Glass Fibres

76 Glass is the traditional medium used in the manufacture of optical fibre, relying until recently on materials used for high quality lenses.

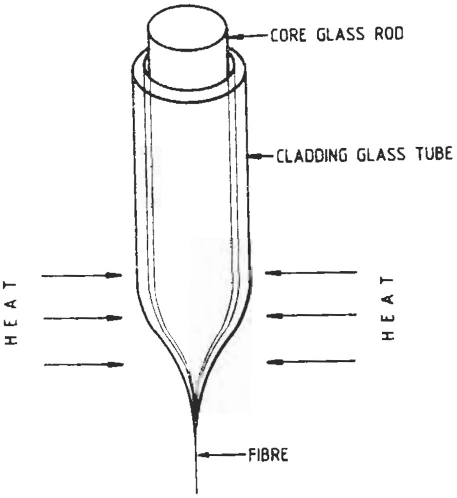


FIG 8.18 GLASS FIBRE MANUFACTURE FROM ROD AND TUBE

77 For many years fibres have been manufactured by the 'rod and tube' method, in which concentric billets of core and cladding glasses are heated in a furnace and drawn out into a thin fibre. These fibres used to exhibit losses in excess of 500 dB/km, but research into materials and processes has reduced this to levels compatible with short and medium range communication requirements.

78 Alternatively, glass fibres can be extruded directly from concentric platinum crucibles containing the core and cladding glasses in a molten state. This is capable of producing very low loss fibres and has the potential advantage of being a continuous process, there being no limit imposed on the length of fibre produced if the raw materials are replenished at regular intervals.

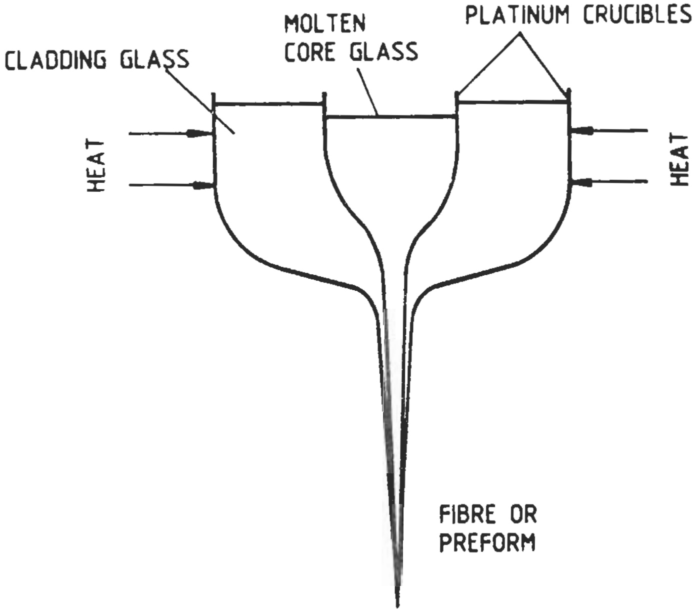


FIG 8.19 DOUBLE CRUCIBLE TECHNIQUE

Silica Fibres

79 Silica (SiO2) is a material which occurs naturally in the form of quartz, or can be produced synthetically, and which exhibits very low intrinsic optical loss making it an ideal candidate for the manufacture of fibres. However, it also has a very low refractive index so that the requirement for a still lower index cladding has necessitated the development of special manufacturing techniques.

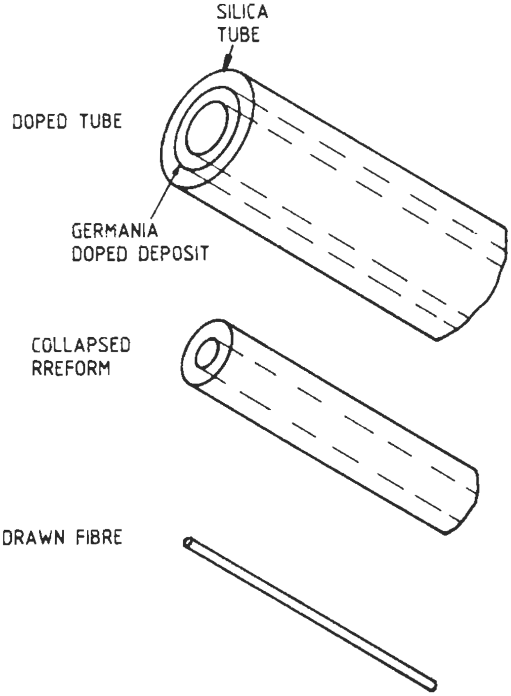


FIG 8.20 MANUFACTURE OF VAPOUR DEPOSITED SILICA FIBRES

80 One of these techniques, vapour deposited silica (VDS), involves laying radial layers of germania-doped silica on the inside of a silica tube to form a region of increased refractive index. This forms the core when the tube is later collapsed into a solid rod and subsequently drawn into a fibre. These layers are produced by passing suitable gases through the tube whilst being heated. By varying the constituents of these gases, both core and cladding regions can be formed. Alternatively, the refractive index profile may be changed gradually, to produce graded index fibres. Not surprisingly, this technique is fairly expensive, but produces very low loss fibres (< 1 dB/km), 5 dB/km probably representing a realistic commercial value at the present time.

Plastic Clad Silica (PCS) Fibres

81 A fundamentally different solution to the problem of providing a lower index cladding is achieved by applying a thin layer of low refractive index silicone resin to a pure silica core after it has been drawn into a fibre.

82 This is an attractive technique, producing large core diameter fibres at costs determined principally by the raw materials used. Losses are not among the lowest obtainable due to absorption within the lossy cladding - some ray penetration of the cladding always occurs during total internal reflection - but are acceptable for many applications.

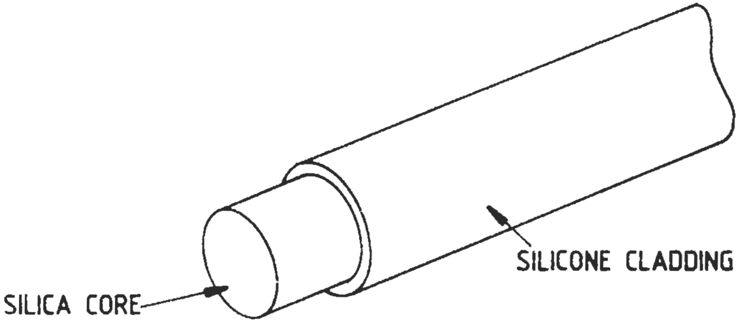
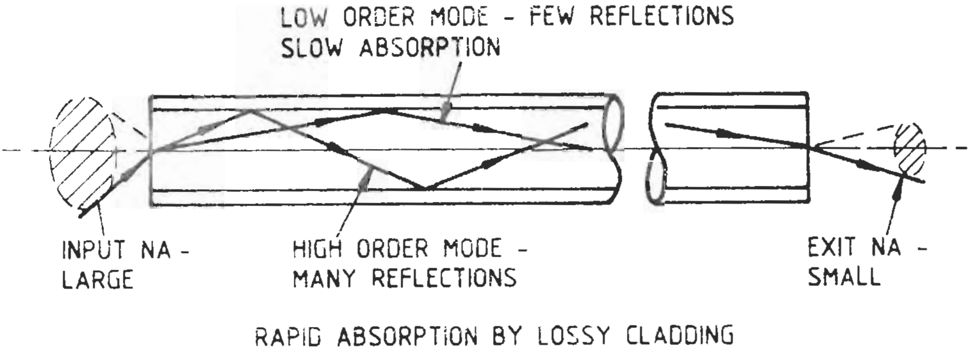


FIG 8.21 PLASTIC CLAD SILICA (PCS) FIBRE

83 This absorption in the cladding leads to a unique phenomenon. Rays travelling at high angles to the optical axis (high order modes) clearly intersect the interface more frequently than lower orders, and hence are absorbed to a greater extent over a given length. This leads to a gradual reduction of the effective numerical aperture of the fibre over the first few tens of metres, until an equilibrium NA is reached when the loss of high order modes is balanced by mode conversion from lower orders.

