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LINEAR AND NON-LINEAR DISPERSION COMPENSATION AT ULTRA-HIGH DATA RATES USING MID POINT SPECTRAL INVERSION

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Abstract

We report experimental and numerical results on transmission of short pulses in systems with midspan spectral inversion and standard fibre. It is shown that a larger amount of nonlinearities can be tolerated if the spectral inversion is moved away from the midpoint of the span. Full recovery of the initial pulsewidth is experimentally demonstrated in the presence of nonlinearities.

Introduction

Midspan spectral inversion (MSSI) using phase conjugation can cancel group velocity dispersion (GVD) induced distortion, [1]. Recently, the possibility of cancelling the distortion caused by interplay between dispersion and self phase modulation (SPM) has been studied numerically, [2, 3], and experimentally, [4, 5]. The cancellation of four wave mixing (FWM) has also been demonstrated, [6, 7]. It has been pointed out that in order to achieve cancellation of both GVD and SPM, the total dispersion has to be identical in the two spans, and the power distribution has to be symmetrical along the fibre. The latter requirement cannot be met in a practical system with fibre loss. However there exist cases where the requirements are less stringent. If either the change in power level, the SPM induced spectral distortion, or the signal distortion due to dispersion is small between the amplifiers, the system may be sufficiently symmetric to achieve good compensation.

The experiments reported in [4-7] have been performed using the NRZ modulation format. We report experimental and numerical results on transmission of narrow pulses over standard fibre. The effect of imbalance in power levels in the two links has been investigated and possible implications for system design will be presented.

Experiments

The experimental setup is shown in figure 1. The pulse source is a sliding frequency laser which generates transform limited pulses with $sech^2()$ shape. The pulsewidth is typically 5-7ps depending on pump power and polarisation alignment. The repetition rate is low, approximately 100MHz, allowing study of transmission properties of single pulses without interference and interaction between pulses. The first link is 60km of standard non dispersion shifted fibre.

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At this point the signal pulses at 1532nm and the pump at 1535nm are combined and amplified before transmitting through 13km of dispersion shifted (DSF) fibre in which the conjugate signal at 1538nm is generated by four wave mixing. After filtering and amplification, the conjugated pulses are transmitted through a second link of standard fibre. When the second link is approximately 59km the GVD in the two links are equal. A length difference of 1km is due to differences in dispersion and pulse wavelength in the two links. The pulses have been characterised with an autocorrelator, optical spectrum analyzer and a high speed detector and oscilloscope with approximately 20ps resolution. In the experimental results on pulsewidth measurements using the autocorrelator, we have assumed a sech^2() shape of the pulses, and divided the autocorrelated FWHM by 1.55 to obtain the FWHM pulse width.

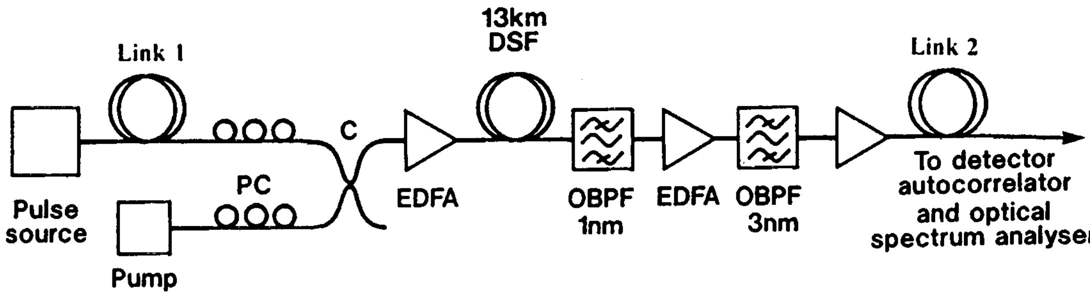

Figure 1: **Schematic of experimental setup.**
ATT: variable optical attenuator, PC: polarisation controller, C: 50% coupler, EDFA: erbium doped fibre amplifier, OBPF: optical band pass filter

Experimental results on linear transmission

In the first experiments, the pulse power were sufficiently low to avoid SPM in the transmission fibre. Measurements of pulsewidth versus offset from the 59km length of link 2 is shown in figure 2. In this experiment the input pulse width was 5.0ps. The minimum output pulsewidth is 2.5ps broader due to effects which are not cancelled by MSSI. These are third order dispersion, spectral filtering and polarisation mode dispersion.

