

Optical fibres based on phosphosilicate glass

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Indexing terms: Fibre optics, Glass, Vapour deposition

Abstract

The homogeneous chemical vapour-deposition technique, developed for the preparation of phosphosilicate glass fibres, is described. The properties of the binary phosphosilicate glass are outlined and details of preform fabrication and fibre drawing are given. Multimode graded-index fibres have been produced in lengths up to 4km, with numerical apertures up to 0.25, attenuations as low as 2 dB/km and with pulse dispersions of below 1ns/km depending on the source used. Single-mode fibres have also been made with attenuations close to that of pure bulk silica at the design wavelength and with a pulse dispersion of less than 0.1 ns/km.

1 Introduction

When, in their classic paper¹ of 1966, Kao and Hockham proposed the use of clad 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 or plasma-arc oxidation of silicon tetrachloride, was available having a bulk transmission loss of less than 5 dB/km. Two of the reasons for the availability of silica in very pure form are first that 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 is sufficiently compatible with silica to be drawn into a composite fibre. It is not easy to make ultra-low-loss glasses by conventional methods and an alternative approach is to modify the properties of silica by the addition of a second component to increase or decrease the refractive index from that of pure silica. 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 hydrolysis² resulted in the first low-loss fibre, having an attenuation of 20 dB/km. Another combination, having a refractive index lower than that of silica and hence suitable for use as a cladding, is a borosilicate glass initially made³ 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 glass⁴ fibres and germania-doped⁵ silica fibres; there have also been reports of the doping of silica with alumina⁶ and fluorine⁷.

The present paper describes both the properties of fibres based on phosphosilicate-glass cores and the method, developed in the Southampton laboratories, for their manufacture. The technique involves a homogeneous gas-phase reaction and produces a high deposition rate of clear phosphosilicate glass on the inside of a tube which is subsequently collapsed and drawn into fibre.

The starting materials, volatile chlorides, are vapourised, diluted with excess oxygen and passed through a silica supporting tube which is traversed by a short hot zone at a temperature of about 1500°C. Within the hot zone, simultaneous oxidation and fusion of the chlorides occurs to produce a layer of glass, typically 10–15µm thick, on the inside walls.

2 Phosphosilicate glasses

The addition of another oxide component to silica to form a binary glass by homogeneous chemical vapour-deposition requires (a) that a volatile halide of the proposed additive exists which is preferably a liquid at room temperature and (b) that this halide reacts spontaneously with oxygen at an elevated temperature, which is below that of the softening point of the silica substrate (~1500°C). These two requirements restrict the choice of glass system considerably but we have found that P₂O₅ is suitable, producing very low-loss fibres although, as will be shown, the technique is applicable to other

oxides, either separately or in combinations with that of phosphorus.

The P₂O₅/SiO₂ glass system has not been extensively studied as it is difficult to make by conventional means because of the volatility of phosphorus pentoxide. Furthermore, P₂O₅ is not an obvious choice as a component which can be added to silica since it sublimes at 300°C, is hygroscopic and has an expansion coefficient some 25 times larger. However, in combination with silica it forms a stable glass having an expansion coefficient compatible with that of pure silica at least for concentrations up to about 25m/o. The resultant glass shows no tendency either to phase separation or to devitrification and preliminary measurements indicate a good resistance to attack by water.

The variation of the refractive index of the deposited phosphosilicate glass is shown in Fig. 1 as a function of the equivalent proportion of P₂O₅ in the gas stream. The experimental points were obtained from measurements of the numerical aperture of a series of fibres fabricated using different gas phase ratios of POCl₃ to SiCl₄. Microprobe analysis and etch-rate tests have shown that, at least for P₂O₅ contents below 10m/o, the deposited glass has a similar composition to that expected from the ratio of the reactants in the vapour. Thus, the data for the lower P₂O₅ concentrations fit fairly closely to the dashed curve which is drawn assuming a purely additive and linear relationship between the refractive indices of silica (1.458) and pure phosphorus pentoxide (1.52). However, the departure at higher concentrations may either represent inherent nonadditivity in the P₂O₅/SiO₂ system, or, more probably, it may indicate that the deposited-glass composition no longer reflects that in the reacting gases.

It may also be seen from the figure that at a P₂O₅ concentration of 24 m/o the refractive index differs from that of silica by 0.85% corresponding to a numerical aperture of 0.19. At this concentration, corresponding to a relative weight of 43% P₂O₅, there is also a difference in the expansion coefficient and the viscosity compared with silica. The expansion coefficients of P₂O₅ and SiO₂ are, respectively, 140 × 10⁻⁷ C⁻¹ and 5.5 × 10⁻⁷ C⁻¹ and the composite phosphosilicate glass will therefore have an increasing expansion coefficient with P₂O₅ content. This fact ultimately limits the amount of P₂O₅ which can be incorporated into the fibre, as the stress resulting from the expansion mismatch between the deposited layers and the silica substrate eventually causes spontaneous fracture of the preform.

The maximum concentration of germania (60 × 10⁻⁷ C⁻¹) and boric oxide (150 × 10⁻⁷ C⁻¹) which can be incorporated into silica is ultimately limited in a similar way.

