Complete Dispersion Compensation for 400-fs Pulse Transmission over 10-km Fiber Link Using Dispersion Compensating Fiber and Spectral Phase Equalizer

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***Abstract*—We have demonstrated essentially complete dispersion compensation for 400-fs pulses over a 10-km fiber link using dispersion compensating fiber and a programmable femtosecond pulse shaper functioning as a spectral phase equalizer. The pulse shaper impresses adjustable quadratic and cubic phases onto the spectrum and removes all the residual dispersion and dispersion slope in the dispersion compensated fiber link. Our work shows that the pulse shaper technique provides a powerful and convenient tool for programmable fiber dispersion compensation over broad optical bandwidth. This allows distortion-free femtosecond pulse transmission over a fiber link in excess of 10 km without requiring the exact trimming of the dispersion-compensating fiber.**

***Index Terms*—Dispersion-compensating fiber, dispersion compensation, femtosecond pulse shaper, fiber transmission.**

I. INTRODUCTION

FEMTOSECOND pulse transmission over optical fibers requires simultaneous compensation of quadratic, cubic, and higher order dispersion. It is a key issue for high-speed lightwave transmission systems, such as time-division multiplexed (TDM) [1], and code-division multiple-access (CDMA) systems [2], [3], and is important to the design of chirped-pulse fiber amplifiers. A variety of dispersion compensating techniques have been investigated previously to cancel the large anomalous dispersion of the standard single-mode fibers (SMF's) at 1.55-μm wavelength. Among them, the dispersion compensating fiber technique (DCF) has been shown to be attractive for femtosecond-pulse transmission [1], [4], [5], because a carefully selected DCF with a precisely adjusted fiber length is able to cancel all the second-order dispersion and effectively suppress much of the third-order dispersion of the SMF. This made possible the propagation of 500-fs pulses over a 2.5-km fiber [5] and 980-fs pulses over a 40-km fiber link [1] with ≤ 2 times pulse broadening. However, it is cumbersome and perhaps impractical to find a DCF to exactly match both the second- and third-order dispersion of different SMF for variety of applications. The residual dispersion in the compensated fiber link imposes a serious limitation on the transmission distance and minimum pulsewidth for femtosecond applications. Recently, a dispersion-shifted fiber (DSF) has been used in a 120-km SMF/DCF link to further reduce the residual dispersion slope for 400-fs pulses [6]. Nonetheless, this technique requires very precise trimming of various fiber lengths. It becomes desirable to develop a technique capable of fine tuning and completely removing the residual dispersion for a nearly compensated fiber link, which would relax the required precision in fiber lengths and increase the tolerance to fiber dispersion variations.

Previously, we demonstrated almost exact cubic-phase correction for 500-fs pulse distortion-free transmission over a 2.5-km SMF/DCF link using a programmable pulse shaper [7]. The pulse shaper, originally developed for ultrafast optics applications [8], 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 letter, we extend the capability of this pulse shaper technique for fiber dispersion compensation, and report essentially distortion-free transmission for ~400-fs pulses over a 10-km fiber link. The figure of merit (fiber length $\times$ pulsewidth^{-3} for dispersion-slope limited femtosecond pulse transmission) in our current work is almost a factor of 8 larger than the previous 500-fs pulse transmission [7] and 4 times higher than the case of 980-fs pulses over the 40-km fiber [1]. Our results demonstrate that the pulse shaper technique can effectively remove both the residual second-order dispersion and the dispersion slope of a dispersion-compensated fiber link in excess of 10 km for femtosecond pulse transmission without the strict requirements on DCF.

II. DISPERSION COMPENSATION WITH DCF AND A PROGRAMMABLE PULSE SHAPER

Fiber dispersion can be characterized by expanding the group delay per unit length $T(\omega)$ (inverse of the group velocity) around the center frequency ω_c as

$$T(\omega) = \frac{d\beta}{d\omega} = \beta_1 + \beta_2(\omega - \omega_c) + \frac{\beta_3}{2}(\omega - \omega_c)^2 + \cdots \quad (1)$$

where $\beta_m = (d^m\beta/d\omega^m)_{\omega=\omega_c}$ represents the mth-order dispersion. It is also often expressed as the variation in group

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delay with respect to wavelength λ as

$$\frac{dT(\omega)}{d\lambda} = D(\lambda_c) + D'(\lambda_c)(\lambda - \lambda_c) + \cdots. \quad (2)$$

