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SOME FUNDAMENTAL PROBLEMS RELATING TO OPTICAL FIBRES
I. The attainment of loss coefficients of 10^{-5} cm^{-1}

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Abstract

SOME FUNDAMENTAL PROBLEMS RELATING TO OPTICAL FIBRES. I. THE ATTAINMENT OF LOSS COEFFICIENTS OF 10^{-5} cm^{-1}.

Fibres for optical communications are currently being made with two types of material, namely low-temperature compound glasses and high-temperature silica-based glasses. The paper outlines the techniques used in the two cases and summarizes the results which have so far been achieved.

1. INTRODUCTION

In the development of fibres for optical communications two factors are of primary importance, namely the transmission loss and the bandwidth. This paper discusses the various ways in which low attenuation may be achieved together with a summary of the results which have been reported. Within the space available it is not possible to make a detailed survey but an introduction will be given to the literature now available, some of which is presented in the references. The subject has developed to the stage where the primary problems, i.e. attenuation and bandwidth, have been largely solved, although a considerable amount of work remains to be done, and much effort has now been shifted to second-stage difficulties such as cabling and cabling losses, mechanical strength, jointing and sources. A review of fibre loss mechanisms and results is therefore timely.

2. LOSS MECHANISMS IN FIBRE MATERIALS

The transmission losses of optical fibres can be broadly classified into two groups, (i) those which are inherent in the materials used and (ii) those arising from the fibre configuration and the form of propagation. Only the former will be considered here while the latter

will be referred to in later sections. In turn the fundamental material loss mechanisms fall into the two simple categories of absorption and scattering, although there are many particular sources which can give rise to these forms of loss.

In order to achieve adequate signal transmission over distances of several kilometres, extremely low losses are essential, certainly below 20dB/km, which is equivalent to an extinction coefficient of $4.6 \times 10^{-5} cm^{-1}$. In fact figures an order of magnitude better, i.e. $\sim 2 \times 10^{-5} cm^{-1}$, have been reported.

2.1. Absorption

Pure glasses can absorb light through, in general, electronic transitions causing strong absorption bands in the ultra-violet region of the spectrum and vibrational resonances of the molecular structure with their associated absorption bands at infra-red wavelengths. For good transmission at visible and near-infra-red wavelengths the UV and IR bands should be as well separated as possible but even so some residual absorption due to the tails of the bands may be detectable in the wavelength region of interest. This inherent absorption loss, as well as the separation and location of the bands, depends very much on the components of the glass. A very common, and often a major, component of glass is silica which fortunately has very attractive optical properties[1] although it is not altogether easy to process or handle.

Until recently, on the other hand, the bulk of the absorption loss was not inherent in the glass itself but was due to impurities. Some of these can have a considerable effect even when present in very small amounts and they have to be reduced to concentrations of as low as a few parts in 10^9 to produce an acceptable loss figure. The major impurities of glasses having a low melting temperature are the transition metal ions which can take several forms of ionic state and can give rise to absorption bands of different positions, intensities and distributions. The detailed effects, and the ratio of ions in the different states, depend both on the particular glass composition and on the method of preparation. The influence of some typical impurities for a particular glass is shown in Fig. 1 and it can be seen that the tail of an absorption band can produce a large attenuation well away from the band centre.

Another impurity which is sometimes difficult to remove is water which produces hydroxyl ions. The stretching and bending vibrations of the hydroxyl bond and the various overtone and combination bands cause absorption peaks at various wavelengths depending on the position of the hydroxyl ion and the type of glass network in which it is situated. Compared with metallic impurities the peaks due to water are sharper so that the tails are less important. However, in glasses made by

