Optical fibre communication

Sub-systems for field demonstrations — 1

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Progress in research contributing to the realisation of an optical-fibre communication system has been rapid. Long-lived, room temperature, c.w. semiconductor lasers are being tested. Several techniques have been shown to be capable of producing multimode or monomode fibre waveguides on a routine basis with attenuation well below 10 dB/km. Fast, reliable silicon avalanche photodiodes are available commercially. Connectors for single-fibre waveguides have been produced with 1-2 dB/km loss and splices with much lower attenuation. Complete analogue and digital laboratory systems have been shown at many conferences and exhibitions. From a position of such strength in the realm of research, it would seem that a wide range of targets would be set for a field trial. However, the introduction of an optical-fibre communication system into an existing network is possibly a more far-reaching step than any that has been taken since the inception of these networks. Because of this, a great deal of engineering confidence has still to be established. A large-scale field demonstration (see August issue, page 70) could achieve this, but many sub-systems must be engineered before this can be held. With careful design, such a demonstration will assist in determining the targets to be set for a field trial.

In 1966 Hockham and Kao[1] described the possibility of an optical communication system using single-mode fibre waveguide as the transmission medium. Such systems would have enormous information carrying capacity, and if attenuations down to 20dB/km could be achieved they would have clear economic advantages over coaxial cables for wideband long-haul applications. At the time, the 20dB/km target seemed highly optimistic, and there were a number of other technology breakthroughs which needed to be established, such as uncooled c.w. semiconductor lasers, before such systems could become a reality.

All these breakthroughs have been achieved, and subsequently confirmed, by several independent groups of researchers. Furthermore, the 20dB/km target, which once seemed so distant, was passed with relative ease, and attenuations of around 3dB/km have now been demonstrated in high silica fibres. If such fibres can be produced routinely in quantity and can be incorporated into practical cables with only modest loss increases, then, even ignoring the plethora of military and other non-PTT applications which look increasingly attractive, a very much broader range of systems than was originally proposed will be viable, particularly in view of the rising cost of conventional materials.

More recently, therefore, the emphasis of the work has shifted towards consolidating research results and tackling the many engineering problems which will have to be solved before optical fibre systems become a reality. This type of work requires a different approach from the earlier research, and is best carried out using a model system approach, where the assumption is made that a demonstration will be held in a typical PTT environment. This ensures that adequate account is taken of the myriad of practical problems which occur with real systems in a field environment, but often cannot be predicted from experimental work in the laboratory.

The PTT situation chosen was that of the British Post Office as this is best known to us. Had the original expectations of Hockham and Kao been only barely realized, the choice would have been simpler, because only at very high bit rates would any economic advantage over coaxial cables have been expected. In fact, we can select from a very wide range of systems from 2Mbit/s to 560 Mbit/s which are all feasible and all economically advantageous in the appropriate PTT environment.

It is still too early for PTTs to know definitely which systems they will wish to procure and install in quantity, and it would require a prodigious and unjustifiable expenditure of resources to cover all possibilities. Fortunately, the problem is not as difficult as it seems at first sight. The solution is an integrated but flexible field demonstration programme, designed to provide sufficient practical information to a broad range of systems, not just the specific one tested, for a PTT administration to see in the work done sufficient justification and technical content to commission a full-scale field trial for whatever type of system turns out to be most appropriate for its needs.

This article describes work being carried out to produce the key sub-systems which will enable realistic field demonstrations to be mounted, thus paving the way to field trials of optical fibre communication systems.

Present status

From many aspects the present time may be regarded as a watershed in optical fibre communication. Progress in most of the lines of research contributing to the realization of a communication system has been extremely rapid, and in several instances confidence is growing that today's results are the harbingers of future progress. We have sufficient confidence now to plan the first steps in engineering aimed ultimately at full-scale field trials. However, before we can examine this new realm, we review the present research status in more detail.

A recent review of propagation in optical fibre waveguides[2] illustrated the progress that has been made during the last few years in building up an understanding of the dispersive and radiative loss mechanisms in dielectric waveguides. A further review[3] considered the various manufacturing technologies that have been developed, all of which are capable of producing low-loss fibre waveguides: in particular those involving high-silica-content glass give total attenuations below 10dB/km on a routine basis.

