NINTH W. E. S. TURNER MEMORIAL LECTURE

Glass, light, and the information revolution*

W. A. Gambling

University of Southampton, Department of Electronics and Information Engineering, Southampton SO9 5NH, England

The ability of glass to transmit light has been known for many centuries and the majority of its uses depend on this property. The fact that the efficiency of optical transmission is quite low has not been a serious disadvantage because the glass thickness is usually small, often only a few millimetres. Recently, however, there have been two developments of profound technological and sociological importance. First, certain types of glass can be made to have unprecedented purity and transparency. Second, glass fibre structures have been devised which provide a flexible guiding path under practical working conditions. The result is an optical transmission line which is light (in weight) strong, and extremely small, yet capable of carrying vast quantities of information over hundreds of kilometres without amplification.

The effects are far-reaching. For example, the use of copper wire and electric currents in the trunk telephone network is being abandoned in favour of glass fibres and light. Parallel developments in microelectronics provide an increasing ability to store and process information. Technologically advanced countries, including our own, are thus in the throes of an information revolution, the effects of which will be as profound as those of the industrial revolution two centuries ago. Increasingly, paper, and even travel, will give way to telecommunications so that services such as electronic mail and electronic newspapers will become commonplace.

It is an honour, which I much appreciate, to present this year's Turner Memorial Lecture. It is also a daunting propect, particularly as I look at the list of past speakers and also recall the stimulating address of Professor Newton which I was privileged to attend last year. The intimidation takes an additional form, because in terms of glass technology I am no more than an interested layman who has applied a very particular aspect of the subject, namely optical transmission, to his own research field of electronics. I am thus in danger of exposing my inadequate knowledge of the subject in a centre which has done so much to advance the scientific and engineering understanding of glass, particularly under the stewardship of Professor W. E. S. Turner, and later of Professor R. W. Douglas and Professor H. Rawson. I did not know Professor Turner but his research and reputation need no amplification from me. Neither could I add anything of significance to the views of earlier lecturers, nor state them so elegantly.

I met Professor Douglas only briefly before he retired but I collaborated with Professor Rawson in the late sixties and received much invaluable help and advice from him, without which we at Southampton would have been in great difficulty. I well remember my first visit to the Department of Glass Technology here and the feeling of alarm at the realisation of the magnitude of the task we were undertaking and with so little background knowledge. Professor Rawson was very patient, surprisingly so, with naive babes-in-the-wood who had wandered unwittingly into the glass technology world of science, technology, cookery, commercial security, vast quantities of empirical data, and, what sometimes seemed to us, downright witchcraft. However Harold Rawson turned out to be a fairy godmother, although even he was reduced to growling at us sometimes.

Glass

Glass is a remarkable material which has been in use in 'pure' form for at least 9000 years. The compositions remained relatively unchanged for millenia and its uses have been widespread, extremely important, but often unspectacular—just think of what life would be like without windows or electric lamps. During the present century the understanding and application of glass have expanded rapidly but without the results being obvious in everyday life.

My own interest in glass, or more particularly glass fibres, has been its use as a new medium for transmitting electronic information. What we set out to investigate in 1966 was whether it might be possible to replace copper wire and electric currents as a means of sending telephone and other types of signal, by glass fibres and light, i.e. replacing electrons by photons. At the time this seemed a very speculative idea, bearing in mind that electric signalling had been commonplace for over a hundred years and the glass fibres then available were totally unsuitable. In fact, research into optical fibres for transmission, initiated in three laboratories in this country, has been spectacularly successful and glass fibres are now in use on a massive scale, as I shall demonstrate.

The properties of glass that makes it of unprecedented value in this application are threefold.

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First, there is a wide range of accessible temperatures where its viscosity is variable and can be well controlled. Most materials, and water and metals are obvious examples, remain liquid until they are cooled down to their freezing temperatures and then suddenly become solid, as shown by the line a b c d in Figure 1. A glass, on the other hand, does not solidify at a discrete freezing temperature but gradually becomes stiffer, going through viscosity stages resembling thin treacle and thick treacle, and eventually becoming hard, as indicated by the line a b e. In the transition region where the glass is soft, it can be easily drawn into a thin fibre. It is rather naughty of me to be lecturing the Society of Glass Technology on such primary, and obvious, properties of glass—but rather fun. The diagram, by the way, is taken from one of Professor Rawson's excellent books(1) which contains a more detailed description of the properties of glass than is possible here. A more scientific but not rigorous, definition is that glass is a product of fusion which has been cooled to a rigid condition without crystallising.

The second crucial property of certain special, but simple, forms of glass, exemplified by silica, is the incredible optical transparency, a point to which I shall return in detail later. This extraordinary transparency requires that certain impurities must be reduced to the extent that in 1000 million parts of the glass there must be no more than a few parts of impurity. Rather special fabrication techniques, one of which was invented at Southampton,(2) have had to be devised.

