Soliton-induced waveguides in an organic photorefractive glass

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We demonstrate optical waveguiding of a probe beam at 980 nm by a soliton beam at 780 nm in an organic photorefractive monolithic glass. Both planar and circular waveguides induced by one- and two-dimensional spatial solitons formed as a result of orientationally enhanced photorefractive nonlinearity are produced in the organic glass. Possibilities for increasing the speed of waveguide formation are discussed. © 2005 Optical Society of America

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Optical spatial solitons[1] have attracted considerable interest in nonlinear optics and photonics. Among such solitons, photorefractive (PR) solitons[1–4] make up an important family. Because of the unique properties of PR materials, a weak PR soliton beam can be used for guiding a strong beam at different wavelengths.[2,3] Many applications based on PR soliton-induced waveguides, such as directional couplers, nonlinear frequency converters, and optical parametric oscillators, have been proposed.[4] Thus far, most experimental demonstrations of PR solitons have been made with expensive inorganic nonlinear crystals. It is desirable to create optical solitons in low-cost organic materials with high PR performance.

Organic PR materials have been investigated extensively during the past decade for many applications because of their low cost, flexible structure, large beam-coupling gain, and ease of fabrication.[5,6] Although much of this research was focused on organic synthesis and characterization of the PR effect in these materials, there has been a suggestion that it might be possible to employ the orientational optical nonlinearity[7] of PR polymers for generation of optical solitons.[8] In fact, self-trapping of a one-dimensional (1D) optical beam in an organic PR monolithic glass containing a new type of photoconductive nonlinear optical chromophore, dicyanomethylenedihydrofuran (DCDHF), was recently successfully demonstrated.[9] Solitons as well as optically induced focusing-to-defocusing switching were observed in such DCDHF-based PR organic glass. Unlike in previous observations of spatial solitons in glass or polymer waveguides,[10,11] which relied on high-power pulsed laser beams, our solitons were achieved in bulk organic materials with a low-power cw laser beam because of the unique saturable orientational PR nonlinearity.

We report what is to our knowledge the first experimental demonstration of two-dimensional (2D) solitons and soliton-induced waveguides in an organic PR glass. In particular, both 1D planar waveguides induced by soliton stripes and 2D circular waveguides induced by 2D solitons were readily observed in a DCDHF-based monolithic glass that was poled by an external field, owing to the orientationally enhanced PR nonlinearity. The speed of soliton–waveguide formation could be greatly increased by synthetic modification of the material as well as by the control of experimental parameters. In addition, we also observed a novel beam-bursting phenomenon once the field was turned off. Our results illustrate the possibility of using organic materials for soliton-based applications.

A schematic drawing of the experimental setup (similar to that described in Ref. 9) is illustrated in Fig. 1. A 780-nm laser diode is used to provide a nearly circular beam after the beam has passed through an anamorphic prism pair. A half-wave plate rotates the polarization of the beam when necessary. The collimated beam is then focused with either a cylindrical or a circular lens onto the input face of a PR organic glass sample (typically 2.5 mm long and 120 μm thick). The sample is made from the amorphous mixture DCDHF-6–DCDHF-6-C7M at a 1:1 weight ratio and sensitized with a small weight percent of C_{60} sandwiched between two conducting indium tin oxide slides. At room temperature the mixture forms stable glass without crystallization.[5,6] To permit optical propagation (along the z direction) over a distance of the sample length, we cover the front and back edges of the sample with pieces of glass to create nearly flat input and output surfaces. In addition, another beam from a 980-nm laser diode is used as a probe beam, following the same path taken by the 780-nm soliton-forming beam. Behind the sample, a CCD camera together with an achromatic imaging lens is used to monitor the beam profiles. With such a setup, self-trapping of light was observed when the beam was polarized perpendicular to the bias field (y polarized), whereas self-defocusing of light was observed when the beam was polarized parallel to the bias field (x polarized).[9]

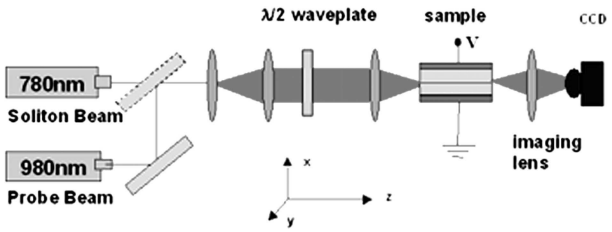

Fig. 1. Schematic drawing of the experimental setup.

