# Fully Dispersion Compensated ~500 fs Pulse Transmission Over 50 km SMF and Application to Ultrafast O-CDMA

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**Abstract:** 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. Application in ultrafast O-CDMA system experiments is demonstrated.

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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 (O-CDMA) [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 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). As an example, we apply the 50 km fiber transmission results in an O-CDMA system context.

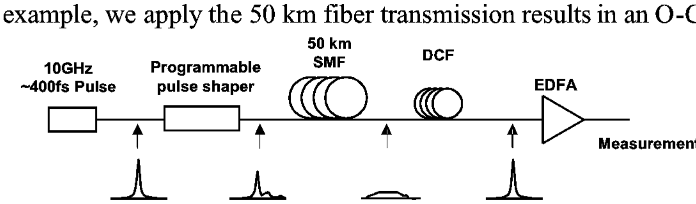

Fig. 1 Experimental apparatus.

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. This allows dispersion control through the relation $\tau(\omega) = -\dfrac{\partial\Phi(\omega)}{\partial\omega}$, where $\tau(\omega)$ and $\Phi(\omega)$ 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). 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 460 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 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 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 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. Please note that the phase applied to the pulse shaper is modulo by 2π, which significantly extends the dispersion compensation range.

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 the calculated residual second-order dispersion. Fig. 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 applying pure cubic spectral phase for third-order dispersion compensation 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.

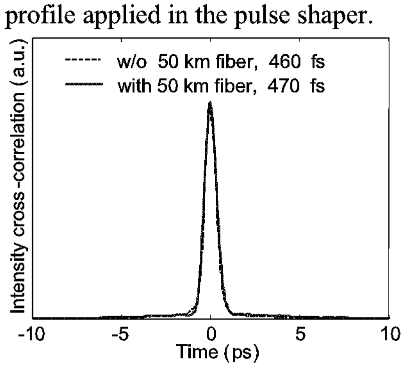


Fig. 2. Intensity cross-correlation with and without SMF/DCF module, demonstrating the distortionless 50 km fiber transmission for sub-500 fs pulse

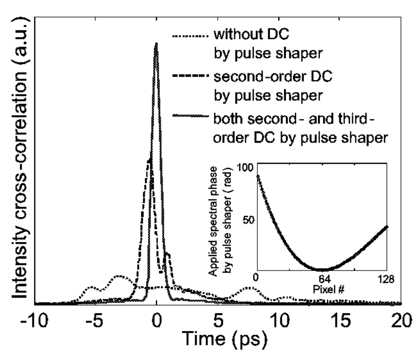


Fig. 3. Intensity cross-correlation for different pulse shaper settings. The inset figure shows the phase profile applied by pulse shaper.

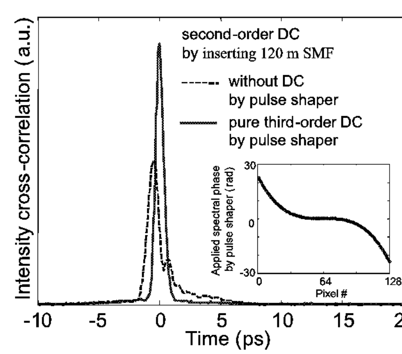


Fig. 4. Intensity cross-correlation for different pulse shaper settings by inserting 120 m SMF for complete second-order DC. The inset figure shows the phase profile applied by the pulse shaper.

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 the 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) [9] starts to appear in our system. In the measurement shown in Fig. 2-4, 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. 5 (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. 5 (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 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.

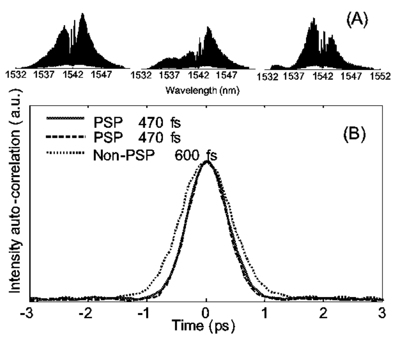


Fig. 5. (A) Spectrum variation caused by PMD. (B) Intensity auto-correlation for different polarization (PSP vs. non-PSP) at fiber link input.

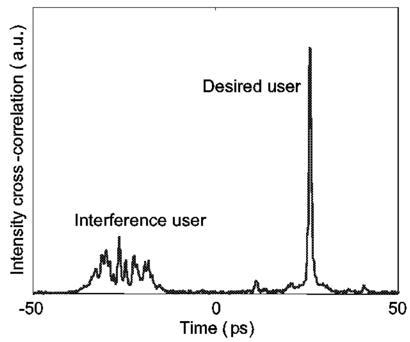


Fig. 6. Intensity cross-correlation for a 2 user O-CDMA system after 50 km fiber transmission.

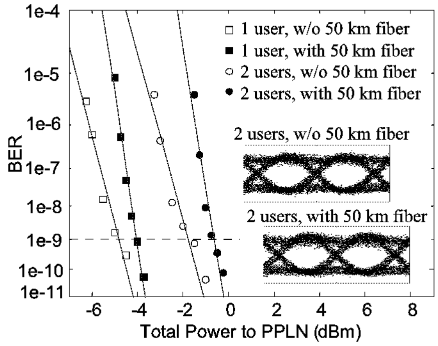


Fig. 7. BER performance for the O-CDMA system with and without 50 km fiber transmission. The inset figures show the eye diagrams for 2 users.

As an application example, we integrate the fiber transmission technique into our O-CDMA testbed [3]. In our O-CDMA testbed, the spectral phase encoding/decoding is also implemented by the pulse shaper. As a result, we can combine the function of dispersion compensation to either the encoder or decoder to simplify system implementation. In O-CDMA, multiple-access is achieved by assigning different, minimally interfering code sequences to different CDMA transmitters. In our spectrally phase coded O-CDMA system, input ultrashort pulses are time-spread during the encoding process into lower intensity noise-like signals. In the receiver, data corresponding to a desired user are separated from multi-access interference (MAI) via decoding operation, in which properly decoded signals are converted back to the original pulse-like signals, while improperly decoded signals remain low-intensity noise-like temporally broadened waveforms. Fig. 6 shows the intensity cross-correlation measurement after 50 km fiber transmission in a 2-user O-CDMA system. For the desired user, the link output is properly decoded back to a short pulse after 50 km SMF transmission, which demonstrates both the successful encoding/decoding process and full dispersion compensation. Compared with the uncoded pulses, also after a transmission through 50 km of fiber, shown in Fig. 2-4, the properly decoded short pulse is somewhat degraded exhibiting side-lobes and a pedestal, which are caused by the encoding/decoding process. The interference user is improperly decoded to a noise-like waveform. To reject the interference user, we use a highly sensitive fiber pigtailed periodically-poled lithium niobate (PPLN) waveguide to perform the nonlinear discrimination function based on second harmonic generation (SHG) [3]. Fig. 7 shows the O-CDMA system performance (eye diagrams and bit error rate BER), where a 2.5 Gb/s PRBS $2^{23}$-1 data stream is impressed on the ~400 fs, 10 GHz mode-locked fiber laser output and then split to generate both desired and interference user. For both single-user and two users, the power penalty at BER=$10^{-9}$ caused by 50 km fiber transmission is less than 1.3 dB.

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. Based on this technique, we have also demonstrated the successful operation of an ultrashort pulse O-CDMA system at the same distance.

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