OPTICAL ELECTRONICS

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What is Information?

Electronics is concerned with information - its generation (or transformation from one form to another), transmission, storage, processing and reproduction. The information can be generated in "electronic" form in a multitude of ways, from speech, pictures, printing and writing, temperature, pressure, chemical processes, blood flow, heart beats, velocity, vibrations and many other sources. In fact anything that can be measured can be translated, assuming a suitable transducer exists, into electronic information. Information, in whatever form it exists, can itself be quantified and therefore measured. It follows that the rate at which information is transmitted (rate should not be confused with velocity or speed), the amount of information stored, the rates at which it can be processed and reproduced, can all be expressed in precise numerical terms.

To take a simple, but realistic, example consider the transmission of letters and words by Morse code where each individual letter is represented by its own characteristic combination of "dots" and "dashes", as few as one or as many as five, see Figure 1. The method of transmission can, for example, be optical with a signalling lamp, or electrical with a Morse key. We could also use cabbages but this form of transmission would not be electronic (or very rapid). The rate of transmission is simply the average number of dots and dashes that can be transmitted in one second; the quantity of information that can be stored is simply the number of dots and dashes or letters that can be held at one time (on paper, magnetic tape, video disc or in a computer); and so on.

Modern information systems do not use dots, dashes and spaces but only dots and spaces, which can also be referred to as dots and blanks, or more usually, ones and zeros. Thus decimal numbers can be coded in "binary" form as in Figure 2. The individual symbols in this form of information representation are called "binary digits" - for obvious reasons - and normally abbreviated to "bits". The rate at which information is transmitted can be quoted in bits per second. Thus if it is possible to switch a lamp on and off in half a second then a message can be conveyed at the rate of 1 bit/s.

The code in Figure 2 requires four bits, which can be either zeros or ones, to indicate a decimal number between 0 and 15 (the reader is invited to complete the subsequent entries up to 15). For simple telex or telegraph transmission an information rate of 55 bit/s is sufficient; telephone speech requires 64,000 bit/s for reasonable quality; high-fidelity music must go to 400,000 bit/s; whilst colour television needs the enormous information rate of about 100 million bit/s, i.e. 100 Mbit/s.

The Social Importance of Communications

All technologically advanced societies are critically dependent on rapid communication techniques for their well-being - just imagine what would happen if telephones, television, radio and computers were to disappear overnight. Another insight can be obtained by looking back into history to the time when information transmission had hardly started.

For example, in 1588 a message was sent from Plymouth to London by the lighting of a series of bonfires on hill tops. This was a common method of sending important signals but, whilst much faster than a man on a horse, was extremely limited in its usefulness. The absence of a bonfire meant "No, the Armada has not been sighted" whilst a flaming bonfire indicated "Yes, the Armada is approaching". The rate of transmission was thus about 1 bit per day, since a second bit could not be sent until the bonfire had burnt out, been rebuilt and re-kindled. Recalling that a single frame of a television picture requires 2,000,000 bits, and that these frames are repeated 50 times a second, shows just how sophisticated modern communication techniques 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 and the rate of transmission is increased from something like one bit of information <u>per day</u> in the case of the beacon to perhaps 5 bits or flashes per <u>second</u>. The modern version of the heliograph is an electric lamp and by means of a shutter, or a dipping reflector, coded flashes of light can be sent.

The rate at which messages can be sent is now limited by two factors, firstly the mechanical shutter and secondly because the human eye has a response time of about a tenth of a second. If the eye did not retain images for this length of time, then we would see, on our television screens, pictures flickering on and off at the rate of fifty times per second, instead of the steady image that there appears to be. Thus the signalling lamp can 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/day to send as much information with a lamp as there is in even a single static colour television picture.

One way of speeding up the transmission of information is to replace the mechanical shutter by an electrical one which can be switched on and off very much more quickly. These came about with the development of transistors. Certain semiconductor diodes emit light quite strongly when an electric current is passed through them, and the intensity of the light varies with the strength of the current. Such devices are called Light-Emitting Diodes and they can be switched on and off by electrical pulses more than a million times per second.

Thus light-emitting diodes can replace the flashing light, and the eye 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 many million bits of information per second, which is enough to send television pictures.

The problem with unguided optical communication is that it is very dependent on weather conditions and the existence of a direct line-of-sight path. The guidance and protection problem was solved in the electric telegraph in about 1860 whereby pulses of electric current, generated by a hand-operated switch or Morse key, are transmitted along a pair of wires. For the first time it became possible to send information, almost instantaneously, over distances up to several thousand miles. The technique was widely used on railways and revolutionised the operation of the New York Stock Exchange.

As the social and economic advantages of the new system became apparent the demand for more and improved services began to grow. In the late nineteenth century Hertz carried out his famous experiments on radio transmission and at the turn of the century Marconi demonstrated that transmission is possible over vast oceans.

With the development of modulation and multiplexing techniques in the nineteen thirties there began the inexorable and powerful pressure for higher operating frequencies, in order to provide larger bandwidths and therefore greater channel capacities (i.e. signalling rates).

Again the driving force was an economic one since it was soon found that the cost per circuit mile fell rapidly with increasing bandwidth. This drive continued until, in the 1960's, the principal methods of long-distance data, telephone and television transmission were radio, coaxial cable, microwave line of sight and satellite, at frequencies up to about 6GHz.

