Fabrication and evaluation of single mode fibres

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The homogeneous chemical vapour deposition technique, normally used for the manufacture of multimode fibres, has been applied to the fabrication of low loss monomode fibres for operation in the 0·6 to 1·6 μm region. The process enables fibres having cores based on phosphosilicate, germanosilicate, and silica glasses to be drawn in lengths up to 5 km. Because an appreciable amount of energy lies outside the core, a low loss cladding of borosilicate glass must also be deposited. A detailed description of the preform deposition and characterisation is presented, and the fibre drawing process is outlined. Core diameters range between 4 and 10 μm for single mode operation in the 0·6 to 1·5 μm region, whilst the index difference between core and cladding is typically 0·3 %. Losses of 2·5 dB/km have been achieved at 1·06 μm.

Fibre characterisation by observation of the far field radiation pattern yields V value, core diameter, and index difference directly. An alternative technique involving loss measurements over a range of wavelengths about the cut off point is prone to serious inaccuracy.

Finally, single mode fibres with extremely low birefringence (less than 3°/m linear retardance) have been developed for instrumentation applications.

The development of the homogeneous chemical vapour deposition technique has made it possible to fabricate multimode fibres with ultra low attenuation in the 0·8 to 1·6 μm region.[1, 2] Intermodal dispersion has been greatly reduced by grading the refractive index profile within the fibre core in a near parabolic manner and, by careful process control, bandwidths in excess of 2 GHz can be achieved over 1 km.[4] However, to achieve such high bandwidths over long distances without repeaters it will be necessary to utilise single mode fibres. The monomode fibre has the distinct advantage that intermodal dispersion is eliminated, and bandwidth is effectively limited only by material and mode dispersion effects; hence bandwidths of 100 GHz km and more may be realised. Furthermore the technique is readily adapted to the fabrication of long lengths of low loss single mode fibre[1, 3, 5] particularly in the 1·3 μm region where both intrinsic loss and material dispersion effects fall to a minimum.

The present paper outlines the various stages of fibre fabrication and describes some of the measurement techniques used to evaluate both single mode fibres and the preforms from which they are drawn. In addition the polarisation properties of single mode fibres exhibiting remarkably low birefringence are reported.

Preform fabrication and characterisation

The homogeneous chemical vapour deposition technique for fabricating multimode fibres is well known and has been documented elsewhere.[1] By using high purity starting materials and taking care to avoid contamination during deposition, attenuations of 0·5 dB/km at 1·2 μm and 0·2 dB/km at 1·6 μm have been observed,[2, 3] corresponding to impurity levels of less than 1 part in 10^8 in the deposited core glass.

The techniques for producing preforms for single mode fibres have a number of distinct differences from the multimode case. Firstly, in the monomode fibre a considerable proportion of the guided power travels within the cladding. Hence to avoid excessive absorption loss the cladding material most be of comparable purity to the core, and a low loss cladding must be deposited. Kapron & Lukowski[6] have presented design data for the required cladding thickness and have shown that a cladding:core diameter ratio of 4:1 should suffice to contain the guided energy within a low loss material. Kawachi *et al.*[7] have considered the diffusion of hydroxyl ions from the silica tube into the cladding, and suggest a barrier cladding: core diameter ratio of 5:1, an area ratio of 24:1. Thus, in contrast to the multimode case, the deposition of the cladding layers will occupy the major portion of the deposition process. Since the refractive index of the cladding must not be greater than that of the silica substate, the choice of cladding material is limited to silica, borosilicate, or fluorosilicate glasses. Borosilicate glass is the most suitable since it allows a high deposition rate without unacceptable shrinkage of the support tube.

Secondly, for true single mode operation the parameters characterised by the core diameter and refractive index difference in the fibre must normally satisfy the condition $V \leqslant 2{\cdot}405$, where the normalised frequency, V, is defined by

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

* On secondment from Pirelli General Cable Works.

