References

1 HORIGUCHI, T., SHIMIZU, K., KURASHIMA, T., TATEDA, M., and KOYAMADA, Y.: 'Development of a distributed sensing technique using Brillouin scattering', *J. Lightwave Technol.*, 1995, **LT-13**, (7), pp. 1296–1302

2 PARKER, T.R., FARHADIROUSHAN, M., FECED, R., HANDEREK, V.A., and ROGERS, A.J.: 'Simultaneous distributed measurement of strain and temperature from noise-initiated Brillouin scattering in optical fibers', *IEEE J. Quantum Electron.*, 1998, **34**, (4), pp. 645–659

3 OGAWA, O., KAMIKATANO, M., and MATSUZAWA, T.: 'A new technique for measuring a time-varying optical fiber strain'. Proc. OFS '96, 1996, pp. 670–673

4 KAMIKATANO, M., OGAWA, O., and MIYAMOTO, M.: 'A time-varying optical fiber strain measurement by using Brillouin ring amplifying system'. Proc. IWCS '96, 1996, pp. 689–694

5 OGAWA, O.: 'Measurement of a time-varying strain on an optical fiber using Brillouin ring amplification system'. Paper SB-11-5, Proc. IEICE Soc. Conf '97, 1997, (in Japanese)

6 OGAWA, O., and KAMIKATANO, M.: 'Measurement of strain distribution on an optical fibre using Brillouin ring amplification system'. Proc. OFC'97, 1997, pp. 158–159

Transmission of dispersion-managed solitons at 20Gbit/s over 20000km

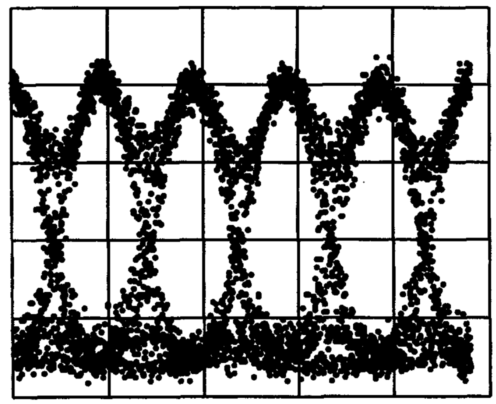
G.M. Carter, R.-M. Mu, V.S. Grigoryan,
C.R. Menyuk, P. Sinha, T.F. Carruthers, M.L. Dennis
and I.N. Duling III

The transmission of 20Gbit/s data over distances of 20000km was achieved using dispersion-managed solitons without significant impairment due to pulse-to-pulse interactions. Error rates of $< 10^{-9}$ were achieved over the entire distance measured.

Since the first demonstration of high bit rate long distance propagation using dispersion-managed solitons [1], an intense research effort has been underway to determine the properties of these nonlinear pulses. In particular there have been theoretical investigations of soliton-soliton interactions in dispersion-managed soliton systems and their potential to limit dispersion-managed soliton transmission [2, 3]. Recent theoretical results indicate that, for certain two-step dispersion maps, these interactions may limit a transmission system with an initial pulse spacing of 50ps, corresponding to 20Gbit/s data rates, to distances of the order of 10000km or less [4, 5]. Our initial experiments at 20Gbit/s and our analysis show that a far more serious limitation of the transmission distance can be caused by excess energy in the tails of the initial pulses which lowers the extinction ratio. By using initial pulses with rapidly decreasing tails along with careful system design and implementation, we transmitted 20Gbit/s data over 20000km at a measured error rate $< 10^{-9}$ without significant impairment due to pulse-to-pulse interactions. This system was ultimately limited by noise growth in the spaces. We have modelled these results using a Monte Carlo simulation, achieving excellent agreement with the measured data. The propagation distance achieved exceeds previously reported single channel dispersion-managed soliton results at 20Gbit/s by > 40% [1].

The experiments used the same recirculating loop, dispersion map, and an in-line 2.8nm bandpass filter reported in [6]. The map consisted of 100km of fibre with a dispersion of –1.1ps/nm km at 1551nm followed by 7km of fibre with a dispersion of +16.7ps/nmkm at 1551nm. The path-averaged dispersion was ~+0.03ps/nmkm (anomalous). The data source was a commercially available synchronously modelocked fibre laser operating at 10GHz. The pulses were encoded with a $2^{23} - 1$ pseudorandom bit pattern. The data stream was divided into two streams and recombined with a relative delay between the streams of ~150ps to produce 20Gbit/s data. By adjusting the power in the optical amplifiers we kept the same equilibrium pulse characteristics as in our previous 10Gbit/s experiments [7]. The pulse energy averaged over the map is 0.06pJ and within the map the pulse has a bandwidth of 0.45nm with a minimum and maximum pulsewidth of 9 and 22ps, respectively.

