Dramatically improved transmission of ultrashort solitons through 40 km of dispersion-decreasing fiber

Andrew J. Stentz and Robert W. Boyd

University of Rochester, Rochester, New York 14627

Alan F. Evans

Corning, Inc., Corning, New York 14831

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A 40-km length of optical fiber whose group-velocity dispersion decreases exponentially along its length has been fabricated. We experimentally compare the propagation of picosecond solitons through the dispersion-decreasing fiber with that through a constant-dispersion fiber of the same path-averaged dispersion. For a wide range of input powers, the output pulse widths of the dispersion-decreasing fiber are found to be as short as the input pulse widths, whereas the output pulse widths of the constant-dispersion fiber are significantly larger. Numerical simulations of the experiment are performed and are in good agreement with the experimental results.

Recent experiments demonstrate that with standard constant-dispersion fiber,[1] soliton-based communication systems can operate at communication rates of tens of gigabits per second. However, the use of constant-dispersion fiber with discrete optical amplifiers places pulse width and amplifier-spacing limitations on these systems.[2] If the solitons are to remain stable as they are periodically attenuated and amplified, the pulses must propagate as guiding-center or average solitons.[3] This regime of operation requires that the solitons do not substantially evolve in one amplifier span and therefore that the soliton period be much larger than the amplifier spacing, L_A, or that the soliton pulse width satisfy the constraint

$$T_0 \gg \sqrt{\frac{|\beta_2| L_A}{4\pi}}\,. \tag{1}$$

Here T_0 is the soliton pulse width and β_2 is the group-velocity-dispersion parameter defined by $\beta_n = (\partial^n \beta / \partial \omega^n)|_{\omega=\omega_0}$, where β is the wave number of the fundamental mode of the fiber. Additionally, in wavelength-division-multiplexed systems, solitons of different wavelengths must collide over more than one amplifier span to path-average the interaction over several discrete amplifiers and prevent asymmetric soliton collisions. Therefore the maximum wavelength separation $\Delta\lambda_{max}$ between solitons must satisfy the constraint[4]

$$\Delta\lambda_{max} < \frac{\lambda^2 T_0}{2\pi c |\beta_2| L_A}\,. \tag{2}$$

Both of these constraints arise from the fact that the use of discrete amplifiers and constant-dispersion fiber, while it maintains a path-averaged balance, upsets the local balance between the effects of self-phase modulation and group-velocity dispersion.

One technique proposed for eliminating these constraints is to use dispersion-decreasing fiber to maintain a local balance.[5,6] To see how dispersion-decreasing fiber can achieve a local balance, we examine the nonlinear Schrödinger equation in dimensionless units

$$i\,\frac{\partial U}{\partial \xi} = \mathrm{sgn}(\beta_2)\frac{1}{2}\,\frac{\partial^2 U}{\partial \tau^2} - N^2 |U|^2 U\,, \tag{3}$$

where U, ξ, and τ are the normalized slowly varying amplitude of the electric field, longitudinal distance, and local time, respectively. All the fiber parameters are contained in the soliton order number N, where

$$N^2 = \frac{\omega_0 n_2 P_0 T_0^2}{c A_{eff} |\beta_2|}\,. \tag{4}$$

Here P_0 is the peak power of the pulse, n_2 is the nonlinear refractive index, and A_{eff} is the effective core area of the fiber. One can see that as the energy of a pulse decreases, the soliton order number N can be held constant if the group-velocity dispersion of the fiber is made to decrease exponentially along the length of the fiber at the same rate as the energy of the pulse. Within the approximation of Eq. (3), the nonlinear propagation of the pulse under these conditions will be exactly the same as that of a soliton propagating in a completely lossless fiber whose constant group-velocity dispersion is equal to the path-averaged dispersion of the dispersion-decreasing fiber. For a fundamental soliton, there should be no localized change in the temporal or spectral profile.

Short lengths of quickly decreasing dispersion fiber have been fabricated for the purposes of pulse compression and soliton train generation.[7] However, in this Letter we report what is to our knowledge the first fabrication and characterization of a dispersion-decreasing fiber that is of a length comparable with those typically used in communication systems. In addition, for the first time to our knowledge, the rate of decrease of the group-velocity dispersion is closely matched with the loss coefficient, making it possible to maintain a local balance between

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group-velocity dispersion and self-phase modulation along the entire length of the fiber. Improvement in the stability of soliton propagation is observed even for a single discrete amplifier span.