Modern Electrical Communication

Radio is not a point-to-point method of communication since anyone having the requisite receiver can receive the broadcast signal, to the embarrassment and inconvenience of the police, for example. Coaxial cable, Figure 3, is the most widely used guiding medium but the transmission loss is such that, at the highest frequencies, the signal must be amplified, or the pulses regenerated, after every 3 to 5km. Microwave relay (line-of-sight) links cover distances of about 50km between repeaters and have to compete, successfully on the whole, with the vagaries of the weather. Satellite transmission makes use of a collimated microwave beam which travels for most of its path through free space, between a geostationary satellite and a ground station. The transmission loss is governed mainly by the degree of collimation of the beam, the aiming accuracy and the collection area of the receiving antenna.

In each of these systems the "carrier" wave on which the signal is impressed is generated in a highly-controlled source and comprises a high-frequency wave of extreme purity. The frequency spread of the carrier is considerably smaller than that of the signal and many different types of signal modulation are possible. The net result is that the bandwidth, i.e. the range of signal frequencies, which can be transmitted can approach roughly 10% of the carrier frequency. Bandwidth and bit rate are directly related and for present purposes we may assume that the maximum bit rate in a communications network is approximately equal to the bandwidth.

Optical Communication

As indicated in the preceding paragraph, the higher the frequency at which a communication system operates then the larger is the attainable bandwidth and thus the information transmission capacity. The invention of the laser in 1960 provided the possibility of a coherent carrier wave operating at optical frequencies. The increase in frequency from microwaves to optical waves of five orders of magnitude should enable a large increase in bandwidth to be obtained. In principle it should also provide much shorter switching times, and higher packing densities of information. For this to be possible the laser would have to be very highly controlled to produce an extremely pure light source, capable of providing a coherent carrier wave, in a device which is cheap, efficient, reliable, robust, stable and easily modulated. Some of the hopes of electronic engineers for the ideal laser have been realised but some have not, at least not yet. Among the successes are optical storage and retrieval on the video and audio discs, as well as information transmission on optical fibres. Commercial exploitation is still awaited for holographic stores, optical integrated circuits and optical computing. Obviously light propagation is very greatly affected by weather conditions and reliable communication is only possible if the light beam is guided and protected in some way.

The losses in the conductors and the dielectric of coaxial transmission lines become prohibitive as the frequency is raised. Some improvement is obtained by changing to metal waveguides but again the attenuation becomes large in the upper part of the microwave frequency band. At optical frequencies metals are so lossy that it is essential to have an all-dielectric guiding medium. The simplest form consists of a thin glass rod, or fibre, supporting a surface wave, a crude form of which was developed in 1959.

Optical Fibres

The first real step forward in optical communication came in 1966 with the suggestion that it might be possible to produce cladded glass fibres of sufficient purity that transmission over long distances would become practicable. The idea, at that time, was very speculative since existing fibres had attenuations of about 1,000 dB/km and had to be improved by at least three orders of magnitude. In fact the development of optical fibres has been such that they form the only optical medium in widespread use today and the installation of optical fibre systems is expanding very rapidly. Indeed British Telecomunications has already announced to cable manufacturers that it will order no more coaxial cable after 1985 and it is expected that over half of all trunk telephone traffic will be carried by fibres by 1991. As may be seen from Table 1, optical fibre transmission lines have much lower attenuation, and vastly greater bandwidth, than coaxial cable and, in addition, have the important virtues of small size, freedom from electromagnetic interference, are not subject to earthing problems and can be used in hazardous situations where any electrical conductor would be prohibited.

TABLE 1

COMPARISON OF MICROWAVE AND OPTICAL FIBRE SYSTEMS

	Microwave	Optical
Transmission distance by cable	2 - 4km	10-100km
Bandwidth x Length	50MHz km	25-100GHz km
Bandwidth/carrier frequency	1%	10^{-5}
Circuit components	Many	None
Multiplexing	Yes	Not yet
Frequency spread/bandwidth	10^{-6}	600 (SCL) 6000 (LED)

Nevertheless, optical fibres are still, in communication terms, in a very primitive state of development. For example, optical sources cannot yet compare with microwave or radio-frequency oscillators in terms of stability or coherence. In effect, optical communication is carried out today by modulation of a noise source since the frequency spread of semiconductor lasers and light-emitting diodes is far greater than the bandwidth of the modulating signal. Thus only amplitude modulation is possible, coupled with direct detection techniques, so that optical communications is really at a comparable stage to the spark transmitter of the last century. Coherent detection techniques are at the research phase, there are very few circuit elements, while wavelength (or frequency) multiplexing has so far proved very difficult to achieve.

Types of Optical Fibre

Despite the limitations outlined above, the performance already achieved with fibres is most impressive. In order to understand how this has come about it is necessary to look briefly at the construction of a fibre transmission line. The type of fibre used in telecommunication systems comprises a cylindrical glass core surrounded by a second, cladding, glass of lower refractive index. For the highest performance both of these materials have to be properly chosen and must have less than a few parts in 10^9 of impurity present. With the type of fabrication most commonly used, namely modified chemical vapour deposition, there is a third, surrounding, region which does not form part of the propagation path. It only serves as a substrate on which the pure materials are deposited and to bring the overall diameter to the standard dimension of about 125μm. The type of transmission loss curve which can be realised is shown in Figure 4. It may be seen that the attenuation is below 0.2dB/km at 1.5μm. There is an enormous transmission window of 100,000 GHz over which the transmission loss is below 1dB/km. It is also remarkably fortuitous that light-emitting diodes and injection lasers, which are small, efficient, reliable and capable of producing output optical powers in the region of milliwatts to watts, can be fabricated.

