ZERO MATERIAL DISPERSION IN OPTICAL FIBRES

Indexing terms: Dispersion (wave), Fibre optics, Optical waveguides

The material dispersion of optical fibres having cores of silica or phosphosilicate glass falls to zero at a wavelength between 1·2 and 1·3 μm. A considerable increase in bandwidth can be obtained, especially with an l.e.d. source, by operation in this region.

Introduction: Recently, we reported[1] a method for the determination of the material dispersion in the core of an optical waveguide. The technique has been applied to the low-loss phosphosilicate-core fibres developed in these laboratories,[2] over the wavelength range 0·7–0·95 μm. When compared with computations of the dispersion of silica (Fig. 1), using the Sellmeier equation of Mallitson,[3] there is found to be a close correspondence over the measured range. A similar correspondence has also been observed[2,4] for the predicted and measured losses of the two materials for wavelengths between 0·43 and 0·9 μm. It would appear therefore that the addition of P_2O_5 does not greatly affect the dispersion and loss of silica in the region where measurements have hitherto been made, and it is not unreasonable to hope that the same may be true for dispersion at longer wavelengths. The material-dispersion calculations for silica have therefore been extended to 2·3 μm and indicate that a zero value is obtained at 1·27 μm. Phosphosilicate glass is expected to behave similarly.

Effect of material dispersion on bandwidth: In a multimode optical fibre, the waveguide and material dispersions have a large influence on the bandwidth; the former is caused mainly by transit-time differences between modes, and the latter by the variation of the core refractive index with wavelength. The two mechanisms are separable provided that the core–cladding refractive-index difference is small.[5]

The relative importance of the material-dispersion limitation depends on the spectral width of the source and on the magnitude of the waveguide dispersion. In a recent publication,[6] it is predicted that, by a suitable choice of refractive-index profile, the waveguide pulse dispersion τ_g can be minimised to give a value of

$$\tau_g = n_0 \Delta^2 L/8c$$

where n_0 = refractive index on the axis

Δ = maximum relative refractive-index difference

L = fibre length

Thus, for the phosphosilicate-core–borosilicate-cladded fibre reported earlier,[7] with $\Delta = 0{\cdot}018$ (n.a. = 0·23), the optimised waveguide dispersion could be as low as 0·1 ns/km, and, to obtain maximum bandwidth, the material-induced pulse dispersion must be kept to a similar value, namely $\simeq$ 0·1 ns/km. The most likely sources for optical-fibre communication are injection lasers or light-emitting diodes having spectral widths of typically 4 and 40 nm, respectively. Operation of a phosphosilicate fibre with an l.e.d. source at 0·9 μm results in a pulse broadening due to material dispersion alone of 2·6 ns/km, and, even for the narrower-spectral-width laser, operating at 0·83 μm, a pulse width of 0·38 ns/km is obtained. Thus the material dispersion of this fibre, or, indeed, of a fibre having a pure silica core, is a serious drawback, and to realise the full potential bandwidth, some attempt must be made to reduce either the source linewidth or the glass material dispersion.

Operation at longer wavelength: As shown in Fig. 1, an appreciable decrease in material dispersion can be obtained by operation at a longer wavelength. However, there are several other factors to consider. The first is the associated fibre attenuation. We have already demonstrated[7] that this can be less than 4 dB/km, provided that the OH content can be kept sufficiently small. The effect of the OH impurity arises partly because of the first overtone at 1·37 μm, but is mainly due to an absorption peak at 1·23 μm attributed to[8] the combinational vibration of the second overtone ($2\nu'_3$) of the fundamental OH resonance at 2·73 μm with the fundamental SiO_4 tetrahedral vibration (ν'_1). The strength of the 1·23 μm line is about twice that at 0·95 μm, and, to limit the peak height above the baseline to an acceptable level of, say, 0·2 dB/km, the OH content must be kept to 0·1 parts in 10.[6] Although this concentration is low, it should be attainable, since, in the borosilicate-cladded–phosphosilicate-core fibre,