Provided that all the relevant physical parameters can be established, there are several methods of fibre transmission analysis available which cover a wide range of complexity and accuracy[4,5]. The physical parameter proviso is far from being a trivial one, although considerable insight can be obtained into the behaviour of optical fibre waveguides by analytical means.

Most of the current methods used to manufacture low-loss fibre waveguides are capable of producing single or multimode guides. In either case the waveguide design may use a simple or multi-layer cladding. In the case of multi-mode guides, a graded-index profile can be used to reduce the dispersion of group velocity of the various propagating modes. The optimum profile can be computed for any particular materials and wavelengths[6] and gives a dispersion of under 100 picoseconds/km for $\Delta n/n = 1\%$, where n is the refractive index; but the best experimental results are still about an order of magnitude greater. Modal dispersion of below 1ns in 1km of fibre waveguide has been demonstrated, but only in cases where either the fibre aperture was not fully illuminated[7] or mode mixing due to residual or applied strain, or other waveguide inhomogeneities, was present[8,9].

Cabling. Apart from the mechanical problems obviously present when cabling optical fibre waveguides, the essential requirement is that the fibre waveguides must remain in a strain-free condition. The effects of an inadequate cabling technology can be quite dramatic. Even comparatively small amplitudes of microbends, a few microns amplitude for instance, can lead to hundreds of dB/km attenuation if the mechanical wavelength is particularly unfortunate[10]. However, these problems can be overcome and several designs have been shown to be capable of producing cables having an overall attenuation around 10dB/km, and which can be installed in conventional ducts.

Jointing. Both demountable connectors and permanent splices have been demonstrated in many laboratories. Particular splicing techniques involve fusion in low-melting-point glasses, cementing or fusing in accurate capillaries, V-groove alignment or three precisely machined pins. Alternatively, adjustable splices can be made with fibres mounted in eccentrically machined holders. All these techniques have involved losses of only a small fraction of a dB and some have already been demonstrated in the field[11]. Connector design has concentrated on modifications to existing electrical connectors which enable the fibres to be accurately aligned when the connectors are coupled. Attention to mechanical tolerances has enabled losses to be reduced to a few dB with 30μm core fibre waveguides and correspondingly lower losses for larger cores.

Optical sources. Although low-bit-rate systems of modest repeater section could be made to operate with conventional light emitting diodes of the kind now commercially available, such systems could hardly be said to stretch the technology of fibre optic communication. Also, although rapid progress is being made with various miniature neodymium lasers, these all require external modulators and must still be regarded as firmly in the realm of research. We can therefore confine our attention to high-intensity light-emitting diodes and semiconductor injection lasers, both of which can be modulated directly by control of their current drive. Both have reached their most advanced state of development using GaAs and/or $Ga_xAl_{1-x}As$ and hence emitting in the spectral range 800 to 900nm. Both are capable of continuous operation at room temperature.

Emission at longer wavelengths, in the range just beyond 1μm, would be attractive for two reasons. The first is that the basic scattering mechanisms reduce at longer wavelengths and many fibre waveguides also show lower absorption. The second reason is that there is a much lower dispersion of group velocity due to the material[12]. This last-mentioned attraction is most pressing for l.e.ds as the combination of material dispersion and their wide spectral width of 20-80nm could well impose the bandwidth limitation in system design.

Light-emitting diodes in $Ga_xIn_{1-x}As$ systems are being investigated to exploit these advantages[13] and initial results are encouraging. From an engineering standpoint l.e.ds offer one outstanding advantage in that they already have a demonstrable life of well over 10 000 hours. Disadvantages arise from their large spectral width, from the isotropic emission of radiation and hence low coupling efficiency to optical fibre waveguides; and from the fact that even small-area l.e.ds designed to launch light into a single multimode fibre have sufficient reactance associated with junction capacitance and an inherent radiative lifetime that makes modulation difficult at over 100Mbit/s when operated at high intensity.

