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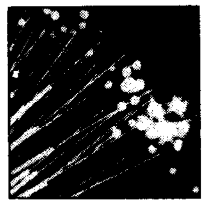


The development of optical communication

Despite recent progress, optical fibre transmission systems remain primitive in comparison with, say, microwaves. This general overview of optical fibre and optoelectronics development looks to the future when the full potential of the medium has been developed

by Prof. W.A. Gambling

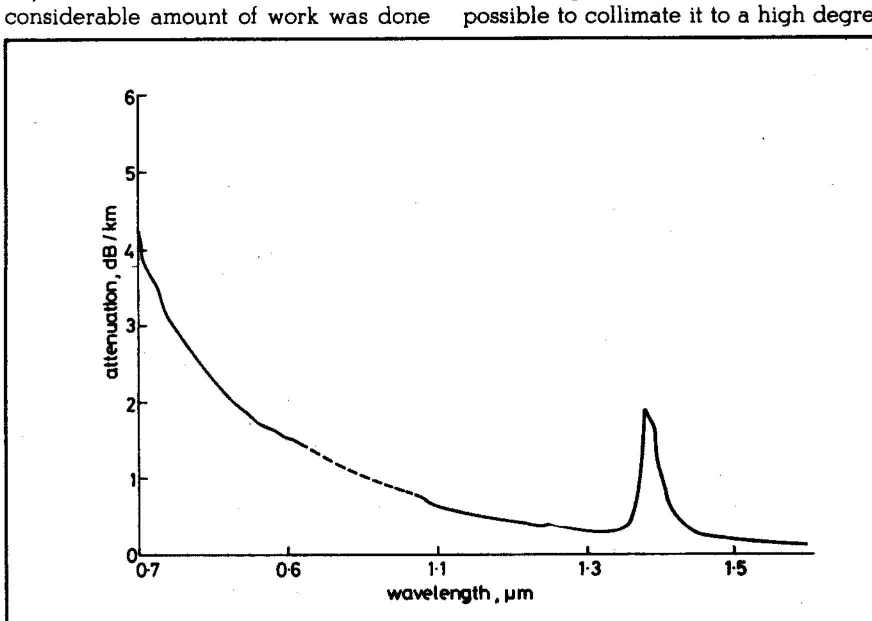
In the early days of research on optical fibres it was convenient to consider light propagation in terms of rays reflecting from the interface between the core and cladding. In this way analysis was simplified and many of the results obtained were of practical validity. In fact, optical transmission was treated rather differently from microwave transmission but of course the difference is one of degree only, but because the frequency ratio is about five orders of magnitude, the transmission lines themselves and the associated components look rather different. It is interesting to compare the progress in optical transmission with microwave communications because, as a result, there are some predictions that one can make for the future.

Microwave transmission methods

The various microwave transmission techniques employed today largely comprise satellite links, microwave line-of-sight propagation and coaxial transmission lines. Satellite transmission makes use of a collimated microwave beam which travels for most of its 40 000 km path through free space, between a geostationary satellite and a ground station. The transmission loss is governed principally by the degree of collimation of the beam, the aiming accuracy and the collection area of the receiving antenna. The problems of microwave relay links are similar to those of satellite communication with the additional hazard that the beam travels through the earth's atmosphere and can therefore be disturbed to some extent by weather conditions. Nevertheless they operate successfully over distances of 50 km, or so. In coaxial transmission lines the loss, and therefore the propagation distance, is determined by the properties of the dielectric and the copper conductors although some additional attenuation is caused by imperfections in the cable and at joints. In addition to these methods a considerable amount of work was done on the overmoded millimetre waveguide where the propagating beam is guided in a metal tube. This method has never been seriously used.

