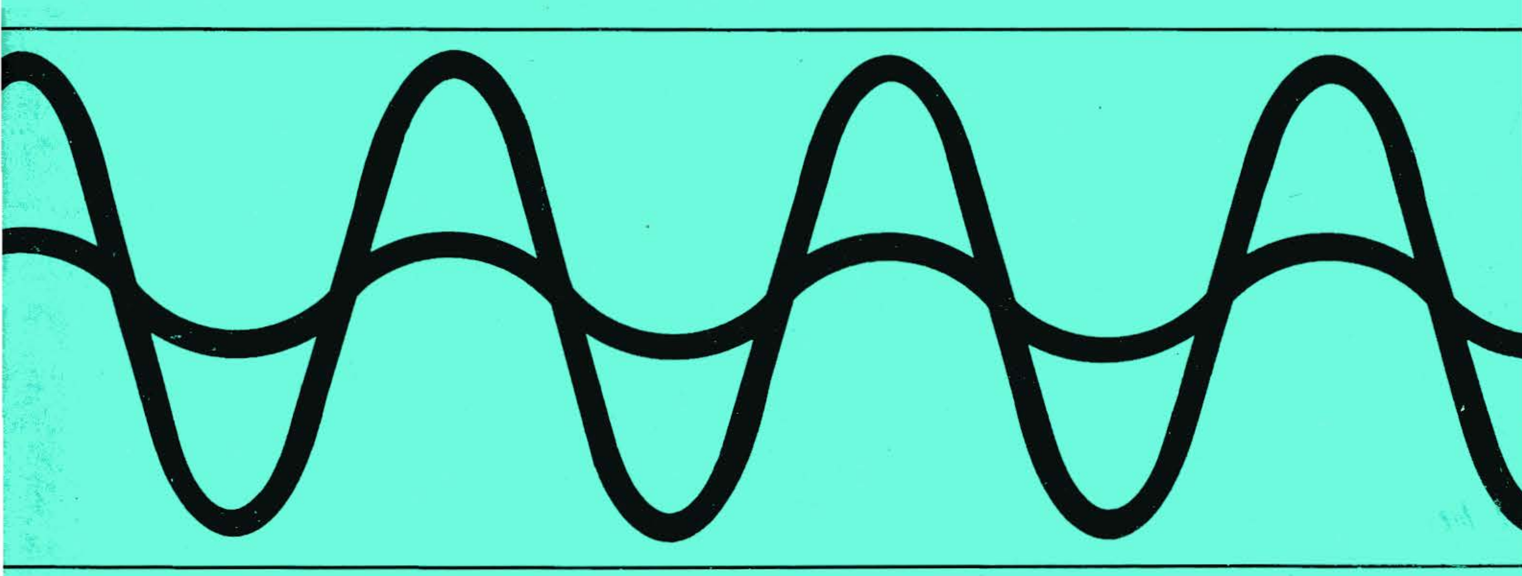
OPTICAL FIBRE COMMUNICATION



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Transmission Department
Network Executive
Telecommunications Headquarters
British Telecom

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Note: A number of mathematical expressions have been included in the text but it has not been considered appropriate to show the derivation of these expressions in this booklet. They are, however, described in a number of other publications and the interested reader is referred to these, particularly those listed in the bibliography at the end of this booklet (Section 10).

Preface

Optical fibre communication has advanced rapidly in the decade or so since its feasibility was first demonstrated and yet we are still only at the dawn of an era. For the last 100 years telephonic communication has employed the principles of electricity but we are now firmly embarked on a new technology – that of optical communication at light frequencies. Current systems are very much hybrid arrangements which involve the conversion of optical signals to electrical signals before they can be processed. Nevertheless it is possible to predict that in the years to come such conversion will not be necessary and that integrated optical techniques will enable all signal processing and switching to be performed optically.

Vast research and development resources are being employed throughout the world in an endeavour to advance the state of this new technology. The rewards and benefits, both social and economic, will be tremendous as optical communication technology spreads to every corner of telecommunications networks throughout the world.

This booklet, which is based on a series of lectures given by the author, has been prepared for the benefit of all those who wish to gain a foothold on the ladder taking us into this exciting new era of optical technology.

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1. Introduction

Throughout the history of radio and carrier telephony on cables there has been a continuing trend to the use of higher frequencies. This is primarily because it is generally more economic to obtain additional capacity by exploiting the higher frequencies than to have a number of co-routed lower capacity systems. With the invention of the laser in 1960 coherent sources of electromagnetic radiation reached the visible spectrum. It was natural therefore that the possibility of communicating at light frequencies should be investigated.

Initially the possibility of transmitting light energy through the atmosphere was examined. Unfortunately as the frequency of electromagnetic signals is increased the signals become severely attenuated by such conditions as fog, rain and snow. This idea was not therefore considered to be feasible for the majority of terrestrial applications, although optical communication in space is already becoming a practical proposition. As far as earthbound systems were concerned the next logical step was the study of suitably guided light signals, since a light waveguide would protect the light beam from atmospheric disturbances.

Early attempts at light guidance over long distances employed lenses enclosed in a suitable tube so that any tendency of light to spread apart by diffraction could be counteracted and extraneous light and moisture could be kept out. Curved mirrors were used to guide the light beam around bends. Systems such as these have not come to fruition because the problems of alignment and positioning of the lenses would have been such that they would not have been economically viable - at least for the foreseeable future.

It has been known for a long time that light can be guided in thin fibres made of transparent dielectric materials. The concept of using glass fibres as a transmission medium was suggested in a paper published in 1966 by Kao and Hockham of Standard Telephone Laboratories (UK). (STL) [1].

British Telecom became interested in the possibilities of optical fibre transmission at about this time and, in conjuction with STL, the most important parameters for an optical fibre transmission system were soon defined. Interest originally centred on fibres capable of sustaining high data rates (eg 100 Mbit/s or greater) in a digital binary transmission system with a laser source. Fibre losses of less than 20 dB/km were considered necessary for an economic system to emerge and the sources of loss in the appropriate glass materials were identified by the Telecom Research Department in collaboration with Sheffield University. The basic requirements were determined during 1966-67 and work commenced to seek solutions to the many problems which had been identified. A major advance came with the announcement in 1970 by Corning Glass Works (USA) [2] of the first 20 dB/km loss optical fibre. It thus became clear that the original targets set some years earlier were indeed feasible and world wide R&D activity into all aspects of optical fibre systems grew rapidly.

Since then major advances have occurred in every area of the technology to the point where many varieties of system have now been developed and installed in realistic and practical environments around the world. Optical fibre systems have significant advantages over existing transmission systems such as:

i. very large information bandwidth and therefore a potentially high transmission capacity.

ii. potentially low material cost.

iii. small cable size leading to low duct occupancy.

iv. negligible crosstalk.

v. high immunity to interference.

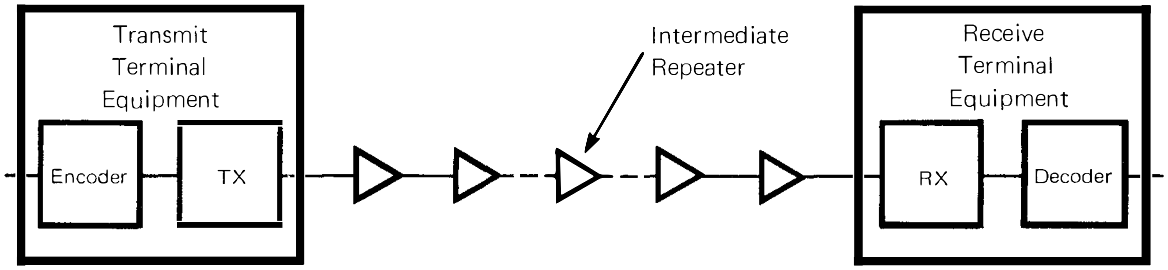
vi. complete electrical isolation.

vii. larger repeater spacings than for equivalent capacity metallic cable systems.

It is for these reasons that optical fibre systems are receiving so much attention.

Digital Optical Fibre Systems are analogous in structure to digital coaxial systems in that they have transmit and receive terminal equipments and may have regenerative repeaters spaced at intervals along the route as shown in Figure 1. The optical parts of the system consist of the light source, usually a laser or light emitting diode, the fibre along which the light beam is transmitted and a light detector, usually some form of photodiode. These three components are now described and are followed by sections on systems design, the present state of the art, and the future prospects for optical systems in telecommunications.

Fig. 1 Basic Arrangement for Line Systems



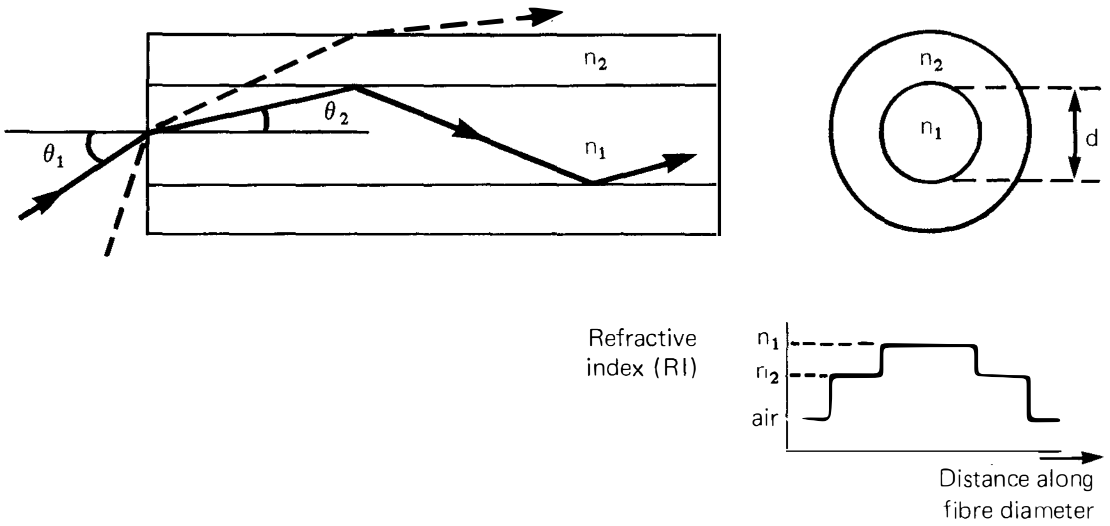
2. The Transmission Medium

2.1 Transmission Characteristics and Fibre Types

2.1.1 Transmission Principles [3]

The simplest way to consider transmission over optical waveguides is to think in terms of total reflection in a medium of refractive index n_1 at the boundary with a medium n_2. This is the situation in a typical multimode step index fibre such as that shown in Figure 2 which would have a circular core of diameter d and uniform refractive index n_1 surrounded by a cladding layer of refractive index n_2. Light launched into the core at angles up to θ_1 will be propagated within the core at angles up to θ_2 to the axis. Light launched at angles greater than θ_1 will not be internally reflected and will be refracted into the cladding or possibly even out of the cladding if the launching angle is large enough and n_1 and n_2 are small enough. The maximum launch angle θ_1 and propagation angle θ_2 for propagation of the ray along the fibre can be expressed as a function of the maximum theoretical numerical aperture (NA) where

Fig. 2 Ray Diagram for Multimode Step Index Optical Waveguide



$$NA = \left(n_1{}^2 - n_2{}^2\right)^{1/2} = \sin\theta_1 = n_1 \sin\theta_2 \qquad \text{..... (1)}$$

Since this is an electromagnetic waveguide propagation, only certain modes which may be regarded as rays corresponding to specific quantized values of θ_2, can propagate.