The third vital property, and one which may come as a surprise, is the intrinsic strength of glass. This statement could be justified by quoting various statistics,(3) but for the present purpose it is sufficient to say that a fine glass fibre, if its surface is properly prepared and protected, is roughly as strong as a steel wire of the same diameter. Its measured strength is about 2 000 000 lb/in², so that a glass fibre of the type used in the telephone network, and having a diameter (125 μm) of twice the thickness of a human hair, will support a load of 40 lb.

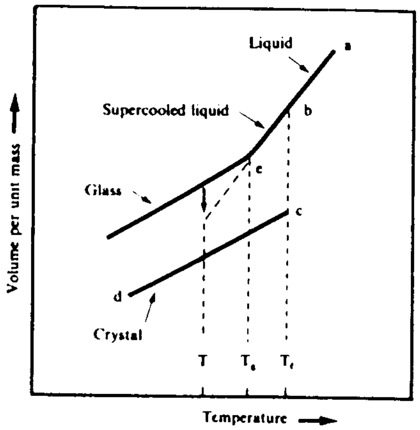

Figure 1. *Relation between the glassy, liquid and solid states*
T_g glass-forming temperature, rapid cooling
T_f crystallisation temperature, slow cooling

The requirement

However, before discussing the use of glass fibres it is necessary to address the question of why a new form of telephone line, or waveguide, is necessary. Figure 2 shows the increase in the number of telephones and telephone calls in this country from 1915 to 1980. The curves are of the classical form demonstrating exponential growth and indicating a doubling of use every five or six years; and this rise is continuing. In 1980, for example, some 20 000 million calls were made, an impressive figure. Assuming an average duration of 5 minutes and that most calls occur between 8.30 a.m. and 5.30 p.m., this suggests that at any time during the working day there are 200 000 people speaking on the telephone—and usually including the people we are trying to contact ourselves. It is worth noting that the telephone system is probably the biggest integrated man-made system in the world. In addition to telephone calls the telephone network increasingly carries television transmissions, computer and other data, and information of many kinds. The total demand on the system is therefore increasing at a far greater rate even than that shown in Figure 2.

One method of providing an increased capacity would be simply to replicate, many times over, the existing system; but if we were to do that we would soon be knee-deep in copper telephone cables. Experience has shown that it is far cheaper to devise a new means of transmission and this inevitably involves operating at higher frequencies, so that one line can carry an increased number of signals simultaneously.

An example of this general, but empirical, result is illustrated in Figure 3. The relative cost of providing a telephone service, for a given distance, with simple

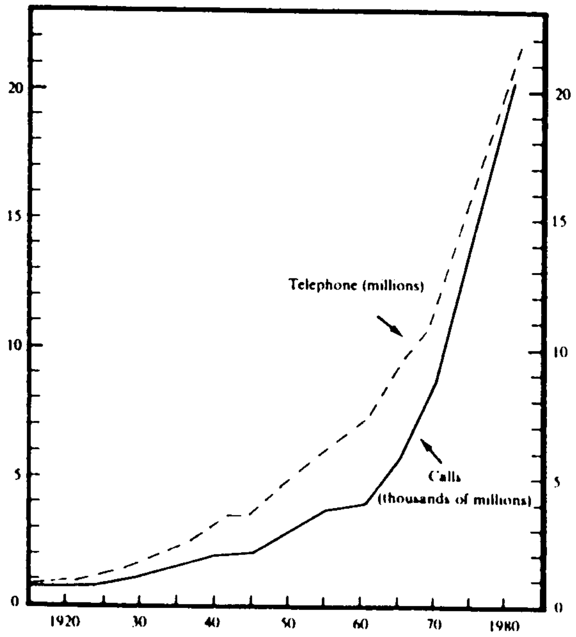

Figure 2. *Numbers of telephones and calls made in the United Kingdom from 1915 to 1980*

