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Optical Fibre Systems [and Discussion]

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Optical fibre systems

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The present state of research and development into optical fibre systems for applications in telecommunications is reviewed and some of the principal problems remaining are discussed. Attenuations close to the intrinsic limits of the materials available have been reached in laboratory fibres and losses in optical cables installed under normal working conditions are below 5 dB/km. Bandwidths available range from 20 MHz km, in step-index multimode fibres with light emitting diode sources, to 10 GHz km with single-mode fibres and semiconductor lasers. If a truly monochromatic laser source operating in the region of minimum material dispersion becomes available then individual fibre capacities up to, or beyond, 100 GHz km are feasible.

The major problems in cabling have already been largely overcome but further improvements in fibre strength, homogeneity and reproducibility are awaited. The difficulties are technological rather than fundamental and will succumb to good innovative engineering within the next few years. The same may be said of the requirements for such mundane, but vitally important, components as splices, connectors, couplers and even the lowly jack plug. Excellent and encouraging progress is being made with all of these items. Of the major hurdles remaining, that of a suitable optical source is by far the most difficult. The lifetime and reliability of existing semiconductor lasers are improving only slowly and need to be increased by at least an order of magnitude. It would also be an advantage if their line width, coherence and beam quality could be made to approximate more closely those of an ideal laser. Fortunately light emitting diodes can also be used if adequate lasers do not become available, but at the expense of system bandwidth and repeater spacing.

Technological forecasting is fraught with hazards for the unwary but it is reasonable to expect systems to be operating in the telephone network in the 1980s at capacities from 140 Mbit/s to 500 Mbit/s at repeater spacings of at least 5 km and perhaps as high as 20 km. Serious study of the application of optical fibres to underwater cables will also have begun. If simple fibre cables can be made cheaply enough for use in installations to individual subscribers a wide range of new developments become possible, but these problems are more relevant to the 1990s.

1. Introduction

Optical communications might seem to be an exotic concept more typical of a science fiction scenario rather than that of the hard and realistic world of long distance telecommunications. Perhaps this is because, when thinking of optical signalling such relatively crude techniques as the lighting of bonfires, semaphore, and the Aldis lamp first come to mind. However, optical techniques are no more than a natural extension of those, employing microwaves and millimetre waves in the continual quest for higher carrier frequencies and larger system bandwidths. On the other hand, the large jump in frequency, by more than four orders of magnitude, means that these techniques and their realization differ in degree if not in kind and the initial systems are not quite of the same form as those originally envisaged. For example, the carrier sources turn out to be narrow-band noise generators and the realizable bandwidth is limited, over short distances at least, by modulation and multiplexing techniques, perhaps also by lack of demand, and not by the medium itself.

The main requirement for any communication system is a flexible, protected, cheap transmission path of low attenuation and high bandwidth. Hitherto high-frequency transmission lines have employed air or a dielectric as the propagation medium but the guiding structure has been of metal. At microwave frequencies the pulse distortion which would be caused by the different group velocities of the various propagation modes is avoided by ensuring that only the dominant mode can be sustained. This is achieved by making at least one cross sectional dimension of the waveguide comparable with the free space wavelength of the carrier. Thus X-band waveguide which is designed for operation in the frequency range 8 to 12 GHz has an internal width of *ca.* 2.5 cm.

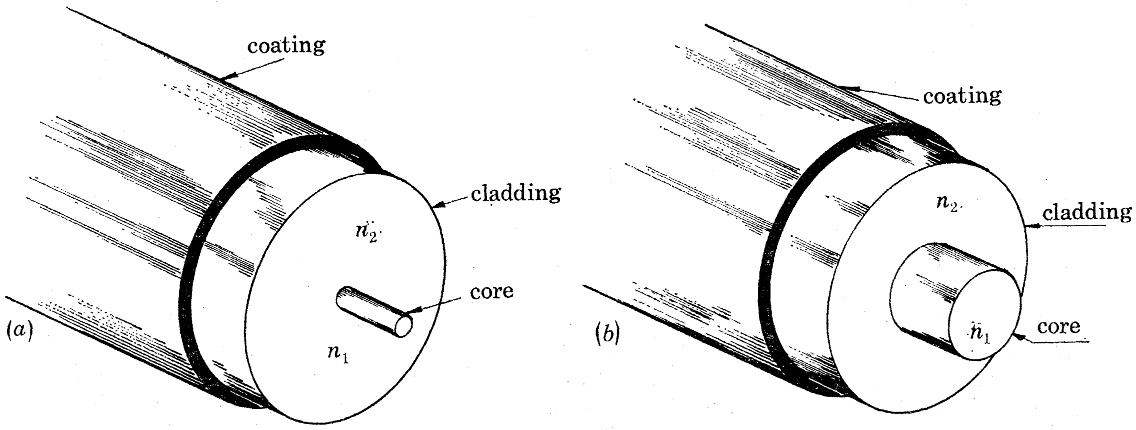

FIGURE 1. Schematic diagram of a single-mode (*a*) and a multimode (*b*) fibre showing, in each case, the core, cladding and surface-protective coating. The core diameter of the single-mode fibre is normally a few micrometres while that of the multimode fibre can be up to 100 μm or more.

With increasing frequency the physical size of the waveguide must be reduced in order to retain single-mode operation but unfortunately the conductor losses then increase (Ramo, Whinnery & Van Duzer 1965). An acceptable attenuation can only be achieved by increasing the ratio area/circumference of the cross section of the waveguide with the result that multimode operation ensues. Thus at millimetre wavelengths an acceptable loss can only be realized by using a highly overmoded waveguide (Davidson 1977, this volume) with an internal diameter of about 5 cm. The necessary bandwidth can be attained by launching a single mode but great care is necessary in fabrication, in components, and in laying out, in order to avoid mode conversion with the consequent fall in bandwidth and increase of loss which would be caused by multimode operation. How can such difficulties be circumvented at the much higher optical frequencies?

For 'light' in the wavelength range 0.5–1.5 μm (i.e. frequencies from 200 to 600 THz) metals have too high a loss to be incorporated as the guiding structure of a transmission line even if the latter is highly overmoded. Resort is therefore made to surface-wave propagation along a dielectric rod in the form of a cladded glass fibre. As the name implies, the guiding region consists of a central core of refractive index n_1 surrounded by a cladding of lower refractive index n_2 (see figure 1), which is sufficiently thick that the surface-wave field intensity is small at the outer surface.

If, as indicated above, the core radius a is comparable with the wavelength λ, or more precisely

$$V = 2\pi a(n_1^2 - n_2^2)^{\frac{1}{2}}/\lambda < 2.405 \tag{1}$$

where $(n_1^2 - n_2^2)^{\frac{1}{2}}$ = numerical aperture (A_n), then only a single mode of propagation in the core is possible. The situation is therefore similar to that with hollow metal waveguides at microwave frequencies. The required cladding thickness of the fibre depends on the normalized frequency or core radius, V, but is usually made about 50 μm for convenience and ease of handling.

