Impact of polarisation mode dispersion in field demonstration of 40Gbit/s soliton transmission over 500km

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40Gbit/s single-wavelength alternate-polarisation soliton transmission over 500km has been successfully demonstrated in a field trial using dispersion-shifted fibre. Comparisons with an equivalent laboratory trial and numerical simulations show that the main source of impairment is polarisation mode dispersion.

Introduction: One of the aims of modern optical communication research is to increase the single-channel bit rate up to 40Gbit/s, keeping a large span loss. In this work, transmission at 40Gbit/s over 500km has been successfully demonstrated over an installed cable using soliton signals with alternate polarisation, without any in-line control. This experiment was carried out with a record 24.5dB span loss. The alternate polarisation method consists in transmitting adjacent pulses with orthogonal states of polarisation; such a technique enables the level of soliton interactions to be decreased and consequently the use of longer pulses, reducing instability effects due to periodical amplification [1, 2].

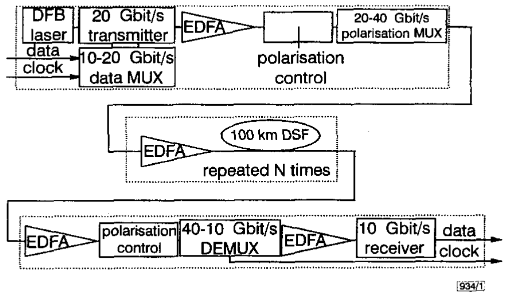

Fig. 1 *Experimental setup for field experiment*

Experimental setup: In Fig. 1 we illustrate the experimental setup. The continuous wave distributed feedback output is fed to the 20Gbit/s transmitter which uses a two-stage electroabsorption modulator (EAM) for 10ps pulse generation and data encoding. The transmitter is fed with a 20GHz clock signal and 20Gbit/s data provided by a 10–20Gbit/s multiplexer. The 20Gbit/s signal is optically time and polarisation multiplexed to obtain a 40Gbit/s signal with alternate polarisation.

At the receiver side, the optical signal is time demultiplexed from 40 to 10Gbit/s by a polarisation insensitive two-stage EAM. The 10Gbit/s receiver output is finally sent to a 10Gbit/s bit error rate (BER) and Q factor performance analyser.

The transmission line is an assembly of 102km dispersion-shifted fibre spans (with 24.5dB loss) and erbium-doped fibre amplifiers (EDFAs). The average chromatic dispersion or group velocity dispersion (GVD) was equal to 0.14ps/nm/km at 1549nm (0.2ps/nm/km at 1550nm), while the average polarisation mode dispersion (PMD) [3] was $0.25 ps/\sqrt{km}$.

Results: In Fig. 2 we show the Q factor against link length characteristics for three different wavelengths and an optimum input power of 8.7dBm. Good performance is observed up to a distance of 500km. The main link limitation comes from PMD. In fact, by replacing the installed cable with fibre spools which have a PMD lower than $0.1 ps/\sqrt{km}$, the system reaches the distance of 700km with a Q factor higher than 6. The Q factor showed strong fluctuations in time for distances > 400km due to the variation of the PMD caused by changes in the environmental conditions.

Typical Q factor time fluctuations are shown in Fig. 3 for 500km at a 1549nm wavelength (Fig. 3*a*) and 1550nm (Fig. 3*b*), with an input power of 8.7dBm. The Figures show two kinds of fluctuation: 'slow' and 'fast' fluctuations. The long term drift can be attributed to the PMD evolution of the buried cable. Fast fluctuations are mainly due to the birefringence evolution of the fibre pieces connecting the buried fibres. Analysing measurements made during a week we observed that, even though at both wavelengths the Q factor oscillates between 5 and 18, the time interval in which Q remained below 6 was limited to a few minutes. Furthermore, at 1550nm, the Q factor can be higher than at 1549nm, even though at 1550nm stronger fast fluctuations are present.

