Full dispersion compensation for ~500 fs pulses over 50 km SMF fiber transmission at 10 GHz using dispersion compensating fiber and a spectral phase equalizer

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Abstract

We demonstrate essentially distortionless 50 km single mode fiber transmission for ~500 fs pulses by the use of dispersion compensating fiber and a programmable pulse shaper as a spectral phase equalizer. This distance is approximately five times longer than previous results at similar pulse widths.

Summary

Long distance transmission is one of the greatest advantages for optical fiber communication systems. Ultrashort optical pulse fiber transmission plays a critical role in high speed optical time division multiplexing (OTDM) [1,2] and optical code division multiple access [3]. However, fiber dispersion may cause serious distortion to a broadband ultrashort pulse. The most successful and commercialized dispersion compensation (DC) technique is the use of dispersion compensating fiber (DCF) specially designed to have opposite dispersion parameters compared to 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-shifted fiber (DSF) has been used in a 120-km SMF/DCF link to further reduce the third-order dispersion for 400-fs pulses [2]. Nonetheless, this technique required special fiber links with very precise trimming of fiber lengths. More seriously, 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 pre-chirped pulse has been demonstrated in a 380 fs, 70 km transmission experiment [4]. However, this synchronous modulation scheme restricts the transmission format. Here we discuss a passive, format independent technique 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 fiber dispersion variations. Previously, our group has demonstrated almost exact third-order correction for 500-fs pulse distortion-free transmission over a 2.5 km [5] and 10 km [6] SMF/DCF links using a programmable pulse shaper [7]. The pulse shaper, originally developed for ultrafast optics applications, functions as an adjustable spectral phase equalizer allowing programmable dispersion compensation and reduces the need for careful DCF selection and precise fiber length trimming. In this paper, we extend the capability of this pulse shaping technique applied to fiber dispersion compensation, and report essentially distortion-free transmission for ~500 fs pulses over a 50 km fiber link. Our results demonstrate that the pulse shaping technique can effectively remove both the 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 (LAN) and metro area network (MAN) using OTDM or OCDMA.

Fig. 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 [7], which incorporates a 128-element liquid crystal modulator array to apply the spectral phase. 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). 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 are compensated by the DCF. The pulse shaper is used for finely tuning dispersion – here we used it in a pre-compensation configuration.

Fig. 2 shows the intensity cross-correlation measurement where the reference arm is a ~400 fs pulse directly from the laser. The pulse is first measured without the SMF/DCF modules (dashed curve) showing a pulse broadened to 464 fs (FWHM) primarily due to the EDFA 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 residual second- and third-order dispersion, and can recover a 473 fs pulse (solid curve), which dramatically demonstrates the capability of essentially complete dispersion compensation for sub-500 fs short pulses in over 50 km of SMF by combining the techniques of DCF and a pulse shaper. Fig. 3 shows the details of the fine DC using the pulse shaper. After the SMF alone, the calculated broadening is ~5 ns! After the SMF/DCF modules, although most second-order and partial third-order dispersion is compensated, the pulse is still significantly distorted and broadened to 13.9 ps (dotted curve). If we program the pulse shaper to compensate the residual second-order dispersion only, the pulse shows an oscillating tail (dashed curve) indicative of residual third-order dispersion. If we program the pulse shaper to compensate both residual second- and third-order dispersion, the pulse is recovered back to 473 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. Please note that the phase applied to the pulse shaper is modulo by 2π, which significantly extends the dispersion compensation range.

In our system, essentially complete second- and third-order dispersion compensation is the key to achieve 50 km SMF transmission for sub-500 fs pulses. The input power to fiber link is 8.7dBm, 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 the rapid pulse broadening in the fibers and fiber loss [8]. However, polarization mode dispersion (PMD) starts to appear in our system. In the measurement shown in Fig. 2, degradation due to PMD was mitigated by coupling the input short pulse into one principal state of polarization (PSP) of the fiber link. To illustrate the effect of PMD, Fig. 4 (A) shows the spectra out of the fiber link through a polarization controller (PC) and linear polarizer for different PC settings. The distorted spectral profiles are a clear sign of PMD. Fig. 4 (B) shows the intensity auto-correlation traces for different input polarization states at the fiber link input. The minimum pulse width can be achieved by tuning the input polarization to two PSP, as shown by the solid and dashed curves. When a non-PSP state is launched, the pulse is broadened to 602 fs (dotted curve). PMD could be a limiting factor in extending the transmission distance further for such short pulses.

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

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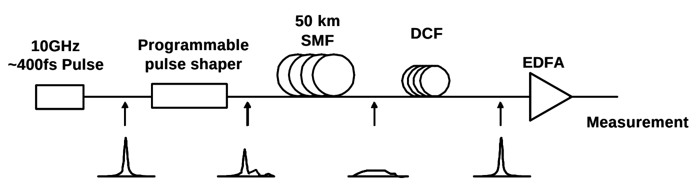

Fig. 1 Experimental apparatus.

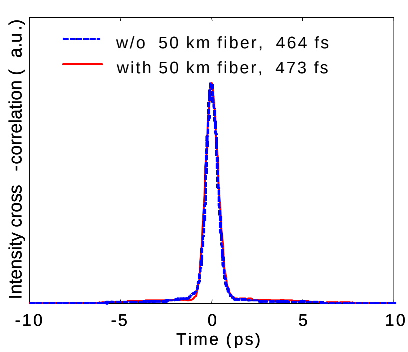

Fig. 2. Intensity cross-correlation with and without SMF/DCF module, demonstrating the distortionless 50 km fiber transmission for sub-500 fs pulse

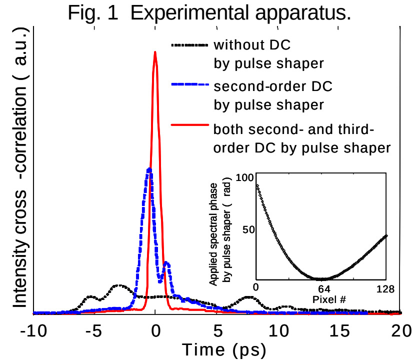

Fig. 3. Intensity cross-correlation for different settings of pulse shaper, The inset figure shows the phase profile applied by pulse shaper.

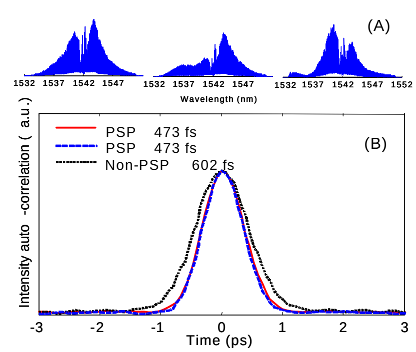

Fig. 4. (A) Spectra variation caused by PMD. (B) Intensity auto-correlation for different polarization (PSP vs. non-PSP) at fiber link input.