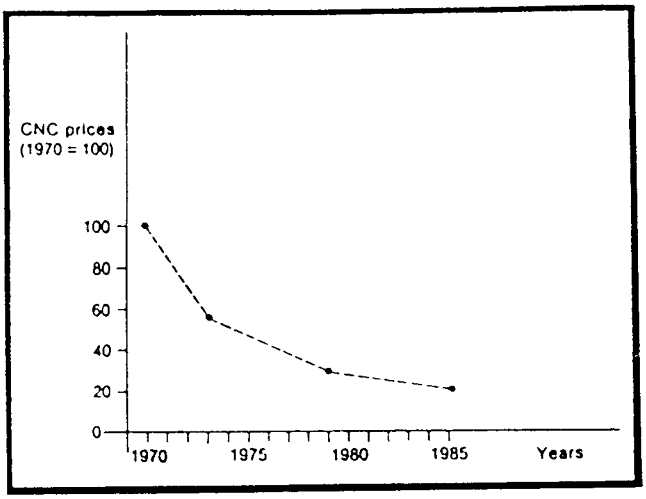


1970-1985 CNC price trend, showing a reduction every five years.

Meeting Held at Burlington House on Monday 1st December 1986.

Given by Professor Gambling DSc, FEng, FRS, FIEE

Fibres, Photons and the Future

Introduction

The purpose of Optical Fibre Communications can be put very simply; it is to replace electric currents and copper wires in all telecommunications systems by glass fibres and light, probably laser light. This is a revolutionary undertaking because copper wire and electric currents have served us well for over a hundred years, and seem almost a fundamental fact of life.

In order to understand why a radical change in technology is necessary consider the curves in Fig. 1, illustrating the growth of the number of telephones, and number of telephone calls, in the United Kingdom over the period 1920 to 1980. 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 not do of course) then at some point in the future no-one will do anything except talk into the telephone. At present the curves are still rising sharply, showing that the demand on the telephone system is increasing extremely rapidly. In 1980, for example, the number of calls made was twenty thousand million and if it is assumed that the telephone system is used for sixteen hours a day and that the average telephone call lasts for approximately five minutes, then at any instant during the working day some half a million people, in the UK, are talking on the telephone, and these usually include the people one is trying to contact oneself.

In addition to carrying telephone calls, increasing use is being made of the telephone system for data transmission, video transmission and other services. Thus many organisations, including airlines, banks and companies are now taking for granted data links between centres; some university staff have terminals on their desks giving access to computers that may be many miles away. Many other services are 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? Fig. 2 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, if the present level of traffic were to be carried on ordinary line pairs then we probably would not be able to see the sun because of a great raft of copper wires everywhere. Thus where the demand exists the adoption of more complex systems can bring down costs appreciably.

In the early 1960's a considerable amount of work was carried out on a millimetre-wave guiding system operating at about 100GHz. There were considerable difficulties in implementing the millimetre-wave technology and a number of us were considering the possibility of going to optical frequencies. The simple argument was that a raising of the carrier frequency by five orders of magnitude should enable the bandwidth of the system to be increased considerably. A related and key question was whether the costs could be contained or even reduced. This formed an excellent topic for research and several groups in this country set out to investigate the fundamental limitations of optical techniques in trying to find a system that was potentially realisable.

The Competition

Existing systems operated at microwave frequencies with bandwidths of a few tens of megahertz. The main transmission channels were coaxial cable, microwave radio relay and satellite, with distances between repeaters, which are necessary to amplify or regenerate the signal, of about 5km with coaxial cable, 50km with microwave radio relay, and 50,000km with satellites. This was the competition that any new optical system would have to contend with. Optical systems of a very primitive sort had been known for quite a long time. I believe the coming of the Armada was signalled from Plymouth to London by the lighting of bonfires on hilltops as a means of communication. The information transmission rate with a chain of bonfires is about 1bit per day, because the bonfire must burn out and be rebuilt before a second digit can be transmitted. The Indians in America achieved a rate of 1bit per minute with their smoke and blankets, whilst a heliograph and the human eye can provide about 1bit per second, but the heliograph, or simple line-of-sight optical communication, would not be very reliable in this country. Contrasting these rates of information transmission with the fact that one frame of a colour television picture contains many million bits, gives an appreciation of the great increase in transmission capacity required.

The Optical Source

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 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 dogs 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 invitably 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 sudden 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 a 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.

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. 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 1cm 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 of a communication system being optically straight is thus avoided and the mechanical flexibility of the transmission line has made a key difference in the application of optical fibres.

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 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 very simple in form and are basically 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.