Multimode fibres, with core diameters typically in the range 20–100 μm, are also possible. The required cladding thickness, which again depends on the normalized frequency, can be 10 μm or less. The total possible number of guided modes, which is given approximately by $\frac{1}{2}V^2$, therefore lies in the range 200–10000 in a multimode fibre.

With overall diameters of 100–150 μm the fibres are flexible, reasonably strong and compact. Provided the radius of curvature is not too small, say below 5 cm, the increase in loss due to bending in single-mode fibres is small, as is the degree of mode conversion in multimode fibres. Glass fibre cables are thus easier to lay than coaxial cables as well as being lighter and smaller. However, let us examine the properties of optical transmission lines in more detail, particularly the attenuation, which determines the permitted repeater spacing and then the bandwidth, which determines the channel capacity.

2. Attenuation

One of the glasses with the most desirable optical properties for fibres is fused silica (Pinnow, Rich, Ostermayer & DiDomenico 1973) which, in very pure form, has very little absorption loss between the tails of the electronic absorptions in the ultraviolet and those of the vibrational bands in the infrared. Superimposed on the absorption is a scattering loss due to microscopic variations in the local dielectric constant associated with the random molecular structure of liquids and glasses. The Rayleigh scattering coefficient varies inversely as the fourth power of the wavelength and has a value in the region of 0.5 dB km^{-1} (10^{-6} cm^{-1}) at 1 μm.

Several binary silicates, notably phosphosilicate glass (Payne & Gambling 1974) and the combination of germania with silica, have a loss very similar to that of silica and if fibres of reasonably pure materials can be made then low-loss fibres are possible. The quality required is such that some commonly found impurities must be reduced to the level of about 10 parts in 10^9 which is a formidable goal. The degree of success achieved so far is illustrated (Horiguchi & Osanai 1976) in figure 2 showing the attenuation curve reported recently of a multimode fibre with a phosphosilicate glass core and a borosilicate cladding. The attenuation is 0.5 dB km^{-1} at 1.2 μm, and below 1 dB km^{-1} from 0.9 to 1.4 μm. This is quite a remarkable result indicating that the ultimate in attenuation has been virtually achieved. The broken line shows that the attenuation at wavelengths below 1.2 μm is largely due to scattering and is unlikely to be improved upon unless a suitable binary silicate glass with a lower fictive temperature (i.e. the temperature at which the glass effectively solidifies) can be found. Lower-temperature ternary glasses such as sodium borosilicate exist but any reduction in scattering due to the lower fictive temperature is largely compensated for by compositional fluctuations.

The loss at wavelengths greater than 1.2 μm in figure 2 is at least partially due (Osanai *et al.*

1976) to the tail of the Si-O vibrational band at 9 μm. It is a basic characteristic of the silica component and thus forms another fundamental limit to the loss that can be attained.

The binary silicate glasses formed by the combination of SiO_2 with certain other oxides such as GeO_2, P_2O_5, B_2O_3 and SiO_2 doped with fluorine can be fabricated by chemical vapour deposition (Gambling, Payne, Hammond & Norman 1976) techniques. The starting materials, consisting of volatile halides, usually in liquid form, are relatively easily purified and the resulting fibres have losses of 2 dB km^{-1} or less. Sodium borosilicate and similar ternary glasses are normally made from solid starting materials by more conventional techniques (Beales *et al.* 1976) and have somewhat higher total losses. The lowest attenuation reported so far for fibres of this type is 6 dB km^{-1}.

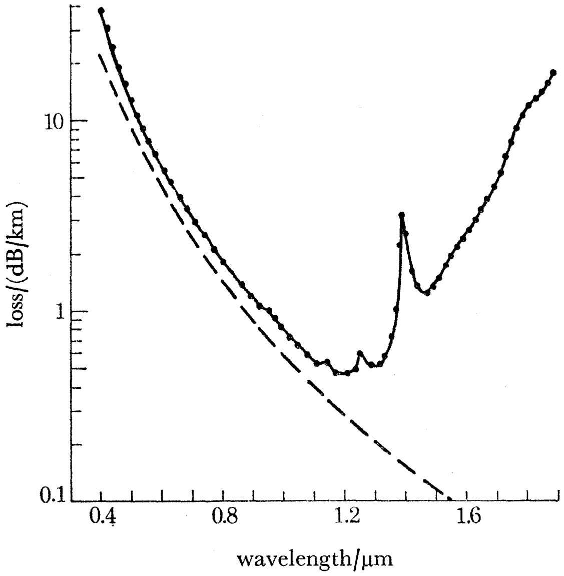

FIGURE 2. Loss spectrum of a 1.2 km length of optical fibre comprising a phosphosilicate glass core in a borosilicate glass cladding (after Horiguchi & Osanai 1976). The broken line shows the fundamental Rayleigh scattering loss.

There has been a considerable degree of success in translating laboratory results into practice. For example, optical cables made by Standard Telecommunication Laboratories and British Insulated Calendars Cables have been installed in Post Office cable ducts and exhibit *in situ* attenuations of between 4 and 5 dB km^{-1}. These are early results and it is reasonable to expect even lower transmission losses along installed cables in the future. Of course there are several outstanding problems to be overcome in the fabrication of fibres, such as the reproducibility of core size and attenuation as well as concentricity of core and cladding. The difficulties are not insuperable and are expected to be overcome within the next few years.

3. BANDWIDTH

An equally important parameter as attenuation is the bandwidth and here optical fibres offer several possibilities. The simplest multimode fibre has a core of uniform refractive index and a diameter of, say, 50–100 μm, compared with an operating wavelength of about 1 μm, and is thus capable of sustaining several thousand modes. Fibres can be made with remarkable dimensional stability and homogeneity so that, in the absence of external stresses, a single mode of this overmoded structure can be launched and will propagate undistorted for appreciable distances (Gambling, Payne & Matsumura 1974). However, if the launching source is a light emitting diode or if, as is likely, mode conversion is introduced by cabling, bends, etc., then the bandwidth falls sharply to perhaps 20 MHz depending on the numerical aperture. This result can be explained in terms of multipath dispersion, since in a multimode fibre it is convenient to use a ray propagation model. The range of angles to the axis at which light rays can persist in the core is given in terms of the numerical aperture as

$$\theta_{\max} = \arcsin(A_{\mathrm{n}}/n_1) = \arcsin[\{(n_1^2-n_2^2)/n_1^2\}^{\frac{1}{2}}].$$

The rays at each permitted angle travel a different path length and therefore have a different propagation time. It may be shown (Dakin *et al.* 1973) that if light is launched into a fibre over all acceptance angles then the difference in propagation times between rays along the axis and at an angle $\theta_{\max}$ to it is $n_1L\Delta/c$, where $\Delta = (n_1-n_2)/n_1$ and L = fibre length.