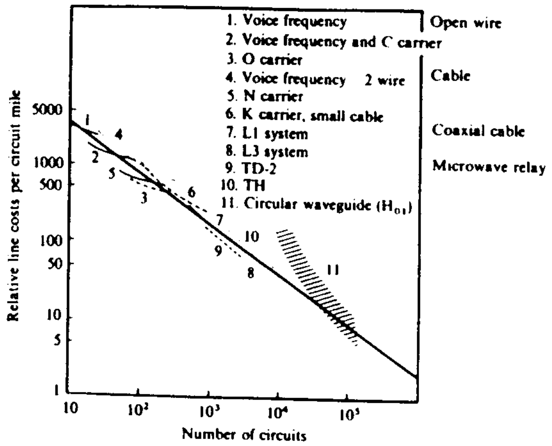

Figure 3. *Variation in the relative cost per circuit mile with the number of circuits in a system*

overhead wires (of the kind that used to be seen strung up on telephone poles up and down the country), is high, as indicated by curves 1 to 4. These circuits operate at low frequencies and therefore with low bandwidths. Subsequent curves are for higher frequencies, reaching microwave frequencies (in curves 9 and 10) of the order of 6 GHz with bandwidths in the region of 20 MHz over 1 km distance, i.e. a bandwidth × length product of 20 MHz km. The relative cost per unit distance is seen to fall dramatically, as more sophisticated technology provides operation at higher frequencies.

Light

Great excitement was generated amongst communications engineers in 1960 with the invention of the laser, because it was soon realised that the increased operating frequency, some 100 000 times greater than other communication sources, could, if it were properly harnessed, increase the information-carrying capacity of one channel by several orders of magnitude. Other optical methods of transmission have of course been used in the past.

Thus the approach of the Armada in 1588 was signalled by the lighting of bonfires on a series of hilltops—there are still many places, especially in the south, which retain the name 'Beacon Hill'. Only one unit of information could be sent at a time, and before another was possible the bonfire had to burn out and be rebuilt. In communication terms the rate of transmission was one 'bit' (binary unit) of information per day. The red indians of America increased this rate, with their smoke signals, to about 1 bit of information per minute, while those more fortunate individuals living in the land of sunshine were able to achieve 1 bit/s with a heliograph. The demands made by modern telecommunication requirements may be illustrated by the fact that a single colour television programme requires 100 million bit/s. It is also interesting to note that all those early methods of optical signalling were digital in form and we are still trying to get back to digital transmission!

In principle the laser is an excellent potential source for optical communications if only it could be made to have the ideal properties of being absolutely monochromatic, stable, robust, efficient, reliable, compact, and economic. Unfortunately such a laser still does not exist and we have to make do with more mundane versions which limit considerably the degree to which optical fibres can be exploited.

Glass fibres

The problem in 1961, when I started laser and optical communication research at Southampton, was to find a suitable guiding system for optical signals, in other words an optical equivalent to the copper wire or waveguide. A number of possibilities had been tried elsewhere but none of them seemed to me to have sufficient potential to merit investigation. Then about three years later, and in common with another group at STL (but unknown to me at the time), speculation began about the possible use of optical fibres. It seemed a long shot because existing fibres were mechanically very weak and could only transmit light over a distance of a few metres. However, at the invitation of your Vice Chancellor, Professor Sims, I read a paper(4) to the British Association for the Advancement of Science in 1964 in which I suggested they could be worth investigation. I also recall being somewhat scathingly cross-examined by the, then, Director of Research of the British Post Office for doing so. The real stimulus to optical fibre research came in 1966, with the now classic paper by Kao & Hockham(5) of STL, which had two important results. First, it showed that silica glass could be made to have a transmission loss below 20 dB/km, which was thought to be the critical value for economic application, and second, the interest aroused by the paper released money to support research!

There were some primitive forerunners of present-day optical fibres. The first recorded demonstration of light guidance by a transparent dielectric was by Tyndall, who put an electric lamp in a water container having a hole in the side. The emerging jet of water was illuminated by the light it transmitted. As far as optical fibres are concerned a patent was applied for(6) in France in 1836 to cover 'Weaving glass...either pure or mixed with silk, wool, cotton or linen'. The fabric received official recognition in 1840 when the remains of Napolean were transported to Les Invalides; the funeral draperies were woven of silk and glass fibre dyed in the mass and giving the appearance of gold brocade. The very fine fibre was produced by drawing ordinary or colloid glass heated by the flame of an enamelling torch.

Silica fibre was later fashioned in a spectacular way by Sir Charles Boys(7) who wanted a very fine, but strong, suspension in a sensitive instrument for the measurement of gravity. Silica was superior to metal because it was perfectly free from hysteresis and after twisting always returned to its original position. Sir Charles, who was a superb experimentalist, heated a rod of silica quartz in a crossbow (to a temperature of about 2000°C) which was then fired across the width of two laboratories. In this way exceptionally fine silica fibres were produced in varying diameters down to less than a 100 000th of an inch (i.e. 0·2 μm). What the Health and Safety at Work Executive would have said I shudder to think. His treatise, written in 1887, on the production of fine threads of various materials is utterly fascinating and contains some graphic descriptions.

For example, he experimented with the rapid drawing of a heated quartz rod into fibre with the aid of a rocket, but concluded that the method 'does not seem altogether convenient'. He also commented: 'Anyone who will stay in the room with a lighted two-ounce rocket, having no stick or head, will obtain a more vivid notion of the value of gravity on the sun than in any other way I know'.

