# Experimental demonstration of 10 GBit/s, 4.7 ps pulse transmission over 4300km in a low dispersion, loss compensating dispersion decreasing fibre

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Continuous, dispersion varying fibres (DVFs) offer a wide range of potential applications for distributed linear/nonlinear pulse manipulation and control. With the development of simple fibre fabrication technology capable of manufacturing up to 40 km lengths of DVF considerable attention has focussed on their potential application as a transmission media in advanced soliton communication systems. As pointed out by Tajima [1] fibres with exponentially varying dispersion matched to follow the fibre loss can be used to eliminate the deleterious effects of the local imbalances in nonlinearity and dispersion that arise as a result of the pulse energy variation between amplifier spans in a conventional soliton transmission line. These localised imbalances restrict the bit-rates that can be used in single channel systems once the soliton period of the pulses approaches that of the amplifier spacing, and also give rise to serious inter-channel effects in soliton WDM systems [5]. Single pulse transmission experiments have recently been demonstrated illustrating loss compensation over single amplifiers spans using loss compensating dispersion decreasing fibre (LCDDF)[2,3]. These early results have been followed by multi amplifier-stage experiments, illustrating application to the periodically amplified case for short pulses in regimes not permitted by conventional average soliton dynamics [4]. However, error free pulse transmission for high bit-rate single channel data transmission was found to be limited by effects such as the soliton acoustic interaction and Gordon Haus jitter which are pronounced due to the high path average path dispersion of the available LCDDFs [4]. In order to obtain significantly better results, LCDDFs with correspondingly smaller absolute dispersion range variations need to be developed. ( Note that the application of a discrete approximation to the desired exponential dispersion profile for enhanced soliton WDM transmission have also been demonstrated [5]). In this paper we present initial results on the development of low dispersion, LCDDFs and present the first experimental results on the use of these more gently tapered fibres in recirculating loop experiments. We show that the lower average dispersion reduces the strong deleterious effects observed in the earlier loop experiments and obtain error free, 10 GBit/s, 4.7ps pulse transmission over fibre lengths in excess of 4300km.

The low dispersion LCDDF was fabricated from a dispersion shifted index profile preform by tapering the fibre during the draw. A 20km fibre with an exponential dispersion profile matched to a fibre loss of 0.2 dB/km with an output dispersion of 0.15 ps/(nm.km)at 1550nm was targeted, based on our anticipated dispersion accuracy of +/- 0.10 ps/(nm.km) over the length. 1 km constant diameter sections were pulled at the beginning and end of the pull to enable us to obtain an idea of the fibre dispersion profile. The resulting fibre loss was measured to be 0.205 dB/km. The dispersion of the fibre at the input, output and it's average along the span were measured to be 0.22 (+/- 0.02), 0.10 (+/-0.02), 0.167(+/- 0.005) ps/(nm.km) respectively at 1550 nm, indicating a significant deviation from the desired form, particularly at the high dispersion (input) end. This offset corresponds to an error in the dispersion zero wavelength of the fibre by ~0.7nm at the fibre input and ~2nm at the fibre output illustrating the tight tolerances involved in the fabrication of such gently profiled fibres. Similar dispersion errors were observed in our previous fibre pulls using step index profile preforms although their impact was obviously far less significant due to the higher design dispersions in these cases. Note, however, that for the measured loss and input dispersion the required average and output dispersions turn out to be 0.17 and 0.26 ps/(nm.km) respectively, close to the corresponding experimentally determined values. Despite the undoubted deviation from the design dispersion profile the fibre appears to exhibit a significant dispersion taper which should result in a degree of loss compensation and enhanced soliton transmission characteristics.

We investigated the LCDDF's performance in a recirculating loop experiment. The experimental setup is similar to that described in Ref[4]. 4.7 ps, 10 GHz pulses from a wavelength tunable, regeneratively mode-locked erbium doped fibre laser were modulated at 10 GBit/s and loaded into the loop which comprised an input coupler (80:20), a monitor coupler (90:10), a single 20 km section of LCDDF (described above), a 5nm flat-topped band pass filter and an EDFA. The average dispersion of the span at the nominal design wavelength of 1550nm was ~0.17 ps/(nm.km) and therefore the loop length corresponded to ~0.4 soliton periods. The BER characteristics, spectral and temporal form of the loop output could be measured as a function of loop circulations (distance) by pulse burst gating and synchronisation of a 10 GBit/s BER test set, and appropriate time gating of an optical spectrum analyser and autocorrelator respectively.

System performance was investigated for a range of wavelengths around the initial target dispersion profile wavelength of 1550nm. A plot of the measured BER curves as a function of wavelength and transmission distance are plotted in Fig.1 where it is seen that a maximum error free (BER 1e-9) distance of 4300 km is obtained. The plot also illustrates the narrow wavelength operating window obtained due to our close proximity to the zero dispersion wavelength of the fibre and the significant dispersion slope of the fibre (0.07 ps/(nm$^2$.km)). Note that the maximum error free propagation distance represents ~215 loop circulations corresponding to a total transmission distance of ~80 soliton periods.

An experimentally determined plot of the pulse spectral evolution as a function of propagation distance is plotted in Fig.3, where it is seen that excellent spectral stability is obtained over the full propagation distance. The RMS spectral bandwidth changes by less than 5% over the full propagation distance. It can be seen from Fig.3 that the central frequency of the pulses changes slightly with propagation distance (~0.2 nm over a distance of 4500km) due presumably to the effects of soliton self frequency shift, which can start to become significant for such short pulses.