84 The result of this NA change is a non-linear attentuation characteristic as far as the equilibrium length. Consequently, estimates of path loss with this fibre must include an excess loss calculated from the squared ratio of the initial to equilibrium NAs. Although such estimates will be pessimistic on short lengths, it is inadvisable to use a lower figure as the exact shape of the non-linear region is indeterminate, being significantly influenced by the degree of curvature present in the fibre.

85 A reduction in NA is also seen at low temperatures, because, as the silicone resin is cooled, it becomes denser and it refractive index increases. Thus the environmental performance of PCS is limited, but is is nevertheless an ideal choice for many industrial applications.



THE RESULT - INITIAL NON-LINEAR ATTENUATION

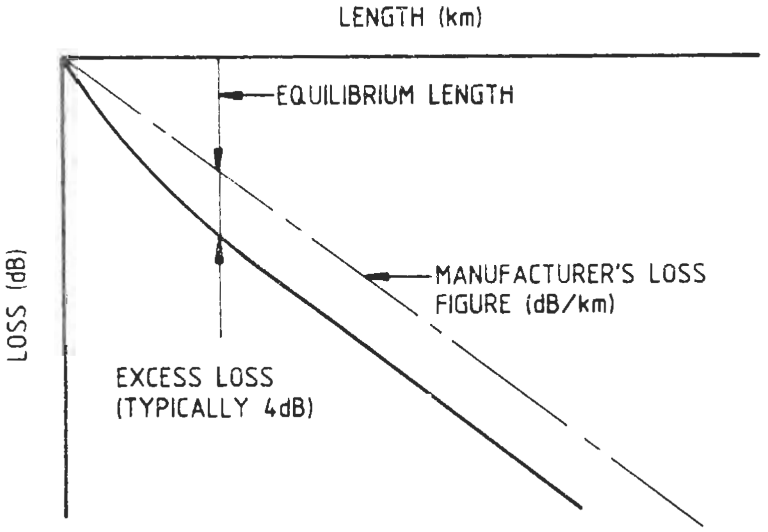


FIG 8.22 THE REDUCTION OF NA IN PCS FIBRE

FIBRE CABLES

Primary and Secondary Coatings

86 The majority of fibres exhibit considerable tensile strength, which for freshly drawn silica fibres can exceed that of best quality steels. Unfortunately, surface damage caused by handling or even atmospheric attack rapidly leads to a dramatic degradation in strength. This can be prevented by protecting the fibre with a thin plastic coating, immediately after manufacture, and usually as an on-line process. This coating is referred to as a primary coating. Since the silicone resin used in the manufacture of PCS fibre makes an excellent primary coating, this is frequently used with other fibres.

87 Although the primary coating maintains the intrinsic tensile strength of the fibre, being relatively thin and soft it does little to protect the fibre from external mechanical damage. Consequently a further secondary coating is added to give protection and improve handling quality.

88 Two schools of thought have arisen regarding the form that the secondary coating should take - namely whether or not it should be a loose or a tight fit over the primary coated fibre. This is because the addition of protective coatings must not be detrimental to the optical properties of the fibre, and in particular must avoid introducing microbending loss, ie additional attenuation caused by local inhomogeneities in the coating material which lead to a distortion of the fibre.

89 Loose tube constructions provide a simple solution to this problem, and accordingly have been adopted by several fibre manufacturers. Unfortunately this design suffers from other problems due to the instability of the plastic coating material. For example, when this shrinks with age or changing temperature (as invariably happens as longitudinal extrusion stresses are relieved) the fibre is forced to take the form of a helix within the loose tube. In severe cases this also can cause increased attenuation because of the minute but continuous leakage of light from the curved fibre. The process is further complicated by the high coefficients of expansion of the plastics used.

90 STC have adopted the alternative tight tube construction avoiding the problems of microbending by strict material and process control. Although shrinkage of the coating material can still occur, this merely puts the fibre into compression and has no detrimental effect on attenuation or strength. It does, however, produce an additional problem at each end of the fibre, since the shrinkage causes the fibre end surface to protrude beyond the end of the protective coating. This phenomenon has been termed 'growing-out' and puts the fibre at risk in connectors. Consequently, termination techniques have had to be developed which are sufficiently sound to resist this movement and the forces involved. This problem overcome, the result is a very stable structure.

Cable Construction

91 The overall design of a ruggedised fibre cable depends on the application and the number of communication channels required, but invariably features some form of tensile strength member and a tough outer sheath to provide the necessary mechanical and environmental protection.

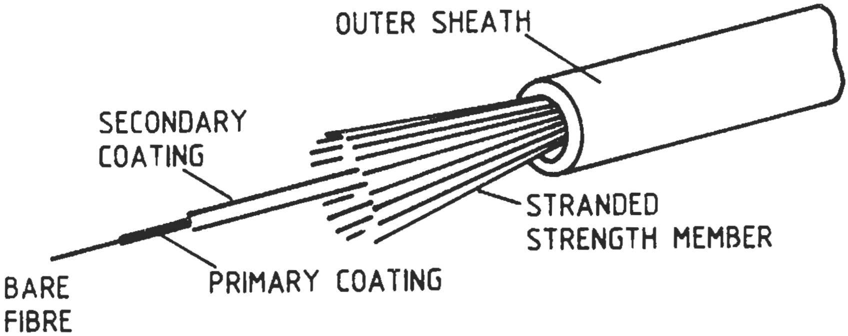


FIG 8.23 A TYPICAL SINGLE FIBRE CABLE

92 Ruggedised single fibre cables usually employ a fibrous external strength member (such as Kevlar) which is either laid helically, or braided around the secondary coated fibre. This is surrounded by a plastic outer jacket for additional crush and abrasion protection.

93 Multifibre cables are made in a variety of configurations. The simplest involves grouping a number of ruggedised single fibre cables within a further outer jacket. This is not a low cost construction, but it is strong and has the advantage that, when the outer jacket is removed at each end of the cable the individual ruggedised cables can be terminated in separate single way connectors. Thus a very high degree of immunity to mechanical and handling damage can be achieved in the region which is often subjected to considerable stress.

