Optical Fibre Communications

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Major-General D R Horsfield OBE was in the Chair

INTRODUCTION

Chairman: Welcome to the annual Technological Lecture of the Royal Signals Institution. I must first thank the Commandant for allowing us to have it here, and through him also, all those people who have done a good deal of work to meet our various requirements.

I am sad that Colonel Edward Day is not here today; he has had to rush up to Cheshire because his mother died, but this would have been the last occasion on which he, the retiring Secretary of the Institution, would have been in front of you all and it would have been a very good opportunity to thank him for the many things he has done on behalf of the Institution in the years he has been with us.

I must now warn the miscellany of regular attenders at this lecture, that there is a minor variation to the way in which we run it. We have in the past had a substantial break between the lecture itself and the discussion. This year, for one reason or another, we are going to have a very short break, so that when the moment comes please do not wander too far afield.

The Commandant of a rival school, not awfully far north of here, used to have a standard opening address for new courses. He used to say: Gentlemen, if you do not know why you are here for God's sake find out! This is a much better run establishment; I am sure that all of you have found that the subject of our lecture this evening is 'Optical Fibre Communications'. So at this point it is my pleasure to introduce Professor Alec Gambling from Southampton University, who is the immediate past Dean of the Faculty of Engineering and Applied Science, and Professor of Electronics there. He is an old friend of Signals and perhaps in particular of the School of Signals, having been for some years one of the moderators appointed by the IEE for the Telecommunications Engineering Courses when we ran them. I am told that his research interests are in microwaves, lasers, and optical fibre communication. So I now invite him, as indeed he has been warned, to speak on the last of these three subjects. Professor Gambling.

LECTURE

Introduction

GENERAL, ladies and gentlemen. The warning has been duly heeded and fortunately I can actually remember the topic on which I have been asked to speak! There is a very reasonable chance that I will talk about optical fibre communications.

When invited to give this annual technological lecture I was naturally both pleased and honoured and immediately accepted. But as the time approached my apprehension increased and I feel in the position of the celebrated person who tried to teach his grandmother to suck eggs. After all, I think it is a little foolhardy for an academic, particularly one whose only contact with a real live telecommunications system is occasionally to use the telephone, to address such a distinguished, expert, audience on a topic which is quite new and has hardly yet emerged from the research laboratory. I have the feeling that I will tend to talk rather enthusiastically about a new toy, forgetting many of the practical problems that will be faced by the users in the field.

I hope, therefore, that you will forgive my temerity as well as the somewhat informal approach. I have always been very impressed by the highly professional presentations which are characteristic of the Services and particularly those which I have heard given in this hall, as General Horsfield says, by officers on various TE courses in the past. I think that other teaching institutions, including universities, could learn a lot from you. I hope that I have learnt a little, but nevertheless I fear that I cannot match the quality to which you are accustomed, although I will do my best.

My talk is concerned with light as a communications medium and the aim of the work I am about

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to describe is to make the application of optical techniques as practical and as widespread as possible. The principles can be illustrated by reference to the telephone network and I do not need to tell you that the input to the telephone network comes from an instrument of the kind in Fig 1. Modern ones are somewhat different in external appearance but the basic operation has not changed much in very many years.

The output from a telephone handset consists of a modulated electric current which flows to a local exchange: from the local exchange the signal may be taken to an intermediate exchange and, for long-distance calls, batches of signals are then sent to a trunk exchange. The multiplexed signals between trunk exchanges are transmitted by cable, microwave link or satellite as illustrated in Fig 2. Most modern long-distance systems operate at frequencies up to 4GHz or so in the microwave region. Satellite communication has, for the first time, enabled us to watch televised events, such as the Olympics in Japan, from the other side of the world, with only a fractional delay (underwater cables do not have sufficient bandwidth). The overmoded waveguide is not yet in operation but has been developed in an effort to cope with a rapidly increasing amount of trunk telephone traffic. The latter has been doubling every six years or so in most technologically advanced countries, but whether this trend will continue with the recent swingeing increases in telephone charges is doubtful but certainly the present rate of increase is very large so that new systems are urgently needed. The application of fibres with which I shall be primarily concerned is in these trunk circuits.

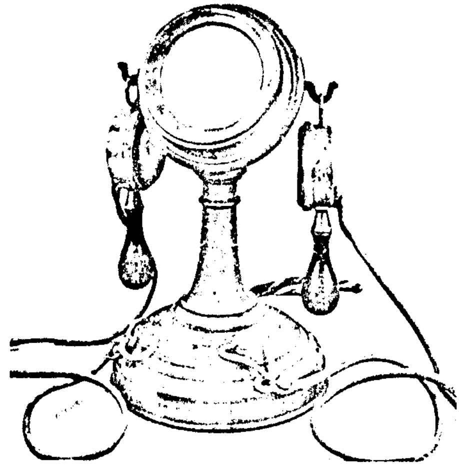


Fig 1—An early telephone

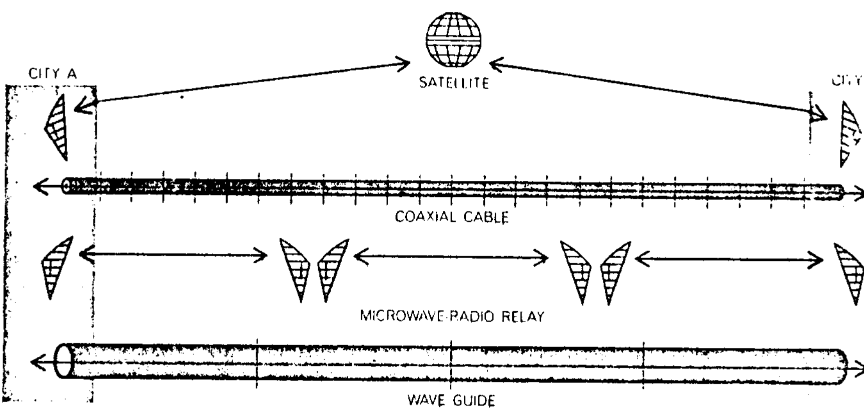


Fig 2—Four Electrical Techniques for transmitting a large volume of messages over a long distance are available at present. The newest technique involves the use of artificial earth satellites (top). The coaxial-cable system (second from top) still carries a large proportion of the communication traffic between cities in the US. The largest share of the intercity traffic in the US is transmitted through the air by means of microwave-radio relay systems (second from bottom), with amplifying stations spaced some 20 to 30 miles apart. The wave guide technique (bottom), which has recently been perfected, will be able to carry more communication traffic than any other system currently available. Amplifiers (short broken lines) are spaced two to four miles apart in the coaxial-cable system and 10 to 15 miles apart in the wave guide system. Microwave-radio relay horns are actually 10 to 15 feet in diameter.

Optical Communications

The overmoded waveguide is one possibility, but when the laser was developed in 1960 communications engineers, or some of them in research laboratories at least, saw it as potentially a new carrier source operating at a frequency several orders of magnitude higher than the existing microwave ones and therefore potentially capable of a correspondingly higher bandwidth. Obviously there were many problems to be overcome before the laser could be put to large-scale practical use The first is the necessity to make it operate in a manner equivalent to that of a sine-wave oscillator. It certainly did not do so in the early days but a number of them do now. But if we assume that we can make a laser operate satisfactorily it is necessary to consider the type of transmission medium to be used.

