Observation of spatial optical solitons in a nonlinear glass waveguide

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We report the observation of spatial optical solitons due to the Kerr nonlinearity in a planar glass waveguide and present measurements of the nonlinear response obtained by placing a pinhole at the output of the waveguide. For input intensities greater than that required for the fundamental soliton, we observe breakup of the output owing to the effect of two-photon absorption.

Stable self-trapping of a laser beam propagating in two-dimensional space has been predicted[1] and experimentally observed in CS_2 liquid.[2] In this Letter we report the observation of this phenomenon in a single-mode planar glass waveguide, which could potentially be used as a building block for an integrated all-optical switching circuit. Our results constitute the first observation, to our knowledge, of spatial optical solitons in a solid-state material.

Three-dimensional self-focusing of optical beams in solids has been extensively studied and is known to be unstable at the critical power, leading to filamentation of the beam and sample breakdown. However, in the two-dimensional case, diffraction and self-focusing can compensate for each other, resulting in a stable channel in which the beam can propagate without spreading. This is analogous to the situation that exists in the time domain for optical pulses in the anomalous dispersion regime of single-mode fibers, where self-phase modulation and group-velocity dispersion can compensate for each other, leading to the formation of a temporal soliton.[3]

The propagation of an optical beam in a two-dimensional medium, in the presence of an intensity-dependent refractive index, can be described by the nonlinear Schrödinger equation[1]

$$2ik\frac{\partial E}{\partial z} = -\frac{\partial^2 E}{\partial x^2} - 2k^2\frac{n_2}{n_0}|E|^2E, \tag{1}$$

where E is the envelope of the electric field, n_0 is the linear refractive index, n_2 is the nonlinear index coefficient, defined by $n = n_0 + n_2|E^2|$, and k is the wave vector. The first term on the right-hand side accounts for diffraction, and the second term accounts for the effect of the nonlinear contribution to the refractive index. The fundamental solution of Eq. (1) is

$$E(x, z) = \frac{1}{ka_0}\sqrt{\frac{n_0}{n_2}}\exp\left(\frac{iz}{2ka_0{}^2}\right)\mathrm{sech}\left(\frac{x - x_0}{a_0}\right), \tag{2}$$

where a_0 is a measure of the beam width. The integrated intensity over the beam is

$$P_s = \int |E|^2\, dx = \frac{n_0}{n_2}\frac{2}{a_0k^2}. \tag{3}$$

The total soliton power in the beam is

$$P_t = \frac{n_0 2w}{n_2 a_0 k^2}. \tag{4}$$

Effective two-dimensional propagation can be obtained in a slab waveguide in which the transverse mode size w is much smaller than the soliton width a_0. Under these conditions the self-focusing effects will be limited to one spatial direction only. At this power level (P_t), the induced self-focusing exactly compensates for diffraction, and the beam will propagate undistorted in its own channel. Higher-order solutions exist at intensity levels of N^2P_t, where N is an integer. The higher-order solitons exhibit a periodic variation in width as a function of distance along the sample.

The formation of a spatial soliton requires a transparent optical material with a positive nonlinear coefficient and characteristics that allow it to be formed into a waveguide. Although glass has a low value of n_2, it is a potentially good choice because of its low background absorption.[4] Our sample was a 5.0-mm-long single-mode slab waveguide formed in Schott B270 glass. A potassium–sodium ion exchange was used to produce a surface layer with an increase in the refractive index of $\Delta n \sim 0.007$ over the bulk value of $n_0 = 1.53$. This planar waveguide was then buried with a second exchange to reduce scattering due to surface imperfections. The resulting waveguide layer was approximately 3–4 μm thick.

The experimental arrangement used to measure the nonlinear response of the sample is shown in Fig. 1. The source used in these experiments was a colliding-pulse mode-locked dye laser and copper-vapor-laser-pumped dye amplifier system.[5] This system produced 620-nm, 75-fsec pulses with energies of several microjoules at a repetition rate of 8.6 kHz. A prism pair (not shown) was used in a double-pass geometry to compensate for pulse broadening, due to group-

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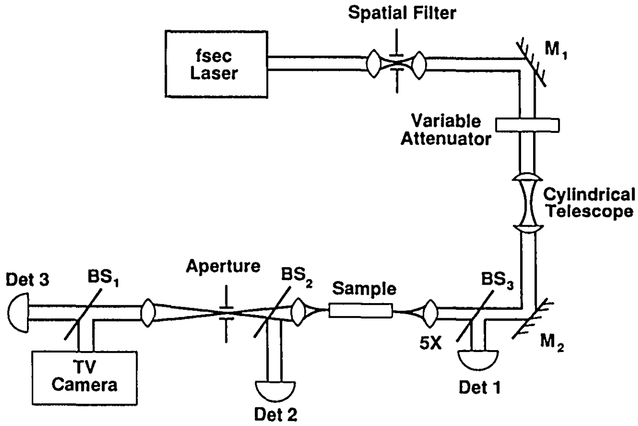

