All Optical Quasi-Steady-State Photorefractive Spatial Solitons

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(Received 6 January 2000)

We have created a one- (rather than two-) dimensional quasi-steady-state photorefractive spatial soliton induced by a laser beam instead of an applied electric field. The formation of this type of spatial soliton depends on the intensity of the self-trapped beam, which is different from quasi-steady-state spatial solitons reported in the literature. The optically induced spatial soliton can be exploited in all optical switching applications.

PACS numbers: 42.65.Tg, 42.65.Hw

The possibility of the formation of optical spatial solitons was predicted more than 30 years ago [1]. In the last decade, optical spatial solitons have been actively investigated because of their potential applications in all optical switching [2,3]. The fact that the formation of a photorefractive spatial soliton (SS) requires an optical power of μW to mW levels makes it very attractive in low optical power switching applications [4]. We will call the light beam that forms a SS the signal beam (intensity I_s). Three types of known SS's are photovoltaic [4–8], screening [9–12], and quasi-steady-state SS's [13–20]. Some of these SS's can be formed by coherent light [6,12,15], while others by incoherent [10], or partially incoherent [21], or white light [22]. The formation of a screening SS requires an applied electric field [12,22]. A photovoltaic (PV) SS can be formed in a crystal with a strong PV effect without an applied electric field [6]. To facilitate the formation of a screening or a PV SS, a background beam propagating along the same direction and having spatial overlap with I_s is usually introduced. These two types of SS's can be 2D [4,5,9,11]. A quasi-steady-state SS (QSS) [13,15,19], the formation of which also requires an applied electric field, exists within a time interval after the formation of photorefractive grating and before significant screening of the applied field. The refractive index perturbation (Δn) experienced by a bright QSS is positive, i.e., opposite to that experienced by a bright screening SS. Consider I_s propagating along the z direction. Let $\mathbf{q}_1$ and $\mathbf{q}_2$ be the components of the wave vectors of two constituent plane waves such that $\mathbf{q}_1 \cdot \mathbf{z} = 0$ and $\mathbf{q}_2 \cdot \mathbf{z} = 0$. According to the existing theories [13,14], Δn depends explicitly on $\mathbf{q}_1 - \mathbf{q}_2$. Since the crystal is anisotropic, so are $\mathbf{q}_1 - \mathbf{q}_2$ and Δn. Effects of the Δn's along the x and y directions, in general, do not exactly compensate the diffraction effects simultaneously. Therefore QSS's are 1D (formed in this work). It is interesting that all QSS's reported are 2D [15,17]. In this Letter, we report on a new type of photorefractive SS the formation of which is induced by another laser beam (intensity I_i) which does not have spatial overlap with I_s. It can be formed in copper doped $K_{0.25}Na_{0.75}Sr_{1.5}Ba_{0.5}Nb_{0.5}O_{15}$ (Cu:KNSBN) [8] whose PV effect is strong.

The experimental setup is shown in the inset in Fig. 1. I_i (o ray, vertically polarized) used was mostly the 488 nm radiation from an argon ion laser in multimode operation. Unless otherwise stated, I_s was the 514.5 nm radiation (e ray, polarized along the c axis) from the same laser.

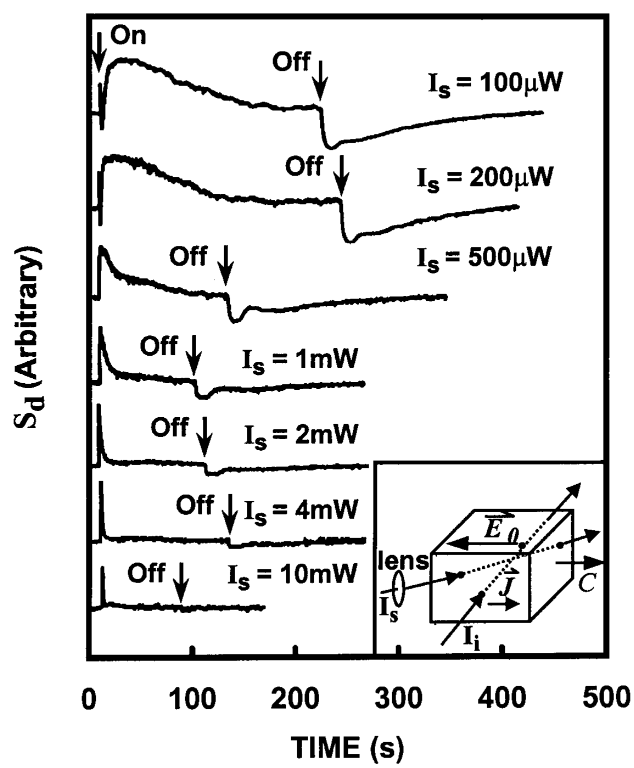

FIG. 1. S_d vs time for different I_s values. Inset shows the experimental setup and the induced macroscopic field $\mathbf{E}_0$ resulting from $\mathbf{J}$ which is the transient total current induced by I_i.

