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Transmission of 6 ps Linear Pulses Over 50 km of Standard Fiber Using Midpoint Spectral Inversion to Eliminate Dispersion

Richard I. Laming, David J. Richardson, Domino Taverner, and David N. Payne

Abstract—**Transmission of 6 ps linear pulse pairs over 50 km of standard fiber is demonstrated by employing midpoint spectral inversion (phase conjugation) of the data signal to compensate dispersion effects. Pulse broadening as low as 10 percent and faithful reconstruction of the pulse patterns are observed and confirm the applicability of this technique to bit rates greater than 100 Gb^{-1}.**

INTRODUCTION

THE advent of erbium-doped fiber amplifiers (EDFA's) has made high-capacity transparent optical networks operating around 1.55 μm a reality. However, since the majority of the world's installed fiber is designed to operate around 1.3 μm, the minimum dispersion region, there is strong commercial pressure to upgrade these links. At present there are two options: either to develop 1.3 μm amplifiers based on Pr^{3+}- or Nd^{3+}-doped fiber [1], [2] or to employ dispersion compensators [3]–[6] to allow the fiber to be used around 1.5 μm, where the EDFA operates.

Dispersion compensation techniques include the incorporation of a special dispersion-equalizing fiber, such as two-mode fiber [3], to reduce the net link dispersion or the use of optical phase conjugation (spectral inversion) of the data spectrum at the midpoint of the transmission link [4]–[6]. In the latter case, the pulse disperses in the first half of the link, at which point its spectrum is inverted such that the dispersion in the second half acts in the opposite sense and recompresses the pulse.

Nondegenerate four-wave mixing (FWM) in both a semiconductor amplifier [4] and a dispersion-shifted fiber [5] (to obtain phase matching) has been employed to provide spectral inversion. By employing the latter, the transmission of 10 Gb^{-1} NRZ data over 360 km of standard fiber has been demonstrated [6].

In this paper we investigate the applicability of the spectral-inversion technique to bit rates greater than 100 Gb^{-1}. We demonstrate linear transmission, phase conjugation, and retransmission of 6.2 ps pulse pairs (mark–space ratio in the range of 2–5) over a total distance of 50 km of standard fiber. It is necessary to place the phase conjugator slightly away from the midpoint of the data link to compensate for the discrete wavelength shift that occurs after spectral inversion and that results in the two sections of the link having marginally different dispersions. A minimum pulse broadening of ~ 10 percent is observed limited primarily by spectral shaping in the optical filters employed. In addition, no pulse-to-pulse jitter is observed, and thus, the results confirm the applicability of the technique to bit rates greater than 100 Gb^{-1}.

EXPERIMENT

The experimental configuration is shown in Fig. 1. A polarization-maintaining, passively mode-locked figure-eight erbium-doped fiber laser was employed to generate short soliton pulses at an average repetition rate of ~ 200 MHz and a center wavelength of 1532 nm [7]. These were coupled through a short section (~ 30 m) of dispersion-shifted (DS) fiber (lab to lab), attenuated and split with an 80 : 20 coupler. An autocorrelation trace and spectrum of the pulses measured at this point are shown in Fig. 2(a) and (b) and indicate a pulse width of 6.2 ps and spectral half-width of 0.44 nm, corresponding to a time–bandwidth product of 0.34, which indicates that the pulses were slightly chirped due to propagation through the 30 m section of DS fiber. The pulses were propagated over 24.6 km of standard fiber ($D = 16.6$ ps/nm · km and $dD/d\lambda = 0.06$ ps/nm^2 · km) with input power reduced to ~ −16 dB (1 mW) (~ 20 mW peak power) to ensure that linear transmission (i.e., nonsolitonic) occurred. At the fiber output the pulses were extensively dispersed (~ 200 ps).