Fig. 1. Schematic of the apparatus used for the experiments. BS's, beam splitters; M's, mirrors.

velocity dispersion, in the amplifier system and in the optics in front of the sample.[6] The output was spatially filtered to improve the beam quality, then shaped using the cylindrical telescope to produce an elliptical profile, with a 10:1 ratio.

The use of a shaped beam permits efficient coupling of a wide (~15-μm) beam into the waveguide. From Eq. (3) we see that the soliton intensity depends on $1/a_0$: use of an elliptical input beam with a relatively large width helps to keep the soliton intensity below the damage threshold of the glass. The TE_0 mode of the waveguide was excited by end-fire coupling the shaped beam with a 5X microscope objective. The output facet was imaged onto an intermediate image plane, where an aperture could be placed, and then onto a television camera and detector. The input intensity could be adjusted by a stepper-motor-driven attenuator wheel under computer control. The transmission through an aperture was recorded by using a chopper, a power meter, and a lock-in amplifier. The computer causes the attenuator wheel to rotate, and it acquires data by digitizing the lock-in output. Detector 1 (Det 1) monitored the total input power, detector 2 (Det 2) monitored the total output, and detector 3 (Det 3) monitored the apertured output power.

Figure 2 shows (time-averaged) spatial profiles of the output beam as a function of input power. At low powers, the output beam has diffracted to a width of 4.6 times the input beam width, as expected from the ~15-μm FWHM width of the input beam. As the input power is increased, the spatial width of the output beam decreases, until at P = 400 kW the (time-averaged) output beam is almost as narrow as the input beam.

Figure 3(a) shows the transmission through an aperture placed to transmit the center of the output mode. The aperture was chosen so that its width was the same as the effective FWHM width of the input beam. From the experimental data it can be seen that the transmission of the central part of the beam increases by a factor of ~2 as the input power is increased. When the aperture is moved onto one of the wings of the output beam [Fig. 3(b)], the transmission decreases as a function of increasing input power.

From Eq. (3) we can estimate the power required to observe the fundamental soliton. Using n = 1.53 and $n_2 = 3.4 \times 10^{-16}$ cm^2 W^{-1} (the value of n_2 for a similar crown glass[7]), we find that P_t = 230 kW. This is the power required for the given input pulse to propagate undistorted across the sample. It should be noted that for input intensity levels between $0.25P_t$ and

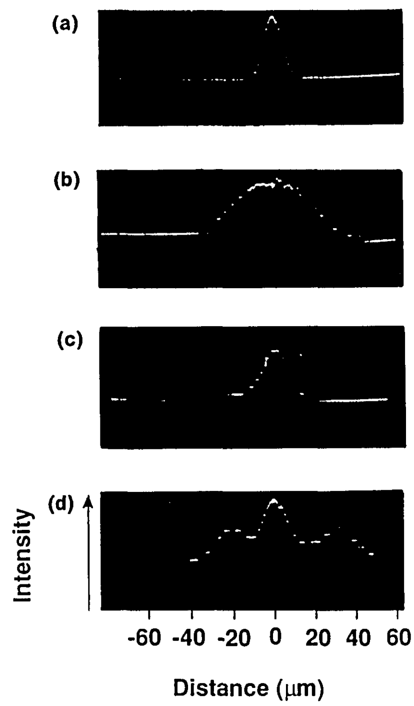

Fig. 2. Experimentally measured time-averaged beam profiles as a function of input power. (a) Input beam profile; (b) output beam profile, peak power 24 kW; (c) output beam profile, peak power 400 kW; (d) output beam profile, peak power 1.25 MW.

