Strong Spatiotemporal Localization in a Silica Nonlinear Waveguide Array

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(Received 14 July 2003; published 24 November 2003)

We investigate the propagation of short, intense laser pulses in arrays of coupled silica waveguides, in the anomalous dispersion regime. The nonlinearity induces trapping of the pulse in a single waveguide, over a wide range of input parameters. A sharp transition is observed for single waveguide excitation, from strong diffraction at low powers to strong localization at high powers.

DOI: 10.1103/PhysRevLett.91.223901 PACS numbers: 42.65.Tg, 42.65.Jx, 42.65.Sf, 42.65.Wi

Optical solitons are localized electromagnetic waves that propagate in nonlinear media where dispersion and/or diffraction are present. They are the most thoroughly studied form of solitons, in view of their potential application in optical communications and switching devices. Optical solitons that exhibit confinement in one transverse dimension, either spatial or temporal, have been the subject of extensive theoretical and experimental investigations [1]. Far less is known about multidimensional solitons that exhibit confinement in more than one transverse dimension, and, in particular, about spatiotemporal solitons (STS). One of the most intriguing cases is when diffraction and dispersion have the same magnitude. In this situation, the nonlinearity may simultaneously balance both, leading to the formation of an STS that is symmetrical in all transverse dimensions. Such STS are sometimes called "light bullets," and were originally proposed in the context of media with a positive Kerr nonlinearity and anomalous dispersion [2]. However, basic analysis shows that these STS are unstable, and tend to either disperse or experience a catastrophic self-focusing ("collapse") for pulse energies that exceed a certain critical value [2]. Nevertheless, such a mathematical collapse is usually avoided in experiments, due to higher-order nonlinearities and dispersion, which become increasingly important during the collapse. The interplay of these effects was studied recently in a planar glass waveguide, where the pulse disperses in one dimension and diffracts in another (this is known as a "1 + 2" case, where the "1" denotes the direction of propagation and the "2" refers to the number of transverse dimensions in which the wave packet can diffract or disperse) [3]. In that experiment, simultaneous spatial and temporal self-focusing was observed in the anomalous dispersion regime, and multiphoton absorption (MPA) and stimulated Raman scattering (SRS) were suggested as possible mechanisms that arrest the collapse. In parallel, STS have been generated in bulk quadratic media, where stable propagation was demonstrated in the temporal dimension and in one spatial dimension, while diffraction occurred in the remaining spatial dimension [4]. Thus, the realization of a true STS, especially in Kerr media, remains an important goal in the field of soliton physics.

A particularly interesting situation arises when a pulse propagates in an array of coupled one-dimensional waveguides. Such a periodic array is a one-dimensional photonic crystal, and in many respects its behavior is intermediate between one-dimensional ("1 + 1") and two-dimensional ("1 + 2"). For example, diffraction in these structures takes the form of a weak coupling between adjacent waveguides, and leads to a characteristic discrete diffraction where the light distribution has the form of a Bessel function [5]. Spatial solitons also form in these structures, and have been studied extensively both theoretically [6] and experimentally [7]. These discrete solitons present a number of novel and intriguing dynamical properties. For example, both stable and unstable spatial solitons are supported, and the difference of energy between the two, called the Peierls-Nabarro potential, accounts for the tendency of discrete solitons to lock to the waveguide direction at high powers, or to acquire transverse momentum and shift laterally, depending on the input parameters [8]. Moreover, the sign and value of diffraction in waveguide arrays is a function of the propagation direction [9], with important consequences to the linear and nonlinear properties [10].

These peculiar properties of discrete solitons have been studied extensively in AlGaAs waveguide arrays [7,8,10]. However, AlGaAs has a normal dispersion, and therefore cannot support STS. Indeed, with anomalous dispersion, which is a prerequisite for the formation of STS, the differences between discrete and continuum solitons are expected to be significant. In addition, the instability and collapse of STS is expected to disappear in coupled waveguide arrays. Using coupled mode theory, in the form of linearly coupled one-dimensional nonlinear Schrödinger equations (NLSE), Aceves *et al.* have shown that the discrete nature of the structure effectively acts as a saturable nonlinearity and, instead of a catastrophic collapse, energy localization in a single waveguide is expected, accompanied by strong temporal compression [11]. The localization and temporal compression in an array were demonstrated numerically [11]. Self-trapping was also demonstrated numerically [12]. However, the necessary initial conditions for such STS-like behavior were not clearly identified.