A particular advantage of the phosphosilicate combination is that even small admixtures of P₂O₅ lower the viscosity of silica appreciably, enabling the soot formed in the gas-phase reaction to fuse into a clear glass layer at a temperature well below that at which the silica tube deforms. At a high P₂O₅ content, however, the viscosity becomes so low that care must be taken to prevent deformation of the core during the preform collapse stage.

3 The homogeneous chemical vapour-deposition technique for phosphosilicate fibres

Chemical vapour deposition of glasses is not new, it 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. For this application, soot formation is avoided by employing a heterogeneous (surface) reaction at low temperatures and low reactant concentrations with the result that the deposition rate is also low. To increase the deposition rate we have developed a technique

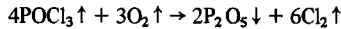
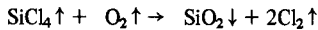
Paper 7674E, first received 18th December 1975 and in revised form 27th February 1976

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which utilises the homogeneous (gas-phase) reaction at high temperature and with high reactant concentrations. A dense dispersion of small glass particles is produced and is fused onto the walls of the supporting tube at temperatures of approximately 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 according to the following equations:



After fusion the oxides form a binary phosphosilicate glass in which the concentration of phosphorus pentoxide appears to follow that in the vapour phase. The vapours are collected by bubbling oxygen streams through temperature-controlled Dreschel bottles containing the liquid chlorides, Fig. 2A. It would be possible to use phosphorus trichloride instead of the oxychloride but an inert carrier gas would be necessary as PCl_3 oxidises to POCl_3 in the presence of oxygen with an accompanying rise in temperature. This would cause a temperature, and thus a vapour pressure, fluctuation in the Dreschel bottle with the risk of instability in the ratio of the deposited oxides; POCl_3 is, therefore, rather more convenient requiring, as it does, only one carrier gas. The ratio R of the oxygen flow rate through the phosphorous oxychloride to that through the silicon tetrachloride is related to the molar fraction M of phosphorus pentoxide in the vapour phase by

$$R = K \left(\frac{M}{1-M} \right)$$

where K is a constant which depends on the vapour pressures of the liquid chlorides. It is assumed that the oxygen streams are fully saturated with vapour. At 20°C the vapour pressure of silicon tetrachloride is 193 torr, that of phosphorous oxychloride is 28 torr so that $K = 17.3$. Thus, R lies between 0.17 and 4.45 for M ranging

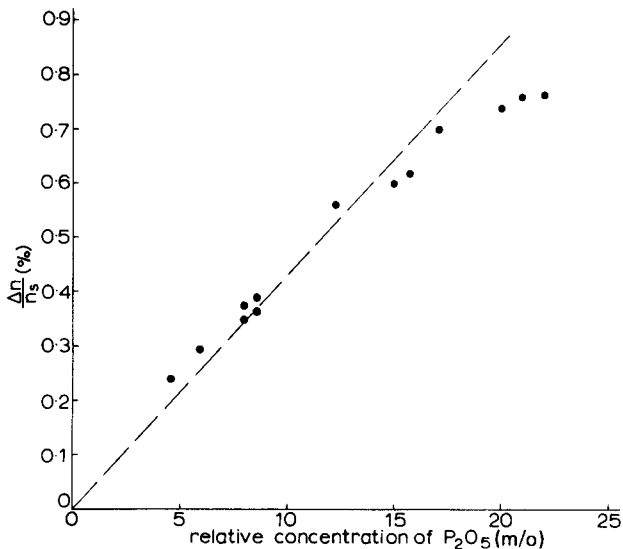


Fig. 1 Increase in refractive index Δn compared with silica n_s for phosphosilicate glass as the relative proportion of P_2O_5 is raised

from 1 m/o to 20 m/o. In practice, M is most easily controlled by holding the oxygen flow rate through the silicon tetrachloride constant and varying the oxygen flow through the phosphorous oxychloride. The rate of glass deposition has been studied for the above conditions and for our particular tube dimensions and equipment in which the hot-zone length is about 5 cm. A typical result is given by Fig. 3 which shows the variation in deposited layer thickness, produced in a single pass of the hot zone, as a function of traverse speed and reactant concentration expressed as the flow rate of SiCl_4 for a given $\text{P}_2\text{O}_5/\text{SiCl}_4$ ratio of 10 m/o. It can be seen, first that for any given traverse speed the layer thickness may be increased by increasing the reactant concentrations. Secondly, the thickness of an individual layer may be increased by reducing the traverse speed; but, on the other hand, fewer traverses can then be made in a given period of time. Thus, while the traverse speed affects the individual layer thickness it has little effect on the overall deposition rate of a

multilayer structure which is controlled mainly by the reactant concentrations. The best flow rates and traverse speeds have been determined experimentally and typical values of 100 ml/min for the oxygen flow through the silicon tetrachloride and 120 mm/min respectively, give a very adequate deposition rate of a 10 μm thick phosphosilicate-glass layer per traverse. Under these conditions the yield of the process is in the range 40–60% by weight of vapour deposited as glass.

