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Photons and Fibres: The New World of Communications

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INTRODUCTION

It gives me very great pleasure to present this Royal Academy of Engineering address on Information Technology to the British Association for the Advancement of Science. I also gave a lecture on information technology—although the subject was not referred to in that way at the time—when the BA meeting was last held in Southampton, in August 1964. In that lecture I speculated on the possible use of glass fibres and laser light as replacements for copper wire and electric currents in the telephone network. This was a very speculative idea at the time and I was rather taken to task by the Director of Research of the then Post Office Research station (now British Telecom Research Laboratories) who was in the audience. He asked some detailed practical questions which at that very formative stage of "blue sky" thinking it was not possible to answer.

In my address today, 28 years later, I shall describe how developments in optical fibre communication, whilst slow initially, have become spectacular. The objective of replacing copper cables in the telephone network, and elsewhere, by optical glass fibres is well under way and now anyone making other than a local call is likely to be speaking through a glass fibre and using laser light, whether the call is to the next town, or to the continent, USA, Japan, Australia and so on. A remarkable revolution is well underway. This is very satisfying to me, particularly as I was told on several occasions in the early days that the idea was unrealistic and misguided.

Information

Society is totally dependent on information—its acquisition, transmission and processing—for business, industry, education, entertainment and for almost every other aspect of our lives. Information can be passed by word of mouth, in writing, or by some form of signalling. For transmission by signalling (and even in writing) the information has to be coded in a suitable way, various examples being indian smoke signals, the heliograph, semaphore, Morse codes, telephone, television and facsimile. At the receiver the transmitted signal must be decoded and reproduced in a convenient manner, usually as a reasonably accurate reproduction of the original information, but not necessarily. For example, the "hotness" of a furnace is represented in the control room as a numerical temperature, rather than by reproducing it as an equivalent "heat", which would not be convenient!

Information Transmission

By far the cheapest method of transmitting information over a reasonable distance is by telecommunication, except perhaps for extra-sensory perception which (if it exists) is limited to a few individuals and low information rates. Information is typically coded into "bits", or binary digits—pulses in other words—and it is interesting to compare the transmission rates of the different signalling systems. Indian smoke signals are capable of roughly one bit (or puff!) per minute; the heliograph or semaphore can manage 1 bit (flash) per second, whilst speaking is equivalent to about 100,000 bits/second. In contrast a still colour television picture is composed of roughly 1,000,000 bits and successive frames are flashed onto the television screen at the rate of 50 times per second. (Thus to transmit a television programme by semaphore would take 50,000,000 operators and the distance covered would be limited to line of sight).

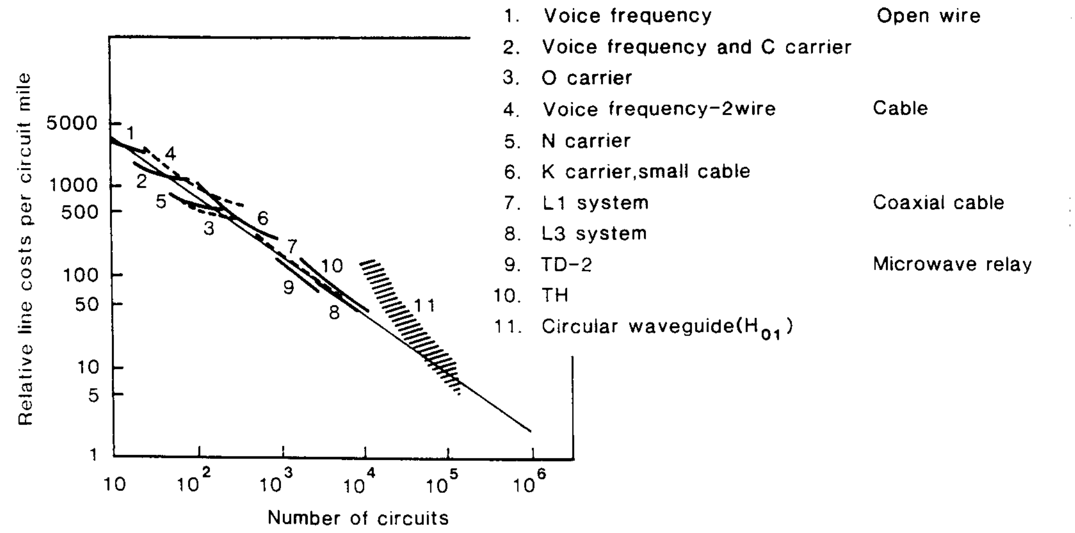


Figure 1: Fall in relative cost of a telephone circuit with increase in the number of circuits (ie. the bandwidth) in the system.

Until ten or so years ago the standard method of telecommunication involved the sending of modulated electric currents along copper wire (eg. the telephone system) or modulated radio waves through the atmosphere (radio and television). Alternatively the information can be coded in the form of bits, but the principle is exactly the same. The former method—analogue modulation—is still widely used but increasingly modern systems rely on bit, ie. digital modulation which has many advantages, including ease of handling and lower distortion, although is does require a much larger bandwidth—until recently the perennial cry of communication system designers.

The importance of the bandwidth, ie. the information carrying capacity, cannot be over-emphasised. Obviously there is a capital cost, usually large, involved in setting up any communication system, so that the larger the bandwidth the lower is the cost of each individual circuit, eg. each telephone call. As an example Figure 1 shows that the cost of long-distance telephone calls has fallen to one hundredth that of the original two-wire (telephone pole) systems, with bandwidths of a few kilohertz, to the microwave relay systems (20 megahertz) still in use today.

What, then, determines the bandwidth? Several factors come into play. Firstly, practical ones such as the rate at which the transmitter can be modulated, the speed of response of the receiver and the properties of the transmission path. However, there is a more fundamental limit determined by the frequency of operation. Thus if a carrier wave is undergoing sinusoidal oscillation at f cycles per second it cannot be modulated to produce decipherable pulses at a greater rate than this. In fact it is not normally possible to get anywhere near that rate. But it does follow that the higher the carrier frequency the greater will be the permissible bandwidth.

In 1966 the highest carrier frequency used in telecommunication was in the microwave region at 4GHz to 6GHz. The laser had been invented in 1960 and the thought occurred to communication engineers that if suitable devices could be sufficiently well controlled there was a possibility that it could provide an optical carrier wave for communications purposes. If so then the potential bandwidth available from a single carrier might, in principle, be increased some one hundred thousand times, because the frequency of an optical wave at a wavelength of 1μm is 300,000 GHz, compared with the few gigahertz at microwave frequencies. Thus the potential advantage was immense—but so were the technical problems to be overcome.

In order to understand why a radical change in technology is necessary, consider the curves in Figure 2 illustrating the growth of the number of telephones and number of telephone calls in the United Kingdom over the period 1920 to 1990. The telephone calls are numbered in thousands of millions and represent an exponential growth. It is interesting to speculate that were the trend to continue (which it will

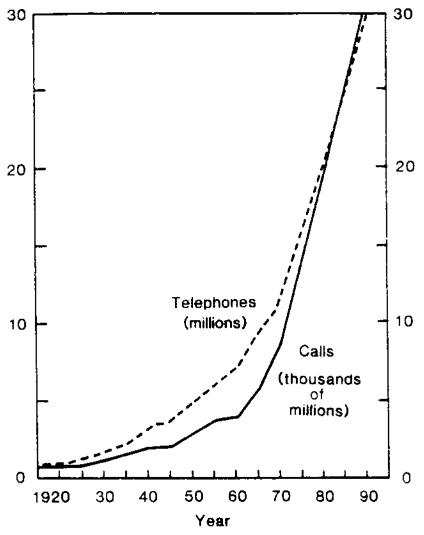


Figure 2:
Numbers of telephones and calls made in the United Kingdom from 1915 to 1990.

not do of course) then at some point in the future no-one will do anything except talk into the telephone all day! At present the curves are still rising sharply, showing that the demand on the telephone system is increasing extremely rapidly. In 1990, for example, the number of calls made was thirty thousand million and if it is assumed that the average telephone call lasts for approximately five minutes, then at any instant during the working part of the day almost a million people, in the UK alone, are talking on the telephone, (and these usually include the people one is trying to get through to oneself!).