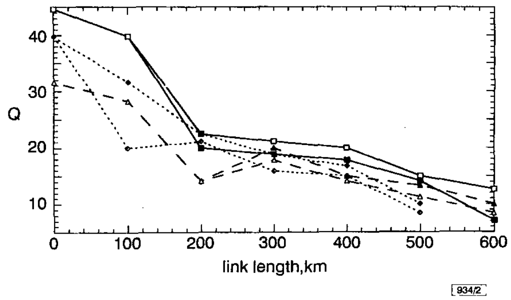

Fig. 2 *Q-measurements against distance for both orthogonal polarisation streams (A and B) for three wavelengths*

■ 1549nm A
□ 1549nm B
▲ 1549.5nm A
△ 1549.5nm B
● 1550nm A
◇ 1550nm B

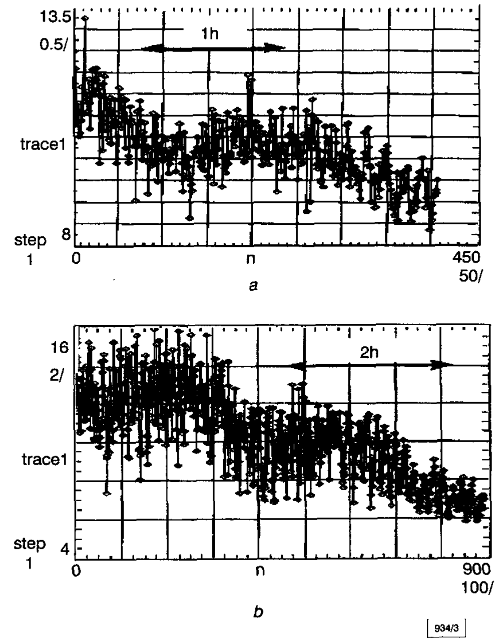

Fig. 3 *Q-measurements obtained at different times at 500km and 1549nm (0.14ps/nm/km) and 1550nm (0.2ps/nm/km)*

a 1549nm (0.14ps/nm/km)
b 1550nm (0.2ps/nm/km)

We explain this behaviour in terms of the self-trapping effect (STE) [4] that permits nonlinear PMD compensation when specific GVD, Kerr effect, PMD and pulse duration conditions are satisfied. Numerical simulations of the field experiments, with the method reported in [5], have shown how the nonlinear process of PMD compensation strongly depends on the realisation of the random mode coupling process.

By investigating the pulse shape at the link output, in the presence of PMD, two effects can be observed: a pulse broadening and a group delay depending on the input state of polarisation [3]. The second effect can substantially impair the performance of a soliton system with alternate polarisation, since it can induce a differential group delay (DGD) between the orthogonal pulses. The STE can compensate only for pulse broadening, hence if the particular realisation of the random mode coupling induces a large DGD the system will have a low Q value both at 1549 and 1550nm. Conversely, if the DGD is lower than 15% of the bit time, a good Q

factor can be obtained at both wavelengths and at 1550nm the conditions are more favourable since STE is more efficient [5].

Conclusions: A field demonstration of 40Gbit/s soliton transmission with 102km–24.5dB spans has been carried out over 500km for the first time. Results highlight the detrimental impact of a PMD equal to 0.25ps/√km on the long term performance of the system.

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Influence of transmission distance on XPM-induced intensity distortion in dispersion-managed, amplified fibre links

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The variation of cross-phase modulation (XPM) induced distortion with transmission distance is investigated for dispersion-managed fibre links using a recirculating loop. New results are reported showing the distance dependence of the XPM-induced distortion in an IM-DD system on channel spacing and dispersion. It is demonstrated that the acquired XPM distortion can be effectively reduced by use of additional dispersive fibre at the receiver.