Excess oxygen is added to the two vapour-carrying oxygen streams, Fig. 2A, 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 nonuniformities in the deposited layer after fusing by the traversing hot zone. An additional oxygen flow of between 300 and 500 ml/min seems to cure this problem by

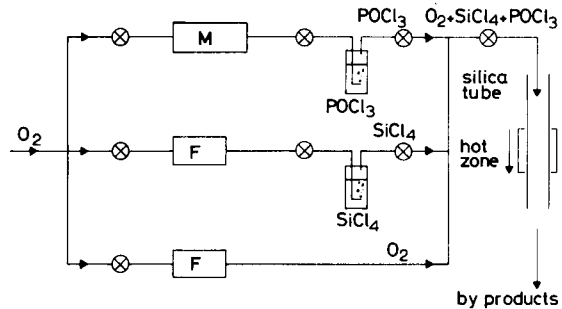


Fig. 2A Schematic diagram of gas distribution system

M denotes mass flow controller
F denotes flowmeter

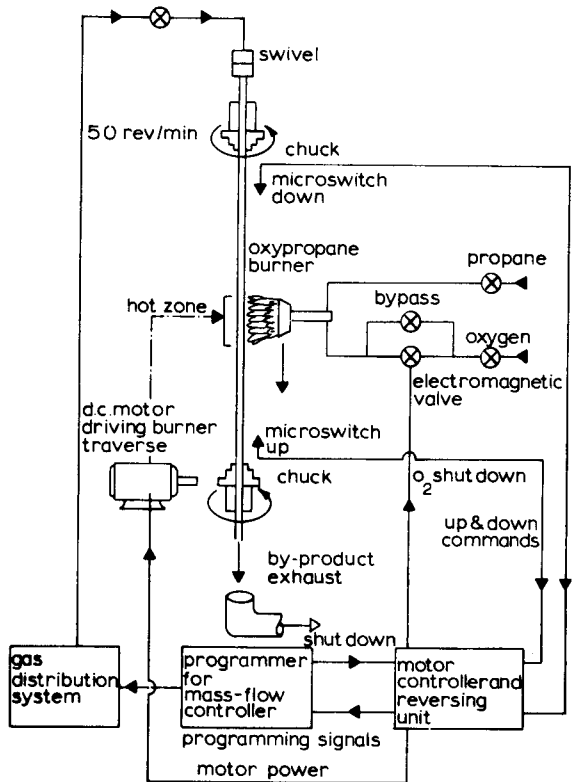


Fig. 2B Schematic diagram of automatic-deposition system

increasing the gas velocity through the tube and preventing soot flocculation.

The hot zone is provided by either a silicon-carbide-resistance furnace or a surface-mix oxypropane gas burner. A burner is convenient for rapid experimentation but for more controlled deposition conditions a silicon-carbide furnace is preferable. The description which follows relates to the use of a gas burner but a similar procedure is followed in the case of a furnace. As the burner moves along the tube the hot-zone temperature is a function of both the flame temperature and its traverse speed. The latter is usually kept constant at a value giving a reasonably thick phosphosilicate-glass layer ($\sim 10 \mu\text{m}$), and the hot-zone temperature is changed by

varying the oxygen flow to the burner. The temperature at which the deposited materials fuse into a clear homogeneous glass layer lies between 1400°C and 1550°C and is a function of phosphorus-pentoxide content, falling slightly with increasing concentration. Provided the ratio of phosphorus-pentoxide present is less than 20 m/o and the hot-zone temperature is below about 1600°C, then the resulting fused-glass composition is largely independent of the hot-zone temperature. This is certainly not the case for germania-silica glass, where the germania concentration in the glass is found to be a strong function of deposition temperature.

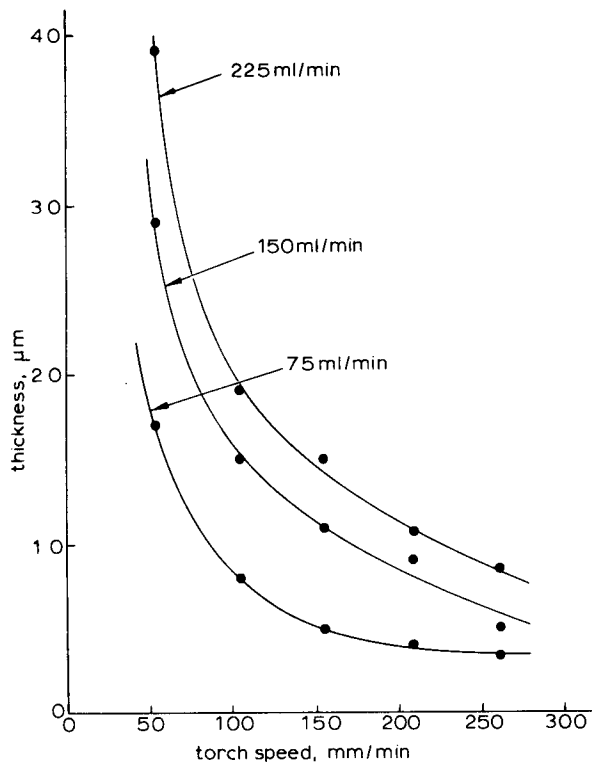


Fig. 3
Variation in thickness of a single deposited phosphosilicate layer as a function of traverse speed of the hot zone and of reactant concentration.

The P_2O_5 content of the glass is 10m/o and the oxygen flow is 300ml/min. The figures on the curves refer to the flow rate of oxygen through the $SiCl_4$ bubbler.

