The Development of Single-Mode Fibre Transmission Systems at BTRL

Part 1—Early Developments

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In this first of two articles, the development of single-mode fibre systems at British Telecom Research Laboratories from 1979 to 1982 is charted with particular emphasis on the field-trial results and the impact upon the evolution of the trunk network. The second part of this article will describe the developments to date and discuss the future potential of single-mode fibre applications.

INTRODUCTION

The origins of single-mode (monomode) fibre as a transmission medium stretch back to the seminal ideas[1] of Kao and Hockham in the mid-1960s. The enormous bandwidth potential of light frequency ($\approx 10^{14}$ Hz) carriers was one of the main attractions of this medium and stimulated an intensive research programme at the British Telecom Research Laboratories (BTRL). It was recognised that, if solutions to the many practical difficulties could be found, then the communication engineers' dream of virtually unlimited bandwidth would be realised. The translation of this dream into reality has taken a more tortuous path than perhaps had first been imagined. However, over the past four years, as this realisation has taken shape, the long-term prospects have come more into focus to indicate areas of application not considered in the early days.

The practicalities of fabricating, splicing and coupling low-loss single-mode fibres, with core dimensions of only a few microns, were identified at an early stage as being among the major problems to be solved. The requirement in the early-1970s for a rapid evolution of fibre technology to the systems demonstration stage meant the temporary abandonment of single-mode fibre for multimode fibre. This fibre, with its large core diameter of several tens of microns, offered simpler splicing and coupling than single mode, albeit with low bandwidth due to the dispersion caused by the variation in the velocity of the many propagating modes. In consequence, a concentration of effort at low bit rates (8 Mbit/s) ensued and, in 1975, at the opening of BTRL at Martlesham Heath, an 8 Mbit/s system operating over a 6 km multimode fibre link was demonstrated.

In 1977, two significant field-trial systems using cabled multimode fibre installed in duct in the Martlesham area were demonstrated[2, 3]. Although originally planned as a step-index multimode experiment, graded-index fibre cable having superior bandwidth performance, due to its mode velocity equalisation property, became available and allowed experiments to be carried out at 140 Mbit/s as well as 8 Mbit/s. These experiments gave the first indications that fibre cables could be successfully installed in duct, spliced (jointed) and operated over repeater sections much longer than conventional copper-media based systems.

During the late-1970s, silica-based fibre, with losses of less than 5 dB/km in the 800–900 nm wavelength region, was beginning to dominate the fibre scene. Reliability performance of the opto-electronic devices (light-emitting diode (LED) or laser and photodiode) was improving and there was the growing prospect of operational systems being required by BT. However, in the mid to late-1970s, research establishments throughout the world were drawing attention to the possibility of lower-loss fibre, perhaps as low as 1 dB/km, at 1300 nm wavelength. Also, the chromatic dispersion, normally a significant bandwidth reducing factor at 800–900 nm with modulated LED and laser sources having wide optical spectra, is virtually zero in silica fibre at 1300 nm wavelength.

Opto-electronic device development for the 1300 nm wavelength region required new materials technology and, in the late-1970s, research programmes were gradually shifted to producing suitable semiconductor lasers and photo diode detectors.

The new wavelength region stimulated a re-awakening of single-mode technology since yet lower loss still, $<0{\cdot}5$ dB/km, could be achieved, and work began in earnest at BTRL in 1978. Since modal dispersion disappears with single-mode propagation and chromatic dispersion had been virtually removed by the shift in wavelength, the fibre now offered almost limitless bandwidth. The development had come full circle, but with the prospect of repeater spacings at least of an order of magnitude greater than for equivalent copper-media systems.

In 1979, BT embarked on a major ordering programme for fibre systems for trunk and junction routes. These orders were for systems operating at 800–900 nm wavelength. Clearly, the future ordering programme would increasingly gravitate towards 1300 nm operation as confidence grew in the device technology for the longer wavelengths. The question then posed was should the network opt for a single-mode or multimode solution. The advantages of the single-mode solution were so attractive for the trunk network that BTRL stepped up the programme of research begun in 1978 to attempt to solve the practical problems that had remained since the early-1970s. In 1980, a demonstration of a 37 km unrepeatered system operating at 140 Mbit/s and 1300 nm during the first Martlesham Open Week indicated the potential of the single-mode approach. This experiment also demonstrated for the first time that the 30 km maximum separation of power feed stations in the UK trunk network could be bridged without a repeater. The components for this demonstration were all developed at BTRL initially for the inland network, but it had been realised that systems using single-mode fibre were well suited to undersea applications where maximising repeater spacing was a prime concern. In 1980, a 10 km link working at 140 Mbit/s and using identical components was demonstrated at Loch Fyne in collaboration with Standard Telecommunication Laboratories (STL). These and other demonstrations of single-mode capability encouraged the development of solutions to the cabling, splicing, coupling and systems problems.

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The culmination of the initial phase of research activity on single-mode fibre systems was the demonstration of field installed cables having low splice losses and carrying digital signals at up to 650 Mbit/s over links up to 60 km without intermediate repeaters. Several demonstrations of this type were undertaken during 1982, with further upgrading experiments performed subsequently, some of which took place in the lower-loss window at 1550 nm.

SINGLE-MODE FIBRE

The description of propagation in single-mode fibre has been dealt with elsewhere[4]; note that the ray-path approach used with multimode structures is no longer applicable and that electromagnetic (EM) field theory must be used. In single-mode fibre, the core diameter can be only 8 μm with a cladding diameter of about 125 μm.

Current single-mode fibres are based on silica, doped with other materials in order to produce the refractive index difference between core and cladding necessary to give guidance or propagation. Various materials-related loss mechanisms in these glasses produce absorption or scattering of the optical power in the propagating mode, and thus limit the available system repeater spacing. At shorter wavelengths, the ultra-violet absorption edge dominates, while at long wavelengths, the infra-red absorption from the oxides of the glass is the major loss effect. In between these two regions, Rayleigh scatter (due to particles of size comparable to the wavelength of the light transmitted) is, for the most part, the dominant loss mechanism. However, at wavelengths corresponding to the oxygen–hydrogen (O–H) bond overtone absorption lines (950 and 1370 nm) and at associated combination bands, absorption losses can be dominant. These effects result in two low-loss windows, at 1300 and 1550 nm. Attenuation in these windows is due to Rayleigh scatter, remnant O–H absorption and absorption from combination bands of the fibre dopants with O–H. Unfortunately, dopants added to the silica to produce the necessary fibre properties tend to increase the Rayleigh scatter. The need to keep processing temperatures as low as possible during fabrication militates against the use of pure silica for either the core or the cladding (in spite of the attraction of such structures on loss grounds). The necessary processing temperatures reduce with increasing dopant levels. These loss mechanisms and the best combination of dopants to use for the core and cladding for lowest loss have been the subjects of extensive study at BTRL[5, 6]. The resulting solution uses a core region uniformly doped with germania (GeO). The cladding region uses both fluorine and phosphorus as dopants. These two dopants have opposite effects on the silica refractive index, allowing the cladding index to be matched to that of silica whilst enabling the processing temperature to be lower than that for pure silica. The dopant concentration in the cladding is arranged to be a maximum furthest from the core, reducing to nearly zero in the most loss-sensitive region near the core. In this way, losses can be reduced to minima of around 0·3 dB/km and 0·2 dB/km in the 1300 and 1550 nm windows, respectively.

Whilst the single-mode fibre eliminates modal dispersion, the small core region presents a challenge for splicing or jointing, since the cores must be accurately aligned, perhaps to within $\pm 0{\cdot}5$ μm. The launching of light from a source such as a semiconductor laser, with its divergent asymmetric radiation pattern, into a small-core fibre is also more demanding in alignment accuracy. These factors were partly responsible for single mode being put to one side in the early to mid-1970s in favour of multimode technology.

In single-mode fibre, chromatic dispersion is the major bandwidth limiting effect. (Polarisation dispersion due to any slight ellipticity of the core also occurs, but this effect can usually be neglected.) Since most light sources, including lasers, do not always emit just a single wavelength, then the dependence of the fibre material refractive index (and hence velocity of propagation) on wavelength leads to dispersion effects. The semiconductor laser often emits a broad spectrum or 'comb' of wavelengths with each 'tooth' having a slightly different propagation velocity and, therefore, transit time along the fibre. The resulting dispersion, which produces intersymbol interference (ISI) in a digital system, can be obviated by reducing the spread of wavelengths (linewidth) emitted by the source and/or choosing the wavelength region of operation to be where the dispersivity is a minimum. Fortuitously, silica exhibits zero chromatic dispersion at 1300 nm, a wavelength at which the fibre loss is invitingly low (<0·5 dB/km).