In this work, we present experimental evidence for such strong spatial localization in a single waveguide, with anomalous dispersion. We use arrays of silica waveguides, where the dispersion is anomalous for laser pulses with wavelengths in the optical communication window ($\lambda \approx 1.5\ \mu$m). We employ two different experimental configurations that result in different initial conditions: a broad input beam and single waveguide excitation. In the first configuration, the observed behavior is reminiscent of the collapse in the "1 + 2" case [3], while in the second configuration we observe an extremely sharp transition from a regime of strong diffraction to a regime of strong spatial localization, as a function of the input power. The latter suggests the existence of a range of parameters where quasistable propagation may exist.

The sample that we used is 2.5 cm long, and consists of several one-dimensional periodic arrays, each with 101 weakly coupled optical waveguides, buried inside a layer of flame hydrolysis deposited silica. The core of each single-mode waveguide is germanium-boron doped silica, has a square cross section of $4\ \mu\text{m} \times 4\ \mu\text{m}$, and is surrounded by a silica cladding. The refractive index step between the cladding and the core is $\Delta n = 0.75\%$. The period of the different arrays d (see Fig. 1) varies between 11 μm and 13 μm, in order to modify the degree of coupling between adjacent waveguides. We inject transform-limited 60 fs pulses, at a wavelength of 1520 nm and with peak powers up to 2 MW, generated by a Spectra Physics OPA 800 optical parametric amplifier. The spatial profile of the input beam is varied as to excite just one or several waveguides. A microscope objective and a cylindrical lens are combined in order to obtain an elliptical input beam, $\simeq 170\ \mu$m wide, with a flat phase front at the input facet of the sample. This arrangement allows matching of the beam size, and thereby the diffraction length, to the dispersion length. The cylindrical lens may be removed to allow single waveguide excitation. The output facet of the sample is imaged onto an infrared camera. A portion of the beam is directed to a spectrometer, and another portion to a noncollinear autocorrelator. The 100 μm thick beta barium borate crystal in the autocorrelator allows accurate measurements of pulse durations down to 10 fs, and the glass in the optical path to the autocorrelator introduces a systematic error of less than 10 fs in the measurements. An aperture, placed in an image plane of the output facet, allows temporal and spectral characterization of the central part of the output beam. The spatial cross section, power spectrum, autocorrelation, and output power are measured as a function of the input power. The experimental data shows little variation between the different arrays, and the results presented here are typical to all of them.

Figure 2 presents images of the sample's output facet, recorded under different excitation conditions. Figures 2(a) and 2(b) were both obtained with a broad input beam (i.e., equal dispersion and diffraction lengths). The three images in Fig. 2(a) depict a stable spatial soliton, and correspond to the lowest input power, maximum spatial compression, and maximum input power (top to bottom). It can be seen that, as the power of the incoming beam is increased, the beam width first contracts to about 10 μm, and then gradually broadens. At the minimum width most of the pulse energy is concentrated in a single waveguide, with two small satellite pulses in the neighboring waveguides. A small tilt of the input facet relative to the input beam allows excitation of an unstable soliton, which is peculiar to the array [8]. As seen in Fig. 2(b), the self-focusing obtained in this case is rather weak. In contrast, the spatial compression of the stable soliton is remarkable. It is substantially stronger than that observed in the case of normal dispersion [7], and is also more pronounced than the compression in the perfect planar configuration [3]. In the following, we focus on the

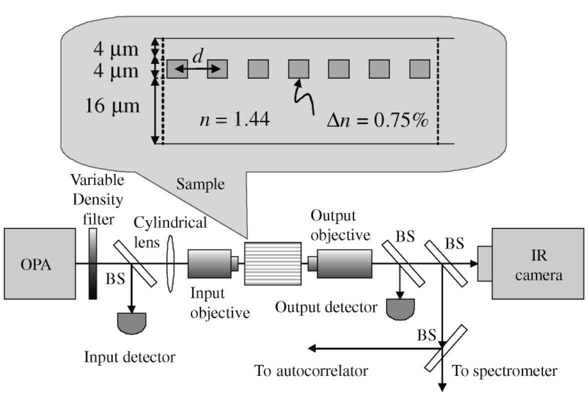

FIG. 1. Experimental setup and sample cross section.

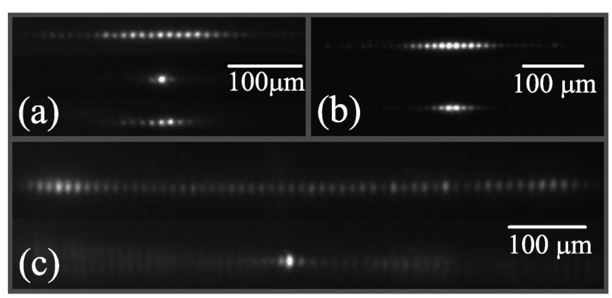

FIG. 2. Images of the sample's output facet under different excitation conditions. (a) Broad input beam (equal dispersion and diffraction lengths): top to bottom, 0.09, 0.45, and 0.74 MW. (b) The unstable mode is excited with the broad input beam: top, low power; bottom, high power. (c) Single waveguide excitation: top, 0.07 MW; bottom, 0.44 MW.