The bandwidth available depends on details of the fibre structure. In the simplest form, namely the step-index, multimode fibre, the core is uniform and extends to a diameter of about 50μm. Propagation can be understood in terms of rays of light injected at the input end which are continually bounced off the core/cladding interface by total internal reflection and are thereby "conducted" to the far end of the fibre. The range of permitted ray angles to the axis is determined by the refractive indices of core and cladding. Rays at larger angles are refracted at the core/cladding interface, rather than totally reflected, and suffer a loss of energy. The bandwidth of such a fibre can be simply estimated by calculating the difference in transmission times of a ray parallel to the axis and a ray at the maximum permitted angle. Taking a core refractive index of 1.5 and a relative index difference between core and cladding of 1% gives a pulse dispersion over 1km of about 50ns. The corresponding bandwidth is comparable to that of a good coaxial cable.

The effect of multipath dispersion can be greatly reduced by introducing an appropriate radial variation of refractive index in the core region. Thus if the refractive index decreases from a maximum at the core centre in roughly parabolic fashion, the precise variation depending on the materials, then the transmission time difference between low-angle and high-angle rays can be minimised. The bandwidth is then increased from a few tens of megahertz over 1km to something in the region of one gigahertz. For convenience the core diameter of such a fibre is also standardised to 50μm. Ray propagation in multimode fibres is illustrated in Figure 5.

The effects of multipath, i.e. multimode, dispersion can be totally eliminated by ensuring that only one mode of propagation is possible. This can be achieved by reducing the core diameter, typically, to about 5μm resulting in a single-mode fibre. In the absence of intermode dispersion the limiting mechanisms now become material dispersion and intramode waveguide dispersion. The former arises because glass is a dispersive medium. It can be shown that even in a bulk material an optical pulse spreads at a rate determined by the material dispersion parameter M given by $M = (\lambda/c)(d^2n/d\lambda^2)$. In a single-mode fibre the effects of both core and cladding must be taken into account, but the effect is qualitatively the same. Intramode waveguide dispersion is due to the fact that the group velocity in a dielectric waveguide is a non-linear function of wavelength. It has been shown that at wavelengths greater than 1.3 μm the variation of material dispersion and group velocity dispersion with wavelength are in opposite senses so that by judicious fibre design they can be made to cancel each other at any wavelength between 1.3 μm and 1.6 μm. The prediction of this effect was a major development which has been verified in practice. Enormous bandwidths are thus possible even with sources which are not monochromatic.

The next limit to bandwidth is brought about by the fact that in a circular structure it is possible for two orthogonally-polarised modes to propagate. Quite small departures from perfection caused by non-circularity of the core, or non-symmetric thermal strains between core and cladding, can cause the group velocities of the two orthogonal modes to differ. However this limit to bandwidth has not yet been observed and measurements over long lengths of single-mode fibre have shown that polarisation-dispersion is less than 1ps/km. This corresponds to a bandwidth x length product of 1,000 GHz km. Thus over a transmission distance between repeaters of 200km a system bandwidth approaching 5 Gbit/s is possible.

Present Applications

The bulk of present applications of optical fibre transmission lines is in telephone networks and examples of the performance which can be obtained are given by the transmission of 140 Mbit/s over 100km and 656 Mbit/s over 60km by British Telecom and a rate of 1 Gbit/s over 120km at Bell Telephone Laboratories. Fibres are also beginning to find their way into less sophisticated applications where the other advantages, apart from low loss and bandwidth, are sufficient attraction. Often simpler fibres are adequate and the range of possible installations is large, ranging from cable television, the local telephone network, computer interconnection, missile guidance and many others. For any application cost is of paramount importance and it is interesting to observe that the price of high-quality telecommunication fibre per foot is less than that of a hot dog. A more sophisticated comparison with line and radio transmission is shown in Figure 6.

Problems

One important difference between glasses and metals is that the former are brittle. Thus if a copper wire is stretched beyond its elastic limit it will flow, and therefore stretch, considerably before it breaks. Glass, unfortunately, is not so obliging. Nevertheless strength is much less of a problem with optical fibres than might be imagined because glass is inherently a strong material with a Young's modulus comparable with that of steel. Providing the surface can be maintained in a pristine state a fibre of 125µm overall diameter can withstand a load of 5kg. Techniques of fabrication and cabling have been developed which allow fibres to be used in practice without insurmountable problems.

Another potential problem is that of jointing, especially in a single-mode fibre where core alignments of better than 0.1µm are necessary. Again satisfactory techniques have been developed which allow fusion jointing to be performed giving joint losses of 0.1dB or less.

In the early days of microwave transmission, before isolators were developed, it was standard practice to insert a 10dB pad at the output of a microwave oscillator to prevent reflections from the line causing detuning and instability. Thus only 10% of the output power was available for practical utilisation. We are in approximately the same position with optical sources, especially semiconductor lasers, and with such low transmission losses reflections from quite large distances can be troublesome. There is thus an urgent need for a cheap, compact, low-loss isolator - indeed for an isolator of almost any kind.

Again, imagine how difficult it would be to operate microwave circuits without directional couplers but such devices are not readily available for use with fibres. The operating principles of fibre directional couplers are well understood but the technology for making them reliably and cheaply still awaits development.

The need for techniques of wavelength division multiplexing has already been mentioned. So far we are only able to use up to about 1 GHz of the 10^5 GHz available from a fibre.

