FIBRE OPTICS

COMMUNICATION

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FIBRE OPTICS COMMUNICATION

INTRODUCTION

1 Fibre optics communication is a technology resulting from the successful integration of:

(1) Optical communication - the transmission of information as a modulated beam of light.

(2) Fibre optics - the guidance of light within flexible filaments often no thicker than a human hair.

2 Both these technologies have enjoyed a limited following in their separate fields, but it has been the additional benefits provided by their combination that have attracted worldwide interest, and have led to the establishment of major research and development programmes by several organisations.

3 Fibre optics communication has now moved out of the laboratory! STC, for example, offer as a complete package a fully specified link for commercial applications. Whilst this can be successfully installed and operated without specialised knowledge or skill, an understanding of the basic principles is not difficult to acquire: indeed, it is desirable as it leads to a better understanding of both the potential and the limitations of the technology.

4 A frequently encountered deterrent is the need to extract the relevant facts from the abundance of information available, much of which is either more detailed than required for the non-specialist, or alternatively is too limited in its scope. This publication is aimed to fill the need for a basic fibre optics communication manual, by describing the principles of the technology in a concise but thorough form, whilst avoiding unnecessary mathematical theory.

History of Fibre Optics

5 The principle of guidance of light within a 'transparent conductor' is not new - in 1870 John Tyndall demonstrated to fellow members of the Royal Society that light would follow the curved jet of water issuing from a container.

6 Later, J L Baird filed patents covering the transmission of light in glass rods - intended for use in an early colour television system. However, the practical implementation of this and other proposals was held up by the high intrinsic optical loss inherent in the materials available, and by the absence of optical cladding.

7 It was not until the 1950s that fibre optics became a realistic propostion, with many applications being developed principally devoted to the transmission of visible light, either for remote illumination or for the transfer of images in flexible viewing instruments (eg for medical applications).

8 In 1966 Charles Kao and George Hockham, two scientists working at Standard Telecommunication Laboratories Harlow, proposed the principle of information transmission via a transparent dielectric medium (eg glass fibre). One of the requirements postulated for a viable system was a reduction in fibre attenuation to a target figure of 20 dB/km. With available fibres typically exhibiting 500-1000 dB/km the necessary advance in materials technology to achieve such a drastic reduction in attenuation appeared hopelessly optimistic, yet it took only four years for this target to be achieved.

9 Such have been the further advances in the technology that commercial fibres with losses one quarter of the target figure are now commonplace, and laboratory values of less than 1 dB/km have been recorded.

Advantages of Optical Communication

10 Although great interest in fibre optics communication has been shown by the telecommunications industry as a possible alternative for long-haul high-bandwidth systems, many simple short distance applications - for example industrial process control, computer installations and high voltage monitoring - are likely to predominate in the near future.

11 The principal advantages to be gained from using fibre optics are listed below:

(1) Low loss - potentially long distances between terminals or repeaters.

(2) High bandwidth - high rates of data transmission.

(3) Lightweight/small size - aircraft/mobile applications.

(4) Electrical isolation - high voltage monitoring or control.

(5) Freedom from electro-magnetic interference - no pickup in electrically noisy environments.

(6) No spark hazard - operation in explosive atmospheres.

(7) Security - very difficult to locate and 'tap'.

(8) Opern circuit failure mode - no 'short circuit' fault damage to terminals.