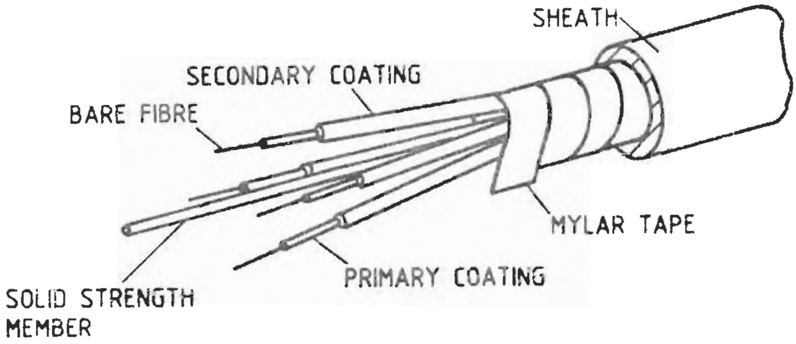


FIG 8.24 STC MULTIWAY CABLE

94 STC multifibre cables normally feature a solid central strength member with secondary coated fibres laid in a helix around it. The strength member can be steel in applications where the cable is not required to have isolating properties. Cables to this design are available with either 4 or 8 communication fibres, or featuring a mix of optical and electrical conductors.

95 Alternatively, an external fibrous strength member can be used, or, for highest tensile load requirements (eg aerial cables) a combination of both.

96 When the outer jacket of a multifibre cable is removed, the less well protected secondary coated fibres will usually be exposed. In order to minimise the risk of mechanical and environmental damage, cables should ideally be terminated with multiway connectors featuring appropriate cable and strength member tie-off facilities in order to provide protection at this point.

<u>Cable Testing</u>

97 It is an interesting feature of the progress made in the development of fibre optics cables that the specifications now being achieved exceed those of many conventional communication cables.

98 <u>Tensile Strength</u>. The tensile strength of freshly drawn glass fibres is comparable to that of any high tensile material including steel, and the introduction of primary coatings has virtually eliminated degradation caused by mechanical and atmospheric damage.

99 The failure of fibres now being manufactured is generally caused by microscopic surface flaws which occur infrequently and at random intervals. Consequently it is essential that sufficient fibre is tested (ie a large number of short samples or a smaller number of long samples) in order to obtain meaningful values of ultimate tensile strength.

100 In order to illustrate the statistical failure mechanism within the fibre, the results of many identical tensile tests are plotted as a Wiebull chart, ie accumulated number of failures versus breaking strain (strain is used as the load parameter since this is independent of fibre diameter). On this chart, an ideal fibre featuring a constant breaking load is represented by a vertical line. Less than ideal fibres will show variable degrees of slope.

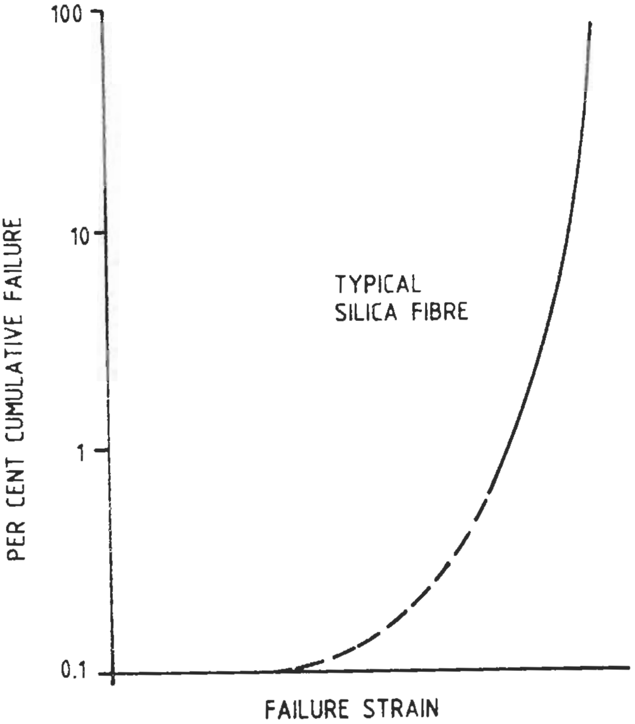


FIG 8.25 CUMULATIVE FAILURE PLOT (WEIBULL CHART)

101 Many commercial silica fibres will withstand proof strains exceeding 1% with an ultimate failure strain of greater than 5%. Consequently, cables are designed with sufficient tensile stiffness so that, at the maximum rated load, the fibre strain is limited to the safe lower value of 1%. Typical STC multiway cables are rated at 1500 N (150 kg) and rugged single cables at 500N.

102 Crush Resistance. Resistance to crushing loads is provided primarily by the cushioning effect of the outer cable sheath, although even secondary coated fibres exhibit considerable tolerance to physical abuse. The cables are subjected to a gradually applied load simulating the pressure that could be generated by the heel of a 100 kg man. A second test involves a radiused anvil representing obstructions such as a ladder rung. Both multiway and rugged single fibre cables have been tested in this manner without failure after 1000 cycles.

103 Impact Resistance. Repeated impact can induce failure by causing permanent changes in the plastic components of a cable. In an STC test based on a US Military specification, blows are delivered from a height of 100 mm at a rate of one per second by a 12.5 mm radiussed head with the cable on a flat steel anvil. Loads can be varied from 500 g to 4 kg.

104 Despite severe cable distortion, all fibres in the multiway cable construction have survived 1000 blows at 2 kg. It is of interest to note that in cables containing a mix of optical fibres and copper conductors, the copper elements all failed before the fibres. In designs, with steel strength members, the fibres have outlasted the steel.

105 On a more mundane, yet possibly more convincing level, an eight fibre multiway cable was laid across a busy car park entrance. Some 40,000 vehicles and several sceptical boots later, the cable was intact, with a deep groove worn in the tarmac surface.

106 Resistance to Bending Failure. A cable may be subjected to a considerable degree of feeling during its life and therefore the effects of bending must be considered during its design. Conventional cables usually specify a minimum bend radius of 20 cable diameters but fibre cables manufactured by STC are subjected to a more rigorous bend test in which four turns of cable are wound in a grooved mandrel with a radius of approximately 5 D at a tension of 100 N. Continuous winding and unwinding has shown no failure up to 100 cycles.

107 Environmental Tests. Tests involving temperature and humidity cycling have been designed to suit various applications. Current cable design show very little attenuation change over -15°C to +60°C and are unaffected by humidity.

108 The primary coated fibre is stable over a very wide temperature range (-50°C to 200°C) and the overall performance of a cable is governed by the choice of plastic sheathing materials. High temperature cables require the use of expensive fluoropolymers and consequently are reserved for essential applications.

Static Fatigue

109 Unlike many conventional engineering materials which exhibit fatigue failures when subjected by cyclic strains, glass and silica fibres will eventually fail if a constant tensile strain less than the normal failure strain is present for a sufficiently long period of time. This is called static fatigue and is caused by the propagation of cracks from surface flaws as a result of a process known as stress corrosion.

110 Research into the phenomenon has indicated that fatigue life (ie the mean life to failure) is a very sensitive function of tensile strain - typically $(\text{strain})^{14}$ - although, not surprisingly there is some difference of opinion regarding the exact relationship.