dynamics of this stable mode of the array. Its evolution as a function of input power is seen in Fig. 3(a), which shows a contour plot of a set of ten spatial cross sections of the beam at the output facet. The corresponding variations of the beam width and pulse duration are plotted in Fig. 4(a). The strongest spatial compression lags slightly behind the maximum temporal compression, possibly due to a small mismatch between the dispersion and diffraction lengths. More importantly, the compression is very asymmetric: While the beam compresses by a factor of ≈ 10 relative to its width at the input, the pulse duration reduces by less than 10%. This contrasts with the more symmetric compression that was observed under similar conditions in the "$1 + 2$" case [3]. This behavior demonstrates that the symmetry between the spatial and temporal coordinates is broken, and strongly suggests that the sudden onset of significant nonlinear effects, as the pulse compresses into a single waveguide, induces temporal broadening, followed by diffraction. Thus, the symmetry breaking in the array indeed restrains the collapse. Except for this pronounced asymmetry, the behavior that we observe with a broad input beam is very similar to the quasicollapse in two dimensions [3]. Yet, the dynamics at high input powers, beyond the point of maximum compression, reveal more subtle differences between the two geometries. As the spectral data in Fig. 4(b) demonstrates, the spectrum of the output beam mainly broadens before maximum compression is achieved, but beyond that point it strongly shifts to longer wavelengths. The shift is due to SRS, and is accompanied by a significant broadening of the pulse [Fig. 4(a)]. This effectively breaks the symmetry between the spatial and temporal coordinates, and stops the compression. The broadened pulse then starts to diffract. The diffraction is more regular than in the two-dimensional case, where a breakup of the beam to filaments was observed at high input power [3].

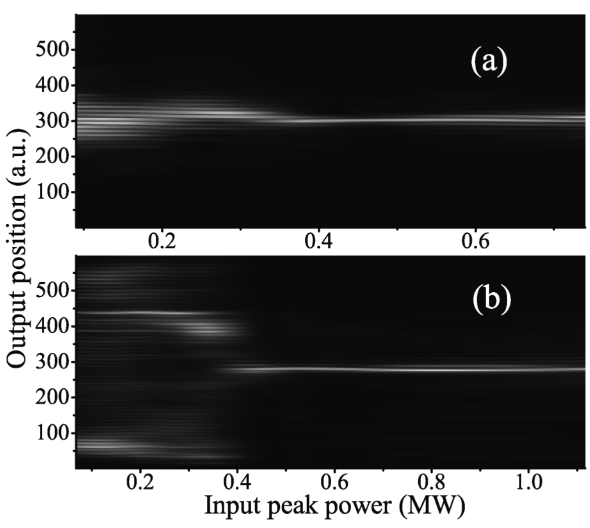

FIG. 3. Contour plots of the spatial cross sections at the output facet, measured as a function of input power, for a broad input beam (a) and for single waveguide excitation (b).

Also in contrast with the two-dimensional case [3], in the present experiment the output power is proportional to the input power, and there is no evidence for nonlinear loss. This fact also shows that the array restrains the collapse more effectively.

A totally different picture is observed when the input beam is focused into a single waveguide. At low input powers, the beam strongly diffracts [top image of Fig. 2(c)], and shows the characteristic Bessel function light distribution of discrete diffraction [5]. Beyond a certain, well-defined input power, however, the beam abruptly contracts, and all the power is essentially localized in one waveguide [bottom image of Fig. 2(c)]. The spatial distribution at the output facet then shows very little change as the input power is further increased. The variation of the beam width at the output facet as a function of the input power, and the corresponding changes of the pulse duration and spectrum are plotted in Figs. 4(a) and 4(c). The evolution of the spatial profile can also be seen in Fig. 3(b), which is a contour plot of a set of 11 spatial cross sections of the beam at the output facet, measured as a function of input power. Two different regimes are clearly seen, with an extremely sharp transition between them. Also note that the pulse duration at the output facet increases monotonically, and that following the abrupt localization in a single waveguide the temporal broadening and redshift due to SRS