The Future

It is not too ambitious a prediction to say that within the next few years suitable isolators, couplers, multiplexers and other components will surely be developed and the applicability of fibre techniques will be correspondingly increased.

At the present time a considerable amount of promising work is leading to the demonstration of the possibilities of coherent, heterodyne detection. The stability of a semiconductor laser can be considerably improved by injection locking from a separate stabilised laser. With the low fibre losses readily available a gain in detector sensitivity of 10-15dB implies an increase in transmission distance of some 50-75km. It might therefore be possible to look forward to repeater spacings of, say, 300km which will be of considerable economic importance for long-distance routes and particularly underwater cables.

The economic impact of underwater optical fibre cables over the next ten to twenty years is likely to be considerable. For example, a half of all the existing underwater cables leaving the United Kingdom are less than 250 km in length and one half of all the underwater cables worldwide are shorter than 400 km. Thus it will soon be possible to replace all these copper links with optical fibre cables requiring no submerged repeaters. This means in turn that no copper wires will be required for supplying power to the repeaters, the cables will thus become smaller, lighter, more flexible and cheaper and the information-carrying capacity of an optical fibre is already enormously greater than that of any copper cable. For example the first transatlantic optical fibre cable, for which contracts have been placed and is due for installation in 1988, will carry more than half the telephone traffic presently being conveyed on all existing transatlantic cables. Underwater copper cables do not have sufficient bandwidth to carry television circuits which have to be beamed at microwave frequencies via a satellite. Optical fibre underwater cables will be capable of carrying television traffic, as well as data and telephone circuits, and are likely eventually to supersede satellites for this application. The first underwater optical fibre cable in operation is between Portsmouth and the Isle of Wight and another cable has been laid between this country and Belgium.

From the loss figures of 1,000 dB/km of 1966 there has already been a reduction to less than 0.2dB/km. It has been pointed out that there are certain materials which intrinsically have even lower losses in the wavelength region 5-10μm, maybe even as low as 0.01dB/km, as shown in Figure 7. These materials are much more difficult to process and handle than glass but a loss of a few dB/km has already been demonstrated in one of them. There is still a long way to go, but it is intriguing to speculate on whether it might be conceivable to operate over repeater spacings of several thousands of kilometers rather than a few hundred. This might result in transoceanic transmission with no submerged repeaters at all. Unfortunately the dispersion at these longer wavelengths is likely to be significantly greater than the figures quoted above for existing single-mode fibres.

Economic Prospects

Optical fibre communications is only a part, albeit a major component, of the rapidly growing industry and technology of optical electronics, or opto-electronics as it is being increasingly called. A number of market surveys have been carried out and all predict an explosive growth over the next ten years. One estimates a world market by 1990 in excess of £M4,000 and whilst the precise figure is no more than an educated guess the order of magnitude is generally agreed between the various experts. Sales of optical fibres in Japan, to take one example, amounted to £M16 in 1979 and is expected to increase by an order of magnitude by 1990. The present applications of optical fibres, also in Japan, are given in Table 2. One of the sectors which may achieve a growth rate rivalling that of communications will be industrial process control where a considerable amount of interest is currently being generated.

TABLE 2

RELATIVE IMPORTANCE OF VARIOUS FIBRE APPLICATIONS IN JAPAN

(EXPRESSED AS A PERCENTAGE)

Telecommunications	35
Electrical Power Plant	24
Industrial process control	9
Transport	9
Education	7
Cable television	5
Military	5
Other	6
	100%

Local Area Networks

The main application of optical fibres so far has been long-distance, point-to-point communication and there are many major installations, with an increasing number in the planning stage, in many industrialised countries. The more difficult problem of underwater optical fibre cables is being addressed and the long-term impact is going to be considerable. However, a considerable amount of information transfer takes place over distances of a kilometre or so, rather than hundreds and thousands of kilometres. At the moment this largely takes place over the local telephone network which has a bandwidth only just large enough for speech transmission. A number of experiments are now taking place in many parts of the world on the application of fibres to short distances, including communication within buildings and factories. Fibres would increase the bandwidth available very considerably and would allow many additional services, such as video transmission, electronic mail, etc., into the individual office and home. The technological problem here lies not with the fibre itself but with the requirement for many joints, junctions, switches and other simple, but vital and difficult, circuit components. These are not yet available sufficiently cheaply and reliably. Cable television is another possible application and the range of services which will become available into the home as well as inter and intra-office links, will increase rapidly when these technical problems are solved.

Integrated Circuits ("The Silicon Chip")

The great revolution which is taking place in our ability to handle information has come about through (a) the ability to store and process vast quantities of information cheaply and quickly in electronic microcircuits, (b) our ability to transmit vast quantities of information cheaply and reliably over long distances through optical fibres and (c) the ability of computers to control and handle this electronic revolution. Progress in integrated circuits has been phenomenal but limitations to their construction are now beginning to appear. For example, chips containing up to 100,000 gates may require as many as 300 electrical pins to take the signals to and from the chips. Even this number of pins makes it impossible to exploit fully the inherent capability of the high-speed microelectronic family. As the number of circuits on the chip increases, the number of pins required will become prohibitive and some other method of transferring the information must be sought. Research has recently begun into the possibility of using optical fibres instead of electric wires for interconnections and these, I suppose, would be the shortest optical fibre links that one can imagine.