A typical spectral-loss plot for single-mode fibre is shown in Fig. 1. The two low-loss windows are evident; one around 1300 nm and the other centered on 1550 nm. A large part of the loss is due to Rayleigh scatter in the silica. Since this loss reduces with the fourth power of wavelength, the fibre loss is lower at 1550 nm than at 1300 nm. However, the chromatic dispersion at 1550 nm is not zero and narrow linewidth laser sources will be needed to exploit effectively the lower loss.

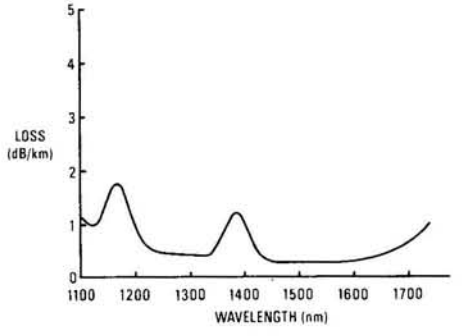


FIG. 1—Spectral loss of a single-mode fibre

Single-Mode Fibre Design and Specification

A more detailed investigation of the design of the single-mode fibre is necessary to assess properly the above properties. One of the main aims was to arrive at a fibre design that would work well in existing cable structures and allow 'standard' cabling techniques in manufacture and installation to be used for both multimode and single-mode fibre.

The need to minimise overall link loss produces several detailed constraints on the fibre design:

(*a*) *Cut-off wavelength* This is the wavelength which marks the transition between multi- and single-mode operation; above this wavelength the operation is single mode. In general, the cut-off wavelength must be below the operating wavelength.

(*b*) *Intrinsic fibre loss* This is the combination of Rayleigh scatter and losses due to dopants introduced into the silica to form the fibre core and/or to water (O–H ions) in the fibre.

(*c*) *Incremental cable loss due to microbending* This is superficially similar to the same phenomenon in multimode fibre, but here concerns minute bends in the fibre, coupling only one guided mode out of the core.

(*d*) *Splice loss* This is due to a combination of concentricity error, EM field mismatch and splicing techniques used.

Work at BTRL in the late-1970s was concerned with experimentally investigating these factors to arrive at the optimum design. The fibre design is specified in terms of the two measured parameters: the mode cut-off wavelength and

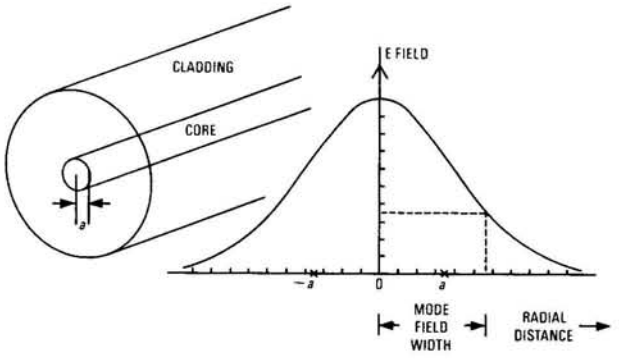


FIG. 2—Approximation to the electric field (mode field) distribution in a single-mode fibre

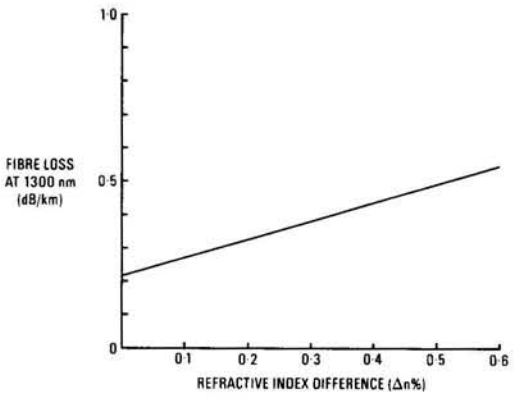


FIG. 4—Dopant level dependent loss as a function of index difference (Δn%)

some measure of the mode field width (Fig. 2). Care must be taken to link these experimentally-determined quantities to the measurement technique used, an important technique being that of the offset joint[7].

If a plot with these two quantities as axes is produced, the fibre specification appears as an area on the plot, with the constraints as lines bordering the specification 'box'. This is shown in Fig. 3. Taking each constraint in turn:

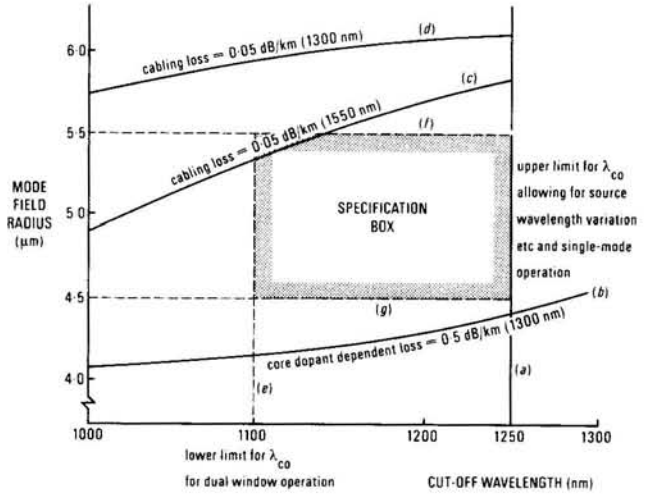


FIG. 3—Fibre design diagram

Cut-Off Wavelength

From a consideration of source wavelength variations, it is desirable to specify the fibre loss and to operate the systems over a wavelength range of 1275–1325 nm in the 1300 nm window. To avoid any possibility of bi-moded fibre at an operating wavelength, an upper value of 1250 nm is placed on the cut-off wavelength—this is line (*a*). A lower limit of 1100 nm has been adopted in order to minimise the effects of cabling loss and dispersion—this is line (*e*).

Intrinsic Fibre Loss

Fibre loss increases with doping level (germanium and fluorine are added to the fibre core to raise its refractive index above that of the cladding) and with O–H content. The dopant-level dependent loss places an upper bound on the fibre refractive index difference, leading to a lower bound on the field width for any particular cut-off wavelength. Fig. 4 shows empirical data for this loss at 1300 nm as a function of index difference, after the O–H contribution has been removed. If 0·5 dB/km is taken as a maximum for this loss, boundary line (*b*) in Fig. 3 is produced. The O–H contribution can be expected to add less than 0·05 dB/km to this figure.

Incremental Cabling Loss

In step-index single-mode fibre, the mode becomes less well guided as the wavelength is increased away from the cut-off, and eventually becomes susceptible to microbending loss from the cable structure. A fibre for operation in both windows must have the cut-off below 1300 nm and the microbending loss edge beyond 1550 nm. For any particular fibre core diameter, this places a lower limit on the fibre refractive index difference, corresponding to an upper limit on the mode field width. Since various types of cable are used by BT, it becomes a matter of some difficulty to determine the level of microbending to which any particular fibre will be subjected. Empirical data for a loose-tube coating is shown in Fig. 5. The worst-case situation for this cable type corresponds with the fibre left under some tension against the tube wall. Fig. 6 shows similar data for a tight secondary fibre coating. In spite of the very different cabling situation, a similar lower limit on index difference (Δn) is obtained in each case. Assuming a limit of 0·05 dB/km incremental loss from microbending, the loose-tube data is plotted in Fig. 3 as line (*c*). If operation at 1300 nm only is required, the data can be converted theoretically to show the same limit at 1300 nm as line (*d*). Fibre within the

