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PERIODICALLY AMPLIFIED TRANSMISSION SYSTEM BASED ON LOSS COMPENSATING DISPERSION DECREASING FIBRE

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D.J. Richardson, L. Dong, R.P. Chamberlin, A.D. Ellis, T. Widdowson and
W.A. Pender

Amplified transmission lines based on loss compensating dispersion decreasing fibres (LCDDFs), i.e. fibres in which the dispersion profile is made to follow that of the fibre loss, are a promising medium for the transmission of high bit-rate, ultrashort soliton pulses [1,2]. Due to the perfect match between nonlinearity and dispersion at all points in the fibre LCDDFs provide access to propagation regimes (both single channel and WDM) made inaccessible by the periodic amplification process in systems based on conventional dispersion shifted fibre (DSF) [3]. To date soliton loss compensation has only been demonstrated in single pulse, single span propagation experiments [4,5]. In this presentation, we describe the first experimental demonstration of a periodically amplified transmission system based on LCDDFs. We report error free transmission of: (a) 10 Gbit/s, 6.5ps pulses over 8 amplification cycles (304km) for a system with a mean dispersion of 2.4ps/(nm.km) and 38km amplifier spacing, $L_{amp} \approx 5$ soliton periods (z_0); and (b) 10 GBit/s 11.0ps pulses over 2200km in a system with lower mean dispersion 1.1ps/(nm.km) and 18 km amplifier spacing ($\approx 0.4z_0$). The results indicate the potential of the technique to enter propagation regimes made inaccessible by conventional average soliton techniques. The measurements also highlight the limiting effect of the soliton acoustic interaction [6] which can be severe in these types of system, in which the minimum realistically achievable RMS path average dispersion tends to be higher than that of a conventional DSF system. The limiting effects of third order dispersion are also observed.

The experimental configuration is shown in Fig.1. 4.1ps pulses from a 10 GHz, regeneratively mode-locked, erbium doped ring laser are modulated at 10 GBit/s and loaded into a recirculating loop structure. The loop consists of an input coupler (80:20), an isolated EDFA and monitor coupler (90:10), a 2.7nm bandpass filter and a 38km LCDDF. The LCDDF (see Fig.2 and more fully described in Ref[4]) had an exponential dispersion profile at 1550nm ranging from 6 ps/(nm.km) at the input to 0.55 ps/(nm.km) at the output that was well matched to the average fibre loss of 0.265 dB/km. Third order dispersion was 0.053 ps/(nm^2.km). The average fibre dispersion over the span was 2.4 ps/(nm.km) and therefore the loop length (L_{amp}) corresponds to $5.4z_0$ for 6.5 ps pulses. The BER characteristics and spectral form of the loop output could be measured as a function of number of loop circulations (distance) by pulse burst gating and synchronisation of a 10 Gbit/s BER test set and time gating of an optical spectrum analyzer respectively.

To illustrate the quality of the loss compensation process we initially examined the evolution of pulse spectra as a function of propagation distance. The results of one such measurement with 6.5 ps pulses are shown in the contour plot in Fig.2, where we see that after an initial stage of spectral narrowing due to the 2.7nm intra-loop filter and amplifier setting, the spectrum stabilises and remains constant for a total transmission distance in excess of 300km. This distance corresponds to 8 amplification cycles.

D.J. Richardson, L. Dong, R.P. Chamberlin are with the Optoelectronics Research Centre, Southampton University, UK.
A.D. Ellis, T. Widdowson, W.A. Pender are with BT Laboratories, Martlesham Heath, UK.