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. It is not yet possible to carry out any sophisticated signal processing, nor anything other than amplitude modulation. 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 Fig. 3, the core is uniform and extends to a diameter of about 50 μm. 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 a longer time 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 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 × length product of ~20MHz km which is comparable with that of a good coaxial cable.

The effect of multipath, or 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 Fig. 3. 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 × 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 is almost infinite for most practical purposes.

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, i.e. 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 in my research group at Southampton that the broadening of a propagating pulse of light due to material dispersion decreases at longer wavelengths, see Fig. 4, 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 Fig. 4, 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 has not yet been observed and measurements over long lengths of single-mode fibre have shown that polarisation dispersion is less than 1 ps/km. This corresponds to a bandwidth × length product of more than 1,000 GHz km. Thus over a transmission distance between repeaters of 200km a system bandwidth approaching 5 GBit/s is possible.

It is clear, therefore, that single-mode fibres are capable of enormous bandwidths although the system bandwidth is limited to a few gigahertz by the maximum rate at which the semiconductor laser source can be modulated. The future development of efficient wavelength-division-multiplexing schemes will remove this limitation.

Attenuation and Transmission Distance

When research into optical fibre communications began in the middle 1960's 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 or so. The main reason for the attenuation was scattering due to the non-homogeneous nature of glass and 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 Fig. 5, steadily improved. The curve flattens 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.

Fig. 6 shows the transmission loss of a good silica optical fibre as a function of wavelength. In the near infra-red region of 1.0-1.7m 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, more recently, lasers based on ternary and quaternary materials have been operated 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.

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. Fig. 7 illustrates an early optical fibre cable and a standard copper coaxial cables of the kind buried under the pavements in the telephone network. One of the tiny optical fibres can carry at least ten 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 were designed and fabricated in the University of Southampton, cabled by Pirelli General and installed at the Dinorwic Pumped Power Storage Station in North Wales. Thus the research group can, from time to time, become involved in practical applications.

Glass has the reputation for being fragile and brittle. 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 wil 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 on the surface of car parks for several years without suffering damage.

Optical fibre cables are being laid 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 laid in electrically-noisy environments and in fact the new Mercury telecommunications network is being laid 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.

Applications of Optical Fibres

Optical fibres for long-distance signal transmission have moved out of the research laboratories and into widespread application. Fig. 8 indicates that the length of fibre installed worldwide rose between 1980 and 1986 by three orders of magnitude. By 1990, which is only three years away, it is estimated that nearly 60% of all trunk telephone traffic in the UK will be carried on optical fibres. British Telecom has ceased to order any more coaxial cable for the trunk system and fibres are now beginning to enter the intermediate part of the network. A considerable amount of R and D is aimed at the possible introduction of optical fibres into the local network. Similar developments are happening worldwide, especially in Europe, Japan and the USA. Fibres are no longer a research curiosity but are here to stay.

An application where the extraordinary properties of fibres can be fully exploited is in underwater transmission because the ability to have large distances between repeaters is of enormous economic importance. There is already an operating underwater fibre cable between the South of England and the Isle of Wight and between the UK and Belgium. The first transatlantic optical fibre cable, TAT 8, is under construction and will be installed next year. Table 2 illustrates some of the improvements on the most recent copper coaxial transatlantic telephone cables TAT 6 and TAT 7. Despite technical developments over 30 years the number of circuits across the Atlantic is still only 4,000, the total loss in the cable is 50,000dB, and there are 1200 repeaters. In comparison TAT 8 is an extremely simple cable, containing just six fibres; one each way between the USA and the UK, one each way between USA and France, with two spare. Even though the optical fibre cable is of simple design the capacity is nearly twice that of all existing coaxial cables under the Atlantic. The low attenuation enables the number of repeaters to be reduced by a factor of six. The maximum distance between the repeaters in TAT 6 and TAT 7 is 10km whilst in TAT 8 it is 50km. Demonstration systems have been operated in the laboratory over several hundred kilometres and it is not unlikely that the number of repeaters in future transatlantic cables can be reduced from 200 to about 50 and the total bandwidth increased considerably.

Fig. 9 is another illustration of the reduction in the cost per circuit as the system capacity is increased. Since the first telephone cable went across the Atlantic in 1956 the technology has improved and the cost has fallen by nearly two orders of magnitude. The first optical fibre cable has a cost per circuit which is already appreciably lower than the best coaxial cable and as the optical technology improves the cost per circuit will fall greatly. In addition the capacity will increase enormously so that whereas with the copper systems it is not possible to transmit video signals across the Atlantic optical cables will provide multivideo transmission. It is interesting to speculate on the social implications of these developments and on the competition between optical fibre transmission and satellite transmission.