In addition to carrying telephone calls, increasing use is being made of the telephone system for data transmission, video transmission and other services. Business organisations, including airlines, banks and companies are now taking for granted data links between centres; facsimile, electronic mail, etc. Many people have terminals on their desks giving access to computers and data bases that may be many miles away. A host of other services is also being provided.

The next question is how to meet the increased demand on the telephone system. Do we build another network of the same kind? Figure 1 illustrates that this is not the answer because the relative costs per circuit mile fall with increasing operating frequency. Clearly it is enormously cheaper in expanding a telecommunications network, to move to higher carrier frequencies and larger bandwidths than it is simply to duplicate the existing system. Furthermore, there is probably insufficient copper in the world for the present level of traffic to be carried on ordinary line pairs. Thus where the demand exists the adoption of more complex systems can bring down costs, and increase convenience, appreciably.

THE COMPETITION

As indicated above, systems operating at microwave frequencies have bandwidths of a few tens of megahertz. The main transmission channels are coaxial cable, microwave radio relay and satellite, with distances between repeaters, which are necessary to amplify or regenerate the signal, of about 5 km with coaxial cable, 50km with microwave radio relay, and 50,000km with satellites. This was the competition that any new optical system had to contend with.

OPTICAL TRANSMISSION

The invention of the laser in 1960 seemed to provide an ideal optical source because it was, in principle, monochromatic and capable of modulation in the same way as carrier waves at lower frequencies. It can be collimated quite accurately, because the angle of spread of a diffraction-limited beam is given simply by the ratio of the beam diameter to the wavelength. The first, elementary, concept was therefore to collimate a modulated, or pulsed laser beam and point it at a distant receiver as is done with

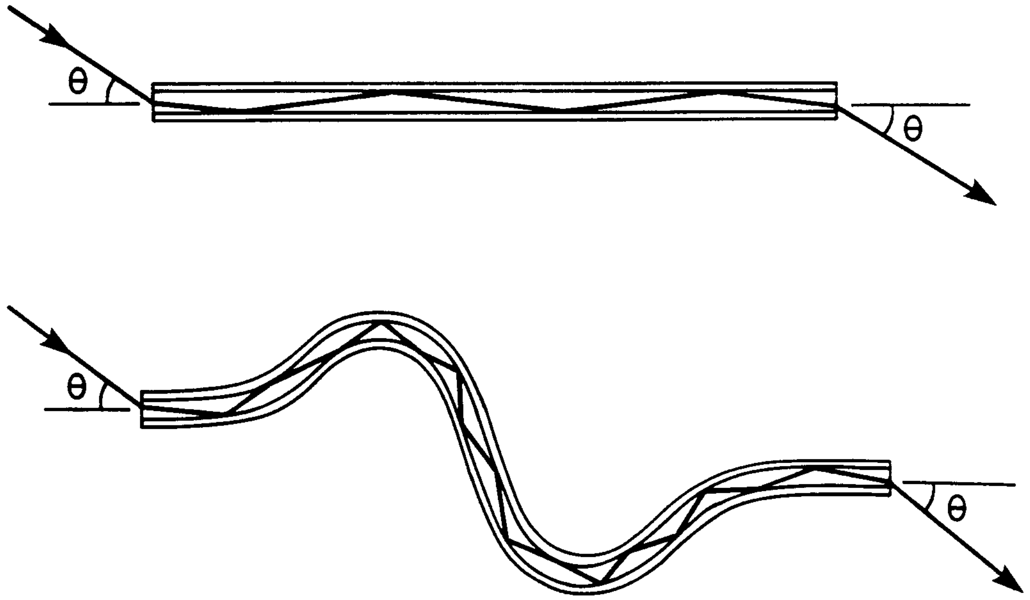


Figure 3: Rays of light being guided in straight and curved glass fibres.

microwave radio relay. However, in addition to problems with precipitation, temperature gradients within the earth's atmosphere cause great difficulties. For example, a beam 5cm in diameter and one kilometre long requires a temperature difference across it of only one thousandth of one degree to cause it to be deflected by an amount equal to its own diameter. Thus if the temperature gradient fluctuates by just one thousandth of a degree the beam will wander in position at the receiver. Of course temperature gradients are normally much greater than this, and are not uniform, so that the beam breaks up randomly into smaller elements, each of which is waving around like a dog's tail. It turns out that free-space, unguided, optical propagation is only possible with 99% reliability over distances of about a kilometre.

In order to do any better within the earth's atmosphere the beam has to be protected in some way, such as being contained within a pipe, which is either evacuated, or kept at a well-controlled temperature. The beam inevitably spreads by diffraction but must not be allowed to strike the sides of the pipe because of the high losses induced by reflections and a great increase in dispersion. Various techniques for containing the beam, such as the introduction of a periodic sequence of lenses to correct for the diffraction spread, were actually demonstrated but clearly would be extremely expensive to develop, to maintain, to install and to operate, since the light conduits would effectively have to be optically straight.

Optical Fibres

A great variety of such beam-guiding schemes were considered but the first real possibility of a practical long-distance telecommunication system at optical frequencies came with the concept of perhaps devising some kind of guiding mechanism based on a glass fibre. Glass is an interesting and important material in the fabrication of optical fibres because its viscosity changes gradually with temperature. A crystalline material is liquid above its melting point and solidifies into a crystal if held fractionally below the melting temperature, when the volume per unit mass undergoes a marked change. This transformation in material properties is quite sudden, in temperature terms, and is difficult to control. A glass, on the other hand, does not experience this step function change in bulk properties; the volume per unit mass continues to decrease steadily as the temperature is reduced, and the viscosity increases. There is a gradual change of state at the glass-forming temperature, the precise value of which depends on the rate of cooling. The material could initially be classified as a super-cooled liquid and then becomes glass, but throughout the whole temperature span the viscosity changes quite slowly. Thus a glass heated to the vicinity of the glass-forming temperature becomes soft and pliable and can be worked. That is why it is relatively easy to turn bulk glass into a fibre.

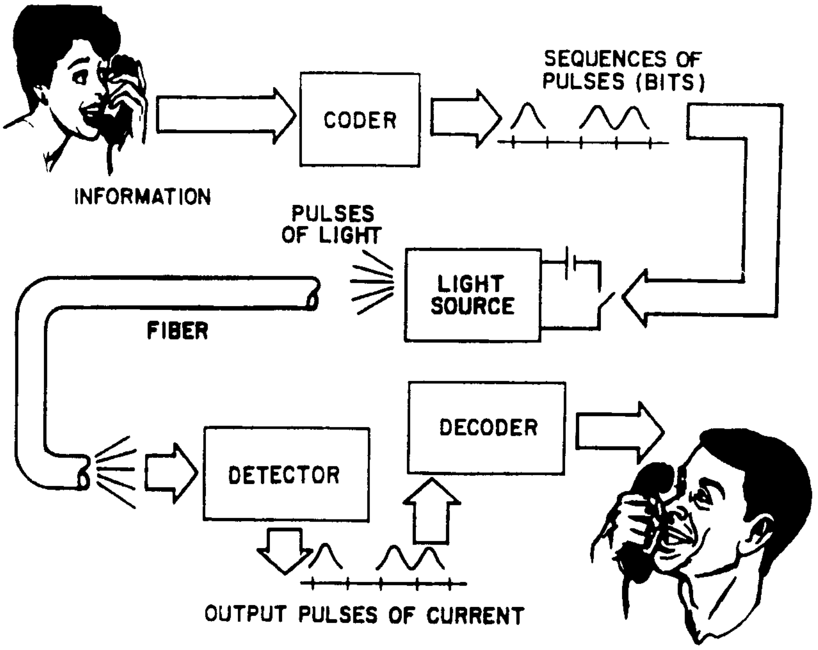


Figure 4: Simple optical fibre communication system.