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First, we present our experimental results for 1D soliton-induced waveguides (Fig. 2). For these experiments a y-polarized soliton-forming beam (Fig. 2, top) with a beam power of 18.2 mW was focused with a cylindrical lens into a quasi-1D stripe beam. The stripe beam had a FWHM of ~10 μm at the input face of the sample [Fig. 2(a)]. After propagating through the sample, the beam diffracted to ~60 μm in the absence of the poling electric field [Fig. 2(b)]. With a voltage of 2.7 kV applied across the 120-μm-thick sample, the stripe beam experienced self-focusing gradually, and an 11-μm 1D soliton was formed within ~90 s [Fig. 2(c)]. To test the waveguide property of the soliton beam we then used a 980-nm probe beam (Fig. 2, bottom), also y polarized and focused properly. The probe beam's width at the input was ~9 μm. Without the soliton waveguide, the probe beam diffracted normally to ~90 μm at the output of the sample. Once the soliton was formed, the 780-nm beam was replaced by the probe beam. We observed instantaneous guidance of the probe beam by the soliton-induced waveguide [Fig. 2(c), bottom], with ~30% loss of power that resulted mainly from scattering and absorption. The probe beam, guided for more than 30 min with the external field still applied, then slowly went back to normal diffraction. We emphasize that, without the soliton beam, the 980-nm probe beam alone did not experience any self-focusing effects under the same experimental conditions (i.e., same intensity, same bias field, etc.). This is so because the sensitizer (C_{60}) responsible for charge photogeneration does not exhibit sensitivity at this wavelength sufficient for the formation of the space-charge field necessary for creating the PR screening solitons. Thus the probe itself does not show appreciable nonlinear self-action; rather, its beam confinement is due to the linear guidance by the soliton beam. When we turned the bias field off immediately after the probe beam experienced waveguiding, we observed a phenomenon similar to beam bursting, i.e., splitting of the probe beam into two pieces at the output [Fig. 2(d)]. Instead of the sample relaxing to the unperturbed index to reveal a linear diffraction pattern, turning off the field after soliton formation resulted in a transient splitting intensity pattern, indicating that the index variation somehow had changed from a waveguide to an antiguide structure. Such a beam-bursting phenomenon is similar to that observed for solitons in centrosymmetric PR crystals dominated by a quadratic electro-optic effect,[12,13] which has been proposed for soliton electro-optic manipulation.[14] However, the mechanism for this phenomenon in our PR organic glass is not quite clear and certainly merits further investigation.

Next, it is natural to ask whether it is feasible to generate 2D solitons and circular waveguides in our sample, as DCDHF-based organic glasses are highly birefringent and anisotropic nonlinear materials. To achieve this end we performed experiments with a 2D Gaussian-like beam and obtained the results illustrated in Fig. 3. The 2D beam was focused to ~19 μm at the input face of the sample [Fig. 3(a)]. Without the applied field, the beam diffracted to ~34 μm after 2.5-mm propagation [Fig. 3(b)]. After a dc field of 16.7 V/μm was applied, self-trapping of the 2D beam was obtained in ~65 s [Fig. 3(c)] when the beam was y polarized. Similarly to the 1D soliton,[9] the 2D soliton stayed for quite a long time (>30 min) without significant decay in its intensity, and appropriate background illumination such as from a white-light source favored steady-state soliton formation. Once the soliton was formed, we replaced the soliton beam with a Gaussian-like probe beam (Fig. 3, bottom) to test its induced waveguide. Without the soliton beam, the probe beam diffracted normally [Fig. 3(b)]. With the soliton waveguide, however, the probe was guided well, as its size at the output of the sample was reduced significantly [Fig. 3(c)]. We point out again that the guidance occurred almost instantaneously when we launched the probe into the soliton channel. Under the same experimental conditions, we found that the 980-nm probe beam alone did not show appreciable self-focusing even after the field was applied for more than 30 min.

The experiment was repeated at various beam power levels and bias fields as well as with samples

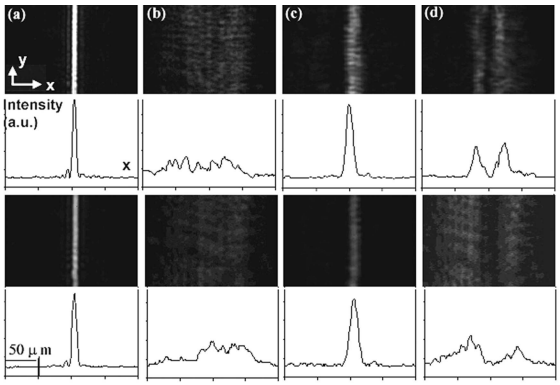

Fig. 2. Planar waveguides induced by 1D solitons. Shown are intensity patterns and beam profiles taken at (a) input, (b) linear output, (c) nonlinear output, and (d) output of (c) at turn-off of the field. Top, 780-nm soliton beam; bottom, 980-nm probe beam.