Thus for a step-index fibre with a difference in refractive index between core and cladding of 1 %, the permissible bandwidth, in the absence of mode conversion and mode filtering, over a 1 km length is *ca.* 20 MHz. The transmission capacity, though limited, may be adequate for many applications, particularly short-distance ones.

A stepped refractive-index distribution is only one example of a wide range of possible core profiles. It transpires that the spread of ray propagation times, or more accurately of the group velocities of the modes, can be greatly reduced by tailoring the refractive index so that it is a maximum at the core centre and falls off monotonically towards the cladding. In particular for the class of profiles where the radial refractive index variation n_r is of the form

$$n_r = n_1\{1-2\Delta(r/a)^{\alpha}\}^{\frac{1}{2}},$$

where $0 < r < a$, the spread of group velocities is minimized to the value $\frac{1}{8}Ln_1\Delta^2/c$ when the profile parameter α is optimized (Gloge & Marcatili 1973). The optimum profile parameter is a function of the material of the core and of the wavelength and is generally close to the value $\alpha = 2$ so that the refractive index distribution is approximately parabolic. With the correct profile the spread in group delays is reduced to about 0.05 ns km^{-1}, again for $\Delta = 0.01$, but any departure rapidly increases the dispersion. In practice, control of fibre fabrication to the required accuracy, i.e. to an index deviation of less than 10^{-4}, is not possible and measured bandwidths in graded-index fibres are in the region of 1 GHz km. Even so, graded-index fibres have the advantage of a considerable bandwidth even when used with light-emitting diode sources. The core diameter can still be some 50 μm or more so that the problems of jointing, launching, etc. are only slightly more difficult than with step-index fibres (Adams, Payne & Sladen 1976).

The ultimate in bandwidth is provided by the single-mode fibre since only one mode is present and hence all the transmitted energy travels at the same group velocity. The remaining dispersion arises from the variation in mode group velocity with frequency (which can be made small) and from the optical dispersion of the fibre material. In the latter case the relevant factor is the second derivative of refractive index (Luther-Davies, Payne & Gambling 1975) with wavelength, namely $\delta = (\lambda/c)(\mathrm{d}^2n/\mathrm{d}\lambda^2)$. At least in the binary silicate glasses the value of δ at a wavelength of 0.9 μm is such that with a monochromatic source the bandwidth can be *ca.* 30 GHz km. However, the finite line-width (2–4 nm) of the semiconductor laser reduces it to about 3 GHz.

On the other hand the material dispersion in silica and phosphosilicate glasses (figure 3) falls progressively at longer wavelengths and goes through zero at about 1.25 μm. Thus the material dispersion limitations can be largely overcome by changing the operating wavelength so that even with a source which is far from ideal a bandwidth of 100 GHz km becomes possible (Payne & Gambling 1975). It should be noted that at the same time the fibre attenuation would be at a minimum (see figure 2).

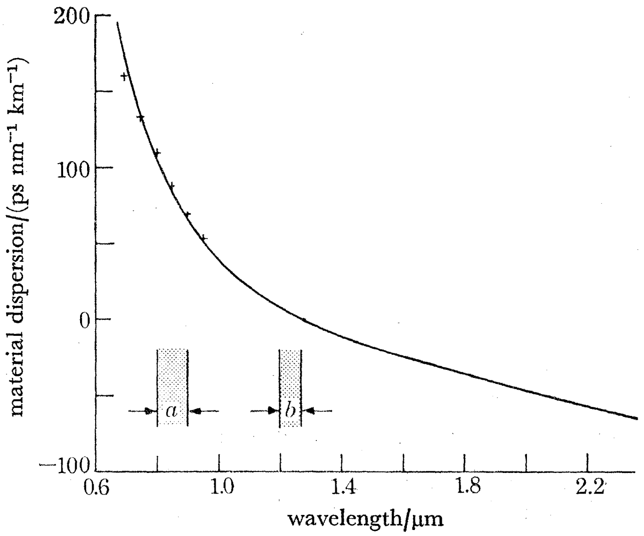

Figure 3. Material dispersion factor $(\lambda/c)(d^2n/d\lambda^2)$ calculated for pure silica (solid line) and measured in a fibre having a phosphosilicate glass core (experimental points) as a function of wavelength (after Payne & Gambling 1975): *a*, GaAs device region; *b*, region of negligible material dispersion.

4. Sources

Despite the considerable advances made in the development of the transmission medium, system progress remains heavily dependent on the emergence of a cheap and reliable optical source. The present contenders are the injection laser (Selway 1976) and its cousin, the light-emitting diode (l.e.d.) (Bergh & Dean 1976), both based on gallium–aluminium–arsenide technology, and the l.e.d.-pumped miniature neodymium laser (Iwamota, Hino, Matsumoto & Inoue 1976). The properties of the fibre transmission medium are best complimented by a source which (*a*) has microscopic dimensions, (*b*) possesses a high conversion efficiency from electrical to optical signals so as to reduce repeater power feeding requirements and (*c*) is easy to modulate. Other, perhaps more obvious, requirements are fast response and sufficient reliability to permit operation in repeater stations for a minimum period of twenty years.

The source which comes closest to the ideal in all respects but reliability is the double-heterojunction, stripe-geometry, gallium–aluminium–arsenide laser diode (figure 4*a*), emitting in the wavelength range 0.8–0.9 μm. It offers a coherent and well-defined radiation pattern which may be efficiently coupled to the fibre to give an injected power of greater than a milliwatt. In addition, high-speed modulation of the laser output up to more than 500 Mbit/s can be readily achieved by variation of the bias current (Ramsay 1976). On the debit side, the device is sensitive to temperature variations and requires a feedback circuit to stabilize its output. In addition its spectral linewidth is relatively broad for a laser (2–4 nm). The combination of the latter property with a wavelength of operation at which the material dispersion is significant (see figure 3) ultimately limits the transmission capacity when used with highbandwidth graded-index or single-mode guides. Measures aimed at improving the spectral purity of the laser have met with some success but are still in the research phase.