One is not necessarily limited to glassy materials for making optical guiding structures but it turns out that certain types of glass, such as silica and materials based on silica, have incredibly low transmission losses in an interesting wavelength range.

Light Guidance

If a ray of light, propagating in a glass rod surrounded by air, strikes the external surface of the rod at an angle (with the normal to the surface) greater than the critical angle, then it will be totally internally reflected with, under ideal conditions, no loss of energy. Hence the first requirement of guidance by optical fibres is simply to ensure that any rays of light entering the end of a fibre strike the external surface at an angle greater than the critical angle. If the surface is smooth, and providing the materials do not absorb unduly, then all of the energy striking that surface will be totally reflected and by a series of successive reflections all of the light will emerge at the far end of the fibre. It follows that there is a finite cone of collection angles at the input end and light launched outside that acceptance cone will not strike the surface beyond the critical angle and some energy will be refracted out. The transmission loss is thus increased.

If the glass rod is bent then, providing the radius of the bend is not too large, most of the rays launched within the acceptance cone continue to propagate by total internal reflection around the bend (Figure 3). Rays very near the critical angle at the bend will suffer some radiation loss by refraction as the radius of the curvature at the bend is decreased and so the loss gradually increases. In practical terms the fibre can be curved to a radius of about a centimetre without any appreciable additional loss being caused by bending. The glass fibre therefore provides a flexible transmission path, because within this limitation of a 1 cm bend radius, the light rays still continue to travel in straight lines within the fibre, but all rays entering within the acceptance cone emerge at the output end. The constraint for the communication path to be optically straight is thus avoided and the mechanical flexibility of the transmission line is a crucial feature in the application of optical fibres in effect it produces an "optical conductor".

The surface of glass deteriorates when exposed to the air and it is necessary to clad the guiding core with a suitable second glass. In order to maintain conditions for total internal reflection the refractive index n_2 of the cladding must be less than that of the core n_1. The optical quality of the cladding glass must be comparable with that of the core, since some of the electromagnetic field penetrates from the

TABLE 1

PARAMETERS OF OPTICAL FIBRES

- Numerical Aperture

$$NA = \sin\theta_m = (n_1^2 - n_2^2)^{1/2} \propto n_1(2\Delta)^{1/2}$$

where θ_m = maximum acceptance angle in air
n_1, n_2 = refractive indices of core, cladding

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \propto \frac{n_1 - n_2}{n_1}$$

- Difference in propagation times of axial and extreme rays in
(a) Step-index multimode fibre:

$$(\Delta t)_s = \frac{n_1 L}{c}\left(\frac{n_1 - n_2}{n_1}\right) \propto \frac{n_1 L}{c}\Delta$$

(b) Parabolic-index multimode fibre:

$$(\Delta t)_m \propto \frac{n_1 L}{c} \cdot \frac{\Delta^2}{8}$$

where L = fibre length
c = c x 10^{x}m s^{-1}.

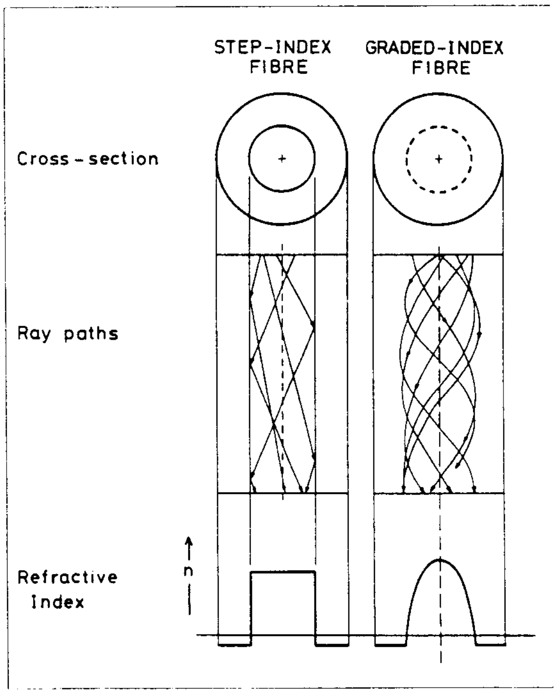


Figure 5:
(above)
Cross-section,
refractive-index profile
and ray paths in a step-index
and a graded-index fibre.

core into the cladding. An optical fibre thus basically consists of a two-layer coaxial structure comprising a cylindrical central core and an annular cladding. More sophisticated fibres may contain additional regions to enhance their properties.

OPTICAL FIBRE COMMUNICATION SYSTEMS

The optical fibre transmission systems enjoying widespread application today are basically very simple and are limited to transmitting information over large distances. The electrical information, in whatever form it is available, is fed into a suitable transducer, which could be a light-emitting diode or a semiconductor laser, to produce a modulated optical output which is launched into the optical fibre, Figure 4.

In order to maintain the required signal/noise ratio the optical signal must be amplified or regenerated before it falls below a critical level. In practice there is always some attenuation of the propagating optical wave due to absorption and scattering in the glass and imperfections in the fibre waveguide. In order to amplify the signal it is necessary to reconvert the optical carrier into an electrical one in a fast optical detector, such as a p-i-n, or avalanche, photodiode. The amplification is thus carried out electrically and the signal then converted back to optical form for onward transmission.

The optical part of the system is thus rather simple and primitive, consisting of a light source, fibre transmission line and a detector. Nevertheless, as indicated in subsequent sections, the transmission distances possible, and the bandwidth, are orders of magnitude greater than with coaxial cable operation.

The bandwidth available depends on details of the fibre structure. In the simplest form, namely the step-index, multimode fibre, illustrated in Figure 5 the core is uniform and extends to a diameter of 50μm. Propagation can be understood, as indicated above, 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 launched beam normally comprises rays at all angles within the acceptance cone, with the result that the geometrical path travelled by a ray depends on its angle to the axis. If the input signal consists of a short pulse of light then some of the rays travel parallel to the axis and take a short time to reach the output, others are at various angles and take longer times to reach the output. The result is multipath dispersion similar to that with short-wave radio transmission in the atmosphere.

The bandwidth can be simply estimated by calculating the difference in propagation times of a ray travelling along the axis and a ray travelling at the maximum permitted angle. The refractive index of glass is about 1.5, the refractive-index difference between core and cladding is, in practice, about 1% and the formula in Table 1 (facing page) gives a relative delay between these extreme rays over one kilometre of about 50 nanoseconds, roughly equivalent to a bandwidth of about 20MHz. Thus a multimode, step-index optical fibre has a bandwidth x length product of ~20MHz km which is comparable with that of a good coaxial cable.

The effect of multipath, or equivalently multimode, dispersion can be greatly reduced by introducing an appropriate variation of refractive index in the core, with a maximum at the centre and falling in approximately parabolic fashion towards the edge (see Figure 5 opposite). The fibre becomes, in effect, a distributed lens of very weak focusing power in which the rays of light are curved and the difference in propagation times between a ray travelling along the axis and one entering at a large angle, is greatly reduced. In fact Table 1 shows that the time difference is reduced by the factor $\Delta/8$ for the optimum refractive-index distribution, which depends on the materials of the core and cladding. Since Δ is about 1% the improvement is about one thousand times. Thus the simple expedient of changing from a constant refractive index in the core to a quasi-parabolic distribution reduces the multipath delay by a factor of 1000. A fibre with the optimum distribution may thus exhibit a bandwidth x length product some three orders of magnitude greater than is possible with coaxial cable. In practice it is not possible to approach the required refractive-index distribution sufficiently accurately over distances of tens of kilometres and the actual improvement in installed systems is limited to two orders of magnitude which, nevertheless, is substantial.