Launching efficiency can be improved and the limitations due to spectral width overcome by using lasers. Most commercially available lasers have a broad contact and emit over a junction width of over 100μm. Under these circumstances there is little prospect of providing an adequate thermal path away from the junction and operation must be limited to less than a 30% duty factor. Striped contact mesa techniques and proton bombardment have all been used to confine the current and emission to a narrow region[14]. These are becoming commercially available. Continuous operation at room temperature can be effected by any of these techniques, and, when the change in refractive index at the boundary of the active region is small, single transverse mode operation can be obtained. Under these circumstances reasonably efficient launching is possible even with single-mode optical fibre waveguides.

Lifetime has long been the major problem with semiconductor lasers, but rapid strides have recently been made and many institutions now report lifetimes of several thousand hours, with best results of well over 10 000 hours and extrapolations being made to around 100 000 hours[15].

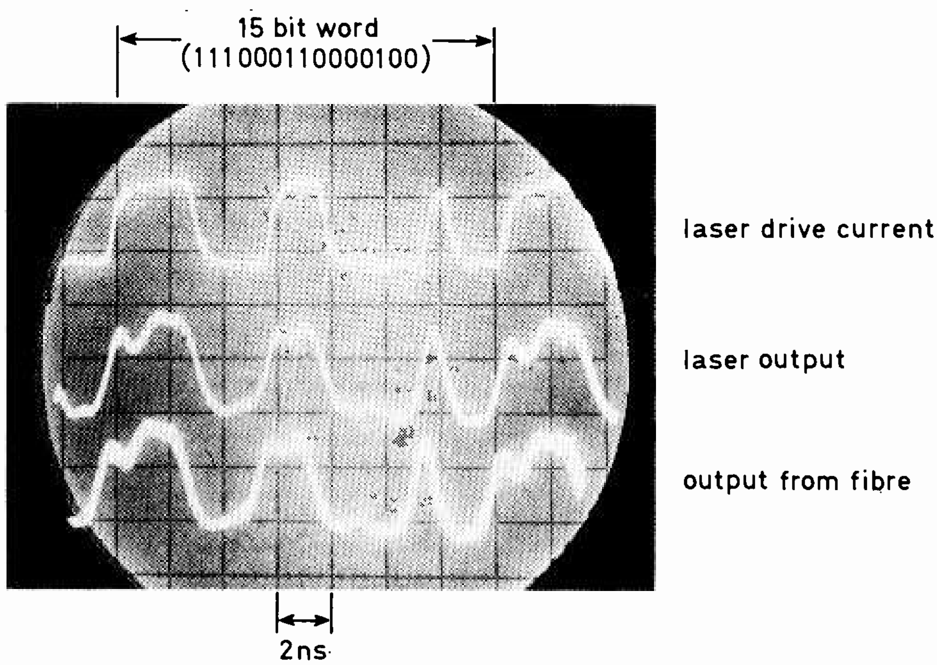


Fig. 1. 1 Gbit/s single-mode fibre. Laser current, laser light output and fibre output after light has been transmitted through nearly 1km of single mode fibre.

