GLASS FIBRES FOR OPTICAL COMMUNICATIONS

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Foreword: the evolution of low loss optical fibres

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The possibility of guiding light by a dielectric cylinder has been known for many years and was demonstrated, for example, by the classic experiment of Tyndall(1) using a water jet. However the effect was no more than a scientific curiosity and was not applied with any serious intent until 1951 when Hopkins & Kapany and also van Heel attempted image transmission in short coherent fibre bundles.(2) Nevertheless real progress was not made until the idea of surrounding the light guiding core by a protective cladding was introduced in 1958. Two types of application then emerged, namely the short coherent bundle about 1 cm long in fibre optic faceplates, for example, and the incoherent flexible fibre bundle for use simply as a light conductor over distances of about 1 m.

With the invention of the laser in 1960, communications engineers became excited at the possibility of using it as a source of carrier waves with the prospect, if a sufficiently high degree of monochromaticity could be obtained, of enormously large bandwidths. Unfortunately no suitable transmission path was available as the atmosphere is inhomogeneous and unstable, while protection of the laser beam in an evacuated pipe or lens guiding system(3) proved hopelessly uneconomic and difficult.

Suggestions that cladded glass fibres might be used to guide laser light for telecommunications purposes were made, for example, in 1964(4) but the first detailed study was that by Kao & Hockham(5) in 1966. The prospect was a daunting one at the time since the attenuation of commercially available, cladded glass fibres was about 1 000 dB/km and an improvement by two orders of magnitude was essential to approach an economically viable system. However, Kao & Hockham postulated that it might be possible to produce losses of about the required order, especially if the iron content could be reduced to 1 ppm.

The potential advantages which fibres were seen to have over free space and beam-guiding structures were small size, flexibility, and cheapness. The installation of a beam waveguide, consisting of a periodic sequence of lenses spaced about 100 m apart in a pipe of perhaps 10 cm diameter and required to be nearly optically straight, would be extremely costly. Optical fibres of 0·2 mm diameter could, on the other hand, be laid in existing cable ducts with no additional civil engineering work, land acquisition, and so on. The cost differential with conventional coaxial and wire cables was not so marked, but even so the cross-sectional area of an optical fibre cable is about 100 times smaller than that of a comparable coaxial one.

Thus although in 1966 the potentialities of optical fibres were seen to be very attractive, the difficulties were formidable. A reduction in optical loss by at least two orders of magnitude required the development of suitable glasses with transition metal ion impurity levels of, in fact, only a few parts in 10^9. Little was known about the reliable production of precision cladded fibres with cores of $\sim$2 μm diameter which, it was thought, would be needed and whether glass, which is brittle, could be made strong enough for the required manhandling, drawing into cable ducts under high tensile stress, and so on. Even the relatively trivial but essential operations of jointing, connecting, and cutting seemed to be themselves major hurdles. Apart from the fibre itself and the associated problems, no suitable sources were available. The semiconductor laser with its very small size, high efficiency, and capability of being directly modulated at high speed was the obvious choice but the output radiation was unstable, even during a single pulse, and far from coherent. Indeed it was no more than a narrow band noise generator with a linewidth of 5 nm or more and an unreliable one at that. Above all, device lifetimes were measured in minutes rather than the required hundreds of thousands of hours. Nevertheless three research programmes were begun in the United Kingdom; at Standard Telecommunication Laboratories, Harlow, at the Post Office Research Station, Dollis Hill, and jointly between the Signals Research & Development Establishment, Christchurch, and Southampton University.

Early work

Although it was thought possible to produce silica in very pure form the required drawing temperature for fibre fabrication of $\sim$2 000 °C was inconveniently high. Furthermore no suitable cladding material was known. In addition to its high softening temperature the refractive index and the thermal expansion coefficient of silica are very low. Thus it was difficult to find a cladding material of lower refractive index, and other common glasses would liquify and run off a preform before the silica had even softened. Finally, because of the expansion mismatch the fibre would be fragile.

Initially, therefore, attempts were made in 1967 to produce low loss fibres from conventional, low melting point glasses. Two independent approaches were adopted. Thus, a group at the Post Office Research Station set out to fabricate bulk core and cladding glasses by conventional methods, great attention being paid to the purity of the raw (solid) materials and processing methods; these bulk glasses were then to be drawn into fibre by the concentric crucible technique. The other approach, at Southampton University, was to investigate commercially available glasses to see how the fibre drawing process could be improved. For the latter purpose a precision drawing machine was designed and constructed in which the whole structure was made stiff to avoid vibrations; the temperature of the wire-wound furnace was controlled to ±1 degC and the drawing speed to ±1%. With careful cleaning and preparation, the fibre loss was soon reduced by the group at Southampton in discrete steps to 400, 200, and then 150 dB/km. The materials were Schott F7 rod in Pilkington ME1 tubing, which were drawn into fibre by the well known rod and tube technique. In retrospect the achievement of 150 dB/km seems laughable but the excitement generated at the time was an indication of the magnitude of the task. The reduction in attenuation from 1 000 to 200 dB/km was largely brought about by removing imperfections and impurities at the core-cladding interface. Measurements on the starting rods showed that the loss at the 150 dB/km level was due to the inherent loss of the bulk F7 glass itself.