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where a is the core diameter (μm), λ is the wavelength of operation (μm), and n_1 and n_2 are the indices of the core and cladding respectively.[8]

The choice of core size and index difference is dictated by the trade off between high index difference, small core fibres which have good microbending performance, and large core fibres with small index difference in which jointing tolerances are somewhat eased. In practice, an index difference of $\Delta = 0{\cdot}3\%$ (numerical aperture $= 0{\cdot}12$) provides good mode confinement at $V = 1{\cdot}6$ and above. The doping levels are therefore very much lower than those in multimode fibres where typically $\Delta = 1{\cdot}3\%$ (numerical aperture $= 0{\cdot}24$).

A single mode preform with a germanosilicate core and borosilicate cladding is formed as follows: A precision bore, 14 mm diameter Heraeus WG silica tube with a wall thickness of 1·5 mm was thoroughly cleaned, lightly etched in HF, rinsed in water then acetone, and dried before being fire polished at 1 700 °C by two passes at 10 cm/min to provide a pristine inner surface. High purity $SiCl_4$, BBr_3, and $GeGl_4$ were used as the source materials. Eighteen cladding layers of borosilicate glass containing 3 mol% B_2O_3 were deposited at 1 650 °C. A single layer of GeO_2 doped silica was deposited as the core at 1 650 °C. The composite tube was then collapsed by three passes at 5 cm/min of a hot zone at 1 850 °C to form a rod 40 cm long with a diameter of 8·05 mm. Figure 1 shows a transverse cross section of the preform viewed under transmitted light. The core and cladding layers can be clearly distinguished inside the silica supporting structure, and it can be seen that the circularity and concentricity of the preform are excellent. The diameter over the borosilicate cladding in the preform was 4·0 mm whilst the core diameter was 0·9 mm.

Before the draw down ratio for fibre drawing can be calculated it is necessary to evaluate the refractive index difference between core and cladding. One technique involves the laborious polishing of a thin slice of preform which is later examined by interference microscopy.[5] An alternative, and very simple, technique is to draw a short section of rod from one end of the preform, prepare its ends by cleaving, and measure directly the numerical aperture of the rod from its far field radiation pattern. Having established the core diameter and index difference in the preform, the draw down ratio is readily calculated to achieve the desired V value at the selected operating wavelength. Because the partially drawn rod is a highly multimode structure it can also be evaluated using techniques normally reserved for multimode fibres: for example, the refractive index profile in the preform can be evaluated using the near field scanning technique.[9]

Figure 2 shows the near field power distribution measured in a short section of partially drawn preform approximately 2 mm in diameter, with a core diameter of 192 μm and a measured numerical aperture of 0·12; the V value of 131 shows that the rod was highly multimode at the measuring wavelength of 0·55 μm. The solid curve in the figure shows the refractive index profile obtained by applying leaky mode correction factors to the near field distribution.

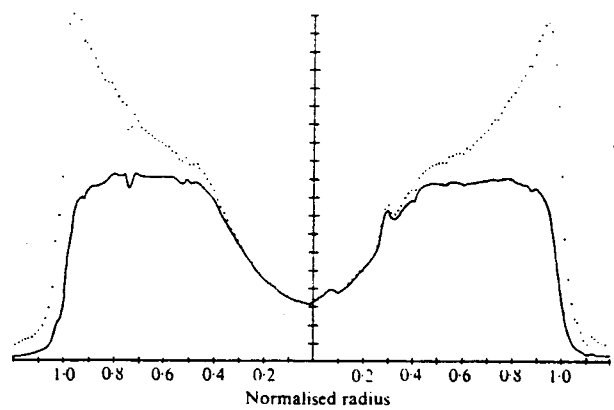

Figure 2. *Near field power distribution (dotted curve) and refractive index profile (solid curve) of a GeO_2 doped core in a single mode preform. Length 7·2 cm, radius 96 μm, numerical aperture 0·12, wavelength 0·55 μm, V = 131·6, x = 0·05*