The simplest possible medium is free space in which a laser beam—assuming it is coherent as indicated in Fig 3(a)—can be transmitted over long distances and there are two main problems to be considered. One is that the beam expands as it propagates but the law of diffraction is a very simple one, namely that the half-angle of spread is given by the ratio of the wavelength to the beam diameter. Thus a laser beam having a wavelength of $1\mu m$, say, when transmitted through an aperture of about 1m, equivalent to a moderate-sized telescope, broadens at a rate of only about 10^{-6} radians. Over a quarter million miles such a beam will only become about a kilometre in diameter. In fact this particular experiment was carried out some years ago and, by measuring the time of reflection of a short pulse of light, the distance from the earth to the moon was measured with an accuracy of a few centimetres, so we now know where the moon is! The second problem is that of aiming the beam accurately which, as the moon experiment shows, is not insuperable for realistic distances. Calculations have also shown that, providing we can aim with the required precision and stability, it is possible to communicate over distances of the order of ten light-years, given a perfect 200-inch telescope. It is an interesting thought but it would be a very leisurely sort of war in which one could afford to wait twenty years for a reply to a signal.

Obviously any large-scale practical application will be within the earth's atmosphere and here a major problem is that a light beam is easily deflected by a refractive-index gradient. For example, a beam of, say, 5cm diameter propagating over a distance of 1km, only requires a transverse temperature difference of 10^{-3} °C to deflect it through a distance at the receiving end equal to its own diameter. Temperature gradients in the atmosphere are normally much greater than this and in addition there is turbulence, so not only does the beam flap up and down like a dog's tail but it breaks up into smaller beams and these in turn wave about randomly. The nett result is that free-space propagation within the earth's atmosphere is limited to distances of the order of a kilometre for reasonably reliable communication, even in clear weather. As far as I know there has been only one commercial application of unguided propagation and that is by the Japanese post office across Tokyo.

Beam Guidance

The beam can, of course, be protected from the vagaries of the atmosphere by putting it inside a pipe. The latter can be evacuated, or lagged and buried underground, to produce a constant-temperature enclosure and there is then a reasonable chance of getting reliable propagation over kilometre distances. However spreading of the beam due to diffraction ultimately causes it to be reflected from the walls, thereby producing loss and the phenomenon of multipath dispersion.

A novel suggestion was made, some ten or so years ago, of correcting for the diffraction spread of the beam by a series of converging lenses as shown in Fig 3(b). Some idea of the physical size of the structure may be gauged from the fact that lens diameters are typically a few centimetres with separations of a few hundred metres. Experimental systems have been built and in an experimental 1km length the measured transmission loss was about 1dB/km. That particular system was mounted above ground and could only be used for 20 minutes or so during the night because of the ambient temperature fluctuations but in principle it could be evacuated or buried underground and lagged. Another disadavantage is that light travels in straight lines and a beam transmission line laid between New York and Chicago, or London and Glasgow, would have to be optically straight. Corners could be turned using mirrors and some fine control would be possible by controlling the angular position of each of the lenses but the difficulties of crossing cities and urban conurbations generally, as well as correcting for subsidence and slight earth movements, can be imagined.

Obviously, then, a system of this kind would be very expensive; despite the low transmission loss and the enormous bandwidth which would be limited, in fact, not by the transmission line itself but by the modulator used on the input beam.

Optical Fibres

A good deal of work was done on the beam guiding system, almost entirely in the United States, but it just is not a feasible proposition, especially for this country, in the foreseeable future. Thus ten years ago the concept of optical communications was not making much progress. However in 1966 Kao and

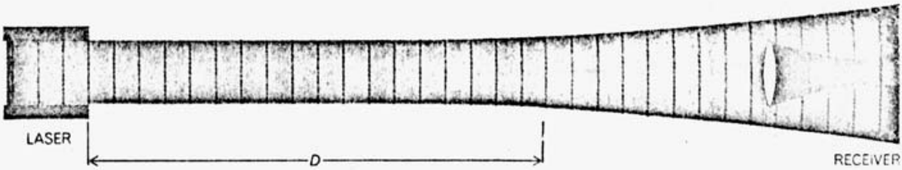


Fig 3(a)—Spatial Coherence of a laser beam makes possible highly directional transmission. A plane-wave laser source radiates a beam that is almost constant in width for a distance (D) equal to the diameter of the source squared, divided by four times the wavelength of the radiation. Beyond this distance the beam gradually expands to form a cone. The expansion of the beam is greatly exaggerated here; in actuality D would be about three-fifths of a mile for a two-inch beam with a wavelength of some 6,300 angstrom units.

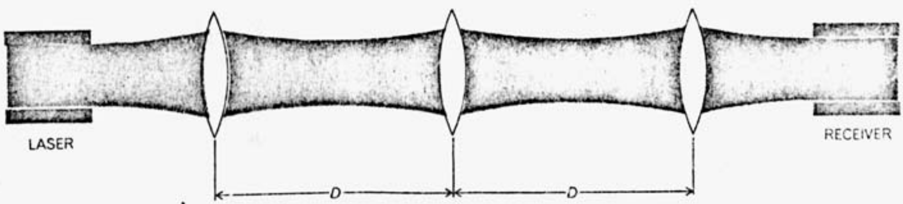


Fig 3(b)—Series of Lenses spaced at the distance D apart could be used to confine the laser beam and guide it to the receiver. The power loss at each lens due to beam expansion could in principle be made as small as one part in 100,000 or even less by making the lens spacing 20 to 40 per cent less than D. Again the beam expansion has been greatly exaggerated and the horizontal scale compressed.

Hockham at Standard Telecommunications Laboratories suggested that a glass fibre might be used as a light-guiding medium. The physical principles behind this are extremely simple and I would like to remind you briefly of some O-level physics. Fig 4(a) shows a ray of light propagating in a dense medium (ie one having a refractive index n_1) and incident on an interface with a less dense medium (lower refractive index n_2). In general a ray in the dense medium striking the interface is (a) partially reflected and (b) partially transmitted and simultaneously refracted. The relation between the angles of incidence and refraction is given by Snell's law as

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

As the angle which the incident ray makes with the normal increases, so also does the angle of the refracted ray. Thus the refracted ray moves closer to the interface until the point is reached where it does not enter the second medium but travels along the

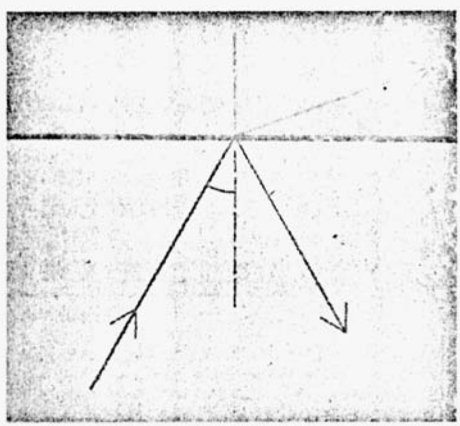


Fig 4(a)—At Shallow Angle to perpendicular most of light travelling through one transparent medium will cross interface (heavy line) into another such medium.

surface, Fig 4(b). If the angle of incidence is further increased Fig 4(c) shows that there is no longer any transmitted energy in the second medium and all of the incident energy is reflected. It has been assumed that both media are lossless so that there is a perfect reflection. This simple physical phenomenon is the basis for light propagation along fibres.

The practical configuration for an optical fibre, Fig 5, comprises a cylindrical core region of refractive index n_1 surrounded by a cladding of refractive index n_2 where $n_1 > n_2$. Thus a ray entering at not too large an angle with the axis, given perfect media, propagates unattenuated and is guided by successive reflections at the core/cladding interface. Now between reflections the ray travels in a straight line but the fibre can be bent since, providing the radius of curvature is always much larger than the diameter of the fibre, the only effect is to change the angle of reflection slightly and there is little loss of energy through the cladding. As we will see later, the diameter of the fibre need be no more than 50-100μm, ie about the thickness of a human hair, so that it bends quite easily. The ray still reflects at the interface and propagates around the bend with ease.

The propogation mechanism is illustrated, and summarised, in Fig 6. It can be seen that rays at small angles to the axis travel along the core of the fibre by successive reflection with no loss of energy, while rays at larger angles, as illustrated by the short-dashed line, suffer some loss by refraction at each reflection and thus experience a large transmission loss. Fig 6 shows that this method of propagation results in multi-path dispersion.