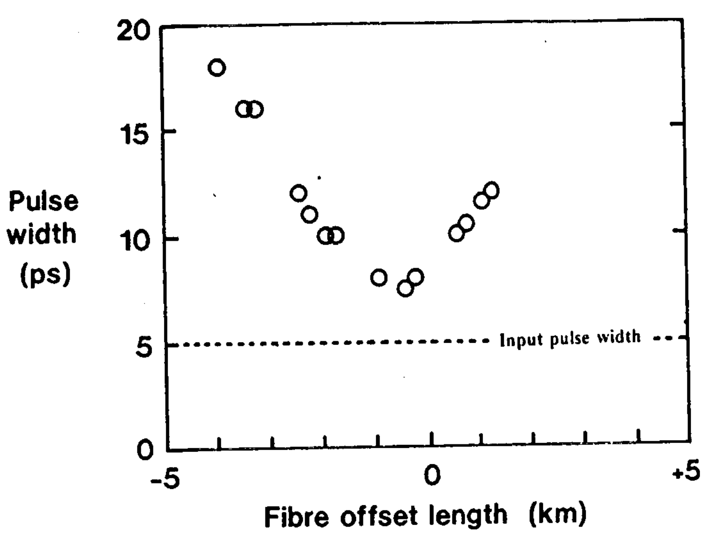

Figure 2: Measured pulsewidth versus length of second link.

Experimental results on nonlinear transmission

In a second experiment the power level in the 60km first link is varied using an optical attenuator at the fibre input and output pulsewidths measured for various lengths of the second link. Results are shown in figure 3 for four different pulse energies in the first link. The pulse energy in the second link was kept low to avoid SPM. Without a length offset in link 2 the pulsewidth is broadened with increasing SPM, while for shorter lengths, the SPM in the first link reduces the pulsewidth compared to the linear case. However, the minimum pulsewidth is slightly broadened compared to the input pulsewidth of 6.5ps.

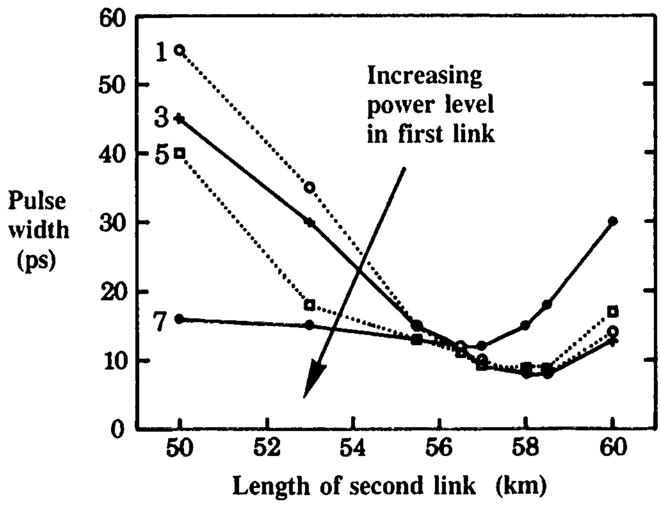

Figure 3: Measured pulsewidth versus length of second link. Transmission in first span is nonlinear while second span is kept linear. Increment in pulse energy between each curve is 2dB.

Experiments were also carried out to demonstrate that this broadening due to SPM in the first link could be cancelled by SPM in the second link. In this experiment, an amplifier was inserted after 50km in the second link in order to reach high pulse power. An example with SPM in both links is shown in figure 4 demonstrating that the initial pulsewidth was recovered. Both the input and output pulsewidth is 6.5ps when a $sech^2()$ shape is assumed. This shows that not only the broadening due to SPM is cancelled, but also the broadening due to PMD, higher order dispersion and spectral filtering have been cancelled. We found that the length of the second link had to be shortened by 2km to achieve the minimum pulsewidth, compared to the linear case in figure 2.