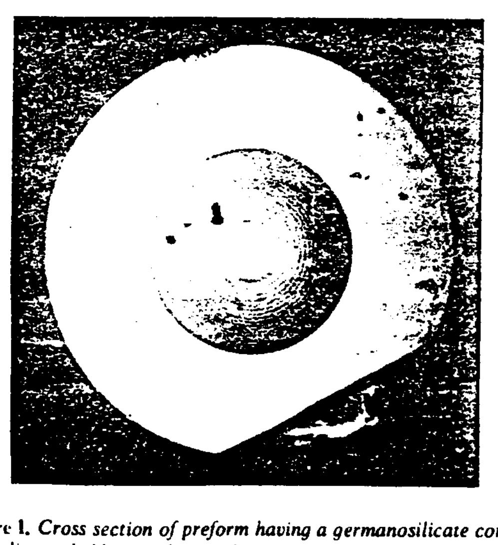

Figure 1. *Cross section of preform having a germanosilicate core and borosilicate cladding within a silica support structure*

As would be expected, the preform has a nearly stepped refractive index profile with an axial dip due to diffusion of dopant from the inner core layer during collapse. The relative index difference between the depleted axial region and the edge of the core is some 66% of the total index difference, and the depleted zone occupies 40% of the total core diameter. Gambling *et al.*[10] have studied the effect of a refractive index dip at the centre of the core in single mode fibres, and have shown that the dip yields a reduction in the degree of mode confinement, the energy spreading from the centre of the core towards the edge. However, in practical terms they conclude that for an index distribution of the form shown in Figure 2, the propagation characteristics are almost identical with those of the step index fibre. Of course, dopant depletion may be eliminated by using a pure silica core or by creating a dopant rich atmosphere in the closure zone during collapse.

Fibre drawing

The preform is subsequently drawn into a monomode fibre using a conventional fibre drawing machine incorporating a graphite resistance-heated furnace and equipment for measuring fibre diameter.[1] It is usually necessary to insert the preform into one or more silica tubes to increase the overall diameter of the fibre to a reasonable value. For example, if the preform of Figure 1 were to be directly drawn into a fibre with $V = 2{\cdot}4$ at 1·2 μm (requiring a core diameter of 7·6 μm), then the overall fibre diameter would be only 68 μm: by nesting the preform inside another tube, a 125 μm fibre may be obtained. More than 5 km of fibre can be drawn from the single preform. An on line coating of soft silicone rubber is applied to reduce the effect of microbends and to preserve the high inherent strength of the fibres.

Figure 3 shows the cross section of a fibre designed for monomode operation at 0·633 μm. The fibre, GSB2, drawn from the preform of Figure 2, has a germanosilicate core in a borosilicate cladding, supported within a silica substrate. The core diameter, calculated from the dimensions of the collapsed preform and the fibre drawing ratio, is 4 μm, the cladding diameter is 18 μm, and the overall fibre diameter is 90 μm. The index difference between core and cladding, measured in the preform, was $\Delta = 0{\cdot}33\%$. Hence, assuming that no diffusion of the dopant occurs during the drawing of the fibre, the V value at 0·633 μm is 2·4.

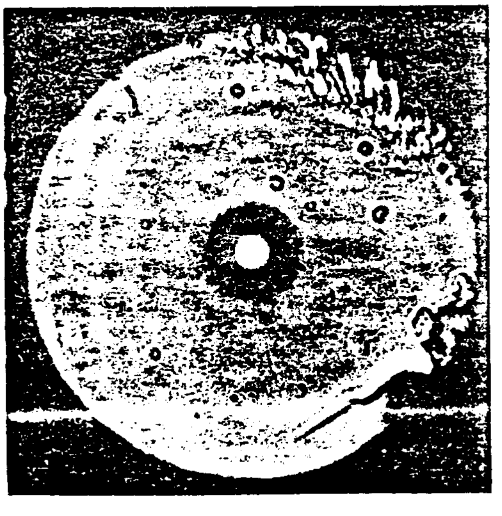

Figure 3. *Cross section of single mode fibre with V = 2·4 at 0.633 μm. Core diameter 4 μm, cladding diameter 18 μm, overall diameter 90 μm*

