Corsica 1978

A COMPARISON OF SINGLE-MODE AND MULTIMODE FIBRES FOR LONG-DISTANCE TELECOMMUNICATIONS

W. A. Gambling and H. Matsumura

Department of Electronics

University of Southampton, Southampton SO9 5NH, England

When research on optical fibre communications was first started in 1966[1] the main interest was in single-mode fibres since it was thought that the bandwidth of step-index fibres, the only type under consideration at the time, would be rather limited. Subsequently, with the development of SELFOC and other types of graded-index fibres, a high degree of equalisation of the group velocities of the fibre modes became possible so that the bandwidth available with multimode fibres was greatly increased. Interest then shifted away from single-mode fibres because of the difficulties of handling, launching, jointing and fabrication and also because the lifetimes of semiconductor lasers, the only small and relatively efficient sources possible, were not high. However the limits of bandwidth which are theoretically possible with an optimum refractive-index distribution are difficult to achieve in practice and the technology has now advanced to the stage where single-mode fibres may not be as difficult to incorporate into a practical system as was first thought. A renewed interest has therefore been shown in small-core fibres and a comparison of their properties with those of multimode fibres is presented here.

Attenuation

Transmission loss due to the fibre material itself is no longer a serious problem. Attenuations in both single-mode and multimode fibres have been reduced[2,3], in the laboratory at least, to levels below 1dB/km with minima of 0.5dB/km at a wavelength of 1.27μm. In single-mode fibres the loss in the region of cladding adjacent to the core is important since it carries an appreciable proportion of the transmitted power. A minimum thickness of high-quality cladding of about 7 times the core radius[4] is necessary to keep the effect of a lossy jacket below 1dB/km. Nevertheless the total volume of ultra-low loss material required is much less than in the case of the multimode fibre. A disadvantage is that mode conversion or mode scattering, which can be caused by inhomogeneities or core/cladding interface imperfections, including microbending, cause an additional power loss in the core of single-mode fibres but has no effect on the bandwidth whereas the opposite may be the case with multimode fibres depending on the degree of excitation. Thus in multimode fibres which are underexcited, due to the launching conditions or because of the loss of higher-order modes during propagation, mode conversion is likely to produce additional bound modes so that the total transmitted power is unchanged but the bandwidth may be decreased. Careful choice of the numerical aperture (NA) is necessary[5,6] with the single-mode fibre to minimise such loss due to weak confinement and values of 0.1 to 0.12 are preferred. With larger values the core diameter becomes too small to be practicable.

Fabrication

Both vapour deposition and double-crucible methods can be used for the fabrication of either type of fibre although the former method is much the more flexible. With multimode fibres chemical vapour deposition can produce a desired refractive-index profile so as to minimise the group velocity spread between modes. Either method is suitable, in principle, for making single-mode fibres which generally can be produced faster and more cheaply than the graded-index multimode fibres. Particularly with vapour deposition much longer lengths can be made for the same quantity of deposited material. In the double-crucible process the whole of the cladding must be of the highest quality and not simply that region nearest the core so that the quantity of extremely pure glass required is much greater.

Limiting core diameter for single-mode operation

Dielectric fibres can sustain one or more modes depending on the ratio of core radius a to wavelength λ and the relative refractive-index difference $\Delta = (n_1 - n_2)/n_2$ between core and cladding. Single-mode operation requires[7], approximately, that:

$$(ka)\{2\int_0^1 [n^2(R) - n_2^2]RdR\}^{\frac{1}{2}} < 2.405 \qquad \ldots\ (1)$$

where $k = 2\pi/\lambda$, $R = r/a$ is the normalized radial co-ordinate and $n(R)$ the radial variation of refractive index. With a constant refractive index in the core this simplifies to

$$V = (ka)(n_1^2 - n_2^2)^{\frac{1}{2}} < 2.405 \qquad \ldots\ (2)$$

where V is the normalized radius or normalized frequency of the fibre. During fabrication some diffusion of material occurs at the core/cladding interface so that there is a radial variation of refractive index and since the guidance factor of the fibre is thereby decreased the normalized frequency is increased. An interesting class of profiles is represented by

$$\begin{aligned} n(R)^2 &= n_o^2(1 - 2\Delta R^{\alpha}) \qquad R < 1 \\ &= n_o^2(1 - 2\Delta) = n_2^2 \qquad R > 1 \end{aligned} \qquad \ldots (3)$$