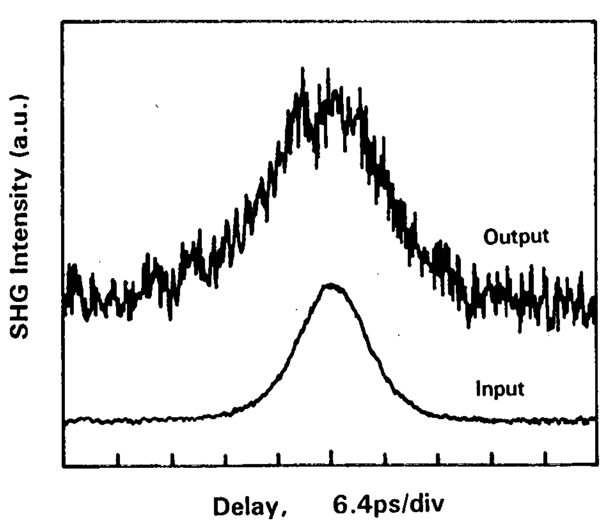

Figure 4: Measured autocorrelation traces. Upper curve is output pulse after 117km. Lower curve is input pulse. Transmission in both links are nonlinear.

Numerical results

In order to study these effects in more detail, numerical calculations on pulse transmission with MSSI have been carried out. FWHM pulsewidth versus distance for various power levels are shown in figure 5. An ideal conjugation is carried out after 10km and the fibre loss is 0.2dB/km. The pulses experience the same GVD in both links and higher order dispersion has been omitted. The different curves are for different pulse energy at the input of the first link. The most nonlinear case corresponds to a first order soliton at the input. The pulse energy at the input of the second link is fixed. In figure 5a the pulse energy after 20km is 5dB less than a first order soliton with 10ps FWHM. In figure 5b the pulse energy in the second link is 3dB higher than the case in figure 5a.