The Future

Despite the extraordinary performance which has already been achieved optical fibre systems are still, in communication terms, extremely crude. The fibre has almost infinite bandwidth but the maximum bandwidth attainable from a fibre network is only a few gigahertz—although this is over very long lengths so that the gain × bandwidth product is ~200 GHz/km. The limitation lies not in the fibre but in laser sources which cannot yet be modulated at a rate much greater than 1GHz. Moreover the laser diodes available are not ideal lasers but mainly generate optical noise. Thus the modulation bandwidth of 1GHz is small compared with the linewidth of a normal laser diode (i.e. the spread of wavelengths in the output beam) of about 600GHz. This is quite different from the situation at microwave and lower frequencies of a relatively narrow carrier spectrum and a wide modulation bandwidth. Because the carrier source is incoherent amplitude modulation is the only form of modulation possible.

Fig. 10 is a fairly complicated diagram illustrating present system performance and indicating what may be possible for practical applications in the near future. The first-generation systems operated with gallium arsenide sources at 0.85μm where the fibre loss of 2dB/km limits the range, or the distance between repeaters, to about 10km at a bandwidth of 200MHz or so. By moving to 1.3μm where the transmission loss is 0.4dB/km the transmission distance increases to several tens of kilometre and the bandwidth also increases because the dispersion is smaller. Third generation systems will operate at 1.55μm, where the loss of well below 0.2dB/km allows a transmission distance of several hundred kilometres and the bandwidth × length product can be enormously high.

Should it be possible to reduce the fibre attenuation to the ultimate limit of silica glass the transmission distance could approach 500 to 600km. If, at the same time, the output from laser diodes could be made reasonably monochromatic then the bandwidth in operating systems could become several hundred gigahertz.

Optical Signal Processing

A considerable improvement in versatility will emerge, and the system will be able to carry many more individual channels, each of high bandwidth, when optical signal-processing techniques are developed. The present necessity to revert to electronic frequencies is a severe limitation. Passive circuit components are beginning to appear, including directional couplers, switches, filters and multiplexers. As yet they are too expensive and unreliable to find widespread application. Active fibre components are also emerging, in research laboratories at least, such as modulators, optical frequency changers and mixers, and fibre lasers. If a sufficiently reliable, efficient, cheap, small laser with a far better coherence than is possible at the present time could be made, then coherent modulation and detection schemes could be introduced, allowing superheterodyne detection, phase modulation and frequency modulation techniques to be exploited.

There are two major advantages of coherent modulation. One is that the signal/noise ratio at the detector can be improved, as at radio frequencies, by some 15dB. With a transmission loss of less than 0.2dB/km then the transmission distance can be extended by some 75km. The second principal advantage is that wavelength-division multiplexing becomes possible, thus allowing a single fibre to carry many independent channels. Coherent transmission has certainly been demonstrated in the laboratory, but as far as I am aware, there are no plans to introduce it into practical networks as yet, although the technology exists.

The Information Revolution

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

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

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

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

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

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

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

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

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

There are lots of other exciting ideas—it has even been suggested that instead of commuting to work we will communicate to work.

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

Exotic Fibres

The work on optical fibres described so far has been mainly directed to long-distance information transmission. Much present research is investigating the possibility of creating optical circuit components based on fibres. At Southampton we have been looking at new types of fibre structure. Fig. 11 shows the cross section of a single-mode fibre in which sectors of high expansion coefficient, e.g. borosilicate glass, have been introduced in close proximity to the core. As the fibre cools from the drawing temperature of 2000°C to room temperature a very large asymmetric strain is produced which, in turn, causes a large difference in the refractive-index distributions in the two orthogonal principal planes. Such fibres are highly birefringent and can control the plane of linear polarisation in both communication and sensor applications. The Southampton bow-tie cross section has the largest birefringence and the lowest transmission loss, 0.2dB/km, yet reported. In a survey carried out at the US Naval Research Laboratories it was found to be the best available. By suitable design it can also be made into a highly efficient polariser.

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

If a preform is inserted into a hole drilled off-axis in a silica rod and the whole is then drawn into fibre whilst being rotated, as shown schematically in Fig. 12, the core of the fibre is no longer straight but helical. This kind of fibre has a high degree of circular birefringence, ten times greater than has been produced by any other technique. The helical-core fibre can also be used to control the polarisation in communication and sensor applications and is relatively unaffected by external influences such as bends, pressure, change of temperature, and so on. However it must be of larger diameter, and is therefore stiffer, whilst jointing a launching light into it are more difficult.

