Table 1 RESULTS OF SINGLE-ENDED FIELD SPLICE LOSS MEASUREMENTS

Splice	Primary loss from Telecom House	Primary loss from exchange	Absolute loss, two-way method	Real image loss from Telecom House	Absolute loss, one-way method	Error in one-way method
	dB	dB	dB	dB	dB	dB
1	0·30	0·27	0·285	0·27	0·285	0
2	0·05	−0·01	0·02	−0·02	0·015	−0·005
3	0·02	−0·02	0	−0·02	0	0
4	0·31	0·26	0·285	0·22	0·265	−0·02
5	0·18	0·05	0·115	−0·02	0·08	−0·035
6	0·46	0·44	0·45	0·25	0·355	−0·095
7	0·08	0·14	0·11	0·14	0·11	0
8	0·21	0·18	0·195	0·13	0·17	−0·025
9	0·33	0·33	0·33	0·21	0·27	−0·06
10	0·02	0·04	0·03	0·04	0·03	0
11	0·36	0·35	0·355	0·28	0·32	−0·035

the conventional two-way measurements and one way pulse reflection measurements are given in Table 1.

The measurement errors were largely of the order $\pm 0{\cdot}03$ dB and are fully consistent with those obtained theoretically by adding the effect of the mirror and OTDR reflections to standard OTDR theory. Splice measurements 6 and 9 are a little outside the error range; this is attributed to a fluctuation in the level of the reflection from the OTDR. Investigation has concluded that this reflection is generally between 6 and 10% of the incident light and is dependent on the quality of connection made to the optical fibre under test. Although no special precautions were taken to minimise OTDR reflections, it is evident that with careful design of the launch and receive optics, the error produced by the secondary 'virtual image' may be minimised.

Conclusion: A method to characterise a link from one end using an OTDR and a mirror surface has been described. A previously unreported feature was observed on the OTDR secondary trace termed the secondary 'virtual image' and was determined to be due to pulse reflections from the OTDR end. The maximum measurement error observed in the field experiment was less than $\pm 0{\cdot}1$ dB and could be reduced to $\pm 0{\cdot}03$ dB if reflections from the OTDR end were minimised. A measurement method based on this principle should therefore prove effective to reduce installation and maintenance costs of short optical links in the local and junction environments.

Acknowledgment: We thank the Director of British Telecom Research Laboratories and British Telecom NSET2 for permission to publish this paper.

J. PEACOCK
J. SCARFE
J. REID
S. R. MALLINSON

British Telecom Research Laboratories
Martlesham Heath
Ipswich IP5 7RE, United Kingdom

30th January 1989

References

1 GOLD, M. R., HARTOG, A. H., and PAYNE, D. N.: 'New approach to splice-loss monitoring using a long range OTDR', *Electron. Lett.*, 1984, **20**, pp. 338–340
2 FALTIN, L.: 'Two-sided OTDR measurements from the same fibre end', *J. Optical Comms.*, 1988, **9**, pp. 24–26
3 BUCKLAND, E. L., and NISHIMURA, A.: 'Bidirectional OTDR measurements utilizing an improved folded-path technique'. Tech. Digest Sympos. on Optical Fibre Measurements, 1988, pp. 15–18

16 Gbit/s, 70 km PULSE TRANSMISSION BY SIMULTANEOUS DISPERSION AND LOSS COMPENSATION WITH 1·5 μm OPTICAL AMPLIFIERS

Indexing terms: Optical communications, Optical transmission, Optical dispersion, Semiconductor lasers

A scheme for using semiconductor laser amplifiers for simultaneous compensation of both the fibre loss and the fibre dispersion in the 1·5 μm region is proposed and demonstrated. Experimentally, we demonstrate propagation of 16 Gbit/s pulses over 70 km of non-dispersion-shifted fibre at 1·53 μm wavelength. This distance is four times longer than the fundamental dispersion limit for transform-limited pulses.

