Fully dispersion-compensated ∼500 fs pulse transmission over 50 km single-mode fiber

Z. Jiang, S.-D. Yang, D. E. Leaird, and A. M. Weiner

School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Avenue, West Lafayette, Indiana 47907-2035

Received December 14, 2004

We demonstrate essentially distortionless 50 km fiber transmission for ∼500 fs pulses, using dispersion-compensating fiber and a programmable pulse shaper as a spectral phase equalizer. This distance is approximately five times longer than previously achieved at similar pulse widths. © 2005 Optical Society of America

OCIS codes: 320.7160, 320.5540, 060.2330.

Ultrashort optical pulse fiber transmission plays a critical role in high-speed optical time-division multiplexing[1,2] and optical code-division multiple access.[3,4] However, fiber dispersion may cause serious distortion of a broadband ultrashort pulse. The most successful and most widely commercially used dispersion-compensation (DC) technique is the use of dispersion-compensating fiber (DCF) specially designed to have opposite dispersion parameters from single-mode fiber (SMF), in which most second-order and partial third-order dispersion are compensated. For ultrashort pulses, accumulated residual second- and third-order dispersion in a fiber link can still cause serious distortion, even if high-quality DCF is used. One solution is to design fiber links with special fiber characteristics and trim the fiber length precisely to match dispersion and minimize distortion. For example, a dispersion slope compensation fiber has been used in a 120 km link to reduce the third-order dispersion for 400 fs pulses.[2] Nonetheless, this technique required special fiber links with precise trimming of fiber lengths. More importantly, the pulse is still broadened significantly (to 700 fs) because complete DC is extremely difficult if not impossible. A technique for fine tuning of higher-order dispersion based on synchronous phase modulation of a prechirped pulse has been demonstrated in a 380 fs, 70 km transmission experiment.[5] However, this synchronous modulation scheme restricts the transmission format. Here we discuss a passive, format-independent technique that is capable of fine tuning and completely removing the residual dispersion for a nearly compensated fiber link, which relaxes the required precision in fiber lengths and increases the tolerance to variations in fiber dispersion. Previously, our group demonstrated almost exact third-order correction for 500 fs pulse distortion-free transmission over 2.5 (Ref. 6) and 10 km (Ref. 7) SMF–DCF links, using a programmable pulse shaper.[8] The pulse shaper, originally developed for ultrafast optics applications, functions as an adjustable spectral phase equalizer that permits programmable dispersion compensation and reduces the need for careful DCF selection and precise fiber length trimming. In this Letter we extend the capability of this pulse shaping technique to fiber dispersion compensation and report essentially distortion-free transmission for ∼500 fs pulses over a 50 km fiber link. The fiber link is a commercial fiber module (directly from the vendor) with no extra effort made to further control fiber length to minimize residual dispersion. Our results demonstrate that the pulse shaping technique can effectively remove both residual second- and third-order dispersion for femtosecond pulse transmission in excess of 50 km without strict requirements on the DCF length, which covers the distance range of practical interest for local area network and metro area network applications by use of optical time-division multiplexing or optical code-division multiple access. We have also observed a polarization mode dispersion (PMD) effect, which usually plays a role only in long-haul fiber transmission systems.

Figure 1 shows a schematic diagram of our experimental apparatus. An actively mode-locked fiber laser followed by a dispersion-decreasing fiber soliton compressor producing nearly transform-limited 400 fs pulses at 10 GHz centered near 1542 nm is used as the pulse source. These ultrashort pulses are input into a fiber-coupled Fourier-transform pulse shaper,[8] which incorporates a 128-element liquid-crystal modulator array to apply the spectral phase. This pulse shaper facilitates dispersion control through the relation $\tau(\omega)=-[\partial\Psi(\omega)/\partial\omega]$, where $\tau(\omega)$ and $\Psi(\omega)$ are the frequency-dependent delay and spectral phase, respectively. The fiber-to-fiber insertion loss of the pulse shaper is less than 5 dB. The output of the pulse shaper is connected to SMF (50.164 km) and DCF modules (OFS Fitel). The total loss for the SMF–DCF link is 14.4 dB. An erbium-doped fiber amplifier (EDFA) is used for loss compensation of the whole system. In our system, most second-order and partial third-order dispersion is compensated for by the DCF. The pulse shaper is

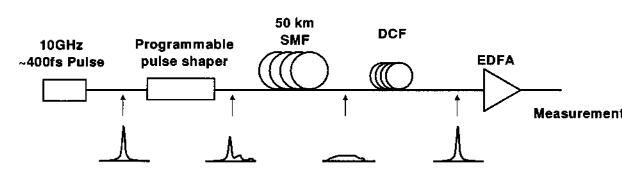

Fig. 1. Experimental apparatus.

