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LINEAR AND NON-LINEAR DISPERSION COMPENSATION OF SHORT PULSES USING MIDSPAN SPECTRAL INVERSION

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Abstract

Fibre nonlinearity and dispersion may limit the repeater spacing in high speed fibreoptic transmission systems. We report experimental and numerical results on the nonlinear propagation of short optical pulses over standard non-dispersion shifted fibre links which are dispersion compensated using midspan spectral inversion. It has been found that an increased transmission nonlinearity 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. A system design based on these results is presented, allowing high transmitted power and long repeater spacing.

Introduction

Midspan spectral inversion (MSSI) has been shown to cancel group velocity dispersion (GVD) induced distortion, [1]. Linear transmission of 40Gbit/s optical time division multiplexed (OTDM) data over 200km standard fibre [2] has demonstrated the suitability of the technique for high speed transmission. In addition, the possibility of cancelling the distortion caused by the interplay between dispersion and self phase modulation (SPM) has been studied experimentally, [3, 4]. It has been pointed out that in order to achieve cancellation of both GVD and SPM, both the optical power level and GVD have to be symmetrical along the fibre. However the requirement on symmetric power level cannot be met in a practical system with fibre loss. The experiments reported in [3, 4] were performed using 5 and 10Gbit/s NRZ modulation respectively, with dispersion lengths comparable to the amplifier spacing, giving relaxed constraints on the symmetry requirements.

In this Letter we report experimental and numerical results on nonlinear transmission of short optical pulses (<10ps), with short dispersion lengths (<1km), suitable for high speed (>>10Gbit/s) optical time domain multiplexing (OTDM). With such short dispersion lengths, an exact compensation of nonlinearity is not compatible with long repeater spacing. The effect of an asymmetric power distribution in the two links has been investigated and a possible system design is presented which allows a combination of high transmitted power, short dispersion lengths and long repeater spacing.

Experiment

The experimental setup is shown in figure 1. The pulse source is a sliding frequency laser operating at 1532nm which generates 5-7ps full width at half maximum (FWHM) transform limited pulses with a sech^2 profile. The repetition rate is low, approximately 100MHz, allowing the study of the transmission properties of single pulses without interference and interaction between adjacent pulses. The pulses are propagated through the first link consisting of 60km of standard non-dispersion shifted fibre (D=15.5ps/nm·km). The broadened signal is then combined with the pump at 1535nm 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. The GVD in the two links is matched when the second link is approximately 58.5km. The pulses have been characterised with an autocorrelator, optical spectrum analyzer, and a high speed detector and oscilloscope combination with approximately 20ps resolution. A sech^2 pulse profile is assumed in all cases and thus the autocorrelation FWHM is divided by 1.55 to obtain the FWHM pulsewidth.

Experimental results

The transmitted pulsewidth versus offset from the 58.5km length of link 2 was measured for an input pulsewidth of 6.5ps. With linear transmission, the minimum output pulsewidth was broadened by 2.0ps due to effects which are not cancelled by MSSI. These are third-order dispersion, spectral filtering and polarisation mode dispersion [5]. The power level in the 60km first link was then varied using an optical attenuator at the link input and the output pulsewidth measured for various lengths of the second link. Results are shown in figure 2 for four different pulse energies input to the first link. In the most nonlinear case, the launch pulse power is approximately 1dB less than that corresponding to a first order soliton and the difference in launch pulse power between each curve is 2dB. 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 output pulsewidth. However, in this case the minimum observed pulsewidth is slightly broadened compared to the input pulsewidth of 6.5ps.

Experiments were also carried out to demonstrate that the 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 and reinsert the nonlinearity. In this case the initial width and shape of the autocorrelation trace was recovered as shown in figure 3. We found that the length of the second link had to be shortened by 1.5km to 57km in order to achieve the minimum pulsewidth.

