Broadband fiber dispersion compensation for sub-100-fs pulses with a compression ratio of 300

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We report what is, to our knowledge, the first experimental demonstration of nearly dispersion-free transmission of sub-100-fs pulses over several tens of meters of fiber. 62-fs pulses are broadened initially and recompressed by a ratio of 300 over a 42-m concatenated fiber link consisting of standard single-mode and dispersion-compensating fibers. This dispersion-compensated fiber link is estimated to have a third-order dispersion ~6 times lower than that of dispersion-shifted fiber.

Dispersion imposes important limitations on ultrashort pulse transmission in optical fibers. The limitations are particularly severe for femtosecond pulse transmission. Linear pulse propagation with dispersion compensation is important for time-division-multiplexed and code-division multiple-access[1] optical communication as well as for special applications such as femtosecond chirped-pulse fiber amplifier systems.[2] In this Letter we report on the use of dispersion-compensating fiber for 300-fold pulse recompression of sub-100-fs pulses. Compared to other femtosecond all-fiber dispersion-compensation experiments,[3] we achieve nearly a factor of 5 higher compression ratio with ~7 times shorter pulses.

Over the past several years researchers have intensively investigated a variety of dispersion-compensation techniques for fiber system experiments operating below a few tens of gigabits per second.[4] One of the key drivers for this research is the desire to upgrade 1.3-μm standard single-mode fibers (SMF's) for use in state-of-the-art systems at 1.5 μm. In addition, a number of fiber experiments exploring linear dispersion compensation with femtosecond pulses are beginning to appear. One recent system experiment used linear propagation with dispersion compensation for transmission of 980-fs pulses to demonstrate 400-Gbit/s time-division-multiplexed transmission.[5] Chirped-fiber Bragg gratings were also applied to 400-fs pulse transmission[3] and femtosecond all-fiber chirped-pulse amplification,[2] for which compensation of linear chirps induced by second-order dispersion was successfully demonstrated. However, chirped-fiber Bragg gratings generally have reflectivity bandwidths of 5–15 nm, which may constrain femtosecond applications in which larger bandwidths are often involved. For even shorter pulses, second-order dispersion compensation alone is not sufficient because wavelength components away from the center of the spectrum still experience dispersion because of the uncompensated dispersion slope.[6,7] Simultaneous second- and third-order dispersion compensation for femtosecond pulses was studied by use of a bulk-optic diffraction grating pair.[6] In our research we are interested in extending the use of dispersion-compensating fibers[8,9] (DCF's), which is an all-fiber technique, to simultaneous second- and third-order dispersion compensation for femtosecond pulse experiments. Our present results demonstrate nearly complete dispersion compensation for 62-fs pulses transmitted over a 42-m SMF–DCF concatenated fiber link. To our knowledge this is the first experimental demonstration of sub-100-fs pulse propagation over several tens of meters of fiber. Our experiments with extremely short pulses and still rather short fiber lengths may be of immediate interest for femtosecond chirped-pulse fiber amplifier systems, which have been limited to ~400-fs pulses[2] and also serve as an extremely sensitive test for measuring small amounts of residual dispersion in the compensated fiber link. The results of our measurements can be used to extrapolate dispersion-compensation performance for somewhat longer pulses (a few hundred femtoseconds) over fiber links in the kilometer range suitable for local area network applications.

The idea of the DCF technique is to concatenate a SMF with a DCF whose dispersion–length product is equal in magnitude and opposite in sign to that of the SMF. The dispersion of a concatenated SMF–DCF fiber link can be characterized by an equivalent dispersion given as $D_{\mathrm{eq}}(\lambda) = [RD_{\mathrm{SMF}}(\lambda) + D_{\mathrm{DCF}}(\lambda)]/(1 + R)$, where R is the length ratio of the SMF to the DCF and D_{SMF} and D_{DCF} are the dispersions of the SMF and the DCF, respectively. $D_{\mathrm{eq}}(\lambda)$ can be expanded about the center wavelength λ_c as $D_{\mathrm{eq}}(\lambda) = D_{\mathrm{eq}}(\lambda_c) + D_{\mathrm{eq}}'(\lambda_c)(\lambda - \lambda_c) + \ldots$. Here D_{eq}' is the first derivative of D_{eq} with respect to wavelength

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λ. $D_{eq}(\lambda_c)$ and $D_{eq}'(\lambda_c)$ are called the dispersion and the dispersion slope, respectively. When the second-order dispersion is compensated (D and $\beta_2 = 0$), the remaining dispersion is usually dominated by the third-order dispersion or the dispersion slope. To compensate for the dispersion experienced in a SMF that has an anomalous dispersion $D \approx 17$ ps/(nm km) and a positive dispersion slope $D' \approx 0.06$ ps/(km nm^2) at 1550 nm, a DCF with favorable dispersion characteristics (i.e., large normal dispersion and a negative dispersion slope) is required for ultrashort pulse transmission. Simultaneous cancellation of second- and third-order dispersion can potentially permit propagation distances over 100 km for subpicosecond pulses, as we showed numerically in the case of a two-mode fiber dispersion compensator.[7]