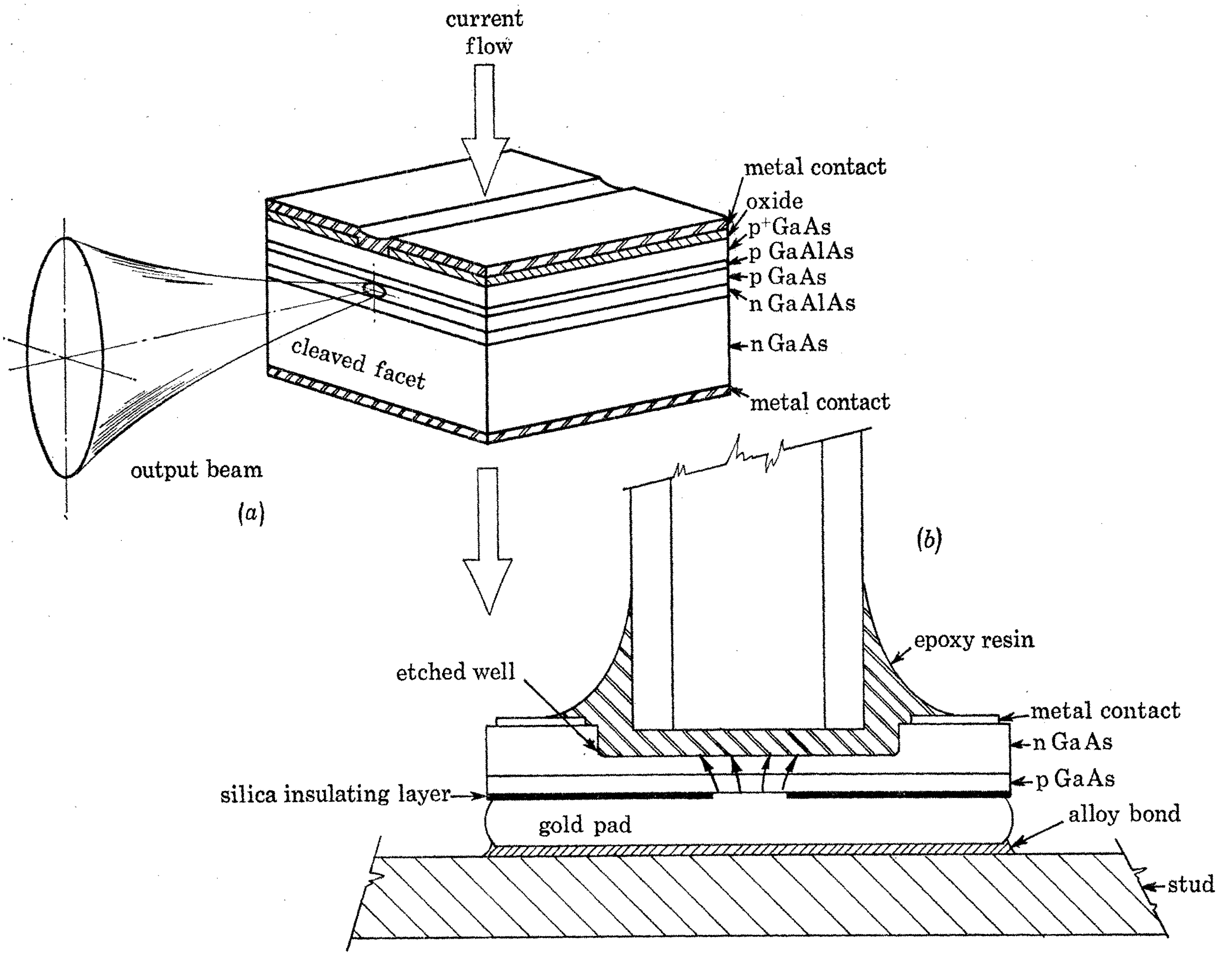

FIGURE 4. Semiconductor electroluminescent devices based on GaAs. (*a*) Stripe-geometry, double-heterojunction laser structure with output beam shown schematically. (*b*) High-brightness Burrus l.e.d. showing how the incoherent emission is coupled into a fibre.

Although considerable advances have been made since the early achievement of continuous, room-temperature, laser operation, when device lifetimes were measured with a stop watch, the reliability of the gallium–aluminium–arsenide laser still falls short of that required for telecommunications service. The longest surviving device has currently logged some 30000 h and encouraging reports of extrapolated lifetimes of 10^5 h obtained from accelerated life tests have been made (Hartman & Dixon 1975). However, few manufacturers are currently prepared to guarantee their device survival for even 1000 h and the number of lasers which fail during the initial burn-in period remains unspecified. Nevertheless, improvements in material perfection and the reduction of strains in the semiconductor crystal structure are expected to lead to further progress in the future.

The gallium–aluminium–arsenide high-radiance l.e.d. has fewer lifetime problems and devices designed for optical communications currently have adequate extrapolated lifetimes. The l.e.d., in either its edge-emitting (Ettenberg, Kressel & Wittke 1976) or surface-emitting (King, Straus, Szentesi & Springthorpe 1976) (Burrus) form, figure 4*b*, has some of the advantages of the laser, but possesses a larger spectral linewidth (40–50 nm) and a reduced modulation bandwidth of some 200 MHz. Unlike the laser, the l.e.d. emits light incoherently over a wide range of angles and thus presents a poor match to the optical fibre acceptance cone. The launching efficiency is consequently less than that of the laser and a typical high-radiance l.e.d. couples less than 0.1 mW into a fibre. The situation is improved by choosing a fibre having a high numerical aperture.

The l.e.d. represents an alternative to the heterojunction laser in the unlikely event of the lifetime problem proving insuperable. In addition it provides a low cost solution in applications, such as inter-office links, which do not demand the ultimate in data rate or repeater spacing offered by the laser. For analogue transmission the l.e.d. is particularly attractive, since it provides low signal distortion without sophisticated drive circuitry and bias stabilization.

Although the GaAlAs devices operate within a spectral region where fibre transmission properties are good, the advantages offered by the 1.0–1.4 μm region has stimulated several laboratories to investigate semiconductor junction devices operating at longer wavelengths (Mabbitt & Mobsby 1975). Promising materials are ternary or quaternary III–V compound semiconductors and various combinations of these have been reported in both laser and l.e.d. form. L.e.ds based on GaInAs operating at 1.06 μm in high-radiance Burrus configuration are now commercially available and very encouraging reports have been made of the longevity (3000 h) obtainable in early samples of GaInAsP/InP diode lasers (Shen, Hsieh & Lind 1977). It would be ironic if the degradation characteristics of the more complex quaternary semiconductor devices should prove less troublesome than those of GaAlAs-based sources on which so much work has been done.

The l.e.d.-pumped Nd-YAG laser appears something of an outsider at present, largely as a result of its low overall efficiency and the difficulty of modulating its output. Nevertheless it has the advantage of a well collimated, coherent beam of high spectral purity and is thus well matched to the single-mode fibre.

5. Detectors

At optical frequencies the quantum nature of electromagnetic radiation provides the ultimate limitation to the sensitivity of a receiver. The random arrival of individual photons at the photodetector results in a degree of uncertainty as to whether a signal bit has arrived. Thus it is possible to specify the minimum number of photons necessary per pulse to ensure a given error rate. At a wavelength of 0.9 μm about 10 photons per bit interval results in an error probability of 10^{-9}. In practice, however, optical receiver sensitivity is dominated by sources of noise within the detector and following amplifier, resulting in a performance which is one or two orders of magnitude inferior to the quantum noise limit.