A typical multimode fibre exhibiting multipath or multimode dispersion may have a core diameter typically in the range 40-80μm compared with an operating wavelength of about 1μm. One method of reducing multi-path dispersion is to remove higher-order modes by making the core cross-section smaller.

In fact, if the core diameter is in the range 2 to 10μm, depending on the refractive index between core and cladding, single-mode operation results. The single-mode fibre, Fig 7, behaves in an entirely comparable way to, say, X-band waveguide, the width of which is selected to give single-mode operation at a frequency of about 10GHz (more accurately, over a range of frequencies in this region). The bandwidth possible in single-mode fibres, turns out to be tens of gigahertz over tens of kilometres. The outside diameter over the cladding of the fibre is made 50-100μm for convenience in handling and may be compared with a present-day coaxial cable having a bandwidth of something less than 50MHz and a diameter of several centimetres. Thus in the cross-sectional area occupied by a coaxial telephone (long-distance) cable may be inserted many thousands of fibres each having a much larger bandwidth. There

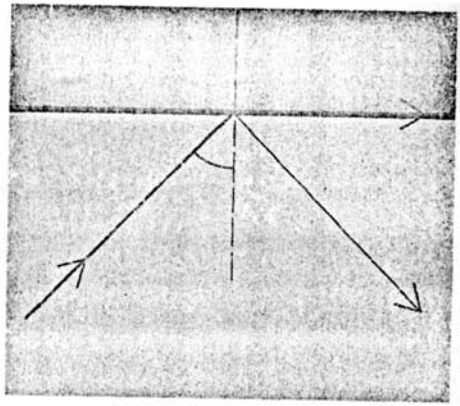


Fig 4(b)—At Critical Angle most of the light will travel along the interface, and remainder is reflected within the first medium.

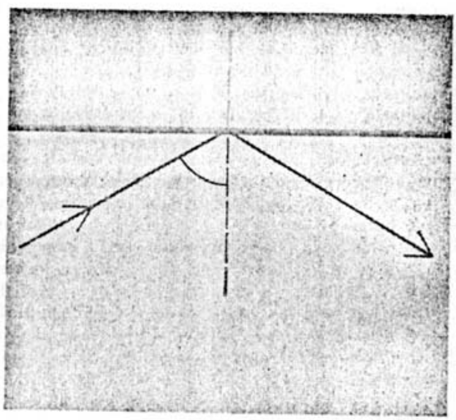
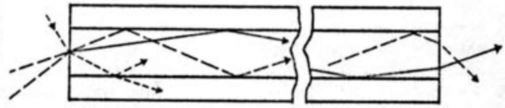


Fig 4(c)—At Steep Angle all the light is reflected from the interface and continues its journey wholly within the original medium.



(a)

Fig 6—Ray propogation along a cladded multimode fibre. Rays incident on the core/cladding interface at an angle greater than the critical angle are completely reflected (if the cladding is lossless) and are guided by the core. The ray illustrated by the dotted line falls outside the numerical aperture and loses energy at each reflection.

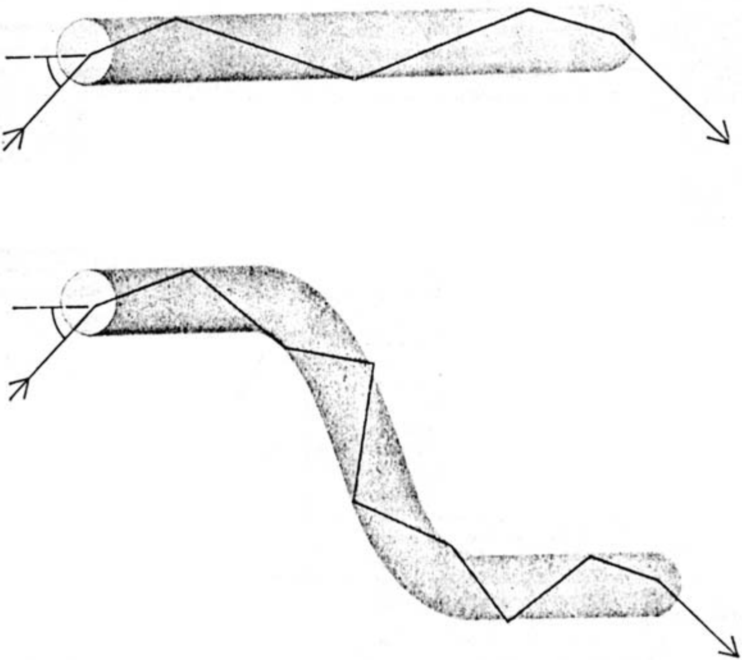


Fig 5—Angle of Exit of light emerging from a fibre (top) is same as angle of entry. Even if the fibre is bent many times (bottom) the light will travel all the way through it.

is thus the possibility of a very high degree of spatial multiplexing.

The objective of optical-fibre communications is to replace copper wires and electric currents with glass fibres and light and, as you can imagine, this is a fairly challenging task. We have managed with electric currents and copper wires for a long time and the chances of being able to replace them with a completely new system seemed to be rather slim in 1966 when the best optical materials available had bulk transmission losses of many hundreds of decibels per kilometre and the corresponding figures for fibres were some 1,000dB/km. Fibres of this kind, bound together in bundles by a plastic coating were, and still are, used for short distance "conduction" of unmodulated light, ie as a flexible light guide for such applications as medical endoscopy and so on.

Fibre Fabrication

In the past ten years tremendous progress has been made in developing fibres suitable for long-distance transmission. In order to reduce losses to a reasonable level, eg less than 20dB/km, it is necessary to make materials that are extremely pure, indeed the concentration of some common impurities such as copper, iron and chromium, have to be reduced to the level of a few parts in 10^9. This is an almost unprecedented degree of perfection, not often achieved, but a lot of work has been done with quite startling results. I do not intend to dwell for very long on methods of making fibres, but it might be interesting to scan briefly through two distinct methods which are used today. The first of these involves deposition of a glass from a gas or a vapour and at Southampton we have been fortunate in producing some interesting developments. Basically the method is comparatively simple. As shown in Fig 8 it is possible to deposit phosphosilicate glass, which happens to be a good material for fibre applications, by passing through a silica supporting tube the chlorides of phosphorus and silicon in vapour form, together with oxygen. When the mixture is heated the chlorides are oxidised to phosphorus pentoxide and silica which deposit as a glass directly on the inside walls of the tube. Having deposited the appropriate number of layers in the tube the composite structure has to be processed into a fibre. The way this is done is shown in the second line of Fig 8, namely to collapse the tube into a solid preform and then to draw that preform into fibre. One of the virtues of this technique is that it can be applied under relatively unsophisticated conditions.

The second, and conventional, method of making glasses is to heat solid raw materials in a crucible, then to stir and refine the melt and so on. Optical glass has been made in this way for many years but considerable refinement is necessary to produce a transmission loss of less than 10dB/km. It is as if one wished to make window glass which, in a sheet 1km thick, would only reduce the transmitted light power by 90%. However the conventional glass-making process has been developed quite recently to the stage where this can indeed be done. Very pure raw materials are needed which are very expensive. In addition the ingress of impurities from the crucible and from the ambient gas must be prevented. The system is still basically the classical one of putting raw materials into a crucible, followed by heating, melting and stirring but if this is done properly and with great care, under clean-room conditions, then low-loss glass is obtained.

Fibre Drawing

Two glasses are needed, one for the core and one for the cladding which protects the core from chemical attack, deterioration and damage. By making a rod of the core glass and a tube of the cladding glass a composite preform can be made as shown in Fig 9(a). The preform is placed in a vertical furnace, heated and pulled and the glass then tapers as it is drawn. The diameter of the resulting fibre depends on the relative drawing and preform feed rates. An alternative technique is shown in Fig 9(b) where core glass is fed into an inner crucible and cladding glass into the outer one. Again the combination is heated in a vertical furnace so that the glasses flow out of the concentric nozzles forming a cladded glass fibre.