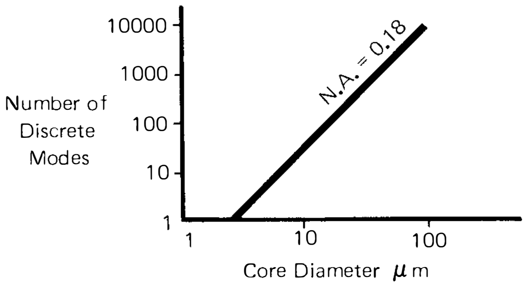
The number of discrete modes, N, for light having a wavelength of λ is given by:

$$N \simeq 0.5 \left(\frac{\pi d\,(NA)}{\lambda}\right)^2 \qquad \text{..... (2)}$$

where d is the diameter of the core.

Thus for a given combination of refractive indices (defined by NA in the equation), as the diameter of the core is reduced, fewer modes propagate. When eventually the diameter becomes of the same order as the wavelength of the light, then only a single mode will propagate. Figure 3 illustrates this point.

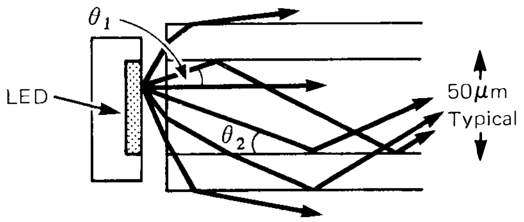
Fig. 3 Graph Showing Reduction in Number of Modes with Reduction in Core Diameter (λ = 850 nm)



2.1.2 Launching conditions

It is now appropriate to consider the problem of launching the light from a source, such as a light emitting diode (led), into the fibre. Figure 4 shows a typical ray diagram for a light emitting diode in close proximity to a multimode fibre. It can be seen that to ensure maximum launching efficiency the diameter of the active area of the led should be not greater than the diameter of the core. If the active area of the led were larger than the diameter of the core then light rays would enter the cladding region where they would be severely attenuated. Even if the light source is butted right up to against the fibre core and matches its area exactly, only a portion of the light emitted from the led would propagate, namely those rays which strike the fibre at angles less than θ_1. The higher the numerical aperture of the fibre the more efficient the coupling. Additional optical power can often be launched into the fibre by the use of a lens. Led's with lenses incorporated are commercially available and can be supplied with or without fibre tails. The optical power (watts/sterad/mm^2) which can be coupled into a fibre butted up against a source radiating uniformly is given by:

Fig. 4 Simple Ray Diagram Showing Launching Conditions with an LED Source and Multimode Fibre



$$P_{in} = \pi \,.\, A \,.\, R \,.\, (NA)^2 \qquad \text{..... (3)}$$

where R = radiance (watts/steradian)

A = core or emitting area, whichever is the smaller (mm^2)

2.1.3 Multipath Dispersion

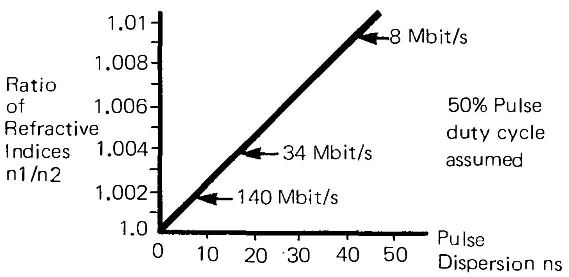
Unfortunately there is a disadvantage in having a high numerical aperture because it means that a fairly large number of modes can propagate along the length of the fibre. (See equation 2.) Now different modes will travel different distances along the fibre and they therefore arrive at the far end at different times. This effect is known as multipath pulse dispersion and becomes a significant problem in high speed digital transmission on optical fibres. The difference in arrival time at the far end of the fibre of a ray travelling along the centre of the fibre and one which propagates with a maximum angle of θ_2 for multimode fibres is:

$$\Delta t = \frac{L}{c}(n_1 - n_2) \qquad \text{..... (4)}$$

Where Δt is known as the multipath (or sometimes 'waveguide') dispersion, L is the length of the fibre and c is the velocity of light in a vacuum.

The variation of multipath pulse dispersion with various values of refractive index ratio n_1/n_2 are shown in Figure 5. From Equation 1, there is a direct relationship between NA and refractive index ratio. It follows that the multipath pulse dispersion increases with increase in numerical aperture, or in other words the bandwidth decreases with increase in numerical aperture.

Fig. 5 Graph Showing Variation of Pulse Dispersion with Refractive Index Ratio n1/n2 for 1km Length of Step Index Fibre



A typical value of maximum theoretical numerical aperture for optical fibres used in telecommunications long-distance applications is 0.2. Fibres for use with short-haul data links can however have NA's as large as 0.5 because of the shorter distances and lower bit-rates at which they operate.

2.1.4 Material Dispersion

As the number of modes that can propagate is reduced by reducing the diameter of the fibre core and also by restricting the refractive index difference to very small values, then material dispersion rather than multipath dispersion becomes a problem.

Material dispersion occurs as a result of the fact that the refractive index of the medium and hence the velocity of propagation varies according to the wavelength of the transmitted light. It can be a problem when optical sources having wide spectral spreads are used because dispersion of the transmitted pulse results. Material dispersion effects are however generally much smaller than those due to multimode dispersion and high speed digital transmission is still possible provided the light source has a narrow enough line width, eg semiconductor lasers. The way in which the material dispersion is dependent on wavelength is shown in Figure 6. The advantages of systems operating at wavelengths around 1300 nm are quite apparent.[4]

To illustrate the mechanism of material dispersion consider for instance a light emitting diode which has a spectral width of approximately 40 nm. Dispersion will occur owing to the fact that the light energy from the led comprises a number of different frequencies whose time to travel through the fibre will be different giving a dispersed pulse at the far end. Typical pulse spreading for this example might be 4 ns/km. (See Figure 7.) Fortunately this can be significantly reduced by using lasers which generally have spectral widths of 2 nm or less. Such lasers would give a pulse spreading of about 0.1 ns/km when connected to monomode fibre and are thus capable of transmitting signals at rates of 1 Gbit/s or

Fig. 6 Relationship Between Material Dispersion and Wavelength for a Typical Fibre

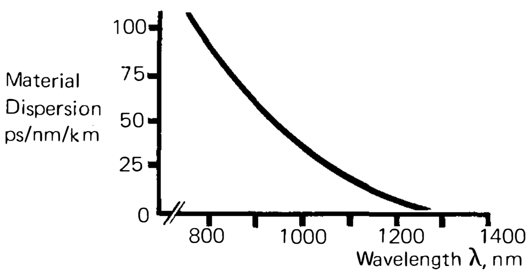
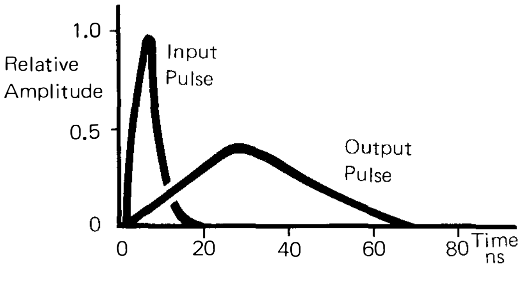


Fig. 7 Pulse Dispersion for Typical 1km Length of Multimode Step Index Fibre



more. The material dispersion bandwidth is given by:

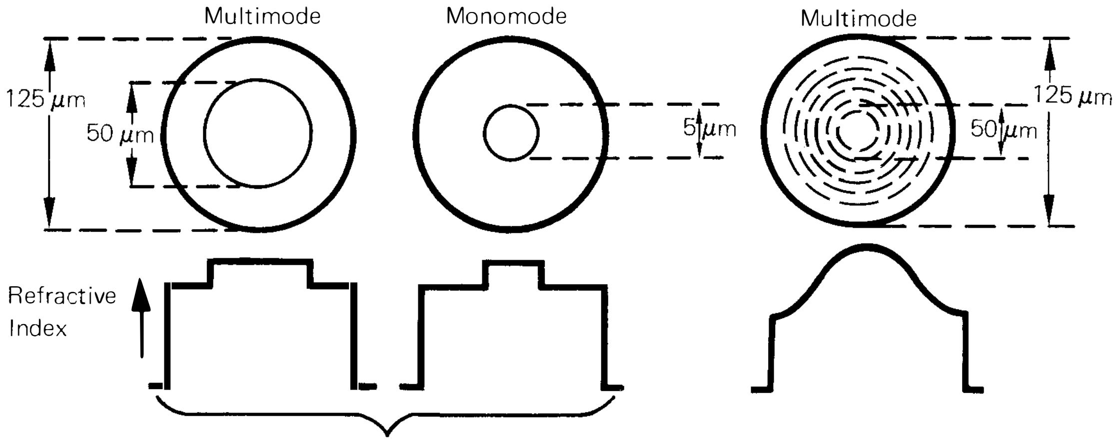
$$f_d = \frac{f_{dk}}{L . \lambda_s} \qquad ..... (5)$$

where f_{dk} = 3 dB electrical signal bandwidth owing to material dispersion of 1 km of fibre for 1 nm spectral spread of the source – typically 3.3 GHz/km/nm for silica.

λ_s = spectral spread of the source in nm between optical half power points.

L = length of fibre in km.

Fig. 8 Refractive Index Profiles *(Typical Dimensions shown)*



a) Step Index Profiles

b) Graded Index Profile

2.1.5 Graded Index Fibres

So far the discussion has been limited to step index fibres, that is optical fibres whose refractive index difference between the core and the cladding is a discrete step as shown in Figure 8(a). It is possible however to construct an optical waveguide by using a graded continuous index profile [5] as shown in Figure 8(b). Such a fibre does not have a distinct core and cladding region. Instead, the refractive index changes continuously from its maximum value on-axis to a lower value at the fibre boundary. The optimum index distribution for a graded index fibre is given by:

$$n_r = n_{max}\left(1 - 2\Delta_n r^{\alpha} a^{-\alpha}\right)^{\frac{1}{2}} \qquad ..... (6)$$

n_r = refractive index at distance r from fibre axis

n_{max} = refractive index at the fibre axis

n_{min} = refractive index at outer edge of fibre

$\Delta n = n_{max} - n_{min}$

r = distance from fibre axis

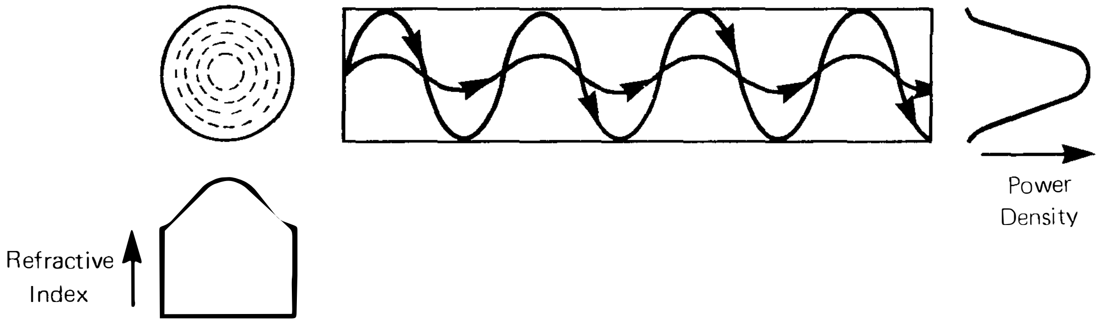
a = radius of the fibre core

$\alpha \simeq 2$ (but depends on exact composition of the fibre core and operating wavelength.)

This optimum index distribution corresponds to a near parabolic refractive index profile.