D and D' are closely related to β_2 and β_3 [5]. They represent the second- and third-order dispersion (dispersion slope), respectively. When a femtosecond pulse travels through a standard SMF ($\beta_2 < 0$) at 1.55 μm, its output pulsewidth can be broadened significantly. The idea of the DCF technique is to recompress the broadened pulse through concatenating the SMF with a carefully selected DCF which has the opposite sign of dispersion and dispersion slope to the SMF. With a precisely adjusted length ratio between them, the DCF cancels all the second-order dispersion and suppresses most of the dispersion slope in the SMF. Since the third-order dispersion of the DCF normally does not match the SMF exactly, the residual dispersion slope in the compensated link leads to an asymmetric pulse broadening and distortion in the form of an oscillatory tail. This residual dispersion can be conveniently and *programmably* equalized in a femtosecond pulse shaper with a liquid-crystal phase modulator array (LCM). Since the spectral components of the input pulse are spatially dispersed across the Fourier plane of the pulse shaper [7], appropriate quadratic and cubic phase curves (and potentially higher order terms) can be added to the laser spectrum simply through applying the required voltage pattern across the LCM. The phases provided by the nth LCM pixel can be formulated as

$$\Phi_n = \frac{\phi_2}{2}\left(n - \frac{N}{2}\right)^2 \delta\omega^2 + \frac{\phi_3}{6}\left(n - \frac{N}{2}\right)^3 \delta\omega^3 \cdots, \quad n = 1, 2, \cdots, N \quad (3)$$

where N is the total number of pixels. ϕ_2 and ϕ_3 represent the second- and third-order phase dispersion, respectively. $\delta\omega$ is the angular frequency increment between the adjacent pixels. Since the additional phase variation used to compensate the residual dispersion is sampled over N pixels, where N is normally large (128 in our case), the moderate phase variation can be considered as continuously sampled. Therefore, exact second- and third-order phase equalization is feasible. The capacity of the phase correction is limited by the spectral resolution of the setup and the finite pixel-width of the LCM [8]. In our experiment, we demonstrate that a femtosecond pulse shaper is able to completely remove the phase distortion for 400-fs pulse transmission over a 10-km dispersion-compensated fiber link.

III. Experiments and Results

The experimental setup for *programmably* compensating the residual dispersion in a 10-km fiber is shown in Fig. 1. We used a passively mode-locked fiber laser and an interference filter to generate femtosecond pulses centered at 1559 nm. The laser pulses were then launched into a 10.60-km dispersion-compensated fiber link, which consists of 9.10-km SMF (Corning SMF-28) and 1.50-km DCF (from Bell Laboratories). No specific attempt was made in the selection of the DCF to precisely match the dispersion slope of the SMF. The total insertion loss in the fiber link including splicing losses is ~6 dB. After a chirped-pulse fiber amplifier, a programmable pulse shaper was used to compensate the residual dispersion in the 10-km fiber. The pulse shaper consists of a grating pair and a lens pair with a 128-pixel LCM located in the Fourier plane [8]. The spectral dispersion of the LCM is ~0.12 nm/pixel and the spatial width of each pixel is 100 μm. The pulse shaper has as small as 6-dB fiber-to-fiber insertion loss and introduces zero dispersion when a constant phase is applied across the LCM. The output pulsewidth was measured through optical intensity autocorrelation based on non collinear second-harmonic generation with ±20-fs accuracy.

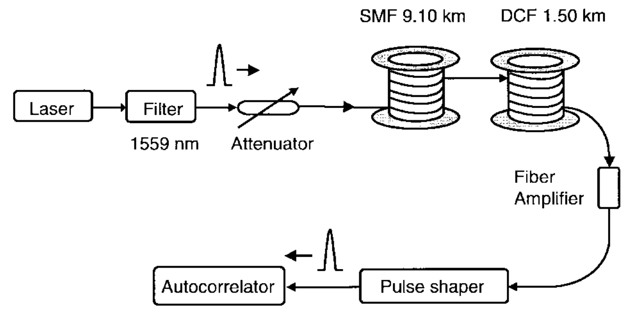

Fig. 1. Experimental setup for dispersion compensated 400-fs pulse transmission over 10-km SMF/DCF link by the use of a programmable pulse shaper.

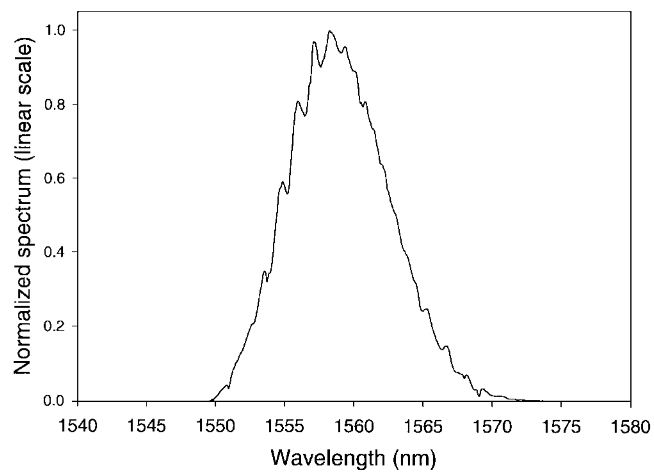

Fig. 2. Output spectrum after the pulse shaper (linear scale).