To achieve a fibre diameter/core diameter ratio of, say, 2.5:1 from a 13 mm bore silica tube, of wall thickness 1.5 mm, requires a total deposition thickness on the walls of the tube of 300 μm. Typically, we lay down from 20 to 60 glass layers which, as indicated by Fig. 3, may take between two and four hours. A section of a deposited tube is shown in Fig. 4.

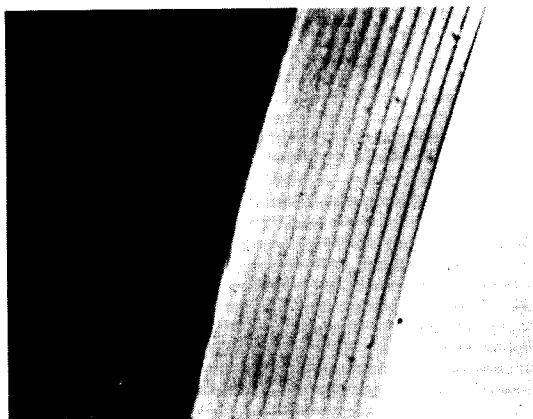


Fig. 4
Cross-section of a portion of the silica tube showing the deposited layers.

The first 3 layers comprise a borosilicate glass of constant composition while in the next 3 the B_2O_3 content falls in stages to zero. In the succeeding 14 layers the P_2O_5 content is gradually increased. [Optics Communications]

To simplify fibre fabrication an automated machine has been developed to carry out the chemical vapour-deposition process, Fig. 2B. The vertical silica support tube is held at each end by coaxial chucks that are rotated at the same speed, about 50 rev/min, so that there is no relative motion between them. The gas mixture from the gas distribution system of Fig. 2A is fed into the top of the silica tube via a rotary swivel joint, and the reaction byproducts and excess reactants are extracted at the bottom. The oxypropane burner is moved by a d.c. motor and gearing so that the 50 mm long hot-zone travels down the tube at a controlled constant speed of up to 350 mm/min. At the end of the downward pass the burner is driven rapidly back to the top of the tube, at a reduced temperature to prevent deposition, and the cycle repeats itself. 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, Fig. 2A, to control 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; the stepped structure is not observed.

In addition to the binary phosphosilicate glass we have applied the chemical vapour-deposition technique to other combinations. For example, the borosilicate glass consisting of boric oxide and silica, has been used as a cladding glass with fibres⁸ having a phosphosilicate core. The glass is formed in the same way by simultaneous oxidation and fusion of boron trichloride or boron tribromide and silicon tetrachloride within the silica tube. Boron tribromide is a liquid at 20°C and may be introduced into one of the Dreschel bottles in the gas distribution system of Fig. 2. On the other hand boron trichloride is a gas, so there is no need for an oxygen bubbler.

It has been found⁷ that the addition of fluorine to silica also lowers its refractive index, and we have fabricated phosphosilicate fibres with fluorine-doped silica claddings. The fluorine is obtained by dissociating sulphur hexafluoride or a fluorocarbon, which is fed at an appropriate flow rate into the silicon tetrachloride and excess oxygen stream before it enters the silica tube. Fibres have also been made having cores of the ternary glass system formed by phosphorus pentoxide, germania and silica. The addition of phosphorus pentoxide to germania-silica glass considerably reduces the viscosity, and helps prevent bubble formation within the fibre core layers.

4 Tube collapse

The second stage in fibre fabrication is the collapse of the composite tube and deposition layers into a solid preform. It has been found that, while 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 with an oxy-hydrogen burner. At this temperature the viscosity of the glass is sufficiently low for surface tension forces to initiate tube collapse. The hot-zone, which is about 20 mm 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 min.

When fibres having a high concentration of P_2O_5 in the core are being manufactured there is an increased tendency for the tube to form an elliptical cross-section during the collapsing process. This may be counteracted by applying a slight positive pressure (approximately 1 millibar) to the inside of the tube during collapse and by using a controlled high-pressure air-stream to quench the preform shortly after its closure into a rod and immediately after the traverse of the burner.

One problem which has not been completely overcome, however, is the volatilisation of P_2O_5 from the innermost phosphosilicate layer during the high-temperature collapse. This effect is commonly observed in fibres having binary glass cores in which one component is more volatile than the other and causes a characteristic dip in the refractive index profile at the centre of the core region, Fig. 5. It can be minimised by (i) increasing the total deposition thickness (ii) increasing the concentration of the more volatile component in the final layer and (iii) substituting, or adding, a less volatile component to the last layer.

Depending on the initial dimensions of the silica tube and on the number of layers deposited, preforms produced by the above technique may be from 6.5 mm to 9.5 mm in diameter, and from 400 mm to 1 m in length. Diameter variation along the deposited length of the preform is generally less than 1.5%

5 Fibre drawing

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 greater than 0.1%.