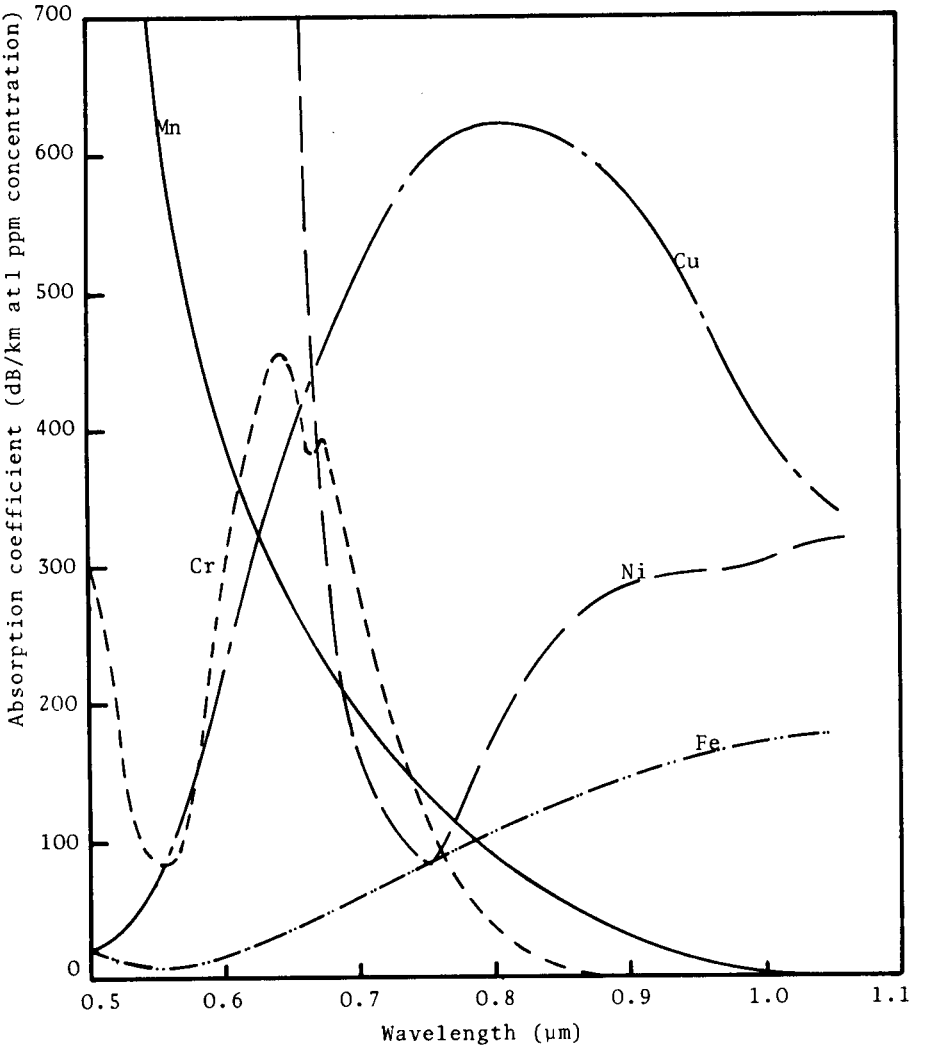

FIG.1. Absorption coefficients for various impurities in low-melting-temperature glass.

vapour deposition one OH peak occurs at about 0.95μm and, particularly in the GeO_2/SiO_2 glasses [2]. the tail can produce an appreciable attenuation at the GaAs laser wavelength of 0.9μm.

Other absorption mechanisms such as defects induced while the fibre is being drawn[3] and colour centres due to ionizing radiation[4] are generally of secondary importance.

2.2. Scattering

With the progressive reduction in the loss due to absorption the effect of scattering has become correspondingly more important. In the limit, inhomogeneities in the density and local fluctuations in composition smaller than the light wavelength cause Rayleigh scattering. The resulting scatter loss varies with wavelength as λ^{-4} and thus decreases rapidly towards the infra-red, and for typical fibre glasses is ~1dB/km at 1μm. Density fluctuations are frozen into the glass on cooling and are therefore greater the higher the temperature at which the glass solidifies. Scatter due to density fluctuations is therefore higher in pure silica which is drawn into fibre at a temperature ~2000°C than in, say, a potassium silicate glass[5] which is drawn at ~1000°C. On the other hand, the latter has an additional scatter loss due to compositional fluctuations.

Scattering from inhomogeneities or particulate impurities which are not small on a wavelength scale, so-called Mie scattering, is more difficult to calculate but it produces mainly scattering in the forward direction. The effect may be eliminated by suitable fibre fabrication techniques and, with one exception, will not be considered further. The exception concerns inhomogeneities which can be caused at the core/cladding interface mainly during cabling or by coiling a fibre on a rough surface. Such "microbending"[6] can cause rays to be deflected to angles smaller than the critical angle at the interface so that energy is lost from the core. Transmission losses of several tens of dB/km can be caused in this way, but again they can be avoided in principle.

3. FIBRE FABRICATION

In general two types of material are used at the present time for making low-loss optical fibres, namely low-melting point (~1000°C) materials prepared by conventional glass-making techniques and high-melting point (~2000°C) materials deposited from vapours which are heated and oxidized. The latter are relatively easy to produce and have given the lowest losses to date but require the preparation of a preform from which the fibre is drawn. The former demand extremely pure raw materials and clean room conditions for preparation but should have the advantage of giving unlimited continuous lengths.

