Lasers, Light and Telephones

by Prof. W. A. Gambling, D.Sc., Ph.D., FIERE*

1. EARLY FORMS OF OPTICAL COMMUNICATION

In 1588, when the Armada was sighted sailing up the English Channel for the invasion of England, a warning signal was sent to the Queen by the lighting of bonfires on a chain of hilltops from Devon to London. This was a common method of sending important messages for many centuries and the hills on which the fires or beacons were made, came to be known as 'Beacon Hill'—a name which many of them still retain. Although nowadays it seems a crude and clumsy technique, it represents one of the earliest forms of an optical communication system. Only the simplest possible message could be sent, either a 'Yes' or a 'No'—the absence of the fire meaning 'No, the Armada has not been sighted', changing when the bonfire was lit to 'Yes, the Armada is coming'. In the jargon of the communications engineer only one 'binary digit' or 'bit' of information could be sent at a time and it could not be repeated until the beacon had burnt out and was rebuilt. When one realises that it takes nearly four million bits of information to make one frame of a colour television picture and the frames are flashed on to the screen fifty times every second, it is possible to appreciate just how sophisticated present-day communications systems have become.

An improvement on beacons is the heliograph which consists of a mirror so adjusted as to reflect sunlight to an observer. By tilting the mirror a series of flashes can be sent in the form of Morse code and the rate of transmission is increased from something like one bit of information *per day* in the case of the beacon to perhaps five bits or flashes *per second*. The heliograph can only be used if the sun is visible but in the modern version an artificial light source in the form of an electric lamp is provided and by means of a shutter, or a dipping reflector, coded flashes of light can be sent, as in a naval signalling lamp. However, the rate at which messages can be sent is limited by two factors, firstly by the mechanical shutter and secondly by the fact that both the human eye and brain are limited in their ability to respond to and decode messages sent by flashing lights. Thus the signalling lamp can be used to send relatively slow and simple messages, such as those required between ships at sea when radios cannot be used, but it would take a long time, no less than 278 hours or 11½ days at 24 hours a day to send as much information with a lamp as there is in even a single static colour television picture.

2. SIMPLE OPTICAL SIGNALLING SYSTEMS

One way of speeding up the transmission of information is to replace the mechanical shutter with an electrical one which can be switched on and off much faster. This came about with the development of transistors. Certain semiconductor diodes emit light when an electric current is passed through them, and the intensity of the light varies with the strength of the current. These devices are called Light-Emitting Diodes and some versions can be switched on and off by electrical pulses more than a hundred million times per second. The most common use of such devices is in electronic pocket calculators which came on to the market only a year or so ago. The numbers in red are produced by arrays of light-emitting diodes, seven little diodes to each figure. Thus light-emitting diodes can replace the flashing light and the eye, in turn, can be replaced by a semiconductor diode detector which also can have a very fast response. A light detector acts more-or-less in the opposite way to a light-emitting diode in that it can be so operated that when light of varying intensity falls on it, an electric current of varying strength is produced. The combination of light-emitting diode and diode detector can be used to transmit more than a hundred million bits of information per second which is enough to send many television pictures simultaneously.

Although a lot of information can be sent along such a light link it cannot be sent very far because the light from ordinary lamps and diodes and even from car headlamps and searchlights, however carefully they are collimated, always spread out. As a result, when the detector is far away the light is spread over a large area and not enough gets into the detector to give a usable signal. What is needed therefore for long-distance transmission is a new type of light source producing very pure light which can be accurately controlled, so that it can be made into a narrow beam which does not spread as much. Such a light source is the Laser.

3. THE LASER

The laser is completely different from any other light source. The light it produces is very pure and although a searchlight looks bright a laser beam is much brighter, since brightness is defined in terms of power per unit area per unit solid angle. The laser behaves almost like an electronic oscillator which operates at a single, very high frequency, typically 5×10^{14} Hertz. This particular property has several consequences which are of great importance. Firstly it is possible to collimate the output radiation very accurately. Even the smallest and cheapest model produces a narrow pencil-like beam which can be sent over long distances without spreading too much. This directional ability has been used in an experiment where a laser beam was directed at the moon from a 60-in telescope, with the result that in travelling a quarter million miles it only spread to a spot half-a-mile across. In other words the beam spread only by 1 inch in every 10 miles of travel. Incidentally the distance to the moon was measured to an accuracy of about an inch, so now we know where the moon is!