The limiting dispersion in multimode fibres is caused by rays travelling at different angles. The rays in multimode fibres are closely analogous to modes and for every permitted ray angle there is a corresponding mode of propagation. In any waveguiding system each mode has its own characteristic propagation velocity. The number of modes falls as the transverse dimension of the waveguide is made smaller. Hence if the core diameter in an optical fibre is made sufficiently small only one mode will be capable of propagating. Multipath dispersion is thus eliminated. Single-mode operation might be expected to occur when the core diameter is comparable with the wavelength of the light used, which is usually between 0.5 and 1.5μm in the case of optical fibres. The actual diameter in practice is about 5μm. The bandwidth of the fibre is now increased considerably, even more than the two orders of magnitude achieved with the graded-index multimode fibre and can be made almost infinite for most practical purposes, as shown below.

Obviously the overall dispersion cannot literally become zero, even in the absence of multipath dispersion, because there are other mechanisms which now become the limiting factors. These are quite simple. One is the fact that the fibre, ie. the guiding structure, is made from glass which is a dispersive medium. In school physics laboratories glass prisms are used to demonstrate the dispersal of white light into its different colours confirming that the group velocity of propagation in glass is a function of wavelength. 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.

Secondly, the fibre waveguide itself is a transversely bounded structure in which the group velocity is a non-linear function of wavelength so that, in the same way as a metal waveguide, it has dispersion. A very fortunate factor now comes into play. We were able to show at Southampton that the broadening of a propagating pulse of light due to material dispersion decreases at longer wavelengths (see Figure

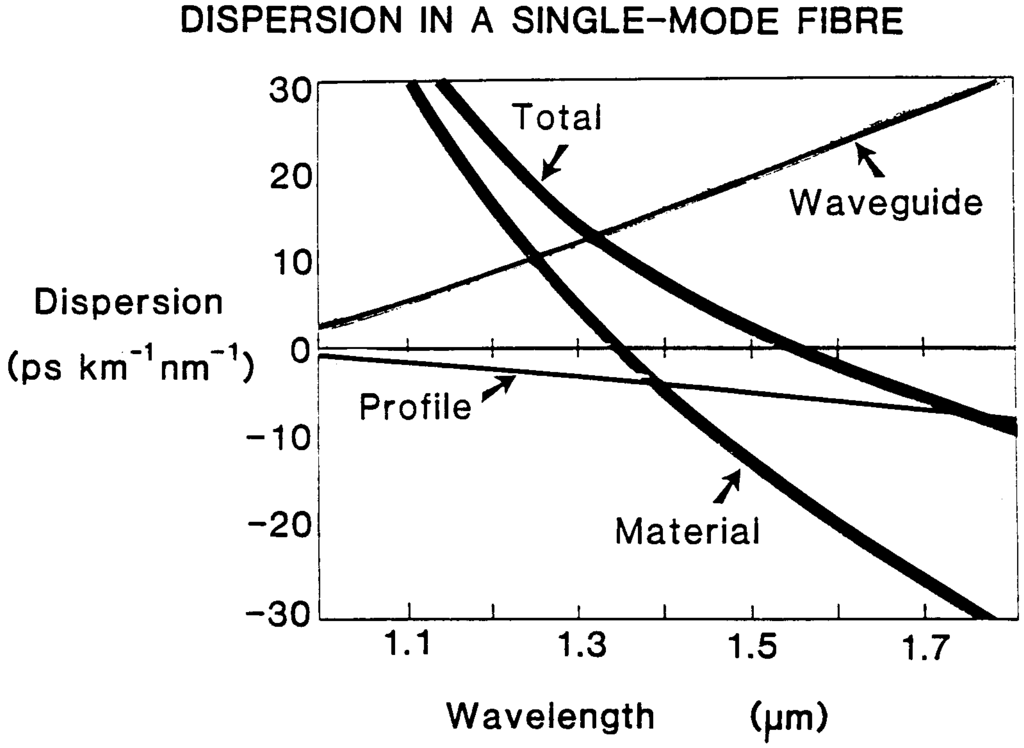


Figure 6: Sources of dispersion in a single mode fibre.

6) falling to zero at about 1.3µm and then becoming negative. Thus by operating at a wavelength of 1.3µm the effect of material dispersion becomes zero, to a first approximation, in both multimode and single-mode fibres. The waveguide dispersion for a typical single-mode fibre, see Figure 6, is finite but positive at 1.3µm and increases with increasing wavelength. Clearly at wavelengths where the material dispersion is negative and the waveguide dispersion is positive the one can be balanced against the other. So by proper design of the waveguide structure the sum of the waveguide and material dispersions can be made zero at a desired wavelength. The combined effects of material and waveguide dispersions are thus eliminated. The wavelength of zero total dispersion is determined by the design of the waveguide and can be made to occur anywhere between 1.3µm and about 2µm relatively easily.

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 the bandwidth is very small and measurements over long lengths of single-mode fibre have shown that polarisation dispersion is far less than 1 ps/km. This corresponds to a bandwidth x length product of well over 1,000 GHz km.

It is clear, therefore, that single-mode fibres are capable of enormous bandwidths although the system bandwidth is limited to a few tens of gigahertz by the maximum rate at which the semiconductor laser source can be modulated. Future developments in components will remove this limitation.

Attenuation and Transmission Distance

When research into optical fibre communications began in the middle 1960s some crude optical fibres existed and were used in fairly primitive endoscopes for medical applications, but the transmission loss was so high that propagation was only possible over distances of a metre of so. The main reason for the attenuation was *(a)* scattering due to the non-homogeneous nature of glass and *(b)* absorption of the light due to impurities. With gradual improvement in fabrication techniques the loss decreased and the transmission distance, assuming a permissible 40dB loss in Figure 7, steadily improved. The curve flattens