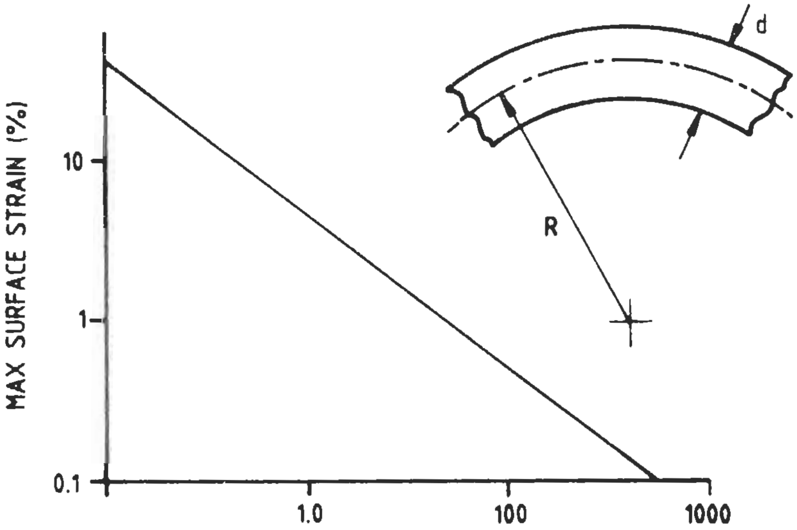


FIG 8.26 SURFACE STRAIN IN CURVED FIBRES

111 Long term strains are most likely to occur in fibre bends, and here a simple relationship connects maximum tensile strain to bend radius R Hence:

$$\text{Fatigue Life} \propto \left(\frac{R}{d}\right)^{14} \quad \text{where } d = \text{fibre diameter}$$

112 The sensitivity of this function is dramatically illustrated by considering the effect of halving an appropriate bend radius. Life expectancy is then reduced by a factor 2^{14} (say from 25 years to 13 hours. Halved again, to 3 seconds!)

113 Static fatigue failures are unlikely to be experienced by the user since cables are designed to restrict minimum bend radius to a safe value. Tests have also shown that cyclic bending is not a significant contributory factor. Static fatigue is of most significance in the design of right angle connectors where the constraints of size dictate small bend radii.

FIBRE TERMINATION AND CONNECTORS

Fresnel Loss

114 To avoid unnecessary loss of light, the input and exit surfaces of an optical fibre must be smooth and perpendicular to the axis.

115 Even with optically flat ends, a small proportion of the incident light is reflected back, this being an unavoidable phenomenon associated with a step change in refractive index called Fresnel reflection. The magnitude of this reflection is about 4% for a typical glass-air interface, and is the same whether light is entering or leaving the fibre. Consequently, a fibre-to-fibre coupling, involving two interfaces, introduces a total loss of nearly 8%, or about 0.35 dB.

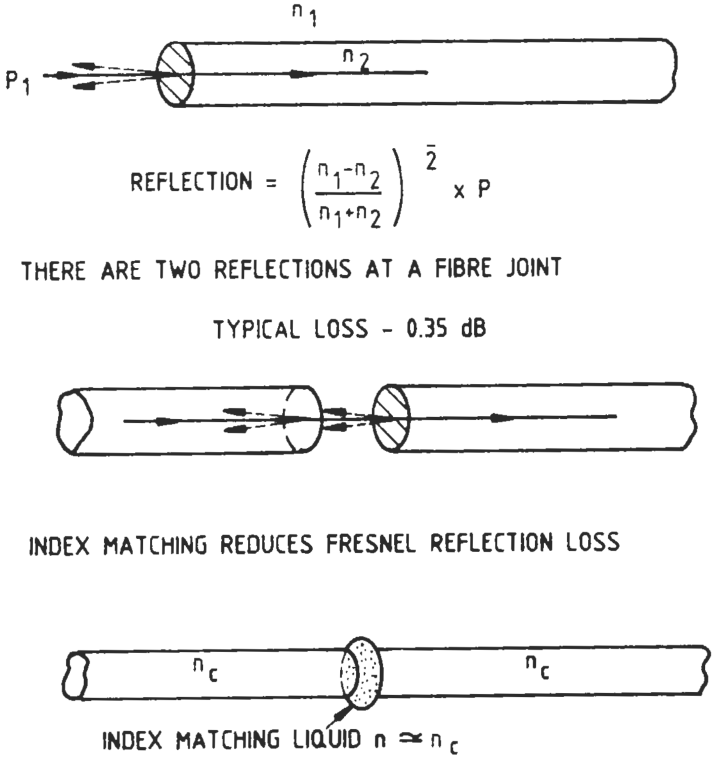


FIG 8.27 FRESNEL REFLECTION AT AN INTERFACE

116 Fresnel reflection can be reduced to a very low level by filling the gap between adjacent fibre ends with an index matching liquid, that is, a liquid which exhibits the same refractive index as the fibre core.

117 Index matching is not considered to be a practical approach in demountable connectors since dirt collection is a major problem with such liquids. However it can be successfully employed in more permanent joints such as a mechanical splice.

Fibre Termination

118 A bare fibre end is quite fragile and, if not adequately protected, prone to damage in service. Consequently it is usually terminated in a suitable receptacle called a ferrule. This must provide accurate location of the fibre on its geometric axis, and be sufficiently well secured to both fibre and secondary coating to resist the axial 'growing-out' movement referred to earlier.

119 To prevent growing-out, the fibre is sometimes cemented into the ferrule with an epoxy resin, and subsequently ground flat and polished to an optical finish. This process, referred to as cement and polish, has been used by STC with a wide variety of fibre types, and its reliability has been verified over a range of environmental conditions. Its disadvantage is that a delay is introduced whilst the epoxy resin cures, but this has been reduced to an acceptably short period (5-10 minutes) by heating the assembly in a special fixture, so that a completed termination can be achieved in about 20 minutes.

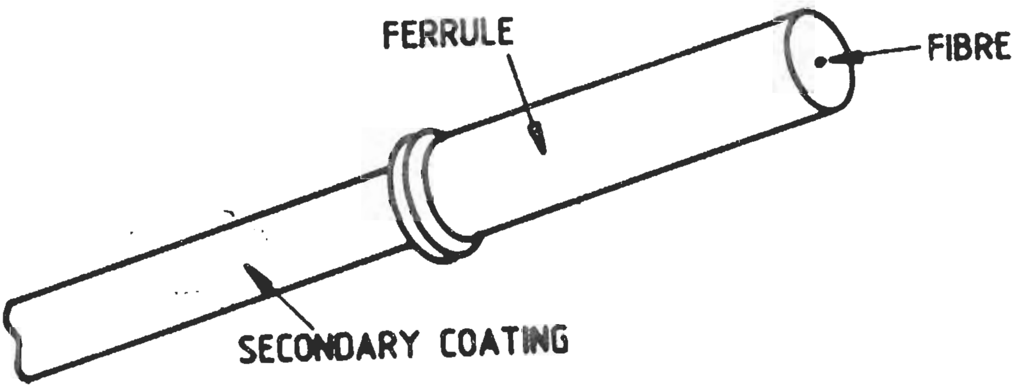


FIG. 8.28 A FIBRE TERMINATED IN A FERRULE

120 An alternative termination technique has also been developed by STC for use with large core PCS fibres. With such fibres, the cement and polish process is not suitable, since external adhesion to the silicone resin cladding is not good enough to resist growing-out forces. Neither can the cladding be removed to permit direct adhesion to the fibre core, since the higher index adhesive would prevent the vital total internal reflection in that region, and lead to considerable loss of light.