In multimode fibres a suitable value of α is chosen so as to minimise waveguide dispersion; usually $\alpha \simeq 2$. The same equation has been used[8] to estimate the effect on the normalized cut-off frequency V_c of diffusion at the core/cladding interface in the single-mode fibre, with the result shown in Fig.1. The solid curve gives the exact result while the dashed curve is obtained from the approximate eqn(1). It can be seen that as the profile becomes more rounded V_c rises, being about 3.6 for a square-law profile. In fibres made by vapour deposition an evaporation of some of the constituents may take place during the preform collapsing stage and this gives rise to a depression, or dip, in the refractive index at the centre of the core. Because the degree of guidance is somewhat decreased, a rise in cut-off frequency again occurs[9] but to a lesser extent than for a comparable loss of the same constituent at the edge of the core. The reason may lie in the fact that the second-order (LP_{11}) mode has a zero of intensity at the core centre.

Multimode fibres typically have core diameters in the range 50∿80μm and attempts are being made to standardise at about 60μm. If microbending loss is to be restricted to an acceptable value then the core diameter of a step-index single-mode fibre must not be greater than about 4μm. However, with a graded profile and operation at λ = 1.3μm the corresponding limit is 10μm or even more so that the difference compared with multimode fibres is much reduced.

Bandwidth

As stated above, the bandwidth of multimode fibres is primarily determined by the spread in group velocities in the various propagating modes. This spread can be minimized by choice of the appropriate refractive index distribution and for the so-called α profile of eqn(3) the optimum value, in the absence of material dispersion, is in the region of $\alpha = 2$ depending on the materials used. The spread in group velocities is then given approximately by $n_o L\Delta^2/8c$ where L is the fibre length and $c = 3\text{x}10^8 \text{ms}^{-1}$ and for $n_o = 1.5, \Delta = 0.01$ the resulting predicted bandwidth is a few tens of gigahertz over 1km. Unfortunately this bandwidth has not been achieved in practice for a number of reasons. Firstly, it is extremely difficult to realise the required refractive-index distribution to the very high degree of accuracy[10] required. Secondly, the radial variation in refractive index requires a corresponding variation in composition which, in turn, implies a variation in material dispersion. The result is that a degradation in pulse dispersion is observed even though the radial variation of material dispersion (i.e. profile dispersion) can be taken into account[11]. In a single-mode fibre group delay dispersion is absent and, to a first approximation, the refractive-index distribution is immaterial. The limiting dispersion parameters are then mode dispersion of the HE_{11} mode and material dispersion. With a monochromatic source bandwidths of hundreds of gigahertz over 1km become possible although they have not yet been measured experimentally. In practice the available bandwidth is somewhat reduced because of the finite width of the semiconductor lasers available and there is therefore great advantage to be gained by operation at a wavelength where the material dispersion is zero[12]. For silica-based fibres the optimum wavelength is near the range 1.25-1.30μm and the advantage to be gained by operating in this region for both single-mode and multimode fibres is illustrated by Fig.2.

A critical feature is, of course, the linewidth of the source and a great improvement could be obtained at non-optimum wavelengths for both types of fibre if semiconductor lasers could be produced which operated stably in a single longitudinal mode, unaffected by changes of driving current and temperature. If the problems posed by material dispersion, and the resulting profile dispersion in multimode fibres, can be overcome then waveguide dispersion becomes dominant and in this respect single-mode fibres are clearly superior. In fact single-mode fibres are essential if the maximum use is to be made of the low attenuation which is now possible. For example, if cables can be manufactured having a loss of 1dB/km then a repeater spacing of perhaps 50km becomes possible. However with a multimode fibre having a bandwidth x length product of 1GHz km, which is still not easy to achieve in practice, then the total system bandwidth is limited to $10^9/50 = 20$MHz. In order to obtain a system bandwidth of, say, 500MHz a bandwidth x length product of 25GHz is required and this can only be achieved with a single-mode fibre. It has not yet proved possible to measure the pulse dispersion in single-mode fibres, but the best reported value[13,14] so far of less than 0.1ns/km being limited by the time resolution of the equipment used.