The silicon photodetector, in either p-i-n or avalanche photodiode (a.p.d.) configuration, is ideally matched to sources based on GaAs, since its peak sensitivity occurs at 0.9 μm. The p-i-n photodiode offers low cost and simple bias circuitry together with low noise. Unfortunately the photo-current produced by the received signal is very small and therefore the thermal noise contribution of the following amplifier significantly degrades the error rate. An improvement of 10–15 dB in sensitivity can be obtained by using an avalanche photodiode. This detector is similar in construction to the p-i-n photodiode, but has the attribute of multiplying the photoelectrons internally – typically by a factor of 100 – within a high-field avalanche region. Thus the signal is magnified to a relatively high level before the thermal noise of following amplifier stages is added. Being random in nature, the avalanche process introduces its own noise contribution and so limits the maximum gain which can be used. Inevitably the improved performance is obtained at the expense of additional cost, both of the a.p.d. itself and of the high-voltage power supply and bias stabilization circuitry required to eliminate the effects of temperature fluctuations.

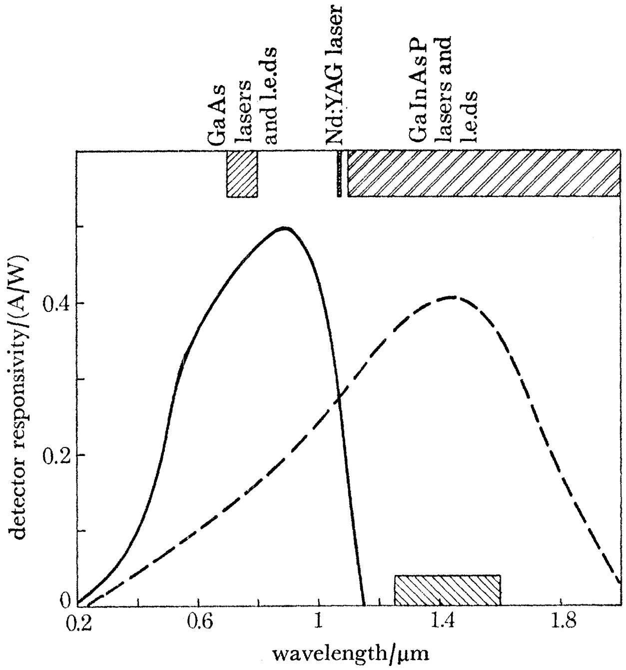

Figure 5. Spectral response of silicon (solid line) and germanium (broken line) photodiodes. The emission regions for various optical sources (shaded areas, top) and the region of minimum fibre attenuation (shaded area, bottom) are also shown.

Despite the relatively low detectivity of the silicon device when compared to the theoretical quantum noise limit, the sensitivity is still such as to permit an error probability of 10^{-9} at a bit rate of 100 Mbit/s for a received optical signal of only 10^{-8} W. Thus in conjunction with a GaAlAs semiconductor laser injecting 1 mW into the fibre we see that a transmission loss of 50 dB is acceptable before significant signal degradation occurs. With modern fibre cable technology able to offer an attenuation of 5 dB km^{-1}, a repeater spacing of 10 km is possible, with every prospect of this being increased as cables improve.

Detectors for the 1–1.4 μm region currently present something of a problem. Silicon devices fail to respond to radiation at a wavelength greater than 1.1 μm (figure 5), leaving germanium photodiodes as the only remaining choice. Although possessing a response to wavelengths up to 1.8 μm, the smaller bandgap in germanium results in a considerable increase in thermally generated leakage current (dark current), which is some 10^3 times greater in a germanium than in a silicon device. The accompanying increase in device noise degrades the detector sensitivity. Although there are favourable reports of detectors based on InGaAs, considerable effort is required to develop devices for the longer wavelength region.

6. Fibre strength

Optical cables differ from their copper-based counterparts in that failure is by brittle fracture, which is essentially a statistical phenomenon. Thus although pristine glass fibres have a tensile strength greater than most other materials and can withstand a stress as high as 2×10^6 lbf in^{-2} (*ca.* 13 GPa), a microscopic surface flaw will result in failure at a small fraction of the intrinsic strength. Surface flaws or cracks are initiated remarkably easily, for example by contact with a hard surface or by dust in the air. Unprotected fibres rarely exceed a tensile strength of more than a few hundred grams after having been wound onto a drum.

The relatively unflawed condition of the fibre surface as it emerges from the pulling furnace may be preserved by in-line coating with a thin layer of an organic polymer, such as EVA, or a silicone elastomer. The coating serves only to prevent abrasion of the surface and does not act as a strength member. Thus protected, the effective fibre strength increases dramatically and depends on the perfection with which the buffer coating can be applied and on the number and size of the remaining flaws. The fibre breaks at the weakest link and therefore the measured strength depends on the length tested, since a long section has a higher probability of containing a large flaw than a short section.

A further complication is that tensile failure depends not only on the size and distribution of the flaws initially present but also on their slow growth with time and applied stress. Thus although a cable may survive the stress of being drawn into a duct, the small residual cable stresses result in a deepening and widening of the flaws and this may cause spontaneous fracture within the required 20 year life span.

Statistical predictions of permissible residual stress levels for zero failure within 20 years may be made by subjecting the fibres to a screening procedure. Initially every fibre is proof tested over its entire length at a high stress level to ensure that the cable will meet its initial strength specification. This test also establishes the maximum possible size of flaw present in the length tested, since it is known that a flaw deeper than a certain value will result in failure. Having thus determined the initial condition of the fibre surface, fracture mechanics theory permits a projection of service life with the residual cable stress likely to be found in practice.

Advances recently made (Schonhorn *et al.* 1976) in the protection of fibres indicate that the problems accompanying the maturity of optical fibre technology are being successfully mastered. Care in the quality of the glass preforms from which the fibre is drawn and a clean processing atmosphere results in 90% of fibres passing a screen test conducted at a very high stress level (5×10^5 lbf in^{-2}; *ca.* 3.4 GPa), representing a tensile load of 8.8 lbf (39.15 N) for a 120 μm diameter fibre. Extrapolations indicate that such a fibre will also withstand a residual stress of 10^5 lbf in^{-2} (*ca.* 680 MPa) for the lifetime of the optical transmission system.

7. Splices, connectors and couplers

Accompanying the size advantage of the optical fibre and its ability to transmit large information rates within a very small area is the disadvantage that it requires high precision jointing techniques. The permanent fibre-to-fibre splice, the demountable connector – either fibre-to-fibre or fibre-to-terminal device – and the power-dividing coupler, are all essential elements of a telecommunication network. To obtain low insertion loss all have the same requirements of (*a*) good fibre end preparation and (*b*) maintenance of extremely small transverse offsets. Several techniques are now available which satisfy these demands and laboratory examples of all three junctions have been reported with insertion losses of only a small fraction of a decibel. It remains to be seen whether these techniques can be successfully transplanted into the more hostile field environment.

