Experimental Observation of the Fundamental Dark Soliton in Optical Fibers

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We present evidence of soliton propagation by 185-fsec dark pulses at a wavelength of 0.62 μm in a 1.4-m length of single-mode optical fiber. Our experiments utilize specially shaped, antisymmetric input pulses, which closely correspond to the form of the fundamental dark soliton. At appropriate power levels the dark pulses propagate without broadening. Our measurements are in quantitative agreement with numerical solutions to the nonlinear Schrödinger equation and constitute the first clear observation of the fundamental dark soliton in optical fibers.

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Although soliton phenomena arise in many distinct areas of physics, the single-mode optical fiber has been found an especially convenient medium for their study. Hasegawa and Tappert proposed in 1973 that the nonlinear refractive index in glass optical fibers could be utilized to compensate for group velocity dispersion (GVD), resulting in optical solitons which could propagate without distortion.[1] Since then, soliton propagation of bright optical pulses has been verified in a number of elegant experiments performed in the negative GVD region of the spectrum ($\lambda > 1.3\ \mu$m in standard single-mode fibers)[2]; most recently, transmission of 55-psec optical pulses through 4000 km of fiber was achieved, by use of a combination of nonlinear soliton propagation to avoid pulse spreading and Raman amplification to overcome losses.[3] For positive dispersion ($\lambda < 1.3\ \mu$m), bright pulses cannot propagate as solitons, and the interaction of the nonlinear index with GVD leads to spectral and temporal broadening of the propagating pulses. These effects form the basis for the fiber-and-grating pulse compressor,[4,5] which was utilized to produce the shortest optical pulses (6 fsec) ever reported.[6] For both signs of GVD, the experimental results are in quantitative agreement with the predictions of the nonlinear Schrödinger equation (NLSE).

Although bright solitons are allowed only for negative dispersion, the NLSE admits other soliton solutions for positive GVD.[1,7] These solutions are "dark-pulse solitons," consisting of a rapid dip in the intensity of a broad pulse or a cw background. The fundamental dark soliton, for which we report here the first experimental observation, is predicted to be an antisymmetric function of time, with an abrupt π phase shift and zero intensity at its center. Other dark solitons with a reduced contrast and a lesser, more gradual phase modulation also exist. Throughout the text we will use the terms "black" and "gray" soliton, respectively, to refer to the fundamental and to the lower-contrast dark-soliton solutions.

As a result of difficulty in generating the required input dark pulses, previous experimental evidence for dark-soliton propagation in fibers is limited. Krokel *et al.*[8] reported the evolution of an even-symmetry, 300-fsec dark pulse into a complementary pair of low-contrast dark pulses, which they interpreted as gray solitons. Emplit *et al.*[9] performed experiments utilizing odd-symmetry dark pulses $\simeq 5$ psec long. However, because the characteristic length for soliton propagation exceeded the attenuation length in their fiber, and because of insufficient temporal resolution in their pulse-shaping and pulse-measurement apparatus, they did not obtain clear indications of soliton propagation.

We have recently demonstrated a technique for synthesizing arbitrarily shaped femtosecond pulses,[10] and we apply this technique to generate 185-fsec, odd-symmetry dark pulses for studies of nonlinear propagation in a 1.4-m length of single-mode optical fiber ($\simeq 5X$ the characteristic length for soliton propagation of these pulses). Attenuation is negligible in this length of fiber, and our input pulse shape closely resembles the fundamental dark-soliton solution to the NLSE. At low input power we observe substantial broadening of the dark pulses by GVD; but at input powers corresponding to the soliton power,[1] we find that the dark pulses emerge from the fiber unbroadened. Our data are in quantitative agreement with numerical solutions to the NLSE. These results constitute the first clear evidence for fundamental dark-soliton propagation in optical fibers.