With this type of profile many modes can propagate. Two of these are illustrated in Figure 9. However the modes which travel in the outer regions of the fibre are in a region of lower refractive index and therefore travel faster than those travelling in the higher refractive index region near the fibre axis. The net effect, given the appropriate refractive index profile, is that the light rays

Fig. 9 Typical Ray Paths for Graded Index Fibre



although travelling by different modes arrive at the far end of the fibre at about the same time, ie with minimal multipath pulse dispersion. Thus the advantage of a multimode parabolic or graded index fibre lies in its ability to transmit signals with less distortion (multipath pulse dispersion) than the simpler multimode step index fibre. The pulse width of an infinitely narrow input pulse by the time it reaches the far end of a graded index fibre of length L (otherwise known as multipath or waveguide dispersion) is given approximately by:

$$\Delta t = \frac{L}{2c} \cdot n_{max} \ \delta^2 \qquad \text{..... (7)}$$

where δ = parameter which determines the rate of change of refractive index.

For comparison purposes if one assumes n_{max} = 1.5 and δ = 0.01 the graded index fibre corresponds roughly with the multimode step index fibre discussed above having n_1/n_2 = 1.01. However instead of a pulse width of 50 ns for the step index fibre the graded index fibre contributes only 0.25 ns (see Figure 5 for comparison with step index fibre). The signal distortion of the multimode graded index fibre is thus considerably less than the multimode step index fibre and the former type of refractive index profile is clearly superior where large bandwidths are an important requirement.

2.1.6 Monomode Fibres

Graded index fibres are certainly capable of offering very high bandwidth capability compared with step index multimode fibres. However, even graded index fibres eventually present bandwidth limitations for high bit-rate systems and/or when large repeater spacings are required. The answer for these applications has been to eliminate multipath dispersion by reducing the core diameter from typically 50 μm for multimode step-index fibres to about 5 μm. The number of modes which can then propagate along the fibre is severely restricted and in a true monomode fibre only one mode can propagate.

It follows that if only one mode can propagate then multipath dispersion will not be present. The effects of material dispersion become more noticeable in monomode fibres because of higher bandwidths which are expected from them. These effects can however be counteracted by arranging for a limited amount of waveguide dispersion to be present, thus achieving zero overall dispersion.

2.2 Fibre Loss Mechanisms

Fibre losses are an important consideration determining the feasibility of optical fibres for systems use. The most important fibre loss mechanisms are discussed below.

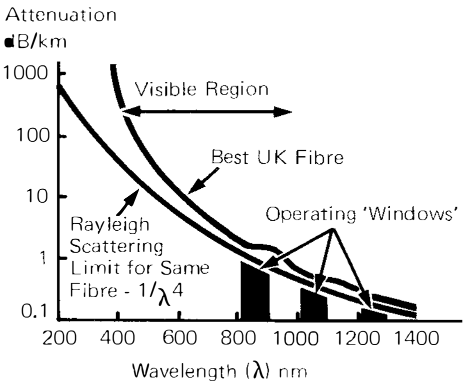
i. Absorption Loss

Absorption losses in glasses are mainly due to the presence of impurity ions. [6]. Table 1 shows the concentration of certain materials which would give rise to an attenuation in glass solely due to absorption loss.

Table 1: Absorption of different types of glass at 850nm for impurity concentrations of one part per million.

Impurity	Absorption peak nm	Absorption dB/km	
		Borosilicate type glass	Fused silica
Fe	1100	5	130
Cu	800	500	22
Cr	650	25	1300
Co	700	10	24
Ni	1200	200	27
Mn	500	11	60
OH	950	15	10

Fig. 10 Optical Fibre Attenuation



It can be seen that the requirements for the purity of the glass from contamination with metal ions are very stringent and are comparable with the purity requirements for semiconductor manufacture. A typical attenuation/wavelength characteristic is shown in Figure 10. The presence of water in the glass gives rise to harmonics of vibration (of the OH radical) which produce absorption losses in the wavelength bands of interest. The fundamental frequency of OH vibration corresponds to a wavelength of 2800 nm and it is the third and fourth harmonics which occur at 945 nm and 720 nm which are particularly troublesome. It can be seen from Figure 10 that there is an attenuation 'window' between 800 and 900 nm and because devices which operate at these wavelengths have been readily available the 800-900 nm band has been the first to be used for optical fibre systems. Nevertheless it will be realised that lower attenuations can be achieved if the systems could operate at higher wavelengths. In addition, reference to Fig 6 indicates that the effects of material dispersion are much reduced at the higher wavelengths. For these reasons much work is being carried out on devices which can operate in the 1100 and 1300 nm wavelength bands.

Well established methods such as RF melting, and chemical vapour deposition are commonly used in the production process and great care is taken to avoid contamination of the glass. There are two main categories of glass which are generally used in the fabrication of fibres.

Borosilicate Type Glasses. Borosilicate type glasses have a relatively low melting point and fibres using this type of glass are usually made using the double crucible process.

Fused Silica. Pure fused silica glass has a higher melting point and such fibres are generally produced using the chemical vapour deposition technique. These fabrication techniques are discussed later.

ii. Scattering

There are two main scattering mechanisms. The first, known as Rayleigh scattering, is due to inhomogeneities of the dielectric material. These inhomogeneities are unavoidable since the molecules in an amorphous material are randomly distributed. The Rayleigh scattering loss is proportional to the inverse of the fourth power of the wavelength (ie $1/\lambda^4$). Thus it decreases very rapidly with increasing wavelength and low losses are achievable at infra-red wavelengths. A typical characteristic is shown in Figure 10. The Rayleigh scattering loss in fused silica at 1000 nm wavelength is typically 0.8 dB/km.

The other type of scattering is due to irregularities of the core-cladding interface which are normally formed in the fibre fabrication process. These irregularities mean that rays incident at the core-cladding interface at an angle θ, will not be reflected at the same angle. This change in the ray path is known as mode coupling or mode mixing. Some of the modes, of course, may be of the higher order type which are refracted out into the cladding region where they are severely attenuated and effectively lost. It should be pointed out that mode-coupling is not entirely disadvantageous since the mixing of the modes results in an average velocity for the light rays and a corresponding reduction in pulse spreading or dispersion. Indeed in the presence of mode coupling the pulse width no longer increases proportionally to the length of the fibre but only as the square root of its length.

iii. Radiation Loss (Microbending Loss)

It has been stated that total internal reflexion keeps the light rays confined to the core. In actual fact an exact analysis of guided waves [7] indicates that some power is actually carried outside the core in the cladding, and decays exponentially as a function of distance from the core. This evanescent field tail moves along with the field in the core. When the fibre is bent the field tail on the far side from the centre of curvature of the bend is forced to move faster to keep up with the field in the core. At a certain distance from the core the outside field would be forced to move faster than the velocity of light in the cladding. The field resists being dragged along at such high speeds by radiating away. The amount of radiation loss depends on the field intensity at the distance where the evanescent field tail would exceed the speed of light and is very strongly dependent on the radius of curvature of the fibre. Below a certain threshold the radiation losses are negligible but above the threshold the losses become enormous. The critical radius of curvature (R) is given by:

$$R \simeq \frac{3n_1^2\lambda}{4\pi\left(n_1^2 - n_2^2\right)^{3/2}} \qquad \text{.....}\ (8)$$

For $\lambda = 1000$ nm, $n_1 = 1.5$ and $n_1/n_2 = 1.01$, R is calculated to be 58 μm. The critical radius is therefore very small and great care is taken to avoid microbending of the fibre when housed in its cable in order to avoid the very high losses due to radiation. (See para 2.4.)

2.3 Fibre Fabrication

Optical fibres for telecommunications applications of the graded index or multimode step index types generally have a core diameter of 50 μm and a cladding diameter of 125 μm. There are two main methods of fabricating optical fibres currently in common use:

i. Chemical Vapour Deposition (CVD)

This technique [8] involves the preparation of a preform which is manufactured by passing pure silica vapour together with a suitable dopant such as germania or a phosphor compound through an ultra-pure silica tube having a typical overall diameter of about 8 mm, as shown in Figure 11. The dopant is used to increase the refractive index of the deposit formed on the inside of the silica tube. The tube is then collapsed to form a solid rod by heating it in a furnace. The preform, as it is called, is then mounted vertically and its base heated by means of a ring burner through which the fibre is drawn and reeled onto a drum. To protect the fibre

Fig. 11 Chemical Vapour Deposition

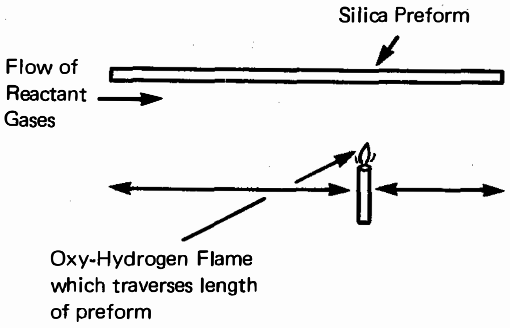
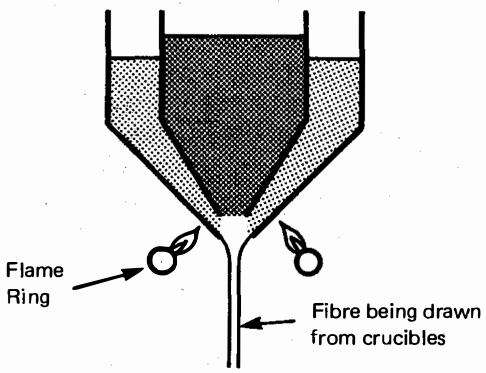


Fig. 12 Double Crucible Method



from microcracks a primary coating of a suitable material (various polymers and varnish have been used) is applied during the fibre-drawing process. Great care is taken in the pulling process since the tension applied to the fibre affects its overall diameter. Accurate servo-control systems are generally used in order to obtain fibres having dimensions within prescribed tolerance limits. Some fibre manufacturers even monitor the fibre attenuation as the fibre is being drawn from the preform.

An alternative technique which has been employed is known as external chemical vapour deposition. In this method suitable gases are passed along the outside of a very pure silica rod. Heat is applied to the rod thereby causing a deposit to form on the outside of the rod. By varying the amount of dopant in the gases a suitable refractive index profile is built up. The preform produced in this way is then drawn in just the same way as the preform formed using a tube (ie the internal CVD method).

The internal CVD method permits better control of contaminants such as water and some of the world's lowest loss fibres have been produced using this method. The external CVD method however enables much longer lengths of fibre to be pulled from a preform of a given length.

ii. Double Crucible

This method [9] uses concentric crucibles in a suitable furnace as shown in Figure 12. Glass is extruded through concentric nozzles at the bottom of the crucibles into a fibre. The core material is contained in the inner crucible and the cladding in the outer crucible. This technique can readily be employed for pulling step-index fibres of either the multimode or monomode types but recently even graded index type fibres have been produced using this technique. By continuously topping up the level of the molten glass in the two crucibles extremely long lengths of fibre can be pulled in one operation. In order to avoid contamination of the glass the crucibles are made from ultra pure platinum. This particular technique is often adopted for the manufacture of low-melting point boro-silicate type glasses.

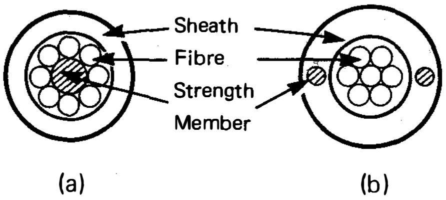
2.4 Cables

There are two fundamental techniques used in the cabling of optical fibres: the first is the tight-jacketed technique involving the coating of the fibres; the second is the loose-tube technique whereby the fibre lies loosely within a plastic tube having an internal diameter of about 1 mm. The advantages of each technique are currently being established and there is strong support for both. The first technique gives a reasonably constant performance over a wide temperature range but high incremental losses on cabling; the loose-tube technique on the other hand has negligible incremental loss but the temperature performance is not quite as good.