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I_s was focused, by a lens of 5.6 cm focal length, at the input crystalline a face of a single domain Cu:KNSBN crystal of dimensions $6 \times 6 \times 6$ mm^3, with its c axis in a horizontal plane. The beam waist was $\sim$2 mm from the a face and the beam sizes (FWHM) at that face were 23 μm along the horizontal and 28 μm along the vertical. The unfocused I_i with a 2.2 mm beam diameter entered the crystal, essentially at normal incidence, such that it did not overlap with I_s ($\sim$3 mm from I_s). I_i and I_s could be varied independently. Within the range of I_s (100 μW–50 mW), I_s by itself did not exhibit self-focusing (SF) or fanning. When I_i was suddenly unblocked, the degree of SF of I_s increased as I_i was increased. For $I_i \geq 380$ mW and I_s between 100 μW and 4 mW, SS was formed for an incident angle θ_i between 5° and 50°. For $I_s > 10$ mW, it did not self-trap but suffered SF for I_i as large as 480 mW. The following results were obtained by using $\theta_i = 30°$.

An aperture of 1.5 mm diam was placed at 19.5 cm from the output face to study the transient behavior of I_s. Light passing through the aperture was focused onto a photodiode. Formation of a SS would result in an increase of photon flux through the aperture and thus an increase of the photodiode signal S_d. Figure 1 shows S_d vs time. In a typical run, I_s was allowed to irradiate the crystal for $\sim$60 s until a steady state had been reached. Then I_i was unblocked and S_d was found to increase to a peak value and then relaxed to a steady-state value. For I_s between 100 μW and 4 mW, SS was formed within a time window that covered the time at which S_d acquired its peak value. Figure 1 shows (i) the observed SS is one kind of QSS in the sense that it is transient [15] and (ii) for larger I_s, SS requires less time to form and exists for a shorter time. With I_s set at 100 μW, 200 μW, 500 μW, 1 mW, 2 mW, and 4 mW, the SS formation times were 11.8, 7.4, 2.2, 1.5, 0.8, and 0.3 s and existed for 42, 40, 6, 1.4, 0.8, and 0.4 s with decay times 100, 100, 31.5, 6.6, 1.6, and 1.4 s, respectively. That is, unlike the QSS's in the literature, the formation of this type of QSS's *depends* on I_s. When I_i was then suddenly blocked, S_d decreased to a minimum value and then slowly recovered to a steady-state value. That is, blocking of I_i resulted in SF of I_s—due to the reversal of the electric field within the crystal after the blocking. Optically induced SS in this work may therefore be exploited in all optical switching applications. The fact that Fig. 1 is similar to that of a short-circuited PV current [23] suggests that the PV effect is responsible for the formation of this type of SS. However, the SS formed in this work cannot be a PV SS because (i) a PV SS is a steady-state phenomenon and (ii) I_s and I_i in this work *do not* have spatial overlap and propagate along *different* directions. We will come back to this point later.

We examined the time variation of the far field pattern of I_s ($I_s = 100$ μW; $I_i = 380$ mW) by placing a white screen $\sim$21 cm from the output face of the crystal. A video camera operated at 25 frames/s was used to record the far field pattern and selected results are shown in Fig. 2.

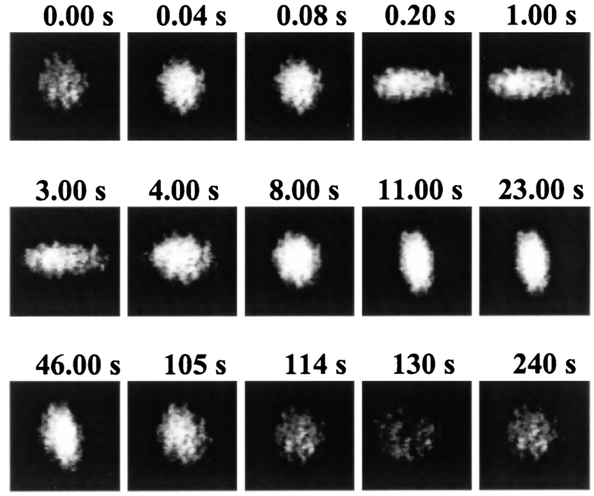

FIG. 2. Snapshots of the signal beam profile at the far field.

The snapshot at 0 s was taken when I_i was unblocked. The snapshot at 0.04 s corresponds to the time at which the spike occurs. Snapshots at 0.08, 0.2, 1.0, and 3.0 s correspond to the rising slope of the main peak of S_d. The three snapshots (0.2 to 3.0 s) clearly show the effect of 1D SF along the horizontal direction. The essentially circular light spot at 0.08 s becomes much elongated along the horizontal direction, meaning that SF formed a cylindrical lens that focused I_s at a point between the output face and the screen. Snapshots at 11 to 46 s are within the time interval which the SS exists. The QSS is clearly 1D, which is different from the QSS's reported in Refs. [15] and [17]. At 114 s, I_i was blocked after which I_s was progressively defocused.