At this point, spectral inversion of the data spectra was carried out using FWM. The dispersed pulses [with an

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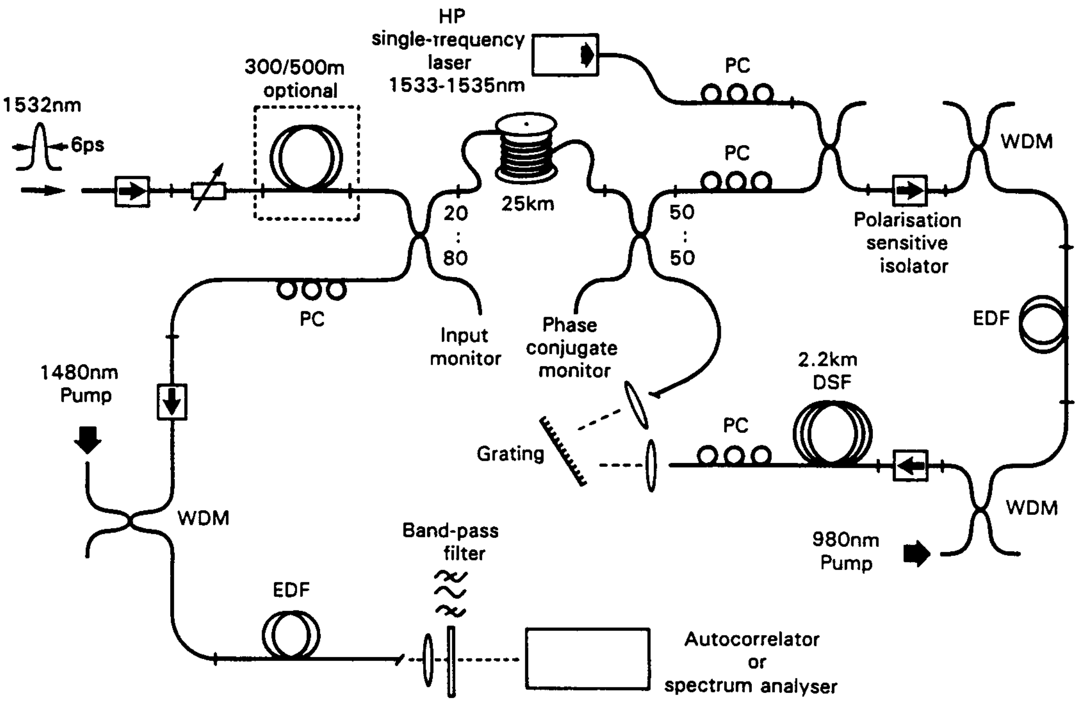
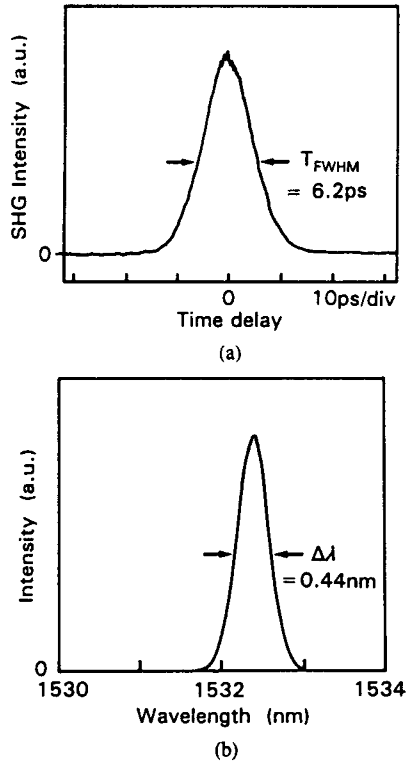


Fig. 1. Experimental configuration.



(a)

(b)

Fig. 2. (a) Autocorrelation trace and (b) spectra of the pulses at the transmission fiber input.

average power of −28 dB (1 mW)] were combined with the output from a tunable single-frequency laser [1533–1535 nm, −11 dB (1 mW)] with polarizations aligned to maximize four-wave-mixing, and input to a 35 m germano–alumino–silicate-based EDFA counter-pumped at 978 nm. The amplified output (~ 50 mW) was propagated through a 2.2 km section of dispersion-shifted fiber that had zero dispersion at 1532 nm, and thus, was phase matched for efficient FWM between the reference and data signals. The wavelength-upshifted and spectrally-inverted conjugate of the data was spectrally filtered using a grating having a 3 dB filter width of ~ 1.5 nm and retransmitted back down the same 24.6 km of fiber. At the relaunch, the power in the phase-conjugated data signal was ~ −25 dB (1 mW). The reconstructed pulses were split via the 80 : 20 coupler, amplified, and input to an autocorrelator. Polarization controllers were included only to maximize, the signal in the presence of polarization-dependent effects in the grating filter and the autocorrelator.