Although the theoretical dark-soliton solution to the NLSE contains a background of infinite extent, with our technique it was most efficient to generate 100–200-fsec duration dark pulses on background pulses 1–4 psec in duration. Because the background pulses broaden and acquire a chirp as they propagate, we performed extensive computer simulations to test whether dark pulses could exhibit stable soliton propagation with finite-extent background pulses. Our numerical simulations indicate that very stable soliton behavior can be expected even with a rapidly evolving background pulse.[11]

The experimental arrangement is depicted in Fig. 1. We start with 75-fsec, 620-nm pulses from a colliding-

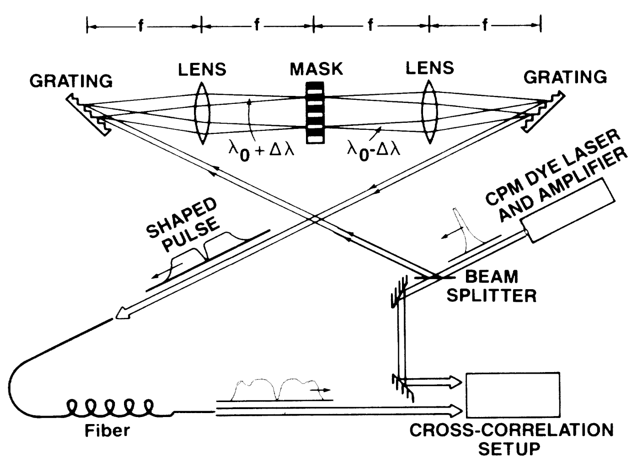

FIG. 1. Schematic of the experimental arrangement. f is the focal length of the lenses.

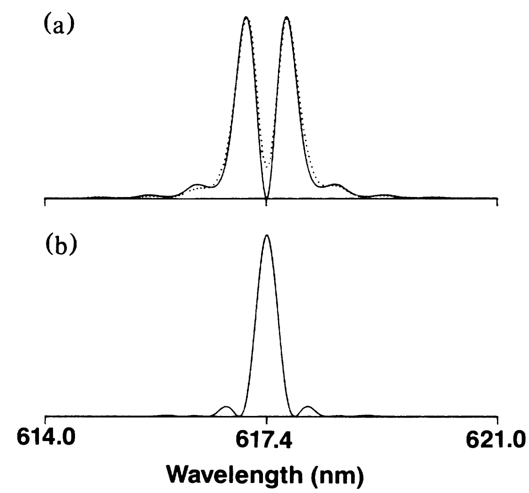

FIG. 2. (a) Calculated (solid line) and measured (dotted line) power spectra of the odd-symmetry dark pulse. (b) Calculated power spectrum of the even-symmetry dark pulse.

pulse-mode-locked (CPM) dye laser,[12] amplified at a 8.6-kHz rate by a copper-vapor laser-pumped dye amplifier system.[13] Pulses are tailored by spatial masking within a temporally nondispersive lens and grating apparatus.[14] Briefly, spatially patterned amplitude and phase masks are positioned midway between the gratings in the plane where the optical frequency components experience maximal spatial separation; the shape of the output pulse is the Fourier transform of the pattern transferred by the masks onto the spectrum.[10,14,15] Both even and odd dark pulses are investigated. In the present study shaped pulses are launched into a 1.4-m length of single-mode, polarization-preserving optical fiber (Newport Corp. F-SPV). A variable attenuator wheel is used to adjust the power coupled into the fiber. The intensity profile of the input pulses and of the pulses emerging from the fiber are measured by cross correlation, with use of 75-fsec pulses directly from the amplifier as the probe. The cross-correlation signal was obtained by noncollinear second-harmonic generation from a 0.3-mm-thick potassium-dihydrogen-phosphate crystal, and standard techniques were used for data acquisition and signal averaging.

For our study of the propagation of odd pulses, we synthesized a hyperbolic-tangent dark pulse on a broader Gaussian background pulse with a duration 10 times that of the dark pulse. The spectrum of this odd pulse is a doubly peaked, antisymmetric function of frequency. To generate this spectrum, we utilized an amplitude mask consisting of a variable transmission metal film on a fused silica substrate, and a separate phase mask etched to introduce a relative phase shift of π into half of the spectrum. Details of the mask fabrication are given elsewhere.[10] The power spectrum of the shaped pulse was measured with a 0.32-m spectrometer and a photodiode array (spectral resolution $\simeq 0.17$ nm). The measurement, plotted as the dotted line in Fig. 2(a), is in excellent agreement with the power spectrum calculated for the targeted antisymmetric input pulse (solid line). For contrast we show the calculated power spectrum for an even-symmetry dark pulse, $|E_{\text{even}}(\omega)|^2$, in Fig. 2(b). The spectrum $E_{\text{even}}(\omega)$ and the corresponding amplitude and phase masks are each symmetric functions of frequency. Thus, we can easily distinguish between even- and odd-symmetry input pulses, by the clear differences in their spectra.