We examined the dependence of the SS formation on I_i by using an imaging system similar to that described in Ref. [15]. Figure 3 shows the horizontal and vertical beam profiles of I_s (4 mW) at the output face recorded at times when S_d acquired maximum values, for various values of I_i. For $I_i < 300$ mW, I_s exhibited SF along the horizontal direction, but it did not form SS. For $I_i >$ 380 mW, SS was observed. Within the range of I_s studied, only weak SF occurred along the vertical direction. We have also observed that (not shown) when I_s was an o ray and $I_i = 480$ mW, only weak SF occurred. We rule out the possibility that the SS observed in this work was of the screening type because we found, by interferometry, that the Δn was positive—opposite to that leading to the formation of a screening SS [11].

There are two plausible explanations for the fact that SS cannot form when I_s exceeds a certain value: (i) Since the photorefractive response time, to a good approximation, is inversely proportional to the optical intensity [24], we expect that the formation time of a SS decreases as I_s increases. Furthermore, the screening of a dc field is faster as I_s increases [11]. When I_s exceeds a certain value, the screening time is too short to allow the formation of a SS

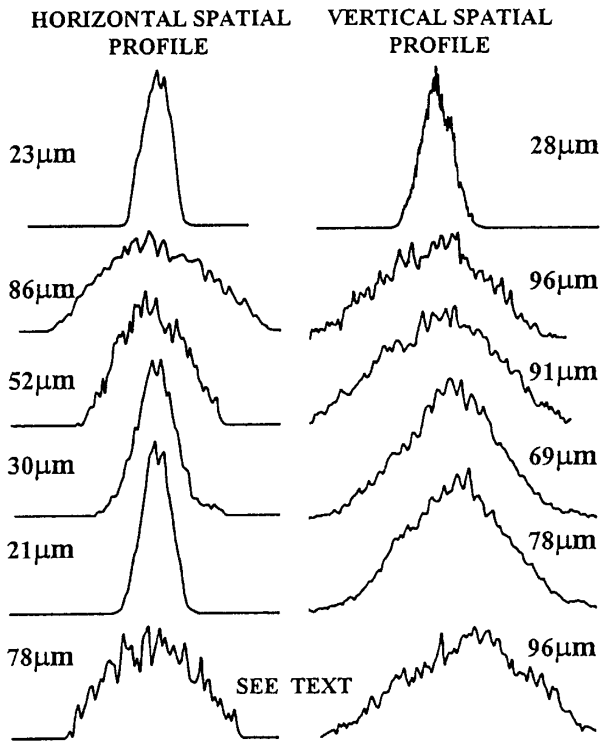

FIG. 3. Horizontal and vertical spatial profiles. Top row: at input face. Others: at output face, from second row, $I_i = 0$, 100, 300, 480, and 380 mW. The number next to each profile is its FWHM.

and thus I_s shows only transient SF (Fig. 1). (ii) When I_s increases, the space-charge (PV) [8] field induced by I_s increases. The direction of this PV field is opposite to the macroscopic field generated by I_i and thus reduces the macroscopic field, which is the reason why a SS cannot form when I_s exceeds a certain value (i.e., the macroscopic field is lower than a critical value). In the published works, the formation of QSS's has been found to be independent of I_s because strontium barium niobate crystals of a small PV coefficient were used. On the other hand, when I_s is below a certain value, I_s shows a high degree of SF (0.2–3.0 s in Fig. 2). When we used a 488 nm I_s (4 mW and $I_i = 380$ mW), only SF was observed, which supports explanation (ii) as the PV coefficient at 514.5 nm is less than that at 488 nm. We also used the 514.5 and 790 nm radiations as I_i and found that, for $I_s = 100$ μW and 4 mW, $I_i = 500$ mW of the 790 nm light could not induce an observable SF. On the other hand, the SF induced by a 400 mW, 514.5 nm I_i was similar to that induced by a 200 mW 488 nm I_i. For $I_i = 380$ mW, the PV voltage generated by the 488 radiation was ~16 kV while those generated by the 514.5 and 790 nm radiations were ~50% and 10 times smaller, respectively. These facts show that the macroscopic field $\mathbf{E}_0$ required for the SS formation is set up by the PV effect. Because of this effect, the transient total current $\mathbf{J}$ (Fig. 1) charges up the two crystalline c faces and thus gives rise to a field which plays the same role as an applied electric field in most SS works. We remark that the pyroelectric effect of I_i may have a contribution to the macroscopic field [25]. However, in view of the fact that the crystal can support stable PV SS [8], the PV contribution should be more important.