3.1. Low-melting-point glasses

Much of the early work on multi-component glasses for optical fibres was carried out by the Nippon Sheet Glass Company (SELFOC fibre) and by the British Post Office.

Generally the glass systems used by the Post Office are sodium borosilicate, sodium/calcium silicate, and sodium and potassium lead silicate. The glasses are prepared by heating premixed, high-purity starting materials (oxides and carbonates) in platinum or refractory crucibles [7]. At a sufficiently high temperature (1000-1400°C) the carbonates decompose and the components react, forming a viscous liquid or melt. Homogenization of the melt is effected by stirring at high temperatures; the temperature, times and stirring techniques required depend on the glass composition, the impurities present and the desired optical quality. The glass is then either cast into moulds or pulled into rods from the surface of the melt.

At all stages of glass making, contamination can occur, the main sources of which are atmospheric dust, transport of impurities from the furnace and dissolving or diffusion of impurities from the crucible. All the glass-making operations are therefore usually carried out in clean rooms, with continuously filtered air.

Vapour-phase transport of the impurities from the hot furnace refractories may be minimized by careful choice of furnace materials and liners and can be completely eliminated by inductively heating a platinum crucible within a cool silica enclosure. However, in this case the platinum can dissolve and contaminate the glass. When the platinum is present in an ionic form it is less important as its absorption bands occur at ultra-violet wavelengths. If, on the other hand, the platinum is precipitated as metallic particles the loss can be very high. Careful choice of glass composition and melting atmosphere can practically eliminate platinum contamination. Nevertheless, even the purest available platinum crucibles have relatively high contents of iron and copper and these can diffuse into the glass at the high melting temperatures, so that special precautions must be taken such as leaching the impurities from the crucibles or using a lower temperature for glass making.

To minimize the problems of contamination it is possible to use fused silica crucibles which are available with a very low degree of impurity. Silica dissolves slowly in the molten glass, producing some inhomogeneity, but losses[8] as low as 6.5dB/km have been obtained.

A new method of reducing contamination[9] involves heating the molten glass directly and not via the crucible which may therefore be held at a lower temperature. Thus a small graphite susceptor is placed in a silica crucible with a small quantity of batch materials and heated by means of a radio-frequency generator. The graphite is now effectively the heat source and a small quantity of glass is formed. In its molten state glass becomes sufficiently conducting to couple directly to the r.f. field and the susceptor may be removed. More raw materials are now added and stirring carried out in the usual way.

Having obtained the required glasses for core and cladding, fibre drawing can be carried out either by first preparing a preform or via the double-crucible technique. The simplest way of making a preform is to take a rod of core glass and tube of cladding glass, insert one into the other and draw down into a cladded fibre in the usual way[10]. Obviously a considerable amount of processing and handling has to be done on the glasses in making the preform, and the possibility of contamination is high. A novel method of preform fabrication[11] direct from the melt involves pouring carefully a layer of cladding glass over the molten core glass in situ in the crucible. A glass rod is then dipped into the melt and withdrawn thus giving a composite core/cladding preform directly and with no further handling or processing. One of the difficulties of the method is in maintaining uniformity of core and overall diameters for sufficient lengths of preform to give kilometres of fibre. It is difficult to produce single-mode fibre using rod-and-tube preforms.

The double-crucible apparatus is illustrated in Fig. 2. The core glass is loaded into the inner crucible with the cladding glass in the outer. The crucibles are usually made of high-purity platinum and may hold from a few hundred grams to several kilograms of glass. Typically, 100 g of glass yields about 5km of fibre. The crucibles are electrically heated to a temperature at which the molten glass begins to flow through the concentric nozzles. The emergent composite flow is then drawn into fibre. Careful control of the temperature distribution and winding speed is necessary to ensure that the correct diameter for core and cladding is obtained. Either single-mode fibre (core diameter about 3-10μm) or multimode fibre (core diameter of about 40-100μm) can be made, depending on the inner nozzle diameter which determines the volume ratios of core to cladding glass and thus the required glass flows. The attainment of low optical loss necessitates careful attention both in the preparation and loading procedures to minimize unwanted contamination of the glass surfaces, and also in the operation of the apparatus. Multimode fibres having losses of about 7dB/km have been produced by this method[8].

A gradation of the refractive index of the core can be obtained, if suitable glasses are chosen, by allowing diffusion between the core and cladding during fibre drawing. This is the technique used to produce the new SELFOC fibre and which has given losses[12] as low as 7dB/km also.