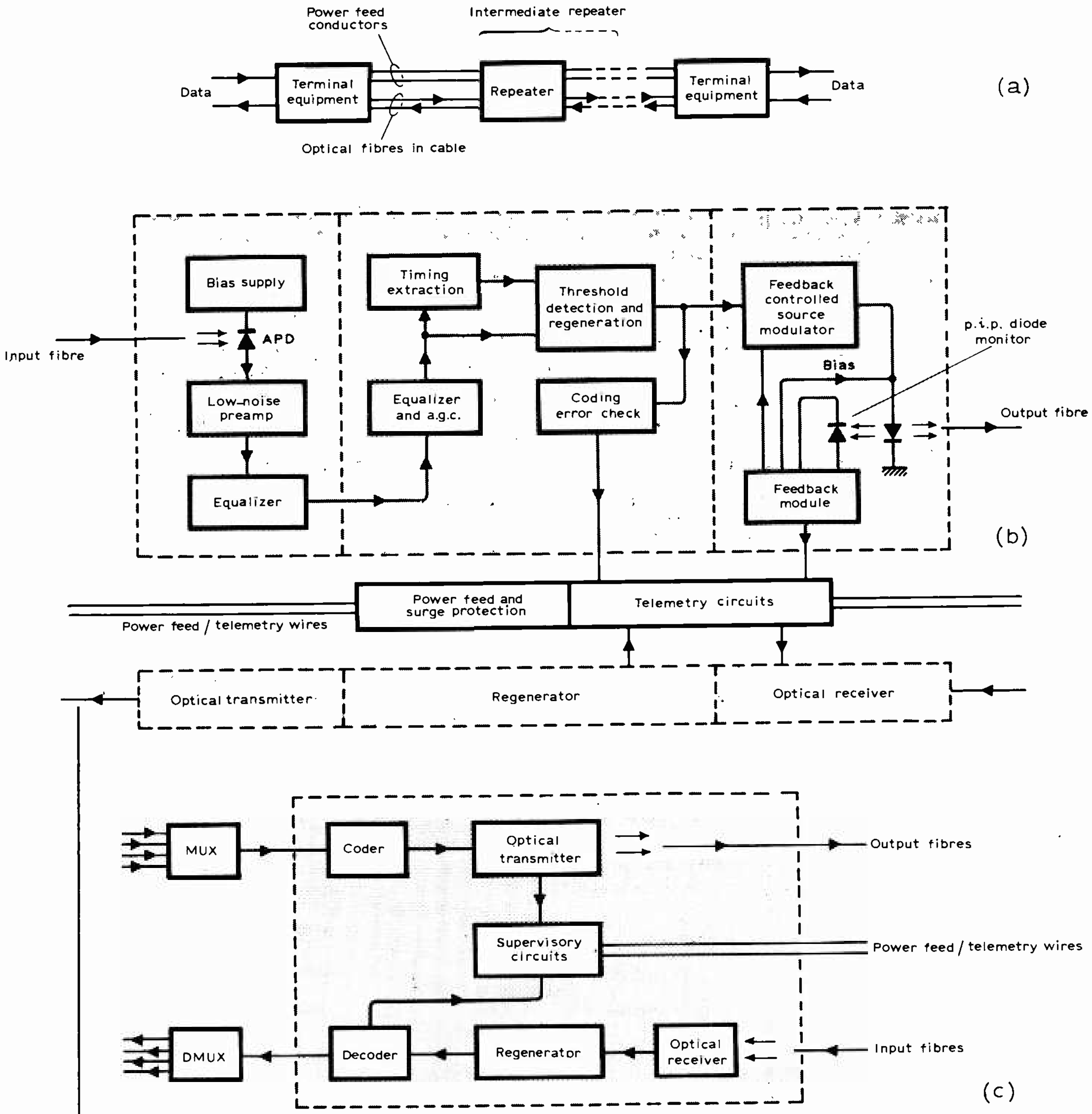


Fig. 2. Overall system block diagram (a) wherein initial system repeater spacing is expected to be 3km. Repeater block diagram (b) shows optical receiver, regenerator and transmitter. Degraded pulse received after transmission is amplified, reshaped and retimed before retransmission. Terminal block diagram (c) shows multiplexing of incoming signals prior to transmission and regeneration and demultiplexing of received signals together with testing equipment and subscircuits.

Detectors. Fortunately, adequate silicon avalanche photodetectors have always been available commercially[16]. Although these detectors may not be optimum and — for some applications packaging deficiencies have been apparent — they have enabled laboratory systems to be constructed with a signal-to-noise penalty of only 5-6dB. Continuing research and new experimental techniques will enable this margin to be narrowed even further.

Systems. Practical considerations rule out heterodyne detection, so attention can be confined to direct detection. Also, two-channel systems show a very minor return at best for the additional complexity[17], and can be ignored. Quantum noise, dark current noise and leakage noise are all manifest as a shot noise characterized by Poisson statistics. With proper system design these will dominate the receiver thermal noise and quantum noise should form the largest element. Design principles to ensure this are well understood[18] and theoretical consideration has been given to other aspects of system design, particularly to optical fibre systems[17].