Numerical simulation

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 4. A 10ps FWHM sech^2 input pulse, fibre loss of 0.2dB/km, and ideal conjugation after 10km are assumed. In addition the pulses experience the same GVD in both links whilst higher-order dispersion has been omitted. The different curves are for different pulse energies at the input of the first link while the pulse energy at the input of the second link is held constant. In both figures, a and b, the most nonlinear case corresponds to a first order soliton at the input of the first link. In figure 4a, the pulse energy launched into the second link, in all cases is 3dB less than that corresponding to a first order soliton (10ps FWHM), whilst in figure 4b the pulse energy launched into the second link is equivalent to that of a first order soliton (10ps FWHM).

Discussion

The experimental results in figure 2 are in good qualitative agreement with the theoretical results (figure 4a) and show that SPM in the first link alone increases the minimum pulsewidth achievable after the second link. This is due to the SPM induced spectral narrowing in the first link. On the contrary, SPM in the second link, where the chirp of the pulse has changed sign, leads to spectral broadening and enhanced pulse compression. Thus SPM can be advantageous since it decreases pulse broadening in the first link and increases pulse compression in the second link The spectral narrowing and broadening was observed both experimentally and numerically when the pulse power was less than that of a first order soliton.

From figure 4b it can be seen that with sufficient SPM in the second link, the pulses can be compressed beyond their initial pulsewidth. This compression is analogous to soliton compression. Both figure 2 and 4 show that for shorter lengths of link 2, it is beneficial to have some SPM in the system. In fact, if a system is to be designed to tolerate some SPM, it may be advantageous to move the conjugator away from the midpoint of the span and have an unequal amount of GVD and SPM in the two links. In this case the combined effect of linear (GVD) and nonlinear (SPM) dispersion may cancel each other. This is demonstrated by the result in figure 3 which also shows that SPM in the second link can be used to compress pulses which have been broadened due to in-line filters, third-order dispersion, and polarisation mode dispersion.

The above results are valid in the case of single pulse transmission. They can also be applied to pulsetrains, provided that the nonlinear interaction between pulses is kept sufficiently low. With nonlinear transmission at the start of link 1, the duty cycle (ratio between input pulsewidth and bitperiod) must be low, typically 0.2 which is near the requirements on duty cycle in a soliton system. Thus the pulse power is reduced sufficiently due to fiber loss and pulse broadening 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 occur after the pulses have compressed sufficiently to avoid nonlinear pulse interaction. In addition, a 180 degree phase shift between adjacent pulses may be desirable.

Our results show that standard fibre and a soliton transmitter with power level ~2dB lower than that corresponding to a fundamental soliton can be used. The well controlled interplay between SPM and GVD at the transmitter is used to allow an increase in transmitted power, while MSSI is used to compensate for GVD and SPM. Transmitted powers of +15dBm may then be allowed in a 20Gbit/s system using 10ps pulses. Simulation result on transmission of a 01110100 pattern in such a system is shown in figure 5. This increase in transmitter power, compared to +6dBm [2], +11dBm [3], and +13dBm [4], can either be used to increase the repeater spacing or improve system margins and S/N ratio at conjugator input.

Conclusion

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

Acknowledgment

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Figure captions:

Figure 1: Schematic of experimental setup.

DSF: Dispersion shifted fibre, PC: polarisation controller, C: 50% coupler, EDFA: erbium doped fibre amplifier, OBPF: optical band pass filter

Figure 2: Measured pulsewidth versus length of second link.

In these measurements the first link was 60km and input FWHM pulsewidth was 6.5ps. Transmission in the first span was in the non-linear regime. The pulse energy was varied in 2dB increments with the highest pulse energy ~1dB less than a first order soliton. The pulse energy launched into the second span was maintained near constant and low such that transmission was in the linear regime.

Figure 3: Autocorrelation trace with nonlinear transmission in both links.

a: Autocorrelation trace of input pulse

b: Autocorrelation trace of output pulse after 117km.

Figure 4: Numerical computed pulsewidth versus fibre length.