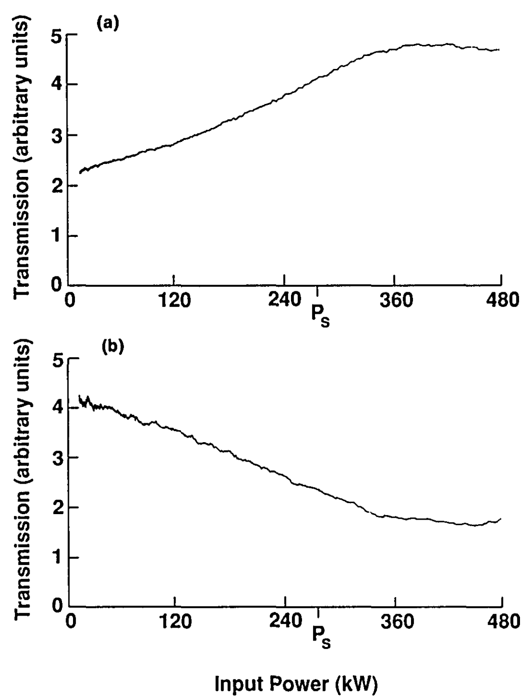

Fig. 3. Experimental measurements of the output power through an aperture of effective diameter 15 μm centered on (a) the output beam and (b) the wing of the output beam.

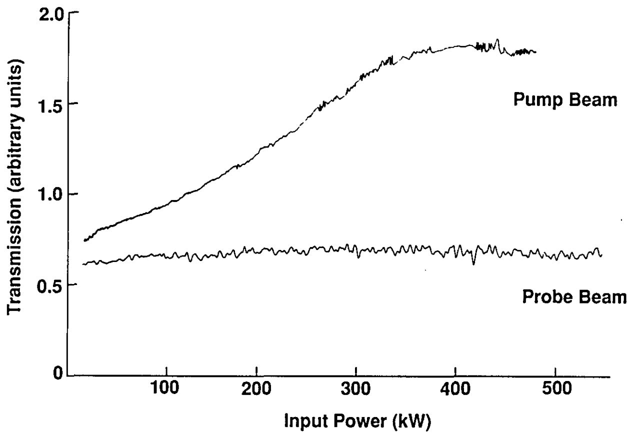

Fig. 4. Pump–probe measurements used to check on the mechanism of the nonlinearity. The top trace shows the transmission of the pump beam through an aperture, and the bottom trace shows the transmission of a delayed probe.

$2.25P_t$ the input beam will also evolve into a fundamental soliton but with an a_0 different from that of the input.[8] We have used the beam-propagation method[9] to model our experiment numerically. From our modeling results, which include an averaging over the temporal intensity profile of the pulse, we predict that the maximum transmission through a central aperture should occur at $1.5P_t$. By comparison with our data [Fig. 3(a)], we obtain an experimental value of $P_t = 275$ kW. We note that at the soliton power we did not observe any two-photon absorption. As the input power was increased to $P = 1.25$ MW, we observed pulse breakup with three peaks in the spatial profile of the output beam [Fig. 2(d)]. These peaks are separated by a much larger distance than that expected for high-order solitons. Our results can be explained, however, by taking into account the effect of two-photon absorption, which we observed at these high powers.[10]

We also performed experiments using a Bellcore experimental glass that was designed to have a large nonlinear coefficient and to be compatible with waveguide processing.[11] This silicate glass, which contains niobium and titanium, exhibited an increase in n_2 to 4×10^{-15} cm^2 W^{-1}. Waveguides were prepared by thallium–potassium ion exchange.[12] Similar soliton formation was observed at power levels ~10 times lower than those required for the B270 glass, as expected from the ~10 times larger nonlinear coefficient. However, two-photon absorption was observed to occur at much lower power levels than for the B270 glass.

The observed self-focusing effects could conceivably be caused by a positive index change resulting from a local heating. In order to investigate this possibility, we performed a pump–probe experiment in which an intense pump beam, which causes soliton formation, and a weak probe beam, delayed by 7 psec, were coupled into the sample. Care was taken to ensure that both beams were spatially overlapped in the waveguide. The weak probe was chopped so that it could be discriminated from the pump at the output. The results of the experiment are shown in Fig. 4. Monitoring only the transmission of the pump pulse through a pinhole, we noted an increase in transmission due to self-focusing. The delayed probe-pulse transmission was independent of the intensity of the pump, indicating that the nonlinear index change recovers in a time that is short compared with 7 psec. Thus we conclude that the spatial soliton effects that have been observed are due to a nonthermal (Kerr) nonlinearity.

In conclusion, we have observed the propagation of the fundamental spatial soliton in a glass waveguide. At low powers the beam diffracts as it propagates across the sample. As the input power is increased, self-focusing due to the bound-electron nonlinearity competes with diffraction, causing the beam to narrow until it propagates undistorted across the sample. Pump–probe measurements show that the mechanism causing this effect responds on a time scale shorter than 7 psec and is thus not of thermal origin. We also observe soliton breakup effects owing to two-photon absorption at higher power levels.

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