Characterisation

It is clear from the above discussion that two important parameters of fibres are the refractive-index difference or profile, from which the numerical aperture can be derived, and the core diameter. These can be obtained for multimode fibres by a number of methods including interferometry[15], reflection measurements[16] and near-field scanning[17]. With single-mode fibres the problems are more severe since the degree of spatial resolution required is comparable with the wavelength of measurement.

One method has been suggested whereby the normalised cut-off frequency of the 2nd higher-order mode is measured by bending the fibre. However it has been shown[18] that this method gives an effective value of V which is much higher than the actual cut-off frequency. This is because microbending in the fibre can produce a high loss of the LP_{11} mode just above its cut-off frequency which increases the effective value of V. In practice we have observed single-mode operation in even short lengths of fibre having V = 2.8.

A simple method has been found[19] for determining a and Δ from the measurement of the far-field pattern at a single wavelength. It can be shown from theory, as well as experimentally, that in addition to the main bean the far-field pattern has several subsidiary lobes. The ratio $\sin\theta_x/\sin\theta_h$, where θ_x is the angular width to the first minimum and θ_h is the output angle at which the intensity has fallen to half of its central maximum, is an unambiguous function of V as is $ka\sin\theta_h$. Therefore measurement of θ_x and θ_h gives V and from the next curve, $ka\sin\theta_h$, the core radius a can be calculated as illustrated in Fig.3.

Another possibility with fibres fabricated by chemical vapour deposition is to make measurements on the preform and assume that only linear changes in geometry occur as the preform is drawn into a fibre. This can only give an approximate result since some diffusion between core and cladding can occur[19] during fibre drawing. Other methods of characterising single-mode fibres reliably are needed, particularly techniques for measuring the refractive index profile.

Bending and Microbending Losses

In general the radiation loss due to bends in a fibre arise from two different physical mechanisms. One is the pure bend effect whereby the velocity of the wave front at some distance from the centre of curvature approaches that of an unguided wave and all energy beyond that point is therefore lost[20]. The other mechanism is the mode conversion which occurs at changes of curvature or, more accurately, the inefficient coupling between the mode appropriate to one degree of curvature to the equivalent mode at the following curvature. At the junction between a straight and a curved fibre the increase in transmission loss might be expected to follow curve A in Fig.4. However the mode conversion or transition loss does not take place instantaneously because the power coupled to the radiation field leaks away gradually and in addition an abrupt change of curvature is prevented by the mechanical stiffness of the fibre. Intuitively one might therefore expect[21] the increase in loss with distance to take the form of curve B. That this is indeed the case is shown by the experimental measurements of Fig.5 which were obtained[21] for a single-mode fibre of V = 2.4 and NA = 0.06. The relative effects of pure bend loss[22] and transition loss[23,24] are shown in Fig.6 as a function of radius of curvature. It is clear that in any practical situation both types of loss must be taken into account.

Microbending losses arise from very localized changes of curvature and again both mode conversion and pure bend loss mechanisms must be considered. Representative microbend loss curves are given in Fig.7 as a function of $2\pi a/\lambda$ for a multimode (dashed curve) and a single-mode (solid curve) fibre. Both curves are calculated for $\Delta = 0.01$ and $n_2 = 1.457$. In the case of the single-mode fibre the microbend loss depends strongly on the index difference Δ and for $NA \simeq 0.1$ it is roughly of the same magnitude as with a multimode fibre.

Splice Losses

A severe problem with single-mode fibres is the very tight mechanical tolerance that must be maintained during splicing and jointing. For permanent connections fusion splices are feasible and losses as low as 0.2dB per splice[25] have been reported. However the design and implementation of demountable connectors is much more difficult. Transverse displacement d and angular misalignment α need to be accurately controlled and contribute interdependently to the joint loss α_t by the following equation[26]

$$\alpha_t = 2.6D^2 + 7.6(\alpha n/NA)^2 + 6.0(\alpha nD/NA)$$

where $D = d/a$. Fig.8 illustrates the combinations of α and d that produce various fixed values of α_t. For a jointing efficiency of 90% an angular misalignment of less than 3° or an offset of less than 1μm is required. The corresponding figures for a multimode fibre of core diameter 50μm are $\alpha = 3^\circ$ (i.e. the same as for a single-mode fibre) and d = 5μm.