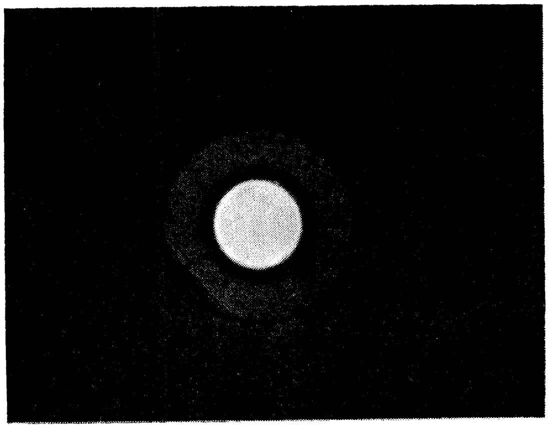

FIGURE 6. Cross section of a typical optical fibre made by chemical vapour deposition illustrating the quality of end surface obtained by the simple technique of scratching and breaking. The small chip visible on the lower left is confined to the outer cladding region and does not therefore affect transmission.

High quality fibre end preparation has proved relatively easy to achieve (figure 6). It is possible to obtain a flat, mirror-like surface perpendicular to the fibre axis by a method of controlled fracture, similar to that used to cut larger glass rods to length. The fibre is scored and snapped under tension, either by hand or in an automatic machine. More laborious methods such as sawing and polishing are also occasionally used.

Alignment of the fibres to each other or to an external device proves more difficult. The coupling loss produced by transverse misalignment between two equal multimode fibres is

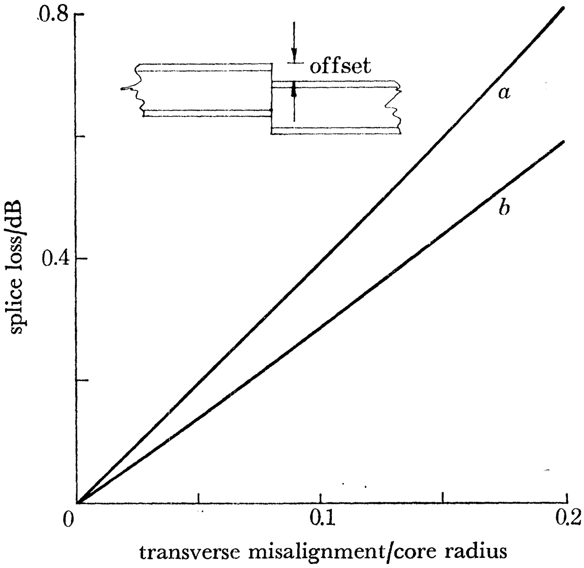

FIGURE 7. Splicing losses produced by transverse offset between fully excited multimode fibres. For a given displacement the loss is 35% larger in parabolic-index fibres (a) than in step-index fibres (b).

shown in figure 7 for both step-index and graded-index fibres. An offset of only 10 % of the core diameter produces a loss of 0.5 dB to which must be added 0.35 dB reflection loss if an index-matching fluid is not used. Thus typical multimode fibres must be aligned to within a few micrometres to achieve acceptable performance.

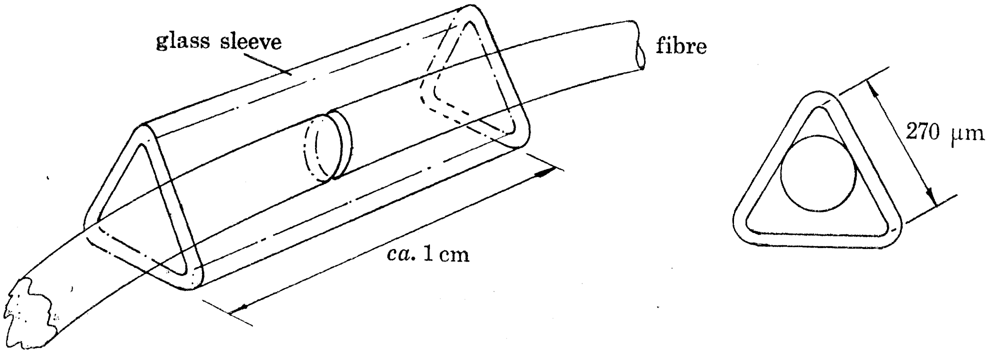

FIGURE 8. Loose-tube technique for splicing fibres.

In general, two methods are commonly used to accomplish the required accuracy, namely the precision-tube splice and the 'V'-groove technique. The former uses a metal, or glass, sleeve chosen to conform closely to the outer diameter of the fibre, into which the fibres are inserted. The sleeve ensures that the fibres are correctly aligned, after which they may be cemented in place to form a permanent splice, or arranged to be demountable with a suitable screw or snap fitting. The losses obtained with this type of joint are usually not as low as those obtained with the V-groove method since the tube is chosen to fit the fibre rather loosely so as to permit easy insertion and to allow for fibre diameter variations.

The V-groove junction exploits the close tolerances to which the fibre diameter and core/cladding concentricity can be held during manufacture. The fibres are laid within an embossed or machined V-groove and butted close to each other. They may then be permanently affixed to the alignment jig, which forms an integral part of the joint, or arranged to be demountable. An example of the method is the loose tube splice shown in figure 8. The fibres are forced into the corner of a square or triangular section tube of glass or metal by bending them slightly, after which they are cemented in place. An advantage of this splice is its small overall diameter.

Numerous variations on the above two basic techniques are now available. One of the more attractive of these involves the fusion of two fibres (Dyott, Stern & Stewart 1972), pre-aligned either by a V-groove or by micromanipulation. The glass is softened by a thermal source such as an electric arc or a flame and fused to form a permanent weld.

Two avenues are currently being explored for the splicing of multi-fibre cables. That currently used in the United Kingdom involves the splicing of individual fibres within the cable, whereas the approach followed by Bell Telephone Labs is to join simultaneously many fibres as a unit. In the latter case one experimental cable has an outer diameter of 1.2 cm and contains 144 fibres arranged in flat tapes of 12. Each tape is spliced using a double-grooved wafer and the whole fibre splice array measures only 5 mm square.

The power-dividing coupler, with three or more ports, has not received as much attention as has the more fundamental jointing problem. One of the few devices which have emerged is the

T-coupler shown in figure 9. The device allows a proportion of the light travelling through the straight-arm sections to be split off by the dielectric coated mirror and directed to a device or another fibre mounted on the third arm.

The above examples are representative of the current art of fibre junctions. It is clear that further work to reduce the losses is necessary particularly for the demountable connector. In contrast to copper transmission lines, the interconnections in fibre systems may form a significant, or even a dominant, proportion of the overall system loss, thus negating much of the advantage of the ultra-low fibre attenuation now being achieved. It is to be hoped that as the technology matures improvements in the reproducibility of fibre geometry will automatically bring reductions in jointing losses.