In these simulations the conjugator is included after 10km. The pulse energy launched into the first link is varied, in 1dB increments, with the highest launched energy corresponding to a first order soliton (10ps FWHM) whilst the pulse energy into the second link is constant and is (a) 3dB less than a first order soliton (10ps FWHM) and (b) corresponds to a first order soliton (10ps FWHM).

Figure 5: Numerical result on transmission of 01110100 pulse pattern.

In these simulations the bitrate is 20Gbit/s and the FWHM pulsewidth is 10ps. The pulse energy launched into the first link is 2dB less than a first order soliton while the transmission in the second link is linear. The first link is 100km and the dispersion in the two links are equal.

Upper trace: input of first link.

Middle trace: after 95km in second link.

Lower trace: after 100km in second link.

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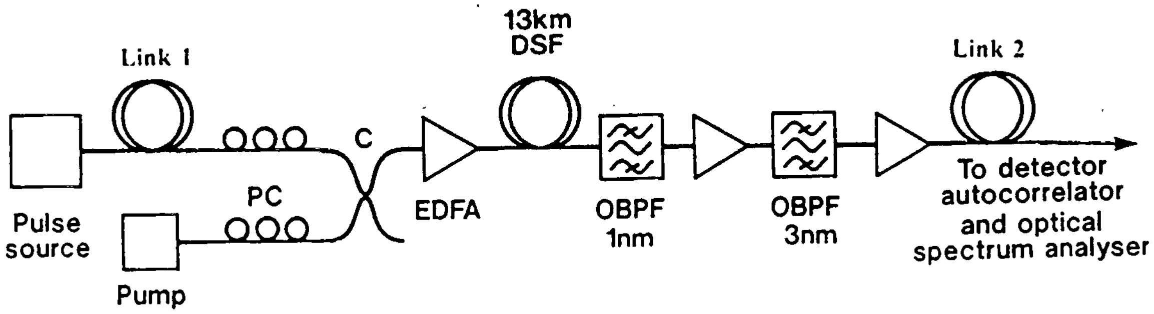


FIGURE 1.