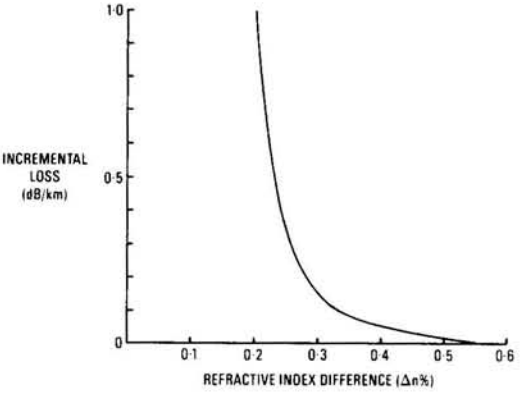


FIG. 5—Incremental loss at 1550 nm for a loose-tube fibre versus index difference (Δn%)

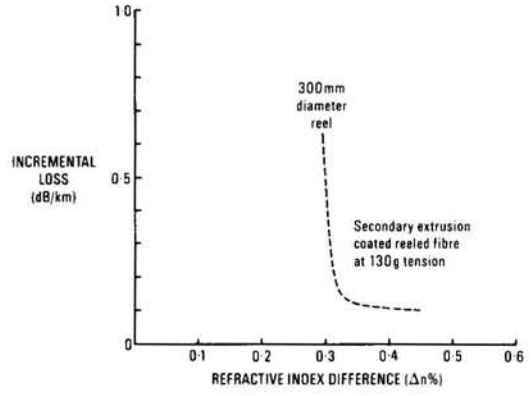


FIG. 6—Incremental loss at 1550 nm for a tight secondary coating versus fibre index difference (Δn%)

specification box could thus be expected to have average losses of around 0·45 dB/km at 1300 nm and 0·3 dB/km at 1550 nm, and could be cabled by using existing cable types with negligible loss increase at either wavelengths.

Dispersion

The nominal step-index profile fibre design adopted by BT has a zero chromatic dispersion point around 1325 nm. Near the dispersion minimum, broad spectrum lasers can be used without incurring a serious penalty. As operation moves from the zero dispersion point, the penalty increases, and ultimately requires the use of narrow spectrum sources.

The dispersion characteristics of step-index fibre meeting the BT specification are shown in Fig. 7. Curve 1 is for a

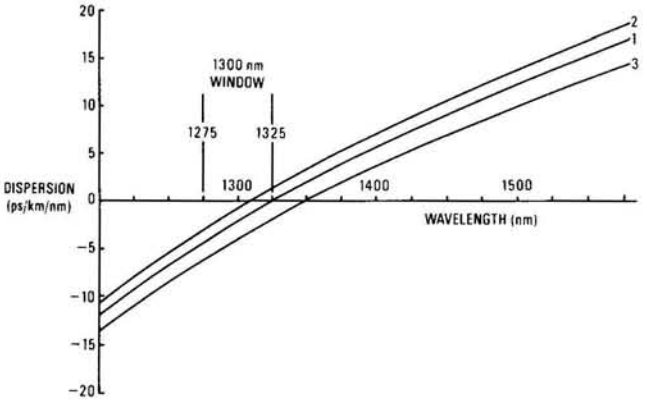


FIG. 7—Dispersion versus wavelength for single-mode fibres

typical fibre with dispersion minimum at 1325 nm and the curves either side show the extremes that are expected for fibre falling within the specification box. Curve 2 corresponds to a fibre in the top-right-hand corner of the box and curve 3 to a fibre in the lower-left-hand corner. It is fibres in this region of the specification box that will first give rise to dispersion penalties and, therefore, is a further incentive to restrict the lower cut-off wavelength bound to 1100 nm.

Splice Loss

The main splicing technique for single-mode fibre is currently electric-arc fusion. Core concentricity and mode field width mismatch form the main fibre-related loss contributors. The effect of any given concentricity error on splice loss reduces as the field width is increased, making it desirable to operate towards the top of the area between the cabling (*c*) and cut-off (*a*) lines. Unfortunately, this reduces the available cut-off range; a good compromise is a field width centre of 5 μm. At this field width, a concentricity error of 0·5 μm in the two fibres could produce a maximum splice loss of around 0·2 dB due to this effect. Fibre production spreads and joint alignment statistics give an average splice loss considerably less than this figure. A field width range of ± 0·5 μm around the 5 μm centre (lines (*f*) and (*g*) in Fig. 3) gives a possible maximum splice loss due to field width mismatch of 0·17 dB. Again, an average value much less than this would be expected when the spread of fibre parameters and the statistical aspects of splicing are taken into account.

SPLICING TECHNIQUES

There are several well-documented techniques for the splicing of single-mode optical fibres and these can be generally classified on the following basis:

(*a*) fully-fused splices using cladding alignment only (optical power monitoring is not used);

(*b*) partially-fused splices using core alignment by optical power monitoring, to reduce losses due to core concentricity errors;

(*c*) fully-fused splices where core offset is minimised by using optical power monitoring and fibre rotation; and

(*d*) glued splices where core alignment by optical power monitoring is used to reduce core-concentricity errors, and core deformation is eliminated by avoiding the fusion process.

The fusion process involves butting together the two fibres to be spliced in the vicinity of some heating device, usually an electric arc. The fibres are then simply melted or fused together. In order to obtain low losses, however, this process has to be very carefully controlled, usually by a microprocessor. The glue technique bonds the fibres together by using some form of transparent adhesive.

The choice of technique to be used depends on the fibre specification, design and its application.

Splice Performance Comparison

The fundamental performance criterion is mean splice loss. In general, the mean splice loss in single-mode fibres can be considered to consist of three components:

(*a*) field width mismatch;
(*b*) core displacement due to core concentricity error; and
(*c*) core deformation due to the fusion technique.

Table 1 summarises the contributions from these components to the total splice loss for the four splicing classifications given above.

Field Width Mismatch

The loss contribution from field width variation is a fundamental splice loss limit. If Gaussian statistics for the distribution of field widths and the limits mentioned above (5 μm ± 0·5 μm) are assumed, then the mean loss introduced is less than 0·03 dB.

Core Concentricity Error

The question of which splicing technique to adopt hinges on the effect of core concentricity on splice loss. The allowable loss that can be allocated for concentricity effects will in turn determine the geometrical parameters in the fibre specification required for each of the splicing techniques discussed. The fibre specification will then determine fibre yields from given manufacturing processes and bear directly on the fibre's cost.

In order to assess the allowable allocation of splice loss arising from the effects of concentricity error alone, it is

TABLE 1

Splice Performance Comparisons

Loss Mechanism	Method (*a*) Fusion Cladding Alignment	Method (*b*) Fusion Core Alignment	Method (*c*) Fusion Fibre Rotation	Method (*d*) Glue Splicing
Field width mismatch	Same for all techniques			
Core displacement due to concentricity error	Depends critically on fibre specification	Does not depend significantly on fibre specification. Limit depends on alignment accuracy	Depends on fibre specification, but may be relaxed compared with method (*a*)	Independent of fibre specification. Limit given by alignment accuracy
Core deformation	Is minimised by machine parameters. <0·08 dB for standard system fibre	Additional deformation due to surface tension forces trying to align claddings. Minimised by short-duration fusion cycle	Same as for method (*a*)	None

necessary to examine system requirements and power budgets. A detailed statistical analysis was used to obtain a value for the mean system splice loss that can be tolerated for a 30 km 140 Mbit/s system. Then, by using the distributions of the component losses (field width mismatch, core deformation and concentricity error), values for the maximum tolerable concentricity error can be determined. (Less than 0·7 μm should give a mean loss below 0·08 dB, which is adequate for this purpose.)

Core Deformation

Splice loss due to core deformation occurs to some degree in all fusion-splicing processses and arises from three major causes.

(*a*) Surface-tension forces act to align the claddings of the fibre at the splice point. The effect, therefore, of any initial cladding misalignment is to introduce a shear force across the faces of the fibres during fusion.

(*b*) End-face angle on the fibres being fused also causes core deformation. When a single-mode fusion splicing machine is set up and operated correctly, end-angle effects are probably the dominant cause of core deformation.

(*c*) Contamination of the fibres by foreign material in the splice region, for example, dirt or primary coating material not being completely removed, is an often underestimated contribution to poor-quality fusion splicing.

Fusion-splicing techniques suffer from about the same amount of core deformation. Method (*b*) using power monitoring during core alignment will be prone to surface-tension forces increasing with core concentricity error. The effect of this may be mitigated by a short-duration heating cycle optimised for this method. On the other hand, method (*a*) uses these surface-tension forces for the final alignment of the fibre claddings. It is found that the initial visual cladding alignment under a low-power microscope is generally accurate to the order of 1 μm and that this residual misalignment produces insignificant core deformation. The glued-splice technique produces no core deformation and, in principle, could produce the lowest loss splices. Note, however, that there may be a small loss due to the refractive index mismatch (Fresnel loss) at the fibre/glue interfaces.