Fibre characterisation

Although the V value may be inferred from the preform characteristics and the fibre drawing parameters, uncertainties exist owing to the possible diffusion of dopants between core and cladding during drawing. It would be very useful, therefore, to have a method of evaluating both the V value and core diameter (and hence index difference) directly from the fibre. A very simple technique, involving only the observation of the far field radiation pattern from the fibre, has been developed by Gambling *et al.*[11] at Southampton University. Inspection of the far field pattern from a single mode fibre reveals a main lobe with additional sidelobes as shown in Figure 4. Theoretical analysis shows that the power distribution within the main lobe and the angular width to the first minimum depend solely upon a, n_1, n_2, and λ. By measuring the half power width of the main lobe and the width of the first minimum, the unknown fibre parameters can be read directly from a set of universal curves.

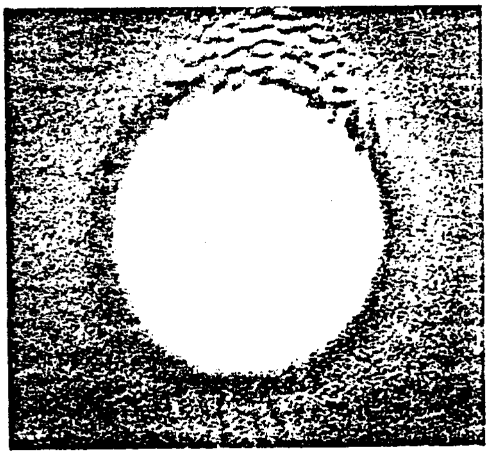

Figure 4. *Far field radiation pattern from the fibre shown in Figure 3 when excited by a He–Ne laser operating at 0·633 μm*

The experimental procedure begins by preparing a short length of fibre and exciting one end using a suitable laser source. The output end of the fibre is positioned perpendicular to, and at a known distance from a traversing photodiode. The diode is translated across a diameter of the far field pattern and the half power and first minimum positions are recorded. The far field pattern in Figure 4 was obtained from fibre GSB2 when excited by a He–Ne laser operating at 0·633 μm. The angles of the half power point and the first minimum were 2·1 and 9·8° respectively, giving a V value of $2{\cdot}4 \pm 0{\cdot}05$, in excellent agreement with the value deduced from the preform. The core diameter on the other hand was 5 μm; it is thought that this discrepancy is due to an enlargement of the mode spot size caused by the axial dip in refractive index and consequent reduction of the angular width of the half power point from which the core size is deduced; see Figure 3(b) of Reference 10. Furthermore, examination of etched fibre ends using a scanning electron microscope reveals that the diffusion of GeO_2 during drawing is negligible.

An alternative technique for determining V values reported by Katsuyama *et al.*[12] consists of measuring the loss peaks corresponding to the cut off wavelengths of the higher order modes in a short length of curved fibre. However, whilst this may be a convenient technique for estimating V, no information on Δ or a is obtained. In fact, it is prone to considerable inaccuracy due to the effects of large scale curvature as well as microbending.[13] To illustrate this point, Figure 5 shows the wavelength dependence of excess loss due to a 1·5 cm radius bend in fibre GSB2. The loss peak at 500 nm corresponds to the loss of the LP_{11} mode at the bend, while the sharp falling edge at 525 nm represents the point at which the mode no longer propagates in either the bent or straight fibre. If, in the straight fibre, the LP_{11} mode was lossless up to cut-off and very lossy thereafter, the wavelength at which the loss curve returns to zero would be that corresponding to $V = 2{\cdot}405$. However, in practice the apparent cut off differs appreciably from the true cut off wavelength, the magnitude of the error depending on the degree of microbending present.[13] Katsuyama's method indicates that fibre GSB2 apparently has a cut off of $V_c = 2{\cdot}405$ at 530 nm compared with the true value of $V_c = 2{\cdot}405$ at 633 nm measured using the far field observation technique. Finally it is worth noting in Figure 5 that the rapid increase in loss at 725 nm is due to the increasing bend loss of the fundamental HE_{11} mode with decreasing V value.