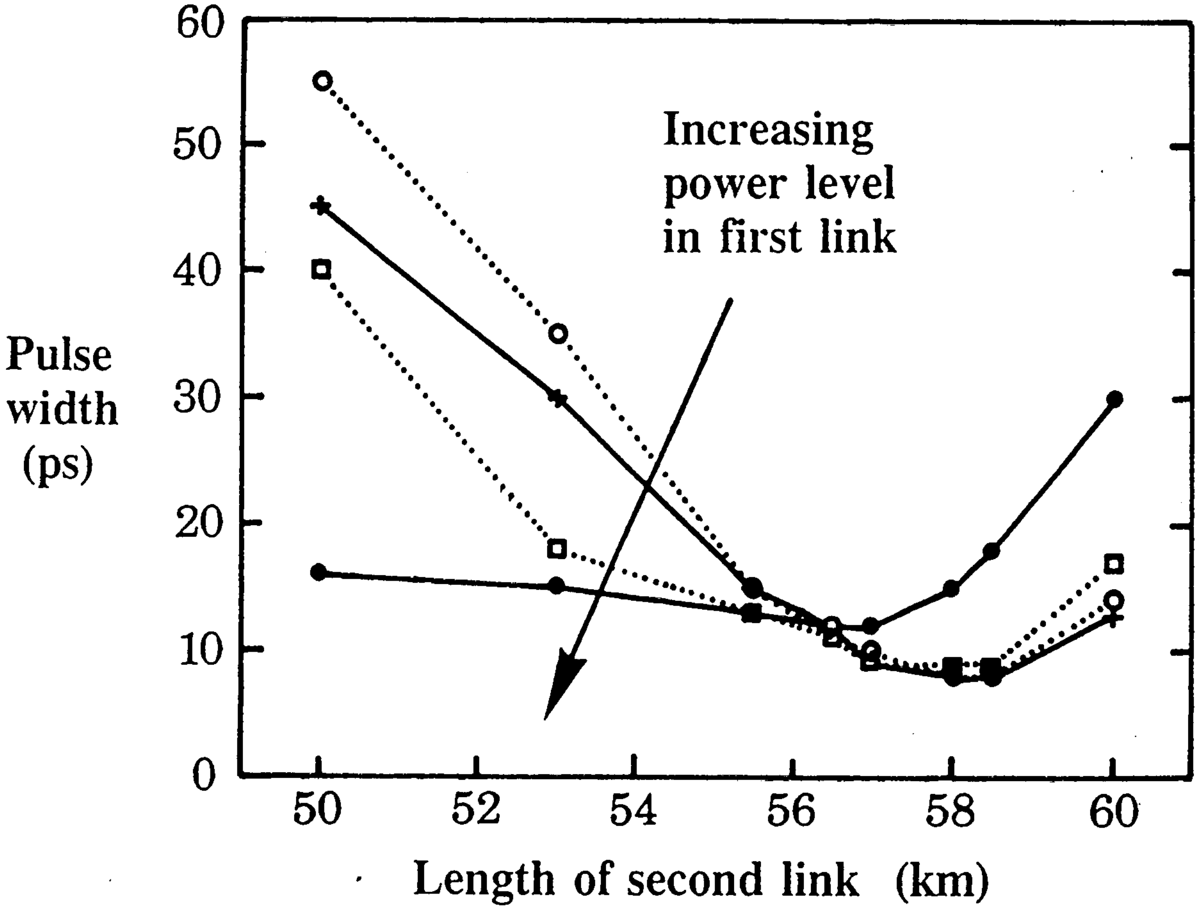

Increasing power level in first link
Pulse width (ps)
60
50
40
30
20
10
0
50
52
54
56
58
60
Length of second link (km)