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

Fibre Lasers

Last year we developed techniques for incorporating rare-earth materials into the core of single-mode fibres. Neodymium, erbium and praesodymium ions produce laser action in bulk and crystal materials. By introducing them into a fibre it has been possible to make a new type of laser based on optical fibres. The structure is very simple, with the basic element being an optical fibre having a core doped with one of the laser ions. Any electronic oscillator consists of an amplifying medium, a feedback path and some kind of resonator structure. Then if the gain in the system exceeds the losses it oscillates. For an optical oscillator the doped fibre forms the gain medium. Normally the ions absorb light and to produce a condition under which they will emit light it is necessary to create a population inversion between the appropriate energy levels. This is done by introducing pumping light of a suitable wavelength into the core of the fibre. The pump source can be a very simple semiconductor laser diode which does not have to emit a well-controlled output.

The creation of a population inversion in the ions produces a gain mechanism along the length of the fibre. Feedback is provided by mirrors at each end of the fibre and the resonator is also formed by these two mirrors. Clearly fibre lasers are very flexible, do not require rigid mirrors which have to be optically aligned and kept in a very stable position. The power to operate the laser is provided by the semiconductor laser which is butted up against the end of the fibre. The laser diode can operate from a battery and a pair of wires. Fibre lasers are very efficient because the lasing ions are confined in a very small transverse region and so the pumping intensity, even from a source producing only a few milliwatts of power, is extremely high. This new type of laser will have a number of possible applications.

As far as telecommunications is concerned, the fibre amplifying action itself could be of considerable interest. As indicated above, most long-distance transmission lines have amplifying repeaters in which a weak incoming optical signal is changed into an electrical signal and amplified electronically, before being reinjected into a laser diode for onward transmission. The repeater is a fairly complex piece of electronics. If it can be replaced by an optical amplifier there would be no need for electrical amplification at all. A short length, say 10cm, of amplifying fibre could be spliced into the transmission fibre and the amplifier immediately becomes extremely simple. Pumping radiation from a simple laser source could be introduced into the fibre through a directional coupler. Preliminary research at Southampton has demonstrated a gain of 25dB at a bit rate of 140Mbit/s.

Conclusions

I hope that I have communicated some of the enthusiasm I feel for optical fibre technology. There are other complementary as well as competing optical techniques. However the full potentiality of optical fibres, not only for telecommunications, but also for more general applications, has hardly yet been touched and the whole world of optical electronic processing is just beginning to expand extremely rapidly. There are going to be very great developments over the next decade or so.

Table 1 Parameters of Optical Fibres

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

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

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

- Difference in propagation times if axial and extreme rays in

(a) Step-index multimode fibre:

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

(b) Parabolic-index multimode fibre:

$$(\Delta t)_m = \simeq \frac{n_1 L}{c} \sqcap \frac{\Delta^2}{8}$$

where L = fibre length
$c = 3 \times 10^8 \text{m s}^{\ 1}$

Table 2 Comparison of Coaxial and Optical Fibre Transatlantic Cables

Characteristics	Coaxial Cable (TAT 6, 7)	Optical Fibre (TAT 8)
Number of circuits	4,200	7500
Number of repeaters	1,200	200
Total transmission loss, dB	50,000	< 5,300
Cable diameter, mm	52	21
Minimum bend radius, m	1.025	< 0.4

FIG 1. NUMBERS OF TELEPHONES AND CALLS MADE IN THE UNITED KINGDOM FROM 1915 TO 1980

FIG 2. FALL IN RELATIVE COST OF A TELEPHONE CIRCUIT WITH INCREASE IN THE NUMBER OF CIRCUITS (I E THE BANDWIDTH) IN THE SYSTEM