Optical fibres can be readily assembled into cables using standard cable making machinery. [10, 11]. The fibres when produced by one of the above processes are generally wound onto small drums. The fibres pass through a stranding machine which brings them together and strands them, followed by a sheathing machine, which applies protective layers of paper or a suitable polymer around the whole assembly and then sheaths them with polythylene or equivalent, thus forming the complete cable assembly.

Various cable structures have been proposed and made. Two of the more common designs are shown in Figure 13. A number of designs have been demonstrated in realistic field conditions with no significant problems. To avoid stressing the fibres when the cables are being installed, strength members, usually of either steel or high tensile nylon, are generally incorporated in the cable.

Fig. 13 Some Common Cable Designs



(a) (b)

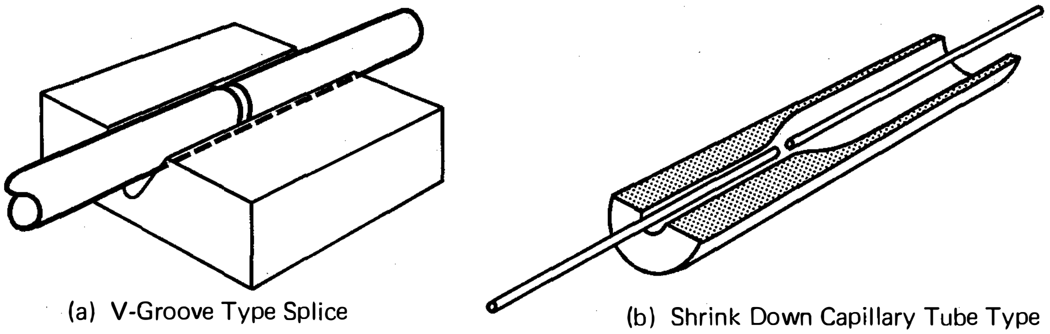
For certain applications it is desirable to incorporate metallic conductors in the optical fibre cable. This is the normal approach when no local sources of power are available for the dependent repeaters. The conductors can be included in most cable designs, particularly those in which the overall diameters of the coated fibres and insulated conductors are of similar size. The requirement for metallic conductors is unlikely to be a long term one since within a few years repeater spacings should be such that intermediate repeaters can be located in surface buildings and locally powered.

The lengths of optical fibre cable which can be manufactured are limited to the maximum lengths of fibre which can be produced in one operation. Cable lengths of 1 km are typical but lengths of 2 km have been made and 5 km lengths are not impossible. Optical fibre cables have been installed in underground ducts in 1 km lengths with considerable success and the installation of longer lengths is being investigated.

2.5 Joints

There are various techniques which have been developed for jointing optical fibres and two of the commonest are shown in Figure 14. The V groove type joint was the first [10] and probably the easiest to perform. It merely consists of a shallow V groove milled out of a small slab of metal, usually copper or

Fig. 14 Some Common Methods of Jointing Fibres



(a) V-Groove Type Splice

(b) Shrink Down Capillary Tube Type

brass. One fibre is placed in the V groove and clamped in position and the other fibre is butted up against it. Index matching fluid is applied as the fibres are brought together which helps to clean the fibre faces and keep out the air and any impurities. Both fibres are either clamped in position or held in position by a suitable epoxy resin.

The other technique shown in Figure 14 uses a glass tube which is heat shrunk over the fibres. A capillary tube whose inner diameter is just sufficiently greater than the overall diameter of the bare fibre (ie without its protective coatings), is shrunk down at one end over one of the fibres to be jointed by applying highly localised heat. The fibre and the end of the capillary tube fuse together. The other fibre to be jointed is then fed into the other end of the capillary tube, together with a drop of index matching fluid. This end is then heated and the capillary tube shrinks and fuses with both fibres providing a simple, slim and effective low loss joint. A slim metal ferrule is sometimes fitted over the whole assembly to give increased mechanical protection.

A third technique which is rapidly becoming very popular is the fusion of the two fibres using either an electric arc or a concentrated gas flame.

In general, the loss through joints is a function of the closeness to which the core and cladding of the two fibres can be aligned. This in turn is a function of the accuracy with which the diameter of the core and the non-circularity and concentricity of the core and the cladding can be maintained in the fibre fabrication process. However typical losses are nowadays very low with losses of as low as 0.1 dB having been reported for joints performed in some laboratories. Certainly joints performed in field conditions average somewhat less than 0.5 dB.

2.6 Connectors

Various techniques have been employed in the design of optical fibre connectors over the years. The most common techniques currently employed are as follows:—

i. Ferrule technique

This method involves the use of small diameter ferrules, usually about 2 mm in external diameter, within which the fibre is accurately positioned. The fibre may be located by means of a precision jewel mounted at the end of the ferrule and is held in position by the application of fast setting epoxy resins. The ferrules forming each half of the connector are then inserted into a precision tube or a barrel formed from a number of metal rods which holds the ferrules in position. Losses of the order of 1 - 2 dB are typical for this technique.

ii. Lens system

The use of a lens in each half of the connector has the advantage that the mechanical tolerances for the connector do not need to be so tight. Moreover in principle the losses can be quite low eg 0.5– 1 dB. The problem with this technique is that, at the present time, the fibres usually need to be accurately positioned with respect to the lens, even though the lens-lens interface itself is not too critical.

iii. Triple (or quadruple) ball system

This technique involves the use of three or four small metal balls (ballbearings are often used) which are held together to form a triangular (or square) shape. By employing balls having appropriate diameters the size of the hole in the middle formed by the balls can be made to be such that the fibre is just held in position. In this way it is possible accurately to align two fibres and losses of less than 1 dB are readily achieved.

iv. Moulded plug and socket

The use of completely plastic connectors has been demonstrated successfully. With this technique the plastic connectors are actually moulded onto the fibres. Losses of 0.5–2.0 dB have been achieved with this technique which promises to be relatively cheap.

The current view is that index-matching fluid is not desirable for use with connectors and as a result there will be a basic loss in every connector, due to Fresnel losses, of the order of 0.35 dB. Mechanical tolerances of the connector and fibre manufacturing tolerances mean that practical losses for connectors are likely to be in the range 0.5–1.0 dB.

3. Optical Light Sources

3.1 General

Section 2.2 indicated that the lowest fibre losses are to be found in the region 800–1600 nm. It follows therefore that the wavelength of an optical light source for an optical fibre system should be in this same region. The other important requirements [12] are that the light source should have high optical power density, minimal beam divergence, high spectral purity and be physically small. These various requirements reduce the number of options considerably so that only semiconductor light sources are feasible. There are two broad categories of semiconductor light source which are commonly employed: light emitting diodes and lasers.

3.2 Light Emitting Diodes

Light emitting diodes currently used for optical fibre communications are based on the semiconductor gallium arsenide (GaAs) which differs from the more common materials, germanium and silicon in that carrier recombination occurs efficiently by the emission of optical radiation at infra-red wavelengths rather than by the production of heat.

In its simplest form the GaAs led is no more than a forward biased p–n junction diode. At high forward bias, electrons are injected into the p-type region and 'holes' (positive charge carriers) are injected into the n-type region and recombination occurs. In practice most of the recombination is by electrons into the p-type material. On recombination the injected electrons release their excess energy as optical radiation in the infra-red wavelength range around 900 nm. An energy band diagram of a forward biased GaAs p–n junction is shown in Figure 15. The light output is obtained by etching a deep well in the n-type region into which an optical fibre, or alternatively a small lens, is fitted. Such a design of led gives rise to a high radiance

Fig. 15 Band Diagram of a Forward Biased Ga - As p - n Junction

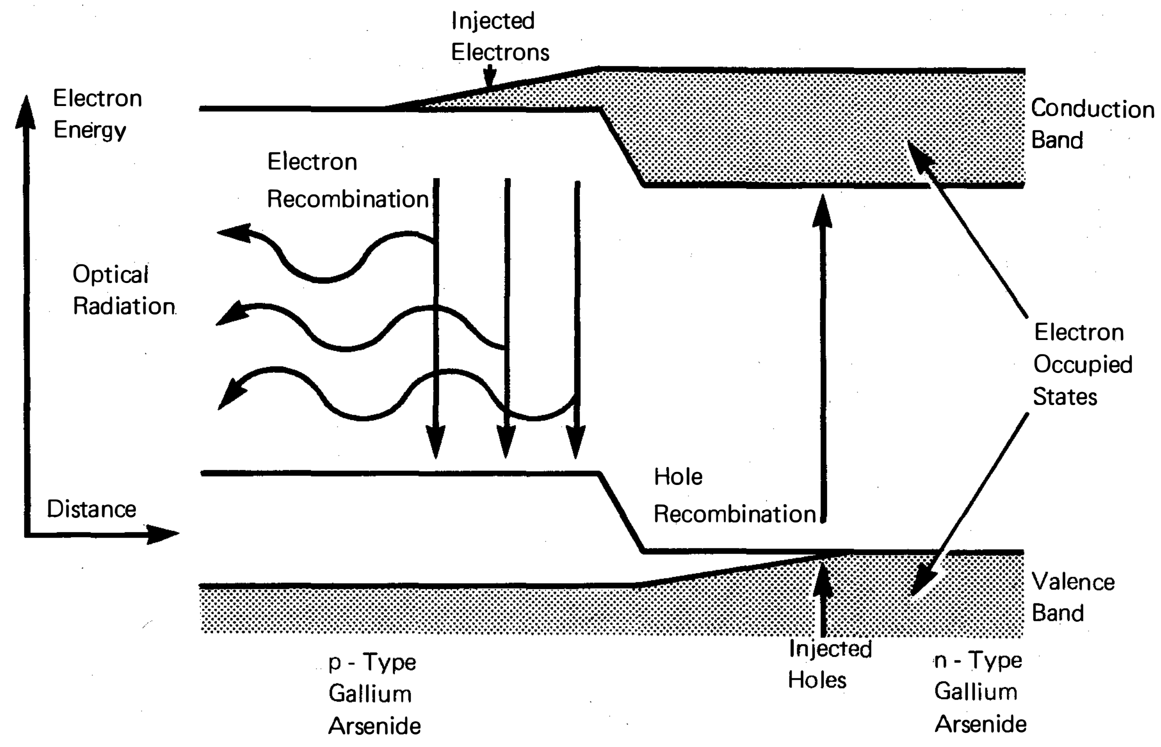
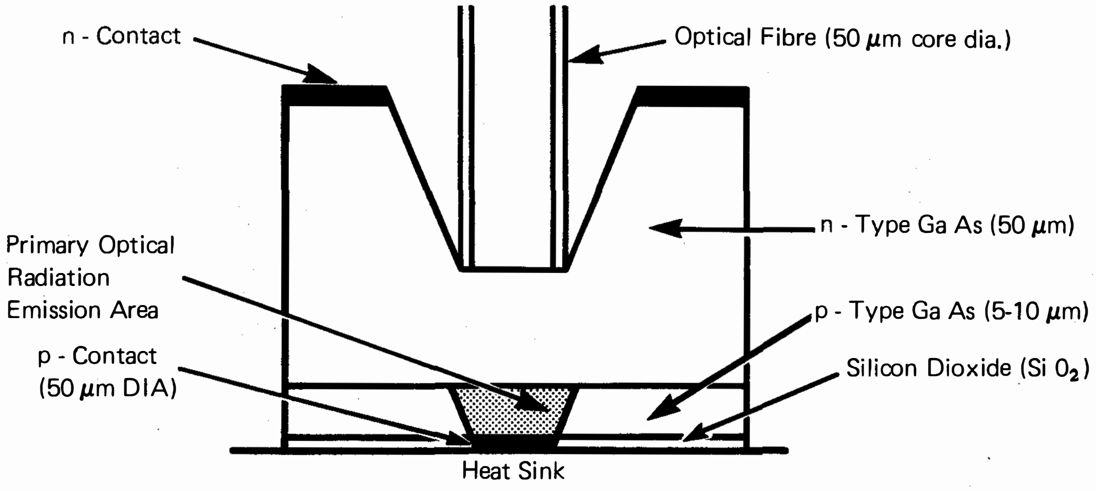
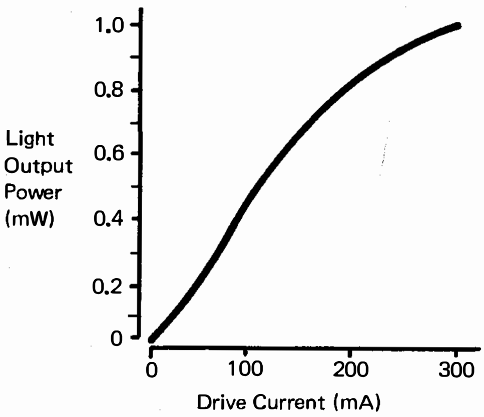


Fig. 16 Cross Section of a Homostructure Burrus-Type Light Emitting Diode



source. A cross-section of a homostructure Burrus-type diode is shown in Figure 16. These led's have a spectral spread of 30–40 nm which tends to restrict their use to lower speed digital systems (eg <35 Mbit/s) due to the effects of material dispersion (see para 2.1.4). However they do have the advantage that they can have a high frequency modulation capability which means that they can be used in both analogue and digital type optical transmission systems. Figure 17 shows the optical power output/drive current characteristic to be fairly linear up to about 300 mA. The typical optical power that can be launched into a fibre having a nominal core diameter of 50-60 µm is around 100 µW (-10 dBm) at the present time.

