varied from 3 to 62 W/cm^2. These values are much shorter than those (~ minutes) in $LiNbO_3$ crystals [14]. The formation time is roughly equal to the rise time of the short circuit PV current in Cu:KNSBN measured by us, which suggests that the observed SS is of the PV type. Figure 1 shows some of the experimental results. We see from the curves of the first column of the figure that there is significant self-focusing of the signal beam even without the background beam [21]. The horizontal width was ~ 50 μm, which is ~ 10 μm narrower than a signal beam propagating in free space due to the dark irradiance in the crystal. The vertical beam profile is similar to its horizontal counterpart. As the laser was multimode, the SS beam profile was expected and was found to be multihump because the profile of refractive index perturbation depends on the light intensity distribution [13,16]. Also note that when the diffusion field is neglected and the charge carrier density is small, the PV field is given by the right-hand side of Eq. (1) and is the *total* space-charge field E if the crystal is open circuit. E is, in general, two-dimensional. Since the signal beam profile was circularly symmetric, so was E. Let n_b be the background refractive index and r be the effective electro-optic coefficient. According to Eq. (5) of Ref. [13], $\Delta n = -n_b^3 r E/2$ is expected to be circularly symmetric also, and so is the SS, which is consistent with our observation [22].

When I_s/I_b was varied between 1 and 8, a SS of essentially constant width was observed. When the signal beam was focused by a lens of 5.6 cm focal length and the input face was ~2 mm behind the beam waists (the spot size at the input face was 23 μm), SS did not form while self-focusing was clearly observed, which meant that the crystal could not support relatively narrow bright SS's. We believe that the reason is as follows. According to Ref. [16], if the macroscopic field due to I_b [the first term of Eq. (2)] is not taken into account, the minimum dimension of a SS is determined by I_s/I_b. This macroscopic field counteracts the PV field [second term of Eq. (2)], and reduces the total space-charge field and thus Δn—meaning that the minimum SS dimension would be larger than that when I_b can be ignored. The Debye length determines the diameter of a screening SS. Whether it also affects the dimension of a PV SS is not known and warrants careful theoretical analysis.

The following evidences show that we observed a PV *photorefractive* SS. When we used an *o* ray as the signal beam, only weak self-focusing occurred within the same range of I_s/I_b. (In Cu:KNSBN, the effective electro-optic coefficient of an *o* ray is $r_{13} = 30 \times 10^{-12}$ m/V, which is roughly 7 times smaller than that of an *e* ray, so that Δn induced by an *o* ray is much less than that of an *e* ray.) When the 514.5 nm radiation (*e* ray) was used as a signal beam (within the same range of I_s/I_b and same beam diameter), only self-focusing was observed which is consistent with the fact that the PV voltage induced by the 514.5 nm wave is approximately one-half of that induced by the 488 nm radiation of the same power and beam diameter.

If we neglect effects of the equivalent field E_o and take $E_{sc} = 28$ kV/cm as mentioned above and use $n_e = 2.27$, $r_{33} = 200 \times 10^{-12}$ m/V [23], the refractive index perturbation $\Delta n = n_e^3 r_{33} E_{sc}$ is then ~0.003 which is much larger than the value (5×10^{-4}) required for the formation of a 10 μm SS in $LiNbO_3$ [16]. The fact that the SS observed by us was much broader than 10 μm can be attributed to the negative effect of the macroscopic field due to I_b as discussed above. Further studies are required to clarify the mechanism involved.

The next step of the experiment was to decrease both I_s and I_b while keeping I_s/I_b fixed at ~1.63. We found that the degree of self-focusing of the signal beam decreased as I_s decreased. When $I_s = 6.5$ W/cm^2, the degree of self-focusing was roughly the same as that when $I_b = 0$. Figure 2 shows the horizontal beam profiles of the signal beam at the output face (the vertical beam profiles are similar). We do not know the reason for this behavior and believe that it is due to diffusion because the diffusion