Splice Strength

High-strength fusion splices may be achieved with care and attention to absolute cleanliness in the preparation of the ends of the fibre. Post-etching in hydrofluoric acid increases the strength of the fusion splices dramatically. This high-strength splicing may be achieved with techniques (*a*) and (*c*). Splices made by using technique (*b*) are likely to be weaker because of the discontinuity in the outside diameter and because a full fusion does not take place. The strength of glued splices is likely to be lower than those achieved by using fusion techniques. In general, for land-based systems, strain relief for the fibres and splices is provided in the joint housing and very-high-strength splices are not essential. The major application for high-strength splices is in undersea systems, where production-line high-strength splicing is required in order to produce long cable lengths without full-joint housings.

Complexity of Splicing Technique

There are two distinct categories of splicing techniques described above: those where optical power monitoring is required and those where it is not. In technique (*a*), the splicing-machine operator visually aligns the fibre claddings to an accuracy in the order of 1 μm by using micromanipulators and a two-axis microscope. The fibres are butted together and automatic fusing takes place under the precise control of a microprocessor. Full fusion occurs, thus allowing the final very precise alignment of the fibres to be brought about by surface-tension forces.

The simplest power-monitoring system requires optical power to be launched into the remote end of the fibre to be spliced and either a distant or local receiver to feed back a signal related to the power coupled into the spliced fibre. The fibres are then aligned either by the operator or automatically so that the coupled power is maximised prior to splicing.

Power-monitoring systems can require an extra team at the launch site and possibly a further team at the receive site if local monitoring is not used. In addition, sequential splicing along a route may often be necessary. This could be disadvantageous since installation practices and local road traffic problems may restrict splicing to times outside normal working hours on difficult or busy sections of the route.

If a local injection/detection scheme is used to avoid the above problems, the length of stripped fibre at the splice could be fairly large, and this increases the risk of damage to the fibre and makes subsequent mechanical protection more difficult. However, injection/detection through the coatings can be used in order to avoid long lengths of uncoated fibre, but this is dependent on the choice of materials used for the primary and secondary coatings.

As a result of the detailed studies of splicing techniques undertaken at BTRL during the late-1970s and early-1980s, BT has adopted fusion splicing without power monitoring

as the initial splicing technique for the trunk network modernisation programme. The main reason for this is the simplicity of the technique for the field environment. As the use of single-mode fibre moves into the junction and local networks, the need for simple and low-cost splicing techniques increases. The fusion process adopted offers the greatest potential for simple low-cost, yet high-quality, splicing.

SINGLE-MODE FIBRE SYSTEMS TRIALS

The production of quantities of experimental single-mode fibre at BTRL with loss less than 0·6 dB/km at 1300 nm wavelength led to a series of system tests beginning in 1980. The development of suitable transmitter and receiver modules at BTRL had been proceeding during the late-1970s, initially for graded-index multimode systems, but subsequently for single-mode fibre applications

Transmitter and Receiver Modules

The basic opto-electronic devices for operation at 1300 nm, that is, lasers and photodetectors, were incorporated into hybrid packages, usually in dual-in-line format, with integral fibre tails for connection to the main transmission fibres. A transmitter module typically comprised an optical source, often a semiconductor laser chip, and the necessary optical coupling components such as miniature lenses and a copper submount alignment jig to achieve an efficient launch of optical power into the single-mode fibre tail[9]. This package, shown in Fig. 8, was also able to incorporate electronic

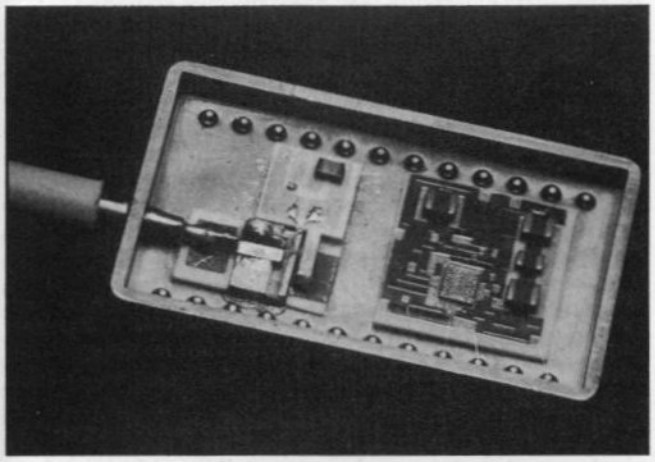


FIG. 8—Laser transmitter module showing fibre (left), submount, laser chip and feedback photodiodes (centre left) and IC controller chip (right)

interfaces in the form of drive and bias circuits. The stabilisation of the laser operating point against temperature variations and ageing was of major importance since it was recognised that 1300 nm lasers were likely to be more temperature sensitive than their 850 nm counterparts. Successful operation at 140 Mbit/s and above in a practical systems environment depended on the effect of laser switch-on delay[10] being minimised without other performance criteria being compromised. The development of the module therefore included a rear laser facet monitoring photodiode and specially developed BTRL integrated circuit for the control of the bias and drive signals[9].

The hybrid packaging concept became vitally important to the development of receivers at 1300 and 1550 nm. Fundamental changes to receiver design became necessary when the new wavelength region was adopted, since the silicon avalanche photodiode (APD) that had given such good performance at 850 nm could not be made to detect beyond about 1100 nm. The APD can be regarded as a device that detects incoming optical signals, and converts them to equivalent electrical current signals which undergo amplification within the device itself by a carrier avalanching effect; the gain is dependent upon the applied voltage. The effective noise figure of such a device is dependent in a complex fashion upon the gain and the level of the input signal. The commercially available silicon APD could be operated with a noise figure much less than that of a conventional transistor amplifier. However, commercially available APD devices operating at 1300 and 1500 nm were germanium based with effective noise figures much higher than those for silicon and with a significant temperature dependency as well.

A number of research laboratories undertook development of APD devices in materials related to those being used for laser development; that is, gallium indium arsenide (GaInAs) and gallium indium arsenide phosphide (GaInAsP) III-V based semiconductor alloys. However, at BTRL, it was believed that any long-wavelength APD development would be on a long time-scale since these devices are structurally complex and therefore difficult to fabricate (true even in silicon, which is a well-characterised material). For this reason, the development of a simple non-avalanche GaInAs PIN structure photodiode was initiated by BTRL both internally and at Plessey Research. In order to achieve adequate sensitivity performance, it proved necessary to ensure that both the photodiode and following transistor preamplifier had low capacitance and that the input transistor was a low-noise device. Only by using hybrid integration techniques was it possible to achieve this first objective. The receiver, shown in Fig. 9, comprised a PIN

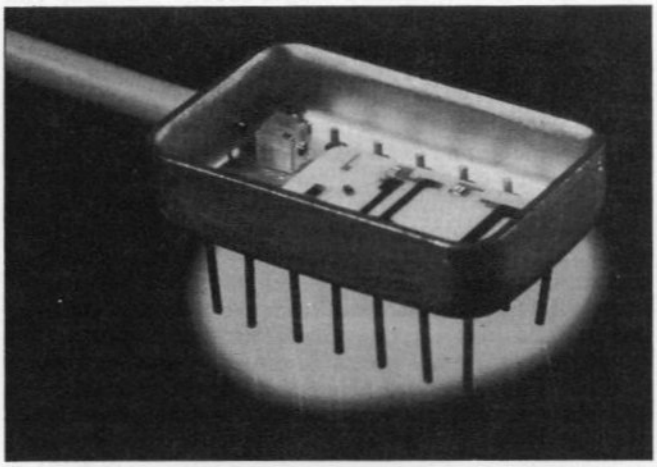


FIG. 9—PINFET receiver module showing fibre entry (left), quartz cube submount for photodiode (centre left) and preamplifier circuit (centre and right)

photodiode connected to a low-noise GaAs field-effect transistor (FET) device forming the first stage of amplification. Further amplification and buffering was also provided in the package by using additional bipolar transistor devices. The resulting module, known as a *PINFET* receiver, had sensitivity performance better than commercial germanium APDs in 1979[11]. More recently, both III-V and germanium-based APDs have been developed in the USA and Japan. These detectors have shown improved sensitivity so that performance is now comparable with PINFET receivers, which have also advanced in this period. Operational considerations are now, and in the future, likely to play a more dominant role in the choice of receiver technology.