As illustrated in Fig. 1, the basic idea of our experiments is to propagate low-power femtosecond pulses through a concatenated SMF–DCF link and then measure the resulting output pulses. The femtosecond pulse source for our experiments was a stretched-pulse mode-locked Er-doped fiber ring laser.[10] Our version of this laser uses a length of DCF with large positive (normal) dispersion, which gives an overall cavity dispersion–length product of $\sim+0.05$ ps^2. The laser generates a stable train of femtosecond pulses at a 34-MHz repetition rate, with one pulse per cavity round-trip time. The power spectrum of the mode-locked pulses has a FWHM bandwidth of 60 nm, as shown in Fig. 2(A).

As depicted in Fig. 1, the output of the fiber ring laser was connected to a 10/90 fiber coupler followed by a second 20/80 fiber coupler to branch out the power for diagnostics and dispersion-compensation experiments. We measured the pulse width by using a standard second-harmonic-generation (SHG) intensity autocorrelator. A length of DCF is spliced between the two fiber couplers to yield, at the 20% output of the second fiber coupler, nearly transform-limited pulses that have an autocorrelation width of 95 fs FWHM [Fig. 2(B)]. Assuming a secant hyperbolic pulse shape, we note that this corresponds to an intensity pulse width of 62 fs FWHM.

For dispersion-compensation experiments the 80% port of the last fiber coupler is connected to a concatenated SMF–DCF fiber link (~42 m total). The DCF is a special fiber that relies on the proper design of the refractive-index profile for large dispersion and a dispersion slope capable of combating second- and third-order dispersion in SMF.[12] The DCF used here (AT&T JRFDC1074C1DC) has $D \approx -76$ ps/(km nm) (or $\beta_2 \approx 96$ ps^2/km) at 1550 nm and a negative dispersion slope to equalize the SMF (AT&T 5D) that has dispersion $D = 17$ ps/(km nm) (or $\beta_2 = -22$ ps^2/km) at 1550 nm and a positive dispersion slope. We measure the pulses propagating through this fiber link (which we denote signal pulses) by performing intensity cross-correlation measurements with the 62-fs reference pulses that emerge out of the 20% port of the fiber coupler. The average optical power sent to the concatenated fiber link is 0.65 mW, corresponding to a peak power of 275 W (~2.8% of the $N = 1$ soliton power for 62-fs pulses in SMF) at the input to the fiber link. Because the pulse width broadens rapidly in the first few meters of propagation, accumulated nonlinear phase shifts are expected to be very small. This contention is supported by nonlinear Schrodinger equation simulations. The power spectrum measured from the output of the 42-m link appears similar to the input spectrum for average powers up to 2.0 mW, the highest we have available, providing further evidence that we are operating in the linear transmission regime as desired.

To minimize the overall link dispersion, we performed a series of measurements in which the lengths of SMF and DCF were iteratively adjusted and fine tuned to reduce the duration of the output signal pulse. The cross-correlation trace of the shortest output pulses is shown in Fig. 3(A). The correlation width is 125 fs FWHM, corresponding to a deconvolved pulse duration of ~110 fs, which is within a factor of 2 of the reference pulse duration. Although we did not measure the pulses after the SMF section alone, we calculate that the pulses should be broadened to ~35 ps at this point. By virtue of the DCF, the final output pulse is recompressed by a ratio of 300. To illustrate the magnitude of pulse stretching and successful recompression, we show in Fig. 3(B) the trace of the optimally recompressed signal pulse together with the calculated 35-ps pulse (the intensity of the 35-ps pulse is magnified 20 times to be discernible). The shortest output pulses are obtained for an optimal fiber length ratio $R_{opt} \sim 4.57$ (34.7 m/7.6 m). The pulse duration increases by 10% when the length ratio is changed by ~0.15%. This indicates that accurate adjustment of the length ratio is important for the success of the DCF technique, as expected for our case of a very high recompression ratio. It appears that the overall dispersion for this SMF–DCF fiber link is dominated by third-order dispersion, which leads to the weak

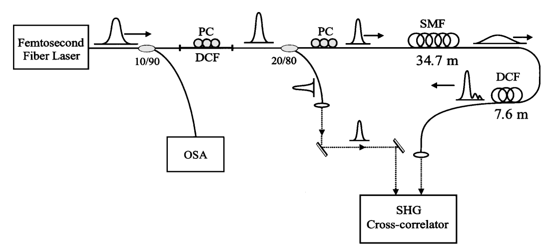

Fig. 1. Experimental layout for dispersion-compensation experiments. 10/90, 20/80, fiber couplers; OSA, optical spectrum analyzer; PC, polarization controller.

