A BOROSILICATE-CLADDED PHOSPHOSILICATE-CORE OPTICAL FIBRE

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A new type of optical fibre waveguide is described having a graded phosphosilicate core in a borosilicate cladding. The attenuation, which is independent of the supporting jacket made from commercial silica, is consistently low over the wide wavelength range 0.75 to 1.25 μm and the numerical aperture is 0.23. The pulse dispersion is 1.3 ns/km.

1. Introduction

A convenient method of making a low-loss optical waveguide is to deposit a suitable glassy material of high silica content on the inside of a silica tube which is subsequently drawn into a fibre. The deposited layer then becomes the core of the fibre and is contained in the silica cladding. Unfortunately most commercial silica tubing contains impurities and in particular the presence of OH radicals can prove to be troublesome, causing a number of peaks in the absorption curve of the fibre, including one at 0.95 μm. This arises because some of the guided energy is present in the cladding, especially in a simple stepped-index configuration, to a degree dependent on the normalized frequency, and cladding impurities therefore contribute to the total fibre attenuation. However, a technique was recently described [1] for making the transmission properties independent of the silica supporting tube and was applied to the phosphosilicate glass fibre. It involves the incorporation of a buffer layer of low P_2O_5 content immediately adjacent to the core with the result that propagation is controlled entirely by the deposited layers and is independent of the silica tube. The latter now acts only as a supporting structure so that relatively low-quality commercial tubing can be used instead of the ultra-pure, and therefore expensive, variety.

An alternative method of isolating the propagating fields from the supporting tube is to increase gradually the P_2O_5 concentration in successive layers [1] so that, after drawing the preform into fibre, a graded refractive index is produced across the core.

However, in both the buffered and graded-index cores the numerical aperture of the fibres is limited by the maximum concentration of P_2O_5, which it is possible to combine with SiO_2 while still retaining a compatible temperature coefficient of expansion with the silica supporting tube. So far we have achieved a value of 0.18 in a core having a diameter of 50 μm; the loss has a minimum value of 2 dB/km and is low over a wide range of wavelengths. In order to increase the efficiency of coupling for incident radiation from a light-emitting diode a higher value of numerical aperture is desirable and can be brought about in two ways. The first is to increase the refractive index of the core and the second is to reduce that of the cladding. We have chosen the second alternative and have replaced the buffer layer by one of a borosilicate glass [2] having a refractive index lower than that of silica. The fabrication technique is similar to that for phosphosilicate glass which is described briefly below.

2. Fibre fabrication

The manufacturing process comprises the three stages of (*i*) chemical vapour deposition of the appropriate glassy layers in a silica tube, (*ii*) collapse of the tube and layers into a solid rod composite preform and (*iii*) drawing the preform into a fibre. The starting materials for the deposition process are volatile chlorides of the required constituents, namely $SiCl_4$, $POCl_3$ and BCl_3. The phosphorous oxychloride is normally distilled in the laboratory in order to improve the purity. To produce a phosphosilicate glass oxygen is bubbled through separate containers of $SiCl_4$ and $POCl_3$ as in fig. 1a, the two vapour-carrying gas

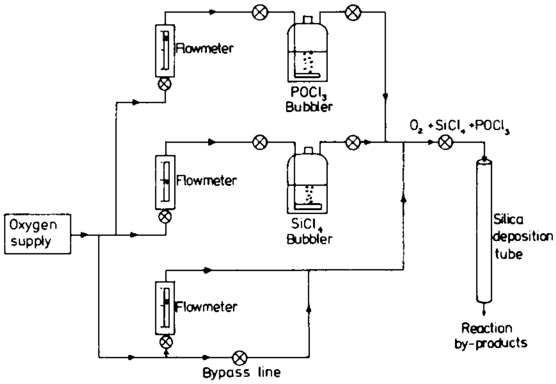

Fig. 1a. Gas flow system for chemical vapour deposition of phosphosilicate glass.

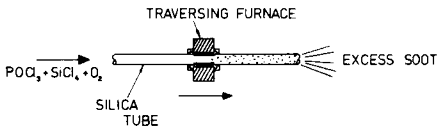

Fig. 1b. Schematic of deposition process showing direction of gas flow together with relative movement of furnace and silica tube.

streams are combined, diluted with further oxygen, and passed through the silica supporting tube. As shown schematically in fig. 1b a short furnace is traversed along the tube and oxidation of the chlorides to produce the relevant oxides takes place.