FIG 3. CROSS-SECTION, REFRACTIVE-INDEX PROFILES AND RAY PATHS IN A STEP-INDEX AND A GRADED-INDEX, FIBRE

FIG 4. SOURCES OF DISPERSION IN A SINGLE-MODE FIBRE

FIG 5. INCREASE IN TRANSMISSION DISTANCE ASSUMING A PERMISSIBLE LOSS OF 40dB BETWEEN REPEATERS

FIG 6. LOSS SPECTRUM OF VAD GRADED-INDEX FIBRE

FIG 7. OPTICAL FIBRE CABLE COMPARED WITH COPPER COAXIAL, AND WIRE PAIR, CABLES

FIG 8. GROWTH IN INSTALLED LENGTH OF OPTICAL FIBRE CABLES IN TELEPHONE NETWORKS

FIG 9. COST COMPARISON OF TRANSATLANTIC CABLE SYSTEMS

FIG 10. SUMMARY OF THE ATTENUATION AND DISPERSION DATA FOR FIBRE SYSTEMS THE CURVES FOR DISPERSION INDICATE THE REGIONS BEYOND WHICH IT SEEMS LIKELY TO BECOME A MAJOR LIMITATION THEY ARE PRESENTED IN TERMS OF SOURCE LINEWIDTH AND DISTANCE OF THE CENTRE WAVELENGTH FROM THE ZERO DISPERSION-WAVELENGTH (Z D W) ASSUMING FIBRE OF THE SINGLY CLAD TYPE

FIG 11. BOW-TIE FIBRE STRUCTURE SHOWING STRESS-PRODUCING SECTORS ON EITHER SIDE OF THE CENTRAL CORE AND CLADDING

FIG 12. FIBRE WITH A HELICAL CORE
(A) FABRICATION
(B) SIDE VIEW OF HELICAL-CORED FIBRE

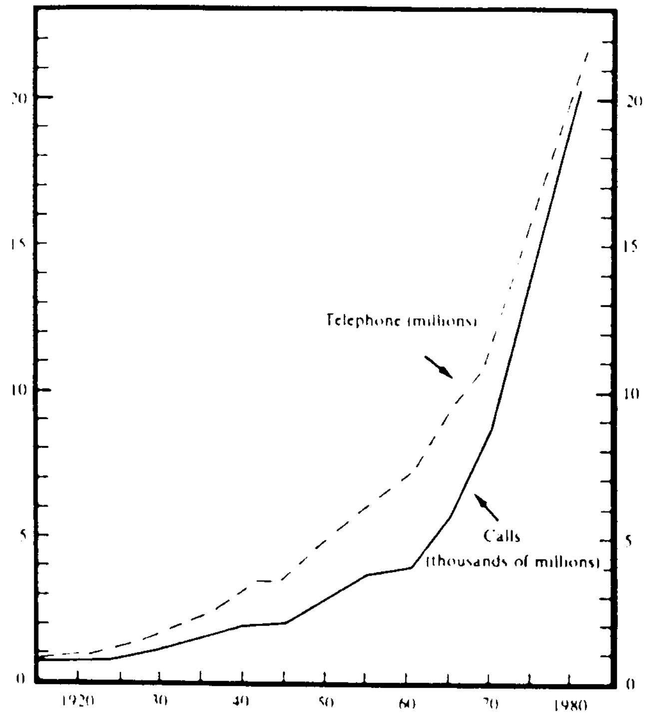

20
15
10
5
0
Telephone (millions)
Calls
(thousands of millions)
1920
30
40
50
60
70
1980

FIG 1.

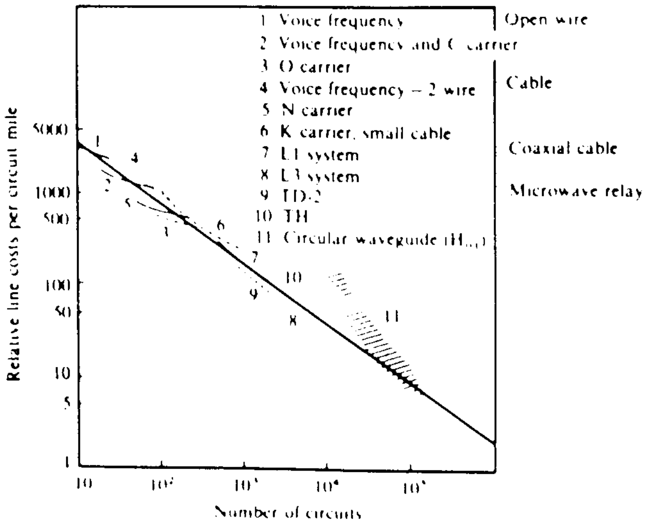

1 Voice frequency
2 Voice frequency and C carrier
3 O carrier
4 Voice frequency – 2 wire
5 N carrier
6 K carrier, small cable
7 L1 system
8 L3 system
9 TD-2
10 TH
11 Circular waveguide (H_{01})
Open wire
Cable
Coaxial cable
Microwave relay
Relative line costs per circuit mile
5000
1000
500
100
50
10
5
1
10
10^2
10^3
10^4
10^5
Number of circuits

FIG 2.

FIG 3.