Optical Fibre Sensors

The major advantages of optical fibres for communication purposes are primarily the low transmission loss, which is one hundred times better than copper wire and coaxial cable, and the almost infinite bandwidth available. There are other advantages which are useful bonuses for telecommunications but which give rise to another range of applications having almost as great a technological importance. These advantages are firstly the freedom from electromagnetic interference, i.e. the fact that fibres can be laid in close proximity without the light in one fibre entering the other and secondly, the fact that there is no sparking hazard with fibres so that they can be used in coal mines, fuel tanks and ammunition lockers without fear of explosion. These applications could be crucial in the field of sensors since optical fibres can be made responsive to a wide range of parameters such as temperature, mechanical strain, acoustic pressure, vibration, magnetic field, electric current, and many others.

An illustration of the potential advantage of fibres is as follows. Tankers carrying thousands of gallons of petrol travel the roads in our cities and towns daily. There are no instruments in the fuel tank to tell the driver whether the pressure is rising, there is a leak, or even whether the fuel is on fire, since it is much too dangerous to have any electrical wires in such an inflammable material. Optical fibres could be laid in the tank with very little hazard and, in fact, the first application of an optical fibre as a sensor in practice was to measuring the fuel level in such vehicles.

The field of research and development in optical fibre sensors is much more difficult than in communications but much work is being carried out and various market surveys predict sales of optical fibre sensor systems of many hundreds of millions of dollars by 1990.

Optical Storage

Any electromagnetic radiation can be focussed to a spot, the diameter of which is comparable with a wavelength. The wavelength of visible light is less than 1μm (10^{-6}m) and it is therefore possible, in principle, to have about one million resolvable spots in an area of only one square millimetre. The difficulty with information stored discretely in this way is that small specks of dust can obliterate some of the spots and therefore prevent access to the bits of information stored there. However the technique of holography differs from the normal photographic process in that each point on the original picture is stored over the whole of the photographic plate. Thus the presence of dirt and scratches merely reduces the contrast available and does not destroy individual pieces of information. Indeed even a portion of a hologram can reproduce the original picture in its entirety.

Unfortunately this technique, while excellent in principle, has not yet been incorporated in practical commercial devices. Experimental systems are capable of storing one hundred million numbers bits of information on a photographic plate some 10cm^2 so that the possibilities are indeed enormous.

There is a great need for higher storage densities and there are strong indications that even the existing requirements for lower costs, greater packing densities and archival quality storage, cannot be met by established technologies. Optical storage potentially can supply all these needs with storage densities in excess of 100Mbit/cm^2 at a cost of one millionth of one penny per bit in the case of very large stores. Optical techniques could also provide long-term archival storage without deterioration and the importance of this may be judged from the fact that magnetic tapes, which are in widespread use today, must be renewed every six to twelve months. Work on holograms continues, and the concept of three-dimensional or volume holograms is being explored but no breakthrough is yet in sight. Other, more conventional, types of optical storage medium certainly exist and the video and compact discs are well-known examples. In the audio compact disc individual bits of information are represented by tiny pits in the surface of the disc which is read by a scanning laser beam (more accurately the laser is stationary and the disc is scanned but the principle is the same). Discs of this kind must be recorded whilst being made and cannot be erased to have fresh programmes inserted on them. Nevertheless they represent a major step forward. More recently has come the announcement of an erasable, and re-recordable, disc which is an impressive development. It is based on a thermo-magneto-optical recording technique and a tiny disc 3.5 inches in diameter can store some 40 megabits of information which is equivalent to 20,000 typewritten pages. To put this into a context which can be more easily grasped the same disc, costing eventually only £20 or so, could record two hours of high-quality stereo music.

Optical Computers

So far I have talked about the transmission and storage of information using optical, rather than electronic, techniques. Let us now ask whether one can use optical photons for information processing and is there, for example, any optical equivalent to the transistor? There are two potential advantages, firstly the possibility of parallel operation rather than the sequential operation inherent in electronic techniques and the fact that optical switching processes are inherently very much faster than electronic ones. Progress in this field has been slow. Early work in 1963 came to nothing but the topic has been taken up again more recently with some encouraging results. Some optical transistor, and switching, devices have been produced using semiconductors such as indium antimonide and gallium arsenide. As with all switching devices there is a trade-off between power and speed but switching times in the picosecond region have been reported at reasonable power levels. However, this area of work is still in the exploratory stage and it is unlikely that practical devices will emerge during this decade. It is always risky to make predictions, given the rapid advance in electronic technology now taking place, but I believe it to be true. Nevertheless I am reminded of a saying of Groucho Marx, "Never prophesy - especially about the future".

Sociological Impact

The information revolution I have referred to will have - indeed is having - an effect on our lives comparable to that of the industrial revolution. Already we take for granted hand-held computers costing only a few tens of pounds, the ease and flexibility of colour television, video recorders and computers. Predicting further advances requires a good deal of lateral thinking but some changes are obvious.

The flexibility and opportunities made available by the interconnection of banks, travel bureaux, computers and the like are only just being grasped. Furthermore if optical fibres can be applied cheaply and successfully in local-area networks then the meagre bandwidth available at the individual telephone will be increased by some ten thousand times enabling video and many other services to become easily available, see Table 3. Some of this is already happening, to some extent, with copper cable in the exploratory cable television networks. The private citizen could have a communication capability exceeding that of any commercial or private enterprise today.