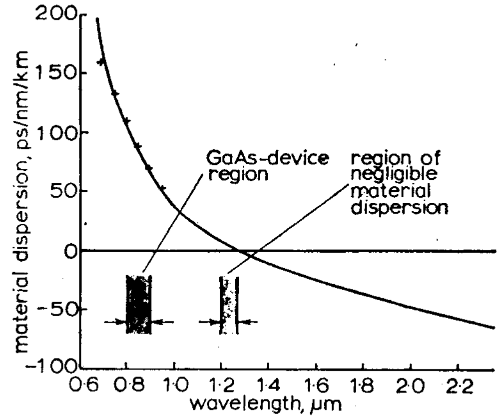

Fig. 1 *Material dispersion $d\tau/d\lambda = (-\lambda/c)d^2n/d\lambda^2$ as function of wavelength*

The solid curve is calculated for silica from the data of Mallitson[3] and the points have been measured in a fibre having a phosphosilicate-glass core

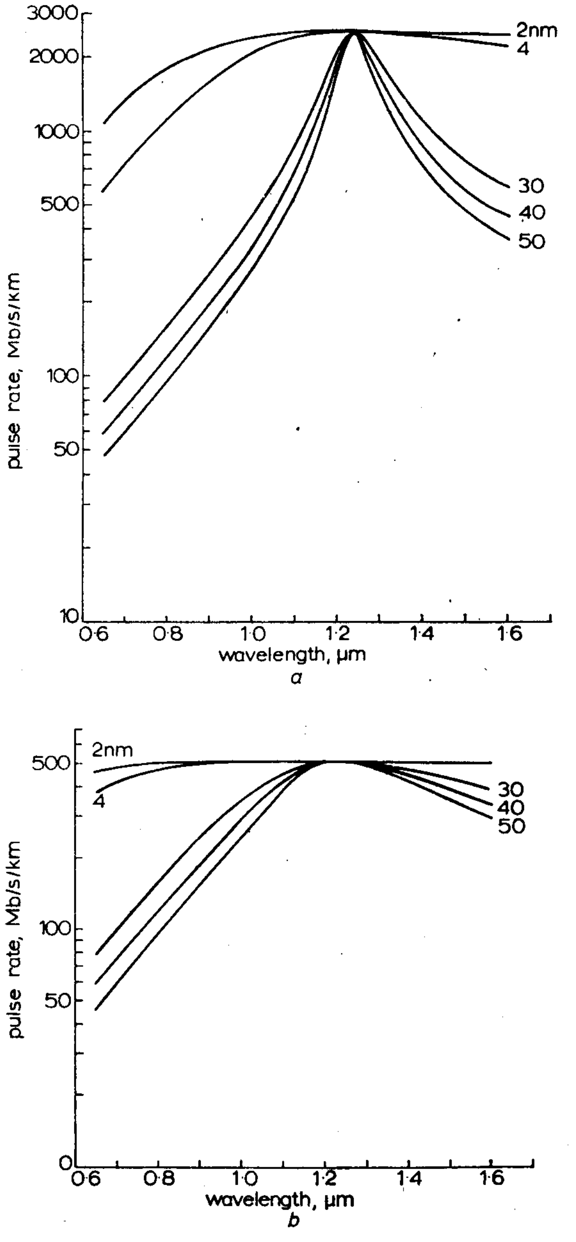

Fig. 2 *Pulse-rate characteristics for fibres having material dispersion shown in Fig. 1 and with source linewidth indicated on curves*

The waveguide dispersion is 0·2 ns/km in *a* and 1 ns/km in *b*

Reprinted from *ELECTRONICS LETTERS 17th April 1975 Vol. 11 No. 8*

which was prepared with relatively low-quality BCl_3, a figure of 0·5 parts in 10^6 has been observed.[7] Potentially, the loss at 1·27 μm is lower than that at 0·9 μm, since both the scattering and intrinsic absorption are reduced. A further advantage for military applications may be a reduced sensitivity of the attenuation to ionising radiation, compared with that at shorter wavelengths.[9]

There seems to be no reason why light-emitting diodes should not be made with adequate radiance at ≃ 1·2 μm and a suitable material[10] might be $Ga_x In_{1-x} As_y P_{1-y}$. Detectors based on silicon are not suitable, and there will be some loss of sensitivity with germanium avalanche photodiodes.