Experimental results for an odd-symmetry input pulse are presented in Fig. 3. Figure 3(a) shows an intensity cross-correlation measurement of the input pulse. The duration of the central hole is 185 fsec full width at half maximum (FWHM) of the intensity, and the background duration is 1.76 psec FWHM. For comparison, a simulated cross-correlation measurement of the desired input pulse is also plotted. Clearly, the actual pulse is an excellent replica of the target pulse. Cross-correlation traces of the output pulses from the 1.4-m fiber are plotted in Figs. 3(b)–3(e) for various power levels. Similar data were recorded for input pulses consisting of an antisymmetric dark pulse on a square background. At the lowest power (1.5-W peak input power), propagation is linear. Because of GVD the input dark pulse broadens to over 600 fsec, and the background pulse develops a ringing structure from interference with the temporally broadened, frequency-swept dark pulse.[16] As the power is increased, the background pulse broadens and acquires a square profile because of the combined effects of the nonlinear index and GVD.[5] At the same time, the width of the output dark pulse decreases; and at 300-W peak input power, the output dark pulse is of essentially the same duration as the input. Thus the dark pulse undergoes solitonlike propagation and emerges from the fiber unchanged, even in the presence of significant broaden-

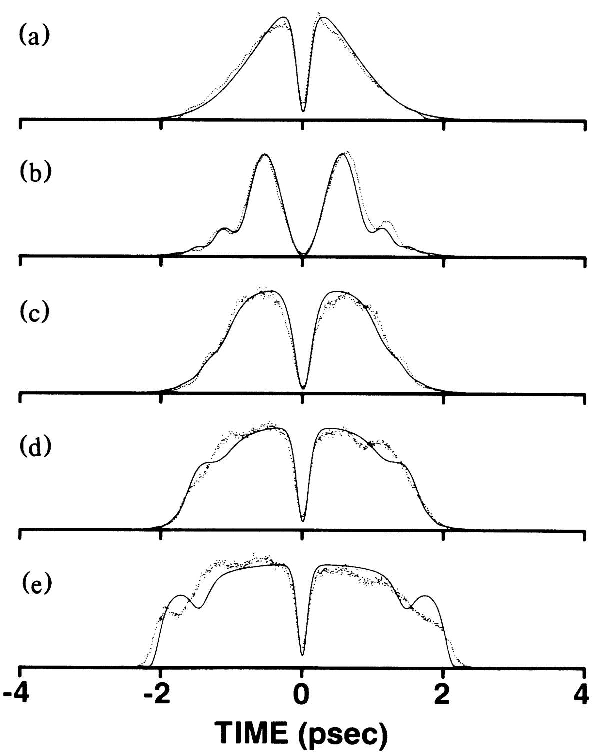

FIG. 3. Measured (dotted lines) and calculated (solid lines) cross-correlation data for the odd-symmetry dark pulse. (a) Input dark pulse. (b)–(e) Pulses emerging from the fiber for peak input power of (b) 1.5, (c) 52.5, (d) 150, and (e) 300 W.