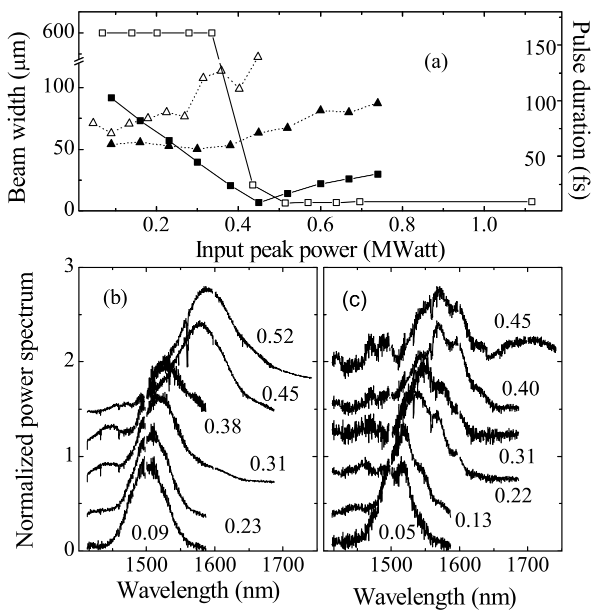

FIG. 4. Spatial, temporal, and spectral data obtained with different excitation parameters: (a) the variations, as function of input power, of the beam width (squares) and pulse duration (triangles), for a broad input beam (full symbols) and for single waveguide excitation (open symbols). (b) and (c) show the evolution of the output spectrum as a function of the input peak power, for a broad input beam and for single waveguide excitation, respectively (the spectral curves are displaced vertically for better clarity, and the numbers next to the traces indicate the input peak powers in MW).

increase dramatically. As in the case of broad beam excitation, the output power is proportional to the input power, and there is no evidence for nonlinear loss. In particular, this means that the fixed spatial distribution that we observe does not correspond to a well-defined pulse energy. Rather, the pulse energy increases as the pulse broadens in the time domain. The peak power at which the trapping occurs is $\approx 0.4 \times 10^6$ W, which is 100 times lower than the peak power of a 60 fs one-dimensional soliton, but consistent with a pulse compressed to 6 fs. Clearly, other effects must intervene to broaden the pulse before it reaches the output facet of the sample. We also note that the observed variation of the output wave packet size as function of its energy is exactly the opposite of that expected of a perfect one-dimensional light bullet in Kerr media [2]. This means that the localization in a single waveguide should not be understood as just a trivial decoupling of the waveguides due to the nonlinearity.

It is clear from the experimental data that higher-order nonlinearities, beyond the Kerr nonlinearity, significantly modify and complicate the dynamics of the propagating pulse. In particular, the temporal compression proposed by Aceves *et al.* [11] is not observed in our experiment. This is mainly due to SRS, and possibly also as a result of high-order dispersion [13]. Nevertheless, the broad regime of strong spatial localization that we observe in the case of single waveguide excitation suggests the existence of a range of parameters where quasistable propagation may indeed occur. Since we are only able to characterize the pulses at the sample's output facet, our experiment does not give a direct and conclusive evidence for such quasistable propagation. However, it is very unlikely that the pulse, which is initially localized in a single waveguide, undergoes some unexpected dynamics inside the sample before reemerging at the output facet in a localized state. More likely, once the nonlinearity is strong enough to overcome the diffraction of the narrow input beam, the pulse is trapped in a single waveguide, and propagates a distance of several centimeters without significantly changing its shape. This pulse is definitely not a symmetrical optical bullet [2], but it is stable in the sense that its shape does not vary dramatically as the input power is further increased. In particular, as the input power is increased, self-focusing does not completely overcome the other processes that tend to broaden the wave packet, and the collapse is arrested. On the other hand, it is obvious that the strong SRS at very high input powers must result from a strong temporal contraction of the pulse and, since this contraction is not observed in the experiment, it is most likely that at these input powers the pulse initially contracts, and then broadens again, as a result of high-order dispersion.

We have compared our experimental results to two-dimensional numerical simulations of the NLSE [3] that use the split-step beam propagation method, and take into account SRS, MPA, high-order dispersion (third and fourth orders), and the periodic variation of the refractive index in the array. We find that high-order dispersion is essential for an effective arrest of the collapse. It also induces temporal broadening, limits the spectral broadening, and quenches MPA, all in agreement with the experiment. The simulations also show that at intermediate input powers the high-order dispersion results in the formation of an asymmetric pulse, which propagates a finite distance with very slow changes of its envelope. The shape of this trapped pulse depends on the magnitude and sign of the high-order dispersion terms. These results are in agreement with a recent theoretical analysis [14], which predicts that a small and negative fourth-order dispersion arrests the collapse and stabilizes optical bullets in Kerr media with dimensionality $d \leq 2$. A detailed discussion of the numerical simulations is beyond the scope of this paper, and will be presented elsewhere. However, they lend support to the interpretation of the experimental data as an indication for quasistable propagation.

This research was supported by the U.S.-Israel Binational Science Foundation and by NSERC in Canada. We are indebted to the staff of the mechanical workshop of Glasgow University. Valuable discussions with G. Fibich and B. Malomed are acknowledged.

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