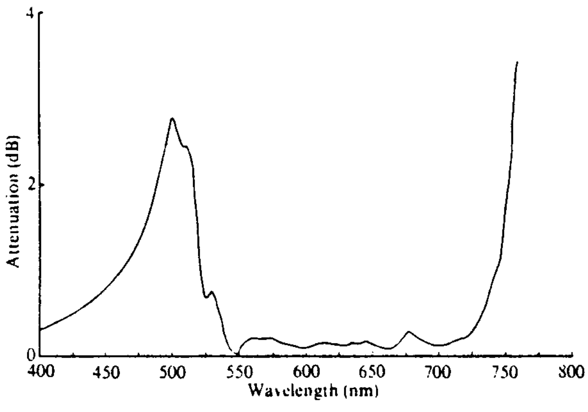

Figure 5. *Wavelength dependence of excess loss due to a 1·5 cm radius bend in single mode fibre*

Figure 6 shows the loss spectrum of a 300 m length of monomode fibre with a phosphosilicate core in borosilicate cladding. The attenuation was measured using phase lock techniques with a tungsten halogen lamp and grating monochromator as light source, and with a Ge photodiode detector. Thermal noise in the detector, combined with the low launch power into the fibre, resulted in a measurement accuracy of $\pm 0{\cdot}2$ dB. The fibre was characterised by an 8 μm core diameter, a barrier cladding:core diameter ratio of approximately 4:1, an overall diameter of 118 μm, and a core/cladding index difference of $\Delta = 0{\cdot}24\%$.

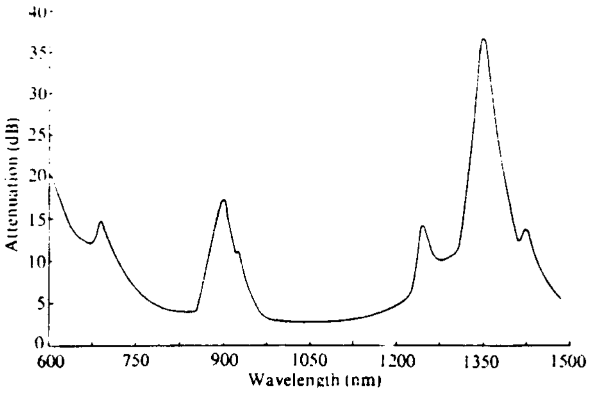

Figure 6. *Loss spectrum of a fibre with a phosphosilicate core and borosilicate cladding. Cut off wavelength 1·0 μm*

The cut off wavelength of the fibre was 1·0 μm, and the V values at 0·85, 1·2, and 1·5 μm were 2·8, 2·0, and 1·6 respectively. Apart from the loss peak centred at 0·9 μm, the attenuation is less than 5 dB/km over the range 0·75 to 1·2 μm, with a minimum value of 2·6 dB/km at 1·05 μm. The loss peaks at 0·9 and 0·7 μm are due to the cut off of the second and third order modes respectively. It is worthwhile noting that an extrapolation of the loss measured in a short length to a 1 km length introduces a systematic error in the height of these peaks. For example, the cut off of the second order modes produces a discrete loss of 4 dB independent of length which, on extrapolation to a 1 km length, becomes a 13 dB peak. Similarly the peak at 0·7 μm indicates a 3 dB/km excess loss rather than a discrete 1 dB loss.