Conventional oxyhydrogen-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 in these laboratories) and a standard s.c.r. power controller. To prevent oxidation of the graphite at the high temperatures required, the furnace is operated with a flow of argon through it. There are several notable features about the design and performance of the furnace⁹. First, it can operate at temperatures up to 2200°C, and having reached set temperature, it is stable to within 0.06 deg C. Secondly, the low thermal mass and efficient insulation of the furnace hot zone results in a power consumption of 1.4 kW at an operating temperature of 2000°C. Thirdly, the high thermal-shock resistance of graphite allows the furnace to be raised from cold to working temperature in approximately 3 min. Fourthly, because of the low thermal mass and high stability of the furnace the response time to a temperature disturbance is very short – typically the furnace will fully respond to a 7.5 deg C temperature step in less than 20 s. Finally, the furnace

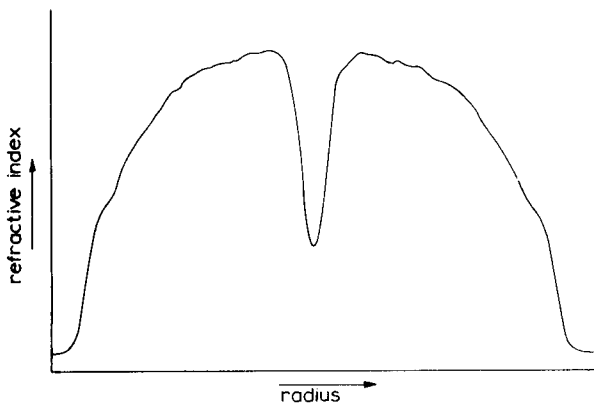


Fig. 5 Refractive-index profile of phosphosilicate fibre obtained by a near-field scanning technique

hot zone has excellent radial and longitudinal temperature uniformity enabling the circularity of the preform to be retained during its transformation to a fibre. The temperature is monitored either with a tungsten-rhenium thermocouple placed close to the hot zone or by an optical pyrometer looking into the hot zone.

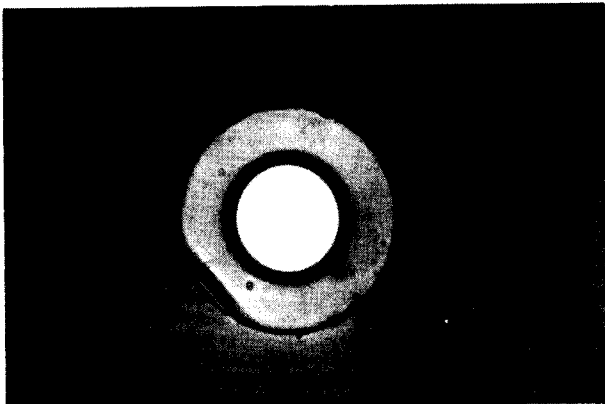


Fig. 6 Cross-section of a borosilicate-cladded phosphosilicate-core optical fibre of numerical aperture 0.23 (see text for details)

Fibre drawing is usually carried out at a temperature of approximately 2040°C, and at pulling speeds in the range 0.75–1.5 m/s. Over lengths in excess of 1 km the fibre diameter variation is less than $\pm 2 \mu\text{m}$ in 150 μm and is generally due to taper in the preform.

Fibre lengths of up to 4 km, with core and overall diameters of 50 μm and 140 μm respectively, can be fabricated from a 1 m length of preform 9 mm in diameter. However, for experimental purposes fibres are fabricated in lengths of approximately 2 km from somewhat shorter preforms.

6 Properties of phosphosilicate fibres

6.1 Numerical aperture

As indicated in earlier sections the maximum numerical aperture which has so far been achieved in fibres having a pure phosphosilicate core and a silica cladding is limited to 0.19 by the change in expansion coefficient with increasing P_2O_5 concentration. On the other hand in a composite structure consisting of a phosphosilicate core in a borosilicate cladding an increase in numerical aperture by 30% to 0.25 has been obtained. The cross-section of such a fibre is shown in Fig. 6. The graded core is surrounded by a borosilicate glass cladding which shows up as a dark ring. The outer annular ring of intermediate brightness is the silica supporting tube. In this particular case the core diameter is 66 μm , overall diameter 140 μm , and the numerical aperture is 0.23. The values of numerical aperture quoted here were determined experimentally from the far-field output pattern for fibres fully excited at the input. Preliminary work in these laboratories with fluorine-doped silica⁷ has shown that an increase in numerical aperture can be obtained but the value achieved so far is not as high as that with a borosilicate cladding.