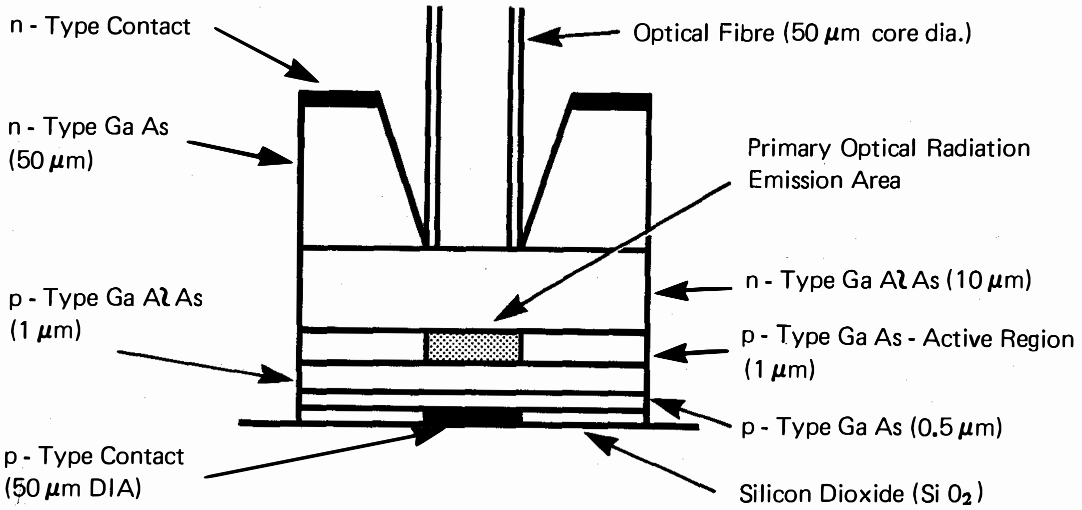
Fig. 17 Typical Light Output/Drive Current Characteristic for a Light Emitting Diode



The type of high radiance led (hr led) described above, known as a homostructure device, does not achieve its maximum theoretical brightness for two reasons: absorption in the GaAs surrounding the p-n junction and inefficiency of the radiative recombination process.

Double heterostructure hrled's have been developed to overcome these problems. In this structure the recombination layer (or active region) is sandwiched between layers of gallium aluminium arsenide (GaAlAs) as

Fig. 18 Cross Section of a Double Heterostructure Burrus Type Light Emitting Diode



shown in Figure 18. The layers of GaAlAs on either side of the active layer provide electrical barriers that prevent carriers being lost from the recombination region but are transparent to the emitted optical radiation. Double-heterostructure led's have been produced which radiate at near the maximum theoretical output power. Unfortunately these devices have spectral spreads of the order of 50 nm which imposes severe restrictions on system performance because of the effects of material dispersion.

Edge-emitting leds also have a double heterostructure construction but in this case the optical output is taken from one of the side faces in line with the stripe. In this respect they can be likened to double heterostructure lasers (see 3.3 below). However, unlike lasers they do not emit stimulated optical radiation; their output characteristic is thus rather similar to the spontaneous region of optical radiation of loss (see Figure 20). Edge-emitting led's have the advantage of having a higher optical output power than other types of led without the disadvantages of close current control required by semiconductor lasers.

Typical light emitting diodes have an overall power conversion efficiency of less than 0.2% and the wide spectral spreads limit the bandwidths which can be achieved. Thus for greater system modulation capacity, ie small spectral spread and greater launching efficiency, semiconductor lasers are often employed.

3.3 Lasers

Semiconductor lasers are used in optical fibre systems because they have the advantages of being extremely small and have reasonable power requirements (compared with gas lasers). The GaAlAs double heterostructure laser overcomes most of the problems of led's and is similar in structure to the Burrus type double-heterostructure led. The complex heterostructure arrangement is required in order to achieve low enough operating currents to permit continuous operation at room temperatures and above. A block diagram of a narrow stripe laser is shown in Figure 19.

Under forward-bias conditions, carriers are injected into the recombination (active) region, as in the case of the double heterostructure led, and optical radiation is emitted. An optical cavity is formed by making opposite ends of the device flat and parallel to each other and perpendicular to the active region. The emitted optical radiation is spontaneous and is in the form of photons, which are quanta of light energy. Those photons which travel in the plane perpendicular to the end faces are partially reflected at the GaAs - air boundary. These reflected photons stimulate the emission of more photons and the stimulated emission content of the optical energy builds up. At a certain critical drive current, known as the threshold current, a round trip gain of unity is achieved and laser action occurs. Above the threshold current electrical energy is efficiently converted into optical radiation some of which is emitted from the end faces (sometimes known as facets) of the laser.

Fig. 19 Cross Section of a Narrow Stripe Double Heterostructure Laser

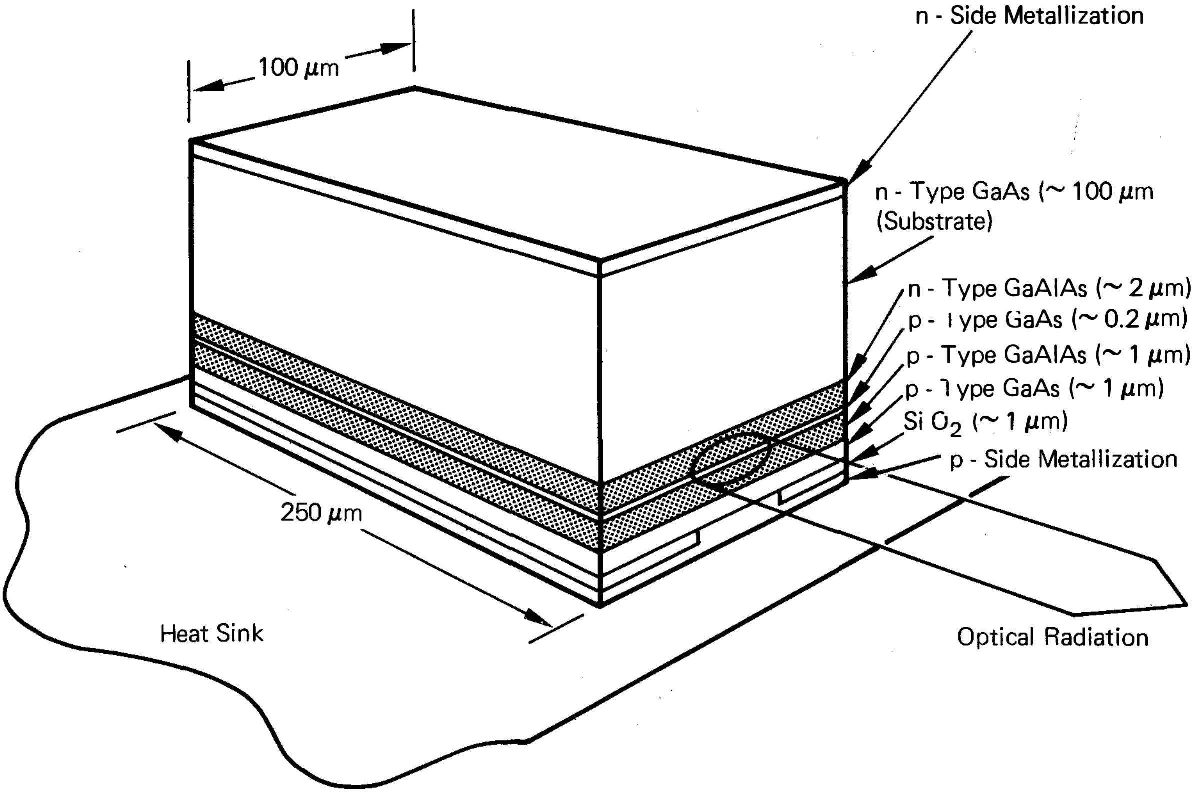
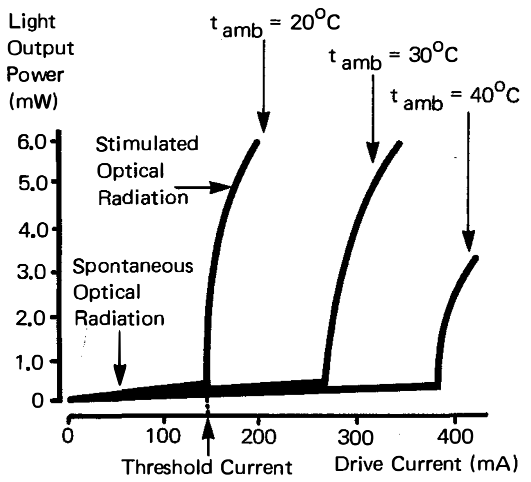


Figure 20 shows a typical optical power/drive current characteristic.

Fig. 20 Typical Light Output/Drive Current Characteristic for a Laser



Points worthy of note are that the threshold current is sensitive to temperature and increases by 1-2%/°C rise in ambient temperature. Although the slope of the characteristic above threshold is relatively insensitive to temperature changes it is rather steep and a comparatively small increase in drive current can cause a considerable increase in optical output. Consequently when incorporated into systems the threshold current and signal modulation current have to be closely controlled, usually by means of a feedback circuit, to prevent damage to the laser.

Lasers can be designed such that the optical radiation emitting area matches the optical fibre to which it is to be connected by altering the stripe width. By reducing the stripe width to less than 10 μm the spectral spread can be reduced to 1-2 nm, a factor of more than 10 times narrower than an hrled. Continuous optical output powers of 10 mW have been reported. Typical overall launching efficiency is around 1-2%.

Further work is continuing to reduce the magnitude of the threshold current from typically 150 mA at the present time to 50 mA or even 10 mA in due course.

The desirability of devices operating at wavelengths of the order of 1300 nm and 1550 nm has not been forgotten and work to produce suitable lasers operating at these wavelengths is building up.

The reliability of lasers is a subject about which there is much discussion. It is a characteristic of optical devices such as lasers that their optical efficiency falls gradually during operation of the device. This degradation of efficiency occurs by an intrinsic process that creates defects close to, and within, the recombination (active) region of the device. These defects then allow carrier recombination to occur without optical emission. The defects, often known as 'dark line defects', orginate in areas of the device which have been subjected to strain due to dislocations in the crystal lattice, the effects of p-type contact metallisation or by bonding procedures.