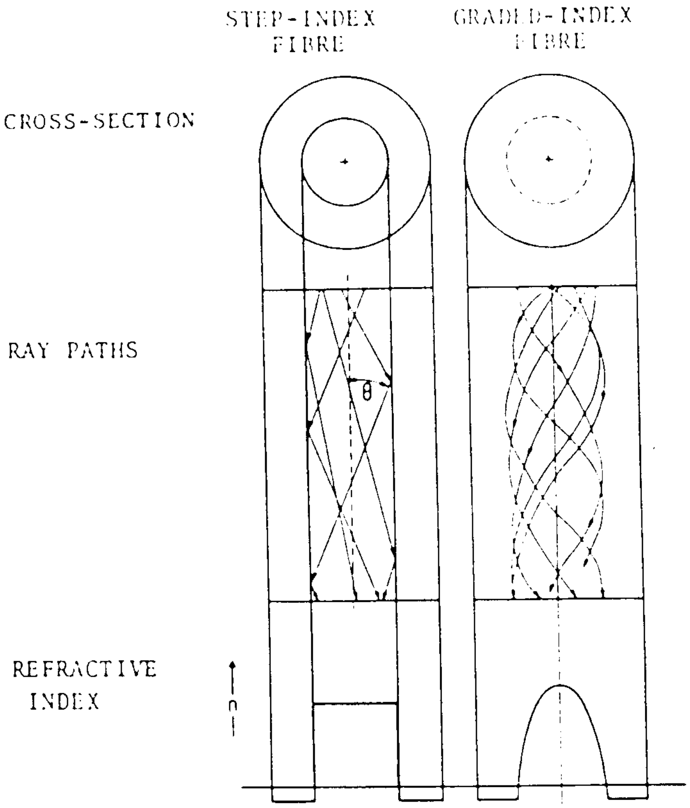
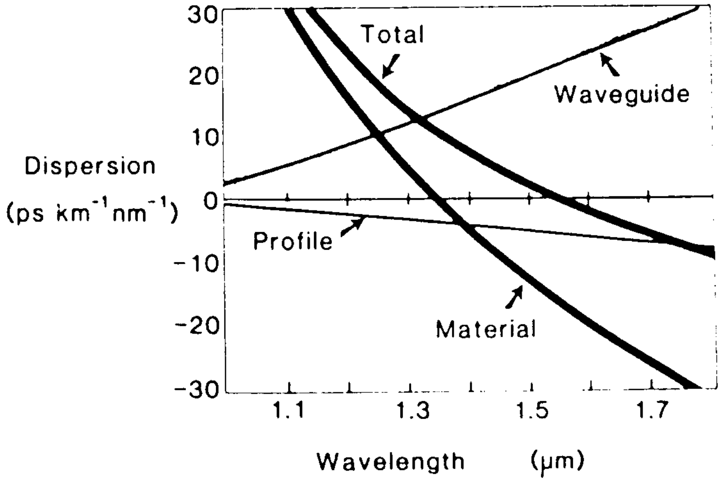

STEP-INDEX FIBRE
GRADED-INDEX FIBRE
CROSS-SECTION
RAY PATHS
θ
REFRACTIVE INDEX
n

FIG 4.


Dispersion (ps km^{-1}nm^{-1})
30
20
10
0
-10
-20
-30
Total
Waveguide
Profile
Material
1.1
1.3
1.5
1.7
Wavelength (μm)

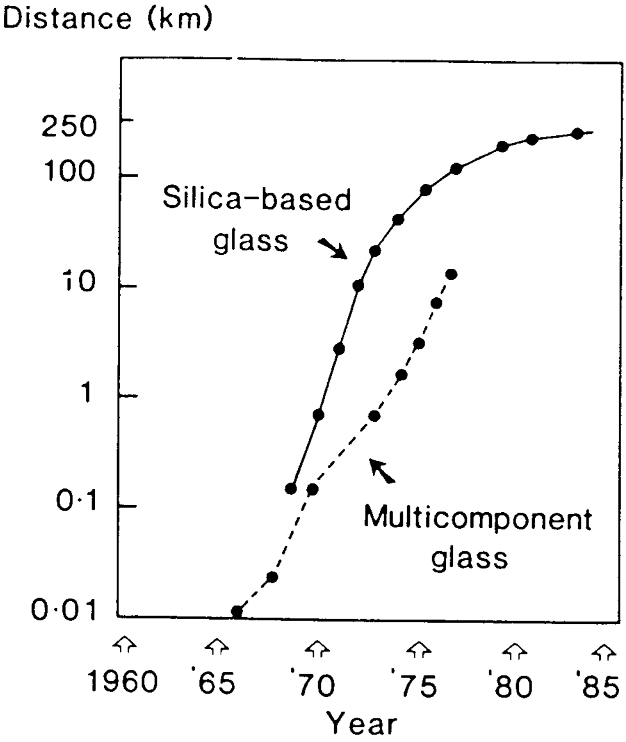

Distance (km)
250
100
10
1
0·1
0·01
Silica-based glass
Multicomponent glass
1960
'65
'70
'75
'80
'85
Year

FIG 5.