Laser beams can also be focused to a spot only 40 millionths of an inch across, thus producing such a high density of power that they can be used to drill holes in very hard materials. Another consequence is the ability to produce interference effects between different parts of a beam, thus giving rise to the new subject of holography, as well as allowing measurements of distance to be made to an accuracy of a millionth of an inch. Laser light can also be modulated, or switched on and off, very much faster than other light sources and can, in principle at least, be used to send many more pulses per second, i.e. more information per second, than any other method including radio, microwaves, etc. Thus, if we can learn to use laser light, and to transmit it efficiently from one place to another, then we

---

* Dept. of Electronics, University of Southampton.

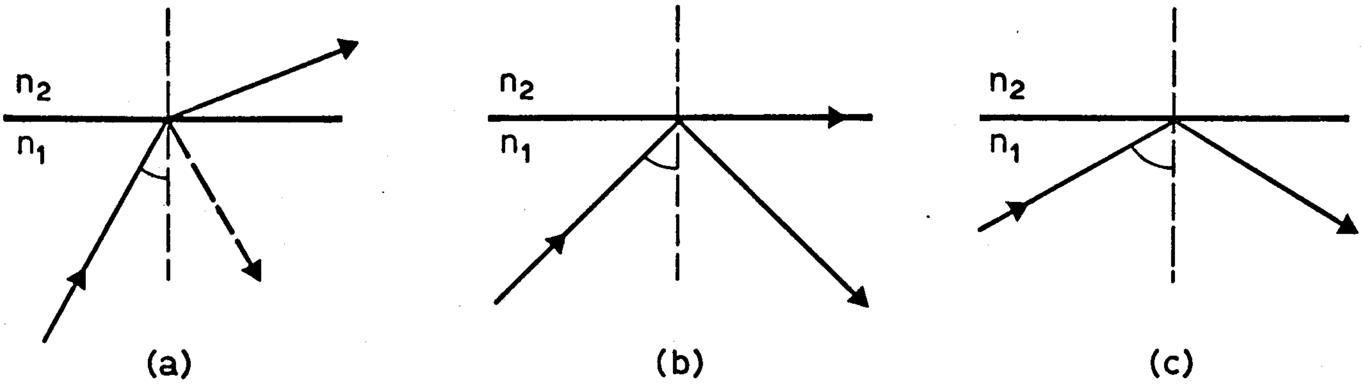

Fig. 1. Total internal reflection of a ray of light at an interface to two media having different refractive indices with $n_1 > n_2$.

(a) A ray at a small angle to the normal to the interface is partially reflected and partially transmitted.

(b) At the critical angle to the normal most of the light travels along the interface but the remainder is reflected back into the dense medium.

(c) At a larger angle to the normal, i.e., at a small angle to the interface, all the incident light is totally reflected within the dense medium.

will have a greatly improved method of sending messages in the form of telephone, television and so on.

4. THE NEED FOR BETTER COMMUNICATIONS

However, before looking into optical communication more closely let us ask the question "Is such a new system needed and will it be of any practical value?" The answer is strongly in the affirmative and telecommunication authorities the world over are spending a lot of money on developing new systems. For example, the number of trunk telephone calls made in this country doubles every five or six years so that the telephone system has to be expanded just to keep up with this growth. Many more connections are being made to computers over the telephone system, and computers are becoming bigger and more numerous, so that more and better telephone lines are required. Again, television programmes are increasingly sent over land lines, and there are other new and interesting applications.

5. LASER SIGNALLING

A simple method of sending a signal along a laser beam is to pass it through an electro-optic crystal which can act as an amplitude modulator to control the intensity of the beam passing through. Thus an ordinary electrical signal such as that from a telephone, or a television signal, when applied to the modulator causes the strength of the beam to vary in synchronism with the signal. If a light detector is placed at the other end of the beam it will pick out the variations in beam intensity and turn them back into electrical signals. These are amplified and used in the normal way. With such a technique signals can be sent on a laser beam quite long distances and when the beam is protected there are no great problems.