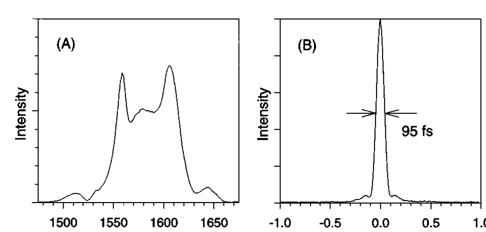

Fig. 2. Femtosecond pulses from a stretched-pulse mode-locked fiber ring laser. (A) Power spectrum, (B) background-free autocorrelation.

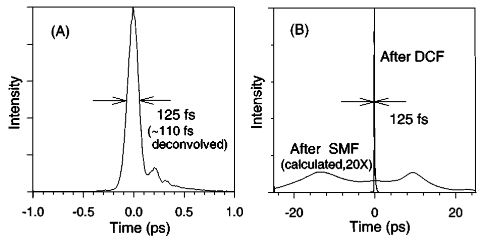

Fig. 3. (A) Optical intensity cross-correlation trace. (B) Output pulse from (A) superimposed upon the calculated pulse after propagation through 35-m of SMF alone (magnified 20 times). This dispersion-compensated pulse shows a recompression ratio of 300.

oscillatory behavior on the trailing tail of the pulse in Fig. 3(A), a phenomenon typical of positive third-order dispersion. By using a spectral interferometry measurement technique,[13] we estimate that the equivalent dispersion slope D_{eq}' is $\sim 0.0088 \pm 0.001$ ps/(km nm^2) at a zero dispersion wavelength of 1591 ± 3 nm, a significant improvement over that of dispersion-shifted fiber, which usually has $D' = 0.05$ ps/(km nm^2). Our estimate of the dispersion slope is consistent with the amount of asymmetric pulse tail observed in Fig. 3(A); however, a quantitative dispersion estimate from the pulse shape alone is difficult because of the irregular laser power spectrum and because the output shape may be somewhat influenced by small amounts of chirp in the input pulse to our experiments.

Note that we directly measured the overall dispersion of the whole SMF–DCF fiber link, rather than measuring the dispersion of the individual fibers separately and weighting them according to their lengths, because we are interested in only the overall uncompensated dispersion effect. Furthermore, measuring the whole link directly provides the most accurate estimate of the total link dispersion (which is dominated by third-order dispersion β_3), whereas in the individual SMF or DCF β_2 is dominant.

Substantially longer transmission distances should be possible with longer femtosecond pulses, provided that dispersion characteristics we have measured here can be scaled to longer concatenated SMF–DCF links. For a fiber link dominated by third-order dispersion, the propagation distance is proportional to the third power of the pulse width for a fixed pulse-broadening ratio.[13] For the present case of 62-fs pulses traveling over a 42-m SMF–DCF fiber link, the broadening ratio is 1.77. Therefore, for example, we expect a comparable broadening ratio for 250- or 500-fs pulses propagating over SMF–DCF fiber links 2.8 or 22 km in length, respectively. (Of course, if much longer fibers are used, amplification may become necessary, which could affect the experimental results.) These lengths should be suitable for local area networking applications. Even better performance should be possible if third-order dispersion could be completely eliminated. This can be achieved for a DCF where the D'/D ratio is the same as for SMF. Our DCF has a D'/D of $\sim$90% that of SMF, which means that 10% of the positive third-order dispersion in the SMF was not compensated. In practice it is difficult to make a perfectly matched DCF. Another approach to compensate second- and third-order dispersion simultaneously is to use a combination of two DCF's, one with D'/D larger than SMF and the other with D'/D smaller. Because both DCF lengths can be adjusted, there are more degrees of freedom to adjust the overall dispersion; therefore this combination of two DCF's should be more versatile in combating dispersion and dispersion slope for a wider wavelength range.

In summary, we have demonstrated nearly dispersion-free, linear transmission of 62-fs pulses over >40 m of fiber. This is made possible by a composite SMF–DCF link with third-order dispersion $\sim$6 times less than that of dispersion-shifted fibers. To our knowledge, this is the first report of several hundredfold broadening and compression of sub-100-fs pulses in an all-fiber system. If our current experiments can be scaled to longer pulses in the 200–500-fs range, substantially longer transmission distances in the range of a few kilometers to tens of kilometers should be possible. Our results should have an effect on ultrashort-pulse fiber transmission as well on as chirped-pulse fiber amplification systems.

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