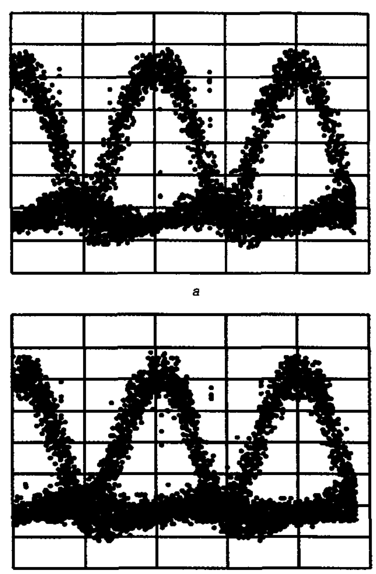
For bit error rate measurements we placed before our receiver a 2:1 demultiplexer, an electro-optic modulator driven by the recovered clock at 10GHz [8]. Fig. 1 shows the 20Gbit/s eye diagram using a 20GHz bandwidth photodetector. Fig. 2 shows the demultiplexed eye measured with the photodetector, followed by a 10GHz preamplifier, at the input to our loop and after 20000km of propagation. The vertical lines in Fig. 2 come from gating the trigger to the sampling oscilloscope and do not represent real errors. The measured error rate in the demultiplexed data was low and remained $< 10^{-9}$ at a distance of 20000km. Several factors observed in the experiments and our Monte Carlo simulation of the experiment lead us to conclude that the pulse-to-pulse interactions are not significant in these experiments. The demultiplexed eye does not show any evidence of intersymbol interference that would be expected if the pulse spacing were altered. Further, the 20GHz tone of the detected 20Gbit/s RZ data shows only a 0.25dB variation over the 20000km propagation distance, again indicating little variation in the pulse-to-pulse spacing.



831/1

Fig. 1 *Measured eye diagram of 20Gbit/s data stream at input of transmission experiment*

Horizontal scale: 50ps/div



831/2

Fig. 2 *Measured eye diagram of 20Gbit/s data stream demultiplexed to 10Gbit/s*

a At 0km
b At 20000km transmission distance
Horizontal scale: 50ps/div

Fig. 3 shows the decision level of the bit error rate tester at an error rate of 10^{-6} as a function of distance, along with the simulation [9] showing excellent agreement. These data show that the build-up of amplified spontaneous emission in the spaces limits transmission as was the case in the 10Gbit/s data [6]. From our previous measurements [7] and estimate of the 20Gbit/s demultiplexed timing window we conclude that timing jitter is not a limitation on the transmission of the 20Gbit/s data at distances up to 20000km. In [6] an intra-loop acousto-optic frequency shifter cancelled out the 100MHz frequency shift of the acousto-optic switch that closes the loop. The shifter was unavailable for the experiments described in this Letter, leaving us with a net 100MHz frequency shift per 107km of propagation distance. As the simulation indicates, the effect of this frequency shift, which is equivalent to frequency sliding filters, is to reduce the build-up of the ASE at distances greater than 20000km. However, taking into account the loop coupling losses (≃ 7dB), the simulation indicates that in a straight-line system having no net frequency shift a bit-error rate < 10^{-9} at distances up to 20000km would still be achieved.

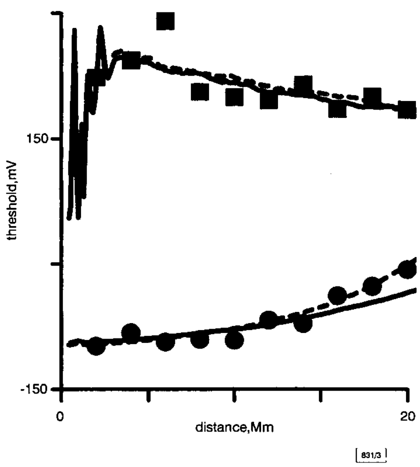


Fig. 3 *Measured and simulated threshold of bit error rate tester at constant bit error rate of 10^{-6}*

■ marks
● spaces
——— simulation for frequency sliding
– – – – simulation for no frequency sliding

In conclusion, we have propagated dispersion-managed solitons at a data rate of 20Gbit/s with an error-rate of < 10^{-9} over a distance of 20000km without observing any significant impairment due to pulse-to-pulse interactions. We have carried out a numerical simulation of our experiment and achieved excellent agreement with the data.

Acknowledgment: We thank PriTel, Inc. for loaning him the modelocked fibre laser used in these experiments and gratefully acknowledge support from the National Science Foundation, Department of Energy, and The Air Force Office of Scientific Research.