We fabricated the 40-km length of dispersion-decreasing fiber by tapering the fiber during the drawing process and thereby altering the waveguide contribution to the group-velocity dispersion. The feedback controls on the dimensions of the fiber were changed during the drawing process[7] more frequently at the higher-dispersion end of the fiber than at the lower-dispersion end to approximate an exponential decrease more closely. The dispersion of the fiber was measured at the input ($-8.74\ \mathrm{ps}^2/\mathrm{km}$), 23 km from the input ($-3.59\ \mathrm{ps}^2/\mathrm{km}$), and at the output ($-1.75\ \mathrm{ps}^2/\mathrm{km}$). An exponential fit to these three points of the form $\beta_2 = \beta_{2,0} \exp(-\gamma z)$ yields a rate of decrease of the dispersion of $\gamma = 0.211$ dB/km, which is closely matched with the measured loss coefficient of 0.224 dB/km. Changing the dimensions of the fiber also alter its effective core area, which changes the soliton number [Eq. (4)]. However, the dependence of the effective core area on the dimensions of the fiber is much weaker than that of the group-velocity dispersion. In this case, the group-velocity dispersion decreases by a factor of almost 7 over the length of the fiber, whereas the effective core area changes by less than 8%. For comparison purposes, a 35-km length of constant-dispersion fiber of approximately the same path-averaged dispersion ($\beta_2 = -3.6\ \mathrm{ps}^2/\mathrm{km}$) also was drawn. The index profile and loss were the same as those of the dispersion-decreasing fiber.

A fiber figure-eight laser was used to generate solitons for testing the fibers. A bandpass filter was incorporated in the laser cavity to eliminate the sharp spectral features caused by dispersive-wave components within the laser cavity and to allow the central wavelength of the output pulses to be tuned. The soliton generated by the laser were nearly transform limited, and they had a pulse width of 1.5 ps and a central wavelength of 1.546 μm. These pulses were passed through an erbium-doped fiber amplifier, through the test fiber, and then into an autocorrelator and a scanning monochromator.

The main experimental results are presented in Fig. 1. The autocorrelation traces of the pulses produced by the fiber laser are shown in Fig. 1(a). Assuming a hyperbolic-secant pulse shape, the pulses have an inferred FWHM of 1.5 ps. Shown in Fig. 1(b) is the autocorrelation of the pulses after they have traversed the constant-dispersion fiber with a path-averaged soliton number of approximately one. The pulses have broadened to a pulse width of 4.4 ps. In contrast, shown in Fig. 1(c) is the autocorrelation of the solitons that have traversed the dispersion-decreasing fiber. Note that the output autocorrelation of the dispersion-decreasing fiber is very similar to the input autocorrelation shown in Fig. 1(a) but with a slightly shorter pulse width of 1.3 ps. This is strong evidence that a local balance between self-phase modulation and group-velocity dispersion is being maintained in the dispersion-decreasing fiber.

The output pulse widths of the constant-dispersion and dispersion-decreasing fibers are plotted in Fig. 2 as functions of the path-averaged soliton number, which is directly proportional to peak input power. Note that for a broad range of input powers the output pulse widths of the dispersion-decreasing fiber are shorter than those from the constant-dispersion fiber. At low powers, as the path-averaged soliton number falls below one, the output pulse widths increase dramatically. This is easily understood because each fiber is more than 100 dispersion lengths long; therefore, if the input pulses are not intense enough to form solitons, the pulses quickly undergo a large amount of dispersion-induced pulse broadening. Less evident is the reason why both plots flatten at higher input power levels. Inspection of the output spectra at the higher power levels (not shown here because of length considerations) shows that intrapulse Raman scattering plays a dominant role. Intrapulse Raman scattering causes the higher-order solitons to break up into fundamental solitons that then shift to longer wavelengths on propagation because of the soliton self-frequency shifts.[8]

As more energetic pulses are injected into the fiber, a smaller percentage of the energy remains in the fundamental soliton whose pulse width is plotted in Fig. 2. At the highest power levels, as intrapulse Raman scattering increases the central wavelength of the pulses, cubic dispersion causes the pulses to experience increasing group-velocity dispersion along the length of the fiber, which then tends to broaden the pulses. This complicated interplay of higher-order effects has been investigated by a number of researchers,[9,10] and although it is not the main subject