0146-9592/05/121449-3/$15.00

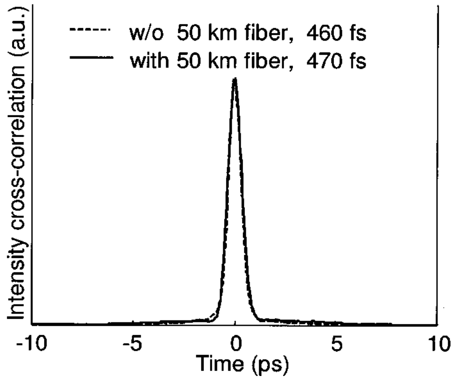

Fig. 2. Intensity cross correlation with and without a SMF–DCF module, demonstrating distortionless 50 km fiber transmission for sub-500 fs pulses.

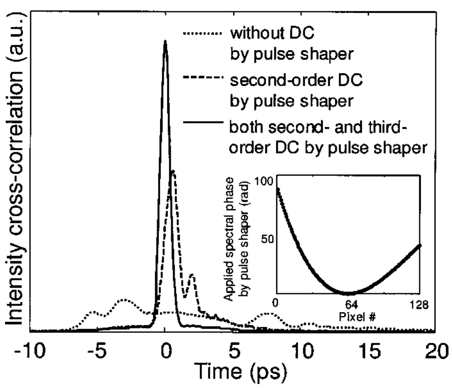

Fig. 3. Intensity cross correlation for various pulse shaper settings. Inset, unwrapped version of the phase profile applied by the pulse shaper. The actual phase profile that is applied is modulo 2π.

used for finely tuning dispersion; here we used it in a precompensation configuration.

Figure 2 shows the intensity cross-correlation measurement when the reference arm is a 400 fs pulse directly from the laser. The pulse is first measured without the SMF–DCF modules (dashed curve) and shows a pulse broadened to 460 fs (FWHM) primarily as a result of the erbium-doped fiber amplifier's gain profile and slight spectral filtering in the pulse shaper. When the 50 km SMF–DCF module is inserted we can fine tune the phase profile of the pulse shaper to compensate for residual second- and third-order dispersion and can recover a 470 fs pulse (solid curve), which dramatically demonstrates the capability of essentially complete dispersion compensation for sub-500-fs short pulses over 50 km of SMF by combining the techniques of a DCF and a pulse shaper. Figure 3 shows the details of fine DC by use of the pulse shaper. After the SMF alone, the calculated pulse broadening (not shown) is ~5 ns. After the SMF–DCF modules, although most second-order and partial third-order dispersion is compensated for, the pulse is still significantly distorted and broadened to 13.9 ps (dotted curve). If we program the pulse shaper to compensate for residual second-order dispersion only, the pulse shows an oscillating tail (dashed curve) that is indicative of residual third-order dispersion. If we program the pulse shaper to compensate for both residual second- and third-order dispersion, the pulse is recovered to 470 fs (solid curve). The inset figure shows the quadratic and cubic phase profile applied by the pulse shaper to cancel the residual second- and third-order dispersion. Note that the phase is actually applied to the pulse shaper modulo 2π, which significantly extends the DC range.

We emphasize that, in our results described above, the fiber link is a commercial fiber module (directly from the vendor) with no extra effort made to further control fiber length to minimize residual dispersion. Based on the spectral phase applied by the pulse shaper, we can calculate the residual dispersion of the SMF–DCF modules. Accordingly, we insert an additional 120 m of SMF to fully compensate for the calculated residual second-order dispersion. Figure 4 shows the intensity cross-correlation measurement (dashed curve), which is still broadened with an oscillating tail caused by residual third-order dispersion. The main point is that even high-quality DCF and precise fiber length control will still result in significant pulse broadening and distortion for such short pulses after fiber transmission. After application of pure cubic spectral phase for third-order DC in the pulse shaper, the short pulse is recovered (solid curve). The inset figure shows the pure cubic spectral phase profile applied in the pulse shaper.

In our system, essentially complete second- and third-order DC is the key to achieving 50 km SMF transmission for sub-500-fs pulses. The power input to the fiber link is 8.7 dBm, corresponding to 740 fJ per pulse at 10 GHz. At this power the primary nonlinear effect, self-phase modulation, is not an important factor because of fiber loss and the rapid pulse broadening in the fibers.[9] However, PMD[10] starts to appear in our system because of the large bandwidth that is inherent in the short pulse. To check the effect of PMD, we examined optical spectra through a polarization controller (PC) and a linear polarizer for several PC settings. Figure 5(a) shows the spectra without the 50 km fiber transmission, demonstrating

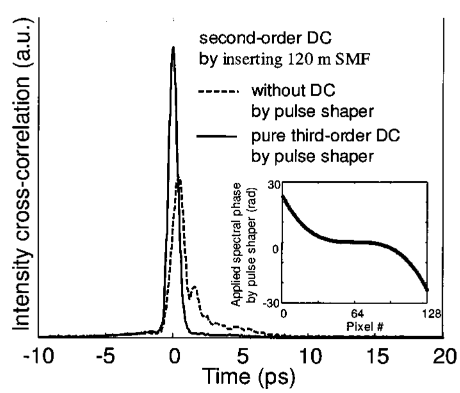

Fig. 4. Intensity cross correlation for different pulse shaper settings by insertion of an additional 120 m SMF for complete second-order DC. Inset, unwrapped phase profile applied by the pulse shaper (again the actual phase is applied modulo 2π).