Little evidence of spectral sideband generation, or energy shedding to the continuum is observed as would be expected within a conventional, periodically amplified system of an equivalent L_{amp}/z_0 ratio [7] and demonstrates the excellent loss-compensating characteristics of the fibre.
We next examined the system performance (BER) as a function of transmission distance and pulse wavelength. Error free transmission (BER=1e-9) was obtained for a maximum transmission distance of 304 km (8 recirculations) at 1550 nm. The maximum error free transmission distance at 1555nm was slightly compromised to 266km (7 recirculations). The system was found to be timing jitter limited for longer propagation distances. We believe the origin of the jitter lies in the soliton acoustic effect, in which the RMS timing jitter scales in proportion to D^2 [6], as opposed to the more familiar Gordon-Haus effect due to amplifier noise in which the RMS timing jitter scales with $D^{0.5}$. The average RMS value of D in this fibre is high $<D^2>^{0.5}$ = 3.7ps/(nm.km) due to the relatively large exponential dispersion variation, a crude estimate of error-free transmission distance yields a value of ≈5-600 km in reasonable accordance with our observations. Although these limitations are initially somewhat surprising it should be noted that current fibre fabrication technology should permit an approximate five-fold reduction in absolute dispersion variation thereby reducing the impact of the electrostriction effect to a tolerable level. The beneficial effects of reducing the average dispersion was confirmed in additional experiments in which only the low dispersion half of the LCDDF (see Ref[4]) was used within the same loop. The LCDDF length, RMS dispersion and mean dispersion were 18km, 1.4 ps/(nm.km) and 1.1 ps/(nm.km) respectively. Optimum performance was obtained at a wavelength of 1549nm, which corresponds well to the fibre design wavelength at which the dispersion profile is most closely matched to the fibre loss. In this case, although still jitter limited, error-free, 10 Gbit/s, 11ps pulse transmission was obtained over 123 amplification cycles=2200km (see Fig.3). In this instance L_{amp}/z_0=0.4 and whilst this ratio does not strongly violate average soliton dynamics for which $L_{amp}/z_0 < 0.8$ is widely recognised as the limit, it does serve to illustrate the advantage of moving to a reduced average dispersion. Note also from Fig.3 that the effects of third order dispersion also become more strongly manifest in this low dispersion regime, which serves to detune the dispersion profile from its desired exponential form at wavelengths away from the design wavelength and thereby disturbing the local balance of dispersion and nonlinearity throughout the system. This effect imposes some limitations for WDM applications of such fibres although in the longer term it may prove possible to fabricate dispersion flattened LCDDFs.

In conclusion we have experimentally demonstrated a periodically amplified transmission system based on LCDDF. We report error free, 10 Gbit/s, 6.5 ps pulse transmission over 8 amplification cycles (304km) in an LCDDF recirculating loop with $L_{amp}/z_o \approx 5$, and of 11.0ps pulses over 123 amplification cycles (2200km) in a loop with $L_{amp}/z_o \approx 0.4$. In addition, we have observed that timing jitter due to the acoustic effect can be a significant limiting factor in such systems unless the path average value of $<D>^2$ is kept sufficiently low, or unless soliton control techniques are implemented. As we progress to shorter pulses and therefore higher bit-rates self Raman scattering will also be expected to have a deleterious effect. Furthermore we have observed that third order dispersion can have a significant effect on pulse transmission in low dispersion LCDDFs. The experiments illustrate the possibilities the techniques offers for transmission beyond the constraints of average soliton dynamics. It should be stated that these results in themselves do not represent the limits of the technique. Realistic improvements in such fibres will allow for considerably longer amplifier spans, significantly shorter pulses and significantly higher data rates than we have so far demonstrated.

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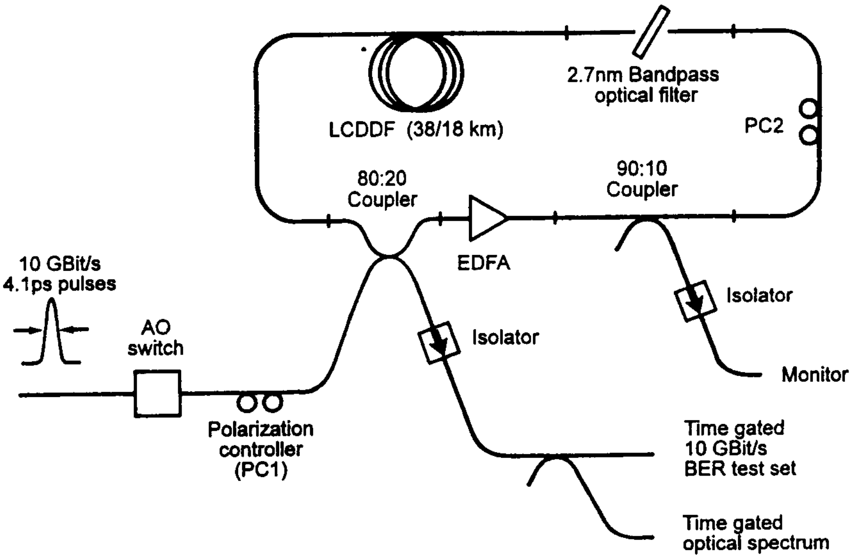