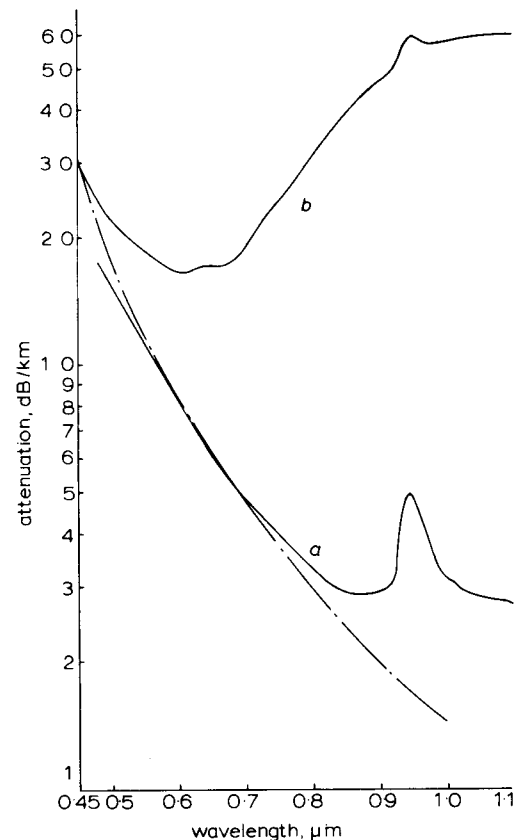
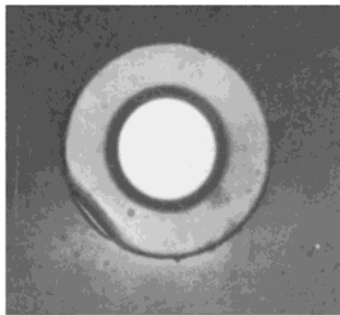
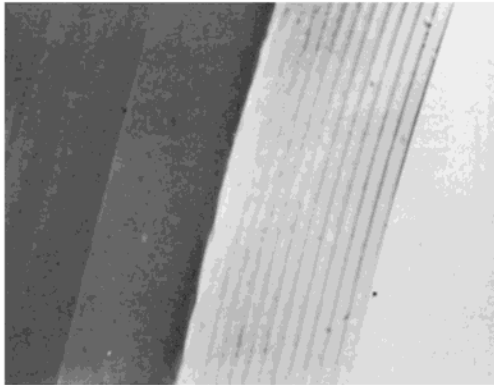


Fig. 7 Spectral attenuation curve (a) of a phosphosilicate fibre compared with the predicted minimum loss of silica shown dashed. Curve (b) was obtained with a slightly corroded stainless-steel valve in the deposition system.

6.2 Attenuation

A characteristic attenuation result for a phosphosilicate fibre of core-diameter 50 μm and numerical aperture 0.16 is shown in Fig. 7. The variation of attenuation with wavelength, obtained with all modes excited and over a length of 1.2 km, is very smooth and has three main features. First the loss is low, particularly at the shorter wavelengths where it is slightly below that predicted for pure



silica¹⁰, showing that the addition of phosphorus pentoxide to pure silica does not greatly increase either absorption or scattering. The loss of the fibre illustrated in Fig.7 has a minimum value of 2.7 dB/km at 1.1 μm although values as low as 2 dB/km have been obtained. Additional measurements⁸ show that it is below 5 dB/km over the considerable wavelength range of 0.7 μm to 1.25 μm . Even at 0.45 μm it is less than 20 dB/km and is considerably better than has been reported for u.v. transmitting fibres. The low loss at short wavelengths indicates the absence of the nonstoichiometry or oxygen deficiency which has been observed when germania or some other oxides are used as a dopant.

The second feature is the small increase in attenuation of 2 dB/km at 0.95 μm due almost entirely to the OH impurities in the silica cladding. In fact in other samples of phosphosilicate-cored fibres⁸ where cladding is formed of borosilicate glass this peak is as low as 0.5 dB/km and measurement of the height of the corresponding peak at 1.39 μm indicates an OH impurity level of as little as 0.5 parts in 10⁶. It is thought that this exceptionally low OH content is due to the hygroscopic nature of P₂O₅ which converts any residual water in the deposition equipment, on contact, to nonvolatile phosphoric acid and is not carried into the deposition zone.

A further characteristic of phosphosilicate glass is its sensitivity to ferrous-ion absorption in the region of 1 μm . Iron can produce appreciable absorption even when present in very small concentrations and the effect might be expected to be greater in phosphosilicate glasses which tend to reduce this particular impurity mainly to the more sensitive ferrous (Fe²⁺), rather than the ferric (Fe³⁺), state. To achieve good results it is essential to exclude iron impurities from both the materials used and the deposition system. The fact that the loss in the region of 1 μm exceeds that of silica may well be due to the presence of some residual ferrous iron. The upper curve in Fig.7 was obtained for a fibre which was made while there was a slightly corroded stainless-steel valve in the gas distribution system and illustrates the sensitivity to iron. The large broad absorption of 60 dB/km centred on 1 μm is consistent with the

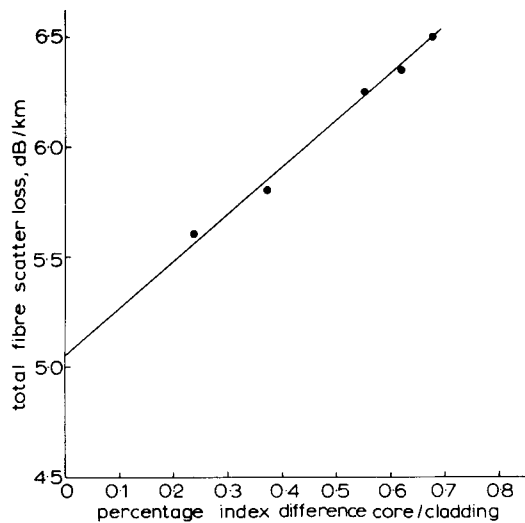


Fig. 8
Scattering loss in a phosphosilicate fibre as a function of the percentage difference in the refractive index compared with silica at a wavelength of 0.633 μm

presence of ferrous iron but the blue loss is largely unaffected indicating that there is little iron present in the ferric state.

