cated these CFBGs using a phase mask multiply overwritten with an electron beam (EB), and their group delay ripple was greatly suppressed [6]. Their typical group delay ripple was (+/–) 10ps around a centre wavelength of 1552.0nm. Fig. 2 shows the transmission spectrum and the group delay spectrum of our 500km transmission line. We measured the group delay with a resolution of 5pm by using a chromatic dispersion measurement system based on the modulation phase-shift method. We set the modulation frequency at 250MHz [7]. The 3dB-reduced bandwidth of the 500km transmission line was 0.75nm. The CFBG compensated for the dispersion of a 500km-long SMF and the residual dispersion of the transmission line was almost zero. However, there were group delay ripples, and their amplitude was larger around shorter wavelengths. The amplitude of the group delay ripples was (+/–) 70ps around a wavelength of 1551.9nm and (+/–) 20ps around a wavelength of 1552.2nm. These ripples were due to the remaining phase error in the mask.

Fig. 3 shows the pulse waveform, which we modulated with the bit sequence '0110110010010', before and after the 500km transmission. We measured these waveforms with a streak camera. Before transmission, the full width at half maximum (FWHM) was 8.7ps, and we observed slight irregularities in the pulse amplitude and an imperfect extinction ratio owing to the insufficient bandwidth of the transmitter. After the 500km transmission, the pulse had broadened to 12.5ps owing to the bandwidth and the group delay ripple of the CFBGs. Numerical analysis showed that the FWHM of a Gaussian-shaped pulse is broadened from 8.7 to 11.3ps when the pulse is passed though an ideal filter with a bandwidth of 0.75nm. We also found that there was degradation in the waveform, and an energy increment in the space-time slot in the waveform after transmission. This was mainly caused by the group delay ripple of the CFBGs.

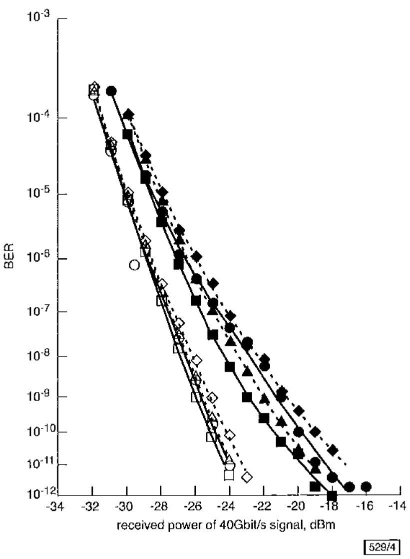

Fig. 4 *BER against received power*

—○—	0km, channel 1	—●—	500km, channel 1
—□—	0km, channel 2	—■—	500km, channel 2
- -◇- -	0km, channel 3	- -◆- -	500km, channel 3
- -△- -	0km, channel 4	- -▲- -	500km, channel 4

Fig. 4 shows the bit error rate as a function of the received optical power of a 40Gbit/s signal. We measured the BER of all the channels of the demultiplexed 10Gbit/s signals. The open symbols show the back-to-back BER, and the filled symbols show the BER after the 500km transmission. We successfully achieved error-free transmission (BER $< 1 \times 10^{-12}$) when the received power was > –15dBm. The power penalty at a BER of 1×10^{-9} was 3 to 4.5dB. The maximum transmission distance seems to be limited by the CFBG performance. If a CFBG with a smaller group delay ripple were fabricated, the transmission quality would be much improved, and the transmission distance would be further extended.

We successfully transmitted a signal at a bit rate of 40Gbit/s over 500km through SMF using a CFBG. The key component was a CFBG with small group delay ripples, which we fabricated using the multiple-overwritten phase mask method. We used this CFBG to achieve an error-free ($< 1 \times 10^{-12}$) transmission, when the received optical power was > –15dBm.

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Annealed optical fibre mode scrambler

J.B. Schlager and A.H. Rose

A mode scrambler based on an annealed step-index fibre is shown to have reproducible performance and source-launch-alignment insensitivity. Devitrification produces scattering centres in the fibre that distribute light uniformly over both angle and radius. An all-fibre mode scrambler with a 10cm length and an insertion loss < 3.5dB is demonstrated.

Introduction: The recent interest in multimode fibre for high-speed (> gigabit-per-second) local area networks has renewed interest in the characterisation of multimode fibres. In particular, measurements of fibre bandwidth with launching conditions that approximate those produced by high-speed laser transmitters are required for the determination of fibre-link performance [1]. Mode scramblers provide a means of generating reproducible launches that overfill the mode volume of the test fibre [2 – 4]. They can also provide a starting point in restricted-mode-launch schemes that employ spatial filtering of an overfilled launch [1]. An ideal mode scrambler should output the required overfilled launch regardless of the launch condition at the scrambler's input. The scrambler should require little optimisation, take up little space, have low insertion loss, and introduce minimal pulse broadening. This Letter describes an all-fibre mode scrambler with many of these features. The scrambler is created with an annealing process that generates scattering centres in the fibre through devitrification [5]. Once made, the fibre mode scrambler is simply inserted between the light source and the test fibre.

Mode scrambler fabrication: The mode scramblers were fabricated using multimode step-index fibre with a silica core, 100μm in diameter, a doped silica cladding with an outer diameter of 140μm, and an acrylate buffer coating with an outer diameter of 250μm. The numerical aperture (NA) of this fibre was 0.37. Seven pieces of fibre were heated in an oven to 1090°C at a heating rate of 10°C/min. The fibres were kept at 1090°C for four hours before being rapidly cooled back to room temperature at a rate of 20°C/min. Such an annealing cycle allows devitrification of the core glass and produces crystals large enough to efficiently scatter light at the test wavelength of 1550nm [5]. Mode-scrambler lengths were under 60cm and had treated lengths of 20cm and 15cm. Shorter mode scramblers (as short as 5cm) were made by cleaving lengths from these annealed sections. The ends of the mode scramblers were terminated with ST style connectors for easy insertion between the launch and test fibres.