RESULTS

Results plotted in Fig. 3 show the transmitted pulse width as a function of the wavelength separation $\Delta\lambda$ between the data and the reference. A sech^2 pulse form is assumed, and thus, the pulse half-width is a factor of 1.56 shorter than the autocorrelation half-width. Three curves are shown, corresponding to transmission and retransmission through 24.6 km of standard fiber alone, and with additional sections of either 300 or 500 m of standard fiber ($D = 17.6$ ps/nm · km) inserted at the input to effectively shift the phase conjugator away from the mid-point of the transmission link. For no additional fiber, the dispersion mismatch between outgoing and return paths increases approximately linearly with wavelength separation, and thus, the transmitted pulse width is observed to increase quasi-quadratically with wavelength separation. A minimum pulse width of 8.7 (±0.7) ps was observed for a minimum practical wavelength separation of 1.5 nm.

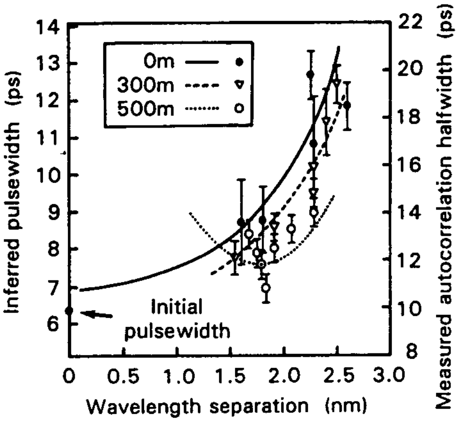
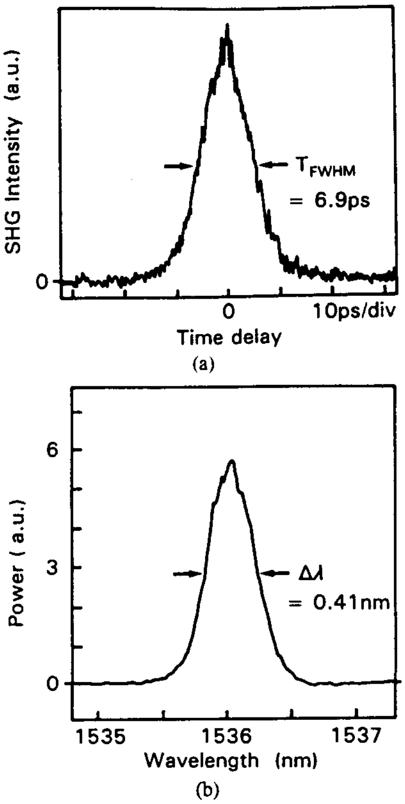


Fig. 3. Output pulse width as a function of the wavelength separation of the data and reference signals.



(a)

(b)

Fig. 4. (a) Autocorrelation trace and (b) spectra of the pulses after transmission.