The experiment was performed by first measuring the output pulses after the pulse shaper without connecting the 10-km fiber link. The fiber amplifier was directly connected at the end of the attenuator. The output average power from the amplifier is ~500 μW. Fig. 2 shows the optical spectrum after the pulse shaper. The spectral bandwidth of the system is 8 nm [full-width at half-maximum (FWHM)]. The corresponding autocorrelation trace after the pulse shaper was shown in Fig. 3 (curve "a") when a constant phase was applied across the LCM. It indicates that the optical pulse from the system without the 10-km fiber has a pulsewidth of 390 fs (deconvolved FWHM assuming secant-hyperbolic pulse shape). The time-bandwidth product of the pulse is ~0.38, which is close to transform-limited. The 10-km fiber

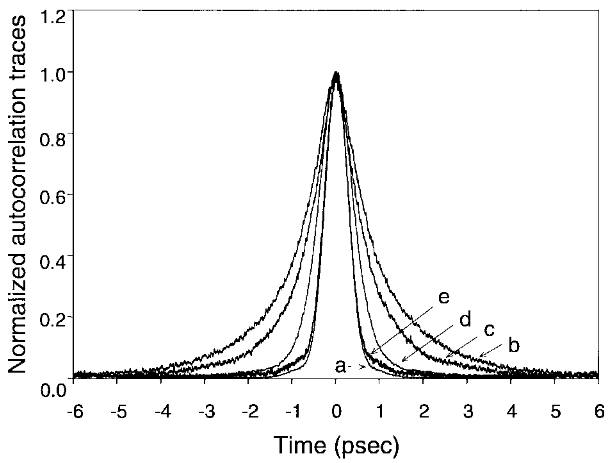

Fig. 3. Autocorrelation traces. (a) Without the 10-km link. (b)–(e) With the link. (b) Constant phase (950 fs). (c) Optimized quadratic phase (770 fs). (d) Optimized cubic phase (550 fs). (e) Both optimized and cubic phases (405 fs). Pulsewidth is deconvolved FWHM.

link was then added between the attenuator and the fiber amplifier. The input power to the link was adjusted to be ~200 μW so that the power to the amplifier was the same for experiments with and without the 10-km link. Consistent with our previous experiments showing the onset of the nonlinearity at ~500 μW for such links [9], no fiber nonlinearity was observed in the 10-km fiber. When a constant phase was applied onto the LCM, we measured an output pulsewidth of ~950 fs (deconvolved FWHM) after the pulse shaper as shown in Fig. 3 (curve "b"). It indicates a pulse broadening due to the small residual dispersion and dispersion slope in the link. Note that the estimated pulsewidth after the SMF alone is ~1.2 ns, which means the DCF is actually compensating 99.9% of the pulse broadening. To remove the remaining dispersion, we iteratively and manually applied quadratic and cubic phases onto the LCM to restore the original input pulse. It is also possible to apply the phases adaptively (computer controlled) for greater flexibility [10]. Fig. 3 shows the autocorrelation traces after the pulse shaper when the optimized quadratic (curve "c": $\phi_2 = 0.050$ ps^2) and cubic phase (curve "d": $\phi_3 = 0.25$ ps^3) were applied on the LCM separately and together (curve "e"). A pulsewidth of ~405 fs (deconvolved FWHM) has been obtained when both quadratic and cubic phases were applied onto the LCM. Compared to the measurement without the 10-km fiber, it shows that the pulse shaper has removed almost all the residual dispersion in the fiber link and has essentially recompressed the laser pulse back to its input pulsewidth. The maximum phase variation provided by the LCM in this case is 8.5π, which was applied modulo 2π. From ϕ_2 and ϕ_3, we estimated the residual dispersion in the compensated link of $\beta_2 = -0.0047$ ps^2/km ($D = 0.0036$ ps/km/nm) and $\beta_3 = -0.0236$ ps^3/km ($D' = -0.0142$ ps/km/nm^2). The residual second-order dispersion compensated by the pulse shaper corresponds to ~2.3-m SMF length deviation from its optimal value. The residual third-order dispersion in our 10-km link is equivalent to that measured in our previous 2.5-km link [5] and is ~4 times less than that for an equivalent length of DSF. However, the cubic phase corrected in our experiment is eight times larger than that demonstrated in our previous work [7]. Our experiment clearly shows that with the use of a programmable femtosecond pulse shaper as a spectral phase equalizer, the distortion-free transmission for 400-fs pulses can be achieved over a fiber link exceeding 10 km with relaxed requirements on the DCF and the SMF.

IV. Conclusion

We have demonstrated almost complete dispersion compensation for ~400-fs pulse transmission over a 10-km dispersion-compensated fiber link using a programmable pulse shaper. The residual dispersion of the fiber link is compensated conveniently in the pulse shaper without requiring strict DCF selection and precise fiber length trimming. Our work shows that the pulse shaper technique makes possible programmable spectral phase equalization for adjustable dispersion compensation for ultrabroad-band femtosecond-pulse transmission.

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