121 For the termination of PCS fibre, the fibre end is prepared by cleaving. This is a technique which has evolved from the discovery that a fibre, scribed with a diamond blade whilst subjected to a particular combination on tensile and bending stresses, will break in a controlled manner, usually leaving a flat mirror finished end. Various hand tools have been developed to exploit this principle.

122 After preparation, the fibre is located inside a special ferrule, with the end butting against a very thin optical 'window' which is fixed to the front of the ferrule. This resists growing out. In addition, the ferrule is secured to the secondary coating by crimping, and an index matching 'gel' is used to eliminate the additional Fresnel reflections which would otherise occur at the fibre-to-window surfaces.

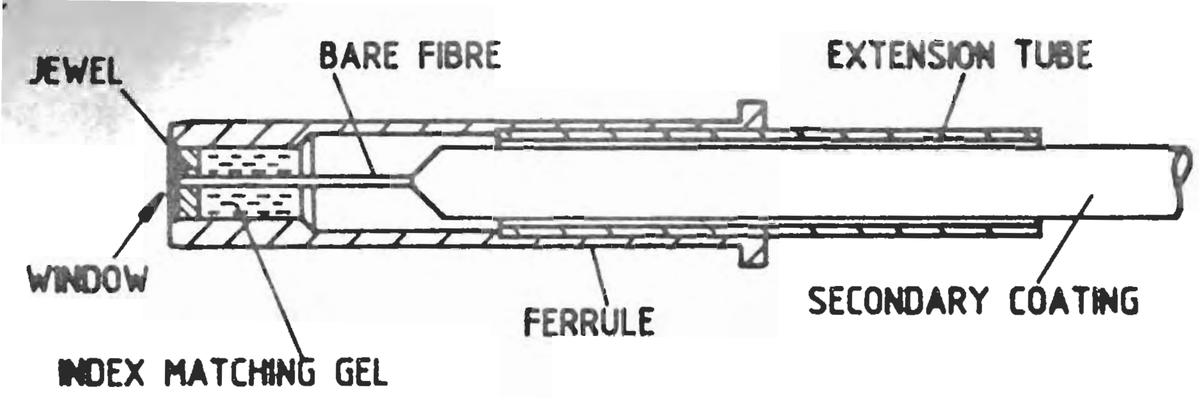


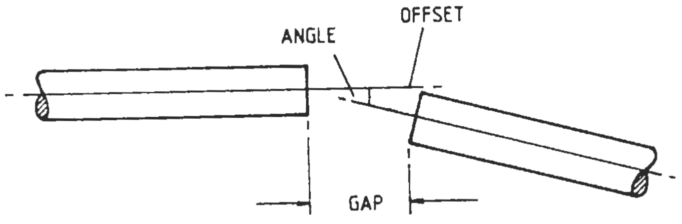
FIG. 8.29 PCS WINDOW FERRULE TERMINATION

123 The window termination technique is easy and quick to perform, and is particularly suitable as a field technique. Currently its use is limited to large core PCS fibres (ie greater than 200 microns) since the effective gap between the fibre ends which is introduced by the windows causes unacceptably high loss between other small core fibres.

Butt-Joint Connectors

124 Coupling between fibres is most frequently accomplished by a direct butt joint between prepared fibre ends. To minimise loss of light at the joint (insertion loss), the two fibres must be accurately aligned, both axially and in an angular sense, and with the minimum possible gap between the ends, but avoiding actual contact to prevent damage from surface abrasion.

125 The most difficult parameter to control is the axial alignment since, with typical core diameters often less than 100 microns, even quite small misalignments will result in appreciable insertion loss.



LOSS CAUSED BY OFFSET AND GAP

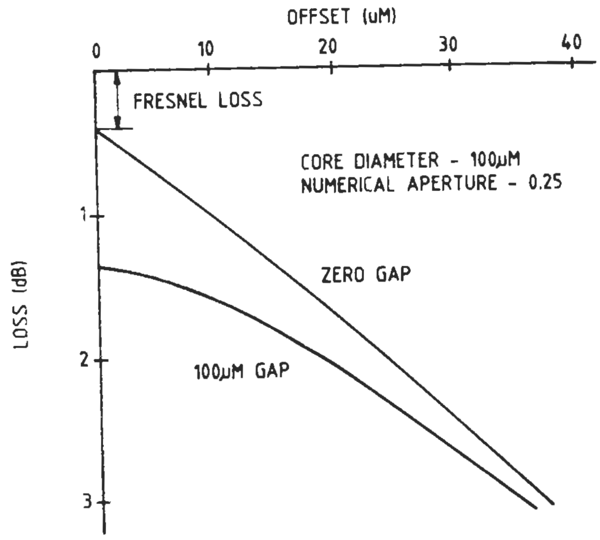
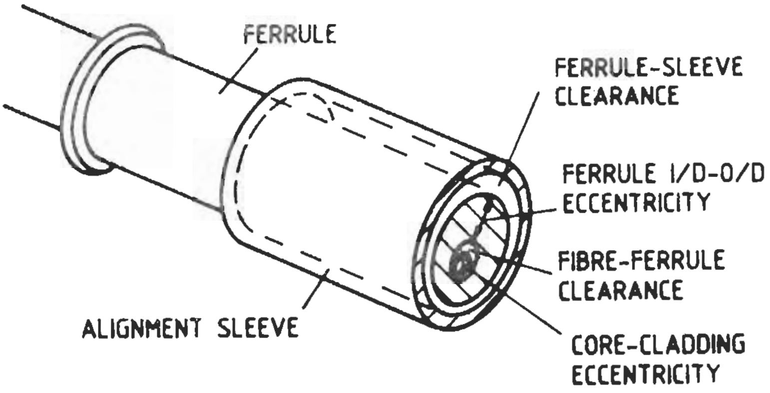


FIG 8.30 THE MAJOR SOURCES OF FIBRE COUPLING LOSS



RESULTING COUPLING LOSS DISTRIBUTION

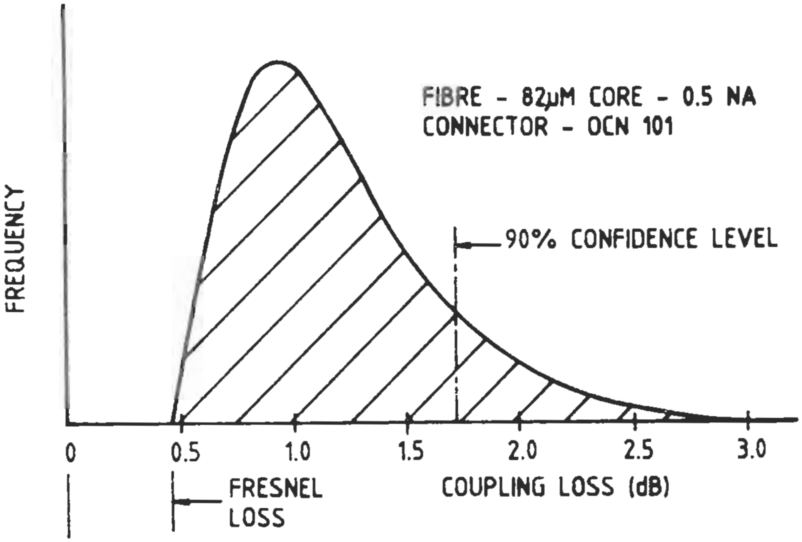


FIG 8.31 SOURCES OF FIBRE MISALIGNMENT (FERRULE-SLEEVE COUPLING)

126 The lowest insertion losses can be achieved by direct alignment of bare fibres (in a V-groove, for example) but the design of a successful connector using this principle is difficult because of the need to protect the exposed fibre in the uncoupled state. More frequently the fibre is totally enclosed in a ferrule with only the flat front surface exposed. Two similar ferrules are aligned by locating in, for example, a closely fitting sleeve. This principle is employed in STC connectors.