FUNDAMENTALS OF FIBRE OPTICS COMMUNICATION LINKS

Function

12

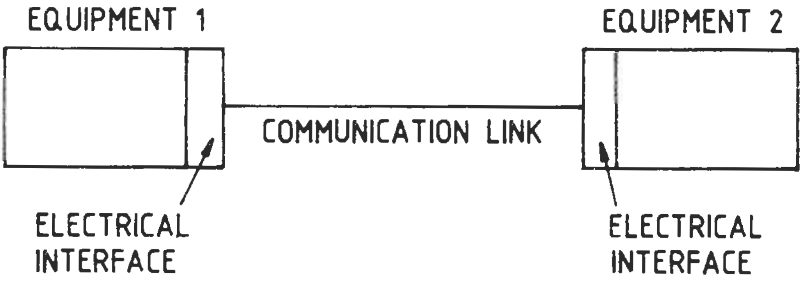


FIG 8.1 ESSENTIAL ELEMENTS OF A COMMUNICATION LINK

A fibre optics link provides an alternative means of communication to wires, twisted pairs, coax or free space radio and microwave systems. The link transmits signals between interfaces in the equipments which are communicating.

Essential Components

13 A fibre optics link is composed of a number of basic components:

(1) Electro-optical signal transducer - the transmitter.

(2) Optical fibre cable.

(3) Opto-electrical signal transducer - the receiver.

Depending on the particular requirements of the system, the link may also include:

(4) Demountable connectors:

- transmitter to fibre
- fibre to fibre
- fibre to receiver.

(5) Branching couplers:

- for multiple access systems.

14 The simplest fibre optics links provide point-to-point communication, that is, a given transmitter is permanently coupled to a designated receiver, with communication in one direction only. Return communications must be provided by an entirely separate link.

15 A 'send and receive' duplex link must include an optical 'Y' coupler at each end of the communications cable to combine the separate transmitter and receiver connections in each terminal. In optical communications an allowance must be made for the halving of power which occurs in each coupler, but because of the unique isolating property of fibre optics no 'send' and 'receive' switching is necessary.

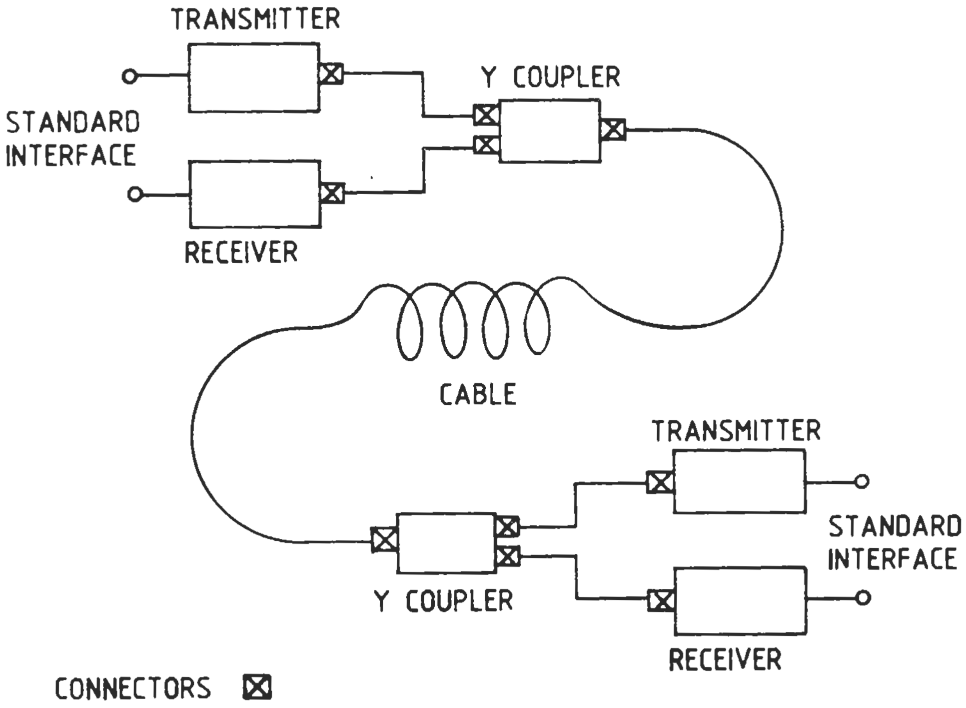


FIG 8.2 A DUPLEX LINK (SEND AND RECEIVE)

16 Cable, connectors and couplers are analogous to their electrical counterparts. These are the interconnection components which permit signal transmission over complex paths between two or more terminals. The design of these components has to satisfy not only the required optical performance, but also mechanical and environmental specifications so that installation and operation will be no more difficult to achieve than with wire cables.