Out of doors, on the other hand, there are two big disadvantages. Firstly the beam can be blocked by rain, clouds and snow, but even in clear weather it will be bent and broken up by temperature gradients or turbulence in the atmosphere and therefore transmission is unreliable. No broadcasting authority would be popular if its TV programme disappeared every time it rained. Secondly, light beams have the habit of travelliing in straight lines, making it difficult to turn corners and get in and out of buildings since it would be necessary to have a highly-reflecting and accurately-positioned mirror at every slightest bend.

6. LIGHT GUIDANCE USING CLADDED GLASS FIBRES

In 1966 two British engineers suggested a very novel method of sending light over long distances. They said that if pure glass could be produced then glass fibres would be capable of guiding light over several kilometres at a time. Glass fibres had been known for many years but at the time they could only send light over a few metres because of the high transmission loss of nearly 1000dB/km (i.e. half the energy is lost in travelling only 3 metres). In order to understand how glass fibres can 'conduct' light it is necessary to recall some very simple physics.

If a ray of light is travelling in a dense medium and strikes the surface of a less-dense medium at an angle near the perpendicular (Figure 1) then some of the light is reflected and some is transmitted through the surface. On the other hand, if the ray strikes the surface at a shallow angle, then it is all reflected, that is, there is no energy lost due to reflection. A perfect reflection of this kind is known as 'total internal reflection' and is the reason why swimmers have difficulty in looking out from an underwater window in a swimming pool, or up through the surface. The angle to the perpendicular at which total internal reflection just occurs is known as the "critical angle".

A light-guiding optical fibre consists of a dense core material of pure glass surrounded by cladding material, also of glass but having a smaller refractive index. Thus if rays enter the fibre and strike the surface of the core at a large angle to the axis (i.e. a small angle to the perpendicular), they are partially reflected and go on to make another reflection at the same angle at the other side of the core, and then another and so on. However, some energy goes into the cladding each time, and after many reflections there is no light left in the core and the ray does not reach the far end of the fibre. An input ray at a shallow angle to the axis is totally reflected with no loss of energy, and if it is not absorbed in the body of the core, it can keep on reflecting right to the end of the fibre. The beauty of this method is that the fibre does not need to be straight.

As can be seen from Figure 2 the rays continue to reflect around curves and, within broad limits, the fibre can be bent as much, and as often, as required. In addition the fibre can be very thin, as fine as a human hair, about 50μm, thus becoming quite flexible and it can be wound around the finger without harm. It behaves much as a piece of copper wire would. An unprotected fibre is rather weak, since surface flaws form very rapidly on exposure to air, but if suitably protected immediately after drawing, a glass fibre, even as small as 100μm diameter, becomes surprisingly difficulty to break by hand. A single fibre is so small that it is difficult to see easily and to handle.

Fibre bundles consisting of a large number of fibres contained in plastic tubing have been used for light transmission over distances of a metre or two for some years. Typical examples are fibre endoscopes for viewing internal cavities of the human body by surgeons and several fibre bundles can be used to form a transmission path for light in a particular configuration to produce display signs, the advantage being that only one simple light bulb is used, instead of many bulbs or expensive fluoroscent tubing. In addition they are less easily damaged by vandals. Traffic signs on motorways are of this type.

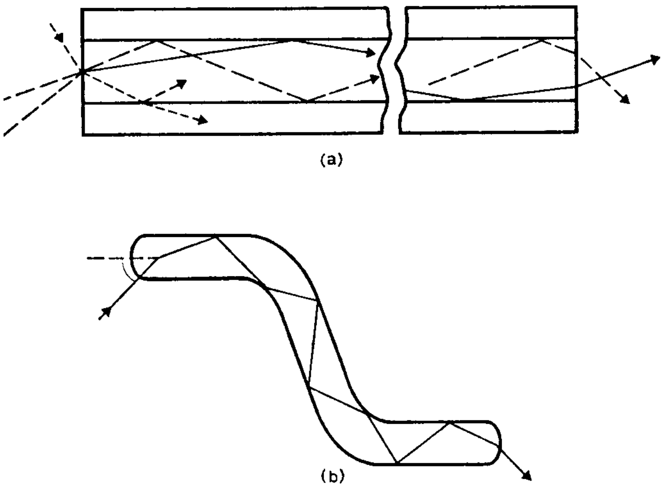

Fig. 2. Ray propagation along a cladded multimode fibre. (a) Rays incident on the core/cladding interface at an angle greater than the critical angle are completely reflected (if core and cladding are lossless) and are guided by the core. The dotted ray falls outside the numerical aperture of the fibre and loses energy at each reflection. (b) Providing a ray strikes the interface at an angle to the normal greater than the critical angle it will continue to be reflected along the fibre even around bends.