Development of optical communication

Comparable methods of optical transmission have been as follows. If one could achieve a truly monochromatic electromagnetic wave then it would be possible to collimate it to a high degree



1 Attenuation of a single-mode fibre. The peak near 1·4 μm is due to water impurity and the dashed region is at cutoff of the second-order mode

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of accuracy. Assuming perfect optics the angular width is proportional to the ratio of wavelength to diameter of the collimating optics so that a laser beam can be made increasingly directive, for a given wavelength, by increasing its launch diameter. Outside the earth's atmosphere the transmission efficiency is then dependent only on the aiming accuracy and the aperture of the receiver, as with the microwave satellite link. An experiment of this type to measure the distance from the earth to the moon was carried out by launching a beam from a pulsed laser through a 60 cm telescope aimed at a retroreflector left on the moon by the Apollo astronauts. By measuring the time of flight of the optical pulse the distance from the earth to the moon was measured with an accuracy of a few centimetres. Now, it seems, we know where the moon is. At the present time there are very few applications of optical communication outside the earth's atmosphere, although design studies have been made of the possibility of employing laser communication between satellites.

An equivalent to microwave link transmission is the propagation of unguided laser beams near the surface of the earth. However, even apart from the problems caused by the weather, an optical beam is easily deflected and split up into filaments by very small temperature gradients and turbulence in the atmosphere. Reliable communication over more than a kilometre or so is therefore not possible.

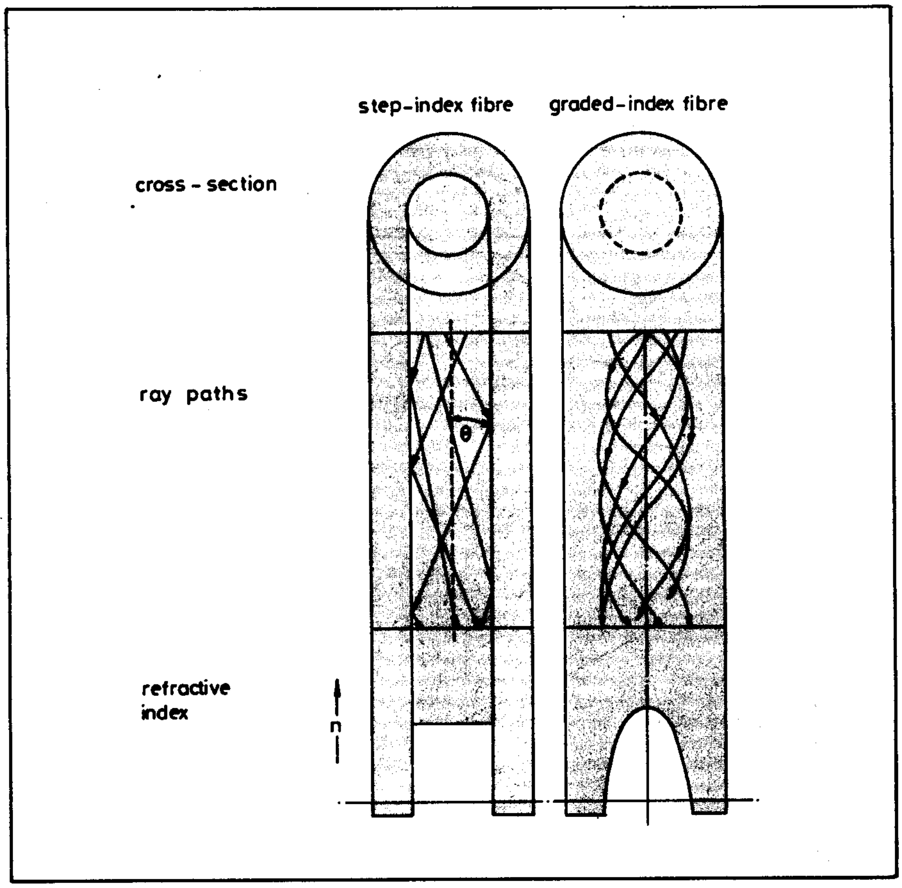
The next development, in the late 1960s, was an attempt to guide a laser beam by enclosing it inside a pipe with highly reflecting walls. However, the losses were extremely high and the pipe had to be laid on an optically straight line. A further development was to introduce lenses, separated by about 100 m to produce periodical refocusing of the beam to counteract the effect of diffraction spread. A few experimental systems were produced, giving transmission losses of about 1 dB/km, but such a beam waveguide, although of very large information-carrying capacity, is extremely expensive to construct, install and maintain as well as being very inflexible. No working system has ever been produced.