A fibre drawing machine is illustrated in Fig 10. In this particular case the furnace operates at a temperature of about 2000°C and is supplied at the top with a silica deposited preform. The furnace heats the preform to a temperature at which the viscosity is similar to that of treacle and the winding drum draws the fibre at a speed of a few metres per second. The drum speed and the preform feed rate are locked together and kept stable to better than 0·1%. The furnace temperature is stabilized to ±0·06°C. Depending on the size of the preform fibre lengths in the range 1 to 4km or more can be drawn. As mentioned above, very low attenuations have now been achieved, particularly with vapour-deposited fibres, and curves for several different materials could be shown. A typical result for the Southampton fibre using phosphosilicate glass, Fig 11, shows that the transmission loss has a minimum value of about 2dB/km and is very low over the wavelength range 0·8 to 1·2μm. Quite recently a Japanese copy was made of the Southampton fibre—identical in materials and concept but superior in performance! A record low loss of 0·5dB/km has been achieved and a summary of various results is given in Table 1.

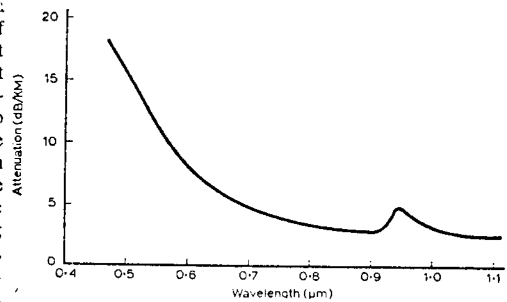


Fig 11—Spectral attenuation curve of 1·2km length of phosilicate-core silica-cladded fibre.

Light Sources

Fibres with low transmission loss can be made in lengths of many kilometres. They have low transmission loss at wavelengths of about 1μm, which is particularly fortunate, because two or three possible light sources operate in this wavelength region. One of these is the semi-conductor injection laser based on GaAs which produces an output between 0·8 and 0·9μm depending on the details of construction and, as well as the laser, there is the corresponding light-emitting diode. Another laser, based on neodymium-doped yttrium aluminium garnet (YAG), operates at 1·06μm but it is larger and more complex than the semi-conductor laser. The latter is very attractive because it is small, about the size of a transistor and made by similar techniques and, in principle at least, relatively cheap. It is driven by passing an electric current through the junction and can be directly modulated, ie the output can be switched on and off very rapidly simply by pulsing the current. In addition the small size makes it compatible with a fibre. One of the problems is that present-day semi-conductor lasers are not sufficiently reliable—lifetimes of the order of 10,000 hours for laboratory specimens have been reported, but for post office applications lifetimes under large-scale production conditions need to be an order of magnitude longer. However progress is being made although semi-conductor lasers might well require considerable further development to produce the required lifetimes. On the other hand light-emitting diodes (LED) of about the same operating wavelength exist and could very possibly be used. Their lifetimes are relatively long and if properly pulsed and used with a power supply having a low output impedance, they can be modulated at rates approaching 1GHz. Thus the light-emitting diode is indeed a possible carrier source for fibre communication systems. But this raises the question of bandwidth and the mode of propagation in the transmission line. We have seen that bandwidths of 1GHz over 10km are possible but to achieve a reasonable launching efficiency in a single-mode fibre a laser source is required. This would seem to rule out a light-emitting diode.

The bandwidth of optical fibre transmission lines

An LED is a Lambertian-type source and gives out its radiation over a solid angle of 2π so that the launching efficiency into a single-mode fibre is effectively zero. The launching efficiency into a multi-mode fibre is reasonable but because of multipath dispersion the bandwidth of a step-index fibre of core diameter, say, 50μm is likely to be $\sim$10MHz over a kilometre, not 10GHz over 10km. However a novel suggestion was made in Japan some years ago. It is a very simple idea and like all simple ideas it seems quite obvious when explained. The Japanese engineers said that the type of fibre having a core of one refractive index and a cladding of another refractive index is only a particular case. Consider the general case of a fibre where the refractive index on the axis is large—ie large relative to the rest of the fibre—and falls off steadily and monotonically in the radial direction. In particular, consider the case where the refractive index falls parabolically with increasing radius. Now if a ray of light is launched along the axis, as shown by the solid line in Fig 12, then that ray will continue to propagate along the axis of the fibre. It will have a certain propagation time in travelling from one end of the fibre to the other. Suppose now another ray is launched parallel to the first but at a distance from the axis. When that ray enters the fibre it experiences a refractive-index gradient. As a result the ray is deflected towards the axis. Naturally on crossing the axis the refractive index gradient reverses direction so that the ray is progressively deflected in the opposite direction, eventually becoming parallel to the axis and then re-crossing it again, and so on. The same happens with any paraxial ray and whatever the distance of the ray from the axis it always passes through the same points of intersection along the length of the fibre.

This is all very interesting but does it help? In fact it does because the optical path lengths of the various rays are identical. The rays which enter at a large distance from the axis follow a longer geometrical path, but they spend more time in a region of low refractive index where they travel faster than a ray along, or nearer, the axis. The latter remains in a region of high refractive index and therefore travels more slowly. As a result the propagation time for each of the rays illustrated in Fig 12 is the same and the effects of multipath dispersion are very neatly avoided.

In practice the method does not work quite as perfectly as that, as might be expected. What I have said is true for rays which are parallel to the axis.

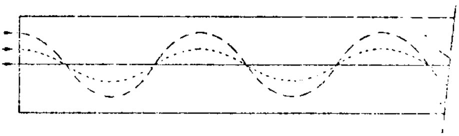


Fig 12—Propagation of paraxial rays in Selfoc.

Unfortunately it is not true for rays which enter off axis and at an angle to it. But all is not lost because there are other refractive index distributions which, while not producing perfect transit-time equalization, nevertheless are substantially better than a step-index fibre.

It is now possible to draw some fairly broad conclusions concerning signal capacity. In principle a very large bandwidth, compared with present-day coaxial cables, can be obtained using a single-mode fibre and a laser. However there are problems to be overcome, particularly in improving the lifetimes of semi-conductor lasers. Furthermore single-mode fibres are difficult to handle because the core diameter is about 1μm; for example to make a low-loss joint the tolerance on traverse alignment when jointing fibres is $\sim$0·1μm. If one thinks of the post office engineer on a dark night in a muddy trench in the rain. . . . I am glad I work in a research lab! On the other hand if multimode fibres could be used then the problem would be eased considerably and the concept of minimising multi-path dispersion with the appropriate refractive index distribution is of key importance. In this way, in principle at least, a multimode fibre could give the same bandwidth as a single-mode one and an added advantage is that a light-emitting diode could be used. These are already available commercially in a form suitable for application and are much cheaper than semiconductor lasers.

There are therefore various possible combinations. Firstly a single-mode fibre with a semi-conductor laser; secondly a multimode fibre with a semi-conductor laser giving a bandwidth of at least 1GHz over 1km; and thirdly a graded-index multimode fibre and a light-emitting diode. That, roughly, is the state of development of the fibres and sources today.

Obviously there are various problems which I have glossed over. I have ignored the fact, for example, that a light-emitting diode is not a monochromatic carrier, but a narrow-band noise source. The semiconductor laser is also effectively a noise source of a rather narrower line spread than an LED. The spread in carrier linewidth causes a degradation in the bandwidth in the presence of material dispersion but there are various ways of circumventing the problem. For example, by moving to a wavelength region where the material dispersion is zero the effect of line spread could be greatly reduced.