Much work has gone into studying the failure mechanisms and dark line defects are practically negligible in modern day devices. The coating of the laser facets is another technique that is being used to improve the lifetimes of lasers still further.

Life tests currently being carried out [13, 14] have indicated that lasers can operate for many tens of thousands of hours without failure and the pace of technology is such that lasers with lives of 200 000 hours or more should be achievable within the next year or two.

To summarise therefore, the double heterostructure semiconductor injection laser is well suited for use with optical fibre communication systems. Its desirable characteristics include small size (the actual chip is the size of a grain of sand), ruggedness, good relative efficiency, and the fact that it can be directly modulated by means of the injected drive current.

4. Optical Detectors

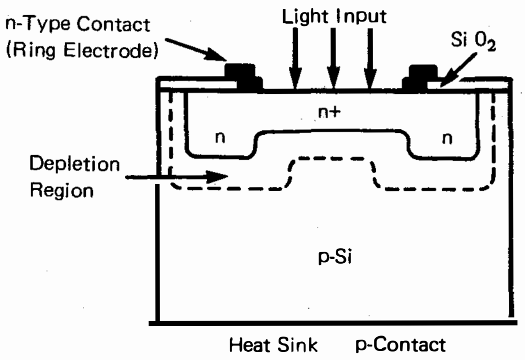
4.1 General

In optical fibre systems some form of optical detector is required at the receive end of the fibre in order to detect the modulated light that is transmitted along the fibre. The most suitable devices are semiconductor photodiodes on grounds of cost, reliability and size. They also have a high optical sensitivity, high speed of response and low noise. The two main types of semiconductor photodiode [15] are the PIN and Avalanche photodiodes; both types are discussed below:

4.2 PIN Photodiodes

A semiconductor photodiode, in its simplest form, is a p–n junction on which the light is usually incident perpendicular to the junction plane as shown in Figure 21. The absorption of light in the vicinity of the junction produces electron–hole pairs, which can come under the action of the electric field present in the depletion region of the junction. The electrons and holes then drift under the action of the electric field in opposite directions across the depletion region, thereby causing a current to flow through a load resistance in an external circuit. The photodiode is reverse biased with a voltage of typically less than 20 volts. A typical current/reverse bias voltage characteristic is shown in Figure 22.

Fig. 21 Cross Section of a Silicon Photodiode (Pin Type)



The performance of the simple p–n junction photodiode can be significantly improved by incorporating a high resistance intrinsic (i) layer which is sandwiched between the p-type and n-type regions. Such a structure is known as a pin photodiode. The thickness of the intrinsic layer can be made much greater than that of the depletion region in a p–n junction, with the consequent advantages of lower junction capacitance and higher quantum efficiency. The increased thickness of the field region due to the intrinsic layer also results in fewer carrier pairs being generated in regions where diffusion processes limit the speed of response.

Fig. 22 Current/Reverse Bias Voltage Characteristic of a Typical Photodiode

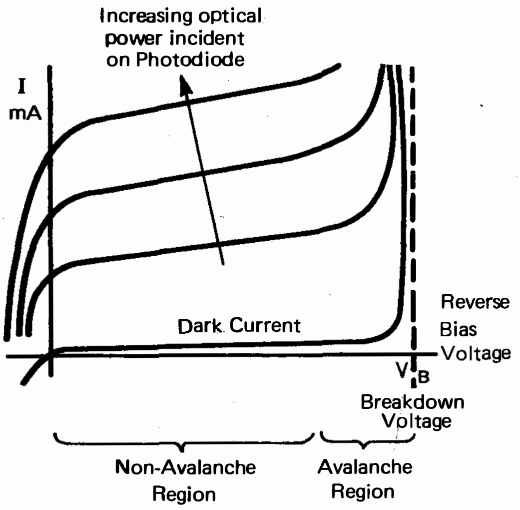
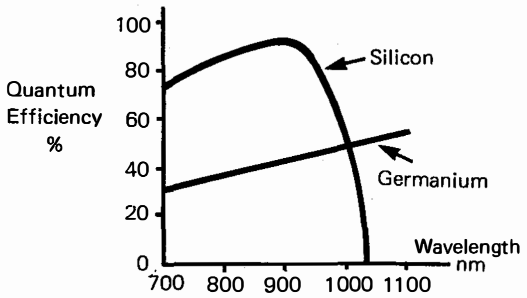


Fig. 23 Quantum Efficiency for Silicon and Germanium Photodiodes

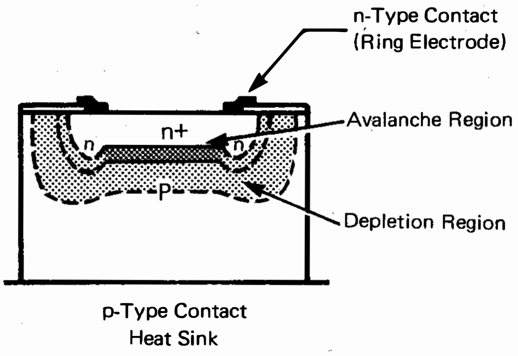


A point worthy of note is that the quantum efficiency of photodiodes varies according to the wavelength for different materials as shown in Figure 23.

Because pin photodiodes are generally less expensive than avalanche photodiodes and because they require much lower operating voltages they are desirable devices for systems use. Work to increase their sensitivity has therefore been carried out by combining the pin photodiode chip and the following FET chip on the same substrate thereby minimising stray capacitances and increasing the sensitivity of the pin diode-FET combination to within 2-3 dB of that of an avalanche photodiode [16].

These pin-photodiode-FET combinations also have the advantage that they are much more sensitive at longer wavelengths than other devices - thus paving the way for the operation of systems at the higher wavelengths.

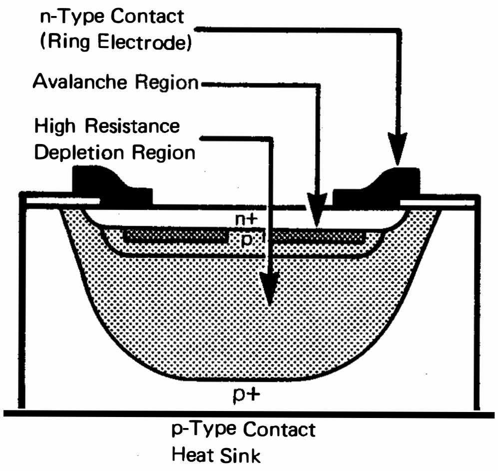
Fig. 24 Cross Section of a Silicon Avalanche Photodiode



4.3 Avalanche Photodiodes (APD's)

When the reverse-bias voltage applied to a p-n junction is close to the breakdown voltage (see Figure 22), the carriers traversing the very high electric field region at the junction gain sufficient energy to create new electron-hole pairs when they interact with the crystal lattice. This process is known as avalanche multiplication and effectively permits, typically, a 10 dB decrease in the minimum detectable power for the same signal to noise ratio at the output of the photodiode. A cross-section through an avalanche photodiode is shown in Figure 24.

Fig. 25 Cross Section of a Silicon Reach-Through Photodiode



Just as the performance of non-avalanche photodiodes is improved by extending the thickness of the depletion region (as in the pin photodiode), so the quantum efficiency of avalanche photodiodes can be significantly increased by extending the depletion region as shown in Figure 25. Such a device is known as a 'reach-through avalanche photodiode'. In this structure the thick high resistance depletion region has a lower field which sweeps the electrons, generated by photon absorption, into the avalanche region giving higher quantum efficiency.

The use of avalanche photodiodes permits significant improvements in system performance but they do suffer from the disadvantages that they require high reverse-bias voltages, typically 300-400 volts, which must be supplied at repeaters by dc-dc converters, and the fact that the breakdown voltage increases with temperature, which causes a decrease in the quantum efficiency. Accordingly special temperature compensation circuitry has to be provided.

Although avalanche photodiodes have hitherto been used quite extensively for experimental work, field trials and in a number of first generation operational systems, the rapid advances in the development of PIN-FET hybrid modules mean that APDs are unlikely to be favoured for general use in the future.

5. Systems Design

The fundamental constituent parts of a digital optical fibre system were shown in Figure 1. The transmit and receive terminal station equipments are shown in more detail in Figure 26. On longer routes, intermediate repeaters (not shown in Figure 26) may be required, which may be either of the buried variety or housed in surface stations.

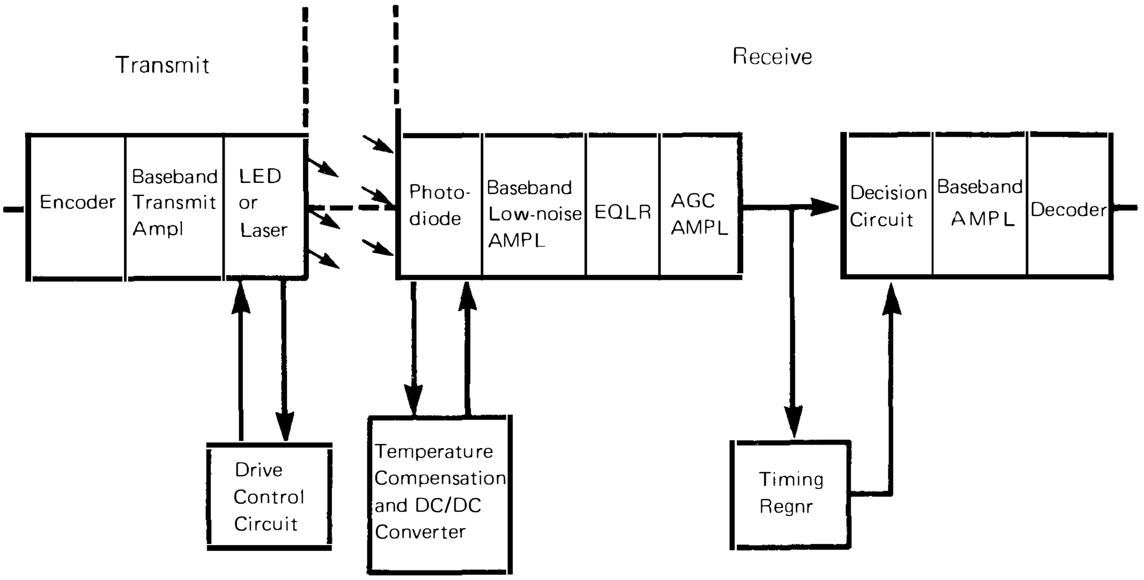
In the simplest analogue system the transmit device would be a light emitting diode, and the receive device would probably be a PIN photodiode. The led would be directly modulated causing the optical power to alter in direct proportion. After detection by the PIN photodiode the signal would be amplified and equalised. Such systems are often used for tv transmission over short distances. Repeater spacings would be of the order of 2–5 km.

Where larger repeater spacings are required the higher output power of the laser is necessary, but simple analogue modulation of the laser is not usually employed. This is because the very large difference between the light emitted above and below the threshold makes the laser a very non-linear device and operation in the stimulated emission region of the laser drive characteristic requires complex control circuitry.

Simple encoding arrangements such as pulse position modulation of the laser where the pulse amplitude is maintained constant are often used. Systems using this technique have been successfully demonstrated for the transmission of colour tv signals over reasonably long distances.

For junction and main (trunk) network telecommunications applications where several repeaters would be required with reasonably large repeater spacings a more complex coding system is employed. Such a system encodes the incoming digital stream such that timing information and error checking information is included in the line signal. The line signal directly modulates the transmit device, which can be either a laser, an led or an edge-emitting led depending on the type of system. When lasers are used, especially on the high speed systems, in order to keep the turn-on delay to a minimum the lasers are not pulsed from zero but from a point just below the threshold. This necessi-

Fig. 26 Block Diagram of a Digital Optical Fibre Transmission System (without repeaters)



tates the use of well-controlled feedback circuitry especially since the threshold point varies with temperature. Circuitry to maintain the light output level constant with time and temperature is also generally provided when lasers are used although this is not so important for led's.