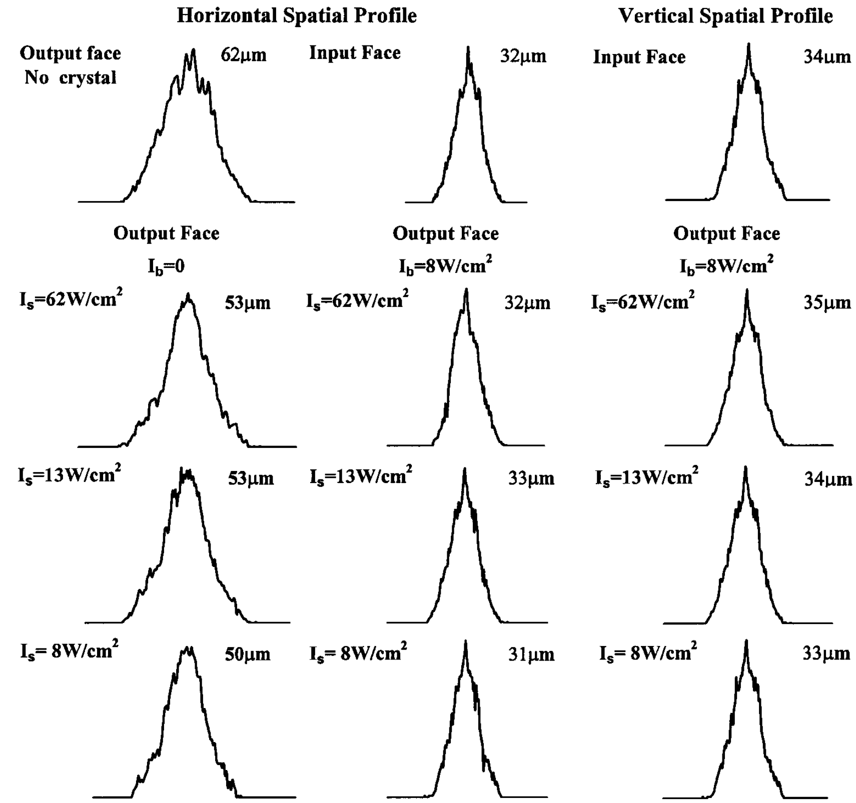

FIG. 1. Beam profiles. The upper curve of the first column is the beam profile at the *position* of the output face after the crystal is *removed*.

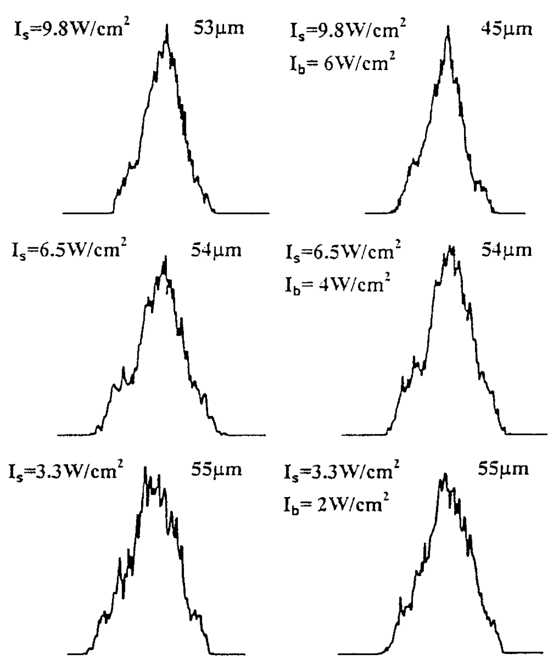

FIG. 2. Horizontal beam profiles at the output face. First column: $I_b = 0$.

space-charge field depends on spatial distributions of light intensity and the temperature and is independent of the total light intensity. On the other hand, E_{sc} does depend on the total light intensity. When the total light intensity is large, the diffusion space-charge field may not be significant. On the other hand, when the total light intensity is small, the diffusion space-charge field could be dominant and thus could result in couplings between constituent components of the plane wave and therefore not favorable for self-focusing, which is consistent with our observation [24].

In conclusion, we have observed two-dimensional bright PV photorefractive spatial soliton for the first time (to our knowledge) in a Cu:KNSBN crystal. The observed SS was broader than that predicted by using E_{sc} of the signal beam alone, which can be explained by an equivalent field induced by the background irradiance.

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