Chemical vapour deposition of glasses is not new and has been used for the production of synthetic silica for some years. Oxidation of silicon tetrachloride is achieved either by flame hydrolysis or by high-temperature plasma-torch pyrolysis. Low-loss optical waveguides have been made by a similar process at the Corning Glass Works. Furthermore in the semiconductor industry thin films of glass have been deposited onto a substrate by means of a low-temperature surface oxidation reaction but the deposition rate is very low. However, the method described here differs from these because we have found [3] that the oxidation reaction of the chlorides of silicon and phosphorous occurs spontaneously in the gas phase at the relatively low temperature of 1300°C to form a dense fog of small glass particles. In addition, provided the viscosity of the glass is substantially lowered by the incorporation of sufficient phosphorous pentoxide (or other suitable component) then the glass particles fuse on the walls of the container to form a clear, uniform, homogeneous layer of phosphosilicate glass. Thus a high deposition rate can be obtained since no gas diluents are required to slow the reaction and the glass deposition may occur directly on the walls of a silica tube which, because of the comparatively low temperature, suffers no deformation. This technique was also developed independently at Bell Telephone Laboratories [4] although the details of our method are somewhat different and so are the materials.

Typical operating conditions are as follows. For a silica tube with a bore of 10 mm the flow rates of oxygen and silicon tetrachloride vapour are kept constant at 600 and 35 ml/min, respectively, while that of the phosphorous oxychloride vapour is varied over the range 1 to 13 ml/min. With a furnace temperature between 1300 and 1450°C the phosphosilicate glass layer is deposited on the inner wall as the tube is passed through. (In practice it is more convenient to keep the furnace fixed in position and to traverse the silica tube.) The deposition time of each layer is 8 minutes for a typical length of 50 cm and the P_2O_5 concentration is between 2 and 15 m/o depending on the flow rate of the phosphorous oxychloride. With these flow rates and temperatures the amount of downstream soot formation is small. The refractive index of successive layers, each about 12 μm thick, can be accurately controlled and a wide range of profiles, from a uniform to a graded-index, can be produced.

With the present fibre the cladding layers of borosilicate glass are produced by a system similar to that in fig. 1a but with an additional input for boron trichloride gas. The flow rates of BCl_3 and $SiCl_4$ are 8 and 35 ml/min, respectively, together with 450 ml/min of oxygen. A cross-section of a portion of a typical series of depositions is shown in fig. 2a. The first 3 layers are of constant composition while the next 3 are formed by reducing the BCl_3 flow rate to zero in stages. The amount of $POCl_3$ is then increased gradually from 0 to 9 ml/min over the next 14 layers, giving a total of 20. The successive depositions of phosphosilicate in particular stand out clearly in fig. 2a but diffusion takes place during the subsequent tube-collapsing and fibre-drawing stages producing some smoothing out of the concentration gradient. A fibre having a graded-index core in a borosilicate cladding is thereby

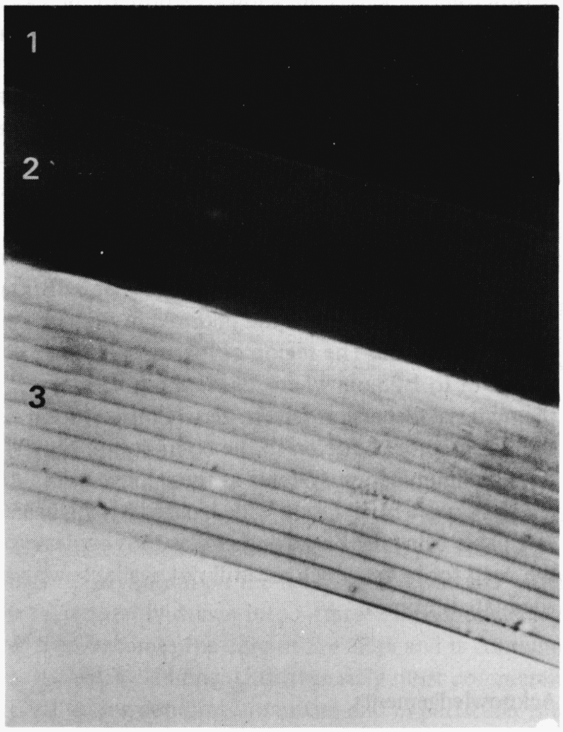

Fig. 2a. Cross-section of a portion of the silica tube showing the deposited layers: 1 = silica; 2 = borosilicate; 3 = phosphosilicate.

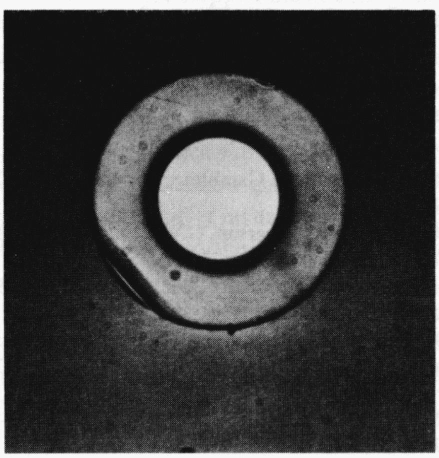

Fig. 2b. Cross-section of borosilicate/phosphosilicate fibre. Numerical aperture = 0.23.

produced.