3.2. Vapour-deposited glasses

When, in 1966, Kao and Hockham[13] carried out a study of the use of cladded optical fibres as long-distance transmission lines, only one material was known to have a sufficiently high transmission. Thus synthetically-produced silica, obtained commercially by flame hydrolysis

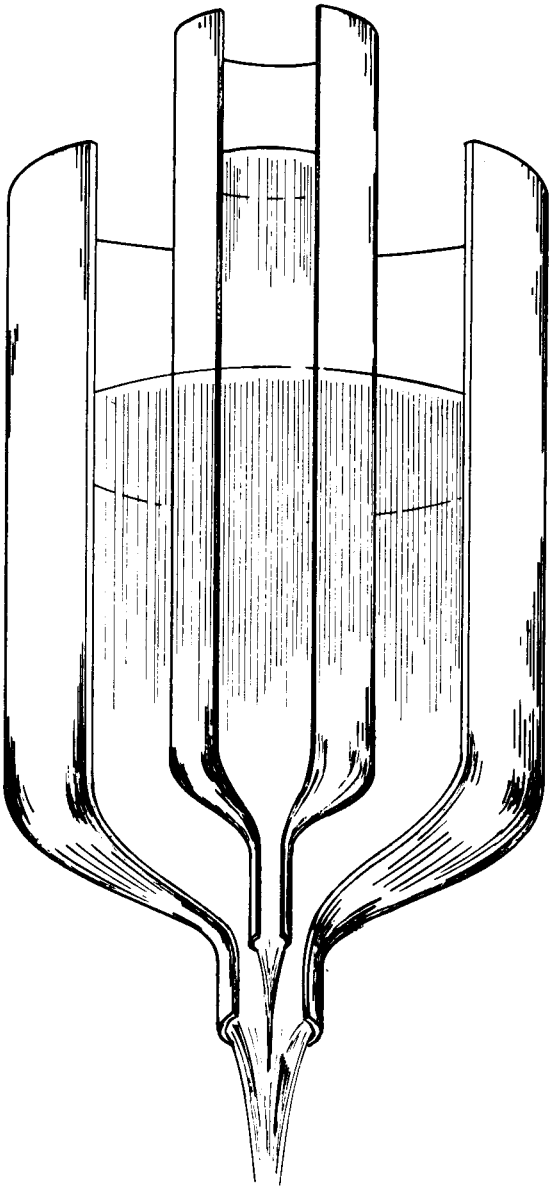

FIG.2. Schematic diagram showing fibre drawing from concentric crucibles.

or plasma-arc oxidation of silicon tetrachloride, was available having a bulk transmission loss of less than 5dB/km. Two of the reasons for the availability of silica in very pure form are: firstly, the starting material, silicon tetrachloride, is a liquid which is easily purified by conventional techniques such as fractional distillation and the associated compounds of the principal contaminants (mainly transition metal elements) of conventional glasses, being of relatively low volatility, may therefore be removed. Secondly, the glass is formed directly and requires no further processing in containers which may introduce impurities.

However, to form a convenient type of guiding structure a second material is required which has a different refractive index and which is sufficiently compatible with silica to be drawn into a composite fibre. As indicated in the previous section, it is not easy to make ultra-low-loss glasses by conventional methods and an alternative approach is so to modify the properties of silica by the addition of a second component as to increase or decrease the refractive index from that of the pure material. This high-silica glass might then be used with silica to produce a core and cladding combination. Several methods and materials have been tried successfully. Thus a silica/titania glass produced by flame hydrolysis [14] resulted in the first low-loss fibre, having an attenuation of 20dB/km. Another combination, having a refractive index lower than that of silica and hence suitable for use as a cladding, is a borosilicate glass [15] initially made by the oxidation of silane and boron trichloride. A new variation of the chemical vapour deposition technique involving the simultaneous oxidation and fusion of the components produced phosphosilicate [16] glass fibres and germania-doped [17] silica fibres, and there have also been reports of the doping of silica with alumina [18] and fluorine [19].

The modern method of making silica-based fibres will be illustrated by referring to the technique used at the University of Southampton with phosphosilicate fibres. It involves a homogeneous gas-phase reaction and produces a high deposition rate of clear phosphosilicate glass on the inside of a supporting tube which is subsequently collapsed and drawn into fibre. The starting materials, volatile chlorides, are vapourized, diluted with excess oxygen and passed through a silica supporting tube. A short hot zone at a temperature of about 1500 °C is traversed along the tube, and within the hot zone simultaneous oxidation and fusion of the chlorides occurs to produce a layer of glass, typically 10 to 15μm thick, on the inside of the walls of the tube.