The optical line signal on a digital system will thus be a series of light pulses according to whether the laser or led is on or off. The bit rate of the line signal is generally greater than the bit rate of the incoming signal due to the addition of the timing and error checking bits. Typical line codes are of the 5B 6B type which which means that for every 5 bits in the incoming bit stream 6 are sent to line. This type of line code has a high redundancy factor eg $\frac{6-5}{6} \times 100 = 16.7\%$ for a 5B 6B code.

Thus an 8.448 Mbit/s digital stream at the input to the system would appear as a 10.137 Mbit/s stream on the line. Various 140 Mbit/s systems have used 7B 8B line codes in order to reduce the redundancy at the expense of coder complexity. Many other codes have been proposed and employed and the reader is referred to the standard texts for further information on coding [17].

The amount of optical power which can be coupled into an optical fibre depends on the

- optical power output from the source
- emitting area of the source
- radiation pattern of the source
- presence or absence of a lens system
- core diameter of optical fibre
- effective numerical aperture of optical fibre

For led's the optical power which can be coupled into an optical fibre is given in equation 3.

More complex expressions apply in the case of semiconductor lasers because currently available devices have a radiation pattern which is not symmetrical about the axis (refer to Section 3 for discussion on this point).

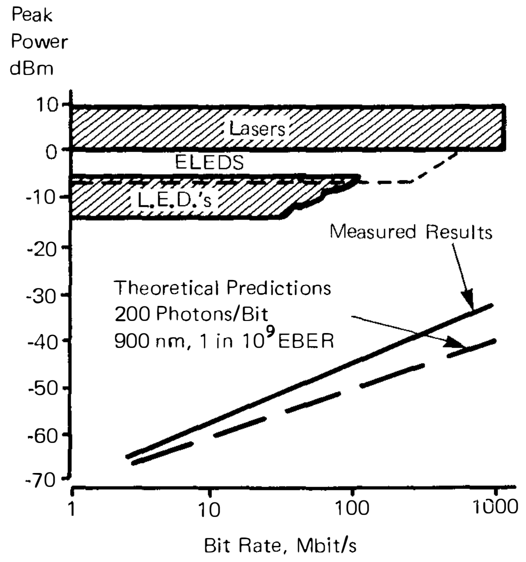
From equation 3 it can clearly be seen that the amount of optical power coupled into a fibre is not only dependent on the source but also on the core diameter and the effective numerical aperture of the fibre.

Typical values of optical power which can be coupled into graded index fibres of the type currently used in telecommunications applications are:

lasers 1.0 mW → 4.0 mW (0 dBm → +6 dBm)
eleds 250 μW → 1.0 mW (-6 dBm → 0 dBm)
leds 50 μW → 150 μW (-13 dBm → -8 dBm)

These levels are shown diagrammatically in Figure 27.

Fig. 27 Power Available for Opitcal Fibre Systems



At the receive end of the repeater section, which might be either at a terminal or at an intermediate repeater, the optical fibre is connected to a photodiode which converts the light pulses into electrical pulses. Hitherto avalanche photodiodes have tended to be used for digital systems because of the extra gain that can be realised by their use, which effectively means that the repeater spacings can be increased by the equivalent of 10-15 dB cable attenuation. The avalanche photodiodes are reverse biased at voltages currently in the range 300-400 V but the actual bias voltage is varied according to the ambient temperature by means of appropriate temperature compensation circuitry. In this way the photodiode performance is maintained reasonably constant for all temperatures within the operating range of the equipment. However the pin photodiode FET combinations, described in para 4.2, are beginning to supersede APD's, because of their longer wavelength potential.

5.1 System Noise

In optical fibre systems design the overall performance is determined largely by the minimum detectable optical power at the receiver [18, 19, 20]. Before discussing the design of receivers, it is appropriate to mention the sources of noise in optical fibre systems. There are three main types: —

i. Thermal Noise

Thermal noise arises from the photodiode load resistance and the amplifier which follows it. It can be expressed as a noise current at the input to the amplifier, i_t, where

$$\overline{i_t^2} = \frac{4kTBF}{R_L} \qquad ..... (9)$$

where k = Boltzmann's constant,
T = absolute temperature,
B = bandwidth,
F = noise figure for the amplifier,
and R_L = photodiode load resistance.

ii. Quantum Noise

Quantum noise arises from the random fluctuations in the rate at which photons arrive at the photodiode (the photons arrive in discrete packages or quanta). These fluctuations of the optical power are converted by the photodiode into a noise current, i_s, called the shot-noise current, where

$$\overline{i_s^2} = 2qI_PB \qquad .... (10)$$

where q is the electron charge and I_P is the signal photocurrent.

This noise source is dependent on the photocurrent and hence on the optical power incident on the detector.

iii. Dark-current Noise

When the optical power incident on the detector is zero a very small current, known as the dark current, still flows and contributes to the total system noise (see Figure 22). The noise associated with the dark current is given by:

$$\overline{i_D^2} = 2qI_DB$$

where I_D is the dark current.

The magnitude of the dark current, I_D, is dependent on the semiconductor material, the area of the p-n junction and the temperature. In present day silicon devices the dark-current can be made to be negligible.

The satisfactory operation of a system requires a minimum signal to noise ratio after detection. The signal to noise ratio for an optical fibre system employing non-avalanche photodiodes, taking account of the most significant noise sources, is given by:

$$S/N = \frac{I_P^2}{\underset{\substack{\uparrow \\ \text{thermal} \\ \text{noise}}}{\frac{4kTBF}{R_L}} + \underset{\substack{\uparrow \\ \text{quantum} \\ \text{noise}}}{2qI_PB}} \qquad ..... (12)$$

For most systems having a bandwidth in excess of 1 MHz thermal noise is usually the dominant noise source. The spacing between repeaters is maximized when the lowest possible signal power, generally known as the minimum detectable power, is incident on the photodiode, consistent with achieving the minimum acceptable signal to noise ratio. It can be shown that for an error rate of 1 in 10^9 bits the minimum signal to noise ratio must not be less than around 21 dB [21]. For practical purposes in order to provide a margin for such effects as inter-symbol interference etc a minimum signal to noise ratio of 25 dB is generally assumed. Figure 27 shows the minimum receive power levels (assuming a 25 dB signal to noise ratio) as a function of line bit rate for avalanche photodiodes.

The input signal to the amplifier which follows the photodiode may be increased with respect to the noise by increasing the load resistance and thus the required signal to noise ratio may be achieved with a lower optical power at the photodiode. However increasing the load resistance increases the time constant of the photodiode circuit and therefore the response time is reduced. To overcome this a simple equaliser is usually fitted after the photodiode amplifier to restore the system bandwidth required as shown in Figure 26. The 3 dB bandwidth of the photodiode circuit is given by:

$$f_P = \frac{1}{2\pi R_L C_P} \qquad \text{..... (13)}$$

C_P = photodiode capacitance

The equalizer network is usually followed by a regenerator which shapes the incoming signal, extracts the timing information inherent in the line code and uses this to open a gate at the appropriate time slots to permit the required line signal to pass through, ie to retime and regenerate the incoming signal.

The output from the regenerator is either amplified or connected straight to a decoder unit where the original digital traffic signal is reconstituted, ie the redundant or parity bits are removed from the bit stream. The digital signal from the output of the system is then passed on to either digital multiplex equipment or another digital line system in the normal way.

The building blocks for an intermediate repeater are the same as those used at the transmit and receive terminals but without the encoder and decoder (see Figure 26).

Figure 27, which shows the typical transmit and receive levels for different line bit rates, enables typical system gains to be calculated for any given bit rate [22]. Thus if the typical loss of the optical fibre connectors and joints is known and a suitable working margin is assumed the appropriate repeater spacing can be calculated.

Table 2 gives typical parameters for various system options.

There are various ancillary facilities which are often provided on line systems such as supervisory, speaker and power feeding facilities. These are not discussed in this paper in the interests of brevity. In principle it may be assumed that similar facilities to those employed on existing digital systems using metallic pairs (balanced or coaxial) will be provided. One exception however concerns the power feeding of intermediate dependent repeaters which, when required, is carried out using metallic interstice wires in the optical fibre cable, this being the most economical arrangement consistent with existing reliability and maintenance criteria. It must not be forgotten however that as the repeater spacings increase, so the need for dependent repeaters and therefore the need for power feeding will diminish, particularly on the shorter routes. Power feeding is thus likely to be a transitory requirement lasting perhaps only a few years.

Table 2: Some Optical Fibre System Options.

System	Transmit Device	Fibre Type	Typical Repeater Spacing km	Network Application
2 Mbit/s	ELED	GI or SI	25 Note 1	Local/ Junction
	LED	GI or SI	20 ″ 1	
8 Mbit/s	Laser	GI	22 ″ 1	Junction/ Main
	LED	GI	18 ″ 1	
34 Mbit/s	Laser	GI	19 ″ 1	Junction/ Main
	LED	GI	14 ″ 1	
140 Mbit/s	Laser	GI	12 ″ 2	Main/ Submarine
		SI Monomode	40 ″ 3	
280 Mbit/s	Laser	GI	8 ″ 2	Main/ Submarine
		SI Monomode	30 ″ 3	
565 Mbit/s	Laser	GI	5 ″ 2	Main/ Submarine
		SI Monomode	20 ″ 3	
Analogue tv etc	Laser	GI or SI	5 ″ 1	Local
	LED		3 ″ 1	

GI = Graded Index SI = Step Index

Note 1: These repeater spacings assume operation in the 800-900 nm band, the use of 2.5 dB/km fibre and an extra 0.5 dB/km allowance for connectors, joints etc. Operation at higher wavelengths eg 1300 nm would enable the repeater spacings quoted to be increased on average by a factor of 2 or 3.

Note 2: These systems are bandwidth limited.

Note 3: It is assumed that systems installed on monomode fibre will be designed to operate in the region 1300-1550 µm.

6. Present Technology and Systems

British Telecom has developed experimental optical fibre systems operating at 2, 8 and 140 Mbit/s [24, 25] and work is presently under way on higher order systems. Similar systems developed by the major British equipment and cable manufacturers have been successfully installed and demonstrated in working environments in the Telecom network. All these systems use graded index fibre operating in the 800-900 nm region. The optical sources on the 2 and 8 Mbit/s systems are high radiance LEDs while the 140 Mbit/s systems use lasers. Avalanche photodiodes have been used as the optical detector on all except the 2 Mbit/s systems where a PIN diode/FET combination is used.

7. British Telecom Plans for Evaluation of Optical Fibre Systems

British Telecom concluded that the time was ripe to follow up the work done on the experimental systems by ordering production systems so that industry on the one hand could gain further experience in the manufacture and installation both of the cable and equipment and British Telecom on the other, could gain operational experience of this new transmission medium. To this end British Telecom placed orders for a total of 34 systems on 15 different routes located throughout the UK [27]. The systems are essentially proprietary ones, designed to meet the needs of both the Telecom network and of export customers. The systems will be a spur to British activity in this important field and not only provide much needed additional capacity for the Telecom network but also enable British industry to demonstrate their products and capabilities in this rapidly evolving field of activity. In the main, the provisioning of the systems is being carried out using the normal procedures applicable to conventional Telecom line transmission systems. One notable exception is that, because there is not yet enough experience to be confident about specifying separately the requirements of optical fibres and their associated equipments, a turnkey contract approach has been adopted whereby a prime contractor is responsible for the total provision of all the cable and equipment on each route. British Telecom specifications, setting out the initial needs for optical fibre systems, were issued as a basis for the tenders. However, because of the proprietary nature of the systems being ordered, only essential features, eg safety and overall performance, have been made mandatory.