The above results show that at least at shorter wavelengths the total loss of phosphosilicate glass, at the concentrations applicable in fibres, is comparable with that of silica. Scattering measurements have been made in an integrating sphere for fibres with cores of varying relative concentrations, using a helium/neon laser operating at a wavelength of 0.633 μm . The laser is focussed so as only to partially excite the fibre, thus ensuring that only Rayleigh scattering within the core is measured, and no waveguide leakage effects are included. The results, shown in Fig. 8, indicate that the amount of scattering increases linearly with change in refractive index. The curve extrapolates to the value reported for Rayleigh scattering in pure silica and it may be concluded that the addition of P₂O₅ to silica causes a small amount of excess scattering presumably arising from concentration fluctuations. However, the effect on the total attenuation is small and amounts to 1.6 dB/km at 0.9 μm and 0.8 dB/km at 1.1 μm .

6.3 Material dispersion

In stepped-index multimode fibres the pulse dispersion, and thus the bandwidth, is limited largely by the spread in mode-transit times. This group delay dispersion can, however, be greatly reduced by introducing an appropriate radial variation of refractive index so that material dispersion then can become the dominant factor particularly when an l.e.d. is used. A technique has been devised for the measurement of material dispersion¹¹ involving the measurement only of the propagation times of pulses of different wavelength. To ensure time coincidence of the 25 ps input pulses the output of a modelocked ruby laser was split into two beams, the wavelength of one was shifted by means of a Raman cell, and they were then combined before being launched into a fibre. The results of the measurements, Fig.9, show that the material dispersion (defined here in terms of the second derivative of refractive index n with respect to wavelength λ , namely $\{(-\lambda/c) d^2 n/d\lambda^2\}$), is the same as that of pure silica for wavelengths from 0.7 to 0.95 μm and is independent of P₂O₅ concentration over the range measured, corresponding to fibre numerical apertures from 0.1 to 0.18. This is in contrast to the case of germania-silica fibres which have a material dispersion larger¹² than that of silica. The low material dispersion of phosphosilicate glass is consistent with the low transmission loss in the blue region of the spectrum¹¹. Silica has a low material dispersion compared with most other optical glasses and it follows that the bandwidth limitation due to material dispersion alone is smaller in phosphosilicate fibres than in most others except for those having a silica core. The magnitude of this limitation is such that for an l.e.d. of 40nm linewidth at a wavelength of 0.9 μm the material dispersion of 69 ps nm⁻¹ km⁻¹ would correspond to a pulse broadening of 2.8 ns/km.

On the other hand, this contribution to pulse broadening could be very greatly reduced by operation at longer wavelengths. Calculations¹³ from the published refractive-index data¹⁴ indicate that the material dispersion of silica (as defined above) goes through zero at a wavelength of 1.27 μm and there is strong reason to assume, from the close correspondence over the range 0.7 to 0.95 μm , that phosphosilicate glass will behave similarly. Thus, for a fibre in which the transit-time differences between modes has been minimised by the appropriate choice of refractive index profile¹⁵ a considerable increase in bandwidth (e.g. by a factor of ~10 for an l.e.d. with a line spread of 40nm) could be achieved by operation at 1.27 μm . The attenuation of the phosphosilicate fibre is less than 5 dB/km at this wavelength but no suitable source is yet available. However, GaInAs light-emitting diodes of high radiance (15W/sr/cm² at 100mA) and capable of being modulated at high rates (3dB bandwidth of 150MHz) with an emission wavelength of 1.06 μm have already been reported¹⁶ as well as devices¹⁷ of Ga_{1-x}In_xAs/Ga_{1-y}In_yP operating at 1.15 μm .

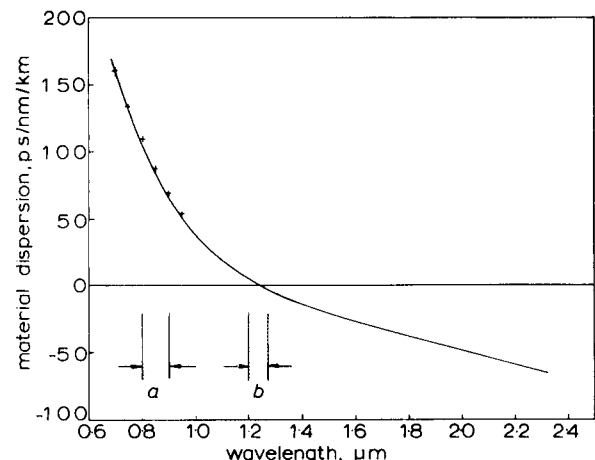


Fig. 9
Material dispersion $d\tau/d\lambda = (-\lambda/c) d^2 n/d\lambda^2$ as a function of wavelength

The solid curve is calculated for silica from the data of Mallitson¹⁴ and the points have been measured in a fibre having a phosphosilicate-glass core
a is the wavelength region for GaAs devices
b is the wavelength region of negligible material dispersion