Chemical vapour deposition of glasses is not new and has been used for some time in the semiconductor industry to deposit thin films of glass on substrates for use as passivation layers or diffusion sources. In order to avoid soot formation a heterogeneous (surface) reaction is made to occur at low temperatures and low reactant concentrations so

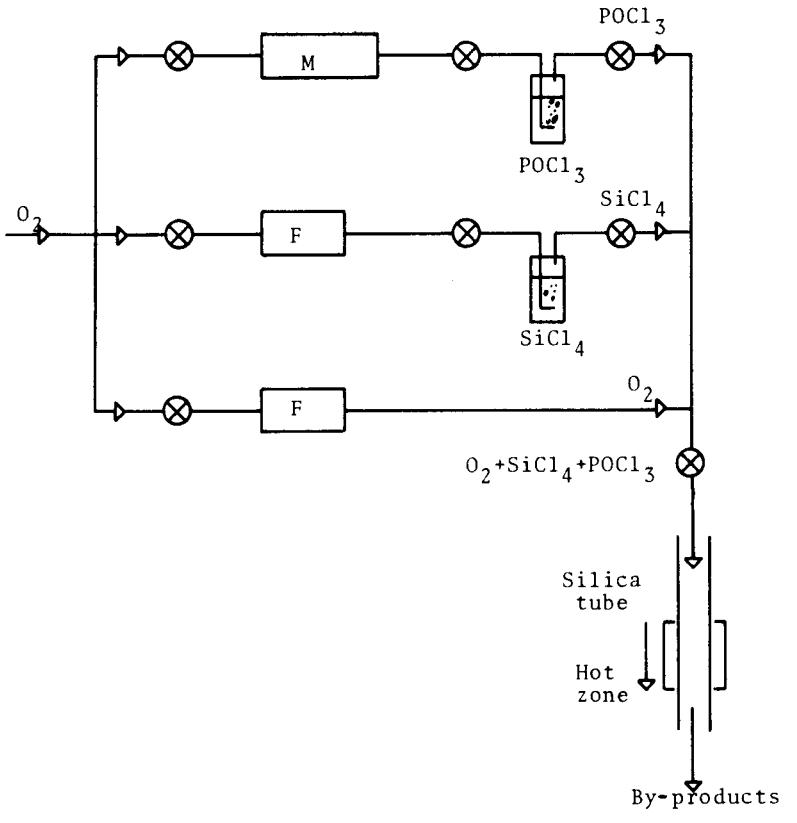

FIG.3. Schematic diagram of gas flow system for vapour deposition of glass. M denotes mass flow controller, F denotes flowmeter.

that the deposition rate is also low. In order to increase the deposition rate a technique has been developed which utilizes the homogeneous (gas phase) reaction at high temperature and with high reactant concentrations. A dense dispersion of small glass particles is formed and is fused onto the walls of the supporting tube at temperatures of ~1400°C, the precise value depending on the composition. The reaction does not involve the presence of hydrogen so that glass of very low OH content is obtained.

Silica and phosphorus pentoxide are derived by direct oxidation of silicon tetrachloride and phosphorus oxychloride vapours which are obtained by bubbling oxygen streams through the liquid chlorides (Fig.3). After fusion the oxides form a binary phosphosilicate glass in which the concentration of phosphorus pentoxide appears to follow that in the vapour phase. Excess oxygen is added to the two vapour-carrying oxygen

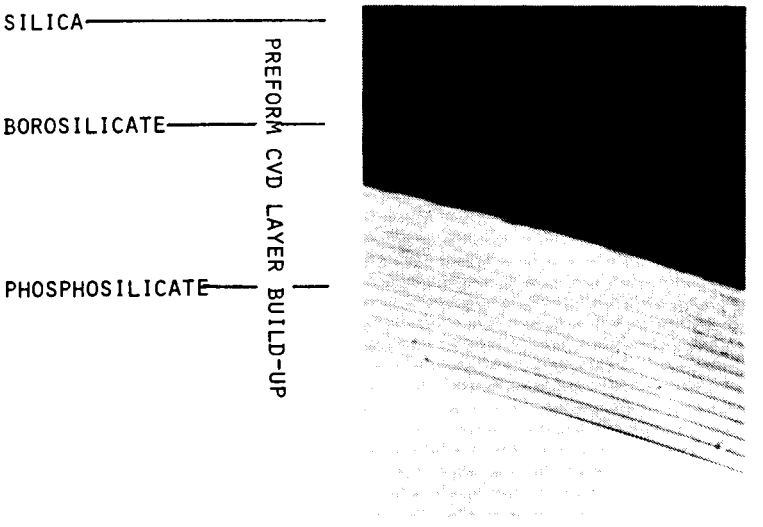

FIG.4. Cross-section of a portion of silica tube showing the deposited layers.

streams in order to control the deposition conditions, particularly the formation of the glass particle dispersion downstream from the hot zone. With little or no excess oxygen the glass particles tend to flocculate and stick to the colder tube walls in large feathery conglomerations which cause non-uniformities in the deposited layer after fusing by the traversing hot zone. An additional oxygen flow seems to cure this problem by cooling the centre of the tube.

