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Transmission of 6 ps Linear Pulses over 50 km of Standard Fibre using Midpoint Spectral Inversion to Eliminate Dispersion

Richard I. Laming, David J. Richardson, Domino Taverner & David N. Payne,
Optoelectronics Research Centre,
The University, Southampton SO9 5NH, UK

Abstract
Transmission of 6ps linear pulses over 50km of standard fibre is demonstrated by employing midpoint spectral-inversion (phase conjugation) of the data signal to compensate dispersion effects. A pulse broadening of as low as 10% is observed and confirms the applicability of this technique to bit-rates greater than 100 Gbits^{-1}.

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

Dispersion compensation techniques include incorporation of a special dispersion-equalizing fibre, such as two-mode fibre[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.

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

In this paper we investigate the applicability of the spectral-inversion technique to bit rates greater than 100 Gbits^{-1}. We demonstrate linear transmission, phase conjugation and retransmission of 6.2ps pulses over a total distance of 50km of standard fibre. It is necessary to place the phase conjugator slightly away from the midpoint of the data link to compensate for the discrete wavelength shift which occurs after spectral inversion and which results in the two sections of the link having different dispersions. A minimum pulse broadening of ~10% is observed, limited primarily by spectral shaping in the optical filters employed.

Experiment
The experimental configuration is shown in Figure 1. A polarisation maintaining, passively mode-locked figure-eight erbium-doped fibre laser was employed to generate short pulses at an average repetition rate of ~1GHz and centre wavelength of 1532nm. These were coupled through a short section (~30m) of standard fibre (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 Figures 2 (a,b) and indicate a pulsewidth of 6.2 ps and spectral halfwidth of 0.44nm, corresponding to a time-bandwidth product of 0.34. The pulses were propagated over 24.6km of standard (ie not dispersion-shifted) fibre with input power reduced to ~-16dBm to ensure that transmission was in the linear regime. At the fibre output the pulses were extensively dispersed.

At this point spectral inversion of the data spectrum was carried out using FWM. The dispersed pulses (with average power -28dBm) were combined with the output from a tunable single-frequency laser (1533-1535nm, -11dBm), with polarisations aligned to maximise 4-wave-mixing, and input to a 35m germano-alumino-silicate based EDFA counter-pumped at 978nm. The amplified output (~50mW) was propagated through a 2.2km section of dispersion-shifted fibre which had a dispersion zero at 1532nm and thus was phase matched for efficient FWM between the reference (DFB) and data signals. The wavelength-upshifted and spectrally-inverted conjugate of the data was spectrally filtered using a grating having a 3dB filter width of ~1.5nm and retransmitted back down the same 24.6km of fibre. At the relaunch the power in the phase-conjugated data signal was ~-25dBm. The reconstructed pulses were split via the 80:20 coupler, amplified and input to an autocorrelator. Polarisation controllers were included to maximise the signal in the presence of polarisation-dependent effects in the grating filter and the autocorrelator.

Results

Results plotted in Figure 3 show the transmitted pulse width as a function of the wavelength separation between the data and the reference. A $sech^2$ pulse form is assumed in deriving the pulsewidth from the observed autocorrelation data. Three curves are shown, corresponding to transmission and re-transmission through 24.6km of standard fibre alone, and with additional sections of either 300m and 500m of standard fibre inserted at the input to effectively shift the phase conjugator away from the midpoint of the transmission link. For no additional fibre the dispersion mismatch between outgoing and return paths increases approximately linearly with wavelength separation and thus the transmitted pulsewidth is observed to increase quasi-quadratically with wavelength separation, with a minimum observed pulsewidth of 8.7(±.7)ps for the minimum practical wavelength separation of 1.5nm.

By adding a fixed dispersion prior to the outgoing fibre, (ie moving the phase conjugator away from the midpoint) the dispersion mismatch between outgoing and return legs caused by the spectral-inversion wavelength shift can be compensated. With an additional 300m section of standard fibre the transmitted pulsewidth is again observed to increase quasi-quadratically with wavelength, however the pulsewidth is now reduced for more practical (ie larger) wavelength separations. The net link dispersion is predicted to be minimised for a wavelength separation of 1.1nm, and experimentally a minimum transmitted pulsewidth of 7.7(±0.3)ps for a wavelength separation of 1.54nm was observed.

In the case of the 500m additional fibre section, the transmitted pulsewidth was minimised for a wavelength separation of 1.85nm. This result is consistent with a fibre third-order dispersion of ~0.09ps/nm^2 km. The experimental data appears to exhibit a more pronounced reduction in pulsewidth around the optimum wavelength separation than might be anticipated. This might be explained by the initial pulses being slightly chirped. Figure 4 (a,b) show the autocorrelation and spectra of the transmitted pulses at this optimum operating point and indicate a minimum pulsewidth of 6.9(±0.3)ps. The slightly-reduced spectrum of 0.41nm is consistent with the filtering imposed primarily by the grating filter, which, in addition to the anticipated broadening due to third-order dispersion (~0.2ps), accounts for the observed minimum pulse broadening of ~10%.

