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RECENT ADVANCES IN OPTICAL FIBRE COMMUNICATIONS

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INTRODUCTION

The purpose of optical-fibre communications is quite revolutionary- namely to introduce a completely new form of transmission line using optical techniques. The transmission distances required can be up to tens of kilometres and the potential applications are seen to be very widespread. In short we wish to replace electric currents and copper wires by glass fibres and light, not only in complete telephone networks but in other communications systems as well, such as aircraft, ships, computers and so on.

In a typical long-distance transmission system, such as the trunk telephone network for example, the signal has to be reamplified (or regenerated in the case of digital modulation) in so-called "repeaters" when the power level has fallen to about -40dB (i.e. to 10^{-4}) of its initial value. The transmission loss of coaxial cables is such that this process has to be carried out after distances of only 2 or 3 km. To increase the repeater separation by, say, a factor of 10, implies attenuations of 1 or 2dB/km, corresponding to extinction coefficients of 10^6 cm^{-1} and impurity levels of 1 part in 10^8 or less. How can this be done?

One practical requirement, apart from low loss, is that the material should be capable of being drawn easily into long lengths of fibre and glass meets this requirement particularly well.

FABRICATION

If we study absorption losses in most conventional glasses the attenuation curve indicates immediately that the only feasible wavelengths of operation lie in the near infra-red region ~1μm which is fortunate since this means that existing semiconductor lasers will suffice. At shorter wavelengths the tails of the electronic resonances in the ultra-violet, as well as Rayleigh scattering as will be shown later, have a dominating influence. Further into the infra-red the wings of the intrinsic vibrational resonances, such as that of the silicon/oxygen bond in silica for example, have a similar effect. When work began in England in 1966 commercially-available fibres had attenuations of 10^3dB/km and an improvement of 2 or 3 orders of magnitude was necessary.

Two general types of approach to the fabrication of fibres have been used. One is via conventional glass-making techniques starting with solid raw materials and perhaps the best result obtained so far, Fig. 1, is that by the British Post Office[1] showing a minimum attenuation of 4dB/km measured at 0.85μm with an NA = 0.25 or 3.4dB/km with a semiconductor laser. Precautions which have to be taken include ensuring a very high degree of purity in the glass-melting crucible, the avoidance of airborne contamination through indirect heating and a clean ambient gas flow coupled with careful materials handling. Part of the difficulty with this method is that solid starting materials are not easy to obtain in sufficiently pure form and in particular that the OH radical is stubbornly persistent.

When the two pure bulk glasses for core and cladding, respectively have been prepared they are drawn into long rods. The core and cladding rods are then fed at a carefully controlled rate into the inner and outer regions of a suitably-heated concentric crucible arrangement from which fibres are drawn in the usual way[2].

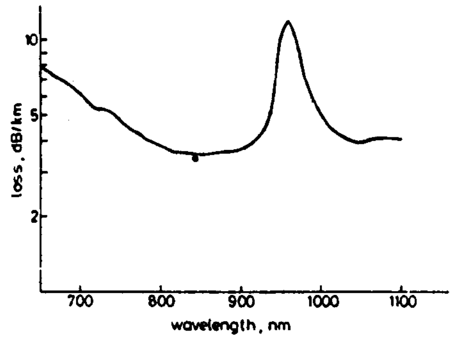

Fig. 1.– Transmission loss[1] of sodium bosorilicate glass fibre over a length of 2.2km and with 0.18 numerical aperture. The solid circle represents the loss of 3.4dB/km at 842nm measured with a GaAlAs laser.

The process is a semi-continuous one in which long lenghts of fibre of moderate bandwidth may be obtained economically.

An alternative approach involves starting with liquids, because they are easy to purify and then depositing from the vapour phase. The most refined method, first reported independently by Southampton University[3] and Bell Telephone Laboratories[4] - the homogeneous or modified CVD method - gives the direct deposition of glass layers normally ~10μm thick, on the inside of a supporting tube. The optical properties of the latter are not important but the wall thickness must be uniform, both azimuthally and longitudinally, and it must be homogeneous as well as mechanically and thermally compatible with the layers to be deposited.