A somewhat more orthodox method is that in which solid glass is heated to its softening temperature and then more gently stretched into a continuous long length which is wound onto a storage drum. Figure 4 is a close-up of a preform silica rod being drawn into fibre in a furnace operating at 2000°C at our laboratory in Southampton. Fibres can be drawn repeatedly with considerable precision, for example with a diameter variation of less than 0·1 μm in a total diameter of 125 μm.

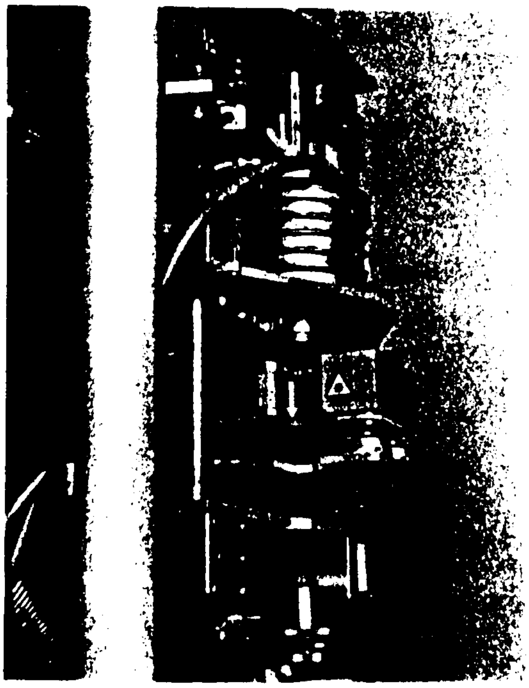

Figure 4. *A preform rod being drawn into a fibre in a furnace operating at 2000°C*

Light propagation in optical fibres

The mechanism of light conduction by glass fibres[8] can be understood in simple terms. Thus a ray of light striking the surface of a glass rod, Figure 5, from the inside, at an angle greater than the critical angle (i.e. at a small angle to the axis) undergoes total internal reflection. Furthermore the fibre can be bent and rays of light will still be successively reflected until they reach the output end. Thus although individual rays can only travel in optically straight lines, the multiple reflections ensure a remarkably flexible transmission path. Two key conditions must be satisfied, first that the surface of the fibre be smooth and uncontaminated, and second that the glass does not scatter or absorb the transmitted light. Bundles containing many fibres of this simple kind bound together were used in the post-war period up to about 1955 for image transmission. However the quality was poor due to light leaking out of the side of the fibres, which tended to break with handling.

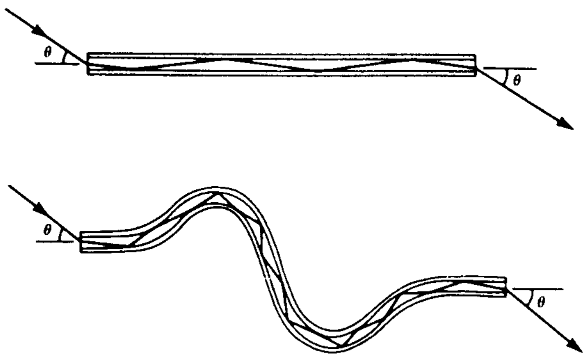

Figure 5. *Rays of light being guided in straight and curved glass fibres*

In 1955 Hopkins devised the idea of adding a second, cladding, layer of glass outside the guiding core to protect its surface.[9] The major requirements of the cladding glass are that its refractive index is lower than that of the core, it has a low optical transmission loss, and it should be mechanically and thermally compatible with the core.

Research begins

Following the realisation from the Kao & Hockham paper that silica was inherently capable of a low transmission loss, three programmes of research were undertaken, all in England. These were at the British Post Office Research Station, Standard Telecommunication Laboratories, and a joint effort between my group at the University of Southampton and the Signals Research & Development Establishment. The Southampton work at that time was mainly concerned with a study of glass materials and methods of fibre fabrication.

In the years up to 1970 there were not many laboratories worldwide studying optical fibre transmission. In particular there had been a deafening silence from Bell Telephone Laboratories. The reason for this was explained to me by Rudi Kompfner in a private discussion some years later and after his retirement from Bell Laboratories. He said he was in charge of optical communications research at the time and his experts had informed him that it would not be possible to reduce material losses in glass to the level required for long distance transmission. They therefore persevered with the work on a beam guiding system.(10) However, in the late 60s he had a visitor from the UK who pointed out the progress that was being made here and, said Kompfner, 'work on optical fibres started at Bell Laboratories the next day'! Interest was quickened much more strongly at the end of 1970 with the report(11) of a single mode fibre loss of 20 dB/km. No indication was given of how it was done, or what materials had been used, but a trickle of work began in other countries, which was soon to become an avalanche.