Although the OH absorption loss at 0·95 μm is barely detectable, the hydroxyl bands at 1·24 and 1·36 μm introduce additional losses of 13 and 38 dB/km respectively, which are considerably higher than those commonly found in our multimode fibres (1 and 12 dB/km). It is probable that the absorption is due to hydroxyl diffusion into the barrier cladding, in conjunction with the increased field penetration into the cladding as V decreases with increasing wavelength. By increasing the cladding thickness and increasing the cut off wavelength it is possible to reduce the hydroxyl absorption to a low level.[7]

Single mode fibres with very low birefringence

Monomode fibres are likely to find a number of applications in instrumentation where their ability to transmit coherent polarised light is most attractive. One application involves the measurement of current by monitoring the Faraday rotation of polarised light propagating in a monomode fibre wound around a power transmitting high voltage bus bar.[14] The sensitivity of such a device is limited by the residual birefringence present within the fibre caused, for example, by anisotropic stress within the fibre and core ellipticity. The latter has the effect of creating fast and slow axes of propagation of the two orthogonally polarised components of the fundamental HE_{11} mode, and the fibre thus acts as a linear retarder, the state of polarisation varying periodically between linear and circular along the fibre. A fibre which is capable of maintaining a defined polarisation state during transmission would be particularly useful in this device. However, practical fibres exhibit a periodicity of polarisation which varies typically from a few centimetres to a metre.

A systematic study of the effects of core ellipticity and intrinsic stress within monomode fibres has been undertaken[15] and fibres exhibiting remarkably low birefringence have been produced. Figure 7 shows the phase retardation as a function of length in three silica based fibres in which core ellipticity alone would be expected to produce a retardation of less than 10°/m. Fibres VD214 and SV1, silica core, borosilicate clad fibres produced by homogeneous chemical vapour deposition and the rod in tube technique respectively, exhibit significantly more birefringence than would be expected. However, in fibre GSB2 the specific retardation has been reduced to less than 3°/m (see Figures 2 and 3) by minimising the effects of the mismatch between the thermal properties of the core and the cladding glasses whilst maintaining a high degree of circularity, giving a periodicity in excess of 120 m. Work is continuing to characterise this fibre and a more detailed description of the properties of the fibres and experimental techniques are given in a separate publication.[16]

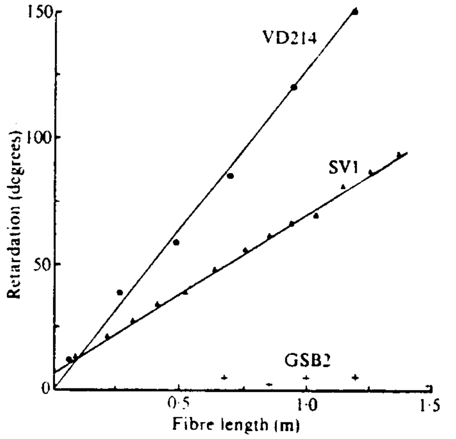

Figure 7. *Phase retardation in three single mode fibres. Specific retardation values are: VD214, 126° m⁻¹; SV1, 66° m⁻¹; and GSB2, 3° m⁻¹*

Conclusions

A technique for the fabrication of low loss single mode fibres has been described. Preforms are produced using the homogeneous chemical vapour deposition technique commonly used for the fabrication of multimode fibres. The process enables monomode fibres having cores based on phosphosilicate, germanosilicate, and silica glasses to be drawn in lengths up to 5 km. A low loss cladding of borosilicate glass is deposited to confine the optical power within a low loss region. The index difference between core and cladding is typically 0·3% and core diameters range between 4 and 10 μm for single mode operation in the 0·6 to 1·5 μm region. Losses of 2·5 dB/km have been achieved at 1·06 μm, and further improvements are certainly possible.

Fibre characterisation can be performed by simple measurements on the far field radiation pattern which directly yield not only the V value but also the core diameter and index difference in the fibre. An alternative technique involving loss measurements over a range of wavelengths about the cut off point is prone to serious inaccuracy and care must be taken in interpreting the results.

Single mode fibres with extremely low birefringence have been developed for instrumentation applications. By paying careful attention to the core and cladding circularity and by minimising anisotropic stress within the fibre, the linear retardation has been reduced to less than 3°/m.

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