As illustrated in Fig. 2 the starting materials are halides which are vapourized by the passage of a carrier gas and combined with oxygen before entering the supporting tube. A short furnace, producing a temperature of 1400-1600°C, is traversed along the tube thus causing oxidation of the halides which are simultaneously sintered into a thin smooth glass layer. The composition of the glass in the deposited layer, and hence its refractive index, can be varied by changing the relative gas flows. Thus by tailoring the composition of successive layers an appropriate refractive-index distribution can be obtained over the cross-section of the fibre. After deposition the composite tube is collapsed into a solid rod preform and drawn into fibre. At present this is a batch process producing lengths of up to 4 or 5 kilometres or so but preliminary results with a continuous version of the process are encouraging.

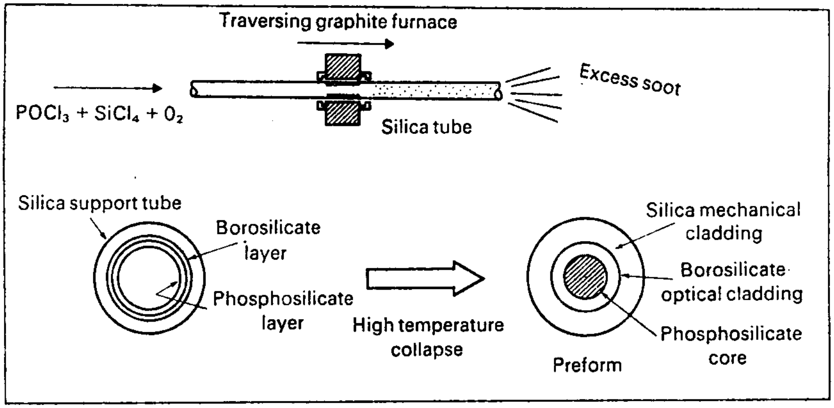

Fig. 2.– Schematic diagram of homogeneous chemical vapour deposition process and collapse of multilayer tube preform into a solid rod.

After fabrication the fibre consists of a high-refractive-index core, a lower-refractive-index cladding and a surrounding region of supporting tube material.

The lowest attenuation reported so far was obtained with a fibre of Southampton University design[5] but fabricated at the NTT and Fujikura laboratories[6] in Japan. The curve shown in Fig. 3 was measured with the rather small launching numerical aperture of 0.05 and shows four main features.

Firstly, a minimum attenuation of 0.5dB/km at $\lambda = 1.2\mu m$. As will be shown later this is also the wavelength at which the material dispersion is zero.

Secondly, at shorter wavelengths the attenuation is largely due to Rayleigh scattering caused by thermodynamic density fluctuations frozen in at the glass-hardening temperature.

Thirdly, a rise in the attenuation at larger wavelengths thought to be due to the Si-0 bond resonance at $\sim 9\mu m$.

Fourthly, small superimposed peaks due to OH radical impurity.

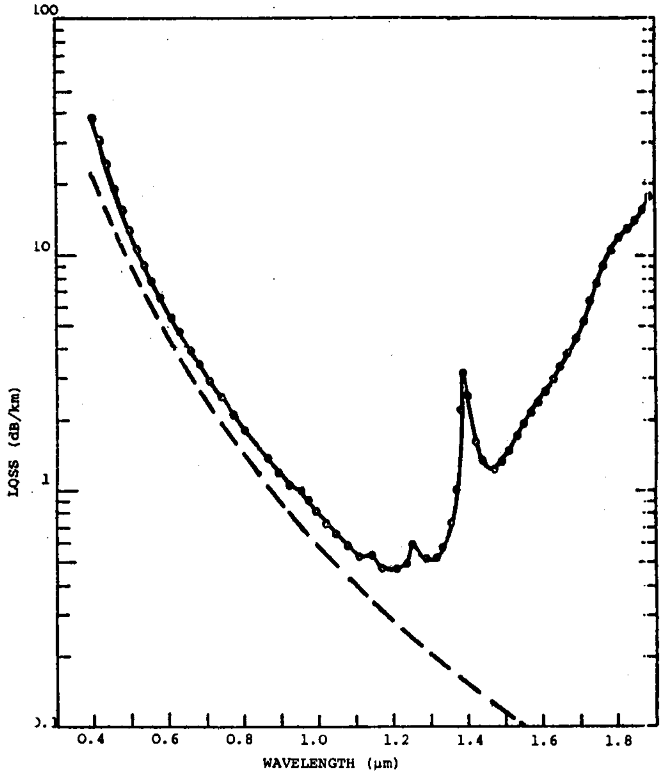

Fig. 3.– Transmission loss[6] of optical fibre comprising phosphosilicate core in borosilicate cladding. The fibre length is 1.2km and the effective numerical aperture at the source is 0.05.