1 December 1998
Electronics Letters Online No: 19990105
DOI: 10.1049/el:19990105

G.M. Carter, C.R. Menyuk and P. Sinha, (*The Laboratory for Physical Sciences, College Park, MD 20740, USA*)

R.-M. Mu and V.S. Grigoryan (*CSEE Department, The University of Maryland Baltimore County, Baltimore, MD 21250, USA*)

T.F. Carruthers, M.L. Dennis and I.N. Duling III (*Optical Sciences Division, Code 5670, Naval Research Laboratory, Washington, DC 20375, USA*)

G.M. Carter, C.R. Menyuk and P. Sinha: Also with CSEE Department, The University of Maryland Baltimore County, Baltimore, MD 21250, USA

References

1 SUZUKI, M., MORITA, I., EDAGAWA, N., YAMAMOTO, S., TAGA, H., and AKIBA, S.: 'Reduction of Gordon-Haus timing jitter by periodic dispersion compensation in soliton transmission', *Electron. Lett.*, 1995, **31**, pp. 2027–2029

2 YU, T., GOLOVCHENKO, E.A., PILIPETSKII, A.N., and MENYUK, C.R.: 'Dispersion-managed soliton interactions in optical fibers', *Opt. Lett.*, 1997, **22**, pp. 793–795

3 SMITH, N.J., DORAN, N.J., FORYSIAK, W., and KNOX, F.M.: 'Soliton transmission using periodic dispersion compensation', *J. Lightwave Technol.*, 1997, **15**, (10), pp. 1808–1822

4 MATSUMOTO, M.: 'Analysis of interaction between stretched pulses propagating in dispersion-managed fibers', *IEEE Photonics Technol. Lett.*, 1998, **10**, pp. 373–375

5 KUMAR, S., WALD, M., LEDERER, F., and HASEGAWA, A.: 'Soliton interaction in strongly dispersion-managed optical fibers', *Opt. Lett.*, 1998, **23**, pp. 1019–1021

6 JACOB, J.M., and CARTER, G.M.: 'Error-free transmission of dispersion-managed solitons at 10Gbit/s over 24500km without frequency sliding', *Electron. Lett.*, 1997, **33**, pp. 1128–1130

7 CARTER, G.M., and JACOB, J.M.: 'Dynamics of solitons in filtered dispersion-managed systems', *IEEE Photonics Technol. Lett.*, 1998, **10**, pp. 546–548

8 ELLIS, A.D., WIDDOWSON, T., SHAN, X., WICKENS, G.E., and SPIRIT, D.M.: 'Transmission of a true single polarisation 40Gbit/s soliton data signal over 205km using a stabilised erbium fibre ring laser and 40GHz electronic timing recovery', *Electron. Lett.*, 1993, **29**, pp. 990–992

9 MU, R.-M., GRIGORYAN, V.S., MENYUK, C.R., CARTER, G.M., and JACOB, J.M.: 'The performance of a 10Gbit/s filtered dispersion-managed soliton system with lumped amplifiers'. Paper WC2, to be published in Tech. Dig. CLEO'99, San Diego, CA, 21–26 February 1999

Slanted gratings UV-written in photosensitive cladding fibre

L. Brilland, D. Pureur, J.F. Bayon and E. Delevaque

Experimental results concerning slanted gratings photo-written in a photosensitive cladding fibre and in a standard step index fibre are presented. The improvements concerning back reflection for an FWHM bandwidth suitable for erbium-doped fibre amplifier gain equalisation are demonstrated in the case of slanted gratings realised within photosensitive cladding fibre.

Introduction: The use of filters to flatten the gain spectrum of erbium-doped fibre amplifiers (EDFAs) has great interest for dense wavelength division multiplexing (DWDM) systems. Recently, long period gratings (LPGs) have been used in such systems [1]; however, their strong temperature sensitivity ($\Delta\lambda \simeq$ 50pm/°C) and the difficulty in developing a passive system to thermally stabilise the centre wavelength makes LPGs difficult to use in gain flattening operations.

Slanted gratings (SGs) have a lower temperature sensitivity than LPGs ($\Delta\lambda \simeq$ 12pm/°C), and can easily be thermally stabilised. However, the limitation of these filters is the residual back reflection level [2]. Indeed, it is always a serious drawback if these components have to be incorporated in amplifier modules because they can lead to a degradation in noise figure. To reduce this back reflection, we have realised SGs in a photosensitive cladding fibre manufactured in our laboratories [3]. We present in this Letter a comparison between the features of slanted gratings realised in a standard step index fibre and in a photosensitive cladding fibre.

Analysis: During the writing process of a Bragg grating, a coupling between the fundamental mode and the cladding modes occurs. The coupling efficiency depends on the photoinduced index change Δn, the spatial overlap of the excited modes and the angle θ defined in [4] between the UV fringes and the cross-section of the fibre. Propagation constants must satisfy the following phase matching conditions:

$$\beta_{LP01} + \beta = \frac{2\pi}{\Lambda}\cos\theta$$

Where β_{LP01} and β are, respectively, the propagation constants of mode LP_{01} and cladding modes, Λ is the grating pitch and θ the blazing angle.

According to coupled-mode theory [5], the level of back reflection R, measured with an optical spectrum analyser at resonance,