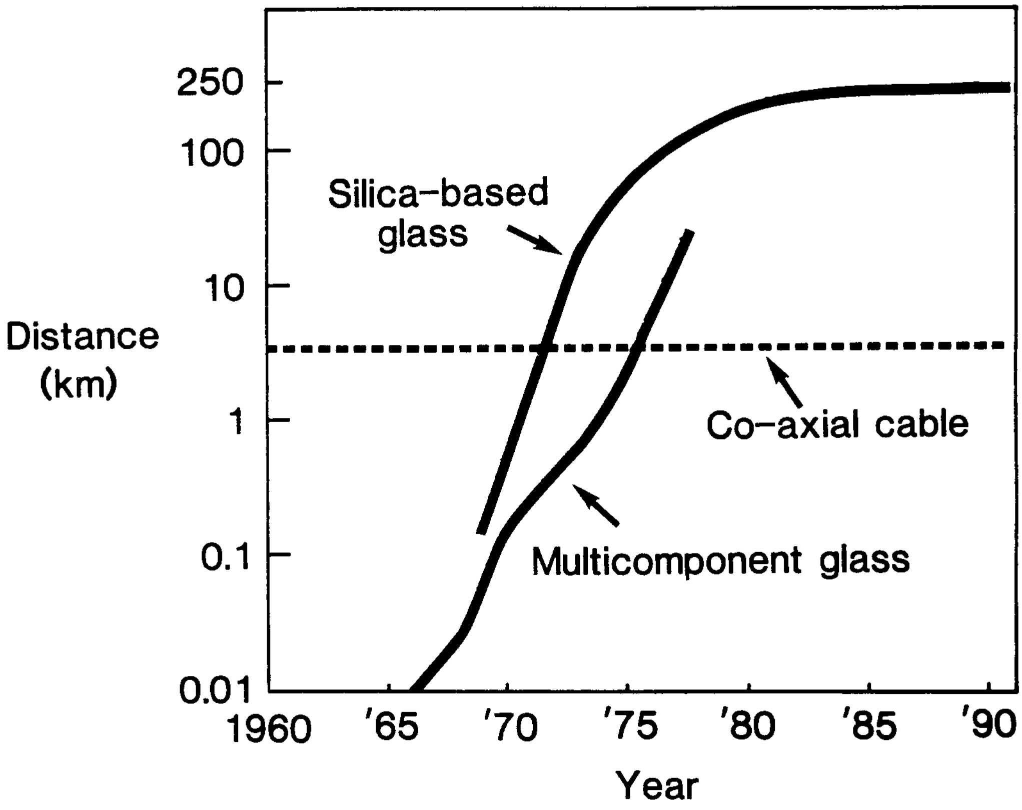
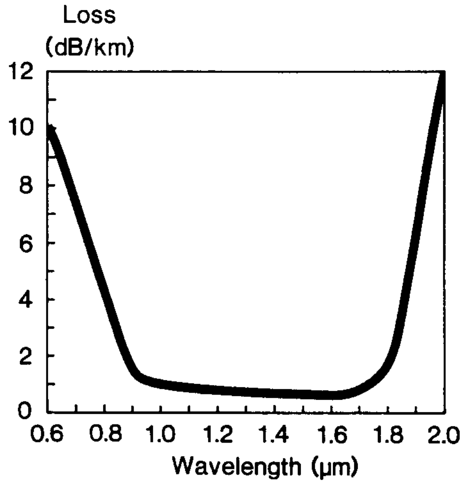


Figure 7: Increase in transmission distance assuming a permissible loss of 40dB between repeaters.

off at 200-300 km transmission distance because the fundamental loss limits of silica-based glasses have been reached. A transmission distance of 200 km can be compared with some 4 or 5 km with coaxial cable.

Figure 8 shows the transmission loss of a good (water-free) silica optical fibre as a function of wavelength. In the near infra-red region of 1.0-1.7μm the attenuation is below 1dB/km, corresponding to a transmission window of over 100,000GHz in a single fibre. At present it is far from possible to exploit more than a minute fraction of that enormous wavelength range. It is fortunate that the minimum attenuation occurs at wavelengths where semiconductor lasers can be made to operate. Gallium arsenide semiconductor lasers and their derivatives operate in the region 0.85 to 0.9μm where the transmission loss is about 2dB/km and lasers based on ternary and quaternary materials operate at 1.3μm, and 1.55μm where the minimum losses are below 0.4 and 0.2 dB/km, respectively. Semiconductor laser diodes are small, very efficient, and can emit at wavelengths where the fibre transmission loss is very low. However, it is still difficult to produce a narrow-linewidth coherent output and they often behave as optical noise generators.

Figure 8: Loss spectrum of VAD graded-index fibre.



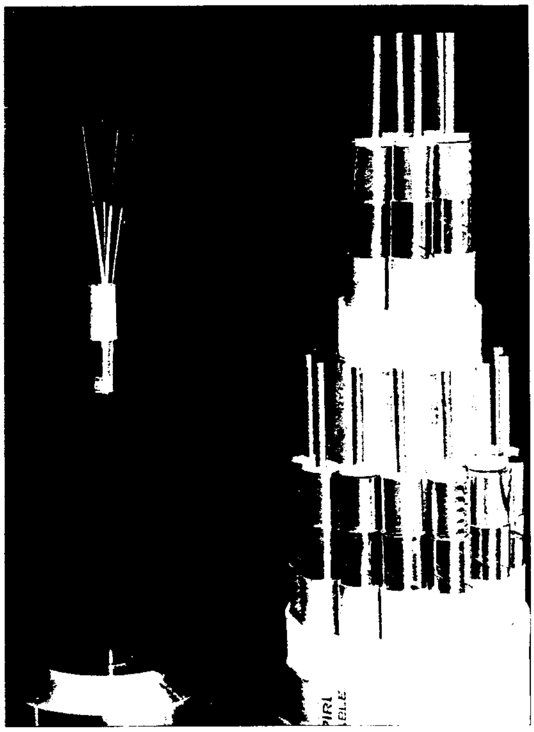


Figure 9:
Optical fibre cable compared with a standard copper coaxial cable.

Optical Fibre Cables

The core of a single-mode fibre has a diameter of about 5μm, whilst that of a multimode fibre is 50μm. The outer diameter of fibres for telecommunications applications is standardised to 125μm, for convenience of handling. Figure 9 illustrates an early optical fibre cable and a standard copper coaxial cable of the kind buried under the pavements in the telephone network. One of the tiny optical fibres can carry many times the amount of information that can be handled by an entire copper cable, indicating that another advantage of optical fibres is their very small size. The fibres in the optical cable of Figure 9 were designed and fabricated in the University of Southampton, cabled by Pirelli General and installed at the Dinorwig Pumped Storage Power Station in North Wales.

Glass is brittle and has the reputation for being fragile. It is certainly fundamentally different in mechanical properties from metals which are ductile. But glass is inherently strong so that a glass fibre has roughly the same breaking strength as a steel wire of the same diameter. The reason that glass tends to break easily in everyday use is the fact that scratches can easily form on the outside surface. Under tension the cracks can spread and the glass eventually breaks. If, on the other hand, the cracks can be prevented from forming in the first place, the glass will retain its characteristic strength. In practice a suitable coating is applied to the outside of a fibre immediately it emerges from the drawing furnace and before dust particles in the air can touch the surface and initiate the cracks. Even quite small and lightweight optical fibre cables are rugged and can be laid from a helicopter, withstanding the tension in the cable as it is laid, the vibration from the helicopter and being dropped on uneven ground. Early optical fibre cables were laid experimentally on the surface of car parks for several years without suffering damage.

Optical fibre cables have been installed in the underground railway in London. This is a third-rail system operating at a low voltage, 600V, with consequently high currents, so that the sliding brake shoes cause considerable sparking and electromagnetic noise to which, of course, the fibres are quite immune. Thus optical cables can be operated in electrically-noisy environments and in fact the new Mercury telecommunications network is along main railway tracks, increasingly being electrified, the advantage being that there is no interference and they can be taken directly into the centre of cities.

Optical fibre cables are being rapidly deployed for underwater transmission because their low transmission loss and large bandwidth provide considerable reduction in cost. For example, the last coaxial telephone under the Atlantic Ocean from the UK to the USA contained 1200 repeaters, each costing about