Fig. 4 gives a similar result but drawn to a linear and not a logarithmic scale. It was obtained at Southampton University, with a launching numerical aperture of 0.25. Thus 25 times as much light was carried by the fibre over a length of 3 km, which is very important from a practical point of view. The pulse dispersion was 0.5ns/km corresponding to a bandwidth x length product of about 2 GHz km.

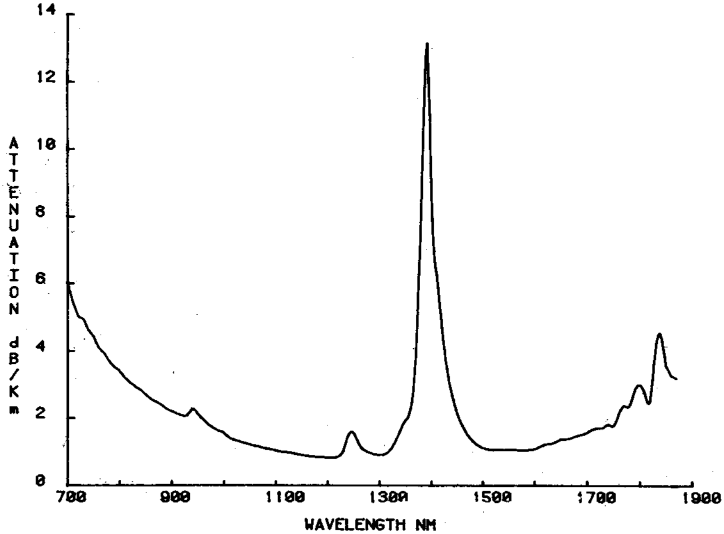

Fig. 4.— Attenuation of 3km length of fibre drawn at Southampton University. The fibre numerical aperture of 0.25 was fully excited and the minimum loss is 0.8dB/km.

BANDWIDTH

In a fibre having a constant refractive index in the core the various rays travelling in straight lines at different angles to the axis arrive at the output at different times. This causes pulse spreading and a limitation on bandwidth due to multipath dispersion, as indicated in Fig. 5.

The range of possible angles is determined by the numerical aperture of the fibre, which is a function of the refractive indices of the core and cladding materials, see Table 1. For a core refractive index $n_1 = 1.5$ and a typical value of relative index difference between core and cladding of $\Delta = 0.01$ the range of acceptance angles (in air) is ±10° corresponding to a numerical aperture of 0.17. The bandwidth x length product is thus limited to about 20MHz km if the launched energy is distributed over all possible ray angles.

The multipath, or multimode, dispersion effect can be reduced by introducing a radial variation of refractive index, as shown on the right-hand side of Fig. 5. In effect the fibre now becomes a weak continuous lens, in which rays at a large angle to the axis spend most of their time in a region of low refractive index and therefore travel faster than an axial ray which traverses a shorter geometrical path length. For the particular refractive-index distribution[8] shown in Table 2 the spread of ray transit times is reduced by a factor $(\Delta/8)$ which, for $\Delta = 0.01$, is nearly three orders of magnitude. Thus, in principle, bandwidth x length products of 20GHz km are possible, compared with a corresponding figure for coaxial cables of a few tens of MHz km.