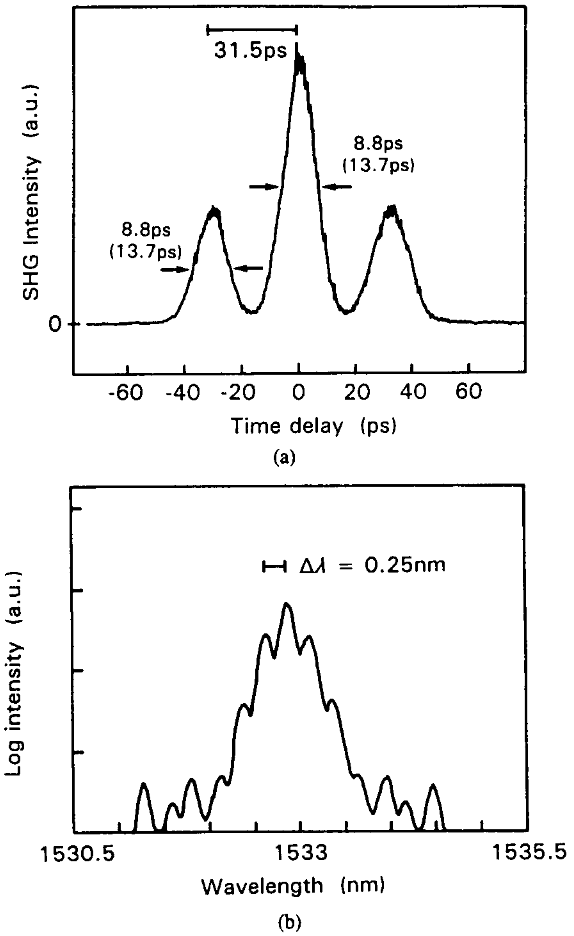
By adding a fixed dispersion prior to the outgoing fiber (i.e., moving the phase conjugator away from the midpoint) the dispersion mismatch between outgoing and return legs caused by the spectral-inversion wavelength shift $\Delta\lambda$ can be compensated. With an additional 300 m section of standard fiber added, the transmitted pulse width is again observed to increase quasi-quadratically with wavelength separation; however, the pulse width is now reduced for more practical (i.e., larger) wavelength separations. For this length of additional fiber, the net link dispersion is predicted to be minimized for a wavelength separation of ~ 1.1 nm, and experimentally a minimum transmitted pulse width of 7.7 (±0.3) ps for a wavelength separation of 1.54 nm was observed.

In the case of the 500 m additional fiber section, the transmitted pulse width was minimized for a wavelength separation of 1.85 nm. This is a larger separation than predicted (1.6 nm) assuming a conjugator of zero length and the known third-order dispersion of the transmission fiber. The discrepancy may arise due to the finite length of the phase conjugator. In addition, the experimental data appear to exhibit a more pronounced reduction in pulse width around the optimum wavelength separation than might be anticipated. This is partially explained by the initial pulses being slightly chirped. Fig. 4(a) and (b) show the autocorrelation and spectra of the transmitted pulses at this optimum operating point and indicate a minimum pulse width of 6.9 (±0.3) ps. The slightly reduced spectrum of 0.41 nm is consistent with the filtering imposed primarily by the grating filter, which in addition to the anticipated broadening due to third-order dispersion (~ 0.2 ps), accounts for the observed minimum pulse broadening of ~ 10 percent.

In order to further assess the quality and linearity of the phase-conjugation process, the propagation of pulse pairs was investigated. The output pulses from the laser were launched into a Michelson interferometer with a variable delay in order to generate individual pulse pairs with a well-defined interpulse separation. In Fig. 5(a) and (b) we show the autocorrelation and spectra of the pulse pairs measured at the 80:20 coupler for a reasonably wide launch pulse duration-to-separation ratio of 1:5. At this measurement point the pulses have already broadened slightly to 8.8 ps from their initial width of 6.2 ps because of the 500 m section of fiber. The pulse separation is observed to be 31.5 ps, corresponding to a repetition rate of 32 GHz. The optical spectrum of the pulses is modulated at a period of 0.25 nm, in agreement with the observed pulse separation. The ratio of the cross to self-correlation peak heights is 2.3:1, instead of exactly 2:1, owing to a slight mismatch in powers from the two arms of the interferometer. The cross-correlation half-width (8.8 ps) is the same as that of the self-correlation half-width, confirming the linearity of the autocorrelator scan.

The corresponding autocorrelation after propagation over the full 50 km is illustrated in Fig. 6(a) and shows a clear trace of the pulse pair. The self- and cross-correlation widths are identical (~ 7.4 ps) and the intrapulse separation (~ 31 ps) is preserved, indicating that no additional jitter has developed, or that significant deformation of the transmitted pulse pairs has occurred.