Initial System Tests

The development of the transmitter and receiver modules at BTRL was undoubtedly a key factor in the successful demonstrations that took place during the 1980s over long lengths of single-mode fibre. In the first of these experiments, a prototype laser transmitter operating at 1275 nm was modulated with a 140 Mbit/s $2^{10}-1$ non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) test signal. The mean output power coupled from the laser into the fibre without lensing was 80 μW, or −11 dBm—an efficiency of about 10%. A continuous 37 km length of single-mode fibre coated, but not packaged or cabled, was butt connected to the fibre tail of the transmitter module. The loss of this fibre was about 0·7 dB/km at 1275 nm, slightly higher than the 1300 nm figure. The short multimode fibre tail of the receiver was connected to the main fibre via a lens connector. The sensitivity of the PINFET receiver was measured to be 50 nW, or −43 dBm, at 140 Mbit/s, with an error rate of 10^{-9}. The photodiode quantum efficiency, the proportion of incoming light that contributes to useful current flow, was 40%. The low-level output signal from a PINFET receiver, usually an integrated version of the received optical signal, was equalised by a differentiator and fed a regenerative repeater.

The repeater comprised linear and limiting wideband amplifiers, a clock extraction circuit and a bistable decision gate. The repeater also included an equaliser, which, in the case of single-mode fibre systems, is usually just a low-pass filter. The gain blocks and digital circuits were implemented by using integrated circuit components; no discrete devices were used. The system block diagram is shown in Fig. 10. This system was successfully operated over the full 37 km unrepeatered length with a system margin of 3 dB. A further experiment was undertaken in the 1550 nm low-loss window where the fibre attenuation averaged about 0·4 dB/km. The laser transmitter was changed for a prototype 1510 nm laser chip mounted on a package header. A BTRL photodiode capable of operating at both 1300 and 1550 nm had been used in the receiver module enabling the receiver/regenerator combination to remain unchanged. The reduced fibre loss enabled an extra 12 km of fibre to be added to the link to form a continuous 49 km length. This system again operated successfully with about a 3 dB system margin. However, some important differences were noted between the two experiments. At 1300 nm, the performance was loss limited, in other words the link length achievable was set only by the laser coupled power, the receiver sensitivity and the fibre loss. On the other hand, at 1510 nm, when the receiver sensitivity was measured through the 49 km length, an additional penalty of about 0·7 dB resulting from the interaction of the broad spectrum of the laser and the fibre dispersion was discovered. The power budgets for these tests are given in Table 2.

TABLE 2

Power Budgets

Wavelength	1275 nm	1510 nm
Link length	37 km	49 km
Bit rate	140 Mbit/s	140 Mbit/s
Path loss	29 dB	24 dB
Transmitter coupled power	−11 dBm	−15·4 dBm
Received power	−40 dBm	−39·4 dBm
Receiver sensitivity	−43·5 dBm	−44·2 dBm
Laser extinction penalty	0 dB	1 dB
Dispersion penalty	0 dB	0·7 dB
System margin	3·5 dB	3·1 dB

Dispersion and Laser Spectrum

The dispersion of the fibre in the 1550 nm window was known to be in the region of 15 ps/nm/km; that is, after 1 km of fibre a launched impulse will have been transformed to a Gaussian pulse with 1/e full width of 15 ps for every nanometre of source linewidth, the linewidth being a measure of the spread of wavelengths emitted by the source. The 1510 nm laser was estimated to have an effective linewidth of 4 nm so that the dispersion amounted to about 3 ns, just under half the bit time for a 140 Mbit/s system. Since the transmitter launched full-width pulses, that is, 7·14 ns wide pulses, and not impulses, the dispersion of the fibre spreads these pulses into their adjacent time-slots, and causes ISI. About 1 dB of ISI penalty results when the dispersion is equivalent to half a time-slot and 5 dB when it is a full time-slot. This initial experiment at 1510 nm was nearing dispersion limited operation.

It was appreciated that if the 1550 nm window of this fibre was to be fully exploited with conventional single-mode fibre, then some measures to narrow the source linewidth needed to be taken. Subsequent 1550 nm source developments were aimed towards achieving this end (at 1300 nm the linewidth problems were of less concern). The spectrum of a semiconductor laser, as mentioned earlier, is often a comb of discrete wavelengths generated by the multiple cavity resonances. When modulated, this spectrum undergoes changes, with the first part of the pulse usually exhibiting the highest degree of instability of spectrum. Under DC conditions, or during the latter part of a long pulse, the spectrum stabilises and, in certain devices, can exhibit nearly single wavelength operation. A possible evolution of the wavelength spectrum of a semiconductor laser is shown in

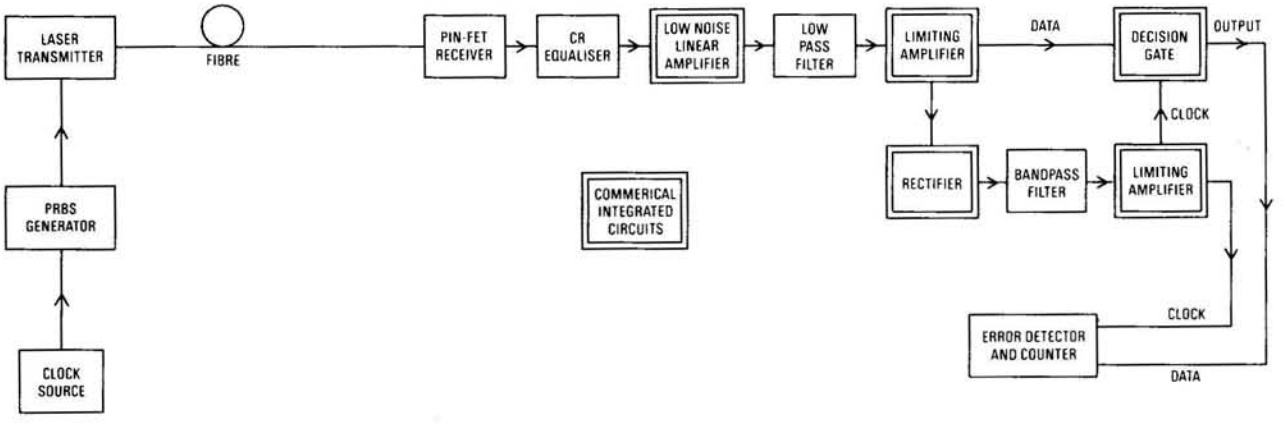


FIG. 10—Block diagram of fibre system under test, showing receiver regenerator configuration

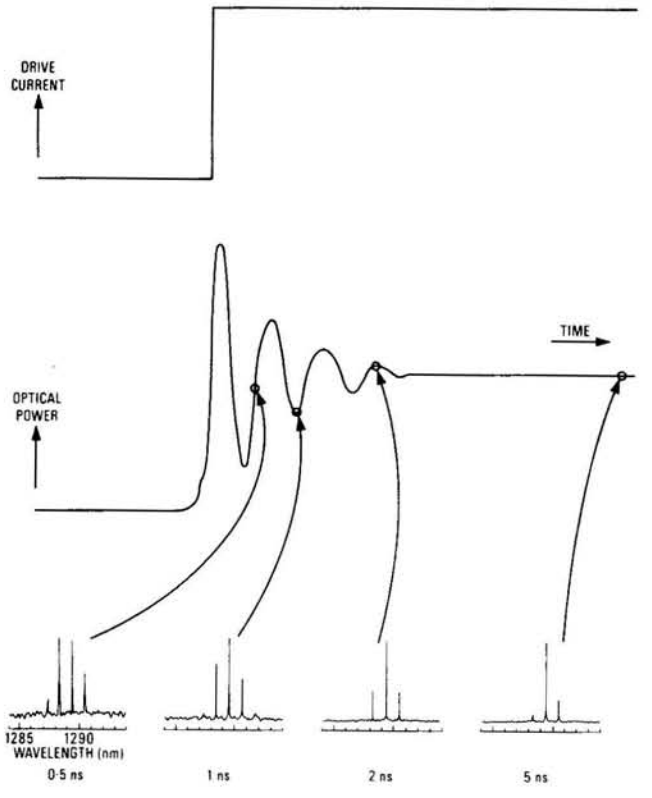


FIG. 11—Evolution of the mode spectrum of a nominal 1300 nm wavelength semiconductor laser

schematic form in Fig. 11. Note the transient ringing of the optical pulse, a distinctive feature of a pulsed semiconductor laser. A spectral line is referred to as a *longitudinal mode* and the presence of just one line referred to as a *single longitudinal mode* (SLM); the term *mode* here means cavity mode rather than propagating mode. The envelope of the comb of wavelengths bring about the dispersion penalty mentioned before, but additional effects were predicted even when an SLM was predominant.