17 The optical transmitter and receiver are unique to fibre optics. The transmitter usually contains an optical emitter which can either be a light emitting diode or a semiconductor laser, together with associated drive circuits. Similarly the receiver contains a PIN or avalanche photodiode, followed by circuits for signal amplification, output level reconstitution and possibly automatic gain control (AGC).

18 Signal coding and decoding may also be incorporated to exploit to the maximum the special features of fibre optics transmission.

Ancillary Equipment and Instrumentation

19 Ancillary equipment is needed for:

(1) Fibre termination, and assembly of connectors to cables.

(2) Permanent jointing or splicing.

20 Techniques may be easy and quick to perform either in the factory or on site, and must result in assemblies of reliable mechanical and environmental performance.

21 Special purpose instrumentation is needed to characterise the optical path, and for fault location and diagnosis.

Single Fibres and Fibre Bundles

22 Two alternative concepts have developed in the manufacture of cables for fibre optics communication, these being the use of either a single fibre or a multiple fibre bundle for each information channel. Historically, the choice has been significantly influenced by the background of the individual manufacturer.

23 For example, those companies already committed to the manufacture of light guides for other fibre optics applications have readily adapted fibre bundles for communications use. This, combined with the relative ease with which they can be coupled to each other and to sources and detectors, has given bundles an early lead in communications technology.

24 Conversely, other companies, with no previous experience of fibre optics but with a background of semiconductor technology, have recognised that likely developments in miniature sources and detectors favour the use of the small size transmission medium offered by single fibres. The economics of high quality low loss fibre production reinforces this conviction, while parallel developments in fibre strength and cable design enables single fibres to withstand a considerable degree of mishandling, thus overcoming one of the major objections to the use of single fibres.

25 Consequently, this manual is essentially dedicated to single fibre communication systems, although many of the principles involved are equally applicable to both.

$$= \frac{\text{SPEED OF LIGHT IN A VACUUM}}{\text{SPEED OF LIGHT IN THE MEDIUM}}$$

FIG. 8.3 REFRACTIVE INDEX

The path of a ray of light in different materials is influenced by the fact that light travels more slowly in an optically dense medium than it does in a less dense one. A measure of this effect is the refractive index.