The various systems ordered operate at 8, 34 and 140 Mbit/s, equivalent to 120, 480 and 1920 telephone channels respectively, and will form part of the evolving digital network being developed by British Telecom leading to the Integrated Services Digital Network in conjunction with System X exchanges.

The 140 Mbit/s systems, six of which have been ordered (on three routes), will be used in the trunk network. These systems will have a typical route length of 60 km and require dependent repeaters located at intervals of about 8 km. (Systems of similar capacity on coaxial cables require repeater spacings of 2 km.) The optical fibre systems will use semiconductor lasers as the light sources.

The 34 Mbit/s systems, four of which have also been ordered for the trunk network (on two routes), are expected to be similar in design to the 140 Mbit/s systems except that their repeater spacings will be 10-11 km. 34 Mbit/s systems are expected to be especially suited to the needs of export markets.

8 Mbit/s systems are being ordered for both the trunk and junction networks. In the former, the route length for the two long-haul type systems is about 50 km whereas for the latter short-haul type systems the lengths are typically between 10 and 20 km. 24 short-haul junction 8 Mbit/s systems (on nine routes) form the largest group of systems to be ordered. Because they are shorter in length, only a few of the systems have intermediate repeaters. When intermediate repeaters are required they are usually housed in surface buildings. Repeater spacings can be up to 12 km.

Various cable designs are to be employed and although about 480 km will be of the underground type, there will be some 46 km which will be aerial cable (cable suspended between poles) and a smaller length which will be sub-aqueous. The optical fibres to be used in the cables are mainly of the graded index type, and low loss fibres (less than 3 dB/km at the wavelength of operation, typically 820–900 nm) will be used on the longer systems where there is economic advantage in so doing. To demonstrate the practicability of optical fibres produced by the double crucible process, a process pioneered by the British Telecom Research Labs, such fibre may be used on one or two suitable routes.

The exercise is a bold step into a new technology which British Telecom is confident will be a geat success. Some of the early systems are already in service and the remainder will follow within a year or two. The data and operational experience gained from the exercise will form a basis for the standard production systems of the future.

8. The Future

Much effort is presently being directed towards the development of sources and detectors that operate at the lower attenuation window of 1060 to 1300 nm where fibre losses are typically below 1 dB/km.

In addition, research into monomode fibre technology has been given greater prominence lately in view of the large bandwidths available on such fibres. Particular difficulties to be overcome include jointing techniques and the improving of launching efficiencies. However, the reward to be gained from this research and development effort is considerable, offering the possibility of high bit rate systems (up to 1 Gbit/s) with repeaters every 30 to 40 km. This would obviate the need for buried regenerative repeaters on almost all trunk systems in the UK with the consequent elimination of power feed conductors.

Monomode fibre will also make submarine cable systems a very attractive proposition and the first such system operating at 140 or 280 Mbit/s could be operational by the mid to late 1980s.

For the junction network multimode fibre will still have an important role to play and by operating at longer wavelengths, larger repeater spacings will be possible, again eliminating buried repeaters. In these applications the emphasis will be on producing low cost systems.

The employment of optical fibre systems generally in the local network is more difficult to predict. Suitable systems are technically feasible and already a number of schemes have been demonstrated in various parts of the world. An explosive demand for communications facilities including wideband visual services into every home could see the rapid introduction of optical fibre systems into the local network, but only if the economics were right.

The potential bandwidth available when working at optical frequencies (ie c. 10^{14} Hz) is phenomenal and a whole frequency division multiplex arrangement having numerous optical carriers can be envisaged and indeed the concept has already been demonstrated in a number of laboratories [28, 29].

Looking even further ahead to the introduction of integrated optics, completely optical repeaters without any electronics can be visualised. Such equipments would then be compatible with optical switches which could be installed in exchanges. It follows therefore that eventually perhaps all switching and transmission in some, or perhaps even all, parts of the network might be carried out entirely at optical frequencies.

Thus it can be seen that there is enormous potential in optical fibre technology. No doubt the techniques currently employed will in 10 or 20 years time be likened to the telegraph systems of 120 years ago, but nevertheless a rapid start has been made in what promises to be an exciting and rewarding technology.

9. References

[1]	Kao K C and Hockham G A	*'Dielectric fibre surface waveguides for optical frequencies',* Proc IEE, Vol 113, No. 7, 1966, pp 1151-1158
[2]	Kapron F P, Keck D B and Maurer R D	*'Radiation losses in glass optical waveguides',* App Physics Letters, Vol 17, No. 15, 1970, pp 423-425
[3]	Dyott R B	*'The optical fibre as a transmission line',* POEEJ, Vol 67, pt 3, 1974, pp 164-168
[4]	Payne D N and Gambling W A	*'Zero material dispersion in optical fibres',* Electronics Letters, 1975, 11, pp 176-178
[5]	Gloge D and Marcatili E A J	*'Multimode theory of graded core fibres',* BSTJ, 1973, 52, p 1563
[6]	Beales K J, Day C R, Duncan W J, Midwinter J E and Newns G R	*'Preparation of sodium borosilicate glass fibre for optical communication',* Proc IEE, 1976, 123, (6), pp 591-596
[7]	Marcatili E A J	*'Bends in Optical Dielectric Waveguides',* BSTJ , Vol 48, 1969, pp 2103-2132
[8]	Di Marcello F V and Williams J C	*'Reproducibility of Optical Fibres prepared by a chemical vapour deposition process',* First European Conference on Optical Communication, London 1975, pp 36-37
[9]	Beales K J	*'Low loss optical fibres prepared by the double crucible technique',* Third European Conference on Optical Communication, Munich 1977, pp 18-20
[10]	Slaughter R J	*'Optical fibre transmission cables and joints',* Systems Technology, No. 25, 1976, pp 2-5
[11]	Baskett R E J and Foord S G	*'Fibre optic cables',* Electrical Communication, Vol 52, No. 1, 1977, pp 49-53
[12]	Newman D H	*'Sources for optical fibre transmission systems',* POEEJ, Vol 67, pt 4, 1975, pp 208- 212
[13]	Goodwin A R et al	*'GaAs Lasers with consistently low degradation rates at room temperature',* Applied Physics Letters, Vol 30, No. 2, 1977, pp 110-113
[14]	Joyce W B, Dixon R W and Hartman R L	*'Statistical characterisation of the lifetimes of continuously operated GaAlAs double heterostructure lasers',* Applied Physics Letters, Vol 28, No. 11, 1976, pp 684-686
[15]	Matthews M R and Smith D R	*'Photodiodes for optical-fibre transmission systems'* POEEJ, Vol 67, pt 4, 1975, pp 213-217

[16] Smith D R et al *'Pin photodiode hybrid optical receivers'* Fifth European Conference on Optical Fibre Communication, Amsterdam 1979, P13 . 4

[17] Bennett W R and Davy J R *'Data Transmission',* McGraw Hill

[18] Personick S D *'Receiver design for digital fibre-optic communication systems',* BSTJ, Vol 52, No. 6, 1973, pp 843–886

[19] Smith D R and Garrett I *'A simplified approach to digital optical receiver design',* Optical and Quantum Electronics, Vol 10, No. 3, 1978, pp 211–221

[20] Hooper R C and Smith D R *'Receiver amplifier design for digital optical communication systems',* Third European Conference on Optical Communications, Munich, 1977, pp 192–194

[21] Bylanski P and Ingram D G W *'Digital Transmission Systems',* Peter Peregrinus Ltd

[22] Midwinter J E *'Optical Communication, today and tomorrow',* Electronics and Power, June 1978, pp 442–447

[23] Lonnen K W J *'The potential application of optical fibre systems in the junction and trunk networks of the BPO',* Third European Conference on Optical Communication, Munich, 1977, pp 220–223

[24] Brace D J and Ravenscroft I A *'Optical Fibre Transmission Systems: the 8 Mbit/s feasibility trial',* POEEJ, Vol 70, pt 3, 1977, pp 146–153

[25] Berry R W and Ravenscroft I A *'Optical Fibre Transmission Systems: the 140 Mbit/s feasibility trial',* POEEJ, Vol 70, pt 4, 1978, pp 261–268

[26] Hill D R, Jessop A and Howard P J *'A 140 Mbit/s field demonstration system',* Third European Conference on Optical Communication, Munich, 1977, pp 240–242

[27] Martin-Royle R D *'Optical Fibres on Order',* Post Office Telecommunications Journal, Summer 1979, Vol 31, No. 2

[28] Ishio H and Miki T *'A preliminary experiment on wavelength multiplexing transmission using led's',* International Optics Conference, Tokyo, July 1977

[29] Kahn D A *'Colour multiplexing techniques and applications in optical waveguide links',* AGARD Conference Proceedings No. 219, pp 101–105

10. Bibliography

Marcuse D	*'Theory of Dielectric Optical Waveguides',* Academic Press
Barnoski M K	*'Fundamentals of Optical Fibre Communications',* Academic Press
Midwinter J E	*'Optical Fibres for Transmission',* Wiley Interscience
Gagliardi R M and Karp S	*'Optical Communications',* Wiley Interscience
Bennett W R and Davy J R	*'Data Transmission',* McGraw Hill
Bylanski P and Ingram D G W	*'Digital Transmission Systems',* Peter Peregrinus Ltd

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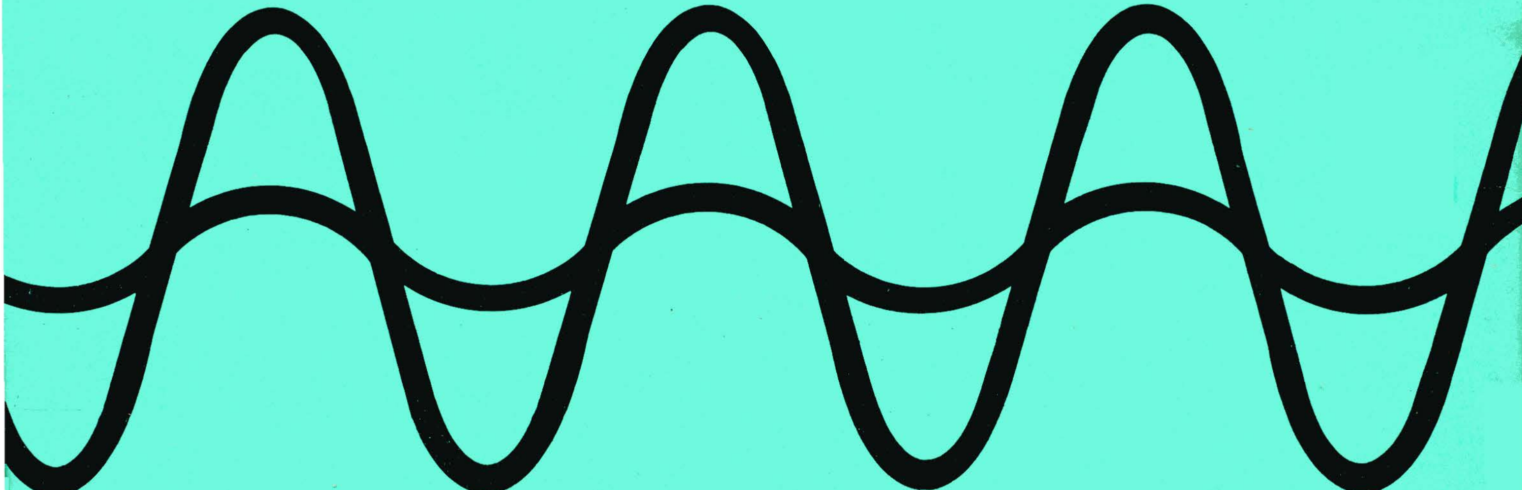

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