Experimental low loss fibres

A considerable breakthrough occurred in 1970 when workers at Corning Glass Works in the USA reported fibre losses of 20 dB/km.(7) No details were released of the materials or method of fabrication but it was surmised that the core consisted of doped silica with a pure silica cladding. It later transpired that the dopant was titanium oxide which was deposited with SiO_2 in the form of a fine soot on the inside of a silica tube which was subsequently drawn into fibre. The TiO_2/SiO_2 glass, having a higher refractive index than that of silica, formed the core with undoped silica as the cladding. These fibres were not suitable for widespread use but served to demonstrate that it was possible to achieve the requisite low losses.

This result produced a very strong impetus to the field and it stimulated much additional research work. One direction followed was an attempt to fabricate fibres out of a single material, that material being silica since it could be produced in sufficiently pure form. Many structures were tried, including one comprising an uncladded fibre resting on a thin membrane which, in turn, was supported in a tube. When drawn down to fibre the membrane had to be less than a wavelength in thickness so as to be cut-off to transverse propagation thus keeping all the energy contained within the core. Such fibres were indeed made, with some difficulty, at Bell Telephone Laboratories(8) and Southampton University(9) but were never a truly practical proposition because, for example, of the problems of jointing, lack of symmetry, and the fact that liquid contamination would immediately be drawn by strong surface tension forces right up inside the hollow fibre.

Another approach was to use a low loss liquid as the core material, introduced under pressure into a tubular glass cladding. The first reported combination, by a group at CSIRO, Australia,(10) was tetrachloroethylene in a silica tube, giving a loss of 15 dB/km. Shortly afterwards a much cheaper combination of butadiene in ordinary impure commercial glass (ME1) tubing was shown at Southampton University to give the remarably good result of 5 dB/km, also at a wavelength of 1·06 μm.(11, 12) Such fibres, while again not being practical propositions, were nevertheless easy to make and provided evidence that the precision of fabrication could be very high indeed with cladding diameter variations of only ±0·5 μm. They enabled a considerable amount of experimental work to be done on propagation in low loss fibres and it was found that the bandwidth could be much larger than expected.(13)

Fibres based on silica

The main thrust, however, has come from progress in silica technology. The relatively low loss silica then available had been made for many years by vapour deposition techniques involving oxidation or hydrolysis of volatile silicon compounds such as silicon tetrachloride or silane. Such techniques were also being used, but at very low deposition rates, in the semiconductor industry. Transition metal impurities, which cause high absorption, are largely prevented because the vapour pressures of their chlorides and hydrides are very much lower than that of silicon. Thus when the vapours of the silicon compounds are generated by passing a carrier gas through the appropriate liquid the impurities are left behind. If the vapours are blown through an oxy-hydrogen flame then oxidation of the vapours occurs and silica is generated as a fine soot which may be deposited on a cool mandrel. When a sufficient thickness has been deposited the mandrel is removed and the porous mass of soot is then sintered and collapsed into solid glass. With this method of preparation the water content can be quite high. There were, of course, variations on this general theme. For example, at Thermal Syndicate Ltd.,(14) although the starting material was also silicon tetrachloride the boule was grown direct with no soot formation and collapse stages. The OH content was 1 400 ppm, with all other impurities well below 1 ppm (usually by at least an order of magnitude). This firm was the first to reduce the hydroxyl concentration drastically, to a few ppm in Spectrosil WF, by using an induction plasma as the heat source.

As indicated above, it later became known that the original Corning single mode fibre was made by blowing soot of silica doped with titania and produced in an oxy-hydrogen flame, into a silica tube where it deposited on the inside walls. After sintering a fibre was drawn. Later,(15) at Bell Laboratories, a borosilicate coating was deposited on a silica rod via a dilute silane oxidation reaction, giving a fibre with a silica core in a borosilicate cladding. The refractive index difference was larger than might have been expected because of the rapid quenching during fibre drawing and because the cladding, having a lower coefficient of thermal expansion than silica, is under tension and therefore at lower than normal density.

The chemical vapour deposition techniques employed in the semiconductor industry enabled a homogeneous deposit to be produced on a surface by a heterogeneous reaction of gas molecules at the surface. The temperature must be low and the reactants in dilute form to prevent the production of a fine powder of silica particles which would result in a poor deposit. Because of the dilution and the low temperature the deposition rate is also small. Furthermore the presence of hydrogen introduces hydroxyl radicals which produce large absorption peaks at a number of inconvenient wavelengths including one at 0·95 μm.