Systems Considerations

Assuming that fibres of low attenuation and large bandwidth become available, what kind of system should they be used in? The complexity of the telephone network suggests that a cautious approach is advisable. It is therefore proposed that the signal is retained in electronic form as long as possible and only converted into light just before launching into the fibre transmission line. The system envisaged, initially at least, is as shown on Fig 13 where the electrical signal, instead of entering a power amplifier and a coaxial cable, is coupled to a current amplifier which drives a light source of some kind, either an LED as indicated or maybe a semi-conductor laser. The LED then produces a modulated signal which is transmitted along a length of fibre and after the appropriate transmission distance it enters a repeater. Here the same philosophy is followed ie the optical signal is converted into an electrical one, by a suitable photo-diode, which is amplified or regenerated using conventional electrical techniques. It is then re-converted into light and transmitted through another length of fibre.

I have a short length of film which illustrates two aspects of fibres rather nicely. The first section shows a fibre-drawing machine in operation while the second part describes a very simple television link. It also illustrates the system simplicity.

A helium/neon laser is used as the experimental light source. The narrow beam can be made to carry speech or other information but here it is channelled inside a fibre. The laser beam travels along the optical fibre which can be several miles long. In this way the laser light can be made to travel around corners in a similar way to electricity flowing through a cable. Glass tubing from which the fine fibre will be drawn is selected for its ability to reflect light internally. A core of glass with a different property, the ability to transmit light, is inserted. The tubes are then placed in a fibre-drawing machine which was designed and built at Southampton University. The tube is lowered into a high-temperature oven to soften the glass which is drawn into a fibre. By carefully controlling the temperature of the oven, and the rate at which the glass tube is lowered into it, an optical fibre of constant thickness is continuously drawn. The speed at which the machine is drawing the fibre is two metres per second, this rate gives the molten glass time to solidify. The thickness of the fibre with its solid glass core is only one hundred microns or twice the thickness of a human hair; about 5 kilometres of fibre can be drawn from each preform. This drum contains half a mile of fibre. In the next experiment a television picture will be transmitted using a standard industrial camera and standard television monitor, but here the difference is that the television signal will be transmitted on a beam of light down the optical fibre. In this test the fibre is not completely solid being filled with a light transmitting fluid instead of the solid glass core. The electrical impulses from the camera are amplified and turned into light pulses, in this instance from a tiny diode not a laser. The actual power transmitted is only one microwatt yet fed into an optical fibre it will faultlessly transmit television picture information. A single fibre will eventually be able to transmit one hundred thousand telephone conversations or two hundred simultaneous colour television programmes.

The equipment and fibre shown in the film were used in January 1971 to give the first commercial demonstration of television transmission over an optical fibre, when an entire colour television programme was sent along it from the Royal Institution to the transmitter. The lecturer at the time, the late Dr G Gouriet, demonstrated that the light was actually passing over the fibre by putting a card between the end of the fibre and the detector. Naturally all the domestic televison screens went blank, and his explanation disappeared with it!

Optical fibre cables

It is clear that fibres can be used in a reasonably simple way. However, there are many problems remaining. First of all we have to ensure that fibres can be handled satisfactorily in the field. Glass is quite strong in tension and compression, so that a pristine fibre has a tensile strength of several tens of kilograms. Thus techniques are being developed for protecting the surface of the fibre, for example, by applying a plastic or an enamel coating immediately it comes out of the furnace and before it goes on the winding drum. Here is an example of a fibre with a nylon coating on it and if anyone can break a piece off afterwards they can have it. No wire cutters allowed! Nylon-coated fibres with breaking strengths of 15kg have been reported which is quite adequate

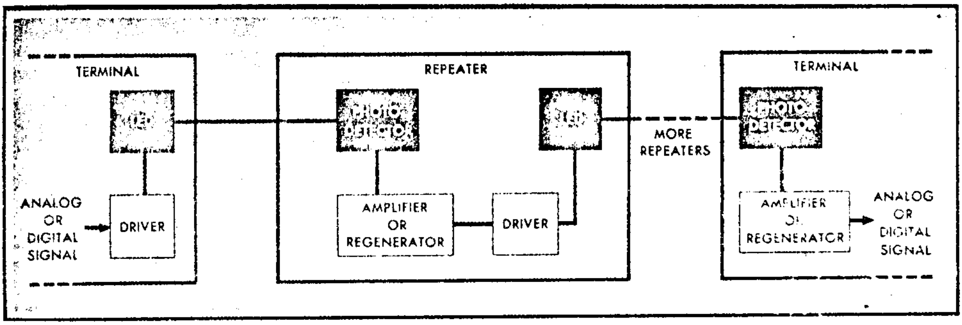


Fig 13—An optical-fibre transmission system employing light-emitting diodes (LED's) could be very simple. The signal to be transmitted is applied directly to the LED through a driver which provides the necessary current gain. Because of loss in the fibre, repeaters are used to boost or regenerate the signals along the way. Each fibre requires its own repeater, which converts the optical signals to baseband and amplifies or regenerates the baseband signals which are then reapplied through another driver to modulate the transmitting LED. With integrated circuits the repeaters would be small and inexpensive. For applications such as interoffice trunks in metropolitan areas, it may be possible to use a cable only a few millimetres thick containing a few hundred fibres, each fibre carrying a channel of a few megahertz bandwidth. Thus, fibres might afford a simple method of spatial multiplexing that is more economical than multiplexing via frequency or time.

for cabling purposes. It is expected that a cable will typically contain half-a-dozen or so individual fibres. A number of experimental designs have been attempted and the corresponding cables are under test. I have here a piece of cable of an early type, containing 7 lengths of fibre each in a plastic tube and contained in a hard plastic armouring. It is quite flexible and strong enough to walk on without being damaged. Thus optical fibre cables are being made and the problem of providing the requisite mechanical strength, without interfering with the optical qualities of the fibre, can be overcome.

Another problem is that of jointing. Even multimode fibres will have core diameters of less than 100μm, ie one tenth of a millimetre, so how may they be joined? Many ingenious techniques have been suggested and have been shown to work. Again the problem is not a trivial one, but it is capable of solution. One method employs a tool resembling an oversized pair of pliers, into which the two fibre ends are inserted and a precision stainless steel tube is crimped over them. Transmission losses through the joint of below 0·5dB are achieved and that can certainly be improved upon.

The choice of sources, as I have said, rests between semiconductor lasers and light-emitting diodes. Detectors are fairly straightforward and probably ordinary p.i.n. diodes are good enough. Alternatively suitable avalanche photodiodes giving internal gains of between 20 and 200 are also available. There are, of course, other practical problems of this kind, and the key factor will be that of economics.

I hope that I have illustrated reasonably clearly the present stage of development of optical fibres. The path of technological progress is strewn with pitfalls of many different kinds and perhaps I can close by reading an extract from a speech* made by the Right Honourable Anthony Wedgewood Benn when he was Postmaster General. He said "In 1878 there was a select committee of the House of Commons to examine the question as to whether it was safe to lay electric cables along the road for electricity supply facilities. They summoned an engineer from the Post Office called Preece and they said 'Mr Preece, we are thinking of authorising the laying of cables and we wondered whether, if we do so, it could have any bearing on the establishment of a telephone service, which we hear has been invented in America, were we ever to start one over here?' 'Well', said Preece, 'the reports on the telephone from America are much exaggerated. We shall never need the telephone in Britain because we have a superabundance of messenger boys, errand boys and the like.' Thus reassured, the Commons authorised the laying of electricity supply cables. Twenty years later in 1898, the House of Commons had a select committee on the Telephone Service itself, which had, by then, begun in Britain, and they called Mr Preece again—

he was still a Post Office engineer. They said. 'In Stockholm and Chicago, Mr Preece, they have things called automatic exchanges. Why don't we have them in Britain?' 'Oh', said Preece, 'these automatic exchanges are very unreliable, and in any case we shall not need them in Britain because we have a large number of cheap girl operators.' The third time I came across Preece's name was in 1912 when he retired, predictably, as Sir William Preece! There was a dinner for him in London at which he was hailed as father of the British Telephone Service."