The new optical fibre fabrication technique

Lack of time compels me to ignore 16 years of intensive research and development, including our collaboration with Professor Rawson, but rather to jump immediately to the present state of optical fibre technology. Nor is it possible to describe the many advances created at Southampton, other than by referring to the 250 research papers, 20 patents, and 15 medals, premiums, and other awards, including the national first prize in the Academic Enterprise Competition, which we are fortunate enough to have been granted.

The critical step forward leading to the application of optical fibres was the development of a method of achieving a very high degree of purity in silica-based glasses. This came about through the choice of liquid starting materials which can be relatively easily purified by fractional distillation. The most widely used method is modified chemical vapour deposition (MCVD) developed simultaneously, but independently, at Southampton(2) and Bell Telephone Laboratories.(12) In this technique the chlorides of the appropriate glass-forming elements, such as silicon, germanium, boron, and phosphorus, are oxidised in a homogeneous reaction at 1500–1600°C and deposited as clear glass layers on the inside of a silica substrate tube.

Typically the initial layers of deposition are of borosilicate or fluorosilicate glass (or a combination of the two) to provide the cladding having a low refractive index. Subsequent layers normally comprise a combination of SiO_2, GeO_2, and P_2O_5 to provide a core of higher refractive index. The refractive indices of consecutive layers may be tailored, if required, by changing the composition, to produce a desired refractive index profile. In addition the numerical aperture of the resulting fibre, and the dimensions of both core and cladding, may be similarly preprogrammed under computer control.

The second stage in the fabrication process is to heat the silica substrate tube to a temperature of just above 2000°C, at which its viscosity decreases to the point where surface tension forces cause it to collapse slowly into a solid preform rod. The latter is drawn into a fibre in the third and final processing stage by the method illustrated in Figure 4. A preform 1 cm diameter and 50 cm long can provide a continuous 3 km length of 125 μm diameter fibre. There are a number of variations in this process but the MCVD method is the one most widely applied. The improvement in fibre transmission brought about by chemical vapour deposition techniques is such that transmission distances of 200 km are now possible compared with only 4 km with copper cable.

The range of optical wavelengths providing low loss covers 0·9 to 2 μm, corresponding to an enormous transmission window of 200 000 GHz, of which we can so far use only 1 GHz because of the limitations of the laser diode. The attenuation can be as low as 0·16 dB/km (i.e. the signal level falls to 50% after 20 km) at a wavelength of 1·55 μm.

An equally important parameter is the signal-carrying capacity, or bandwidth, of a fibre, or indeed of any transmission medium. In the case of single mode fibres there are two principal dispersive mechanisms which cause distortion of a transmitted signal; one is the dispersion of the material itself and the other is the dispersion of the waveguide. Glass, of course, is well known for its dispersive properties and the factor which causes broadening of a transmitted pulse, namely the material dispersion parameter, M, is given by(13)

$$M = \frac{\lambda}{c}\frac{d^2n}{d\lambda^2}$$

where λ is the wavelength, n the refractive index, and $c = 3 \times 10^8$ m/s.

In 1978 at Southampton we showed(14) that at wavelengths greater than 1·3 μm the material dispersion becomes negative and can be used to cancel the positive waveguide dispersion. Thus by suitable fibre design the bandwidth can be made almost infinite for most practical purposes. This method now forms the basis of all single mode fibre designs. The result has been a massive increase in the bandwidth × length product of installed optical fibres.

By their very nature optical fibres are small compared with copper cables, Figure 6, so that they can be installed in existing cable ducts with little difficulty. They are also light (in weight), flexible, and easily handled. Glass differs from a metal in that it is brittle, whereas a metal is ductile. As a result glass is commonly thought to be fragile, as indicated by the epigram below written in about 1665 and referring to the 'Gentlemen of Glass', as the privileged makers of glass were called:(15)

Figure 6. *Coaxial and optical fibre cables*

Votre noblesse est mince
Car ce n'est pas d'un prince,
Daphnis, que vous sortez.

Gentilhomme de verre,
Si vous tombez à terre
Adieu vos qualités.

Apparently all glass-makers were automatically classed as gentlemen—an attitude to technology which we can only envy today—and this quip was written by the rather jealous poet Maynard to a colleague. The same sentiments can be expressed more concisely, but much less elegantly, as 'a piece of glass will break if it is dropped'. Nevertheless a glass fibre is inherently strong if its surface is smooth when it emerges from the drawing furnace and a suitable (thin) protective coating is immediately applied. Even dust in the air can initiate cracks (the well known Griffith cracks) on an uncoated surface which can later lead to fracture under stress. Fortunately suitable coatings can be relatively easily applied so that optical fibre cables are strong, robust, light, flexible, and easily installed.