Many systems have already been demonstrated on a laboratory basis and scale. Pulse-code modulated systems with bit rates ranging from 6.3 to 400Mbit/s have been described[19], and transmission has been reported through nearly 1km of single-mode fibre from a $Ga_xAl_{1-x}As$ injection laser directly modulated at 1Gbit/s[20]; see Fig. 1. Pulse analogue and amplitude modulation systems have also been described, but as regeneration is not possible and as carrier signal-to-noise ratios are inadequate for transmission through many repeater sections, these cannot be considered for PTT applications. Nevertheless, virtually the entire range discussed in the introduction has been covered by present-day laboratory demonstrations.

Overall system design

A field demonstration study is not a prototype system, but a means of collecting the maximum engineering information possible on optical fibre systems under normal operating conditions. The scale must be sufficient to achieve this goal, and will involve a complete, self-contained, two-way system, operating through at least two intermediate repeaters, with both test equipment and partially equipped multiplexers at the terminals.

In view of the rapid advances in the state-of-the-art, flexibility is desirable; spending time and effort on sophisticated and supposedly ultimate solutions, in areas where the scarcity or transience of available data preclude this, is not. A modular approach is essential to maximize the commonality of equipment between terminals and repeaters. Design of the individual modules requires special attention to give scope for later modifications or experiments.

A key decision concerns the bit rate. A good choice is 140Mbit/s which, though not the highest rate which could be demonstrated, enables a searching test of possible exposures to be carried out, corresponds to an economically attractive slot in many PTT networks, and will yield much data relevant to lower bit rate systems.

There are also a number of subsidiary decisions on the system and component details which have to be made, and in the following sub-sections these are discussed with reference to the system and sub-system block diagrams shown in Fig. 2.

Sources and detectors. It seems highly likely that gallium arsenide directly modulated light sources will prove adequate for all but the very highest bit rates. For PTT systems the laser will generally have an advantage, particularly at higher bit rates, because considerably more power can be launched into a suitable fibre, from the dispersion point of view, and the extra repeater spacing potential is economically very desirable. The possible exception is at low bit rates, for example 2Mbit/s, where, because large-core, high-numerical-aperture fibres can be used, the laser may have no advantage.

The choice of detector lies between two silicon devices whose responses are well-matched to the gallium arsenide sources: the p-i-n diode and the avalanche photodiode (a.p.d.). With special high-impedance preamplifier techniques the performance of the p-i-n diode may be comparable with the a.p.d. at low bit rates; but at higher bit rates the a.p.d. has a clear advantage since its internal multiplication provides lower noise gain than have available preamplifiers. Avalanche photodiodes have, however, been unpopular as they require voltages of typically 80-200V and are reputedly difficult to drive.

The best choice for a field demonstration at the present time is expected to be c.w. lasers and a.p.ds and as they will almost certainly eventually emerge as the preferable devices for most PTT applications and because they enable more ambitious systems, in terms of repeater spacing and bit rate, to be evaluated. This in turn will enable more comprehensive data, more closely relevant to an economically realistic system, to be accumulated. The choice can be made with confidence since c.w. lasers with more than adequate lives for such a demonstration are already available and, as will be described in part two, elegant solutions to the problems, real or supposed, of incorporating both devices in practical subsystems are being developed.

Fibre type. The choice of fibre lies between single-mode fibre, with a simple or multilayer cladding, and multimode fibre with step or graded index. Single-mode fibre is in many ways the best understood; it is convenient to make and has the highest bandwidth. However, it does pose jointing problems which, while doubtless being soluble in the long term, are truly formidable in the short term. Step index multimode fibre seems limited in PTT applications to low bit-rates (2Mbits/s and possibly 8Mbit/s). Graded-index multimode fibre is the most interesting possibility. It is certainly suitable for very much higher bit rates than step index fibre and, depending on how precisely the index profile can be maintained on a repeatable basis, it may prove adequate for any likely first-generation system. On the evidence available so far, jointing difficulties appear comparable with step-index fibre of equivalent core size. There are admittedly numerous unknowns associated with this fibre, but in view of its promise it seems the natural choice for a field demonstration. Its performance when produced in pre-production quantities can then be evaluated in an installed, jointed cable in a practical environment.