The hot zone is provided by either a resistance furnace or a gas burner. A burner is convenient for rapid experimentation, but for more controlled deposition conditions a resistance furnace is preferable. The burner is moved along the tube and the hot zone temperature is adjusted so as to give a reasonably thick phosphosilicate glass layer (~10μm). The temperature at which the deposited materials fuse into a clear homogeneous layer lies between 1400°C and 1550°C. To achieve a fibre diameter/core diameter of, say, 2.5:1 from a 13mm bore silica tube of wall thickness 1.5mm requires a total deposition thickness on the walls of the tube of 300μm. Typically some 20 to 60 glass layers are laid down in a time of between two and four hours. A section of a deposited tube is shown in Fig.4.

In order to simplify fibre fabrication an automated machine has been developed to carry out the chemical vapour deposition process (Fig.5). The vertical silica support tube is rotated at about 50 rev/min and the gas mixture is fed into the top of the silica tube via a rotary swivel joint;

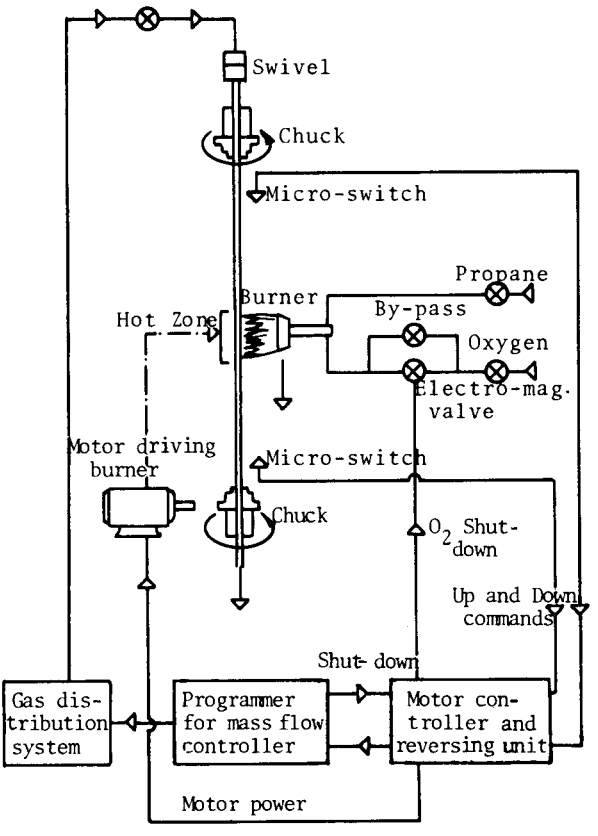

FIG.5. Diagram of automatic HCVD system.

the reaction by-products and excess reactants are extracted at the bottom. The extent of travel of the burner is limited by microswitches which also provide control signals for a programmer linked to the mass-flow controller to meter the flow of phosphorus oxychloride. This enables the phosphorus pentoxide concentration of each layer to be accurately pre-set, and thus a step approximation to any required concentration profile can be produced. During the subsequent preform-collapse and fibre-drawing stages some diffusion occurs between adjacent layers so that in the core of the fibre the concentration gradient, and thus the refractive index profile, becomes smoothed over distances comparable with the layer thickness, and the stepped structure is not observed.

The next stage in fibre fabrication is the collapse of the composite tube and deposition layer into a solid preform. It has been found that, whilst the quality of the core glass is governed by the deposition

process, the circularity of the final preform and concentricity of the core and cladding are mainly controlled by the collapsing process so that great care is therefore required during this stage. To effect collapse one end of the silica tube is heated to approximately 1900°C to lower the viscosity of the glass sufficiently for surface tension forces to initiate tube collapse. The hot zone, which is about 2cm long, is then slowly traversed along the rotating tube to produce a uniform partial collapse. Depending on the traverse speed, between two and four passes are normally sufficient to cause total collapse of the tube into a symmetrical cylindrical preform in a time of about 20 minutes.