Information transmission

An additional advantage of optical fibres is that they are not affected by electromagnetic interference and can be safely installed in situations, such as fuel tanks and petrochemical plant, where metal conductors would produce a sparking hazard. These advantages, combined with low transmission loss, large bandwidth, and small size, have resulted in optical fibres being installed in telephone and other networks on a large scale. Thus the total length of optical fibre installed worldwide has risen from 5000 km in 1980 to 5 000 000 km in 1986—a staggering increase by three orders of magnitude. British Telecom ceased ordering coaxial cable for the trunk telephone network last year and well over 50% of trunk telephone traffic will be carried by fibres within four years. The latest experimental systems(16) have bandwidths providing bit rates up to 8 Gbit/s over distances up to 250 km.

The first optical fibre transatlantic cable is under construction and will be laid in 1988. Although extremely simple in design it will have a cost per circuit mile lower than any existing transatlantic cable and a capacity 40% of that of all existing cables put together. Some 60% of all underwater cables leaving the United Kingdom are shorter than 200 km and all of these could be replaced by cables having no repeaters—a considerable saving in cost. Similarly 50% of all underwater cables worldwide are less than 400 km in length and could be replaced by optical links requiring only a single repeater. The long-term impact on satellite point-to-point transmission, which is limited to microwave frequencies and bandwidths of only 20 MHz or so per channel, will be substantial.

It was possibly Groucho Marx who said 'Never prophesy—especially about the future' but I propose to ignore that advice and list below some of the developments which, I believe, will produce further major advantages in the range and performance of optical communication techniques in particular, and optical electronics in general, during the next decade:

coherent transmission and detection
optical fibre circuit components
opto-electronic sensors
optical storage
displays
optical signal processing and optical logic
organic optical materials

A discussion of these topics would require another paper but I would like to discuss briefly some recent research at Southampton on new types of optical fibre structure, in order to illustrate the wide range of glass fibre designs and materials which are only just beginning to be explored and exploited.

Novel glass fibre designs and circuit elements

Existing optical fibre systems are, in communication terms, very primitive. The optical source is not monochromatic or coherent and resembles instead an optical noise generator. Thus coherent detection techniques which are standard at microwave and lower frequencies, are not yet being applied in practice. Furthermore, optical circuit elements, with the exception of the fibre tapered coupler, have still to appear. In order to carry out any signal processing the optical signals have first to be converted to electronic ones and re-converted after the processing operation. This is obviously inconvenient and inefficient. Research is therefore underway to devise both active and passive circuit elements in fibre structures which are compatible with the fibre transmission lines. Such work has been in progress at Southampton since 1979 and some of the results will be described very briefly in order to illustrate the exciting range of possibilities which are available.

Figure 7 shows the cross section of a single mode fibre in which sectors of high expansion coefficient, e.g. borosilicate, glass have been introduced in close proximity to the core. As the fibre cools from the drawing temperature of 2000°C to room temperature a very large asymmetric strain is produced which, in turn, causes a large difference in the refractive index distributions in the two orthogonal principal planes. Such fibres are highly birefringent and can be used to control the plane of linear polarisation in both communication and sensor applications. The Southampton 'bow tie' cross section(17) has the largest birefringence and the lowest transmission loss, 0·2 dB/km, yet reported. In a survey carried out at the US Naval Research Laboratories it was found to be the best available.(18) By suitable design it can also be made into a highly effective polariser.(19)

By spinning a preform at high speed during fibre drawing the resulting fibre has almost zero birefringence.(20) It can be used for the measurement of high currents at high voltages through the Faraday effect, although birefringence will be reintroduced by external effects if it is not properly handled.

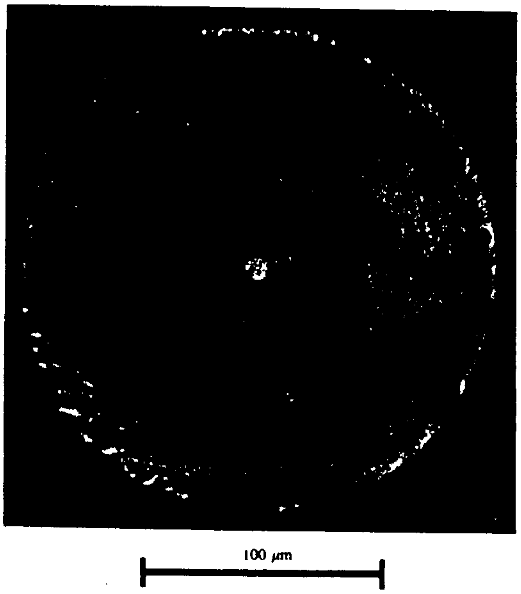

Figure 7. *Bow tie fibre structure showing stress-producing sectors on either side of the central core and cladding*

If an MCVD preform is inserted into a hole drilled off-axis in a silica rod and the whole is then drawn into fibre whilst being rotated, as shown schematically in Figure 8, the core of the fibre is no longer straight but helical. This kind of fibre has a high degree of circular birefringence,(21) ten times greater than has been produced by any other technique. The helical core fibre can also be used to control the polarisation in communication and sensor applications and is relatively unaffected by external influences such as bends, pressure, change of temperature, and so on.