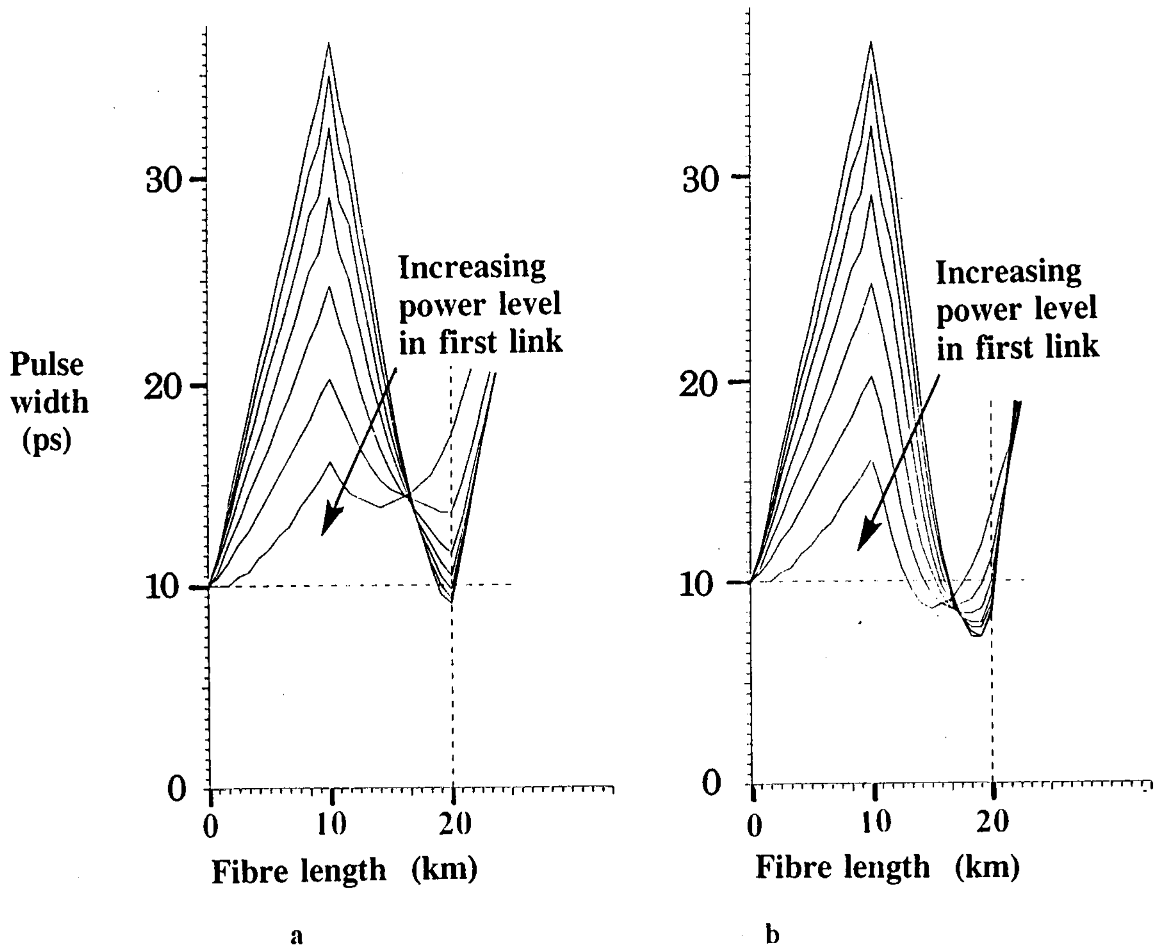

Figure 5: **Numerical computed pulsewidth versus length.**
Conjugator is at 10km. Increment in pulse energy between each curve is 1dB.
a: Nearly linear transmission in second link.
b: Nonlinear transmission in second link.

Discussion of results

The results in figure 5a shows that SPM in the first link alone, increases the minimum pulsewidth in the second link. This is due to the SPM induced spectral narrowing. SPM in the second link, where the chirp of the pulse has changed sign, leads to spectral broadening and enhanced pulse compression. Thus SPM decreases pulse broadening in the first link and increases pulse compression in the second link.

From figure 5b it can be seen that with sufficient SPM in the second link, the pulses can be compressed beyond the initial pulsewidth. This compression is analogous to soliton compression.

Both figure 3 and 5 shows that for shorter lengths of link 2, it is optimum to have some SPM in the system. If a system is to be designed to tolerate some SPM, it may be beneficial to move the conjugator away from the midpoint of the span and have unequal amount of GVD and SPM in the two links. Then the combined effect of linear (GVD) and nonlinear (SPM) dispersion may cancel each other.

The above results are valid in the case of single pulse. In the design of a real system where the pulses may interfere after some broadening, the peak power of the pulses have to be sufficiently reduced before they start to interfere. Similarily, if nonlinear pulse compression is to be used at the receiver end, the amplification of the pulses into the nonlinear regime must happen after the pulses has compressed sufficiently to remove the pulse interference. For this reason, 180 degree phase shift between the pulses may be optimum.

Conclusion

We have experimentally and numerically investigated single pulse transmission with an asymmetric amount of SPM and GVD in the two links in a MSSI system and found that asymmetric GVD may compensate for asymmetric SPM. This may be useful in design of OTDM systems, and can increase the tolerable input power levels in the system.

Acknowledgment

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References

1. A. Yariv, D. Fekete, and D. M. Pepper: "Compensation for channel dispersion by nonlinear optical phase conjugation", Opt. Lett., 1979, **4**, pp. 52-54.

2. C. Kurtzke, and A. Gnauck: "How to increase capacity beyond 200 Tbit/skm without solitons", ECOC'93, PDP ThC12.12, pp. 45-48.

3. K. Kikuchi, and C. Lorattanasane: "Compensation for pulse waveform distortion in ultra-long distance optical communication systems by using midway optical phase conjugator", IEEE Photonics Technol. Lett., 1994, **6**, pp. 104-105.

4. S. Watanabe, T. Chikagama, G. Ishikawa, T. Terahara, and H. Kuwahara: "Compensation of pulse shape distortion due to chromatic dispersion and kerr effect by optical phase conjugation", IEEE Photonics Technol. Lett., 1993, **5**, pp. 1241-1243.

5. W. Pieper, C. Kurtzke, R. Schnabel, D. Breuer, R. Ludwig, K. Petermann, and H. G. Weber: "Nonlinearity-insensitive standard-fibre transmission based on optical-phase conjugation in a semiconductor-laser amplifier", Electron. Lett., 1994, **30**, pp. 724-726.

6. S. Watanabe, and T. Chikagama: "Cancellation of four-wave mixing in multichannel fibre transmission by midway optical phase conjugation", Electron. Lett., 1994, **30**, pp. 1156-1157.

7. A. H. Gnauck, R. M. Jopson, and R. M. Deroisier: "Demonstration of nonlinearity compensation by spectral inversion in a three-channel WDM system", ECOC'94, postdeadline pp. 91-94.