During the life of a laser device, temperature and ageing effects may change the position of the SLM. It is possible that before this happens the device may hop between possible SLM positions. If this is coupled with the dispersion of the fibre, it is possible that with very long lengths, that is, many tens of kilometres, pulses may appear and disappear—a gross ISI effect. This effect leads to the error-rate performance becoming independent of input optical power above a certain threshold level and may result in the target system error rate being unachievable. These considerations led to the development of devices and techniques (external cavity control and distributed feedback (DFB) lasers) to produce more stable SLM operation under modulation for the 1550 nm wavelength region.

Laboratory-Based Cable Tests

Whilst the performance at 1550 nm clearly held out great potential, the development of a laser transmitter with the necessary spectral confinement and stability at 1550 nm was much further away than a suitable 1300 nm laser. The next stage of systems development was therefore centred on 1300 nm systems with the object of demonstrating a more realistic system using a laboratory-based cabled fibre link of about 30 km length. If a system at 140 Mbit/s could be operated over this length in the field without a repeater, then it would remove the need for dependent power-fed repeaters and metallic conductors in the cable for almost all routes in the national trunk network.

Towards the end of 1981, an experimental 31·6 km single-mode fibre link was set up in the laboratory in order to simulate as closely as possible an operational cable route[12]. In this experiment, 14 fibres, each 2·25 km long were cabled in three 2·25 km cables using a loose-tube technique[13]. All the fibres were fully characterised prior to splicing. The three cables were spliced together by using the fusion splicing technique without power monitoring to form a continuous fibre length of 31·6 km. Splice losses were determined by two methods: one was to use an optical time-domain reflectometer (OTDR)[14] to measure the individual splice losses, and the other was to measure the total link loss and then subtract the previously measured cabled-fibre losses to give a figure for the total splice loss. For this system there was good agreement between the two measurements, which indicated that the mean splice loss was between 0·18 and 0·23 dB at 1300 nm and approximately 0·12 dB at 1550 nm. The reduced loss at 1550 nm is due to the increasing field width with longer wavelengths; this helps to reduce the splice losses associated with concentricity error and core deformation. The total link loss for this experimental cable was 17·5 dB at 1300 nm, and permitted several system experiments to be performed in the 1300 nm window.

Transmitter and receiver modules at 1300 nm for operation over the cabled single-mode link were made available for a series of systems tests at 140, 280 and 565 Mbit/s. The transmitter module comprised a GaInAsP 10 μm oxide insulated stripe laser[10] with nominal operating wavelength of 1300 nm. The device was multi-longitudinal mode, with three main modes separated by 1 nm, to give an effective linewidth of about 2 nm. The optical power from the laser facet was launched into a single-mode fibre tail using simple butt coupling. The launched power was 80 μW (−11 dBm) mean when pulsed; no additional power could be coupled into the fibre by increasing the drive current since the main lobe of the laser output radiation saturated at this level and any additional power obtained was lost to uncoupled side lobes. The transmitter module was temperature controlled by a Peltier-effect thermoelectric cooler. This allowed stable transmitter operation to be achieved with these early 1300 nm devices. The threshold current at 16°C was 280 mA and a drive current of 50 mA was required for full modulation of the optical output power. It was envisaged that for most applications, reductions in threshold or bias current and improvements in module design might eventually enable the temperature controller to be dispensed with. Further development of the receiver, particularly with fibre coupling, had taken place. The PIN photodiode was now mounted on a quartz block with an alignment hole for the fibre inputs. The receiver sensitivity at 140 Mbit/s and 1300 nm was now −46 dBm. The principal results of the system tests are given in Table 3.

TABLE 3

Results of System Trials

Wavelength	1280 nm	1280 nm	1280 nm
Link length	31·6 km	31·6 km	31·6 km
Bit rate	140 Mbit/s	280 Mbit/s	565 Mbit/s
Total path loss†	20·5 dB	20·5 dB	20·5 dB
Transmitter power	−11 dBm	−11 dBm	−11 dBm
Received power	−31·5 dBm	−31·5 dBm	−31·5 dBm
Receiver sensitivity	−46 dBm	−41·5 dBm	−36·5 dBm
System margin	14·5 dB	10 dB	5 dB

† The increased loss over the 17·5 dB fibre and splice loss is mainly attributed to the two prototype lens connectors used at each end of the system.

The system margin of 14·5 dB at 140 Mbit/s was very encouraging and was judged sufficient to cover the additional performance degradations usually experienced in transferring laboratory-based systems demonstrations to the working environment. At 565 Mbit/s, the system margin reduces to 5 dB because of the reduction in receiver sensitivity with bit rate. However, it was believed that additional system margin would be obtained by improvements to laser performance and transmitter design. For example, the use of a fibre tail with a specially designed lens[9] fabricated on its end face, as shown in Fig. 12, was predicted to yield perhaps up to a factor of four improvement in coupling efficiency.

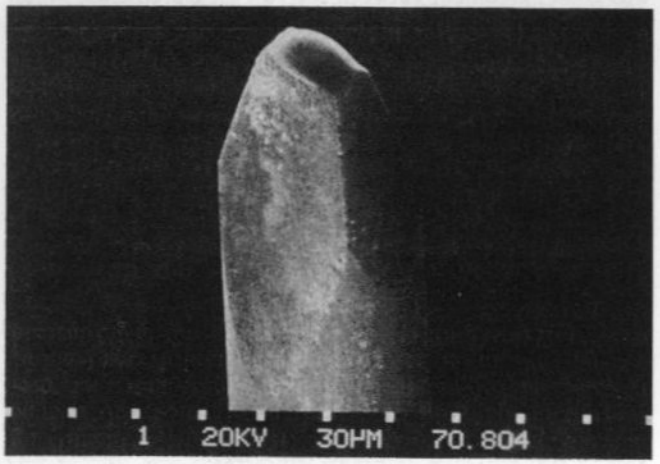


FIG. 12—Single-mode fibre with asymmetric hemispherical lens

The results signified that 140 Mbit/s systems without dependent repeaters were feasible and that such systems, once having been installed, could be upgraded to at least 565 Mbit/s at the same repeater spacing whenever necessary[16]. Indeed, it was becoming evident that repeater spacings greater than 30 km were eventually going to be viable, and this realisation stimulated still further the development of single-mode fibre systems for undersea applications. Some initial tests at 140 Mbit/s using broad linewidth lasers were also undertaken in the 1550 nm window confirming that this wavelength option can be exploited. It remained to show the complete viability of single-mode technology by demonstrating systems over cables installed in the field.

The MIME and Woodbridge System Trials

During the early part of 1982, two major field trials of single-mode fibre technology were carried out. The first of these was a co-operative venture between BTRL and Telephone Cables Limited and involved the installation of a 7.5 km cable link between Martlesham and the nearby town of Woodbridge[17]. The other trial was in association with STL and involved the installation of a 15 km cable route between Martlesham and the town of Ipswich, this latter link being known as the *Martlesham Ipswich Monomode Experiment* (MIME)[18]. A map of the two routes is shown in Fig. 13.