Optical fibres

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

The first real step forward in optical communication came in 1966 with the suggestion that it might be possible to produce cladded glass fibres of sufficient purity that transmission over long distances would become practicable. The idea at the time was very speculative as existing fibres had attenuations of about 1000 dB/km and had to be improved by at least three orders of magnitude. In fact, the development of optical-fibres has been such that they form the only optical medium in widespread use today and the installation of optical-fibre systems is expanding very rapidly. Indeed British Telecom has already announced to cable manufacturers that it will order no more coaxial cable after 1985, and it is expected that over half of all trunk telephone traffic will be carried by fibres by 1991. As may be seen from Table 1, optical-fibre transmission lines have much lower attenuation and vastly greater bandwidth than coaxial cable and, in addition, have the important virtues of small size, freedom from electromagnetic interference, are not subject to earthing problems and can be used in hazardous situations where any electrical conductor would be prohibited.

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



2 Cross-sections, refractive-index profiles and ray paths in step-index and graded-index fibres

Types of optical fibre

Despite the limitations outlined above, the performance already achieved with fibres is most impressive. To understand how this has come about it is necessary to look briefly at the construction of a fibre transmission line.

The type of fibre used in telecommunication systems comprises a cylindrical glass core surrounded by a second, cladding, glass of lower refractive index. For the highest performance both of these materials have to be properly chosen and must have less than a few parts in 10^9 of impurity present. With the type of fabrication most commonly used, namely modified chemical vapour deposition, there is a third, surrounding, region which does not form part of the propagation path. It only serves as a substrate on which the pure materials are deposited and to bring the overall diameter to the standard dimension of about 125 μm. The type of transmission loss which can be realised is shown in Fig. 1. It may be seen that the attenuation is below 0·2 dB/km at 1·5 μm. There is an enormous transmission window of 100 000 GHz over which the transmission loss is below 1 dB/km. It is also remarkably fortuitous that light-emitting diodes and injection lasers which are small, efficient, reliable and capable of producing output optical powers in the region of milliwatts to watts, can be fabricated.

Bandwidth

The bandwidth available depends on details of the fibre structure. In the simplest form, namely the step-index, multimode fibre, the core is uniform and extends to a diameter of about 50 μm. Propagation can be understood in terms of rays of light injected at the input end which are continually bounced off the core/cladding interface by total internal reflection and are thereby 'conducted' to the far end of the fibre. The range of permitted ray angles to the axis is determined by the refractive indices of core and cladding. Rays at larger angles are refracted at the core/cladding interface, rather than totally reflected, and suffer a loss of energy. The bandwidth of such a fibre can be simply estimated by calculating the difference in transmission times of a ray parallel to the axis and a ray at the maximum permitted angle. Taking a core refractive index of 1·5 and a relative index difference between core and cladding of 1% gives a pulse dispersion over 1 km of about 50 ns. The corresponding bandwidth is comparable with that of a good coaxial cable.

The effect of multipath dispersion can be greatly reduced by introducing an appropriate radial variation of refractive index in the core region. Thus, if the refractive index decreases from a maximum at the core centre in a roughly parabolic fashion, the precise variation depending on the materials, then the transmission time difference between low-angle and high-angle rays can be minimised. The bandwidth is then increased from a few tens of megahertz over 1 km to something in the region of 1 GHz. For convenience the core diameter of such a fibre is also standardised to 50 μm. Ray propagation in multimode fibres is illustrated in Fig. 2.