Fig.1 Experimental configuration of the recirculating ring

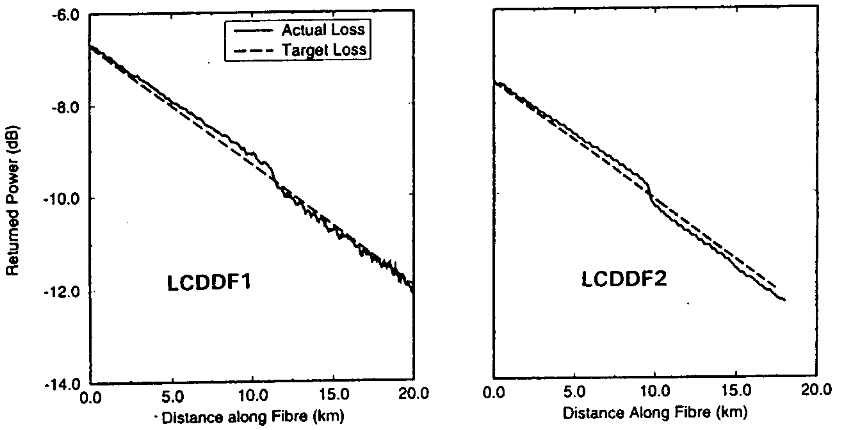

Fig.2 OTDR plots of the loss compensating fibres used in these experiments with the superposed design profiles based on the dispersion profiling. The 38km fibre was constructed from LCDDF1 and LCDDF2 spliced together. LCDDF2 was used in the low average dispersion link measurements.

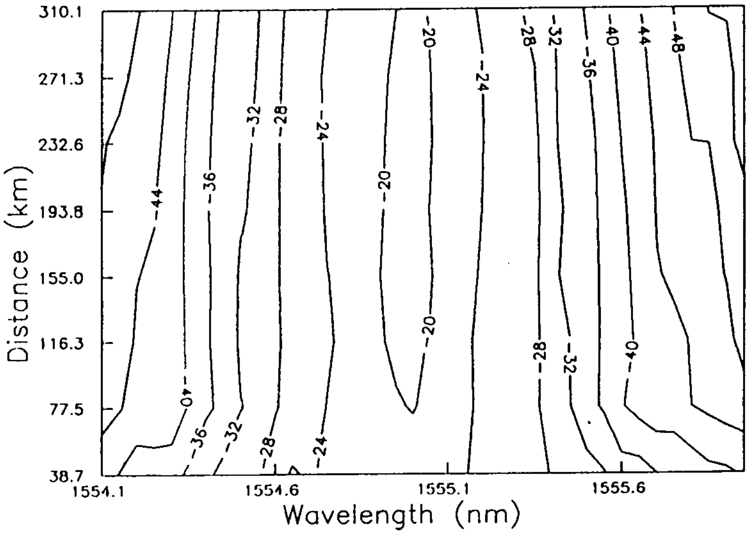

Fig.3 Contour ploy (4dB/contour) illustrating spectral evolution of the pulse trains as a function of transmission distance (number of pulse circulations). After an initial period of stabilisation due to the intra-loop filter, stable 6.5ps pulse propagation is obtained for distances in excess of 300 km.

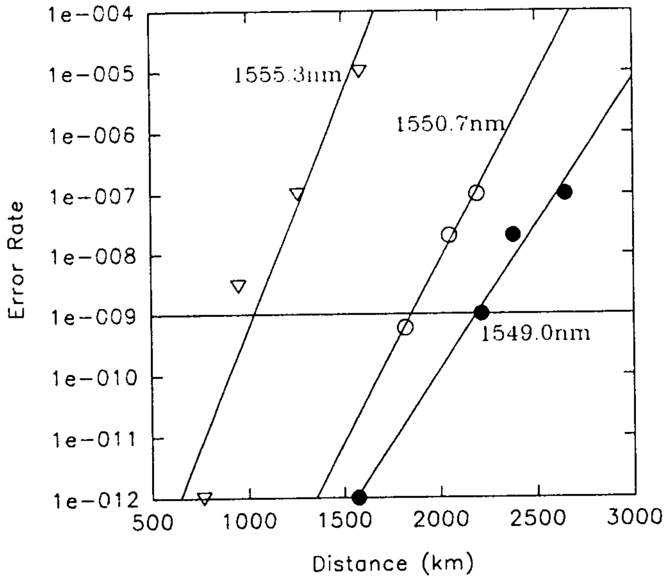

Fig.4 BER plot versus transmission distance as a function of wavelength illustrating error free operation over distances of >2200km and the limiting effects of third order dispersion achievable error free transmission distance.