Semiconductor laser amplifiers have been used in a number of experiments to compensate for the fibre loss in lightwave communication systems, thereby allowing very long transmission distances.[1] With traditional linear optical amplification, the transmission can only be extended as long as the system is loss-limited and fibre dispersion is not a major effect. In the 1·5 μm low-loss window of standard silica fibre the dispersion is about 15 ps/nm km. Assuming that the optical pulses are ideal (transform-limited), the fibre dispersion would limit the maximum fibre distance to 40 km and 10 km for bit rates of 10 Gbit/s and 20 Gbit/s, respectively.[2] One possible way to circumvent this dispersion limitation is the use of solitons,[3] as demonstrated in a recent remarkable transmission experiment.[4] Solitons however, which rely on a balance of self-phase modulation and dispersion in the fibre, require rather high optical powers (not readily available from semiconductor lasers) and cannot tolerate large fibre loss without the need for amplification. Dispersion compensation by predistortion of the optical pulses has also been demonstrated theoretically and experimentally.[5]

In this letter we propose and demonstrate simultaneous loss and dispersion compensation near 1·5 μm in standard silica fibres. In this scheme the fibre dispersion is compensated for by prechirping the optical pulses through self-phase modulation in an optical amplifier.[6] Simultaneously the optical pulses are amplified, which compensates for the optical loss in the fibre.

The experimental setup is shown in Fig. 1. The optical pulse train is generated in a 1·5 μm, mode-locked, external-cavity semiconductor laser (MLECL). The laser emits a pulse train

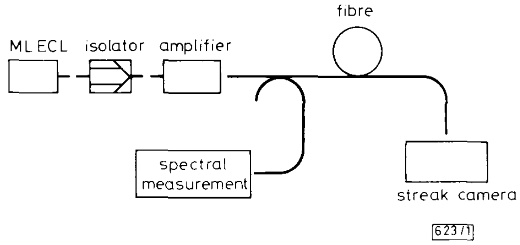

Fig. 1 *Experimental setup*
MLECL is mode-locked external-cavity laser

of 1 GHz or 4 GHz repetition rate and with an adjustable pulse width between 10 ps and 60 ps. The pulses are very close to being transform-limited with time-bandwidth products of 0·45–0·6. The average output power in a collimated beam is typically 100 μW. The output from the MLECL is coupled via an optical isolator into a 1·5 μm travelling-wave amplifier. The maximum amplifier chip gain is around 30 dB and the residual facet reflectivity is less than 0·01%. The output from the optical amplifier is coupled into the transmission fibre with a lensed fibre tip. The fibre is standard AT&T 5D fibre with approximately 0·23 dB/km loss and 15 ps/nm km dispersion at the operating wavelength.

Fig. 2*a* shows the optical spectrum of the MLECL. The external cavity modes, spaced 1 GHz apart, are clearly seen and the spectral FWHM is 8 GHz. When the optical amplifier is operated with low gain, the amplification is linear and the output pulse is a replica of the input pulse. By increasing the gain of the optical amplifier the amplifier saturates, and owing to the gain dependence of the refractive index the pulses become chirped from self-phase modulation.[6] The self-phase modulation is evident from the spectrum, shown in Fig. 2*b*, as a spectral broadening and the appearance of a satellite peak. The pulse shape at the output of the amplifier, however, is nearly unchanged.

To see the effect of the fibre dispersion, we inserted 70 km of fibre between the amplifier and the streak camera. With the MLECL operating at 4 GHz and by interleaving two pulse trains with two fibre couplers and a delay line, a pulse train corresponding to a 16 Gbit/s 0101 ... sequence was achieved. Fig. 3*a* shows the 70 km output pulses when the optical amplifier is operated at low (10 dB) gain and no self-phase modulation takes place. As expected, owing to dispersion, the pulses overlap considerably and the extinction ratio is very poor. After increasing the amplifier gain to 30 dB in Fig. 3*b*, however, the self-phase modulation in the amplifier compensates for the fibre dispersion and the extinction ratio improves to almost 100%. The background light level shown in Figs. 3*a* and *b* were obtained by blocking the output from the MLECL and recording the spontaneous emission from the amplifier and the dark count from the streak camera. We note here that the fundamental dispersion limit for transform-limited pulses at 16 Gbit/s at this wavelength is 15 km.