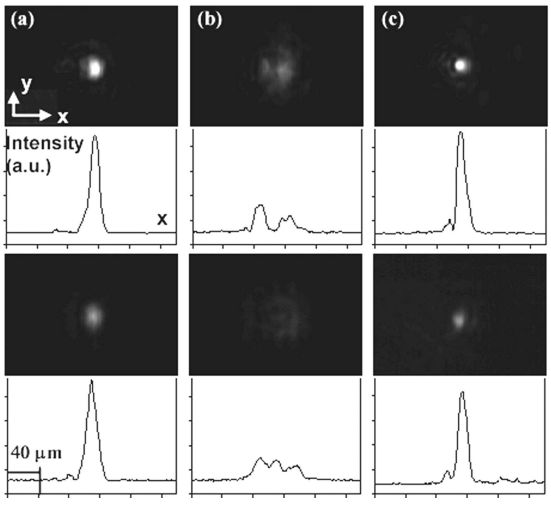

Fig. 3. Circular waveguides induced by 2D solitons. The description of (a)–(c) is similar to that for Fig. 2.

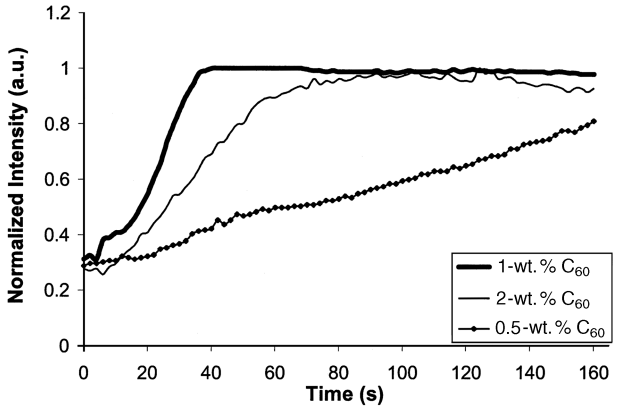

Fig. 4. Normalized peak intensity versus time for samples with various weight percent values of C_{60} at an applied field of 13 V/μm.

with slightly different C_{60} doping percentages; similar phenomena were observed. The observed waveguiding does not depend on the polarity of the dc field, but it does depend on the polarization of the beam. When the polarization was switched to x polarization, the probe beam exhibited enhanced diffraction rather than waveguiding, as the 780-nm beam at this polarization induced an antiguide instead. The nature of the index change and its dependence on the electric field that results from the orientational PR effect was discussed previously.[7,8] Basically, the contribution to index change comes from orientationally enhanced birefringence (BR) and the electro-optic effect. In most low-glass-transition organic PR materials such as the one used here, BR dominates the orientational PR nonlinearity. The index change for x- and y-polarized beams at an applied dc field E can be loosely written as $(\Delta n)_x \cong (1/2n)C_x^{\mathrm{BR}}E^2$ and $(\Delta n)_y \cong -(1/4n)C_x^{\mathrm{BR}}E^2$, respectively, where the BR coefficient C_x^{BR} (proportional to polarizability anisotropy $\alpha_{\parallel} - \alpha_{\perp}$) is typically positive. The dependence of index change on the electric field is quadratic in nature and is insensitive to the polarity of the field. The difference in the sign of the induced index change for x- and y-polarized light accounts for the different behavior (self-focusing or defocusing, waveguiding or antiguiding) observed experimentally.

Finally, we discuss the issue of the speed of waveguide formation. It was shown that the soliton formation time depends on the magnitude of the poling field as well as on the beam power.[9] Here we show that the speed differs in samples with different doping percentages of C_{60} sensitizer. The primary sample used in our experiments (for Figs. 2 and 3) contains 0.5% C_{60} by weight. We also investigated samples with 1% and 2% doped C_{60} and did a comparative analysis with the 0.5% sample. Conditions were kept the same for the three samples. A planar soliton was created in each sample by use of a 780-nm beam at 32 mW and a bias field at 13 V/μm. The response of the material was recorded as normalized peak intensity versus time registered by the CCD camera, as plotted in Fig. 4. It is apparent that the 0.5% sample performed poorly compared with the other two in terms of response time. The 1% sample noticeably outperformed the 2% sample and was a whole order of magnitude faster than the 0.5% sample. Another trial was carried out with a different field of 15 V/μm, and the result again showed that the 1% sample had the fastest response. This improvement in speed of formation when the sensitizer concentration was increased from 0.5% to 1% is due to enhanced charge photogeneration. However, a further increase (as much as 2%) did not improve the performance further, likely because of excessive trap density that hinders the space-charge field formation, which is one of the reasons for keeping the optimal sensitizer concentration below ~1% in most high-performance PR organics.[6] Our further investigation will focus on synthetic modification of the chromophores as well as on mixing their derivatives in various concentrations for faster soliton–waveguide formation.

In summary, we have demonstrated the formation of soliton-induced waveguides in a photorefractive organic glass with low-power cw laser beams.

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