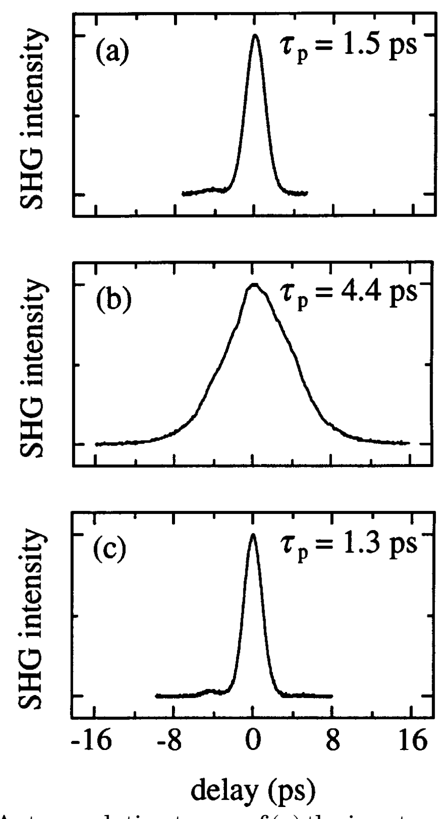

Fig. 1. Autocorrelation traces of (a) the input pulse, (b) the pulse after traversing the constant-dispersion fiber, and (c) the pulse after traversing the dispersion-decreasing fiber.

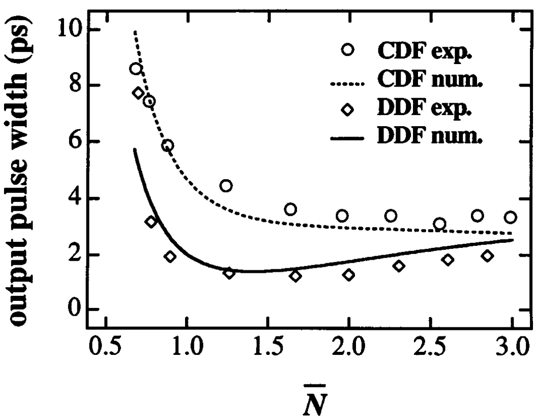

Fig. 2. Experimental and numerical output pulse widths of the constant-dispersion fiber (CDF) and the dispersion-decreasing fiber (DDF) as functions of the path-averaged soliton number.

of this Letter, it is mentioned to explain the insensitivity of the observed pulse width to higher input power levels. For the input power where $N \approx 1$, the spectrum of the solitons that have traversed the dispersion-decreasing fiber has a hyperbolic-secant pulse shape and a time–bandwidth product of 0.36; it has experienced a soliton self-frequency shift of 0.6 nm that agrees well with the theoretically predicted value.[8]

Numerical simulations of the experiment were performed by the standard split-step Fourier method to integrate the generalized nonlinear Schrödinger equation:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial T^3} = i\gamma |A|^2 A - T_R A \frac{\partial |A|^2}{\partial T} \cdot \quad (5)$$

Here A is the slowly varying amplitude of the electric field, z is the longitudinal distance, T is the local time, γ is a constant proportional to n_2, and T_R is the Raman coefficient assumed equal to 5 fs in the simulations. The results of the numerical simulations also are displayed in Fig. 2. The numerical results are in good agreement with the experimental results, particularly at the lower power levels. To achieve better agreement at the higher power levels, a more accurate model of intrapulse Raman scattering would have to be included, because the pulses initially compress to pulse widths as short at 250 fs. To match the experimental and numerical results, the conversion factor between average power out of the laser and path-averaged soliton number in both fibers had to be adjusted by ~30%. Considering that the conversion factor includes measurements of the average power and repetition rate of the laser, the pulse width of the solitons, and the nonlinear refractive index, dispersion, effective core area, and splice losses of the fibers, we believe that this level of agreement is acceptable.

The use of pulse widths as short as 1.5 ps is not necessary for the benefits of dispersion-decreasing fiber to be realized. Input pulse widths as short as 1.5 ps were used in this experiment only for the purpose of showing that more than 100 soliton periods in a single fiber span would bring about an appreciable effect. Dispersion-decreasing fiber would be useful in communication systems that use tens or hundreds of amplifier spans and more practical pulse widths of tens of picoseconds because, in principle, it maintains a local balance between group-velocity dispersion and because it symmetrizes soliton collisions.

In conclusion, we have demonstrated that long lengths of dispersion-decreasing fiber can be fabricated for systems in which the group-velocity dispersion and the energy of the pulses decrease at the same rate. We have experimentally investigated the propagation of 1.5-ps solitons through a dispersion-decreasing fiber and through a constant-dispersion fiber of the same path-averaged dispersion. Over a broad range of input powers, the output pulse widths of the dispersion-decreasing fiber are shorter than those of the constant-dispersion fiber. For fundamental solitons, the output pulse width of the dispersion-decreasing fiber is as short as the input pulse width, whereas the output pulse width of the constant-dispersion fiber has increased by a factor of 3. For higher-order solitons, the evolution of the solitons is dominated by higher-order effects. Numerical simulations of the experiment were performed and are in good agreement with the experimental results.

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