At this point, at the beginning of 1974, two laboratories discovered independently that concentrated reactants can be used in a modified process operating at high temperatures and giving high deposition rates. For example it was observed that concentrated silicon tetrachloride vapour reacts spontaneously with oxygen at ~1 500 °C to form a fine glass soot. If the oxidation reaction takes place in a silica tube the soot may be deposited on the inside wall and simultaneously fused into a clear glass layer. By traversing a localised hot zone along the tube a uniform glass layer, about 10 μm thick, can be produced. In principle, with sufficient traverses the required thickness of glass can be deposited although in practice the high temperature required for pure silica produces deformation of the supporting tube. A particular advantage of this method is that, since the reactants are halides and not hydrides, the hydroxyl contamination is greatly reduced.

At Southampton University(16) a phosphosilicate core glass was formed on the walls of the supporting tube by using a mixture of $SiCl_4$ and $POCl_3$ vapours with oxygen. The deposition temperature required is appreciably lower than that for pure silica and fibres having an attenuation of 2·7 dB/km at 0·83 μm, and with an extremely low hydroxyl content, were obtained. At Bell Telephone Laboratories(17) a germanosilicate core of similarity low loss was obtained with the combination of $GeCl_4$ and $SiCl_4$. In both cases the fibre properties can be made independent of those of the silica supporting tube by depositing a sufficient layer of cladding material of borosilicate glass. The new fabrication process has been referred to as either 'homogeneous chemical vapour deposition' (Southampton University) or 'modified chemical vapour deposition' (BTL). Germania doped silica fibres were also reported by Standard Telecommunication Laboratories(18) although in this case pure germania was deposited on the inside of the silica tube and subsequently diffused into the walls.

The MCVD method has been widely used and has not changed much from its earlier form. Subsequent refinements have produced attenuations of 0·5 dB/km at 1·3 μm and 0·15 dB/km at 1·55 μm. It is a flexible technique capable of producing step index and graded index multimode fibres as well as single mode fibres. Some of these aspects are discussed in the following articles. It has also been developed(19) into a continuous process in the form of the vapour axial deposition method. At the time of the MCVD developments. details of another Corning process had become available in which a hydrolysed doped soot is deposited from a flame on the outside of a mandrel. The latter is subsequently removed and the soot fused to give a clear glass. The type of dopant was kept a closely guarded secret but is now known to have been germania. This outside vapour deposition method is still being used.

Other modes of chemical vapour deposition have since been developed, such as the plasma assisted oxidation process(20) in which a nonisothermal plasma is maintained within the supporting tube, at a reduced pressure, by means of a microwave cavity through which the tube passes. Much lower temperatures, ~1 000 °C, are required and since the reaction is heterogeneously nucleated, no particulate matter is formed in the gas phase and the deposition efficiency is close to 100%.

The double crucible technique

At the same time that the various CVD silica based methods were being developed steady progress was being made with the conventional glass making approach at the Post Office Research Centre in the UK.(21) Through detailed theoretical and experimental studies of various glass systems, and by giving careful attention to the preparation of extremely pure raw materials and to glass melting techniques, very low loss sodium borosilicate glass has been prepared. Fibres are drawn from the bulk material in the double crucible arrangement and again it is necessary to avoid contamination from the crucibles themselves, from the ambient atmosphere, and in the handling procedures. In order to ensure a stable flow through the concentric nozzles, and thus uniform fibres, it is customary to feed the glass into the crucibles via rods of the bulk materials. Thus although the glass making is a batch process the fibre drawing can be continuous. The lowest losses achieved so far are of an order of magnitude higher than with the homogeneous CVD method, namely just below 4 dB/km at a wavelength of 0·85 μm, but nevertheless represent a spectacular improvement over the situation of 10 years ago. Extremely uniform and repeatable fibres can be produced and the losses are quite acceptable for a great many applications. This method is dealt with in several of the following articles.

Single mode fibres

However for the lowest losses and largest bandwidths it is necessary to use single mode fibres at a wavelength of about 1·55 μm. As mentioned above, the attenuation can then be as low as 0·2 dB/km(22) and it has recently been shown(23) that the bandwidth can be made larger than 20 GHz over 1 km. The wavelength of maximum bandwidth can be changed very simply, in a given fibre, over the range 1·3 to 2 μm by adjustment of the core diameter. It is thus possible to envisage transmission distances, without repeaters, of perhaps 100 km or more with a total system bandwidth approaching 1 GHz. Indeed the total system loss will be determined by the joints and connectors rather than by the fibre. The progress which has been made in fibre fabrication over the past ten years has thus been remarkable and the pace of development shows no sign of slowing down. Other fabrication methods than the ones mentioned here have also been reported, some of which are discussed in this issue.

In conclusion it is interesting, and indeed encouraging, to note the classic interplay with optical fibres, as in so many other fields of work, between fundamental science and technology which are so dependent on each other. Glass science indicated the possibility of achieving very low losses thus spurring a technology search for suitable materials and processes. The search has been so successful that an entire new industry has been spawned yielding further new results which aid our understanding of the basic glass properties.

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