Similar data were obtained for interpulse separations ranging from 5:1 to 2.5:1 and the autocorrelation traces agreed well with their predicted forms, although at separations less than 2.5:1 (~ 70 GHz) it was difficult to quantify the quality of the pulse train reconstruction, owing to the relative insensitivity of the autocorrelation shape to changes once the pulses were packed closely together. An example of a 50 GHz trace is presented in Fig. 6(b), where we have resolved a pair of 7.1 ps pulses at



(a)

(b)

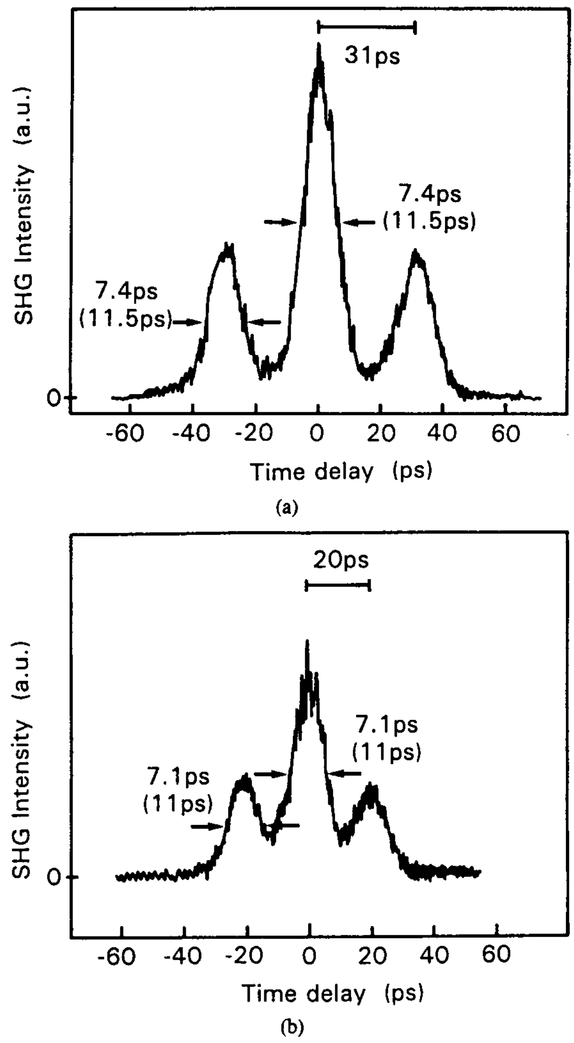
Fig. 5. (a) Autocorrelation trace and (b) spectrum of the pulse pairs at the 24.6 km transmission fiber input. Values are given for both the pulse width and the (autocorrelation half-width).

a separation of 20 ps. Once again, the self- and cross-correlation widths are identical and the period agrees well with the repetition rate predicted on the basis of the 0.37 nm spectral modulation observed on the input pulse spectrum.

Fig. 7 shows the transmitted pulses directly over 50 km (i.e., no phase conjugation) that, taking into account the detector–scope response of 320 ps, indicates a pulse broadening of ~ 400 ps. Thus, a dispersion compensation factor of > 500 is demonstrated.

These results confirm the ability to spectrally invert and reconstruct picosecond pulses, and thus, confirms the applicability of the technique to dispersion compensation at bit rates greater than 100 Gb^{-1}. However, phase conjugation of subpicosecond pulses is likely to be limited by the bandwidth of the phase conjugator, which in the present setup was several nanometers (~ 500 GHz), but can be extended with careful fiber design or the use of a semiconductor [8].

In the present experiments, the input power level was determined such that linear transmission of the pulses occurred, however, it corresponds to a approximately one million photons per pulse and a pulse energy several times greater than that used in current 10–20 Gb^{-1} soliton



(a)

(b)

Fig. 6. Autocorrelation trace of (a) the reconstructed pulse pairs illustrated in Fig. 5 and (b) the reconstructed 50 GHz pulse pairs after transmission through the 50 km circuit. Values are given for both the pulse width and the (autocorrelation half-width).