6.4 Pulse dispersion

In stepped-index fibres the pulse dispersion is dominated by group delay between modes and, for full excitation, values of ~37 ns/km are predicted for a typical phosphosilicate fibre of 0.18 numerical aperture. Measurements with a semiconductor laser gave figures of ~5 ns/km probably because most of the power is launched into the lower-order modes. If the optimum refractive-index profile could be achieved then a reduction to values in the region of 0.1 ns/km

might be expected despite complete mode excitation but such perfection is difficult to attain. Nevertheless, a considerable improvement is possible even when the profile is far from the ideal one. For example, the profile in Fig. 5 was measured on a phosphosilicate core fibre using a simple technique¹⁸ involving a scan of the near-field intensity pattern of a short (~1m) length of fibre when excited by a Lambertian source. Except for points near the axis the profile corresponds to that described¹⁹ by $\alpha = 2.5$ but at the centre the depletion process described in section 4 causes a dip. Nevertheless, the pulse dispersion, measured over a length of 0.65km with a semiconductor laser operating at 0.9 μm , was 1ns/km. A similar measurement with a helium/neon laser producing a smaller degree of excitation and using the same (Gaussian beam) launching conditions that are required for efficient launching into a single-mode fibre gave a dispersion of 0.1ns/km. It would appear, therefore, that a graded-index phosphosilicate fibre produced by the techniques described above is capable of a bandwidth comparable with that of a single-mode fibre, at least when equivalent launching conditions are used and over this length.

The effect of the dip in the refractive-index profile on the dispersion when the fibre is fully excited has still to be determined.

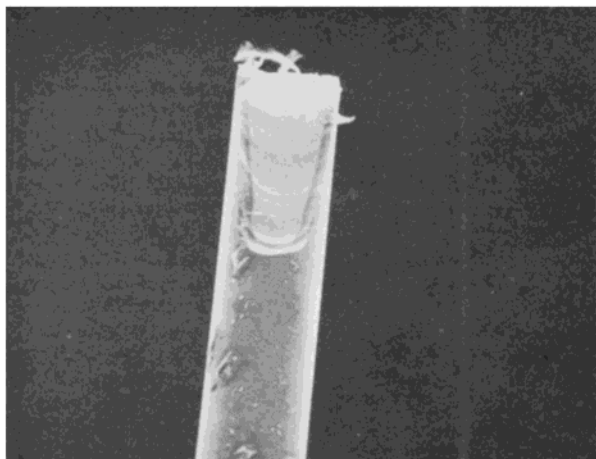


Fig. 10
Remaining preform after a fibre has been drawn

6.5 Single-mode phosphosilicate-core fibres

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 a Suprasil tube was placed in the deposition machine and a single pass of the hot zone made to volatilise the impurities from the inner surface. This was followed by a single deposition pass at greater speed than normal, giving a single thin phosphosilicate-glass layer. The tube was collapsed and drawn in the normal way so as to produce a fibre having a core of about 8 μm diameter, with the result that single-mode operation was obtained at the 0.633 μm wavelength of the helium/neon laser. The transmission loss of 6.1 dB/km is close to the fundamental attenuation limit of pure silica at this wavelength. The guidance property of the fibre is good as the low attenuation was measured with the fibre wound on a 240mm radius drum. In addition calculations and experiment show that the bend loss is negligible down to a bend radius of 100mm. At longer wavelengths the loss increases because the core-diameter/wavelength ratio is smaller and the fields penetrate further into the somewhat lossy cladding. If the core diameter were to be increased, but still kept within the limitation of single-mode operation, the attenuation in the infrared would be less owing to closer confinement of the mode to the core region.

The pulse dispersion was measured with a mode-locked helium/neon laser²⁰ over a length of 0.4 km. No detectable pulse broadening could be observed indicating that the dispersion is less than the resolution of the apparatus, or 0.1 ns/km, thus confirming experimentally the very large bandwidth predicted theoretically for single-mode fibres. This value of dispersion is the lowest reported for any type of fibre.

7 Conclusions

A technique has been described for the deposition of glass layers involving a homogeneous (gas-phase) reaction at high

temperatures and high reactant concentrations. The deposition rate is much higher than is obtained with the heterogeneous (surface) reaction used earlier. The glass layers are deposited in a supporting tube which is subsequently drawn into a fibre. Various types of fibre based on a phosphosilicate glass are now available having very low loss over a wide wavelength range with a minimum of 2 dB/km, numerical apertures up to 0.25 and with values of material dispersion equal to those of silica. The fabrication method is comparatively straightforward and has been made largely automatic, producing fibres up to 4km length and ~50 μm core diameter. The starting materials are cheap and abundant and clean-room conditions are not necessary.

A range of refractive index profiles can be obtained and may be pre-programmed on the controller of the deposition machine. As commonly observed in fibres made by the c.v.d. process, there is a



Fig. 11
Broken end of fibre

small dip in refractive index at the centre of the core. Although the optimum profile has not yet been achieved pulse dispersions as low as 1 ns/km with a semiconductor laser and 0.1 ns/km with a helium/neon laser have been measured in graded-index multimode fibres. The same fabrication technique can be used to produce single-mode fibres which have an attenuation at the design wavelength of 0.633 μm close to that of bulk silica and a pulse dispersion of less than 0.1 ns/km.

8 Acknowledgments

Grateful acknowledgment is made to a number of past and present colleagues whose measurements have been quoted in this review. In particular we are indebted to A. Dyer for the fibre loss measurements; Dr. I. C. Goyal for the values of attenuation due to scattering; Dr. B. Luther-Davies for the results on material dispersion; and F. M. E. Sladen for the refractive-index profile.

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