In practice there are severe difficulties in achieving, with a sufficiently high degree of precision, the required refractive-index distribution. Another problem is that the variation of refractive

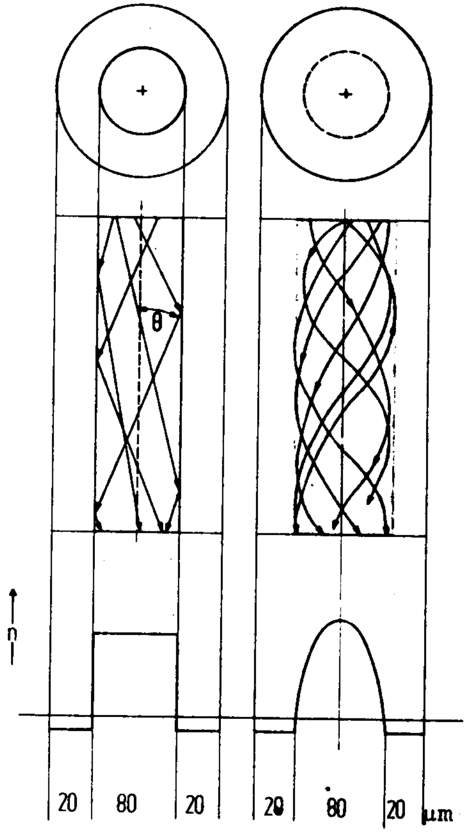

Fig. 5.– Ray propagation in multimode fibres having stepped and graded refractive-index distributions.

TABLE 1

MULTIMODE STEP-INDEX FIBRES

Refractive index: Core n_1 Cladding n_2 $\Delta = \dfrac{n_1 - n_2}{n_1}$

Permitted range of angles to axis in core $= \pm \cos^{-1} \dfrac{n_2}{n_1}$

Difference in propagation times of axial and extreme rays $= n_1 \Delta L/c$

L = fibre length $c = 3 \times 10^8\ \mathrm{ms}^{-1}$

Bandwidth x Length product $\cong$ 20MHz km for $\Delta = 0.01$

$NA = (n_1^2 - n_2^2)^{1/2}$ a = core radius

$V = 2\pi(NA)(a/\lambda)$ = normalized radius frequency

Number of modes $\sim V^2/2 \sim 2500$

for $NA = 0.2$; $a = 50\mu m$; $\lambda = 0.9\mu m$

index with wavelength changes with the radial variation of material composition. Nevertheless bandwidths of 1GHz over a kilometre can be achieved as shown by the input and output pulses over a 3km length of fibre shown in Fig. 6. The correspondieng pulse dispersion is 0.5ns/km.

TABLE 2

MULTIMODE GRADED INDEX FIBRES

$$n(r) = n_o \left[1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha}\right]^{1/2}$$

Spread in ray propagation times $\cong n_1 \Delta^2 L/8c$

Bandwidth x Length product $\cong$ 20GHz km

for $n_1 = 1.5$; $\Delta = 0.01$

NA varies radially

Leaky modes propagate

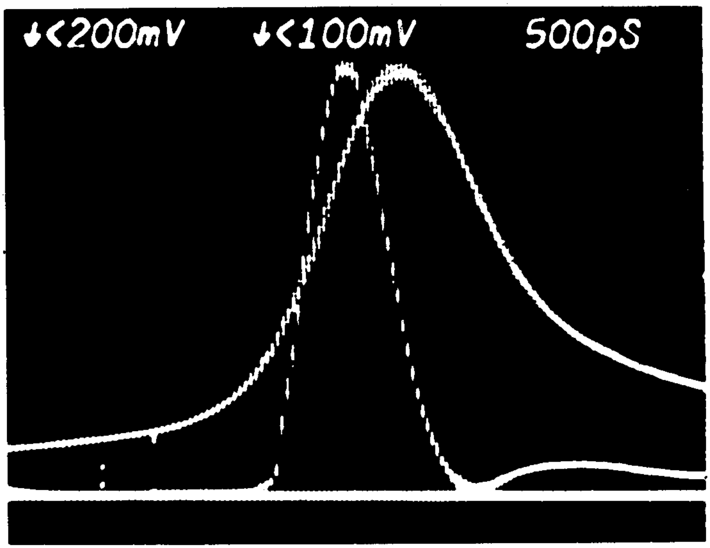

Fig. 6.– Pulse dispersion in graded-index multimode fibre. The input pulse of 0.6ns is broadened to 1.4ns in transmission over a 3km length. This corresponds to a pulse broadening of 0.5ns/km. The fibre was fabricated at Southampton University.