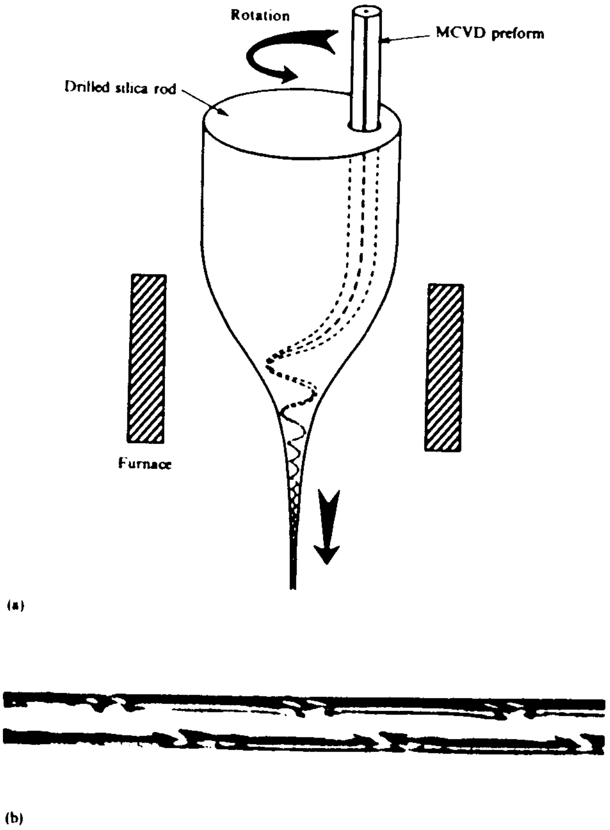

Figure 8. *Fibre with a helical core*
(a) fabrication
(b) side view of helical-cored fibre

Another type of fibre is that in which a metal element is introduced longitudinally and very close to the core. Such structures can also behave as polarisers, can support surface plasmons, and can produce modulation of the transmitted light. Active fibre devices are therefore possible through electro-optical modulation of the core field, as in this case, and also by creating diffraction grating structures directly on the core itself.

Finally, it has proved possible to introduce rare earth ions into the core of single mode fibres(22) without significantly increasing the attenuation at the low-loss wavelengths. As with the MCVD fabrication method, suitable starting materials are the chlorides of the rare earth elements. Unfortunately these are solid at room temperature and are hygroscopic so that a special adaptation of the MCVD equipment is necessary, as indicated in Figure 9. An additional chamber into which the rare earth chloride is inserted is added to the standard preform tube. During deposition of the core layers it is heated to a sufficiently high temperature, usually about 1000°C, to create an adequate vapour pressure of the rare earth chloride for it to be blown down the tube with the other chlorides, oxidised, and deposited in the usual way. Special techniques are required to remove the water chemically bound to the solid.

The technique has been remarkably successful and some five different rare earths have been incorporated so far. Lasing action has been obtained with neodymium at 1·088 μm and erbium at 1·5 μm. These fibre lasers are simple, flexible, highly efficient, and can be pumped at very low powers, for example with only 100 μW from a simple laser diode. They have been operated as amplifiers, can be tuned over a wide range of wavelengths, and can be Q-switched. Glass fibre technology has thus produced a new type of laser which will have important applications in many different areas.

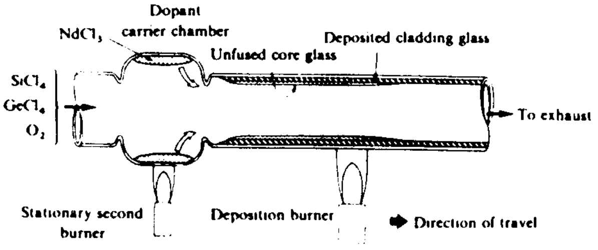

Figure 9. *The doping of optical fibres with rare earth oxides*

The information revolution

Now what effect will optical fibres and light have on our everyday lives?