Finally, the temporal width of the pulse at the output of the system was checked using time gated autocorrelation. The results are shown in Fig.3 where it is seen that little temporal deformation has been observed. The poor ACF signal at the output results from the low signal duty cycle at the output due to the short loop length and large number of loop circulations.

In conclusion, we report the fabrication of a low dispersion, LCDDF. A factor of five reduction in absolute dispersion variation has been obtained relative to previously reported fibres, albeit at the cost of reduced dispersion profile accuracy. The results clearly highlight the tight tolerances in fabrication and characterisation required when producing low dispersion DVFs. Recirculating loop transmission experiments clearly demonstrate the benefits of moving to the low dispersion regime in this form of fibre, allowing high fidelity data transmission of ultrashort (4.7ps) soliton pulses over ultra long distances (~4300km) at amplifier spacings close to the limit imposed by average soliton dynamics. Although these initial results appear encouraging considerable further work on improved fibre fabrication and system evaluation is required to fully conclude whether continuous DVFs represent a practical/worthwhile option for use in future advanced soliton systems.

## References

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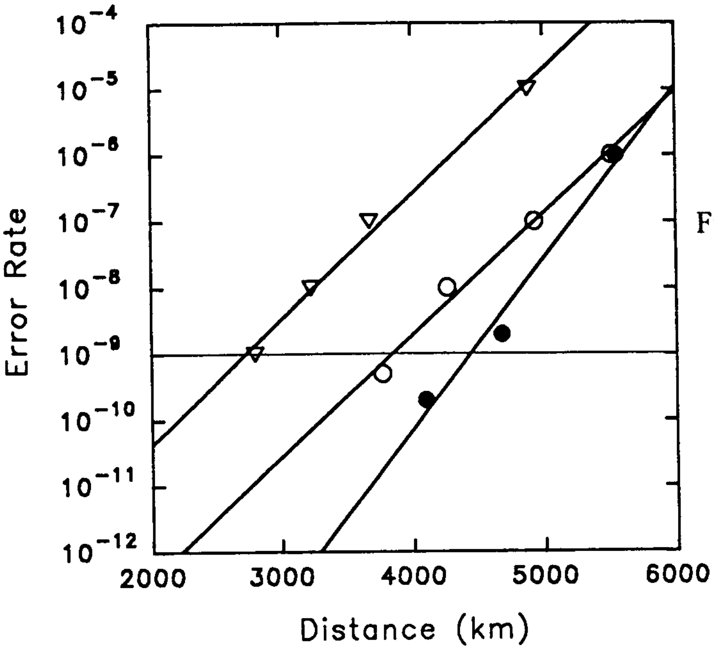

Fig.1 BER versus propagation distance plots illustrating system performance.
Hollow triangles=1551.2nm
Hollow cicles=1549.8 nm
Filled circles=1550.3 nm

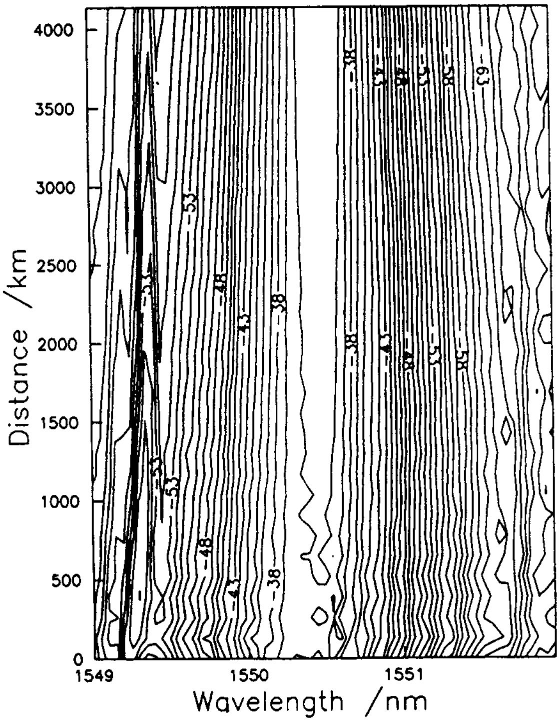

Fig.2 Contour plot showing spectral evolution of 4.7ps pulses as a function of propagation distance (1dB contour).

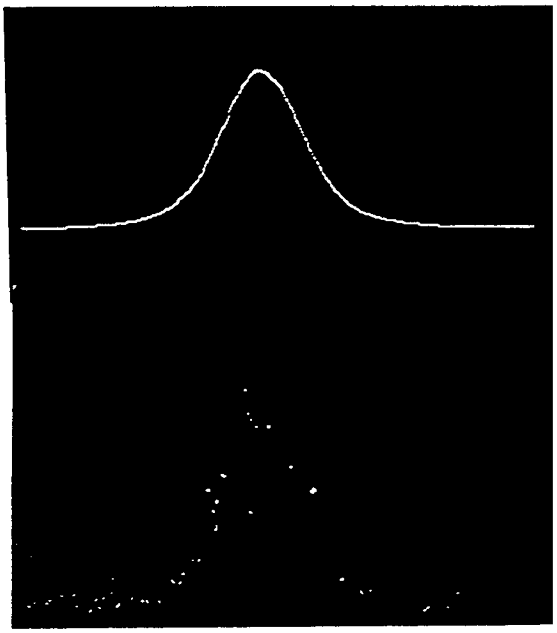

Fig.3 Autocorrelation traces of pulses at
(a) system input (4.7ps)
(b) after 4200 km (4.8ps)