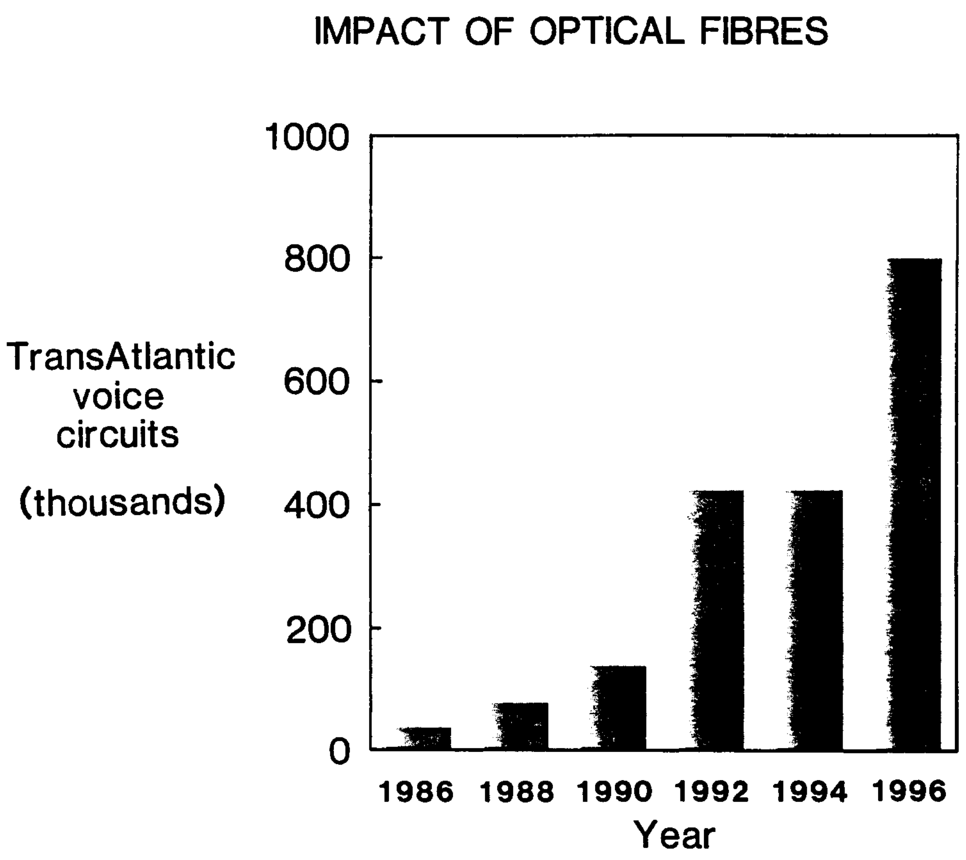


Figure 10: Existing and proposed telephone circuits in trans-Atlantic optical fibre cables.

£500,000, whereas the first optical fibre TransAtlantic Telephone cable (TAT8) required only 200, representing a huge cost reduction. This cable also could carry more simultaneous telephone calls (40,000) than all the then existing TAT cables put together. Figure 10 shows the existing and planned increase in transAtlantic cable traffic carried by optical fibres. A fibre cable across the North Pacific, capable of handling 85,000 calls, came into operation in 1991, as did one from the UK to Germany with a capacity of 200,000 calls.

FIBRE AMPLIFIERS AND LASERS

Optical fibres have thus been developed to a high degree of sophistication for long-distance transmission. Compared with coaxial cables which have a bandwidth of 20MHz or so over distances of 3 to 5km, optical fibres can have almost infinite bandwidth at repeater spacings of several hundred kilometres. They are also small, light in weight, flexible and free from electromagnetic interference. It is not surprising, therefore, that optical fibres have already revolutionised telephone and data networks and are being rapidly installed in most countries of the world. Nevertheless, in normal communications terms optical fibre communication is in a very primitive stage of development. The only operation that can be performed is that of transmitting optical information from one point to another. In order to process the information it must be converted back to electrical form and operated on in complex electronic circuits. The information then has to be reconverted to the optical wavelength. Such methods of signal amplification and processing are complex and expensive.

The next stage of optical fibre communication will require fibre components in both passive and active form. Passive components such as couplers, switches and isolators are now becoming available commercially and research leading to active fibre devices is showing considerable promise.

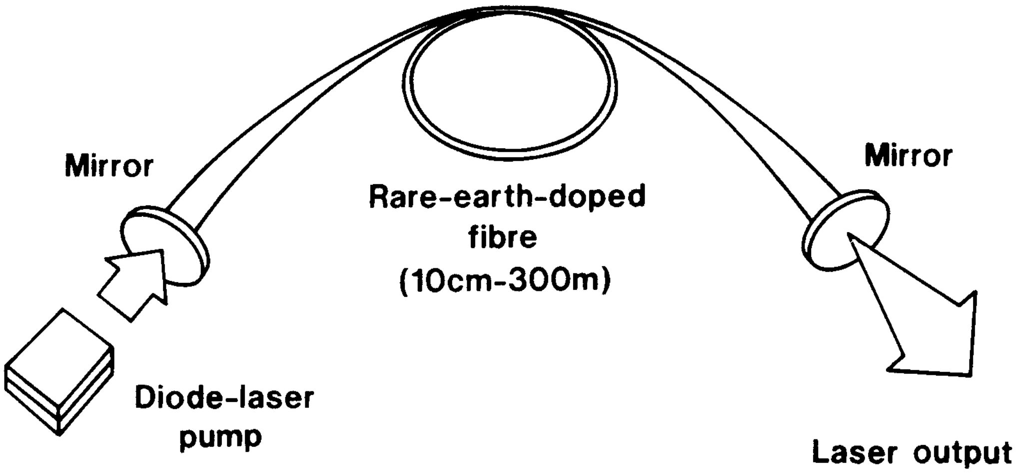


Figure 11: Schematic diagram of an optical fibre laser.

Fibre Lasers

The first major active fibre device was the fibre laser. Laser action is produced by introducing suitable rare-earth ions into the core of a single-mode fibre. When these ions are pumped by an optical source in an absorption band, relaxation occurs rapidly and the ions fall to a metastable energy state. They are then capable of amplifying spontaneous emission which arises from that state.

Laser action may be obtained by placing mirrors at each end of the fibre, as shown in Figure 11. The considerable advantages of the fibre configuration arise from the fact that the pump radiation travels along the axis of the fibre and is guided by the core, as is the lasing radiation. There is therefore very

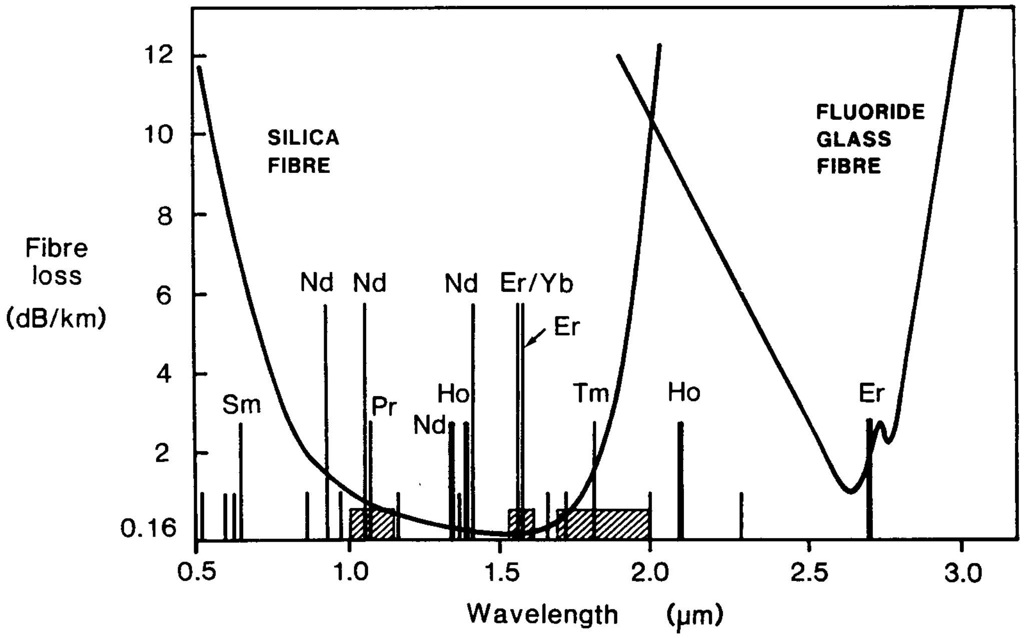


Figure 12: Selected fibre laser emission lines superimposed on the attenuation curves of silica-based fibres and fluoride fibres. The shorter lines are unlabelled to avoid confusion on the diagram. The shaded regions denote the tuning ranges described in the text.