*Delivered to The Royal Society of Arts on November 18, 1968.

Acknowledgements

Many sources have been consulted in the preparation of this lecture and it is not possible to acknowledge them all individually. However I have drawn heavily on the research being carried out in the Department of Electronics at the University of Southampton and I would like to thank my colleagues most warmly for their collaboration. Most of the figures are from articles published by Southampton authors with the exception of Figs 2-5 (Scientific American, 1969), Figs 7 and 13 (Bell Labs Record, 1971) and Fig 1 (taken from a Christmas card received from C N E T, Lannion in 1975).

DISCUSSION

CAPTAIN N J Mayne: What are the possibilities of optical amplification of signals to avoid the electrical interface at repeaters?

Lecturer: Not very great at the moment I think. The Post Office attitude is to keep everything as simple as possible and to restrict any changes to just the fibre and the signal along it. The required repeater functions can be performed quite satisfactorily by existing electronic methods so that optical amplification, which is a very difficult technique and not properly developed, is unnecessary. Optical amplification is technically possible but tends to be rather noisy. Also if a large amount of gain is produced in an optical amplifier then the shape of the output pulse tends to be determined at least partially by the characteristics of the amplifying medium and not by the shape of the input pulse. This is a very complicated way of saying I don't know!

Colonel D J MacIntyre: You mentioned very briefly the economics of the situation viz-a-viz optical fibres. I have read recently that in America the cost of a 20 megahertz cable with a 10dB per metre loss was approaching a dollar a metre. Is this the situation in this country, or are we so far behind? Because, of course, if we are going to make any military use of the application then it has got to be dead cheap.

Lecturer: Yes, something like a dollar a metre seems to be the going rate for fibre at the moment. This is partly because the field is dominated by one firm in the United States which has invested a lot of money and they are trying to recoup. What the long-term costs will be is rather difficult to predict but some estimates indicate that with mass production the costs might come down appreciably, to the order of cents per metre; personally I think this is being rather optimistic. I wish I could remember the figure being charged at the moment by Pilkington's in this country, for their fibre. The loss is not as low as the Corning fibre, it is about 50dB/km, but this is adequate of course for many short-distance applications such as in aircraft. The only other thing I can usefully add is that for the vapour-deposited fibres, the price would be determined almost entirely by the manpower costs since the materials themselves would be very cheap.

Lieutenant-Colonel M Mitchell: I have two distinct questions. The first concerns the type of fibre in which the refractive index varies, I think you said parabolicly according to the distance from the central axis. I can of course see the tremendous advantage of the constant optical path length to maintain the phase coherence of the light, but are there not considerable problems in manufacturing such a fibre and how have these problems been overcome?

The second question concerns the jointing of the fibres. You referred to quite a low figure of attenuation across the joint interface. But is there not also a reflection loss and would not this become considerable with a number of joints in series?

Lecturer: In the laboratory, at least, the reflection loss at joints can be eliminated by inserting index-matching grease or liquid between the fibre ends. The index-matching material must have a refractive index equal to that of the two cores so that optically the light travelling through does not really see a change of the refractive index. Even if index matching cannot be used, the reflection loss itself is of the order of 4% per surface, so for two surfaces which are not actually touching, the reflection loss is about 8%. This is comparatively small compared with the loss due to offset of the cores at the joint or due to the fact that the two cores may not be of exactly the same diameter.

On your question of the graded-index fibres, there are two basic techniques for making them. One was developed by the Nippon Sheet Glass Company who make the parabolic-index fibres. They use the double-crucible, or concentric-crucible, technique where the core material flows from the inner crucible and the cladding glass through the outer one. The latter has a long nozzle so that with the inner nozzle cut short there is an appreciable flow region where the glass is molten and the core glass flows inside the cladding glass. That distance is sufficiently long, say 2mm, for diffusion of ions to take place between the two materials. With the correct temperatures and the appropriate ions, then diffusion occurs from one to the other producing the apropriate refractive-index distribution. The refractive-index profile is determined by the diffusion constants so you can't get any desired refractive-index distribution but you can get something approaching the optimum one. The alternative technique is that of vapour deposition where vapours are passed through a tube and oxidised so that a layer of glass is deposited on the inside surface. The thickness of a single layer is about 10μm and to build up the appropriate thickness of core glass requires maybe 50 to 100 successive layers. If the glass composition in the successive depositions is changed then the appropriate refractive-index distribution can be produced. During the drawing phase a certain amount of diffusion takes place between the layers thus smoothing out the step-like structure. It is obviously more expensive to make fibres with a graded refractive index than with a constant and uniform core. Your question has reminded me of something which I should have said earlier, namely that the concentric-crucible method has been developed to a very high degree of perfection by the Post Office. They argue that because the process is a continuous one the cost should ultimately be low. On the other hand the vapour deposition process, although involving batch operation, requires comparatively simple apparatus and facilities.

Lieutenant-Colonel M R C Weiner: Contrary to uninformed sources, the Ptarmigan Project office is not standing still, and I think the audience might be interested to know that, within the next two weeks, we are going to three firms for a feasibility study of a fibre optic replacement of trunk cables in Ptarmigan. The time scale one is looking for is hopefully that we might expect some B model cables in time for User Trials. I would like to ask the Professor, if I give a few of the operational characteristics, whether he could identify any which he foresees causing problems. The characteristics that we are asking for is that the overall diameter of the cable must not exceed that of the cable that we have today. It must be circular in cross-section and be as flexible as the quad cable, in all directions of flexing, and under all environmental conditions. The cable being laid must be capable of being recovered quickly on a drum and of course up to twice in a 24-hour period. It should be able to withstand the effects of vehicles of all kinds being driven over it, and survive a wide range of environmental conditions. The normal length of cable on a drum would be 500 metres and up to four coupled together giving a maximum length of 2 kilometres for the complete sub-system. Repeaters must not be used.

Lecturer: Yes, you seem to have a problem! I don't quite know where to start, but perhaps I should take the back end first. First of all let me say again that I have no experience of the hard, practical, systems end of things and don't have to manufacture the equipment that I talk so airily about. On the other hand I would have thought that a transmission distance of 2 kilometres without repeaters, should be easily possible. One of the factors that I didn't mention is that of cabling the fibre without causing its attenuation to increase. Until recently one could start off with a fibre of, say 2dB/km transmission loss, which after coating and cabling becomes 200dB/km. This type of problem has largely been overcome and increases in attenuation of only two or three dB/km are now caused by coating. It should easily be possible to produce cabled fibres with attenuations below 10dB/km so that a total loss over two kilometres of 20dB plus, say, a few dB for jointing should cause no problem. As for the strength of cables under the rather severe conditions you describe, I can't really comment. The diameter will be determined almost entirely by the armouring and the tensile strength of the coated fibre itself should be 20 to 30kg. The main difference betwen the fibre and a copper wire of the same diameter is that the former is brittle. The Post Office has a tender out for cables to meet their normal specifications for telecommunication cables, that is for snatch, jerk, tension, etc, produced during cable-laying operations and my understanding from the various cable manufacturers I have talked to is that these mechanical properties are not impossible to meet. What they are more concerned with is the possible deterioration in the optical properties during the cabling process. I feel sure that I have given a rather evasive answer to the question.

Lieutenant-Colonel M R C Weiner: We see the system having the electro-optical conversion, probably inside a vehicle, with a coupler on the outside going in to your fibre cable. Have you any comment on the effect of this coupler; would there be any loss in that?

Lecturer: A number of commercial firms are working on couplers of this type. I can't remember, at the moment, the losses being quoted but my impression is that it is less than 1dB.

Colonel J F Blake: Is there not a possible application in the field of communication security in that a would-be interloper would find it very difficult, if not impossible, to tap into a properly monitored circuit without being detected? And if there is such an application, is it being exploited?