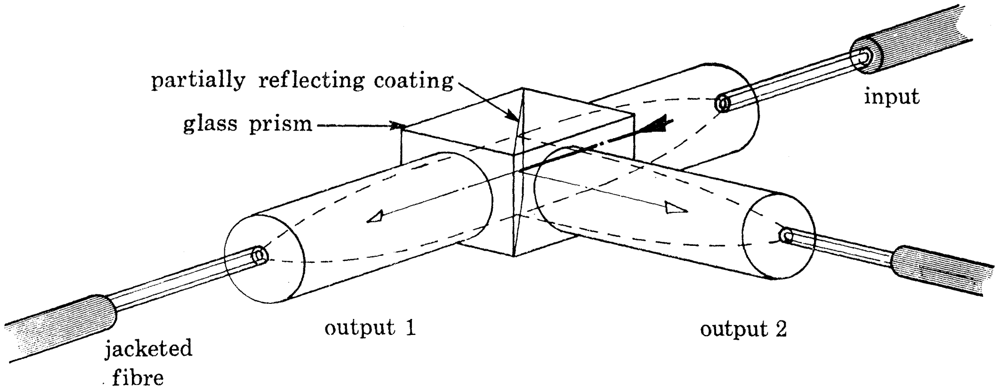

FIGURE 9. T-coupler based on Selfoc rods. The focusing rods are cut to a length which converts the divergent fibre emission to an approximately parallel beam within the central prism. Here power splitting is accomplished by a partially reflecting mirror placed at 45°, after which refocusing of the beam components into the two output fibres occurs.

8. PRESENT SYSTEMS

A number of trial systems have been set up in many countries, the particular configuration depending on the local conditions and the urgency, or otherwise, of the need to expand the existing network. For example, a fortunate circumstance with the U.K. telephone network is that 80 % of all trunk links are shorter than 8 km which is well within the repeater spacing capability of optical fibres. Thus the transmitters and receivers can be installed in telephone exchanges and there is a less critical need for buried repeaters, with a corresponding saving in cost. Again, in Germany the existing coaxial cable installation is adequate for many years to come and consequently the need for an expanded system is less acute. In all cases the present trend is to have electro-optical transducers at each end of the optical fibre cable in order to minimize the degree of change from the existing electrical network.

In order to illustrate the present stage of development, brief details of a few experimental trial installations may be mentioned. The Post Office in this country has installed a 14 km length of B.I.C.C. cable from Martlesham to Ipswich with a single repeater housed in Kesgrave telephone exchange (J. E. Midwinter, private communication). The capacity is 8 Mbit/s with an error rate of better than 2 in 10^{10} over a 12 km cable loop using an S.T.L. laser, but transmission at 140 Mbit/s with an error rate of 1 in 10^{12} has been effected over each of two 6 km lengths. Further 140 Mbit/s studies are planned with subsequent extension to 280 and possibly 560 Mbit/s. Another cable, containing 8 fibres and supplied by S.T.L., has been laid in existing standard cable ducts with bends, 'dog-legs', as well as changes of direction and level at manholes. The cable attenuation and dispersion are 5 dB km^{-1} and 1 ns km^{-1} respectively (C. P. Sandbank, private communication).

One of the Japanese experiments is that by the Nippon Electric Company at a capacity of 400 Mbit/s over a 4.2 km length. The total loss is 30 dB and a semiconductor laser supplies an optical power of 10 mW peak with a launching loss of 4 dB. The detector is an avalanche photodiode.

Another link, taking the form of a field trial, comprises a 6.3 Mbit/s cable of length 3 km. Both the optical cable and a single repeater were installed near 275 kV power cables. The total loss of the 3 km step-index fibres including eight splices and four connectors was between 18 and 21 dB while the measured error rate met the system requirements of 1 in 10^9.

In the U.S.A. an experimental evaluation of an interoffice trunk connection has been carried out over a length of 0.65 km for a capacity of 44.7 Mbit/s. The optical fibre cable contained 144 individual fibres within the 12 mm outer sheath diameter, of which 138 were still active after installation. The average transmission loss was 6 dB km^{-1} at the operating wavelength of 0.82 μm with a spread between individual fibres from roughly 3 to 13 dB km^{-1}. An array connector has been designed for use with the cable (although it was not incorporated in the transmission experiment) which is factory assembled and in which most of the individual fibre joint losses are less than 0.5 dB.

Similar assessments are being made in a number of other countries and formal trials are at an advanced stage of planning. It is clear from the preliminary results already available that optical cable links at capacities up to 100 Mbit/s with error rates of 1 in 10^9 and repeater spacings in excess of 5 km are feasible and realistic.

9. The future

Within the next few years it is possible to anticipate a steady improvement in the lifetime, beam quality and linewidth of semiconductor lasers and in the associated circuitry, enabling them to be pulse modulated at a 10 Gbit/s rate. Similarly the radiance of light-emitting diodes will be further improved so as to increase the relative power which may be coupled into multimode fibres. Some light-emitting diodes have already been operated at pulse lengths approaching 1 ns so that high speed operation can be expected. Both types of device will become available in materials allowing operation at wavelengths up to, and perhaps beyond, 1.25 μm.

In these circumstances the permissible repeater spacing can exceed 20 km, depending on the bandwidth required, and will be limited as much by connections as by the fibre itself. For short lengths, such as are encountered within the local network, a step-index fibre with an l.e.d. source giving a bandwidth of *ca.* 20 MHz km may be quite adequate. However, with proper launching from a laser, larger capacities may be available provided excessive mode conversion at joints and connectors can be avoided.

The homogeneous and other chemical vapour deposition techniques enable graded-index fibres to be produced relatively easily and although perfect grading is likely to prove too difficult a target, bandwidths in excess of 1 GHz km are realistic even with l.e.d. excitation. Again bandwidths up to 5 GHz km or more at 0.9 μm, or 50 GHz km at 1.25 μm, are theoretically possible with a laser.

Single-mode fibres are capable of larger bandwidths than those of perfectly graded multimode fibres. Thus at 0.9 μm the limiting factor is mainly material dispersion and with a monochromatic carrier the modulation frequency spread limits the bandwidth to the region of 100 GHz. With a practical semiconductor laser having a linewidth of, say, 1 nm then this figure falls to about 10 GHz. At 1.25 μm the only remaining limitation to bandwidth is mode dispersion, since mode conversion, which may occur at bends, microbends or joints, affects only the transmission loss whereas in multimode fibres they may also influence the bandwidth. Some of the bandwidth options available are illustrated in figure 10.

In all types of fibre the total bandwidth can be greatly increased by frequency multiplexing, by means of sources operating at adjacent wavelengths over the enormously wide range of 0.8–1.3 μm. Very little attention has hitherto been paid to this aspect since the capacity available without multiplexing is already large.