Collapse of the layered supporting tube into a rod preform is effected by mounting it between rotating chucks on a lathe bed and heating carefully in an oxy-hydrogen flame which is traversed continually along the length. Initially some difficulty was experienced, due to the different expansion coefficients of the layers and the supporting tube, in obtaining a circular preform but this problem has been overcome and good circularity is now the rule rather than the exception. One problem still remaining is the evaporation of some P_2O_5 from the last-deposited layer resulting in a slight dip on the axis in the refractive index profile. Fortunately this small dip has little effect on the attenuation and the dispersion but we expect that it can be eliminated to give a more closely parabolic profile.

The preform is drawn into fibre with a precision fibre-drawing machine [5] having a speed control and stability to better than 0.1%. The furnace is of novel design and uses resistance-heating so that operating temperatures up to 2200°C can be stabilized to 1.0°C. The hot zone is small, giving a short response time, and the temperature distribution is carefully profiled. For experimental purposes a fibre length of 1.2 km is normally drawn from a 50 cm preform although there is no reason why this length should not be considerably greater.

3. Results

Fig. 2b is a photograph of the end of a typical fibre. The graded core of phosphosilicate glass is surrounded by the cladding of borosilicate glass which shows up as a dark ring. The outer annular ring of intermediate brightness is the silica supporting tube. The measured numerical aperture of 0.23 is 40% larger than that of the conventional phosphosilicate fibre and the core diameter is 66 μm. Thus the numerical aperture and core diameter are comparable with those of many multi-component glass fibres.

The attenuation, fig. 3, has been measured over the wide wavelength range of 0.44 μm to 1.65 μm, using a silicon detector below 1.1 μm and a lead sulphide detector at longer wavelengths. It may be seen that there is a broad "window" from 0.75 to 1.25 μm where the loss is low and nearly constant. The minimum value of 3 dB/km is small but would have been lower but for the poor quality of BCl_3 available. The

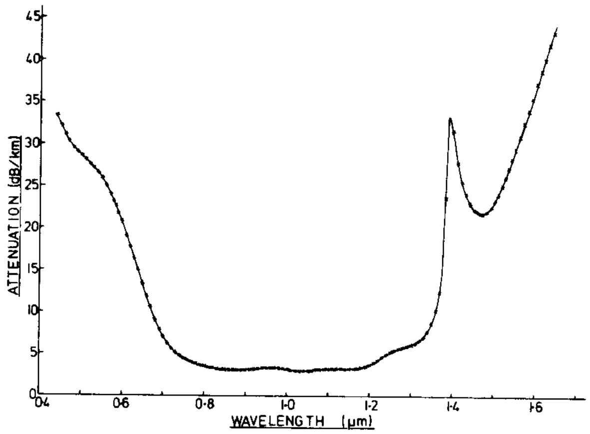

Fig. 3. Attenuation curve of borosilicate/phosphosilicate fibre.

broad peak in the vicinity of 0.6 μm, evidently a drawing-induced absorption since it can be removed by heat treatment, is also caused by the borosilicate glass and is not present in the phosphosilicate fibre. As in the buffered phosphosilicate fibre [1] the OH content is very low and the peak at 0.95 μm is only about 0.5 dB/km. The effect of any OH impurity is more noticeable at longer wavelengths as indicated by the peak at 1.39 μm. The ratio of the heights of these two absorptions is about 40:1 and is comparable with that observed [6] in a fibre having a much higher OH content (100 ppm). The 1.39 μm peak, which has been attributed to the second overtone of the fundamental υ_3' stretching vibration of the OH ion at 2.72 μm, may be used to estimate the concentration of this impurity, giving a value of ~0.5 ppm from fig. 3.

A possible explanation for this exceptionally low OH content is the strongly hygroscopic nature of P_2O_5. Thus any residual water in the deposition equipment is converted on contact to non-volatile phosphoric acid and is not carried into the deposition zone.

The pulse dispersion has been measured at 0.633 μm and is between 1.3 and 1.6 ns/km depending on the launching conditions.

4. Conclusions

By combining a borosilicate glass cladding with a phosphosilicate glass core a low-loss fibre of increased numerical aperture has been produced. The core diameter is quite large thus easing the problem of efficient coupling from light-emitting diodes, as well as facilitating jointing and handling generally. As with phosphosilicate fibres the technique of chemical vapour deposition is used which is flexible and allows a range of refractive index profiles to be easily selected. The raw materials are inexpensive compared with those required for "soft" glass fibres and the low loss of 3 dB/km has been obtained despite the poor quality of the boron trichloride. The region of low attenuation extends out to 1.25 μm where, as we show elsewhere, the material dispersion falls to zero. Consideration should therefore be given to the operation of optical fibre communication systems at these longer wavelengths since a moderately wide bandwidth might be attainable using light-emitting diodes thus obviating the need for lasers which are still not available with adequate lifetimes.

Acknowledgements

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