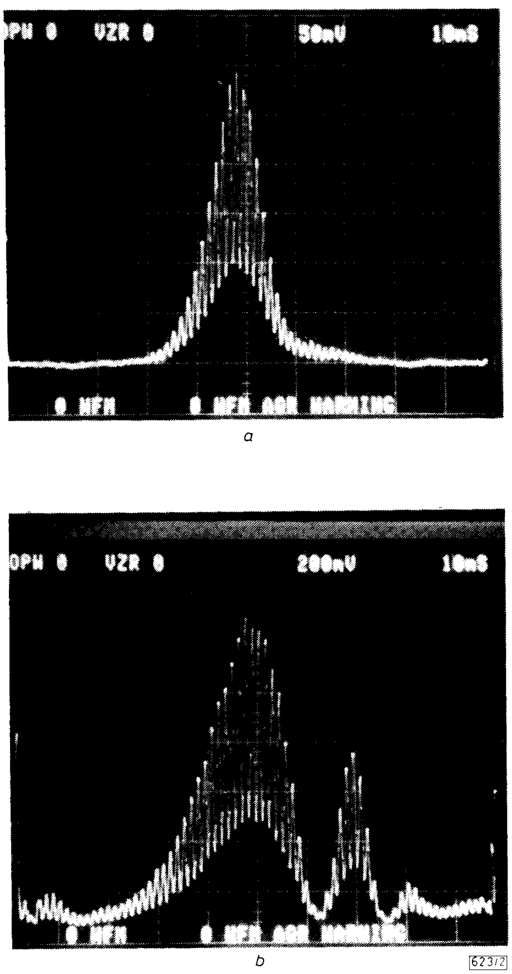

Fig. 2

a Optical spectrum from MLECL. External cavity mode spacing is 1 GHz and spectral FWHM is 8 GHz

b Optical spectrum after amplifier with self-phase modulation in amplifier. Unsaturated chip gain is approximately 30 dB (compare with Fig. 2*a* for spectrum without self-phase modulation)

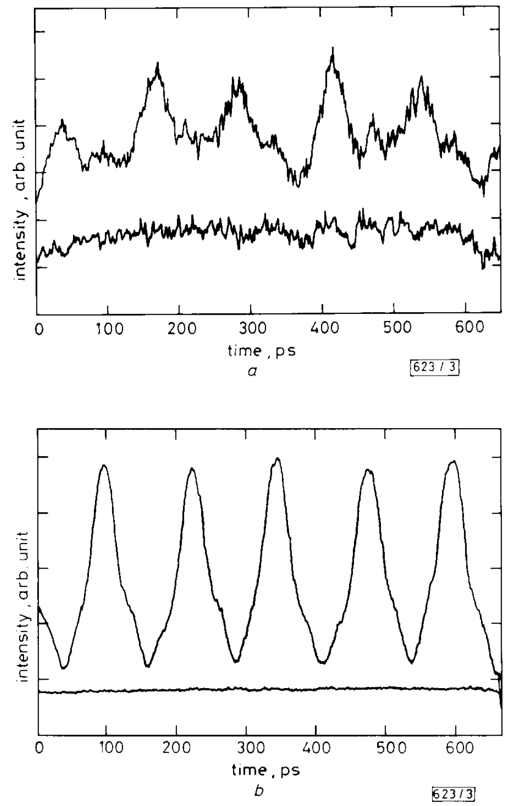

Fig. 3 *Streak camera recording of 16 Gbit/s, 0101 ... pulse train after 70 km of fibre and without dispersion compensation*