Coding. In conventional p.c.m. wire line systems a line code is selected that avoids the transmission of d.c., ensures adequate timing content and allows in-traffic monitoring. The last two requirements are common to an optical system, but as we do not have positive and negative light pulses available, the best method of implementation might be different. The present codes used for conventional wire line systems have evolved only as a result of considerable practical experience, and obviously it is not possible to predict what codes will eventually prove the most effective and efficient in optical systems. There is no point in going to a complicated code until more practical information is available on how optical systems behave and some of the key components develop. This point is illustrated by the fact that any system chosen today would almost certainly be some type of binary code. But even this broad choice could be proved wrong; with the improvement of lasers and the associated driving techniques based on optical feedback described in part two, ternary operation is quite feasible and could be used if it proves advantageous. The natural choice for this trial is therefore a code which satisfies the basic requirements and is simple to implement. Such a code, which would also be compatible with an adaptive equalization scheme, is described in part two.

Power feeding. Possibly the greatest problem unique to optical fibre systems is power feeding, and the optimum solution will differ depending on the type of system and country of installation. For instance, at the lower bit rates it may prove possible in some areas to achieve wide enough spacings for repeaters to be located in, or close to, buildings with existing dependable supplies. In general, however, power feeding along the route is likely to be necessary unless small, efficient, cheap and utterly reliable independent sources become a reality.

It therefore seems prudent to consider in detail route power feeding in any field demonstration, and this can be done either by incorporating conductors into the cable or by laying a parallel separate power feed cable. Unfortunately, either would largely negate the electrical isolation advantage of optical transmission systems. The parallel power feed obviously could be used, but would prove little. Because an integral power feed cable has certain advantages in accommodating route growth and supervision requirements it seems best to use a field demonstration to make a practical evaluation of this technique.

Supervision. In a conventional wire line system the transmission line itself is used not only for power feeding but also as a low-loss supervisory circuit. An all-optical supervisory channel could be devised, but would add significantly to overall system complexity, and probably require amplification at each repeater. If power feed conductors are included in the fibre cable it is obviously attractive to use these for the supervisory channels for at least an interim solution. We also have to consider what supervisory information has to be handled. As with coding, the ultimate supervisory solution cannot be foreseen, particularly as more practical evidence is needed of which parameters should be monitored in an optical system. Indeed, the whole supervision philosophy might be different from a conventional system. It is certainly desirable to avoid the need for any special remote monitoring of the source parameters. It is preferred to rely on optical-feedback-controlled driving techniques which, with the continuously improving source-life characteristics, should provide the best solution to the problem of supervision.

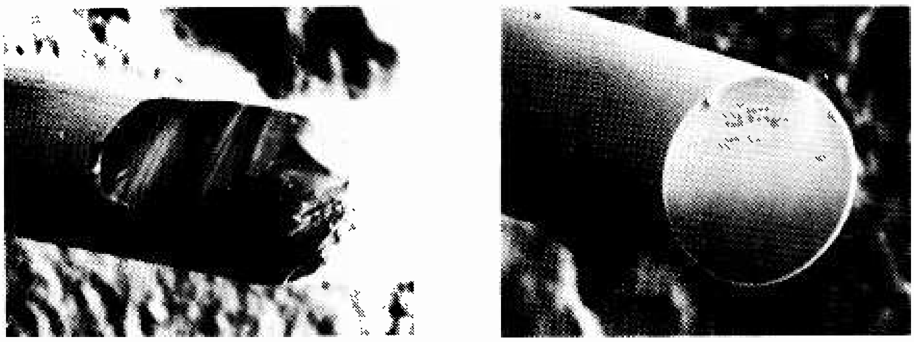
Equalization. The problem of providing equalization in optical systems is basically different from conventional systems in two main respects. Firstly, optical detectors are square-law devices and hence phase information is lost on detection. Secondly, the source of dispersion in a fibre arises from a radically different mechanism from the skin effect in wire cables, and its magnitude, though smaller, is generally far less predictable and reproducible.