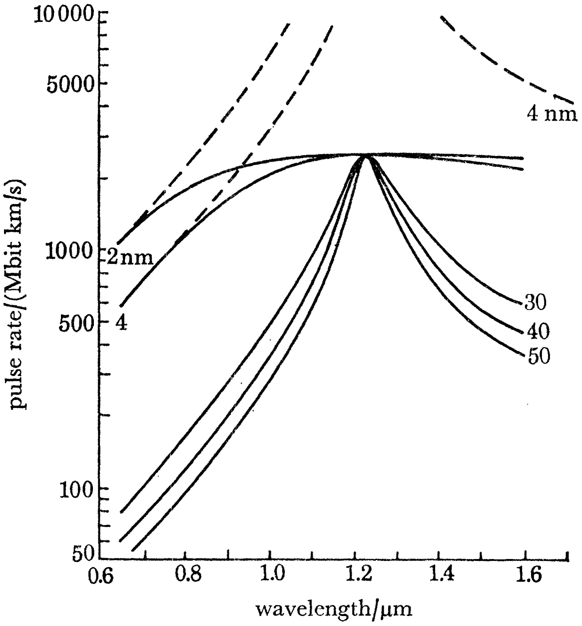

Figure 10. Maximum pulse rates available in fibres having the material dispersion shown in figure 3 for the source linewidths indicated on the curves. The solid lines are for a multimode graded-index fibre having a waveguide dispersion of 0.2 ns km^{-1}; the broken lines are for a single-mode fibre.

10. Conclusions

The progress made in optical fibre transmission systems since 1966 has matched even the most optimistic predictions of that time. Transmission losses close to the fundamental limits of presently known materials have been realized with bandwidths that are too large to be measured by existing techniques. A number of challenging engineering problems remain but the difficulties are not insuperable and a new, economic and flexible transmission line is well on the way to commercial exploitation.

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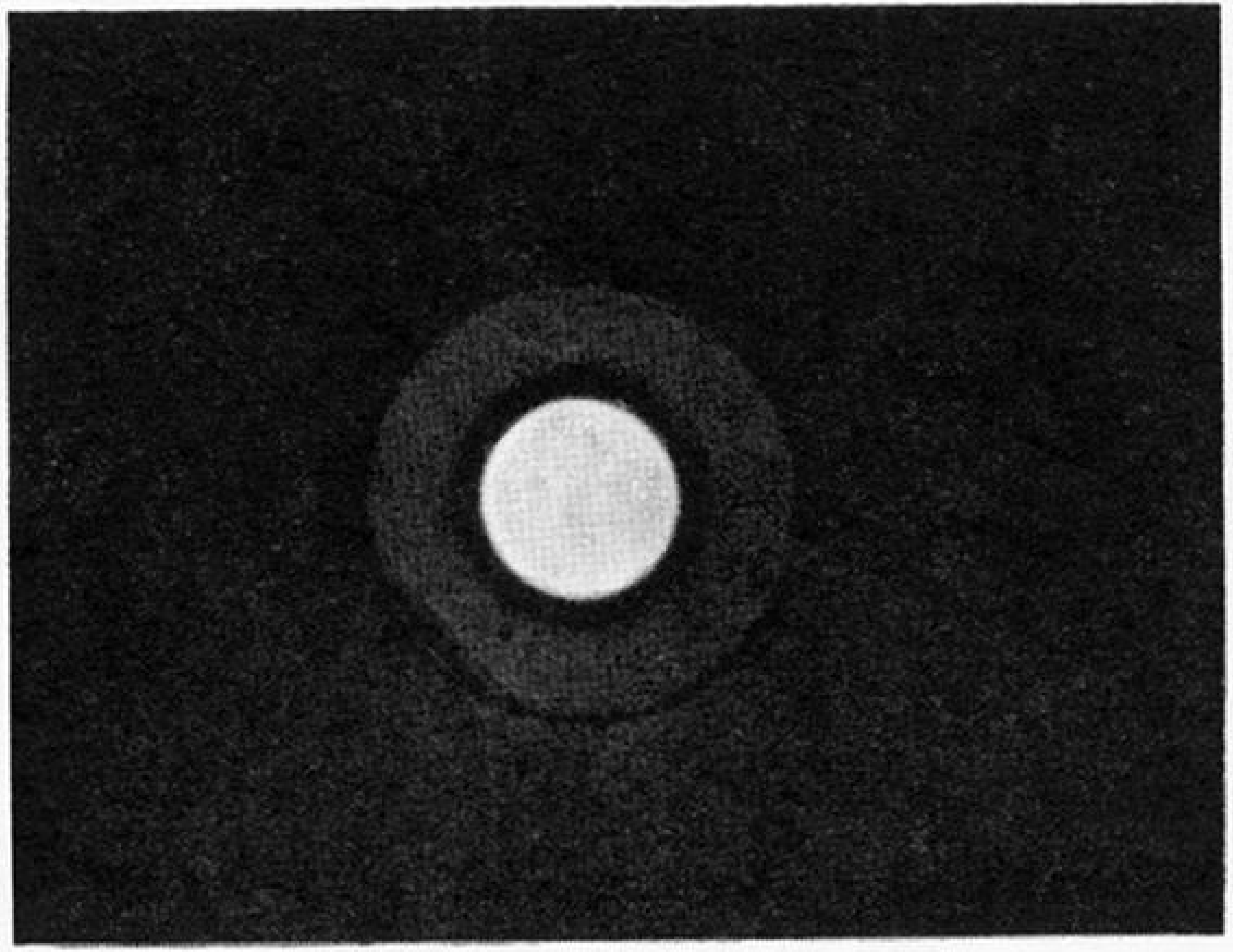
Discussion

P. A. LINDSAY (*Department of Electronics and Electrical Engineering, King's College, Strand, London WC2R 2LS*). Those of us who are interested in the technology of optical fibres would be grateful to Professor Gambling if he cared to comment on the relative merits of multimode and single-mode fibres. Is it fair to say that the future lies with the latter, rather than the former, as some of us strongly suspect?

W. A. GAMBLING. Optical fibre communications is a broad-based technology having a wide range of potential applications. The lecture has emphasized only one of these aspects, namely the replacement of coaxial cables in the trunk telephone network. The present trial installations, involving graded-index multimode fibres and capacities of a few tens of megabits per second over a few kilometres, represent the first tentative steps in this direction. For long distance trunk routes the single-mode fibre can provide capacities approaching 1 Gbit/s over 10 km or more using a single laser source. Furthermore, if frequency multiplexed in the same way as the overmoded millimetre waveguide, the single-mode fibre can rival it in total capacity at a fraction of the cost and with greatly improved flexibility. At a more modest level the medium-loss, step-index, multimode fibre of high numerical aperture is a potential competitor of the versatile twisted pair. Thus the telephone network of the future will probably contain several types of fibre, each at a different level in the system, with the single-mode fibre becoming the mainstay of the long distance, high capacity routes.

PHILOSOPHICAL TRANSACTIONS OF



IGURE 6. Cross section of a typical optical fibre made by chemical vapour deposition illustrating the quality of end surface obtained by the simple technique of scratching and breaking. The small chip visible on the lower left is confined to the outer cladding region and does not therefore affect transmission.