Figure 2

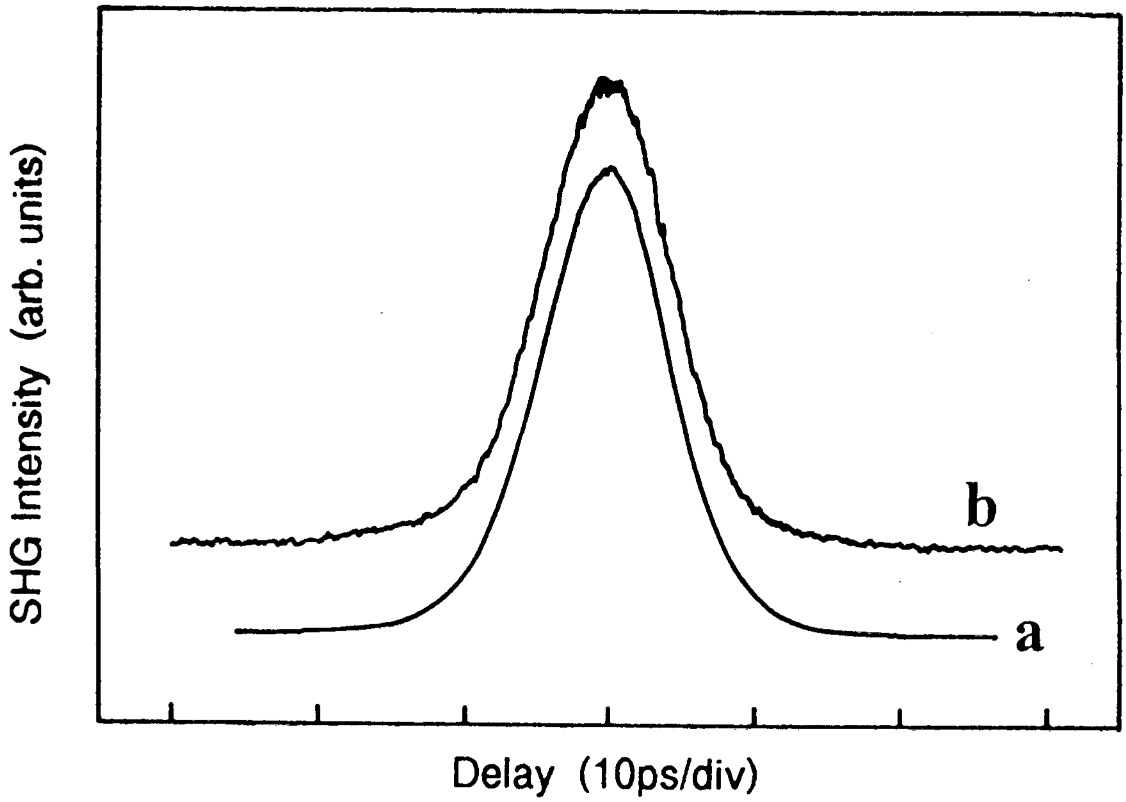
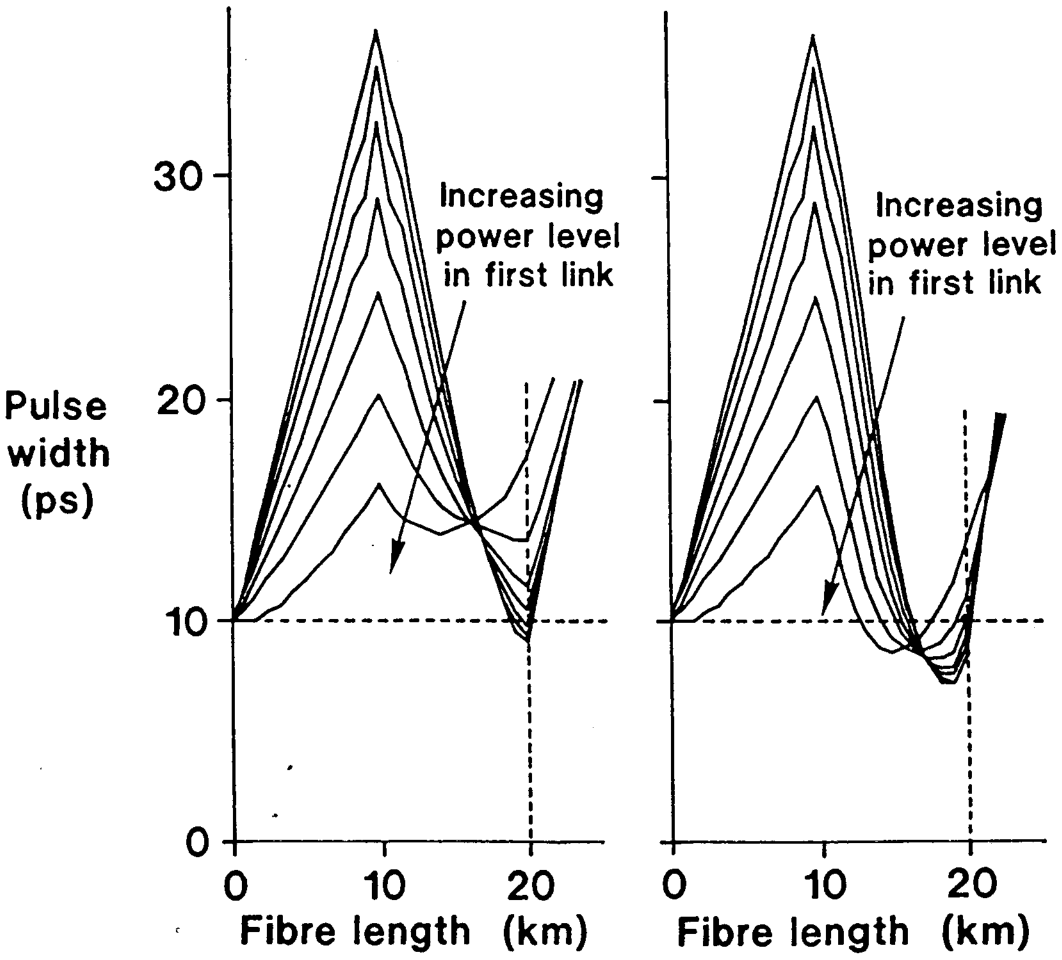