TABLE 3

Future "telephone" services

- Cable television
- Document and picture transmission (facsimile)
- Prestel
- Access to computer network
- Access to libraries
- Electronic mail
- Electronic newspapers

Already attempts are being made to provide computerised 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. It would be interesting to evaluate the total national cost, including buildings, books, periodicals and staff, of all the existing libraries in the country. Most people have television receivers and could have library material displayed on their domestic television screens. Most people with home computers have cheap printers on which the accessed material could be printed, if desired.

We could also change the incredibly archaic present method of distributing news via newspapers, and mail by letter, with electronic systems. We could transmit letters electronically, and instantaneously, anywhere in the world and could dial our favourite newspapers and pages therefrom, within the comfort of our homes and, again, either read them on the television screen or print them out on our own printers. It has even been suggested that instead of commuting to work in the future we will communicate to work. All these developments will depend on our ability to understand, design and produce new and better materials, in an economic and socially-acceptable way.

Figures

Figure 1	Morse Code.
Figure 2	Decimal numbers coded into binary digits and electronic signals.
Figure 3	Microwave transmission methods.
Figure 4	Spectral attenuation of a high-quality optical fibre.
Figure 5	Ray propagation in step-index, and graded-index, multimode fibres.
Figure 6	Cost comparisons of optical fibre systems at 140Mbit/s with digital line and radio systems.
Figure 7	Calculated loss characteristics of some potential fibre materials. The lower dashed line represents the loss due to Rayleigh scattering.

MORSE CODE

A	· —	N	— ·
B	— · · ·	O	— — —
C	— · — ·	P	· — — ·
D	— · ·	Q	— — · —
E	·	R	· — ·
F	· · — ·	S	· · ·
G	— — ·	T	—
H	· · · ·	U	· · —
I	· ·	V	· · · —
J	· — — —	W	· — —
K	— · —	X	— · · —
L	· — · ·	Y	— · — —
M	— —	Z	— — · ·
1.	· — — — —	6.	— · · · ·
2.	· · — — —	7.	— — · · ·
3.	· · · — —	8.	— — — · ·
4.	· · · · —	9.	— — — — ·
5.	· · · · ·	0.	— — — — —

Fig. 1 Morse Code

Decimal number	Binary number	Electronic signal
0	0000	
1	0001	
2	0010	
3	0011	
4	0100	
5	0101	

Fig. 2 Decimal numbers coded into binary digits and electronic signals.