127 The success of this technique is limited by the manufacturing tolerance that can be achieved in the various components. For example, fibre-to-ferrule and ferrule-to-alignment sleeve clearances must necessarily exist, both of which contribute to the total fibre misalignment. Similarly, the ferrule itself must be allowed a manufacturing tolerance on concentricity. Each of these effects exists in both halves of a mated connector, and consequently there are at least six independent sources of fibre misalignment.

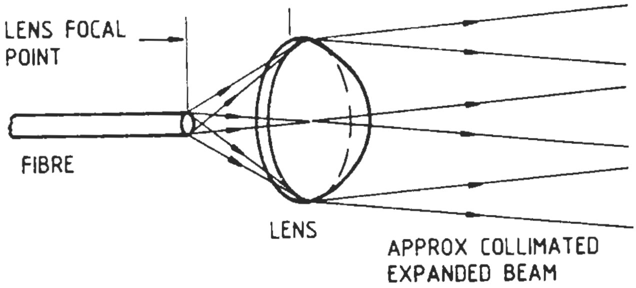
128 The maximum possible misalignment results from the arithmetic sum of all the contributions. In practice, however, each exhibits a variable magnitude and a random direction relative to its neightbours, and a realistic assessment takes this into account. The result is a statistical distribution of connector loss. In the example shown, although a worst case value of 3 dB is possible, a 2 dB maximum can safely be assumed at a high statistical confidence level ($>$ 95%) and appreciably lower values with only a slightly reduced level of confidence. Thus, in practice, acceptable performance can be achieved with even the smallest fibre sizes.

Expanded Beam Connectors

129 An alternative to direct butt joints between fibres is offered by the principle of expanded beam. If the fibre is placed at the focus of a converging lens, an essentially collimated (parallel) beam is produced, the degree of collimation depending on the relative sizes of the lens and fibre.

130 A second similar lens, placed in line some distance away, will refocus the beam to a spot at which the receiving fibre is located. This forms an expanded beam joint.

131 The advantages of this technique accrue from the relatively large diameter and good collimation of the beam between lenses, making optical connectors using this principle correspondingly less sensitive to axial misalignment and gap. In addition, the larger lens surface is less likely to be obscured by small particles of dirt, and is generally easier to clean.



AN EXPANDED BEAM CONNECTOR

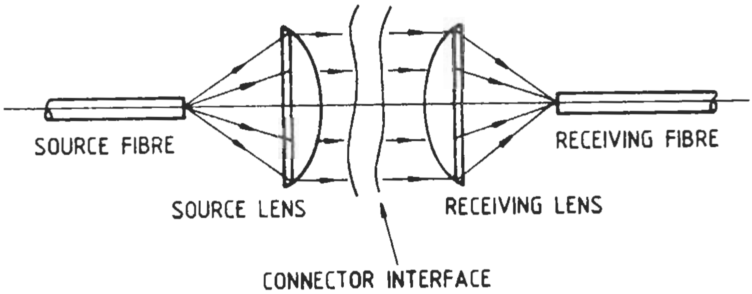


FIG 8.32 THE PRINCIPLE OF EXPANDED BEAM TERMINATION

132 The trade-off for these benefits is that expanded beam connectors are proportionally more sensitive to small angular misalignments. Nevertheless expanded beam will probably become an important feature of future optical communication links, particularly those subjected to severe operating environments.

Cladding Modes

133 The silicone resin which constitutes the optical cladding of a plastic clad silica fibre is commonly used as a primary coating in other fibre constructions featuring conventional core and cladding regions. With these fibres it is frequently observed that light is guided not only within the core but also by the cladding. This is the result of total internal reflection which occurs at the cladding-primary coating boundary.

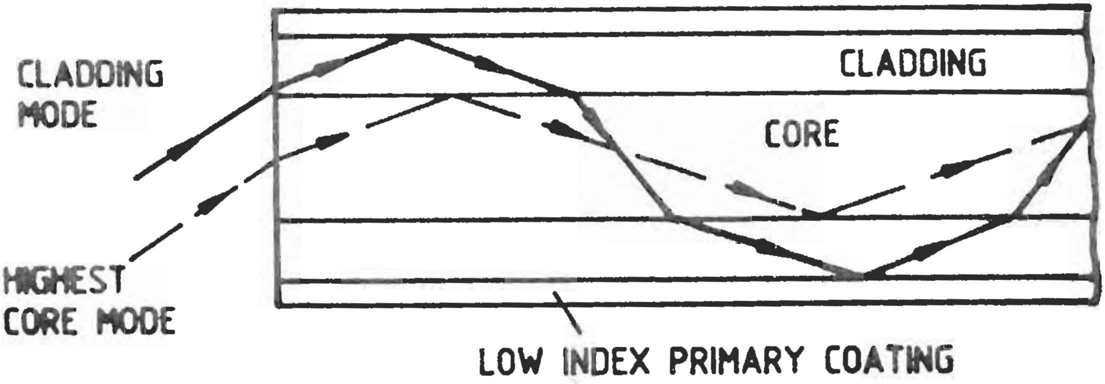


FIG. 8.33 PROPAGATION OF CLADDING MODES

134 Whilst such cladding modes might be considered to be a bonus in terms of transmitted power, in practice they are quite lossy and decay to negligible proportions in lengths exceeding a few hundred metres. They are, however, present to a significant extent in short lengths of fibre, and this can lead to misleadingly optimistic results in connector evaluation trials (since the loss caused by a given fibre misalignment is correspondingly smaller if the entire core plus cladding area is illuminated).

135 Similarly, measurements of transmitter power present in short lengths of the fibre will be artificially high if cladding modes are not removed.

136 For example, a typical telecommunications fibre has a 50μm core diameter and 125 μm overall cladding diameter. Assuming that the core NA is 0.25 and that of the cladding is the same as for a PCS fibre (ie 0.39) the ratio of useful core power to the total fibre power is given by:

$$\left(\frac{50}{125} \times \frac{0.25}{0.39}\right)^2 = 6.6\% \quad \text{ie } - 11.8 \text{ dB}$$

137 Cladding modes can be stripped by ensuring that a sufficiently long length of fibre is bared of its primary coating and surrounded by a high refractive index medium. This can be conveniently accomplished in the ferrule termination using normal epoxy resin.