The preform is drawn into a fibre on a precision fibre-drawing machine consisting of a crosshead drive to feed the preform into a furnace, from which the fibre is drawn onto a winding drum. To maintain constant fibre diameter over the entire pull, the preform feed rate and the fibre pulling rate are interlocked and have a stability of better than 0.1%. Conventional oxy-hydrogen flame furnaces are unsuitable for precision fibre-drawing purposes because of their lack of controllability and repeatability. A novel graphite resistance furnace has therefore been developed specifically for drawing fibres of high silica content. Furnace temperature control is achieved by use of an optical pyrometer (also developed at the University of Southampton) and a standard SCR power controller. To prevent oxidation of the graphite at the high temperatures required, the furnace is operated with a flow of argon through it.

Fibre drawing is usually carried out at a temperature of approximately 2040°C, and at pulling speeds in the range 0.75 to 1.5 m/s. Over lengths in excess of 1 kilometre the fibre diameter variation is less than ±2μm in 150μm and is generally due to taper in the preform. Fibre lengths of up to 4km, with core and overall diameters of 50μm and 140μm respectively, can be fabricated from a 1 metre length of preform 9mm in diameter. However, for experimental purposes fibres are fabricated in lengths of approximately 2km from somewhat shorter preforms.

The flexibility in fibre preform production which vapour deposition allows, particularly in the selection of core diameter, is such that single-mode fibres can be made very simply and quickly. For example[20], a single deposition pass at greater speed than normal in a Suprasil tube gives a single thin phosphosilicate glass layer. When the tube is collapsed and drawn in the normal way a fibre having a core of about 8μm diameter is produced, resulting in single-mode operation at the 0.633μm wavelength of the helium/neon laser. The transmission loss of 6.1dB/km is close to the fundamental attenuation limit of pure silica at this wavelength. The guidance property of the fibre is good since the low attenuation was measured with the fibre wound on a 48cm diameter drum. At longer wavelengths the loss increases because the

core diameter/wavelength ratio is smaller and the fields penetrate further into the cladding. If the core diameter were to be increased, but still kept within the limitation of single-mode operation, the attenuation in the infra-red would be less.

3.3. Summary of fibre properties

It is possible to make fibres of compound glasses in long continuous lengths by the concentric crucible process. The numerical apertures attainable are in the region of 0.2 to 0.3 so that they have reasonable resistance to microbending loss and an acceptable launching efficiency from a light-emitting diode. On the other hand, while in principle the loss can be reduced to ~3dB/km, the best values achieved so far[8] are ~7dB/km in long (0.9km) lengths. Furthermore, the cost of providing raw materials of a much higher degree of purity may be high. SELFOC fibres[12] with losses of 7dB/km have also recently been reported, but under very precise launching conditions.

Of the fibres produced by vapour deposition those having a phosphosilicate glass core and a borosilicate cladding give an ultra-low loss[21] of 2dB/km at 0.9μm and 1dB/km at 1.06μm with a numerical aperture of up to 0.25. Germania fibres[2] have reported losses of ~ 4dB/km

TABLE I. PROPERTIES OF VARIOUS FIBRES

Fibre	Attenuation at 0.9 μm (dB/km)	Fibre N.A.[a]	Core dia. (μm)	Ref.	Excitation N.A.[a]
Sodium borosilicate	~ 6.5		10–20	[8]	0.07
New SELFOC	~ 7			[12]	Plane wave
Phosphosilicate	3	0.18	50–100	[16]	0.18
Phosphosilicate core/ borosilicate cladding	2	0.25	50–100	[21]	0.23
Germania	4	0.23	35	[2]	Not known
Silica core/ borosilicate cladding	2.5	0.17	18	[2]	Not known
Compound glass	9			–	Not known

[a] N.A. = numerical aperture.

at 0.9μm at a numerical aperture of 0.23. Higher numerical apertures of up to 0.35 are possible but at the cost of a considerable rise in attenuation to about 15dB/km. By enclosing a pure silica core in a borosilicate cladding a loss of ∿2.5dB/km has been obtained[2] at 0.9μm with a numerical aperture of 0.17. These various results are summarized in Table I.

4. CONCLUSIONS

Ten years ago it was estimated that it is necessary to reduce fibre transmission losses below 20dB/km in order to produce an economically viable optical fibre transmission system, but this target seemed to be a very distant and difficult one. Today it is relatively commonplace and has been met by a range of materials and configurations. In fact it is now realistic to assume that optical fibre cables will shortly be available with transmission losses of about 5dB/km. A number of problems remain to be solved, apart from the ones discussed so far. For example, it is difficult to make fibres of the desired refractive index profile with low-melting-point glasses, and vapour-deposited fibres usually exhibit a dip in refractive index on the axis. Nevertheless, pulse dispersions with non-ideal fibres have given[20] experimental values for pulse dispersion of 1ns/km with an injection laser and 0.1ns/km with a Gaussian beam, corresponding roughly to bandwidths over 1km of 1GHz and 10GHz, respectively.