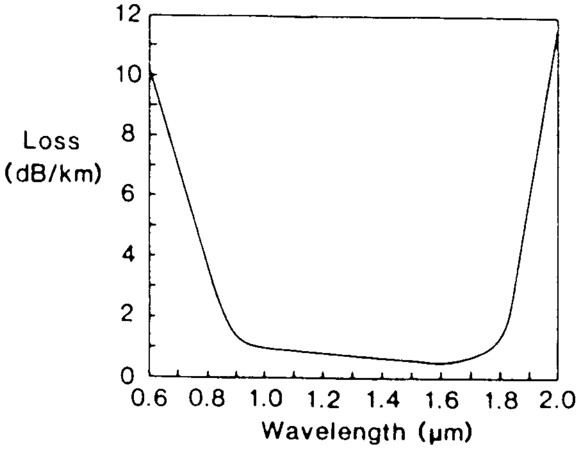

12
10
8
6
4
2
0
Loss (dB/km)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Wavelength (μm)

FIG 6.

FIG 7.

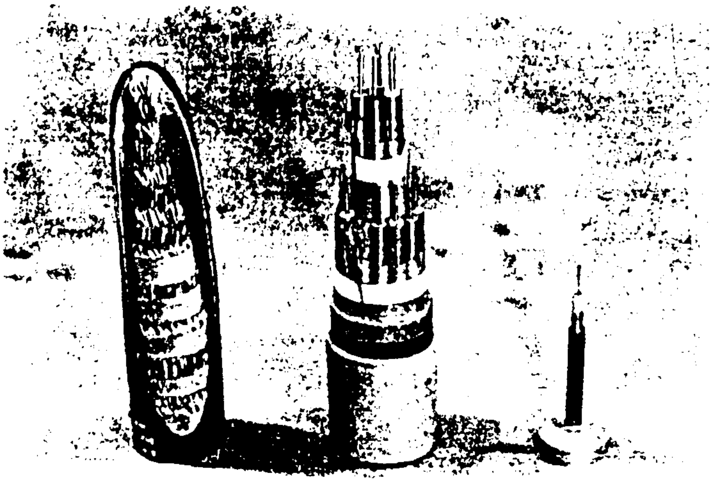
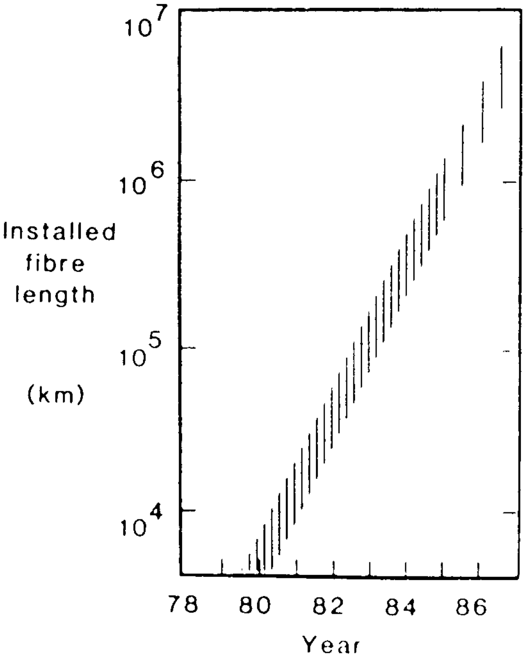


FIG 8.



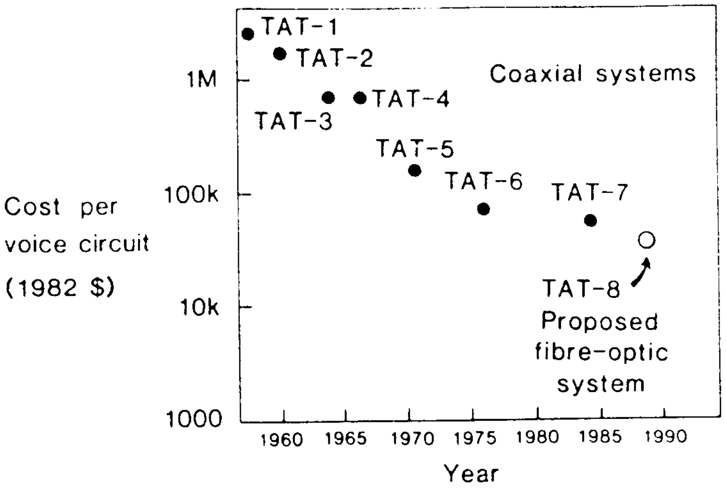


FIG 9.