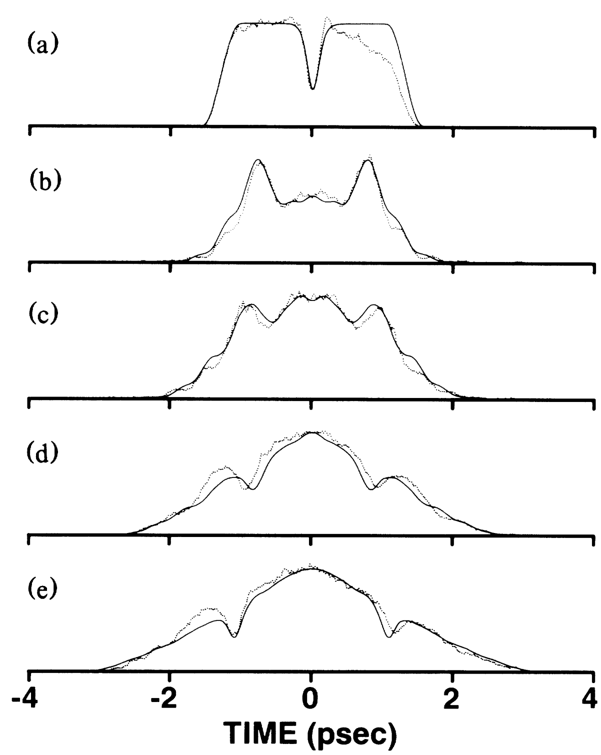

FIG. 4. Measured (dotted lines) and calculated (solid lines) cross-correlation data for the even-symmetry dark pulse. (a) Input dark pulse. (b)–(e) Pulses emerging from the fiber for peak input power of (b) 2.5, (c) 50, (d) 150, (e) 285 W.

ing and chirping of the finite-duration background pulse.

Computer solutions to the plane-wave NLSE are in quantitative agreement with these data. The calculated curves, which have been convolved with a 75-fsec Gaussian to account for the cross correlation performed in the actual experiments, are plotted as solid lines in Figs. 3(b)–3(e). Our calculations were performed without adjustable parameters. We accounted for uncertainties in the nonlinear index, in our peak power measurements, and in the fiber effective area, by measuring the spectral broadening of a standard 2-psec pulse (containing no dark pulse) as a function of power. By comparing the spectral broadening data with the predictions of the NLSE, we determined a calibration factor which we used in all the dark-pulse propagation calculations. At low power [Fig. 3(b)], the numerical results predict broadening of the dark pulse and modulation of the background pulse, in accord with experiment. At higher powers [Figs. 3(d) and 3(e)], the numerical simulation shows that the dark pulse narrows to its original duration while the background broadens, also in close correspondence with the experimental observations.

Data for an even-symmetry dark pulse on a squarelike background are plotted in Fig. 4. Figure 4(a) shows a measurement of the input pulse, which was generated with use of masks designed to produce the spectrum depicted in Fig. 2(b). Cross-correlation measurements of the output pulses from the fiber are shown in Figs. 4(b)–4(e). The trends are similar to those reported previously by Krokel *et al.*[8] At low power the central hole disappears, and the background pulse is reshaped by interference with the chirped, temporally broadened dark pulse. As the power is increased, we observe the formation of two low-contrast holes, separated by $\simeq 2.3$ psec at 285-W peak input power. Again, the data agree closely with numerical solutions to the NLSE (shown as solid lines in Fig. 4). Splitting of an even dark pulse into a complementary pair of gray solitons was predicted theoretically by Blow and Doran.[17] Our computer simulations indicate that the relative velocity between gray solitons increases for higher input powers; our data confirm that the soliton separation increases with power. Our experiments demonstrate the crucial importance of the dark-pulse phase profile: An odd dark pulse propagates undistorted as a soliton, as predicted by theory,[1] while an even dark pulse, which is not a soliton solution to the NLSE, splits into a pair of shallow gray solitons.

We have also investigated dark-pulse propagation at higher input powers. For odd-symmetry input pulses, numerical simulations show that above the soliton power the input dark pulse narrows and spawns a pair of gray solitons, which separate in opposing directions from the black soliton.[11] Such a gray-soliton pair is evident in the theoretical trace in Fig. 3(e), and one of the gray solitons can be observed in the data. At still higher powers, we observed that the central hole shifted to later times within the background pulse and grew shallower. Spectral measurements revealed a blue shift of the central dark pulse. These observations are not predicted by the standard NLSE. A spectral shift to the red was previously reported for bright solitons and explained in terms of Raman amplification of long-wavelength spectral components at the expense of shorter-wavelength components.[18] We find that numerical solutions to a modified NLSE, which includes a Raman contribution to the nonlinear refractive index, do predict the experimentally observed temporal and spectral shift of the dark soliton as well as a loss of contrast. We will discuss this dark-soliton self-frequency shift elsewhere.

In summary, we have investigated nonlinear propagation of visible-wavelength, femtosecond dark pulses in single-mode fiber. Odd-symmetry dark pulses were observed to propagate without distortion, whereas even-symmetry dark pulses split into a pair of low-contrast dark solitons. These results confirm the theoretical prediction that the fundamental dark soliton is an antisymmetric function of time. Our data provide the first unambiguous evidence for fundamental dark-soliton propagation in optical fibers.

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