These results confirm the ability to spectrally-invert and reconstruct ps pulses and thus confirms the applicability of the technique to dispersion compensation at bit-rates greater than 100Gbits^{-1}. Figure 5 shows the transmitted pulses directly over 50km (ie no phase conjugation) which, taking into account the detector/scope response of 320ps, indicate a pulse broadening of ~400ps. Thus a dispersion compensation factor of >500 is demonstrated.

Conclusions

Linear transmission of 6ps pulses over 50km of standard fibre is demonstrated by employing non-degenerate four-wave mixing in a short-section of dispersion-shifted fibre to spectrally invert the data close to the midpoint of the link. By optimising the exact position and wavelength shift of the phase-conjugator, dispersion effects are minimised, resulting in a transmitted pulse width of 6.9ps ie a broadening of 10%.

Acknowledgements

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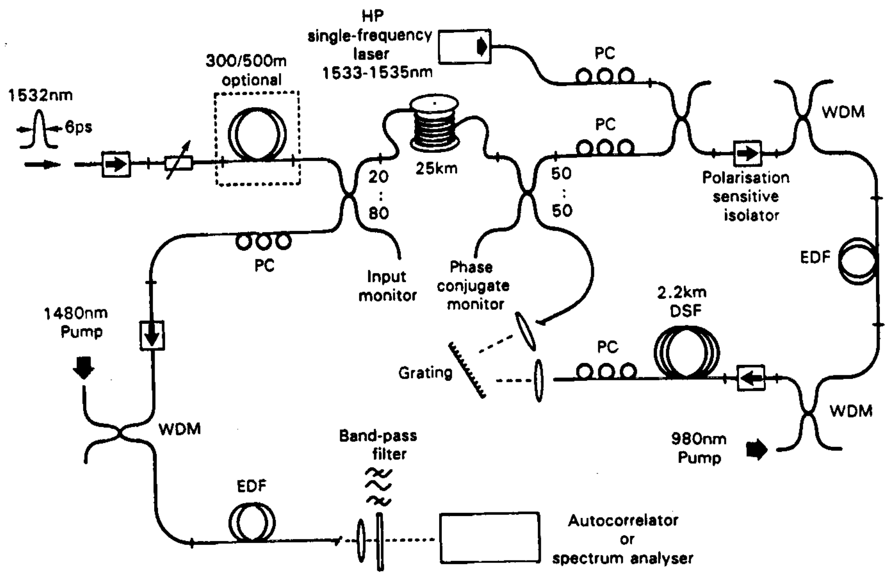


Figure 1. Experimental configuration

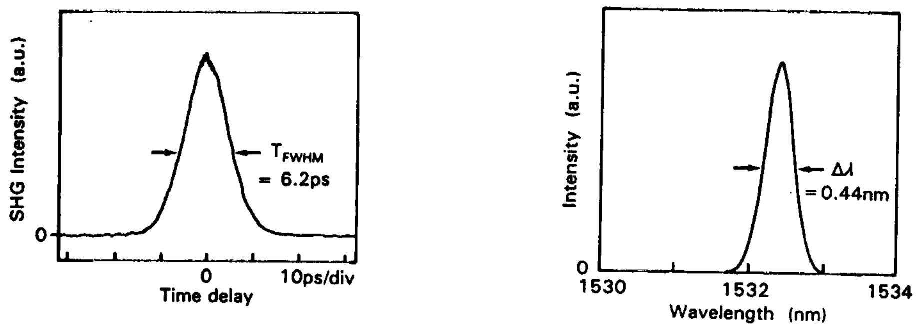


Figure 2. a) Autocorrelation trace and b) spectra of the pulses at the transmission fibre input

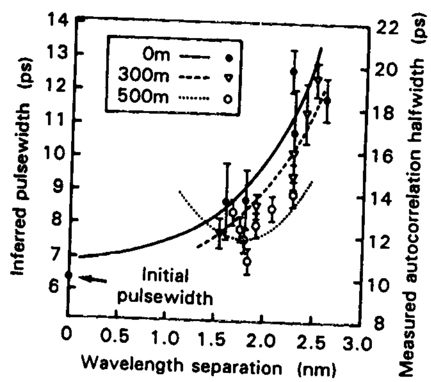


Figure 3. Output pulsewidth as a function of the wavelength separation of the data and reference signals

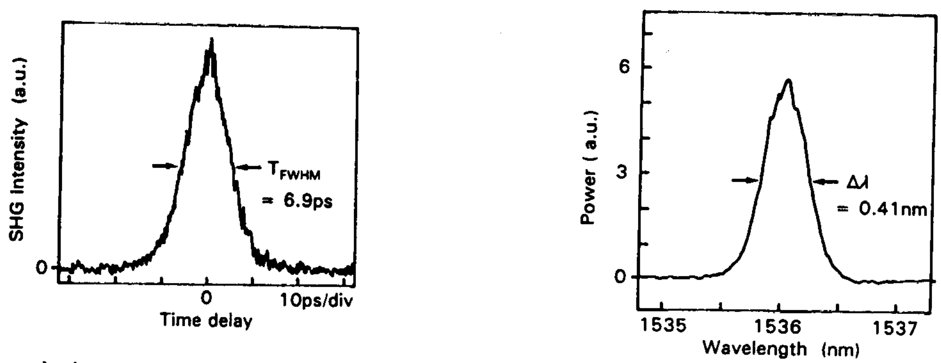


Figure 4. a) Autocorrelation trace and b) spectra of the pulses after transmission