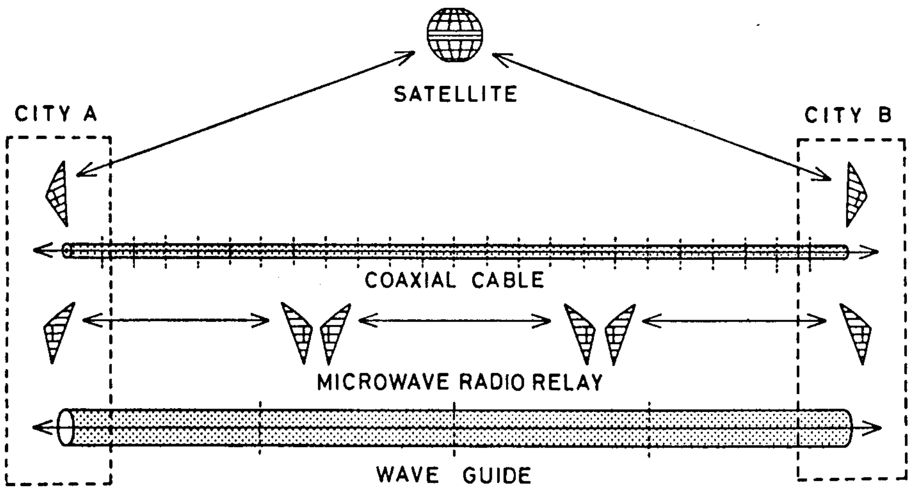

Fig. 3 Microwave Transmission Methods

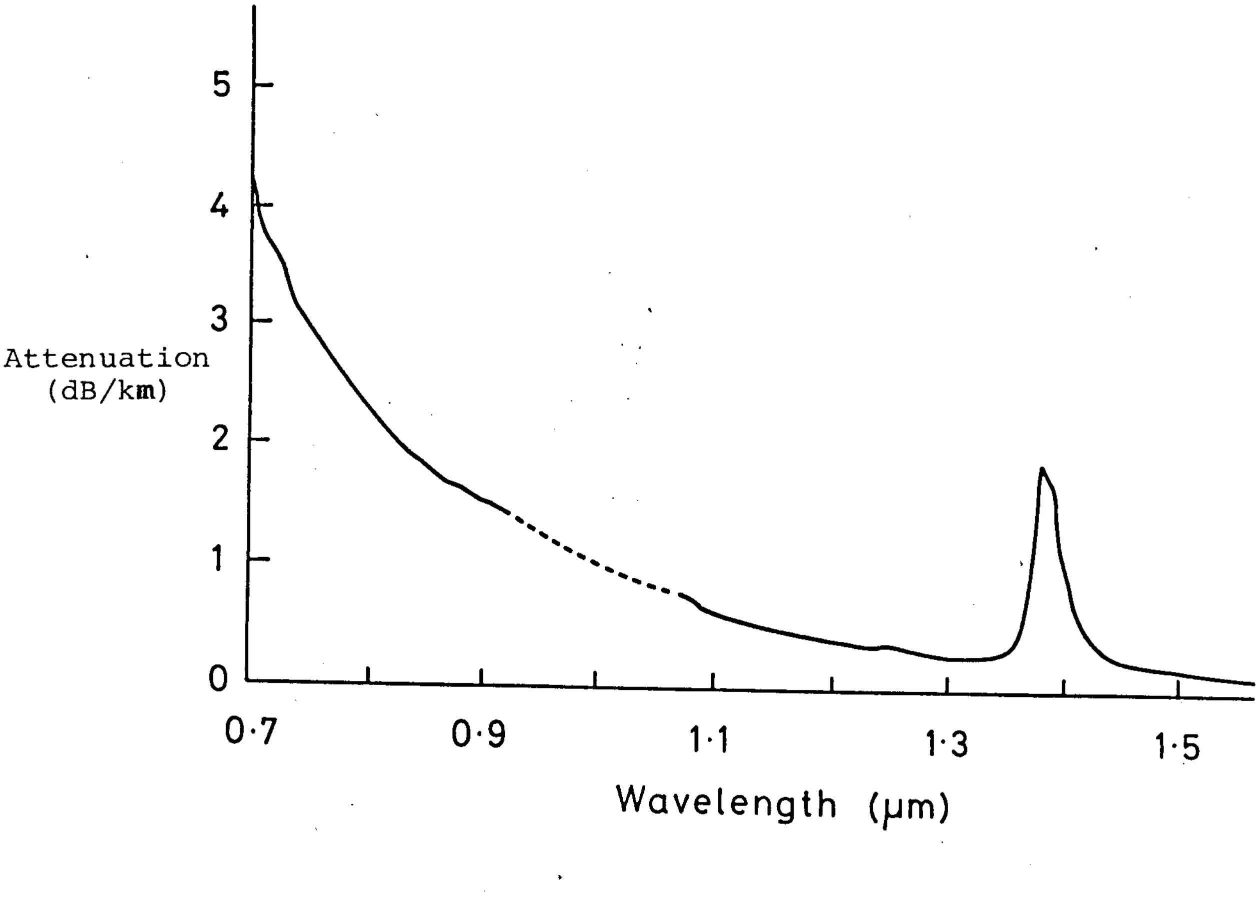

Fig. 4 Spectral attenuation of a high-quality optical fibre

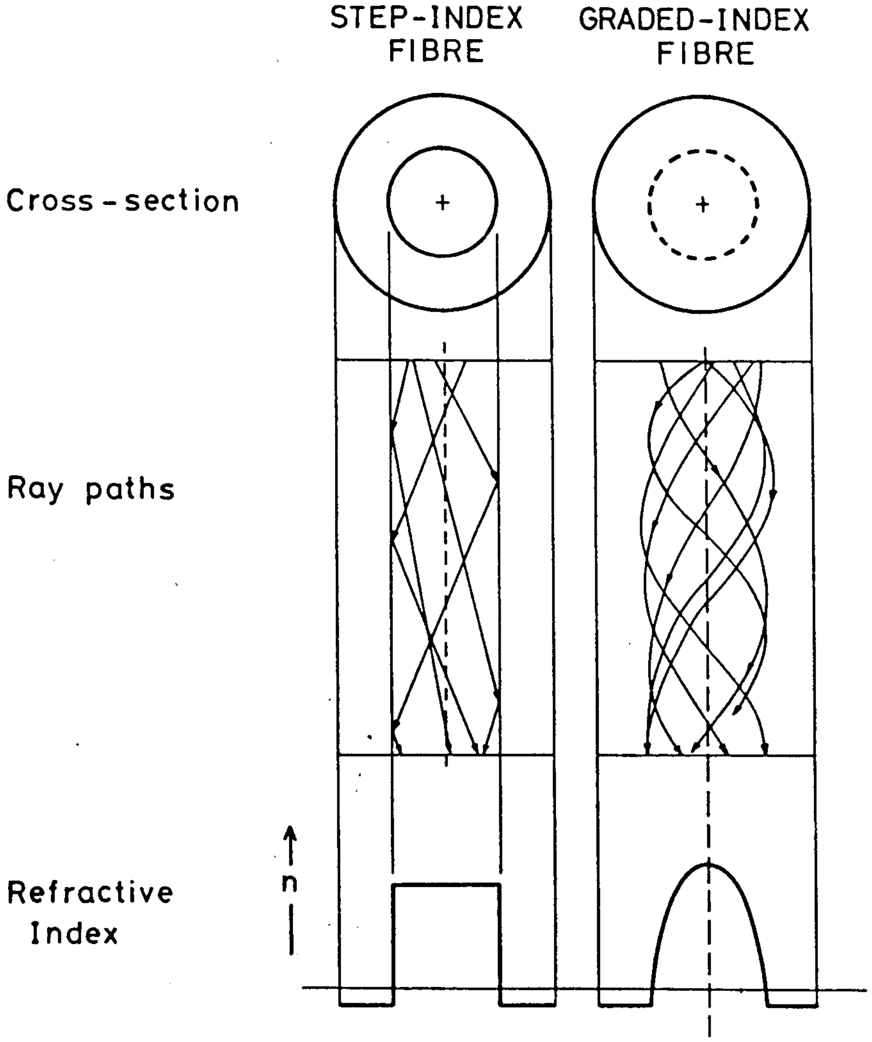

Fig. 5 Ray propagation in step-index, and graded-index, multimode fibres