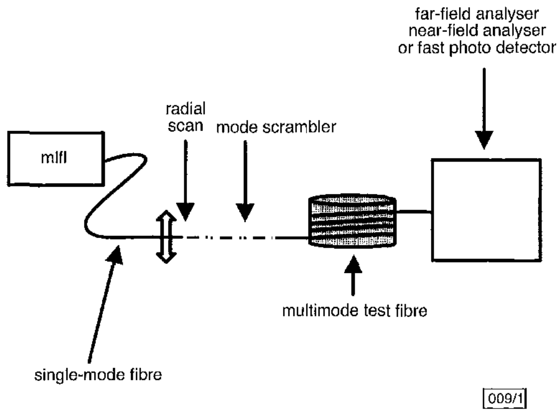

Fig. 1 *Setup for evaluating mode scrambler sensitivity to launch conditions*

mlfl: mode-locked fibre laser at 1550nm

Mode scrambler evaluation: The dependence of mode scrambler output on input launch condition was tested using the setup illustrated in Fig. 1. A singlemode fibre (mode-field diameter = 11μm, *NA* = 0.12) transmitting 10ps pulses from a 1550nm mode-locked fibre laser was scanned across the input face of the fibre mode scrambler. Output from the mode scrambler was coupled to a 62.5μm core, graded-index multimode test fibre (*NA* = 0.275) by use of ST connectors. The output from the test fibre was imaged onto a scanning-slit beam analyser that monitors the near field of the fibre or was collected by a goniometric analyser that gave information on the far-field output of the fibre. A fast photodiode also measured the impulse response and the fibre transfer function to obtain information on the bandwidth and pulse broadening. Scans were made with and without the mode scramblers in place. The performance of the annealed fibre mode scrambler (AFMS) was also compared to a mode scrambler based on a 100/140μm step-index fibre with macrobends [2, 6]. This serpentine-bend mode scrambler (SBMS) design has been used in our lab for years and is described in [6]. Fig. 2 shows the results of four different singlemode fibre scans. A singlemode launch was chosen to severely test the scrambler. Actual launches envisioned for multimode fibre network applications are expected to fill greater mode volumes and thus be less sensitive to launch alignment. Fig. 2*a* shows the extent of the far-field pattern (expressed in terms of the measured *NA* at the 5% intensity points -- the exit *NA*), and the 5% near-field, exit-spot diameter as a function of the SMF scan position for a 50m, 62.5/125μm, graded-index multimode fibre. An abscissa value of 0μm indicates that both fibre axes are aligned. As expected, both the measured exit *NA* and the exit-spot diameter depend strongly on the input launch position. Fig. 2*b* shows similar behaviour for a 7km length of the same fibre, indicating that little mode mixing occurs over this length. Figs. 2*c* and *d* show the scan results on the 50m test fibre with mode scramblers in place. Both the 60cm SBMS (Fig. 2*c*) and the 15cm AFMS (Fig. 2*d*) reduce the sensitivity to the launch position and overfill the multimode test fibre [4]. Variation in the exit spot size with the AFMS was less than 40% of that observed with the SBMS. The insertion losses for the SBMS and AFMS were 2.7 and 5.4dB, respectively. Shorter annealed-fibre mode scramblers with similar performance had lower insertion losses. A 10cm long AFMS with similar performance had an insertion loss of 3.4dB. Bandwidth measurements were performed on a 500m, 62.5/125μm graded-index fibre while a singlemode fibre was scanned across the input face of the AFMS. Variations in the measured bandwidth remained < 5% for annealed-fibre mode scramblers as short as 10cm. In addition, the pulse broadening observed with our detection system (30ps response, full duration at half maximum) was negligible in annealed fibre mode scramblers as long as 15cm.

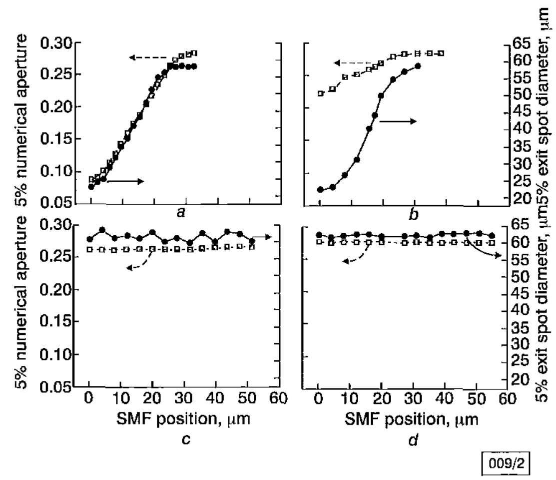

Fig. 2 *Measured numerical aperture and spot diameter (both at 5% intensity points) after multimode test fibre as function of singlemode fibre position at input*

a 50m 62.5/125μm multimode fibre without mode scrambler
b 7km 62.5/125μm multimode fibre without mode scrambler
c 50m 62.5/125μm multimode fibre with 60cm step-index mode scrambler
d 50m 62.5/125μm multimode fibre with 15cm annealed fibre mode scrambler

Conclusion: The annealed-fibre mode scrambler offers a simple and potentially compact alternative to other mode scramblers that rely on longer fibre lengths and/or macrobending to achieve reproducible performance.

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