LOSS AND DISPERSION LIMITATIONS OF OPTICAL FIBRE SYSTEMS

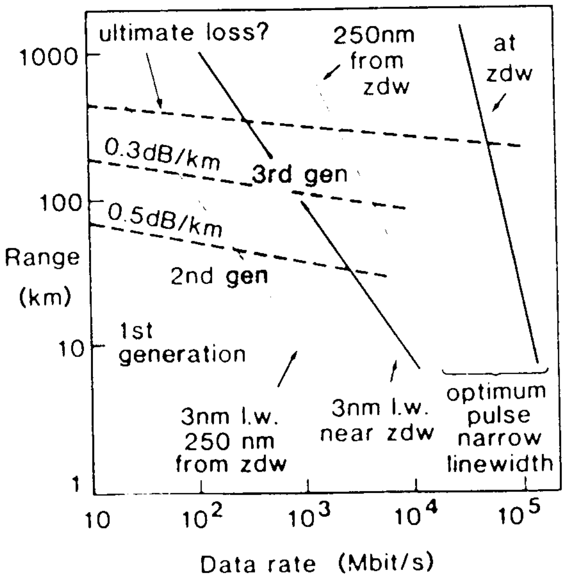
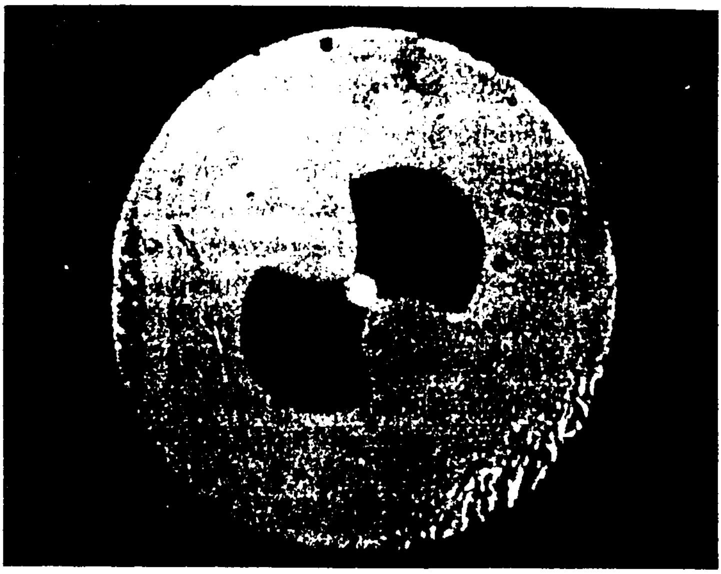


FIG 10.

l.w. . source linewidth

zdw : zero dispersion wavelength

FIG 11



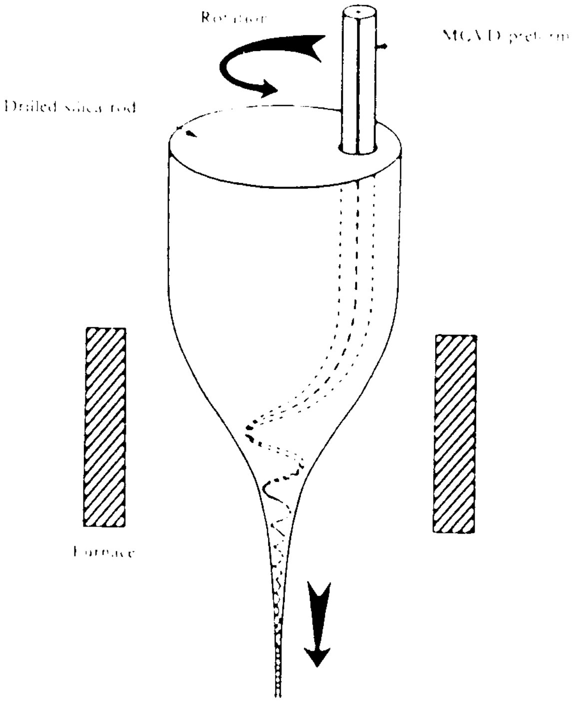


FIG 12