The fibre for the Woodbridge trial was produced on an experimental basis by BTRL and GEC Optical Fibres Ltd. (GECOF), and was not tightly toleranced. The fibre came from both BTRL and GECOF sources and derived from many different and varied experimental preforms. The fibre for the MIME trial was was tightly toleranced and was produced by STL/STC in a pilot manufacturing facility. As a consequence, the MIME fibre was more representative of

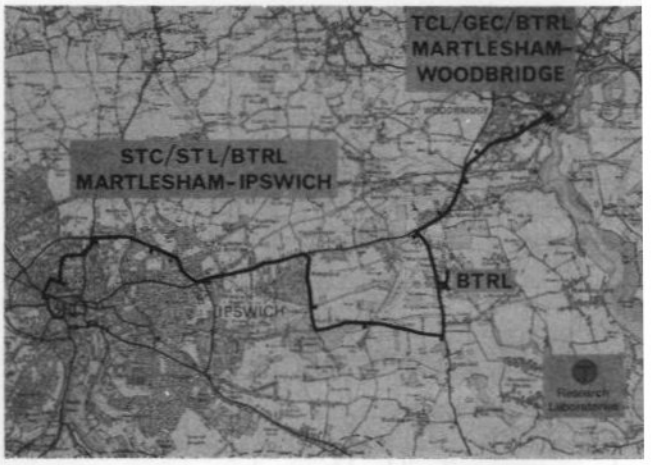


FIG. 13—MIME and Woodbridge single-mode fibre cable installations

the ultimate quality that could be expected from a dedicated production environment. The effect of fibre tolerances clearly manifested itself on the splicing results from the two links. Nevertheless, both links showed encouraging splicing performance.

The links were spliced by using the fusion-splicing technique without power monitoring. The Woodbridge link was spliced by BTRL, and the MIME link by STC field staff trained by STL. The splice-loss distributions from the two links are shown in Fig. 14. The mean splice loss of the Woodbridge link was 0·22 dB. The careful and extensive measurement programme associated with this link allowed calculations to be performed showing that this loss was made up of 0·08 dB due to core deformation, 0·07 dB due to concentricity error and a further 0·07 dB due to field width mismatch. The mean splice loss of the MIME link, however, was only 0·11 dB, indicating the possible level of splice loss that could be achieved with tightly toleranced fibre. Both of these cable installations were then used as test beds for many system experiments and, indeed, in 1985, they still form the major test beds for such experiments.

These cabled single-mode fibre installations gave the first opportunity to test, under field conditions, the operation of systems at 140 Mbit/s and above over repeater spacings of 30 km and greater. Laser transmitters with improved laser designs and lensed fibres were used in this series of experi-

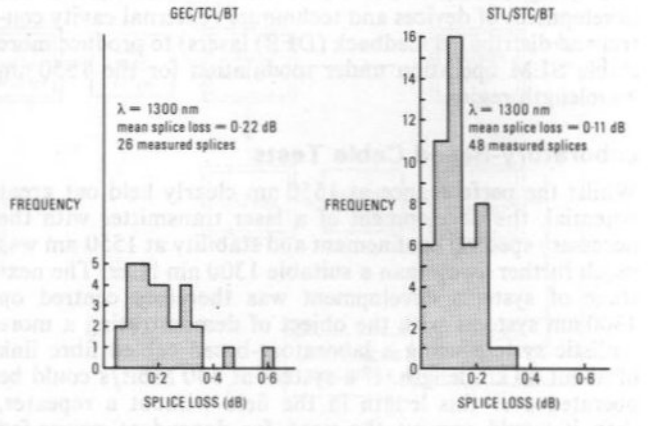


FIG. 14—Splice loss histograms for MIME and Woodbridge field installations

ments at 1300 nm. The transmitter and receiver were connected to the transmission fibres using shaped memory effect ferrule connectors[19]. The receiver and regenerator combination remained essentially the same as in previous experiments. The Woodbridge cable was operated at 140 Mbit/s initially and subsequently at 650 Mbit/s—the highest bit rate then available from test equipment. The MIME cable was operated over a range of bit rates with a final test at 565 Mbit/s over the full 61·3 km of the installation. The power budgets for the 1300 nm experiments are given in Table 4.

TABLE 4

Power Budgets for 1300 nm Experiments

Wavelength	1290 nm	1290 nm	1290 nm
Link length	31·5 km	31·5 km	61·3 km
Bit rate	140 Mbit/s	650 Mbit/s	565 Mbit/s
Path loss	21·9 dB	21·9 dB	30·5 dB
Transmitter power	−7 dBm	−8·7 dBm	−4·5 dBm
Received power	−28·9 dBm	−30·6 dBm	−35 dBm
Receiver sensitivity	−45 dBm	−34 dBm	−36 dBm
System margin	16·1 dB	3·4 dB	1 dB

The system margins achieved in this series of experiments were greater than in previous tests and were large enough to leave virtually no doubt about the eventual practicality of the 30 km spacing up to 650 Mbit/s. Fibre, cable and splicing data from these trials formed the basis for current BT single-mode fibre specifications. Research effort was then put into demonstrating the capabilities of systems operating at 1550 nm.

The 1550 nm System Tests

The initial attempts to stabilise laser devices for narrow line operation at 1550 nm utilised techniques involving external stabilising components. In the first of these experiments, injection locking[20], see Fig. 15, was used wherein a laser was operated continuous wave to give a stabilised SLM. The output from this laser (LD1) feeds a second laser (LD2) forcing it to oscillate exclusively at this same wavelength The second laser (LD2) was modulated in the conventional manner. The technique allowed the transmission of a 140 Mbit/s signal over a 102 km link of conventional fibre on reels without a repeater[20].

A second experiment using a transmitter module with an external cavity comprising a reflector placed at a controlled

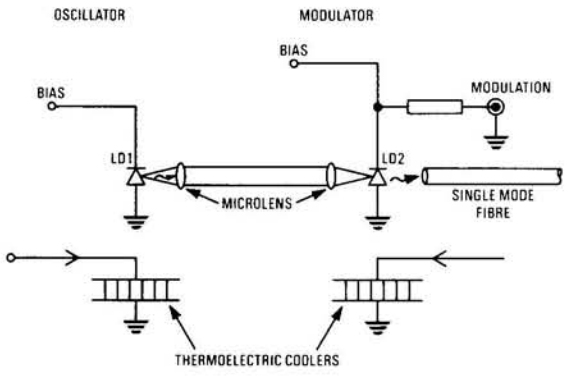


FIG. 15—Injection-locked laser transmitter arrangement

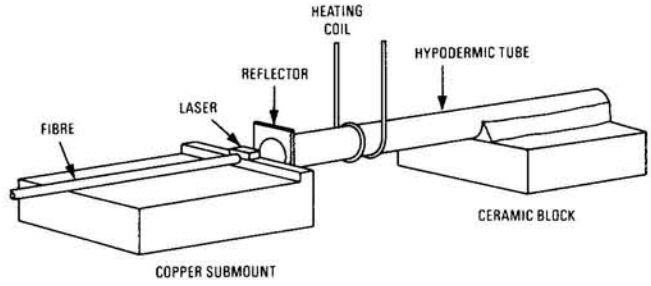


FIG. 16—External cavity laser transmitter arrangement

distance from the rear facet of the laser, see Fig. 16, allowed operation again at 140 Mbit/s and 102 km[21]. The SLM could be tuned in this case by altering the position of the reflector by applying heat via the heating coil to expand the metal tube on which the reflector is placed.

This latter transmitter module was employed in a further systems test in which all of the installed cable was linked together to form a 90·5 km length. Successful operation was achieved at 140 Mbit/s with a margin of about 2·5 dB. This feasibility demonstration, with a field-installed single-mode route, of a system operating over three times the then required unrepeatered span for the trunk network, set the scene for potentially very long unrepeatered systems at 1550 nm of great interest for submerged applications.

The power budgets for these systems tests are given in Table 5.

TABLE 5

1550 nm System Test Power Budgets

Wavelength	1520 nm	1520 nm	1520 nm
Link length	102 km†	102 km†	90·6 km‡
Bit rate	140 Mbit/s	140 Mbit/s	140 Mbit/s
Path loss	34 dB	36 dB	35·7 dB
Transmitter power	−8 dBm	−6 dBm	−7·8 dBm
Received power	−42 dBm	−42 dBm	−43·5 dBm
Receiver sensitivity	−45·7 dBm	−45·7 dBm	−46 dBm
Laser extinction	1 dB	0 dB	0 dB
System penalty*	1·6 dB	0·5 dB	0 dB
System margin	1·1 dB Note 1	3·2 dB Note 2	2·5 dB Note 2

† On reels
‡ MIME + Woodbridge installed fibre
* Miscellaneous Impairments
Note 1: Injection-locked transmitter
Note 2: External-cavity transmitter

CONCLUSION

This article has described the development of single-mode fibre systems at BTRL up to about 1982 and indicated the significant aspects of fibre design, cabling, splicing and systems design that evolved during this period. These developments have had a profound effect upon the ensuing applications of the technology in the trunk and junction networks, and on undersea routes. In the second part of this article, some of the developments that have occurred since the MIME field trials will be described as well as an indication of what the implications are for the future exploitation of the growing single-mode fibre network.