Sources and Detectors

Detectors, of course, are equally applicable to any type of fibre and there is no particular problem to be solved. As far as sources are concerned a multimode fibre can accept radiation from either a light-emitting diode or a laser. The coupling efficiency from a GaAs laser with an output beam width of 30° is approximately 30% into a fibre of NA = 0.15. Coupling into a single-mode fibre is more difficult to achieve but efficiencies of 40% or more may be possible with microlens or other types of coupling.

References

1. K.C.Kao and G.A.Hockham, Proc.IEE 113, 1151-1158,1966.
2. M.Kawachi, A.Kawana and T.Miyashita, Electron.Lett. 13, 442-3,1977
3. M.Horiguchi and H.Osanai,Electron.Lett. 12, 310-312, 1976
4. M.H.Kuhn, Archiv Electron.Ubertragungstech 20, 201-204, 1975
5. R.Olshansky, Second European Conf on Optical Fibre Communication, 101-103,1976
6. K.Petermann, Electron.Lett. 12, 107-109, 1976.
7. W.A.Gambling, H.Matsumura and C.M.Ragdale,Opt. & Quantum Electron. 10, 301-309,1978

8. W.A.Gambling, D.N.Payne and H.Matsumura, Electron.Lett. 13,139-140, 1977
9. W.A.Gambling, D.N.Payne and H.Matsumura,Electron.Lett. 13,174-5 1977
10. R.Olshansky and D.B.Keck, Appl.Opt. 15, 483-491,1976
11. D.Gloge, I.P.Kaminow and H.M.Presby, Electron.Lett.11,469-471,1975
12. D.N.Payne and W.A.Gambling, Electron.Lett. 11,8-10, 1975
13. W.A.Gambling and D.N.Payne, First European Conference on Optical Fibre Communication, Proceedings 197-200, 1975
14. H.Matsumura, unpublished work
15. W.E.Martin, Appl. Opt. 13, 2112-2116, 1974
16. M.Ikeda, M.Tateda and H.Yoshikiyo, Appl.Opt. 14,814-815,1975
17. D.N.Payne, F.M.E.Sladen and M.J.Adams, First European Conf on Optical Fibre Communications, Proceedings 43-45,1975
18. W.A.Gambling, D.N.Payne, H.Matsumura and S.R.Norman, Electron. Lett. 13, 133-135, 1977
19. W.A.Gambling, D.N.Payne, H.Matsumura and R.B.Dyott, Microwaves, Optics and Acoustics 1, 13-17, 1976
20. D.Marcuse, Bell System Technical J. 55, 937-955, 1976
21. W.A.Gambling, H.Matsumura and C.M.Ragdale, Microwaves, Optics and Acoustics 3, 1978 (in the press)
22. E.F.Kuester and D.C.Chang, IEEE J. Quantum Electron. QE11, 903-907, 1975
23. M.Miyagi and G.L.Yip, Opt. and Quantum Electron. 8,335-341,1976
24. W.A.Gambling, H.Matsumura and C.M.Ragdale, Electron.Lett. 14, 130-132, 1978
25. H.Tsuchiya and I.Hatakeyama, Optical Fiber Transmission II, post-deadline paper, 1977
26. W.A.Gambling,H.Matsumura and C.M.Ragdale (to be published)

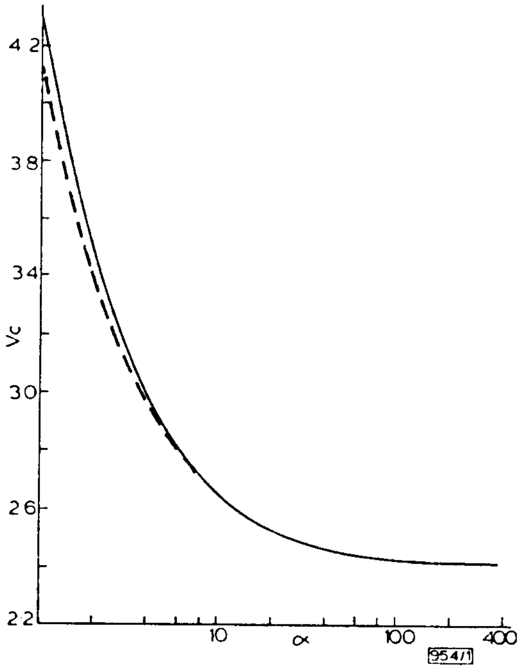

Fig. 1 *Variation with profile parameter α of cut-off frequency V_c in single-mode graded-index fibre*