Effect of source linewidth: To compare the pulse rates that may be attained in a fibre with a phosphosilicate or silica core, for a range of wavelengths and source linewidths, the curves of Fig. 2 have been calculated. The pulse shape will depend on the broadening mechanism, but the pulse rate is conservatively taken as $B = (2\tau)^{-1}$, where τ is the total width of the output pulse for unity mark/space ratio. To obtain τ for a given wavelength, the material dispersion from Fig. 1 is multiplied by the source linewidth representing a semiconductor laser (2 or 4 nm) or an l.e.d. (30, 40 or 50 nm). The pulse width τ_m so obtained is added to the waveguide dispersion τ_g to give $\tau^2 = \tau^2_m + \tau^2_g$ assuming Gaussian pulse shapes.

It has also been assumed in Fig. 2*a* that, at each wavelength, the refractive-index profile and the fibre geometry are nearly optimum, allowing a waveguide dispersion of 0·2 ns/km. The material dispersion thus has an appreciable effect, even with a laser source, except at wavelengths close to 1·2 μm. Taking a typical linewidth for a high-quality gallium-arsenide laser of 4 nm, the maximum pulse rate possible at 0·83 μm is about 1200 Mb/s over 1 km, compared with the waveguide dispersion limit of 2500 Mb/s. On the other hand, for the l.e.d., the pulse rate rises spectacularly from 200 Mb/s over 1 km at 0·9 μm to 2500 at 1·27 μm. The corresponding figures over 7 km, assuming a linear dependence of waveguide dispersion on length, are 29 and 357 Mb/s. Even a shift in l.e.d. wavelength from 0·9 to only 0·98 μm, so that silicon detectors can still be used, would be well worth while as the pulse rate increases by 50% to 300 Mb/s over 1 km.

Fig. 2*b* is for a waveguide dispersion of 1 ns/km, which is currently possible[7] and gives a lower maximum pulse rate of 500 Mb/s over 1 km. The improvement by shifting the laser wavelength from 0·83 μm is small, but becomes substantial (from 180 to 500 Mb/s) with an l.e.d. of 40 nm linewidth.

Modulation capability of l.e.d.s: Another question is whether light-emitting diodes can be modulated sufficiently fast to make use of a reduced overall dispersion. Since, as indicated above, fibre attenuations of 2 dB/km and below are within reach, it is reasonable to consider repeater spacings of, say, 7 km, although this will depend on the light source used and the launching and detector efficiencies. With a waveguide dispersion of 0·2 ns/km, the required pulse rate is 350 Mb/s and should be possible.

Recent work[11] has shown that high modulation rates can be obtained by (*a*) constructing diodes to have low capacitance, (*b*) employing drivers with low output impedance and (*c*) appropriate shaping of the modulation pulse. With a large driving current, the optical pulse risetime can be ≃ 2 ns with negligible (< 1 ns) delay. The minimum pulsewidth is related to the carrier spontaneous recombination time which is ≃ 1 ns. Further, in many applications, the l.e.d., with some sacrifice in driving efficiency, can be modulated at a higher speed than that imposed by the spontaneous recombination time. Thus a pulse rate of 280 Mb/s, and a risetime of 0·7 ns, has been demonstrated[11] under conditions where the l.e.d. was not fully turned on. It is clear, therefore, that high pulse rates are possible and minimisation of the material dispersion is desirable, since, at 0·9 μm, the limit due to material dispersion is ≃ 30 Mb/s in 7 km.