7. OPTICAL FIBRE COMMUNICATIONS

While bundles of fibres can guide light, to send a signal we only need one fibre and a small amount of light which can be modulated in some suitable way. One fibre could guide laser light over distances of several kilometres. By using one of the techniques described earlier, the laser beam itself could be made to carry as many as 100,000 telephone conversations simultaneously, or 100 different colour television programmes. Thus a thin fibre could transmit more information than a telephone cable made of rather expensive copper, and presently about 5 to 10cm in diameter.

Since glass fibres have been used for conducting light for some years one might well ask why they have not been used for communications purposes before. The answer is that glass of sufficient purity has not been available. Ordinary window glass looks quite transparent, but if you look at a pane of glass edge on, it appears quite dark because very little light can come through a thickness of even a foot or so. Even the best available optical commercial glass is not good enough, as after travelling one kilometre the light would be ten thousand million times weaker.

The reason for this is that some of the light propagating along a fibre is lost by absorption due to impurities and some is scattered by even very small inhomogeneities. Some of the impurities are difficult to remove and they can have a serious effect, even if only present as one part in every hundred million of glass. It can been seen that the purity has to be very high indeed. In order that the signal is not lost completely it has to be amplified when the power has fallen to a low value and each amplification is carried out in repeaters spaced at suitable intervals along the fibre. In order to keep the number, and therefore the total cost, down to an economic value the transmission loss has to be as low as possible and certainly less than 20dB/km (corresponding to a fall in signal power to 1% of its original value after travelling 1km).

8. FIBRE FABRICATION

At first it seemed that this requirement would be very difficult to achieve, but in the past four years tremendous advances have been made in several laboratories including the one at Southampton University. In fact two years ago this laboratory held the world record for the best fibre with a loss of only $5\cdot8$dB/km in a configuration consisting of a a fine glass capillary tube as the cladding filled with a special liquid (hexachlorobutadiene) as the core. Other laboratories in the U.S.A. improved on this result using solid fibres consisting of silica doped with titania, germania or boric oxide as one component and pure silica as the other. A year ago it produced another new type of fibre using a rather unexpected material (because it is extremely difficult to make in bulk form), namely a phosphosilicate glass.

This fibre is made by passing vapours of phosphorous oxychloride and silicon tetrachloride, together with oxygen, down a silica tube, which need not be very pure, and heating to a temperature of about 1500°C in a suitable furnace. Layers of phosphosilicate glass can then be deposited on the inside of the tube. The initial layers, which become the cladding, can be made to have a low refractive index by using a small concentration of phosphorous oxychloride (or by using boron trichloride instead) while the later layers of higher refractive index form the core. After deposition of the layers the tube is collapsed to a solid preform which is then drawn into fibre by the precision fibre-drawing machine shown in Figure 3 and the overall process is illustrated by Figure 4. The great advantages of the above process are that the raw materials are cheap and, because they come in liquid form, they are easily purified. The resulting fibre is dimensionally very accurate and has the

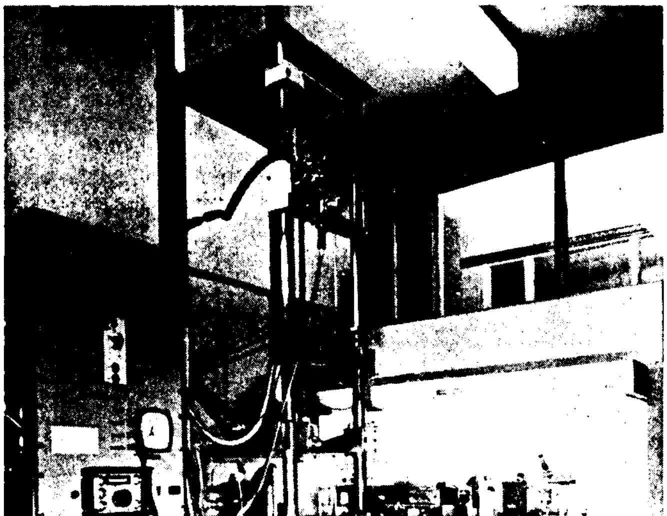

Fig. 3. Fibre-drawing machine built at Southampton University. A glass preform can be seen entering a small vertical furnace and the resulting fibre is drawn on to the winding drum at the bottom. The precision is such that a fibre of diameter 100μm varies by less than 1μm over a distance of several hundred metres. Several kilometres of fibre can be drawn in one continuous operation.