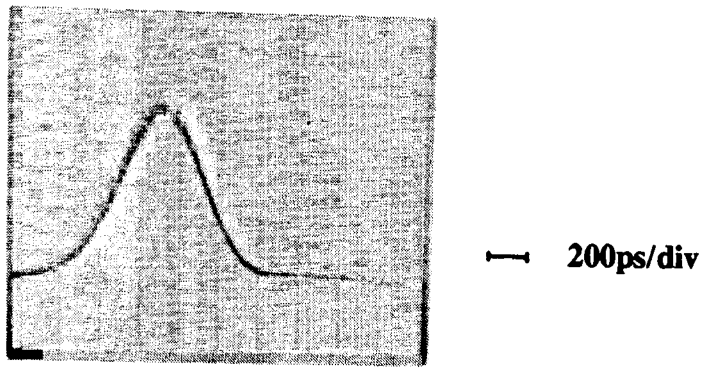


Figure 5. Transmitted pulses directly over 50km. Detector/scope response 320ps.

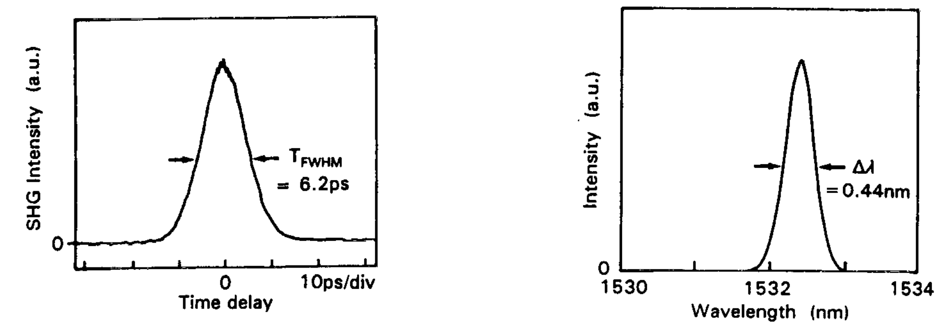
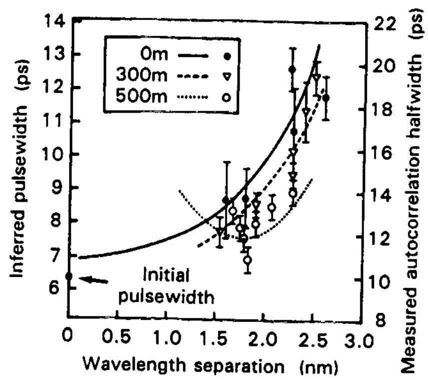


Figure 2. a) Autocorrelation trace and b) spectra of the pulses at the transmission fibre input



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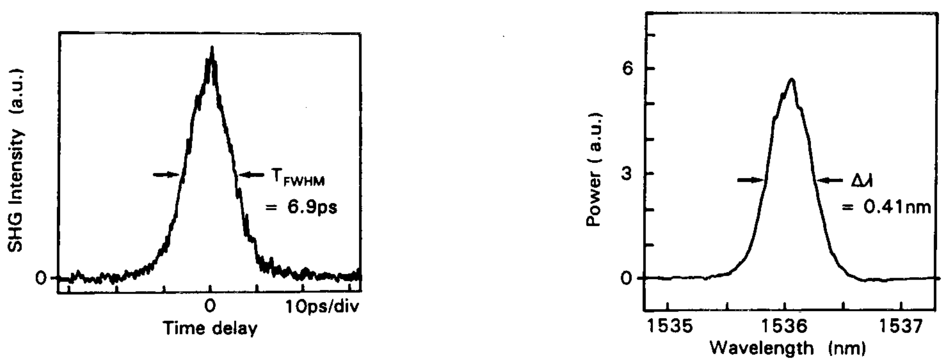

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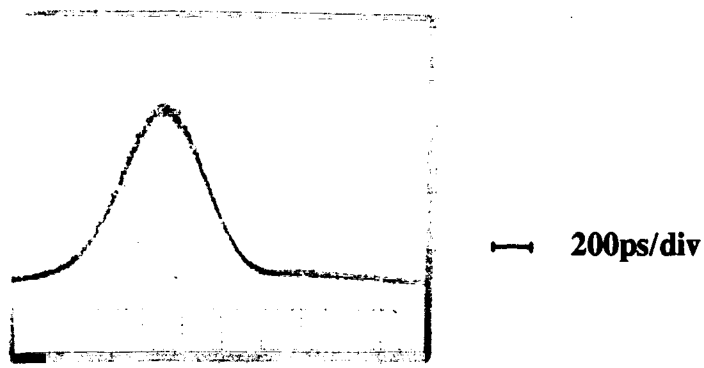

Figure 5. Transmitted pulses directly over 50km. Detector/scope response 320ps.