As a consequence of the first point, electrical equalization is relatively less effective compared with conventional systems, causing one to examine whether optical or pre-detector equalization might be feasible. In principle it could be applied to multimode fibres because the angles at which rays emerge from the fibre serve to label the individual groups of modes, each with its own characteristic velocity, and some method of delay compensation[21] could be applied. It seems unlikely that this would be effective in a practical PTT system, since even with almost perfect fibres the spacings are so long that significant mode mixing will occur, probably further enhanced by joints and microbends. We are thus forced back to electrical equalization, requiring the use of a fibre which introduces relatively little dispersion.

The situation is simpler for single-mode fibres, where the propagation delay correlates directly with the transmitting wavelength, and in principle several optical equalization schemes should be effective. At present this is largely of academic interest as the dispersion of these fibres is so low with single-mode sources that bit-rate-distance products up to tens of Gbit km/s could be transmitted without the need for equalization.

The second point makes it difficult to design the equalization at all, but a prime requirement at this stage is obviously flexibility.

A further point is that in conventional systems, because the amount of equalization required is related to the total attenuation, it is practicable to have an adaptive equalization system. In fibre systems there is no such simple relationship, but with the appropriate choice of coding, an adaptive system as described in part two should be possible, and would obviously be very desirable. Thus, although it may not be practicable to incorporate an adaptive system into the main hardware, it should certainly be possible to use a field demonstration system to evaluate the practicability of building adaptive equalization into a future system.



(a) (b)

Silica fibre of 150mm diameter broken by hand (a) and broken by machine (b).

The propagating medium

The medium for propagation in a field demonstration involves not only the fibre waveguides themselves but also the cabling, the jointing and the installation techniques. Although these techniques are subjects of study in their own right, certain aspects are intimately bound up with the planning of an optical fibre field demonstration and cannot be divorced from it.

Fibre fabrication. In view of the preferred repeater spacing and capacity arrived at earlier, the wide choice of materials and technologies outlined can be narrowed. First, when allowance is made for additional losses in cabling and splicing, sufficiently low attenuations can on be obtained when using high-silica-content glasses. Again, an accurately graded profile can most easily be obtained using chemical vapour deposition. These techniques are flexible and we can contemplate changes in waveguide design or the carrying through of more than one design, provided that the external diameter, stiffness, mass, and other physical properties of the total waveguide are not altered to an extent that could be significant in the cabling processes. It would then be possible to change to single-mode guide for instance at a late stage in the preparation of a field demonstration.

At present most of the available fibre waveguides are the by-products of research programs aimed at the elucidation of many of the remaining problems. As such it is hardly possible to consider the yield and how this can be scaled up. During the preparation for a field trial, though, it will be essential to concentrate on a few uniform products of high consistency. One of these could well be a graded-index fibre with a core diameter somewhere between 30 and $100\mu m$ with a gradation of the form:

$n_r = n_1[1-(\Delta n/n)(r/a)^{\alpha}]$ within the core, and $n_r = n_1[1-\Delta n/n]$ in the cladding.

It would be reasonable to aim for $\Delta n/n > 1\%$, giving a minimum pulse dispersion of below 100ps/km when the exponent α is exactly the optimum. A practical pulse dispersion figure may well be an order of magnitude higher due to small errors in α, but may be reduced by mode mixing. The optimum occurs close to $\alpha=2$ for a GeO_2/SiO_2 core and an operating wavelength near to 850nm. The overall diameter of such a fibre could well be between 100 and $150\mu m$, as this offers a good compromise for cabling purposes. Having chosen such a product many of the parameters will have to remain fixed, and in some respects further research which will point to better designs must be ignored. In part this accounts for engineering margins which may look rather conservative when one considers the rapid progress in this field during the last few years.