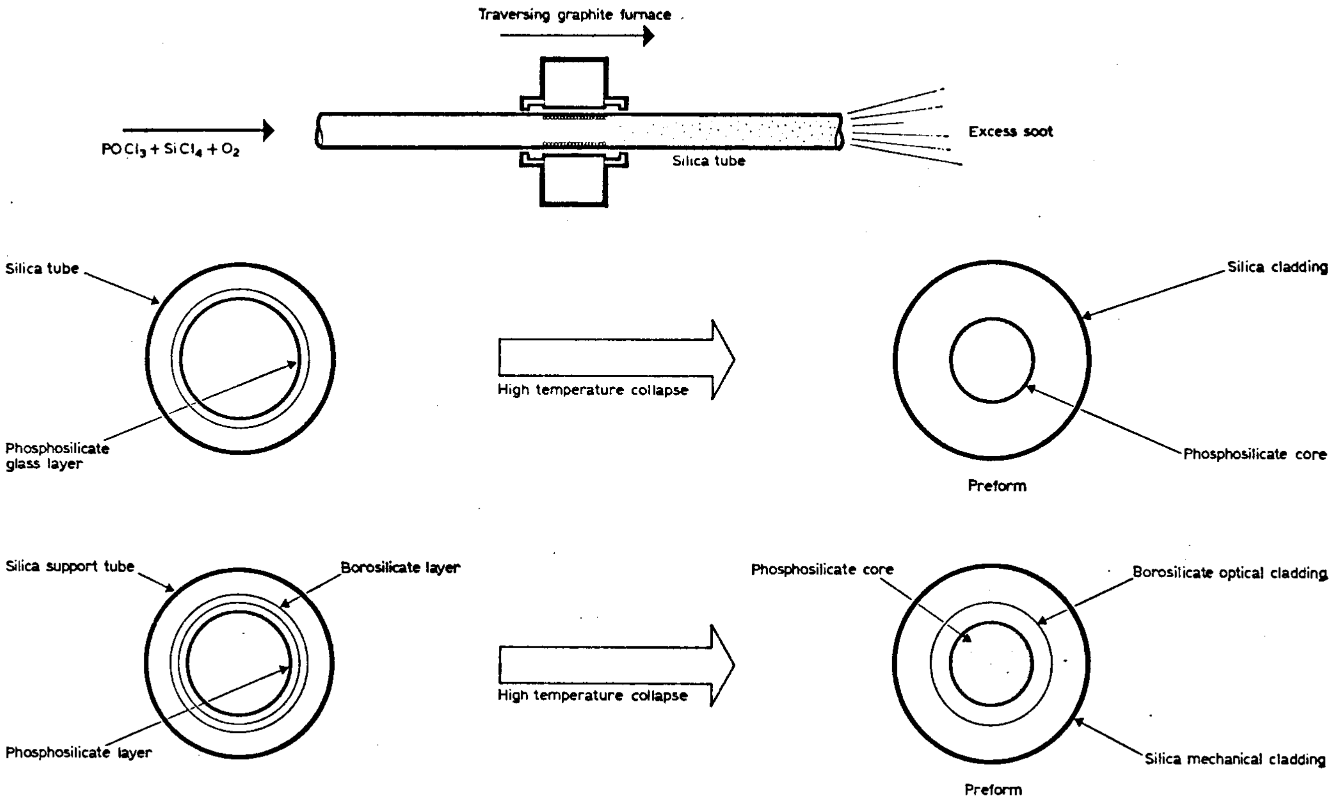

Fig. 4. Manufacture of phosphosilicate fibres. In the two-layer process the silica tube acts only as a supporting structure.

low attenuation of only 2dB/km over the interesting wavelength range of 0·8 to 0·9μm where gallium arsenide lasers and light-emitting diodes operate. Figure 5 shows that the transmission loss is low over a wide range and only one other fibre has been produced having a lower attenuation and that not, apparently, repeatedly.