Theories predict that the formation of a QSS requires the magnitude of Δn, $\widehat{\delta n}(\mathbf{q}_1, \mathbf{q}_2) = \widehat{\delta n}(-\mathbf{q}_1, \mathbf{q}_2)$ [13,14], using the same notations as Ref. [14]. Presumably due to this reason, studies of QSS's have been done using I_s perpendicular to the crystalline c axis. We will see that this condition can be relaxed so that SS's can be formed even if the angle between the c axis and the propagation direction of I_s is as large as 50°. In a 1D theory of SS's [14], the symmetry of $\widehat{\delta n}(q_1, q_2)$ is determined by those of the effective electro-optic coefficient r_{eff} (q_1, q_2) and the space-charge-field coefficient $E_m(q_1, q_2)$ [26]. Since the latter is even in q_1 and q_2 [14], the symmetry of $\widehat{\delta n}(q_1, q_2)$ is determined by the former. For an e ray in KNSBN, since $r_{13} \ll r_{33}, r_{42}$, we have [27]

$$r_{\mathrm{eff}} = \frac{1}{n_e n_o^3}\left[n_e^4 r_{33} \sin\beta_1 \sin\beta_2 + 2n_e^2 n_o^2 r_{42} \cos\left(\frac{\beta_1 + \beta_2}{2}\right)\right] \times \sin\left(\frac{\beta_1 + \beta_2}{2}\right), \quad (1)$$

where β_1 (β_2) is the angle between the c axis and $\mathbf{q}_1$ ($\mathbf{q}_2$). Let the magnitude of the wave vector of I_s be K, the angle between $\hat{\mathbf{z}}$ and the c axis be α, and the angle between $\hat{\mathbf{z}}$ and q_1 (q_2) be α_1 (α_2). Under the paraxial approximation, we find that $\alpha_1 = q_1/K$ and $\alpha_2 = q_2/K$ or $\beta_1 = \alpha - q_1/K$ and $\beta_2 = \alpha - q_2/K$. For $\alpha \geq 60°$, it is a good approximation to set $\beta_1 = \alpha$ and $\beta_2 = \alpha$ because $q_1, q_2 \ll K$ and $\alpha < 90°$. Equation (1) becomes $r_{\mathrm{eff}} \approx (n_e^4 r_{33} \sin^2\alpha + 2n_e^2 n_o^2 r_{42} \cos^2\alpha)\sin\alpha/(n_e n_o^3)$. So, even if α differs significantly from 90°, the symmetry of $\widehat{\delta n}(q_1, q_2)$ is not seriously affected and thus the formation of a SS—in agreement with our observation. For KNSBN $n_o = 2.35$, $n_e = 2.27$, $\varepsilon_{33} = 570$. The electro-optic coefficients r_{13}, r_{33}, and r_{42} are 30, 200, and 820 $\times 10^{-12}$ m/V, respectively [28]. When θ_i (of I_s) was varied from 5° to 50°, α changed from 88° to 70° and we find that r_{eff} ranges from (193–223) $\times 10^{-12}$ m/V. Replacing r_{33} by r_{eff} in Eq. (47) of Ref. [14], we get $[\lambda^2 e^2 P_d^2/(16\pi^2 r_{\mathrm{eff}} n_1^4 \varepsilon_0^2 \varepsilon_{33}^2)]^{1/3} < |\mathbf{E}_0| < [\lambda^2 e^2 P_d^2/(8\pi^2 r_{\mathrm{eff}} n_1^4 \varepsilon_0^2 \varepsilon_{33}^2)]^{1/3}$, where P_d is the trap density and λ is the wavelength of I_s. Taking $r_{\mathrm{eff}} = 193 \times 10^{-12}$ m/V and $P_d = 10^{17}$ cm^{-3}, we find that 14.5 kV/cm $< |\mathbf{E}_0| <$ 18.7 kV/cm. Since $|\mathbf{E}_0|$ is $\sin\alpha$ times the electric field along the c axis, the PV voltage required is between 9.4 and 12 kV (<16 kV measured by us). We therefore conclude that a SS in KNSBN can exist within a large range of θ_i. For an o ray, the required PV voltage is about twice as large, and thus more difficult to form a SS, which is in agreement with our observation.

In conclusion, we have demonstrated for the first time (to our knowledge) that a bright QSS can be formed by all optical means (without an applied electric field). The QSS exhibits some properties which are different from those of the QSS's reported in the literature. In particular, it is 1D (instead of 2D) and its formation is sensitive to I_s.

We thank Dr. M. Segev for his enlightening discussions. This work was supported in part by a fund (C. N. Yang) from the Department of Physics, The Chinese University of Hong Kong, and a Key Project Grant of the Ministry of Education, China.

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