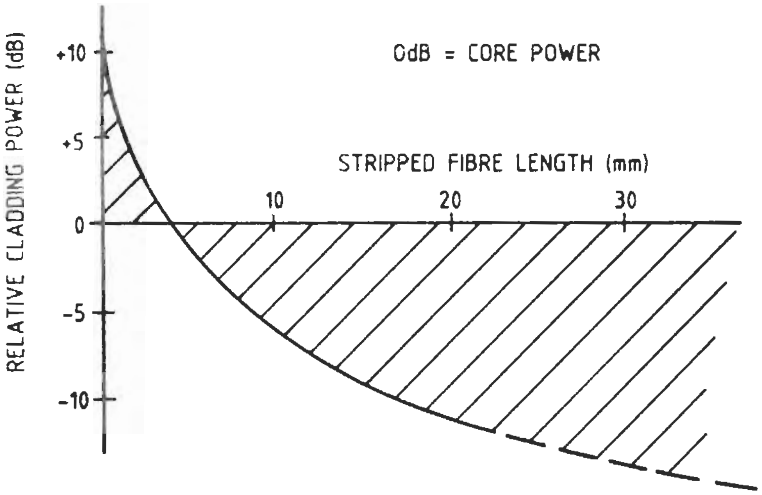


FIG 8.34 LOSS OF CLADDING MODES
IN A 50/125μM SILICA FIBRE

138 Although the removal of cladding modes is an exponential process (since the lower order modes make contact with the boundary very infrequently) it has been found that a stripped length of 20-30 mm will eliminate sufficient cladding power for normal measurement purposes.

139 Cladding mode removal should not be regarded as an essential requirement of an installed link. It may, however, be necessary during evaluation.

LIGHT SOURCES

Power and Brightness

140

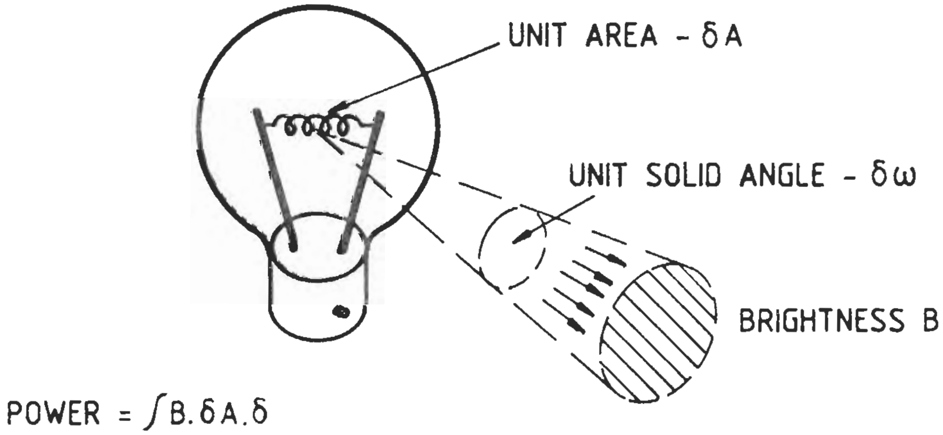


FIG 8.35 DISTINCTION BETWEEN POWER AND BRIGHTNESS

It is important, when specifying light sources for use with fibres, to be aware of two optical principles.

141 First, the distinction between power and brightness. Common experience might lead to the belief that, for example, a 150 watt electric light filament is brighter than an equivalent 60 watt version. This is not so. Admittedly the total optical power emitted is greater, which is useful when illuminating a room, but this is because the filament is larger not brighter. Brightness is

defined as the power emitted per unit area per unit solid angle of emission, and this could well be the same in both cases.

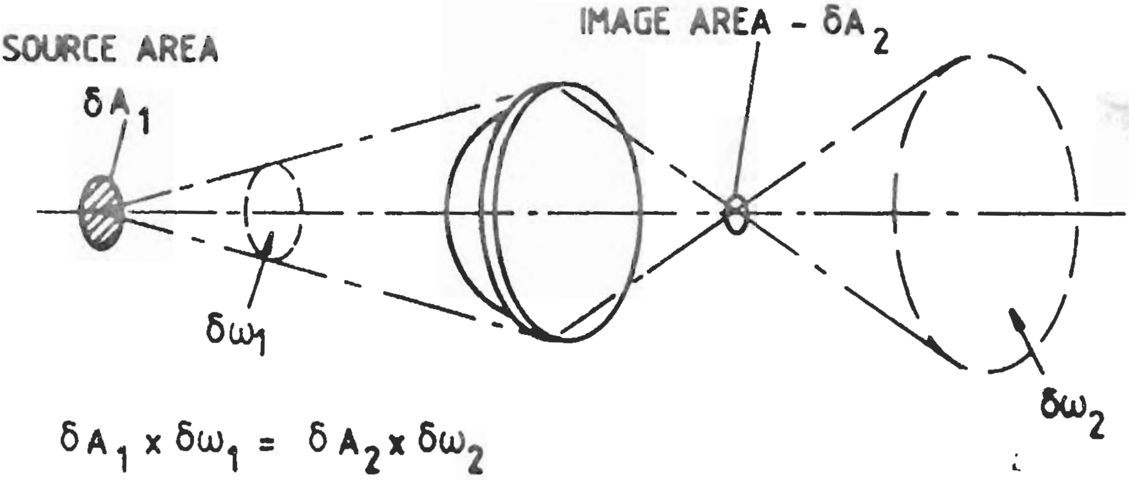


FIG. 8.36 THE BRIGHTNESS OF A BEAM IS CONSTANT

142 Second, it is not possible to increase the brightness of a source by optical means. For example, a lens can be used to reduce its apparent size, but only with a corresponding increase in the beam solid angle. Thus, neglecting losses in the lens, the brightness is unchanged.

143 Given a source that is both large in size and a wide angle emitter, then an optical fibre collects its light in proportion to the brightness of that source, since it defines both the maximum collecting area and the acceptance solid angle.

144 Occasionally, a lens can be used to optimise coupling efficiency by juggling the beam parameters. For example, a semiconductor laser exhibits a rectangular emitting area, with one side much smaller than typical fibre diameters, but with a beam divergence which usually exceeds the fibre NA. In this case, a cylindrical lens can be used to increase the beam size, with a corresponding decrease in beam divergence.

145 If the source is indeed both large in area and a wide angle emitter (as is typical of many light emitting diodes), then no optical improvement over direct coupling of the fibre to the device can be achieved. There may well, however, be engineering advantages to be gained from the use of lens coupling in some cases.

Source Requirements

146 The features of an ideal source for fibre optics communication systems are as follows:

(1) High brightness.

(2) Small emission area (no larger than fibre core).

(3) Small emission cone angle (less than fibre NA).

(4) Close access to emitting surface (to permit direct fibre coupling).

(5) Emission wavelength compatible with fibre and detector.

(6) Fast response to electrical modulation.

(7) Long life.

(8) Low cost.

147 There are two semiconductor devices which approach these ideals, the light emitting diode and the semiconductor laser.

Light Emitting Diodes (LEDs)

148 LEDs are generally manufactured from crystalline materials in the gallium-aluminium arsenide-phosphide family. Using normal semiconductor diffusion growth techniques, a p-n junction is made in the material, across which electrons and holes migrate when the diode is forward biased.

149 Recombination of these carriers results in the emission of a photon of optical energy, with a wavelength approximately equal to the energy gap of the LED material. This wavelength is typically in the range 0.5-0.9 micron, conforming well to the minimum fibre attentuation and optimum detector response.