REFERENCES

[1] PINNOW, D.A., RICH, T.C., OSTERMEYER, F.W., DiDOMENICO, M., Fundamental optical attenuation limits in the liquid and glassy state with application to fibre optical waveguide materials, Appl. Phys. Lett. **22** (1973) 527.
KECK, D.B., MAURER, R.D., SCHULTZ, P.C., On the ultimate lower limit of attenuation in glass optical waveguides, Appl. Phys. Lett. **22** (1973) 307.

[2] FRENCH, W.G., MacCHESNEY, J.B., O'CONNOR, P.B., TASKER, G.W., Optical waveguides with very low losses, Bell Syst. Tech. J. **53** (1974) 951.

[3] KAISER, P., Drawing-induced colouration in vitreous silica fibres, J. Opt. Soc. Am. **64** (1974) 475.

[4] SIGEL, G.H., Jr., EVANS, B.D., Effects of ionising radiation on transmission of optical fibres, Appl. Phys. Lett. **24** (1974) 410.

[5] SCHROEDER, J., MOHR, R., MACEDO, P.B., MONTROSE, C.J., Rayleigh and Brillouin scattering in K_2O-SiO_2 glasses, J. Am. Ceram. Soc. **56** (1973) 510.

[6] GARDNER, W.B., GLOGE, D., "Microbending loss in coated and uncoated optical fibres", paper presented at Topical Meeting on Optical Fibre Transmission, Williamsburg, VA, 1975.

[7] NEWNS, G.R., PANTELLIS, P., WILSON, J.L., UFFEN, R.W., WORTHINGTON, R., Absorption losses in glasses and glass fibre waveguides, Opto-electron. **5** (1973) 289.

[8] NEWNS, G.R., private communication.
[9] SCOTT, B., RAWSON, H., Low-loss glasses for optical fibre communications, Glass Technol. **14** (1973) 115.
SCOTT, B., RAWSON, H., Preparation of low-loss glasses for optical fibre communication systems, Opto-electron. **5** (1973) 285.
[10] PAYNE, D.N., GAMBLING, W.A., The preparation of multimode glass- and liquid-core optical fibres, Opto-electron. **5** (1973) 293.
[11] REID, A.M., HARPER, D.W., FORBES, A., British Patent No.50543 (1969).
[12] KOIZUMI, K., IKEDA, Y., "Low-loss light-focussing fibres made by a continuous process", paper presented at First European Conf. on Optical Fibre Communication, London, 1975.
[13] KAO, K.C., HOCKHAM, G.A., Dielectric-fibre surface waveguides for optical frequencies, Proc. IEEE **113** (1966) 1151.
[14] GLOGE, D., Optical fibers for communication, Appl. Opt. **13** (1974) 249.
[15] KATO, D., Fused-silica core glass fiber as a low-loss optical waveguide, Appl. Phys. Lett. **22** (1973) 2.
FRENCH, W.G., PEARSON, A.D., TASKER, G.W., MacCHESNEY, J.B., Low-loss fused silica optical waveguide with borosilicate cladding, Appl. Phys. Lett. **23** (1973) 338.
[16] PAYNE, D.N., GAMBLING, W.A., New silica-based low-loss optical fibre, Electron. Lett. **10** (1974) 289.
[17] BLACK, P.W., IRVEN, J., BYRON, K., FEW, I.S., WORTHINGTON, R., Measurements on waveguide properties of GeO_2-SiO_2-cored optical fibres, Electron. Lett. **10** (1974) 239.
MacCHESNEY, J.B., O'CONNOR, P.B., PRESBY, H.M., A new technique for the preparation of low-loss and graded-index optical fibres, Proc. IEEE **62** (1974) 1280.
[18] KOBAYASHI, S., NAKAGOME, H., SHIMIZU, N., TSUCHIYA, H., IZAWA, T., Low-loss optical glass fibre with Al_2O_3-SiO_2 core, Electron. Lett. **10** (1974) 410.
[19] MÜHLICH, A., RAU, K., SIMMAT, F., TREBER, N., "A new doped synthetic fused silica as bulk material for low-loss optical fibres", paper presented at First European Conf. on Optical Fibre Communication, London, 1975.
[20] GAMBLING, W.A., PAYNE, D.N., "Some experimental aspects of propagation in optical fibres", invited paper, presented at First European Conf. on Optical Fibre Communication, London, 1975.
[21] GAMBLING, W.A., PAYNE, D.N., HAMMOND, C.R., NORMAN, S.R., Optical fibres based on phosphosilicate glass, Proc. IEEE (in press).