Acknowledgement

The authors wish to acknowledge the contributions made by their many colleagues throughout the optical project at BTRL and elsewhere; in particular that of Dr. C. J. Todd, Head of the Optical Communications Technology Division at BTRL for helpful discussions.

References

[1] KAO, K. C., and HOCKHAM, G. A. Dielectric Surface Waveguide for Optical Frequencies. *Proc. IEE*, 1966, **113**, p. 1151.

[2] BRACE, D. J., and RAVENSCROFT, I. A. Optical-Fibre Transmission Systems: The 8·844 Mbit/s Feasibility Trial. *Post Off. Electr. Engs. J.*, Oct. 1977, **70**, pp. 146–153.

[3] BERRY, R. W., and RAVENSCROFT, I. A. Optical-Fibre Transmission Systems: The 140 Mbit/s Feasibility Trial. *ibid.*, Jan. 1978, **70**, pp. 261–268.

[4] DYOTT, R. B. The Optical Fibre as a Transmission Line. *ibid.*, Oct. 1974, **67**, pp. 164–168.

[5] AINSLIE, B. J., DAY, C. R., FRANCE, P. W., BEALES, K. J., and NEWNES, G. R. Preparation of Long Lengths of Ultra-Low Loss Single-Mode Fibre. *Electron. Lett.*, 1979, **15**(14), pp. 411–413.

[6] AINSLIE, B. J., DAY, C. R., FRANCE, P. W., BEALES, K. J., and NEWNES, G. R. Single Mode Low Loss Silica Fibre Prepared in Long Lengths. Proceedings 5th ECOC, Amsterdam, 1979, pp. 3.6-1– 3.6-4.

[7] MILLAR C. A. Applications of ESI Profiling to a 31·6 km Monomode Fibre System. OFC 82, Phoenix, Paper thEE3.

[8] PAYNE, D. B., and MCCARTNEY, D. J. A comparative study of monomode splicing techniques. ICC 84, Amsterdam.

[9] SMITH, D. W., and MATTHEWS, M. R. Laser transmitter design for optical fibre systems. IEEE Journal on selected areas in communications, Apr. 1983, **SAC-1**(3), pp. 515–523.

[10] NEWMAN, D. H. Sources for Optical-Fibre Transmission Systems. *Post Off. Electr. Engs. J.*, Oct. 1974, **67**, pp. 208–212.

[11] SMITH, D. R., HOOPER, R. C., AHMAD, K., JENKINS, D., MABBITT, A. W., and NICKLIN, R. Pin-FET hybrid optical receiver for longer wavelength optical communications systems. *Electron. Lett.*, Jan 1980, **16**(2), pp. 69–71.

[12] PAYNE, D. B., and MCCARTNEY, D. J., and HEALEY, P. Fusion splicing of a 31.6 km monomode optical fibre system. *ibid.*, 1982, **18**(2), pp. 82–84.

[13] JACKSON, L. A., REEVE, M. H., and DUNN, A. G. Optical fibre packaging in loose fitting tubes of orientated polymer. *Optical and Quantum Electronics*, 1977, **9**, pp. 493–498.

[14] HEALEY, P. OTDR in monomode fibre at 1·3 μm using a semiconductor laser. *Electron. Lett.*, 1981, **17**(2), pp. 62–64.

[15] MACDONALD, B. M., and SAUNDERS, A. G. Coupling of an optical fibre to a substrate entry photodiode. *ibid.*, Oct. 1981, **17**(22), pp. 832–833.

[16] STANLEY, I. W., HOOPER, R. C., SMITH, D. W., and MATTHEWS, M. R. The performance of experimental monomode transmission links. Proceedings of the 8th European Conference on Optical Communications, ECOC, Cannes, France, p. 447

[17] STERN, J. R., *et al.* Field installation of a 31.5 km monomode optical fibre system operated at 140 Mbit/s and 650 Mbit/s. *Electron. Lett.*, 1982, **18**(14), pp. 631–632.

[18] STERN, J. R., *et al.* The characterisation of monomode fibre links installed in operational ducts. Technical Digest of the Symposium on Optical Fibre Measurements, Boulder USA, 1982.

[19] MALLINSON, S. R. A monomode connector using shape memory effect metal. Proceedings 9th European Conference on Optical Communications, Geneva, 1983.

[20] MALYON, D. J., and MCDONNA, A. P. 102 km unrepeatered monomode fibre system experiment at 140 Mbit/s with an injection locked 1·52 μm laser transmitter. *Electron. Lett.*, May 1982, **18**(11), pp. 445–446.

[21] CAMERON, K. H., CHIDGEY, P. J., and PRESTON, K. R. 102 km optical fibre transmission experiments at 1·52 μm using an external cavity controlled laser transmitter module. *ibid.*, July 1982, **15**, pp 650–651.

Bibliography

MIDWINTER, J. E. Studies of monomode long wavelength fiber systems at the British Telecom Research Laboratories. *IEEE J. Quantum Electron.*, June 1981, **QE-17**(6), pp. 911–918.

AINSLIE, B. J. *et al.* Interplay of design parameters and fabrication conditions on the performance of monomode fibres made by MCVD. *ibid.*, **QE-17**(6), pp. 854–857.

WHITE, K. I., *et al.* Characterisation of single-mode optical fibres. *The Radio and Electron. Eng.*, July/Aug. 1981, **51**(7/8), pp. 385–391.

REEVE, M. H. Optical fibre cables. *ibid.*, pp. 327–332.

NEWMAN, D. H. *et al.* Sources for optical fibre communications. *Telecommun. J.* (Geneva), Nov. 1981, **48**, pp. 673–680.

MATTHEWS, M. R., and SMITH, D. R. Photodiodes for Optical Fibre Transmission Systems. *Post Off. Electr. Engs. J.*, Jan. 1974, **67**, pp. 213–217.

Semiconductor Laser Development and Production. *ibid.*, Apr. 1979, **72**, pp. 19–26.

HOOPER, R. C., MIDWINTER, J. E., SMITH, D. W., and STANLEY, I. W. Progress in Monomode Transmission Techniques in the United Kingdom. *Journal of Lightwave Technology LT1*, Dec. 1983, pp. 596–611.

Biographies

Raymond Hooper joined the Post Office as a Trainee Technician Apprentice in London North Area. After graduating with an honours degree in Electrical Engineering from the Middlesex Polytechnic in 1970, he joined the optical-fibre communications project at the Research Department. He bas been involved in all the major BTRL field demonstrations of optical-fibre transmission systems and was responsible for the field systems measurements with the installed single-mode fibre cables. He now heads a group working on advanced direct detection systems and receivers operating at gigabit/s information rates.

David Payne obtained a B.Sc. in Electrical Engineering from the University of Aston in Birmingham in 1971. He then joined the Post Office Research Department and worked on analogue and digital systems design with emphasis on interfacing problems. He was also involved in early work on microprocessor-controlled automatic test equipment. In 1979, he obtained an M.Sc. in Telecommunications Systems from the University of Essex. He then joined the optical-fibre communications project at BTRL and was responsible for single-mode fibre splicing and connectors. During this time, he was also involved in the establishment of the BT single-mode fibre specification. Since then, he has had responsibility for wavelength multiplexing components and is currently head of a group investigating the application of single-mode fibre technology for local networks.

Michael Reeve graduated from the University of Durham in 1973 with a degree in Applied Physics, and joined the Post Office Research Centre in the same year. He has worked on several aspects of optical-fibre communications, including modal properties, strength and cable design. Recently he has worked on the BT single-mode fibre specification and the design of a new type of optical cable—the blown-fibre cable. He is currently head of a group concerned with optical-cable and component design.