Light level with ML-ECL blocked is shown as lower trace

a Low gain *b* With dispersion compensation

A main advantage of this technique for dispersion compensation is that it does not rely on any nonlinearity in the fibre, therefore the compensation is independent of the optical power in the fibre and is not affected by the fibre loss. The technique requires however that the pulses experience an appropriate amount of self-phase modulation in the optical amplifier. The amount of self-phase modulation can easily be controlled by the gain of the amplifier and, as used in our experiments, the required amplifier input pulse energy ($\sim$0·04 pJ) can easily be obtained from semiconductor laser sources.

The main application for this dispersion compensation scheme would be for communication systems operating in the 10–50 Gbit/s range over fibre distances of 100–10 km and utilising the low-loss but dispersive window around 1·5 μm. Without dispersion compensation such systems would be limited to a bit rate distance product of 4000 $(\text{Gbit/s})^2$ km.[2]

N. A. OLSSON
G. P. AGRAWAL
K. W. WECHT

AT&T Bell Laboratories
Murray Hill, NJ 07974, USA

14th March 1989

References

1 OLSSON, N. A., OBERG, M. G., KOSZI, L. A., and PRZYBYLEK, G.: '400 Mbit/s, 372 km coherent transmission experiment using in-line optical amplifiers', *Electron. Lett.*, 1988, **24**, pp. 36–37
2 HENRY, P. S.: 'Lightwave primer', *IEEE J. Quantum Electron.*, 1985, **QE-21**, pp. 1862–1879
3 HASEGAWA, A., and TAPPERT, F.: 'Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers', *Appl. Phys. Lett.*, 1973, **23**, pp. 142–144
4 MOLLENAUER, L. F., and SMITH, K.: 'Demonstration of soliton transmission over more than 4000 km in fiber with loss periodically compensated by Raman gain', *Opt. Lett.*, 1988, **13**, pp. 675–677
5 KOCH, T. L., and ALFERNESS, R. C.: 'Dispersion compensation by active predistorted signal synthesis', *IEEE J. Lightwave Technol.*, 1985, **LT-3**, pp. 800–805
6 OLSSON, N. A., and AGRAWAL, G. P.: 'Spectral shift and distortion due to self-phase modulation of picosecond pulses in 1·5 μm optical amplifiers'. To be published

SPECTRAL INDEX METHOD APPLIED TO COUPLED RIB WAVEGUIDES

Indexing terms: Waveguides, Optical waveguides

The spectral index method is applied to closely coupled rib waveguides. Analytical expressions in terms of the propagation constant β are given for symmetric and antisymmetric polarised modes. The calculated coupling lengths are in excellent agreement with those obtained by mainframe programs.

The spectral index (SI) method has recently been introduced as a new technique for modelling modes in single semiconductor waveguides.[1] It has also been developed in vectorial form which will be published elsewhere. The method saves an order of magnitude in CPU time and uses negligible storage.

Here, the SI method is extended to the directional coupler formed from two closely coupled waveguides. This structure is of increasing importance in the field of semiconductor integrated optics, for example as an all-optical switching element. Power transfers from one guide to the other in a characteristic distance known as the coupling length L_c defined as follows:

$$L_c = \pi/(\beta_s - \beta_{as}) = 0{\cdot}5\lambda_0/(n_s - n_{as}) \tag{1}$$

Here, β_s and β_{as} are the propagation constants for the fundamental symmetric and antisymmetric modes, and n_s and n_{as} are the corresponding mode indices.

Two independent transcendental equations are constructed for β_s and β_{as}. Coupling lengths are obtained and compared principally to those published in a study of eigenmode analysis methods from the IEE 14th European Conference on Optical Communication (ECOC 1988),[2] and to coupling lengths produced by an accurate finite difference program, available on the Sheffield University mainframe computer.[3]

The structure and nomenclature are shown in Fig. 1. This consists of two closely coupled buried heterostructure strip loaded waveguides. The height of each rib is chosen to be so large that it does not influence the results.