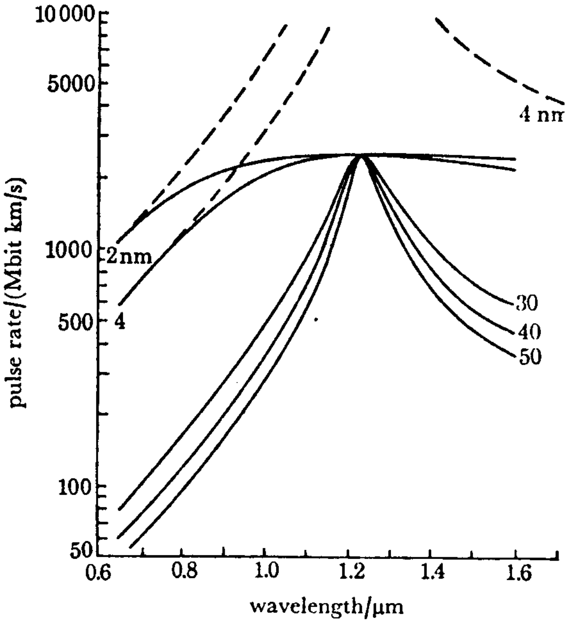

Fig.2 Pulse rate for various source linewidths for graded (solid) and single-mode (dashed) fibres