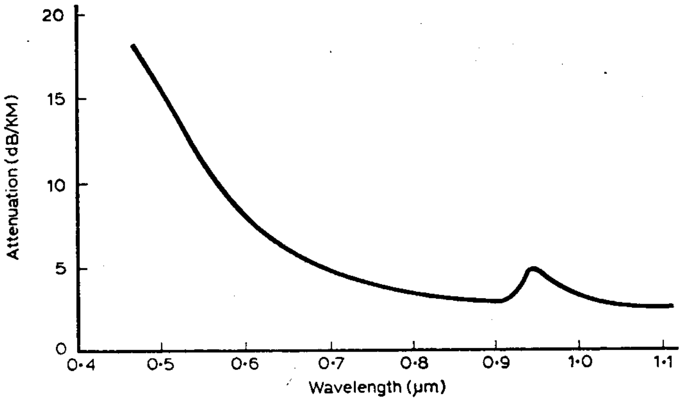

Fig. 5. Spectral attenuation curve of 1.2km length of phosphosilicate-core silica-cladded fibre.

9. BANDWIDTH OF OPTICAL FIBRES

Another major factor of prime importance in the design of optical fibres for signal transmission, and indeed of any communications medium, is the bandwidth or maximum rate at which information can be transmitted. The components of a modulated carrier cover a spread of frequencies and normally all travel at different velocities, an effect called dispersion, so that over a long length of fibre the components become separated in time and distortion occurs. In a single-mode fibre, i.e. one with a very fine core, the limiting dispersion is that caused by the bulk glass and the particular surface wave (HE_{11}) mode and corresponds to pulse rates, or bandwidths, or several gigahertz over several kilometres. However, if a semiconductor laser source is used the spread in its output would limit the overall bandwidth to about 1GHz over 1km or perhaps even less. There are problems with single-mode fibres which arise from the very small core diameter ($\sim$1μm), namely those of launching efficiently from semiconductor lasers and jointing (especially at night in a trench in the rain!) between adjacent sections of fibre. To get fibre ends flat and accurately aligned to an accuracy of better than 0·1μm is no mean problem.

10. MULTIMODE FIBRES

An alternative approach, which was first undertaken in 1967 as a joint project between the Signals Research and Development Establishment and the Department of Electronics at the University of Southampton, U.K., is to consider multimode fibres. These have core diameters in the region 20 to 100μm and are easier to manufacture than single-mode fibres. However, because of the large core diameter they are capable of supporting many modes and it was expected that the bandwidth would be quite small. In a thick-core fibre, instead of modes, it is more convenient to visualise energy propagation in terms of rays, as discussed earlier, which travel along the fibre by total internal reflection from the core/cladding interface. As long as the angle to the interface is not greater than that corresponding to the critical angle, given by $\cos^{-1}(n_2/n_1)$ where n_1, n_2 are the refractive indices of core and cladding respectively, no energy is coupled into the cladding, at least when the latter is lossless.

If an input beam is launched so as to fill the aperture of the fibre, or if scattering occurs, then the spreading of a transmitted pulse could become comparable with the difference in transmission times of the axial and extreme rays which, for a length of 1km and a typical fibre, is 0·5μs. This is equivalent roughly to a bandwidth of 1MHz. However, careful measurements showed that if a narrow beam is properly launched into a well-made fibre a pulse spreading of as little as 0·3ns occurs over 50m with core diameters in the range 50-100μm. It followed that if such a low dispersion could be maintained for greater lengths, a bandwidth exceeding 100MHz over 1km might be achieved. This bandwidth is greater than that currently available from coaxial cables, and the fact that many more fibres can occupy the same cross-section increases the advantage still further.

Later work has confirmed this result and by introducing a refractive index which falls gradually from the axis of the core, instead of having a step change at the core/cladding interface, the phosphosilicate and other fibres can be made to have a bandwidth of 1GHz over a 1km length.