Lecturer: Yes, this was seen as one of the possible virtues of fibres. In fact at Southampton we made a fibre some years ago which was supplied to SHAPE Headquarters with this application in mind. Whether it was successful in this respect or not, I don't know since we have had no feedback from them. Obviously it would be quite difficult to tap a fibre, especially one with a core diameter of a few microns. One method might be to etch away part of the core but if the signal level is continuously monitored any interference should be easy to detect. One other way in which one might couple a signal out of a fibre is by detecting the scattering out of a reasonable length of fibre, but in laying a secure cable unnecessary lengths are unlikely to be left lying around.

Lieutenant-Colonel T B Woods: In terms of the use on aircraft you are suggesting, I can see that there is a possibility of reducing copper weight and achieving economies by using an optical fibre plus its appropriate launch and multiplex facilities, can you see this being applied to multicore cables in buildings, at all?

Lecturer: Perhaps I can make a comment first on the aircraft application. The path of technological progress seems to me to be largely unpredictable and we have been saying for a long time that the great virtue of optical fibres is their small size and large bandwidth so that their major impact should be in the telephone system. It is therefore rather ironic that probably the first reasonably large-scale application of the fibres will be in 'noisy' situations in aircraft and ships where the great virtue is not that of large bandwidth but in freedom from interference. The problems posed by earth loops largely disappear and cables can be laid through magazines and fuel tanks without causing a hazard thus giving greatly increased flexibility in equipment and cable layout. A direct answer to your question must be rather speculative. I am tempted to think that the price of copper will continue to rise over the years while the basic raw material of low-loss glass, namely silica, is present in great abundance. It wouldn't surprise me if simple glass fibre cables become ultimately as cheap as the normal copper telephone wires that presently come into the private home. One can speculate on all sorts of interesting possibilities if domestic subscribers had access to bandwidths of tens of megahertz, but that would form the topic for another lecture.

Captain M A Rice: Are there any ageing effects that can alter the optical properties of cable over a period of time? The sort of thing I am thinking of is that because glass is a super-cooled liquid it could possibly have a tendency to change its shape over a period of time. Will that have any effect on the properties of the cable?

Lecturer: At room temperature the viscosity of glass is pretty high and although it will flow the time scale is measured in thousands of years. But the long-term stability of low-loss fibres has yet to be studied. There is no evidence so far that the fibres themselves deteriorate with time. On the other hand it is still very much an open question as to what happens to the strength of the fibre when coated with nylon or other material. Will that surface nevertheless deteriorate in time and will the strength of the fibre fall over a period of 10 or 20 years? The answer to that sort of question is not yet known. One thing which is fairly certain is that the effect of normal radiation on fibres is likely to be small.

Lieutenant-Colonel M A Philp: I have not so much a specific question to ask the Professor, as making some comments and asking his opinion of them. I do not want to belittle the work and enormous success that has been achieved in optical fibres over the last ten years, but when it is reduced to its fundamentals, you are simply transferring information from A to B. Or, in other words, you are replacing a bit of wire with an optical fibre, although in certain circumstances it may be very advantageous to do so. Having got this far, the question begins to arise—what other possibilities are there of using this technology? Quite a number of things spring to mind. I hasten to add here that the ideas I propose to mention are not my own work, but the extensive picking of other people's brains. Optical fibres are sensitive to pressure. If, therefore, you take a cylinder and block off one end, wind a fibre round the outside and then vary the pressure in the cylinder, the walls of the cylinder will expand and contract causing the pressure on the fibre to change, thereby altering the attenuation. It seems this could lead to an optical microphone. There are many technical problems still to be solved, but it is a possibility. Another idea is based on removing the outer cladding, leaving only the centre core from which you will get extensive scattering because you have removed the refractive index which is designed to retain the light in the core. If you now place a substance on the core, there will be a change in the refractive index, the amount of scatter will change and this will be measurable by a detector at the end of the fibre. Say you put five of these cores side by side and with a suitably coded device place a pad on selected fibres only, some will show increased attenuation others will not. If you now scan the detectors you could effectively get a mark-space ratio and thereby in effect achieve an optical keyboard. This principle could also be used for a liquid level detector. You have different refractive indives between the air and the liquid and by measuring the ratio of the two you can calculate the level. Similarly, if a liquid flowing in a pipe is subjected to some contaminants, and provided you know the change of refrective index which will occur when the contaminants appear, you could have a pollution detector. These are only a number of many ideas. Then, looking down the full length of the science-fiction telescope, it might be possible to switch in the optical mode, and this raises the question whether we will ever see an optical computer. And something which would be highly desirable in the Post Office type of telecommunications—can we get away from electronics entirely and have a purely optical repeater? All this is very much in the future, but it seems to me that here we have got a wonderful, exciting, new technology and we must make the maximum use of it. I would even go so far as to suggest that the optical fibre technology today is at about the same point as the semiconductor technology was when the first germanium diodes were being made. Would you, sir, agree with these views?

Lecturer: As you say, there are many possible applications of fibres that I have not considered since we have our hands full, as it were, on the telecoms cable front. But yes, I think the ideas that you have mentioned are technically possible. One or two others that people have talked about are, firstly the possibility of using fibres for monitoring voltages and currents on transmission lines. For example, it might be possible to dispense with large and expensive current transformers by having the fibre simply wrapped around the transmission line so that the variation of magnetic fields caused by the current flowing can change the polarisation of the light passing along the fibre. Thus by measuring the change of plane of polarisation one gets a measure of the current flowing along the transmission lines. This is a much simpler arrangement than having a huge current transformer with large insulators and so on. A second possible application is for monitoring the corrosion of fuel elements inside nuclear reactors. The technique used at the moment is to lower a smaller laser into the reactors in a very complicated way and to fire the focussed laser beam at the element while monitoring the reflected light. From the first few shots very little light is reflected but when the corrosion has been burned through, the bare metal causes a rapid increase in the reflected light energy. The number of light pulses required is therefore a measure of the corrosion thickness.

So yes indeed, there are lots of possible applications and perhaps we have only touched on the fringe of some of them.

Lieutenant-Colonel B C Complin: Listening to the answers to certain questions, my curiosity is aroused concerning the degree to which external stimulae can affect fibre optic transmission characteristics. Would you please comment on the likely effect on fibre optic cables of magnetic fields and nuclear radiation?

Lecturer: As far as I am aware fibres are not obviously susceptible to any particular kind of external influence. In order to use the effect of change of polarisation due to a magnetic field requires a special kind of fibre designed to emphasise this kind of effect which, in a normal telecoms application, would not be noticeable. One fact that has been mentioned is the possibility of mechanical stress changing the transmission loss of the fibre and, of course, the cable design must be such as to minimise that. Some work has been done on degradation of fibres by nuclear radiation but I am afraid I cannot remember the relevant figures. The Post Office work shows that there are no appreciable long-term effects from natural radiation. On the other hand at radiation levels reached in, or close to, a nuclear explosion, then the transmission loss will go up appreciably, by an amount, and for a time, depending on the intensity of the radiation.

Captain (TOT) B A Kimber: There was an earlier question (by Colonel MacIntyre, I believe) as to whether unauthorized and undetected interception could be achieved by a break or interuption of the fibre—and this was discounted as not being possible. My question is if, as the authorized user, you wanted to make an intentional Y junction, to provide distribution from one fibre cable to two others, is this possible?