On the basis of such a fibre waveguide and the machinery in current use[3], fibre could be produced in batch lengths between 2 and 5km. Two or more batches could be produced per day; but, if the yield is to be high, very close control will be required on all parameters at every stage. In the deposition stage, the mass flow of each gas and the temperature of the reacting zone must not only be closely controlled but must be very uniform throughout every pass. Again, during the collapsing stages temperature and traversing speed must be accurately controlled. In this way a very uniform preform can be obtained. This can be pulled into a homogeneous fibre waveguide, but careful control of temperature and profile in the pulling zone is essential. Also, inadvertent changes in pulling speed must be avoided, but judicious use of feedback control from fibre diameter monitoring can be used on this last parameter to improve the uniformity of the product.

Connectors and splices. Joints will be required at each source and detector. Demountable couplings will be required at the transmitter, receiver and every intermediate repeater. In addition, if we accept the hypothesis that the cable is to be installed in conventional British Post Office ducts, splices will be needed at intervals of between 100 and 500m. Also, allowance must be made for at least two other splices per fibre per repeater section, to take account of accidents during cable manufacture or installation. Although some prefabrication may be possible, the bulk of the splicing operation will have to be performed in the field.

No real problems are anticipated for the joints between waveguide and detector. High transmission efficiency should be obtained between a small laser source and graded index fibre of the proposed design. However, if the energy is launched with isotropic distribution, as it would be from a light-emitting diode for instance, 25% of that launched will be in leaky modes[9]. Improvement is possible with a laser source. As demountable connections occur comparatively seldom, a loss of up to 1dB can be tolerated, but loss at splices should be about 0.1dB and must not be above 0.25dB. This implies that variations in core diameter should be below 1.0%, and lateral tolerances or eccentricities below 3.5% of the core diameter for good splices with a graded-index fibre.

Further information is required on the effect of such splices on modal dispersion. A large amount of mode mixing is introduced at an inaccurate splice, and in the initial stages this could aid the establishment of modal equilibrium. Beyond that the effects of such perturbations are difficult to predict. If single-mode fibre is required, suitable waveguide design can raise the core diameter to values where the above tolerances can be met[2], but other techniques can be used to aid splicing. Localized reduction in the normalized frequency of the fibre waveguide spreads the electric field and reduces the effect of lateral displacement. This can be effected in the field with multicomponent glasses by pulling down the fibre, but a suitable technique is difficult to envisage in silica.

Quality assurance. Measuring techniques are largely diagnostic and involve considerable effort in measurement and analysis. With a highly uniform product such time-consuming processes will not be required after the manufacturing procedures have become firmly established. From this point measurements can be geared to quality assurance and will fall into manufacturing and field categories.

In manufacturing, routine measurements[4] of fibre geometry, core profile and refractive index difference, will be required. These can all be obtained by interference microscopy of a section of fibre[22], or by reflection measurement using a laser scan[23]. Attenuation measurements will be required but not as a complete spectral scan. The attenuation at the operating wavelength is of obvious importance, but other wavelengths will have to be monitored to keep a check on known potential deficiencies. For instance, measurements at 630nm will indicate when problems from drawing-induced colouration are being encountered[24]. Dispersion measurements are also required to monitor uniformity and residual stresses. Steps must be taken to ensure that there are no stresses applied to the fibre during this measurement. Possibly the most sensitive indication of inhomogeneities is the length to modal equilibrium, determined by a shuttle pulse technique.

In the field, measurements of attenuation can be comparatively simple as effects will probably be gross. A portable instrument suitable for carrying out such measurements has been described[25]. More important will be the effects of installation on dispersion. Fortunately, these are most likely to increase the bandwidth of the propagating medium. Two basic methods are available for making these measurements in the field. A portable apparatus for carrying out frequency domain measurements on the transfer characteristic of the waveguide has been demonstrated[26]. This has the advantage that coaxial cable engineers are familiar with the technique and existing systems are specified in this way. However, pulse dispersion measuring apparatus could be made simpler and automatic analysis and presentation in terms of transfer characteristic provided.

(To be concluded.)

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