TABLE 2

RARE-EARTH-DOPED GUIDED-WAVE LASERS

The Future

- Tunable CW output > 1W
- Q-switched output > 10kW
- Mode-locked pulse duration ≪ 1ps, Power > 10kW
- 470nm frequency-doubled output > 100mW
- Intra-cavity non-linear effects in fibres
- Wavelengths $0.9\mu m$ to $4\mu m$ diode-pumped
- Upconverters into the visible and UV
- New transitions

TABLE 3

SOLID-STATE LASERS VS DIODE-LASERS

- Visible emission possible
- Peak powers > 1kW
- Easy resonator access and complex cavities
- Distributed devices
- Polarisation independent
- Quieter, more stable
- Shorter pulses

BUT External modulator required

efficient coupling between the pump radiation and the ions whilst the pump intensity is very high because of the small core diameter. Pumping efficiencies approaching 100% become possible and slope efficiencies exceeding 60% have been measured, as have threshold pump powers of a few hundred microwatts.

Fibre lasers are small, robust, flexible and give easy access to the laser cavity, thus enabling the operations of Q-switching, mode-locking and line-narrowing to be carried out. Because of the large fluorescent linewidths large tuning ranges have been reported—over 70nm in erbium, 150nm in ytterbium and 300nm in thulium. These tuning ranges are enormous (corresponding to frequency bands of 10,000GHz, 45,000GHz and 28,000GHz, respectively). New lasing wavelengths in the visible region of the spectrum at 651nm have been obtained with samarium, as well as at 491nm, 520nm, 605mn, and 635nm in a praseodymium up-conversion laser and others are likely to follow. Figure 12 indicates some of the various wavelengths, ions and fibres so far reported.

Developments in fibre lasers are occurring rapidly and likely performance achievements over the next five years are listed in Table 2. Considering that the new methods of doping the cores of optical fibres with rare-earth and transition-metal ions were only developed six years ago these are remarkable achievements. Fibre lasers have many advantages over diode lasers, as indicated in Table 3, and may well exceed them in performance in all but one aspect. Diode lasers can be directly modulated by an electrical signal whereas the fibre laser requires an external modulator. On the other hand this situation will change as the requirement for higher modulation rates emerges, when the laser diode also will require an external modulator. The balance of advantage will then shift even more strongly to the fibre laser.

Because of the broad fluorescence width of the laser ions, fibre lasers operate on many longitudinal modes and emit over a range of wavelengths. However, in a travelling-wave ring configuration the linewidth has been reduced to 10kHz.

Perhaps the most exciting mode of operation is where the fibre laser generates a regular train of soliton pulses. Pulses as short as 30 femtoseconds at pulse rates of 10GHz have been reported. This fibre laser configuration is an extremely attractive soliton source for future communication systems.

Fibre Amplifiers

The most immediate application of rare-earth-doped (RED) fibres will be as fibre amplifiers, which consist of only a short length of RED fibre with optical pumping radiation coupled into the core via a dichroic coupler, (Figure 13 overleaf). The coupler has a high coupling ratio at the pump wavelength but prevents loss of the signal power. The pump source can be a diode laser of simple construction. It can be seen that the fibre amplifier comprises only three basic components; fibre, coupler and diode laser, so that it is highly reliable, small (1cm to a few metres in length), highly efficient and should eventually be cheap compared with an electronic repeater.

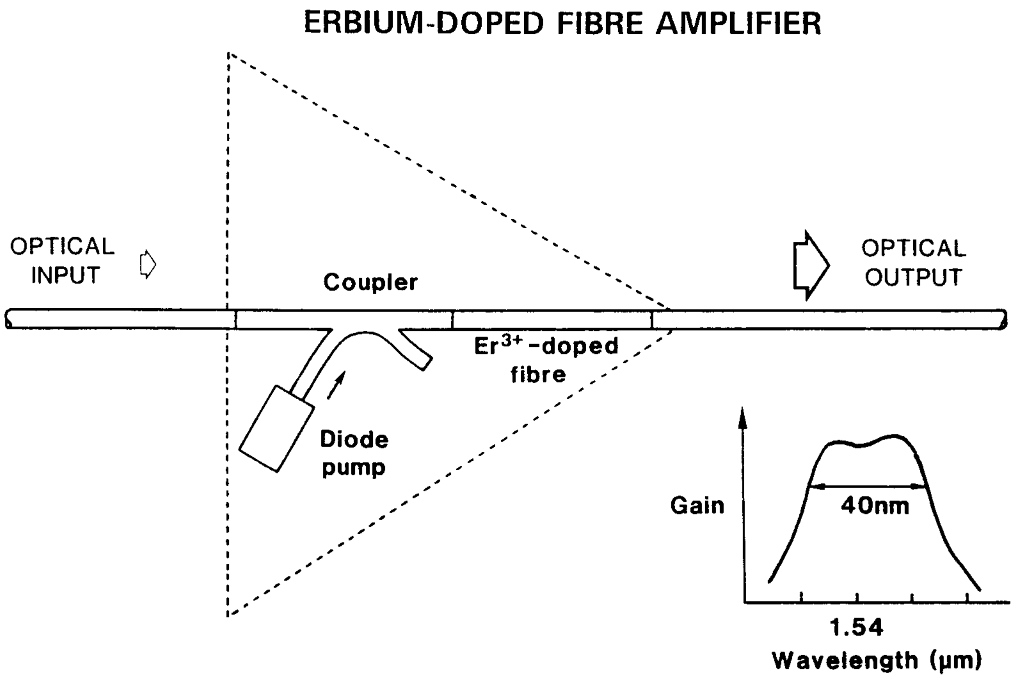


Figure 13: Schematic diagram of a fibre amplifier.

Erbium-Doped Fibre Amplifiers

The erbium-doped fibre amplifier (EFA) has recently attracted very considerable attention in optical fibre communications. The EFA conveniently operates in the preferred telecommunications spectral window located at a wavelength of 1.55μm. It is also possible to produce enormously wide bandwidths. No wonder this is the preferred wavelength of operation in practical systems! It is a most fortuitous coincidence that erbium-doped fibre lasers and amplifiers also operate at this frequency. In addition, the EFA has been shown to have high polarisation-insensitive gain (>50dB), low-crosstalk between signals at different wavelengths, good saturation output power (>0dBm) and a noise figure close to the fundamental quantum-limit (~3dB). The excellent noise characteristics potentially allow hundreds of amplifiers to be incorporated along the length of a fibre telecommunication link, which could then span more than 10,000km. Compared with the alternative of a transmission link using electronic repeaters, an all-optical link has the merit that it is transparent to the transmission code format and bit rate. It can thus be uprated by changing only the transmitter and receiver, and not the repeaters.

Table 4 summarises the properties of the erbium fibre amplifier. High efficiency is achieved by adjusting the combination of length and doping concentration so that all of the pump power entering the core is absorbed in the amplifying region of the fibre. Optical amplifiers are analogue devices but the noise performance is such that they can be concatenated whilst still preserving low distortion/error rates at high bandwidth.

As with other amplifiers the doped fibre amplifier can be operated as a line amplifier, a power amplifier or as a pre-amplifier. Its properties as a line, or signal, amplifier are discussed above. As a power amplifier it is capable of CW output powers ap-

TABLE 4

WHY ERBIUM FIBRE AMPLIFIERS?

- 1.5μm
- Broadband
- High gain (>50dB)
- Fibre
- Polarisation independent
- Quieter, more stable
- Shorter pulses

proaching 1W and one of its first applications could well be to amplify the output of a modulated diode laser to form a powerful transmitter. If the diode output is amplified by, say, 20dB then the permitted transmission distance is increased by 100km. Similarly, when placed immediately prior to a detector the receiver sensitivity can be increased by an even greater amount, giving rise to another increase in transmission distance.