Introduction: The high powers needed to maximise inter-amplifier span lengths in high bit rate, multichannel WDM transmission systems result in increased signal distortion due to fibre nonlinearities. One of the dominant multiwavelength nonlinearities is cross-phase modulation (XPM), which causes a variation in the optical phase due to power fluctuations in the other channels [1 – 4]. This phase variation is converted into amplitude distortion in the signal by the residual system dispersion and leads to eye closure and jitter. In a recent Letter [4], we reported the influence of bit rate and fibre dispersion on the XPM-induced distortion in a single amplified fibre span. In this Letter we report new experimental and theoretical results on the accumulation of XPM induced pulse distortion with distance in dispersion compensated standard singlemode fibre (SSMF), investigated using a recirculating loop. As in [4], the pump-probe experimental configuration is used to separate the XPM effect from other nonlinearities. The channel spacing required to reduce the XPM crosstalk and the influence of different compensating schemes on the resultant distortion are investigated. In particular, we show that although the accumulated nonlinear distortion cannot be fully compensated for, it can be minimised with appropriately chosen lumped dispersion at the receiver.

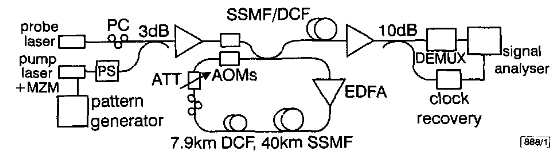

Fig. 1 *Pump-probe setup using recirculating fibre loop*

Experimental setup: The length-dependent experiments were performed using a recirculating fibre loop (Fig. 1) in which dispersion compensating fibre (DCF, $-100 ps \cdot km^{-1} \cdot nm^{-1}$) was used to perfectly compensate 40km of standard singlemode fibre (SSMF, $17 ps \cdot km^{-1} \cdot nm^{-1}$) in each span. Additional lumped compensation of the total residual dispersion was provided at the receiver by 22km of SSMF or the equivalent length of DCF with opposite sign of dispersion. As before [4], two channel pump-probe measurements were carried out with equal average powers of +13dBm/channel. A DFB transmitter with an integrated Mach-Zehnder modulator was used as the pump source, driven by an NRZ pattern with a 10–90% rise time of 56ps for pulse transitions. The channel spacing $\lambda_{pump} - \lambda_{probe}$ could be adjusted by temperature-tuning the pump with respect to the probe. The polarisation scrambled (PS) pump and the probe were both gated into the loop using an acousto-optical switch (AOM). An EDFA with +16dBm saturated output power and noise figure of 4.5dB was used at the start of the loop to compensate for loop losses, and the signals were demultiplexed using a concave grating and analysed using a fast sampling oscilloscope. The XPM distortion was quantified using the index m_x defined as the peak-to-peak fluctuation normalised to the average power in the probe channel [4].

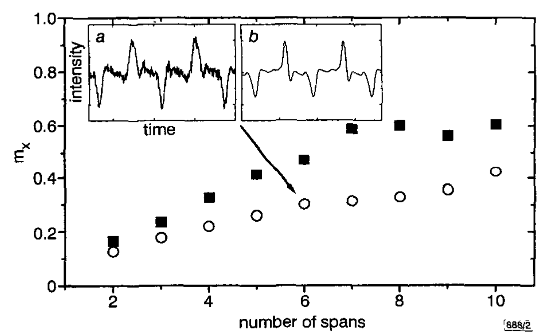

Fig. 2 *Length dependence of XPM-induced distortion m_x in exactly compensated links*

■ $\Delta\lambda$ = 0.6nm, DCF+SSMF
○ SSMF+DCF
Inset: probe waveforms for n = 6 obtained for SSMF+DCF
a Experimental
b Simulated

Results and discussion: The build-up of XPM induced distortion was measured as a function of the number of recirculations. In the case of perfect compensation, the channels were brought back into alignment prior to the subsequent recirculation, resulting in an increase in the distortion m_x with distance. Fig. 2 shows the experimental results for up to 10 spans with a channel separation $\Delta\lambda$ = 0.6nm (75GHz) and 400ps spacing between pulse edges of the pump waveform, corresponding to clusters of 4 × 1bits in a 10Gbit/s NRZ system. Fig. 2 also shows the typical distortion of the probe waveform after n = 6 recirculations, corresponding to a transmission distance of 290km, which, in a WDM transmission system would result in vertical eye closure. The XPM distortion increased almost linearly with distance up to m_x = 0.42 for post-compensation, thus resulting in a contribution of 4% to the signal