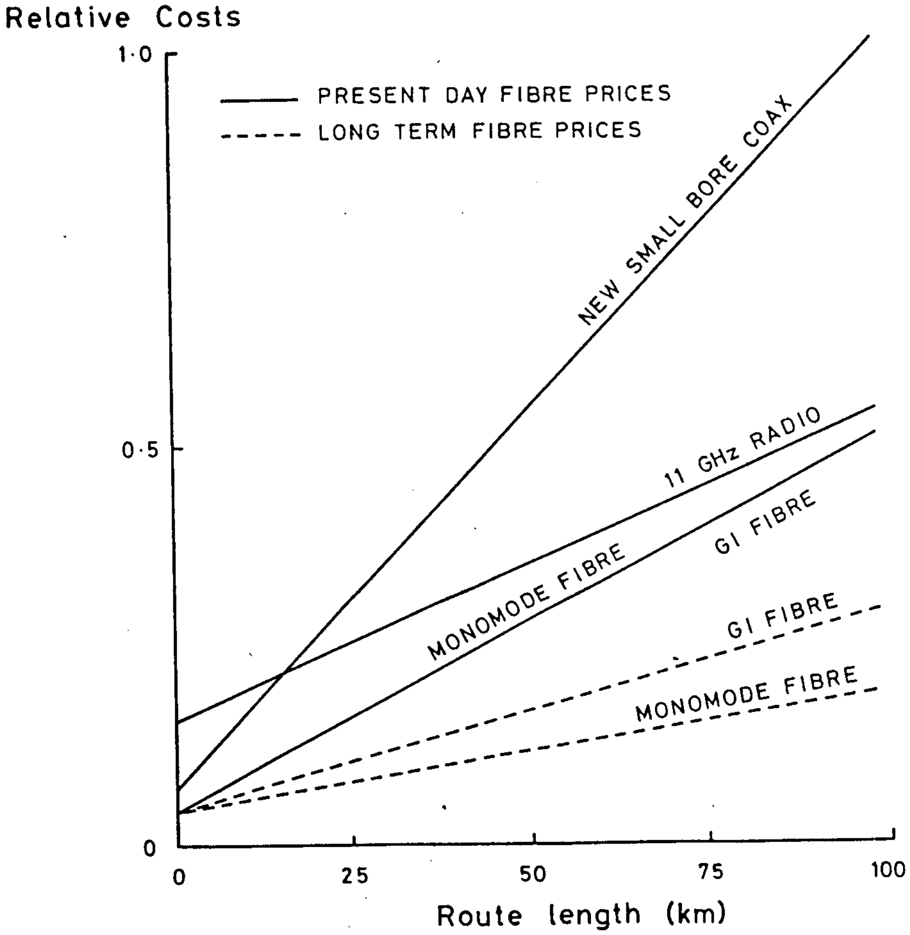

Fig. 6 Cost comparisons of optical fibre systems at 140Mbit/s with digital line and radio systems.

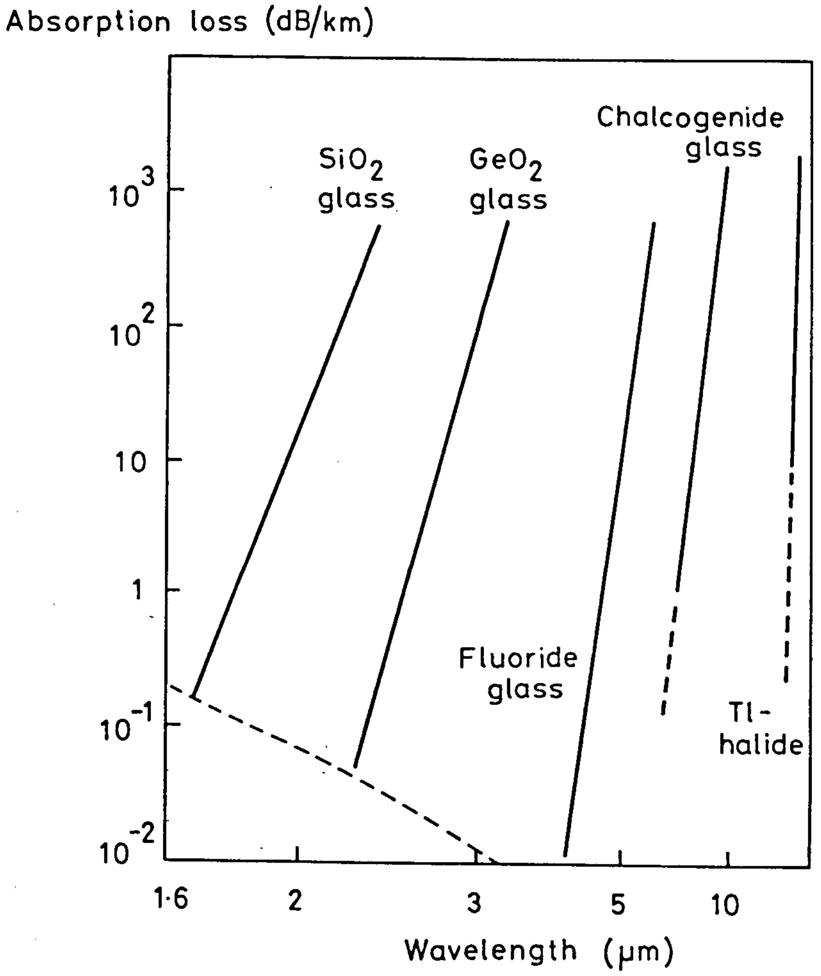

Fig. 7 Calculated loss characteristics of some potential fibre materials. The lower dashed line represents the loss due to Rayleigh scattering.