Unlike a diode amplifier, the erbium-doped fibre amplifier has a saturation output power which increases with pump power, as well as an ability to operate deep in saturation without signal distortion and interchannel crosstalk. Highly-saturated EFAs are efficient power amplifiers with a maximum absolute pump/signal power conversion efficiency as high as 47%. The slope efficiency is near quantum-limited at 53%. It is also noteworthy that power amplifiers operating in the highly-saturated mode have virtually flat spectral-gain characteristics, owing to their largely homogeneously-broadened behaviour.

The erbium fibre amplifier is very stable because the pumping power is stored in a metastable energy level which acts as a form of reservoir from which energy can be drawn when required. Thus the gain is largely independent of both the wavelength and magnitude of the pumping diode over quite large ranges and when saturation begins to occur the gain falls only slowly.

The fibre amplifier is an important new active device that will have applications in many different situations, such as long-distance transmission, local-area networks, sensors, non-linear optics and novel optical circuits. There are already some spectacular examples of the use of the optical fibre amplifier in communications. Thus a transAtlantic cable is planned for 1995 containing only optical amplifiers, thus dispensing completely with the expensive electronic repeaters of the past, and a similar cable across the Pacific Ocean will be laid in 1996. The latter will carry 600,000 telephone circuits. More experimentally, transmission of 45ps solitons at 10Gbit/s through 1000km of dispersion-shifted single-mode fibre has been demonstrated with 22 EFAs separated by 50km. In a related experiment multiple transmission around a 500km loop with amplifiers again spaced by 50km resulted in soliton propagation over a total length of 1,000,000km at 10Gbit/s. By incorporating a novel pulse-shaping and retiming technique the output pulse shapes and pulse trains were indistinguishable from those at the input. This is a remarkable result. A distance of 1,000,000 km corresponds with a round trip from the earth to the moon and back again and obviously there is no practical requirement for such a system. However, the experiment shows that terrestrial optical fibre transmission can now take place over unlimited distances with almost unlimited bandwidths. Even more importantly, the pulse-shaping and retiming technique reduces pulse and timing distortions to what was hitherto an unbelievable level.

Long-distance transmission is only one of the potential applications for the fibre amplifier which, in fact, will become the basic building block of all optical signalling systems. It will become a component as common, ubiquitous and indispensable as a transistor is to electronics. Following long-distance transmission the second key application will be to video and data distribution in local-area networks. Thus an optical fibre carrying signals from a sub-station to a distribution point will be fed directly into an optical amplifier before the signal is split into several hundred lines for distribution to individual houses and buildings. The power supply for the whole operation can remain in the sub-station.

The optical fibre amplifier was first demonstrated at the University of Southampton, Optical Fibre Group, in 1987 and rapidly stimulated world-wide interest. Its importance may be judged from the fact that since the first paper and accompanying patent nearly 1000 papers have appeared in the literature and, in 1989, only AIDS, cold fusion and superconductors generated more interest in the scientific community.

THE FUTURE

The existing revolution in telecommunications brought about by the advent of conventional single-mode optical fibres is only the first stage in their exploitation. The second stage, namely their application to passive components and optical sensors, is proceeding steadily. The third stage, involving the creation of active devices, is upon us and is advancing very rapidly indeed. As a result, by the year 2000 optical fibres are likely to be used wholly, or partially, in all telecommunication systems and installation to the home will have begun.

Active fibre devices can be designed and fabricated for specific applications and wavelengths. Many new devices, sources and sensors are now possible and it is expected that the range will be extended by the introduction of fibres based on new materials, some of which perhaps can only be created in fibre form. At Southampton we have embarked on a research programme for adapting fibre fabrication technique to producing equivalent planar glass optical circuits for ease of mass production. The drive towards creating new devices, particularly those involving non-linear optical effects, is also shedding light on many fundamental optical and materials properties. The next few years will be very fruitful.

The Information Society

Telecommunication has become vital for prosperity. The rapid emergence of optical techniques, or "photonics", as a staggeringly powerful technique which is increasingly taking over many sectors of "electronics", combined with parallel and essential developments in microelectronics, digitisation of switching and transmission and also in software engineering, demands radical new thinking in system design and applications. In addition an improved infrastructure and regulatory environment is essential if social needs and wishes are to be satisfied, as well as to cope with accelerating demands for new products and services.

The explosion in our ability to communicate now being experienced will continue at an every-increasing pace in the next century. Distance and time-delay can be eliminated by the skilled use of intelligent networks which, through appropriate software, can be adapted to individual needs.

Mobile radio techniques will link with fibre and satellite networks enabling people to communicate at any time, at any rate, from any location worldwide. The optical fibre network will have sophisticated ports providing high-capacity communications to cheap mobile radio base stations smaller than a shoe box. Through short-range radio links individuals will be able to receive a wide range of services, from speech to high-definition video conferencing, via personal terminals not much bigger than a match box. Today's car radios will be archaic anachronisms by comparison.

Social Implications

Communication technology has played a major role in the formation of our existing industrial society. It would not be surprising, therefore, if future changes were to lead to further significant developments. The technological advances will not of themselves produce social changes which, rather, will result from society and its agents perceiving and acting upon the opportunities afforded by the new technology. It is thus not possible to predict solely from the technological changes themselves what the social impact will be.

The key features of the new tools will be the provision of small, cheap, powerful devices capable of processing many kinds of data. A wide range of new communication and information services will emerge, some of which we cannot presently foresee. It will be possible to communicate with people and monitor processes to a far greater degree, over a vastly expanded range of locations. Some of these can be tentatively explored.

Thus if appropriate skills and practices can be learned by shopfloor, office and field workers then new styles of organisation can emerge which by-pass existing middle management. New types of media will become available for education, training and social participation as well as for personal communication and entertainment. Obviously there will be problems such as the dangers of information overload and lack of privacy. Individuals will also have to take a greater degree of responsibility.

Fortunately the social implications are likely to appear gradually over a long period since major structures, whether technological or social, cannot be transformed overnight, but the sooner education and informed debate on these issues begin the better.

Information and Travel—Do we need both?

Most business travel by individuals is undertaken for the purpose of communication. Partly as a result there has been a major shift in population in the United Kingdom to the South East and from the North. Despite some government attempts to counteract the effect the trend continues and this pressure of market forces to concentrate the population in and around cities and key areas is likely to accelerate in the next century. The consequent pollution, congestion, as well as increasingly expensive, exhausting

TABLE 5

THE COST OF TRANSPORT

- Global car sales are 100,000 per day
- Transport industries take 7% of EC GDP and 7% of employment
- The world owns 550 million road vehicles
- Italy has one vehicle for every 9m of road
- Energy use: transport 30%, industry 37%, domestic 33%
- Global emissions: transport causes 25% of CO_2, half the NO_x, and a third of particulates
- Noise, land-hungry, disruption of communities, etc
- Congestion: CBI estimates cost to industry of £15bn pa
- Death and injury: DTp put costs at £6bn p.a. in UK
- OECD puts true costs for road transport at 5% of GDP

and wasteful commuting, are already having unacceptable effects on the environment, quality of life and the cost of goods and services. Transport is a luxury we are increasingly unable to afford.

Some significant, if not staggering, statistics relating to transport are given in Table 5. Yet the majority of "white collar" workers whilst requiring access to information and office services do not need to be physically in any particular place for most of the time. Given a good communications link they could work at home, or at a nearby communications centre—in other words "communicate" to the office instead of "commuting" to the office. A few thousands do at the moment whereas tens or hundreds of thousands could do so in the future, with a resulting substantial improvement in the quality of life, increased efficiency in UK businesses, lower drain on national resources and with great benefit to the environment. For example, well over 50% of the carbon dioxide emission caused by transport comes from private cars. The future desirable balance between communications and transport is not easy to assess but I hope that this paper provides some food for thought. The spur to a radical re-thinking must be that:

Information is Green!