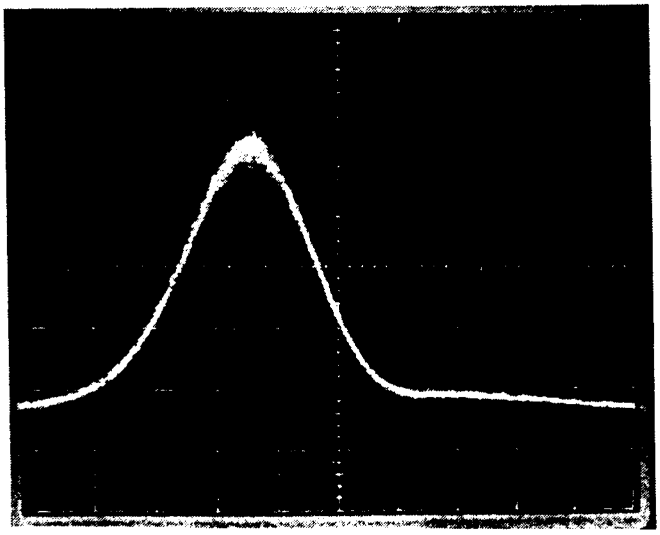


Fig. 7. Transmitted pulses directly over 50 km. 200 ps time/div and detector–scope response 320 ps.

communication systems [9]. In addition, it has recently been shown theoretically that the phase-conjugation process can also compensate for fiber nonlinearities [10]. Thus, it is clear that the technique offers the potential for increased transmission powers and facilitates the use of wavelength division multiplexing (WDM) and increased repeater spacings in long-haul links.

CONCLUSIONS

Linear transmission of 6 ps pulses over 50 km of standard fiber has been achieved by employing nondegenerate four-wave mixing in a short-section of dispersion-shifted fiber to spectrally invert the data close to the midpoint of the link. By optimizing the exact position and wavelength shift of the phase conjugator, dispersion effects are minimized, resulting in a transmitted pulse width of 6.9 ps, i.e., a broadening of only 10 percent. In addition, pulse patterns are reconstructed with no additional pulse-to-pulse jitter, even when they have temporally smeared to the point of extensive pulse overlap in the conjugator. The results directly demonstrate the potential of the technique to extend to data rates greater than 100 Gb^{-1} and shows that optical phase conjugation is a powerful technique that virtually eliminates fiber dispersion, leaving only higher order dispersion uncompensated. For example, we estimate that at 50 Gb^{-1} higher order dispersion will limit transmission distances to ~ 2000 km in standard ($D \simeq 17$ ps/nm · km) fiber. However, a detailed analysis including amplifier and phase-conjugator noise, as well as fiber nonlinearity is required to fully explore this possibility.

ACKNOWLEDGMENTS

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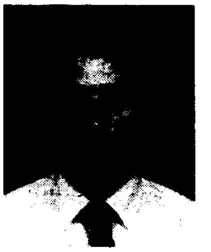

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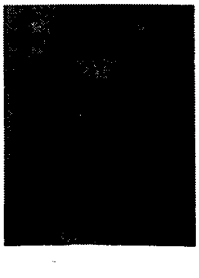

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Since 1969 his research interests have been in Optical Communications and have included preform and fibre fabrication techniques, optical propagation in multimode and single-mode fibres, fibre and preform characterization, wavelength-dispersive properties of optical fibre materials, optical transmission measurements and rare-earth-doped fibre devices. He has published over three hundred and seventy papers and holds twenty five patents. Currently his main fields of interest at 1.3μm amplifiers, soliton communications, dispersion-compensation and fibre components for WDM systems. In 1980 with others he founded York Ltd., a company manufacturing fibre instrumentation.

In recognition of his work, Professor Payne has been honoured by the IEEE with its John Tyndall Award for his outstanding contribution to the design, measurement and fabrication of optical fibers, sensors and fibre devices; the Rank Prize for his contribution to the advancement of optoelectronics; and the UK Department of Trade with its Academic Enterprise Award for the founding of York Technology Ltd. In addition, he has won the Premium of the IEE five times, the Gyr and Landis Commemorative Prize twice, the prize for the best paper at the European Conference on Optical Communications and the Tobie Award for the most significant development in fibre optics. He was elected to a Fellowship of the Royal Society of London in 1992. In 1993 he was awarded the Japanese C & C prize for leading the team which discovered the erbium-doped fibre amplifier. In 1994 he was elected Fellow of the Optical Society of America.