The effects of multipath, i.e. multimode, dispersion can be totally eliminated by ensuring that only one mode of propagation is possible. This can be achieved by reducing the core

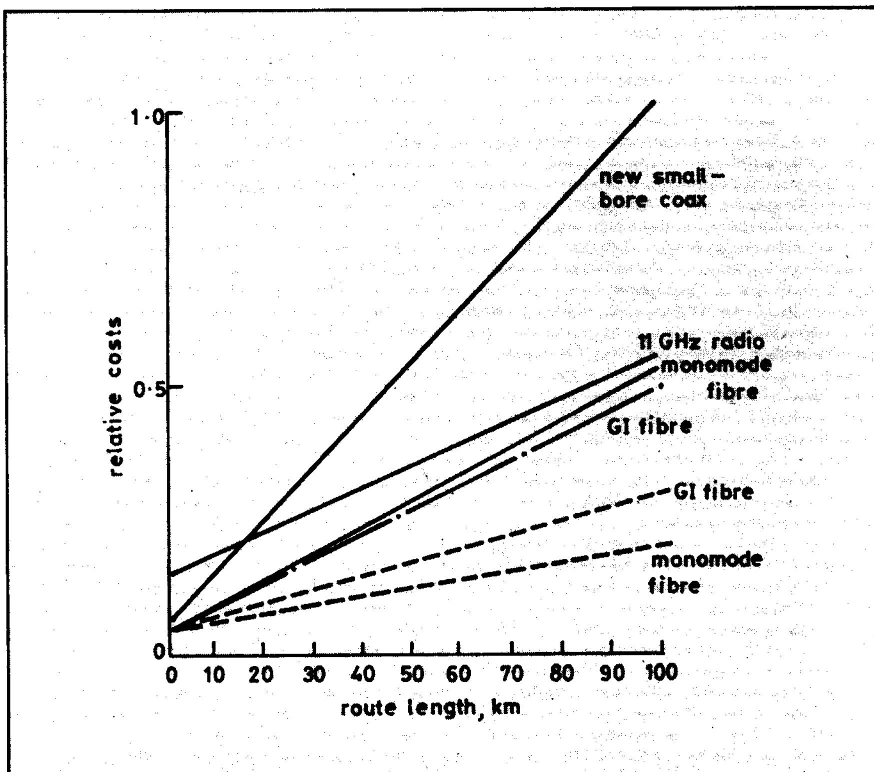
. . . the price of high-quality fibre per foot is less than that of a hot dog

diameter typically to about 5 μm resulting in a single-mode fibre. In the absence of intermode dispersion the limiting mechanisms now become material dispersion and intramode waveguide dispersion. The former arises because glass is a dispersive medium. It can be shown that even in a bulk material an optical pulse spreads at a rate determined by the material dispersion parameter M given by $M = (\lambda c)(d^2n/d\lambda^2)$. In a single-mode fibre the effects of both core and cladding must be taken into account but the effect is qualitatively the same. Intramode waveguide dispersion is due to the fact that the group velocity in a dielectric waveguide is a nonlinear function of wavelength. It has been shown that at wavelengths greater than 1·3 μm the variation of material dispersion and group velocity dispersion with wavelength are in opposite senses so that by judicious fibre design they can be made to cancel each other at any wavelength between 1·3 μm and 1·6 μm, or so. The prediction of this effect was a major development which has been verified in practice. Enormous bandwidths are thus possible even with sources which are not monochromatic.

The next limit to bandwidth is brought about by the fact that in a circular structure it is possible for two orthogonally polarised modes to propagate. Quite small departures from perfection caused by noncircularity of the core, or nonsymmetric thermal strains between core and cladding, can cause the group velocities of the two orthogonal modes to differ. However, this limit to bandwidth has not yet been observed, and measurements over long lengths of single-mode fibres have shown that polarisation dispersion is less than 1 ps/km. This corresponds to a bandwidth-length product of 1000 GHz km. Thus, over a transmission distance between repeaters of 200 km a system bandwidth approaching 5 Gbit/s is possible.