Figure 3


Pulse width (ps)
30
20
10
0
0
10
20
Fibre length (km)
Increasing power level in first link
0
10
20
Fibre length (km)
Increasing power level in first link

a

b

Figure 4

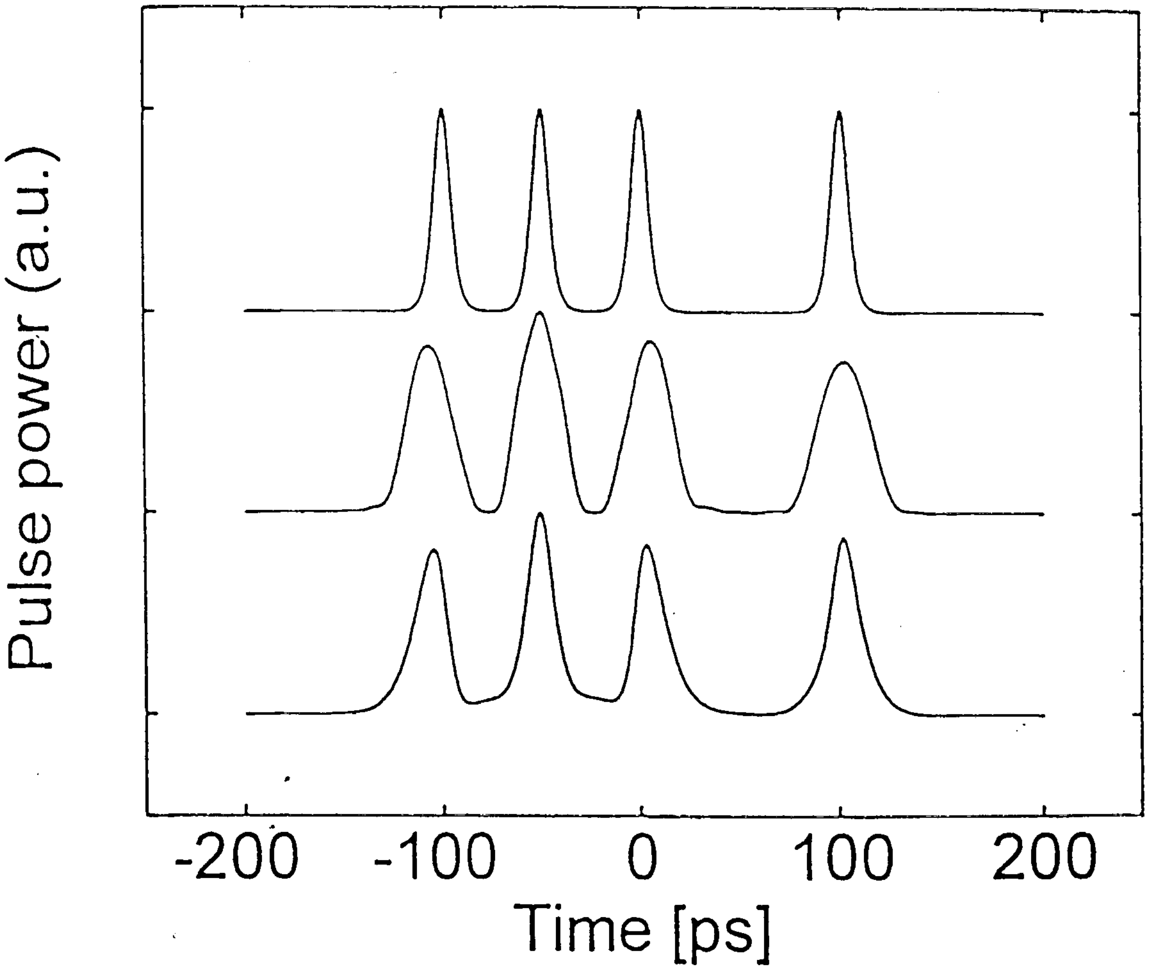


Figure 5