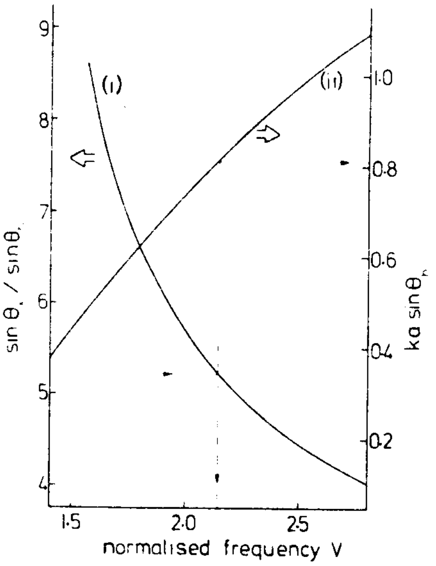

Fig.3 Variation of θ_x and θ_h with V

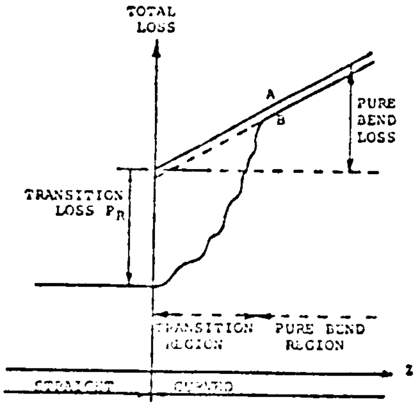

Fig.4 Loss near start of bend

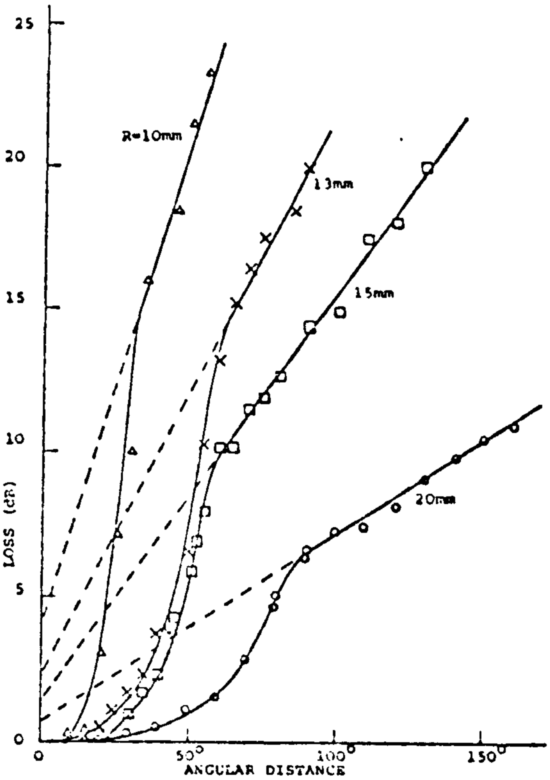

Fig.5 Measured total bend loss

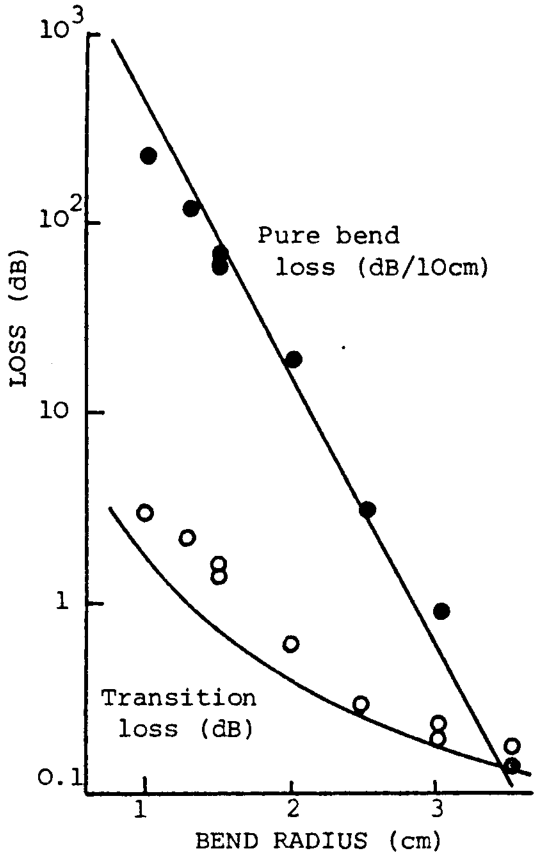

Fig.6 Measured and calculated bend losses

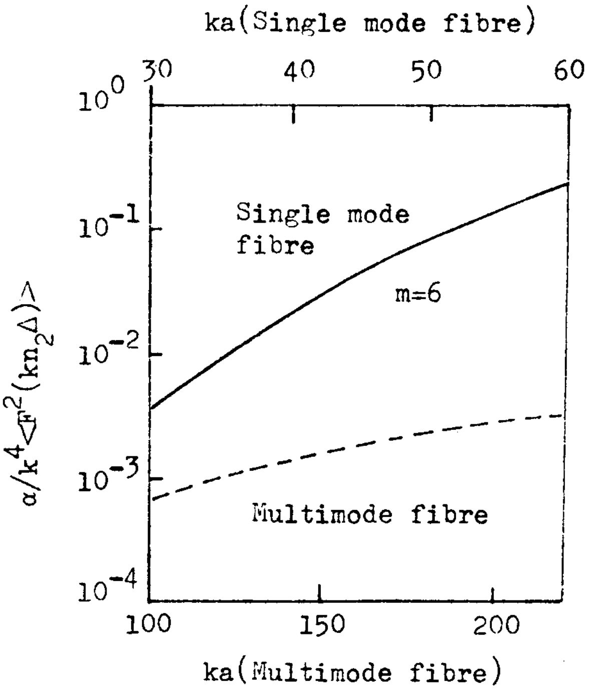

Fig.7 Normalized microbend losses

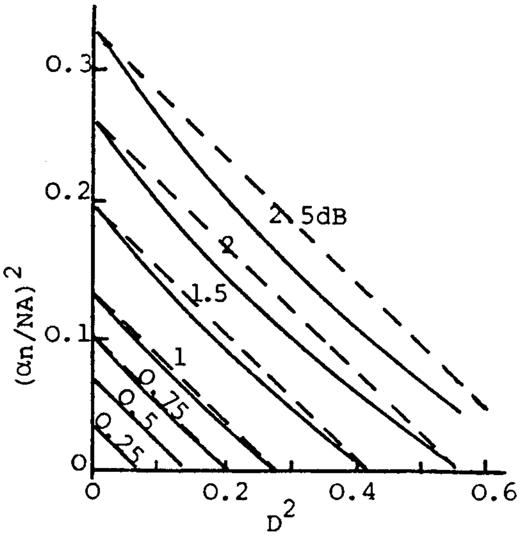

Fig.8 Lines of constant bend loss