Present applications

The bulk of present applications of optical-fibre transmission lines is in telephone networks, and examples of the performance which can be obtained are given by the transmission of 140 Mbit/s over 100 km and 565 Mbit/s over 60 km by British Telecom and a rate of 288 Mbit/s over 100 km at Bell Telephone Laboratories. Fibres are also beginning to find their way into less sophisticated applications where the other advantages, apart from low loss and bandwidth, are sufficient attraction. Often, simpler fibres are adequate and



3 Cost comparisons of 140 Mbit/s digital line and radio systems. Solid line – present-day prices; broken line – long-term prices

Table 1 Comparison between microwave and optical-fibre systems

	microwave	optical
transmission distance by cable	2-4 km	10-100 km
bandwidth × length	50 MHz km	25-100 GHz km
bandwidth relative to carrier frequency	1%	10^{-5}
circuit components	many	none
multiplexing	yes	not yet
carrier frequency spread/bandwidth	10^{-6}	600 (laser diode) 1200 (LED)

Table 2 Relative importance of various fibre applications in Japan (expressed as a percentage)

telecommunication	35
electrical power plant	24
industrial process control	9
transport	9
education	7
cable television	5
military	5
other	6
	100%

the range of possible installations is large, ranging from cable television, the local telephone network, computer interconnection, missile guidance and many others. For any application cost is of paramount importance and it is interesting to observe that the price of high-quality telecommunication fibre per foot is less than that of a hot dog. A more sophisticated comparison with line and radio transmission is shown in Fig.3.

Problems

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

Another potential problem is that of jointing, especially in a single-mode fibre where core alignments of better than 0·1 μm are necessary. Again satisfactory techniques have been developed which allow fusion jointing to be performed giving joint losses of 0·1 dB or less.

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

Again it is difficult to imagine how difficult it would be to operate microwave circuits without directional couplers but such devices are not readily available for use with fibres. The principle of making a directional coupler with fibres is well understood but the technology for doing so still awaits development.

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

The future

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

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

From the loss figures of 1000 dB/km of 1966 there has already been a reduction to less than 0·2 dB/km. It has been pointed out that there are certain materials which intrinsically have even lower losses in the wavelength region of 5-10 μm, may be even as low as 0·01 dB/km. These materials are much more difficult to process and handle than glass but a loss of a few decibels per kilometre has already been demonstrated in one of them. There is still a long way to go but it is intriguing to speculate on whether it might be conceivable to operate over repeater spacings of several thousands of kilometres rather than a few hundred. This might result in transoceanic transmission with no submerged repeaters at all. Unfortunately, the dispersion at these longer wavelengths is likely to be significantly greater than the figures quoted above for existing single-mode fibres.

Economic prospects

Optical-fibre communication is only a part, albeit a major component, of the rapidly growing industry and technology of optical electronics, or opto-electronics as it is being increasingly called. A number of market surveys have been carried out and all predict an explosive growth over the next 10 years. One estimates a world market by 1990 in excess of £4000 million and although the precise figure is no more than an educated guess the order of magnitude is generally agreed among the various experts. Sales of optical fibres in Japan, to take one example, amounted to £16 million in 1979 and is expected to increase by an order of magnitude by 1990. The present applications of optical fibres, also in Japan, are given in Table 2. In my view, one of the sectors which may achieve a growth rate rivalling that of communication will be industrial process control where a considerable amount of interest is currently being generated.

Conclusions

It is clear that even in the field of telecommunications, optical techniques are going to be of considerable commercial significance and we can look forward to a large growth in the optoelectronics industry. In addition the applicability of fibres in other fields is also being studied. Under certain conditions, for example, the propagation properties of fibres are sensitive to such environmental factors as pressure, temperature, strain, vibration and magnetic field. It is tempting, therefore, to attempt to use these properties in conjunction with the well known advantages of freedom from electromagnetic interference, earthing problems and sparking hazards. Thus a market for fibre sensors in instrumentation and process control has been estimated at $200 million by 1990.

It is clear that the technology of optical fibres is still relatively in a very primitive state and so far we have seen only a tentative beginning to an entirely new technology.

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