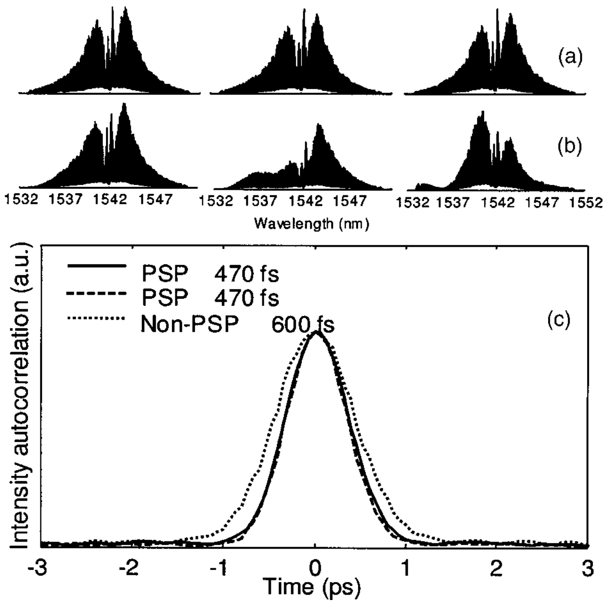

Fig. 5. (a) Spectra before the 50 km fiber link. (b) Spectra out of the 50 km fiber link, showing spectral variation caused by PMD. Both (a) and (b) were measured through a polarizer; the three traces represent different polarization components. (c) Intensity autocorrelation for PSP versus non-PSP at fiber link input.

no variation across the spectra for different PC settings. Figure 5(b) shows several spectra of the 50 km fiber link for various PC settings. The variation of the spectral profiles as a function of polarization component is a clear sign of PMD. In the measurements shown in Figs. 2–4 we mitigated the degradation that was due to PMD by coupling the input short pulse into one principal state of polarization (PSP) of the fiber link. Figure 5(c) shows the intensity autocorrelation traces out of the 50 km fiber link for a number of input polarization states at the fiber link input. One can achieve the minimum pulse width by tuning the input polarization to either of the two PSPs, as shown by the solid and dashed curves. When a non-PSP state is launched, the pulse is broadened to 600 fs (dotted curve). PMD could be a limiting factor in extending the transmission distance further for such short pulses. Finally, note that the pulse shaper works as desired only if the phase shift per pixel is sufficiently below π. This imposes a time aperature limit—the broadening that is to be compensated (13.9 ps in our experiment) should remain safely below the inverse of the frequency bandwidth per pixel ($\sim$60 ps for the current pulse shaper).[11] This limit can be further relaxed by pulse shaper design.

In summary, we have demonstrated essentially distortionless 50 km SMF transmission for sub-500-fs pulses by the use of dispersion-compensating fiber and a programmable pulse shaper as a spectral phase equalizer. This transmission distance is five times longer than in previous demonstrations for similar pulse widths.

This material is based on work supported by the Defense Advanced Research Projects Agency under grant MDA972-03-1-0014. The authors acknowledge the work of D. S. Seo in constructing the laser. Z. Jiang's e-mail address is zjiang@purdue.edu.

References

1. J. P. Turkiewicz, E. Tangdiongga, G. D. Khoe, H. de Waardt, W. Schairer, H. Rohde, G. Lehmann, E. S. R. Sikora, Y. R. Zhou, A. Lord, and D. Payne, in *Optical Fiber Communication Conference*, Vol. 95 of OSA Trends in Optics and Photonics Series (Optical Society of America, 2004), paper PDP1.
2. E. Yoshida, T. Yamamoto, A. Sahara, and M. Nakazawa, Electron. Lett. **34**, 1004 (1998).
3. Z. Jiang, D. S. Seo, S.-D. Yang, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, J. Lightwave Technol. **23**, 143 (2005).
4. Z. Jiang, D. S. Seo, S.-D. Yang, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, IEEE Photon. Technol. Lett., **17**, 705 (2005).
5. T. Yamamoto and M. Nakazawa, Opt. Lett. **26**, 647 (2001).
6. C. C. Chang, H. P. Sardesai, and A. M. Weiner, Opt. Lett. **23**, 283 (1998).
7. S. Shen and A. M. Weiner, IEEE Photon. Technol. Lett. **11**, 827 (1999).
8. A. M. Weiner, Rev. Sci. Instrum. **71**, 1929 (2000).
9. S. Shen, C. C. Chang, H. P. Sardesai, V. Binjrajka, and A. M. Weiner, J. Lightwave Technol. **17**, 452 (1999).
10. C. D. Poole and J. Nagel, in *Optical Fiber Telecommunications*, I. P. Kaminow and T. L. Koch, eds. (Academic, 1997), Vol. IIIA.
11. A. M. Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, IEEE J. Quantum Electron. **28**, 908 (1992).