150 The emission direction of the radiation is quite random, making the polar distribution isotropic within the material. At the surface of the LED, however, a refraction occurs, and the external radiation field closely resembles a lambertian, or cosine, distribution. This is a wide angle emission typical of ground or frosted glass surfaces.

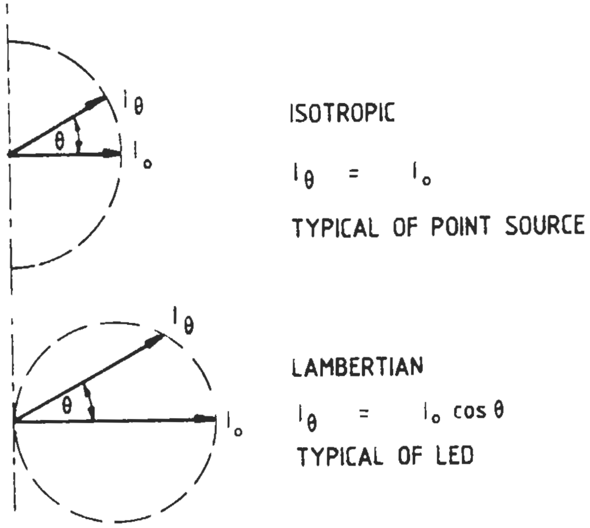


FIG 8.37 POLAR DISTRIBUTIONS OF INTENSITY

151 Thus, in this respect the LED departs from the ideal requirements of a fibre optic source. In most other respects, the LED represents a good compromise between performance and cost, and in fact has found large markets in display and computer peripheral applications. Access to the emitting surface in display devices is often poor, but glass or plastic lenses can usually be removed to enable reasonable coupling efficiencies to be achieved.

152 A number of high radiance (brightness) devices specifically designed for fibre optics use are now commercially available. These are quite expensive, but the design has been optimised to launch considerable power into quite small core fibres, and, in some cases, the device is supplied with a SHORT FIBRE permanently coupled. Other manufacturers, including STC, prefer to provide a disconnection facility at the device interface. This is often a simple screw or bayonet coupling, with no user adjustment provided or required.

Semiconductor Lasers

153 In any laser, spontaneous photon emission is generated isotropically between two parallel reflecting surfaces. Whilst most of this escapes, a small proportion is reflected to and fro between the reflectors. Given a sufficiently high initial energy level, the confined radiation stimulates the release of further photons, emitted with the same wavelength, phase and direction.

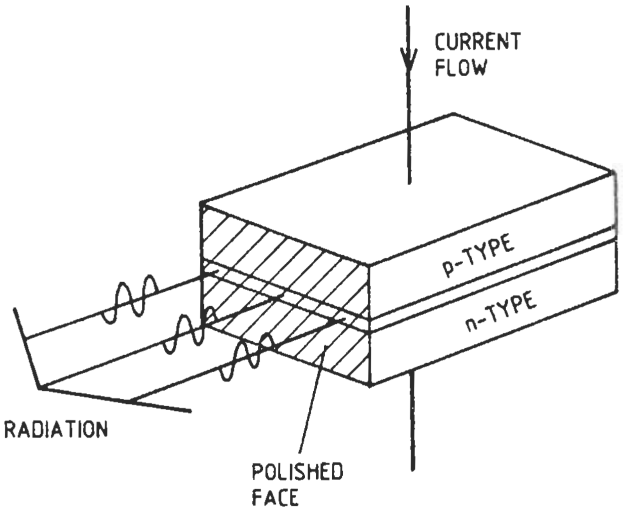


FIG 8.38 SCHEMATIC DIAGRAM OF A SEMI-CONDUCTOR LASER

154 This is a cumulative process, very rapidly leading to a highly intense collimated and monochromatic beam between the two reflectors. One of these is slightly transmissive, allowing a proportion of the beam to emerge for external use.

155 The initial emission in a semiconductor laser is generated by the recombination of holes and electrons (as in the LED) with opposite faces of the chip forming the reflecting surfaces or facets. Since the dimensions of this device are very small, the beam is not so well collimated as in, for example, a HeNe gas laser. Nevertheless, the external beam is quite narrow, and is generated within such a small area that very high power levels can be launched into even the smallest optical fibre.

156 Laser characteristics exhibit two distinct regions. At low values of forward current, the device behaves as an LED, generating light approximately in proportion to the forward current. At a certain threshold current, when losses are overcome, lasing takes place, marked by a dramatic increase in output and efficiency.

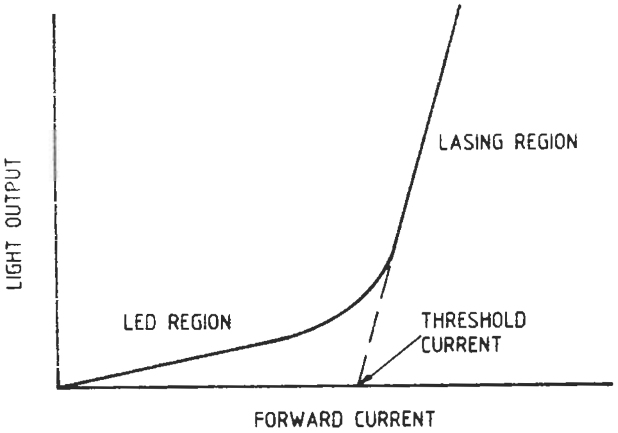


FIG 8.39 THE OUTPUT CHARACTERISTIC OF A SEMI-CONDUCTOR LASER

Different categories of semiconductor laser are termed continuous wave (CW) or pulsed, depending on whether or not a 100% duty cycle is permissible. Many pulsed lasers may only be operated at a 10% maximum duty cycle.

Modal Noise

158 One problem is using a highly coherent source, such as a laser, with multimode fibres is that light propagating in each mode is coherent with light in all other modes. Interference between these modes leads to the formation of a speckle pattern at the output of the fibre, the spatial distribution of which is continuously changing as a result of temperature or mechanical effects. This is clearly visible when projected onto a screen.

159 If this pattern is filtered by, for example, a misaligned connector, a form of noise results called modal noise, which may be a contributory factor in the overall system performance.

Laser Safety

160 The high degree of collimation and brightness of some laser beams makes them a potential hazard to the human eye, and suitable safety precautions have to be taken in their operation. Semiconductor lasers, although generally of lower brightness and poorer collimation, can also be a hazard if viewed under particularly unfavourable conditions.

161 Strict codes of practice governing the use of all lasers have now been evolved by both the British Standards and the American National Standard Institutions. The conditions laid down will ensure that the use of lasers is restricted to essential applications, and that user protection is afforded by electrical and/or mechanical interlocks, unless the output is limited to an intrinsically safe level (Class 1 or A lasers).

162 With certain exceptions (high radiance devices) the radiation from LEDs is quite safe to the naked eye. However, as a precaution, no energised optical source or illuminated fibre should be viewed through a microscope.

OPTICAL DETECTORS

163 The detection of radiation from a fibre is generally carried out using a PIN photodiode, or a refinement of this called an avalanche photodiode. Optically, the requirement for efficient coupling is quite straightforward, it being merely necessary to ensure that the sensitive area is large enough to collect all the exit radiation (which emerges within a cone angle defined by