11. TELEVISION TRANSMISSION BY OPTICAL FIBRE

As a result of these and other developments there is now a great interest, in most technologically advanced countries, in the use of optical fibres for communication. In the U.K. the Post Office has a large research programme and work is also in progress in such firms as the Plessey Co., Pirelli General Cable Co. and Standard Telecommunication Laboratories. The major difficulties of attenuation and bandwidth have been solved but there are many other problems to be faced before fibres find widespread applications such as jointing and cabling but these are not likely to be difficult. The first use of fibres is likely to be for special links such as data or television transmission with trial installations in the telephone network following by the end of this decade.

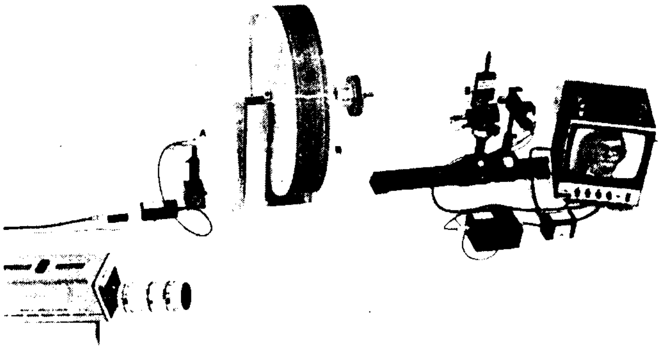

Fig. 6. 1km optical fibre television link. The video signal is fed directly to a light-emitting diode via a drive circuit. The input end of the fibre (A) abuts the diode emitting surface in a simple precision mount. The output from the fibre (B) falls on an avalanche photodiode the output of which is amplified and fed to the television monitor. Due to the fibre being so fine it is indistinguishable on a photograph of this size.

An illustration of the use of optical fibres for television transmission is given in Figure 6. The equipment was developed and built at Southampton University and was used by the BBC for the first commercial use of optical fibre communication by any national network in January 1973 when an entire colour television programme from the Royal Institution was sent through 1·25km of fibre before being broadcast. The electrical signals from the colour camera were taken to drive circuits feeding into a light-emitting diode, which turned the fluctuations of electric current into fluctuations in light intensity passing along the fibre. The light emerging from the fibre was directed onto a fast-acting light detector so as to reproduce faithfully the original electrical signal which was amplified and fed to the television transmitter. Thus the pictures on all the domestic receivers had been transmitted through a long length of fibre. Needless to say there was no deterioration in the normal picture quality.

12. THE FUTURE

The simple but realistic demonstration described above showed that glass fibres can be used for long-distance communication. Various forms exist and while the ideal fibre has perhaps not yet been made, suitable ones are already available. Light detectors are no problem and while present-day diode lasers are not yet reliable enough, they are getting better all the time. Light-emitting diodes can also be used. If optical-fibre transmission lines are put into use what effect will they have on our everyday lives? Initially the result would not be spectacular but it would mean that telephone costs would not rise as fast as they would do otherwise, and telephoning might become easier. Viewphones, which are being experimented with by the Post Office in this country as well as in America and Japan and require 300 times the frequency space of conventional telephones, might become feasible. The branches of banks are connected to a central computer to enable a rapid and up-to-date check to be kept of all accounts. This service is so valuable that perhaps in the future all offices and factories of most firms may be interconnected in the same way, thus requiring a considerable increase in the amount of data transmission throughout the country. Already attempts are being made to provide computerized references for research workers, and the logical extension of this would be to commit all journals and books to some form of computer store. It would then be possible to do away with most school, college, industrial and public libraries in favour of video links to a relatively few regional centres. The advantages would be considerable.

There are many other fascinating 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 and could dial the computerized library of the future from his armchair and have pages from books displayed on his own TV screen. If we miss our favourite TV programme perhaps we could dial it from a video store at a time convenient to us rather than to the television authorities. Viewed objectively the present method of transmitting newspapers is ludicrous. We cut down acres of forest, ship thousands of tons of wood pulp all over the world, then after printing, trains and lorries and vans in every country carry hundreds of tons of newspapers in all directions and thousands of paper boys and girls push them through letterboxes. After that there is the problem of disposing of them. Great damage is done to the environment and there is a 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. There are lots of other exciting ideas—it has even been suggested that instead of *commuting* to work we will *communicate* to work. However, all these developments will depend on our ability to understand, design and produce, new and better materials, to make communicating with light a practical reality.