Conclusion: It is commonly, but not universally, assumed that, for widespread applications of optical-fibre systems, a suitable semiconductor laser capable of long life, continuous, operation at room temperature must be developed. Besides being small, efficient and capable of direct modulation, such devices have the advantage over light-emitting diodes of high brightness, narrow output beam and small wavelength spread. Unfortunately, the reliability and lifetimes of present-day injection lasers are far from adequate. In contrast, existing light-emitting diodes are reliable in operation and easy to modulate. However, their large linewidth results in a low bandwidth at wavelengths normally considered for operation in optical fibres, namely 0·8 to 0·9 μm. We wish to make the point that there is an accessible wavelength region where the transmission loss in phosphosilicate and silica-cored fibres is low and the material dispersion is negligible. The bandwidth, even with an l.e.d. source, is therefore limited only by waveguide dispersion. There appears to be no inherent difficulty in fabricating an l.e.d. in this region of the spectrum, and, for moderate repeater separations, modulation rates compatible with the waveguide capability are possible.

The method of fibre manufacture[7] is ideally suited to production of various core profiles, but it remains to be seen whether fibres can be made sufficiently accurately to keep the waveguide dispersion down to 0·1 ns/km. However, over several kilometres, mode coupling may well decrease the waveguide dispersion and make the pulsewidth increase as the square root of the fibre length. Since the broadening due to material dispersion remains a linear function of length, it imposes a more serious limitation as the fibre length increases. With a refractive-index profile that is not optimum, we have already measured pulse dispersions of 1 ns/km, so that the target of 0·2 ns/km may not be too difficult to obtain.

In a single-mode fibre, the bandwidth could be increased by several orders of magnitude through a shift to 1·27 μm, which would remove material dispersion and leave mode dispersion as the main limitation.

Acknowledgments: We are indebted to C. Barwell for computing the material dispersion of silica from the Sellmeier equation. Grateful acknowledgment is made to the UK Science Research Council for supporting the work and to the Pirelli General Cable Company for the award of a research fellowship.

D. N. PAYNE
W. A. GAMBLING

Department of Electronics
University of Southampton
Southampton SO9 5NH, England

10th March 1975

References

1 LUTHER-DAVIES, B., PAYNE, D. N., and GAMBLING, W.A.: 'Evaluation of material dispersion in low-loss phosphosilicate-core optical fibres', *Opt. Commun.*, 1975, **13**, pp. 84–88.
2 PAYNE, D. N., and GAMBLING, W. A.: 'New silica-based low-loss optical fibre', *Electron. Lett.*, 1974, **10**, pp. 289–290
3 MALLITSON, I. H.: 'Interspecimen comparison of the refractive index of fused silica', *J. Opt. Soc. Am.*, 1965, **55**, pp. 1205–1209
4 PAYNE, D. N., and GAMBLING, W. A.: 'Preparation of water-free silica-based optical-fibre waveguide', *Electron. Lett.*, 1974, **10**, pp. 335–337
5 GLOGE, D.: 'Dispersion in weakly guiding fibres', *Appl. Opt.*, 1971, **10**, pp. 2442–2445
6 GLOGE, D., and MARCATILI, E. A. J.: 'Multimode theory of graded-core fibres', *Bell Syst. Tech. J.*, 1973, **52**, pp. 1563–1578
7 PAYNE, D. N., and GAMBLING, W. A.: 'A borosilicate-cladded phosphosilicate-core optical fibre', *Opt. Commun.* (to be published)
8 KECK, D. B., MAURER, R. D., and SCHULTZ, P. C.: 'On the ultimate lower limit of attenuation in glass optical waveguides', *Appl. Phys. Lett.*, 1973, **22**, pp. 307–309
9 SIGEL, G. H., EVANS, B. D., GINTHER, R. J., FRIEBELE, E. J., GRISCOM, D. L., and BABISKIN, J.: 'Radiation effects in fibre optical waveguides'. NRL Memorandum Report 2943, 1974
10 WEIDER, H.: Private communication, NELC, San Diego
11 LEE, T. P.: 'Effect of junction capacitance on the rise time of LEDs and on the turn-on delay of injection lasers', *Bell Syst. Tech. J.* 1975, **54**, pp. 53–68