This analysis of two closely coupled waveguides using the SI method is an extension of the single rib problem; the same general methodology is applied to both. A trial function, $E = F(x)G(y)$, is selected within the rib(s), where E is the electric field vector and $F(x)$ and $G(y)$ are functions of the single variables x and y only. Outside the ribs, in air, the field is set to zero. Below the ribs the Fourier transform of the wave equation is taken with respect to x. The solution is then similar to that of a slab waveguide. Hence, the problem has been reduced by one dimension. The two solutions are linked across the base of the rib at $y = 0$ by a variational technique.[1]

For the first symmetric mode of the coupler, $F(x)$ is taken as a cosine function with coefficient 1 in each rib. For the first antisymmetric mode, the coefficients are 1 and -1.

The mixing of fields between the ribs occurs on construction of the dispersion equations for β_s and β_{as} by using the variational principle at $y = 0$. Two very similar analytic transcendental equations are produced, as follows:

$$\partial G/\partial y(\beta, 0) = \frac{4}{\pi W}\int_{-\infty}^{+\infty} \Gamma(s, \beta) \times \cos^2 Ws \begin{Bmatrix} \cos^2 Ls \\ \sin^2 Ls \end{Bmatrix} \frac{s_1^2}{(s_1^2 - s^2)^2}\, ds \tag{2}$$

Here, β assumes the values β_s or β_{as} as appropriate, corresponding to taking the upper or lower functions, respectively. Also, s is the spatial spectral variable involved when taking the Fourier transform $\mathscr{F}(s)$ of E; $s_1 = \pi/(2W)$ and $\Gamma(s, \beta)$ is a transfer function defined as in Reference 1. As $\cos s_1 W = 0$, the integrands in the above transcendental equations are nonsingular; they also decay rapidly with s, so that although they oscillate they can be evaluated by simple numerical integration.

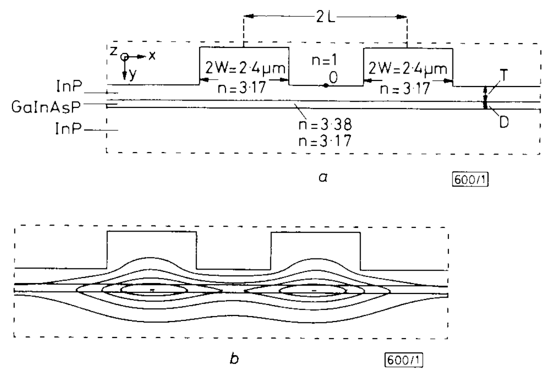

Fig. 1

a Coupled rib waveguides
b Amplitude contours of E for fundamental symmetric mode at intervals of 20% of maximum using SI method

Calculations have been made for the structure in Fig. 1*a*. The wavelength is 1·55 μm. Table 1 shows values of the coupling length for rib spacings $2(L - W)$ of 1, 2, 3 and 4 μm for both TE and TM fundamental modes. Results obtained by a finite difference (FD) program[3] are also shown, along with the percentage difference between the two sets of results. There is excellent agreement, with a maximum difference in coupling length of only 4%.

Fig. 2 compares coupling lengths obtained by a variety of methods for the same set of couplers. Since the results are for

Table 1 COUPLING LENGTHS OF STRUCTURE IN FIG. 1 (mm)

	TE mode			TM mode		
$2(L - W)$	SI method	FD method	Percentage difference	SI method	FD method	Percentage difference
μm						
1	0·351	0·337	+4	0·386	0·381	+1
2	0·698	0·669	+4	0·966	0·958	+1
3	1·360	1·307	+4	2·370	2·385	−1
4	2·618	2·527	+4	5·784	5·898	−2