At first the effect will be gradual but a silent revolution is already taking place, which has three components. First, optical fibres can carry vast quantities of information over large distances. Second, through microelectronics it is possible to produce hundreds of thousands of tiny electronic circuits on a small silicon crystal only a few millimetres square. Information can thus be stored and processed, again in large quantities and very rapidly indeed. Third, through microelectric circuits we have increasingly small, cheap, and very powerful computers. The 'silent revolution' is in fact an electronics revolution which is going to have as profound an effect on our lives as did the industrial revolution 200 years ago. We are entering the age of information.

Consider how archaic are some of the methods used for transmitting information today. Take letters for example. After writing a letter it is put into an envelope and taken to a post box. From there it is collected by a postman and transferred to a sorting office where it, and thousands of other letters, are sorted into bundles for all the various destinations. This transport and sorting may happen several times. The letter is then manually put on a train or truck, and perhaps on an aircraft, being handled manually at every stage. Then the whole process goes into reverse and after being handled maybe 15 or 20 times, the letter finally arrives at its destination. The cost of postage is already high and will rise still more; but how much simpler it is to send letters along the telephone line. More people are acquiring home computers, with a simple, cheap keyboard, on which letters can be sent, while received letters could be printed on a simple printer or displayed on an ordinary television screen.

This may sound futuristic but it is not. Telex services are well known and are available in many offices, factories, and even universities. I can send a letter by telex to many countries and receive a reply the same day. British Telecom has launched a more sophisticated system in which electronic mail can be sent, stored, even redirected if necessary, in far less time than it takes to write a letter.

The telephone could thus be used, in conjunction with the television set or a simple printer, as a data terminal, with which more and more school children are already becoming familiar. Instead of taking days to arrive, with an enormous cost in manpower and energy, letters—and not only letters but also documents, diagrams, pictures, and books—could be sent almost instantaneously.

The branches of banks are today connected to a central computer to enable a rapid and up-to-date check to be kept of all accounts and one can draw money with a coded plastic card at a cash dispenser. In future all offices and factories of most firms will be interconnected in the same way so there will be much less travelling from one branch to another.

Computerised references to books and periodicals are already available and the logical extension would be to connect all journals and books to a computer store so that access would be possible from one's home. The saving in the costs of school, college, industrial, and public libraries would be considerable.

There are many other possibilities. If a glass fibre cable can be made as cheap as the telephone wires that come into the home from the local exchange, then the meagre bandwidth we presently have could be greatly increased. The private citizen could have a communication capability, or bandwidth, exceeding that of any commercial or private enterprise today. He could have direct access to a national or regional computing centre. He could dial the computerised library of the future from his armchair and have pages from books displayed on his own TV screen. Some of this is already happening.

Have you ever thought how crazy is our system of delivering news via newspapers? We begin by cutting down acres of forest and then ship thousands of tons of wood pulp all over the world, while trains, lorries, and vans all over the country carry hundreds of tons of newspapers in all directions and thousands of paper boys and girls push them through letterboxes (or throw them into drives in the rain): the disposal of the newspapers is then a problem. The whole operation involves great damage to the environment and great waste of natural resources. Sending news by electrical or optical means is so much more efficient and easier. It would be more sensible to dial our newspapers from home and read them on the television screen, printing out those parts we want to read at leisure. There are lots of other exciting ideas—it has even been suggested that instead of commuting to work we will communicate to work.

In the future such information services in the home will be taken as much for granted as power and water services are today (Figure 10).

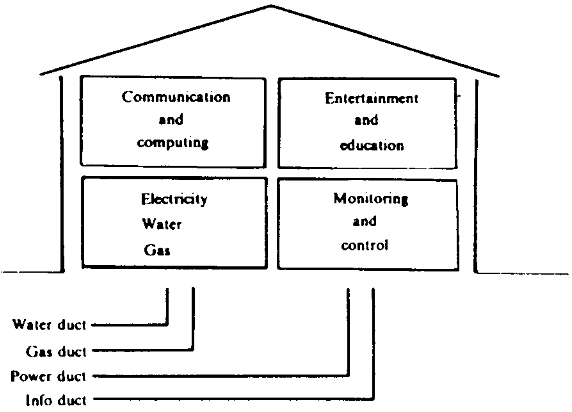

Figure 10. *Services to the 'high-technology' home*

Conclusion

Glass technology in the form of optical fibres has transformed our ability to transmit 'electronic' information. Fibre transmission lines can operate over distances 50 times greater than copper coaxial cable and with bandwidth × length products many orders of magnitude larger. With their additional advantages of small size, flexibility, and freedom from electromagnetic interference they are rapidly displacing other forms of cable in many fields of application including communications, sensors, and optical electronics.

The Department of Glass Technology, under Professor Turner and his successors, has made notable contributions to the basic science and technology of glass and I would like to acknowledge the great debt I, and many others, owe to it.

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