Lecturer: Yes, a lot of work is being done on couplers and junctions at my own laboratory and elsewhere. There are several techniques for making somewhat crude Y junctions at the present time. A very simple arrangement is to take three or more fibres with flat ends and fasten them onto the end of a solid rod of glass. If the surfaces of the glass rod are polished then light from any one fibre entering the rod is reflected from the end surface and is spread over all three ends of the fibres so that the light is coupled from one fibre to the other two. Couplings of this type are being manufactured and are commercially available at the present time. It seems to me that devices of this sort are relatively crude and their performance is not ideal. The transmission loss is determined very largely by the area of the cores compared with the total area of the block. With circular fibres there are bound to be dead spaces between them and the overall loss in a coupler of that kind is measured in dBs and not tenths of a dB. However there are a number of other interesting ideas for more direct coupling and let me just mention one of them.

In a single-mode fibre the energy is carried partly in the core and partly in the cladding because of the surface-mode type of propagation. If the fibre is tapered down, then a larger proportion of the energy is carried in the cladding because the core diameter is smaller and the propagation conditions changes. So if one takes two tapered ends lying in one direction and the third one lying between them in the opposite direction, then quite a high degree of coupling is obtained giving, in effect, a directional optical coupler. Although this has not yet been done on a commercial scale overall efficiencies of about 90% have been demonstrated and this looks much more encouraging than the conventional star coupler that I described earlier.

CLOSING REMARKS

Chairman: Well all that is left now is for me to thank Professor Gambling for a most interesting lecture, giving absolutely the right mix of the practical, the scientific, and the technical for our particular audience, on a subject which obviously can be of the greatest interest to us. Professor Gambling thank you very much indeed. (*Prolonged applause.*)

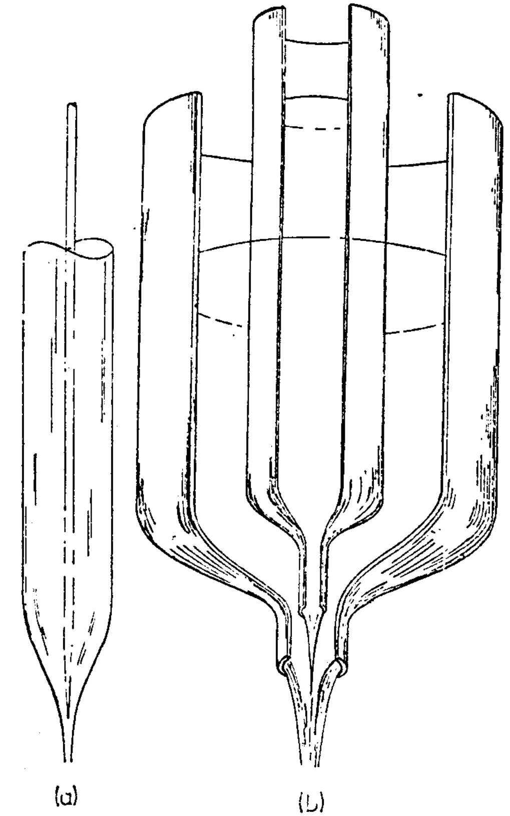


Fig 9—Schematic diagrams showing fibre drawing (a) from a rod-and-tube preform and (b) from concentric crucibles.

TABLE 1:
FIBRE CHARACTERISTICS AT A WAVELENGTH OF 0·9μm

Fibre	Attenuation at 0·9 μm dB/km	N.A.	Core diameter μm	
Phosphosilicate core/borosilicate cladding	3	0·23	50-100	Southampton Univ
	1·2 (At NA=0·05)	0·18	58	Nippon Telephone & Telegraph Corp
Silica core/borosilicate cladding	2·5	0·17	18	Bell Telephone Lab
Phosphosilicate	3	0·18	50-1000	Southampton Univ
Germania	4	0·23	35	Corning Glass Works
Sodium borosilicate	7		10-20	British Post Office
New SELFOC	7			Nippon Sheet Glass
Compound glass	9			Schott

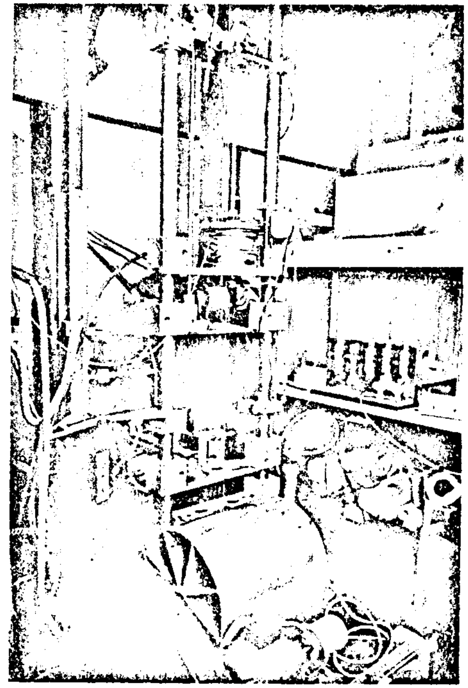


Fig 10—Fibre drawing apparatus

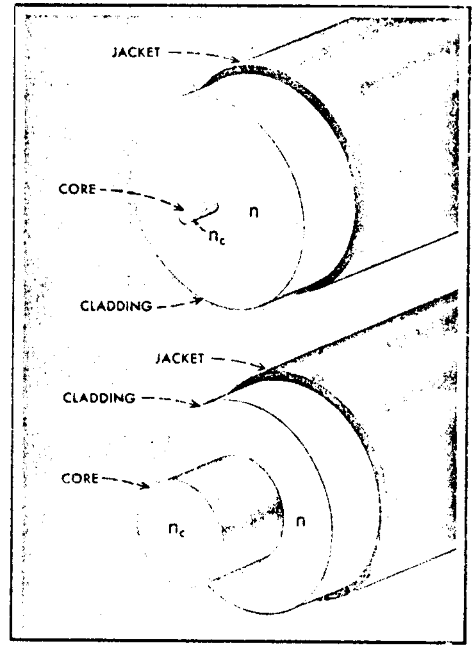


Fig 7—Optical fibres consist of two coaxial transparent glasses surrounded by a light-absorbing jacket. The fibre will guide light if the refractive index of the core material is larger than the refractive index of the cladding. The core diameter of the single-mode fibre (top) is only a few microns, while that of the multimode fibre (bottom) is a few mils. The cladding for both types of fibre is less than 10 mils and is determined more by handling properties of the glass than by optical factors.

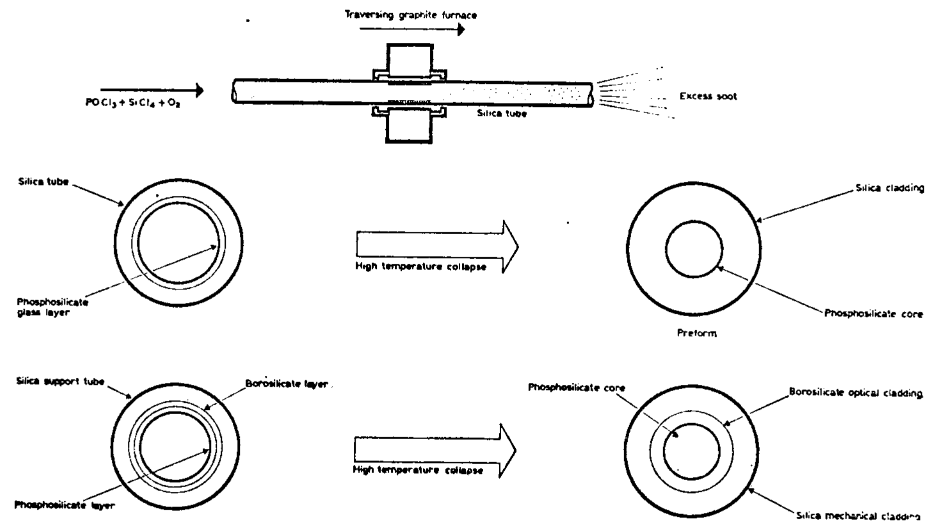


Fig 8—Manufacture of phosphosilicate fibres. In the two-layer process the silica tube acts only as a supporting structure.