Another method of reducing pulse dispersion is by decreasing the number of modes which are capable of propagating. Table 1 shows that the number of modes depends on the ratio of core diameter to wavelength. Thus by reducing the core diameter to, say, 5μm compared to ~50μm for a multimode fibre, only one mode is allowed to propagate. The bandwidth is then limited primarily bymode dispersion, i.e. the variation of mode group velocity with wavelength, and by material dispersion.

The mode dispersion is always finite in the single-mode regime but recently[9] it has been demonstrated that effective single-mode operation can be obtained under conditions where the mode dispersion is zero. The remaining major limitation is then due to the material itself. The property which causes a propagating pulse to broaden is not what is normally known as dispersion, namely $dn/d\lambda$, but the second derivative[10] with respect to wavelength λ, namely $(-\lambda/c)\,(d^2n/d\lambda^2)$. For the types of glass in fibres made by the homogeneous chemical vapour deposition technique the material dispersion falls to zero at a wavelength of about 1.3μm, see Fig. 7, thus enabling its effect to be removed, or at least considerably reduced.

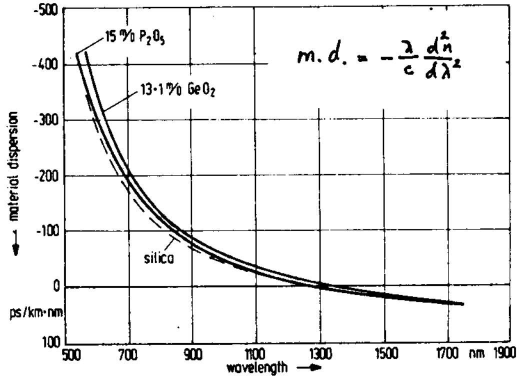

Fig. 7.— Material dispersion in phosphosilicate, germano-silicate and silica fibres.

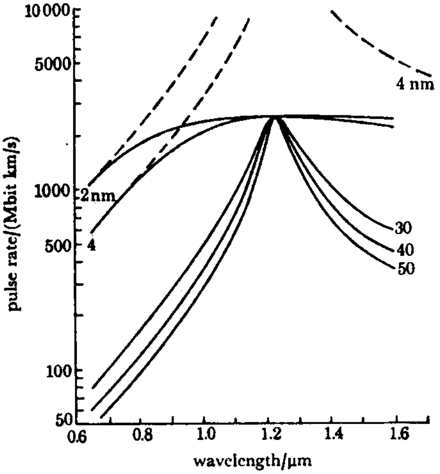

Fig. 8.— Maximum possible pulse rates in phosphosilicate-cored fibres for the source linewidths indicated on the curves. The solid lines represent a multimode graded-index fibre having a waveguide dispersion of 0.2ns km^{-1} while the broken lines are for a single-mode fibre.

The advantage to be gained by operating at the longer wavelength depends on the residual waveguide dispersion and on the source linewidth. An illustration is given in Fig. 8 in terms of the maximum pulse rate which can be transmitted along multimode and single-mode fibres and for linewidths of 2 and 4nm (representing semiconductor lasers) and 30 to 50nm (representing light-emitting diodes). It can be seen that by changing the wavelength of operation from that of GaAs devices, 0.85 to 0.9μm, to 1.3μm an increase in information rate of over an order of magnitude can be obtained for the two combinations of (i) and LED with a multimode fibre and (ii) a laser and a single-mode fibre. As a result a considerable amount of work is being done on the development of devices operating at about 1.3μm, based on quaternary materials such as GaInAsP. In fact a transmission distance of 50km without repeaters has already been reported[11] with a system of this kind.

CONCLUSIONS

Methods have been developed for fabricating both multimode graded-index fibres and single-mode fibres with attenuations as low as 0.5dB/km. In practice multimode fibres have been made into cables with attenuations, after installation in the ground, of less than 5dB/km at a wavelength of 0.85μm. Bandwidth x length products so far realised are approaching 1GHz km and can be improved upon by at least an order of magnitude by exploiting single-mode fibres at longer wavelengths.

The practical problems to be solved are of equal importance to the fundamental ones which have already been tackled so successfully. Thus considerable progress has been made in preserving fibre strength, in developing methods of jointing and coupling and in improving the lifetime and efficiency of suitable sources. Already experimental systems have been installed in many countries and the application of optical fibre communications is on the threshold of an explosive growth.

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