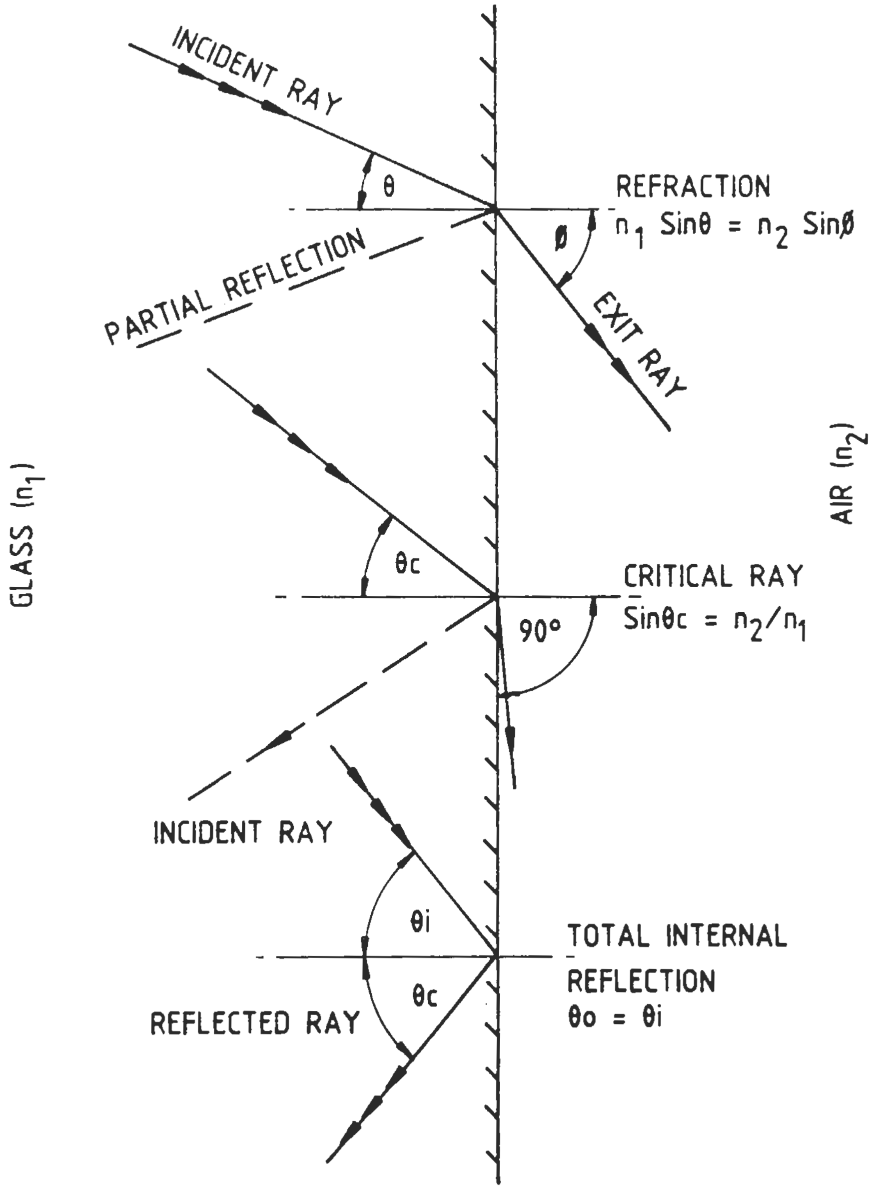


FIG 8.4 ALTERNATIVE RAY DEVIATIONS AT A GLASS-AIR INTERFACE

27 It is observed that a ray, approaching an interface (boundary) between media of different refractive indices (eg glass-air) at angle Θ to the normal in the higher index side, leaves at a greater angle ϕ in the lower index medium. Snell's law of refraction relates these angles by the expression

$$\frac{\sin\Theta}{\sin\phi} = \frac{n_2}{n_1}$$

28 A significant feature of refraction is that a small proportion of the light is reflected back into the originating medium (partial internal reflection).

29 At a particular value of the incident angle Θc, the refracted ray emerges parallel to the interface. This is the critical angle.

30 All shallower rays (ie $\Theta i > \Theta c$) are reflected completely, obeying the familiar law of reflection, $\Theta o = \Theta i$. This is total internal reflection (TIR) and is theoretically 100% efficient. In practice, the efficiency can exceed 99.9%, compared for example with 85-90% for a silvered mirror.

Transmission in Cylindrical Fibres

31 Two parallel glass-air interfaces will trap a ray approaching a suitably shallow angle, and transmit it, virtually without loss, by a series of total internal reflections.

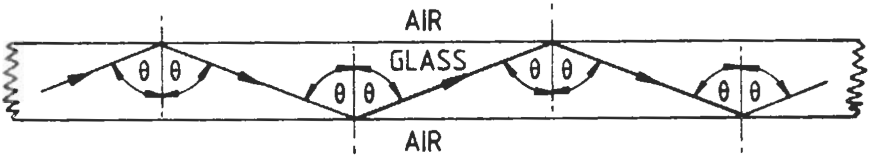


FIG 8.5 A RAY TRAPPED BY TOTAL INTERNAL REFLECTION

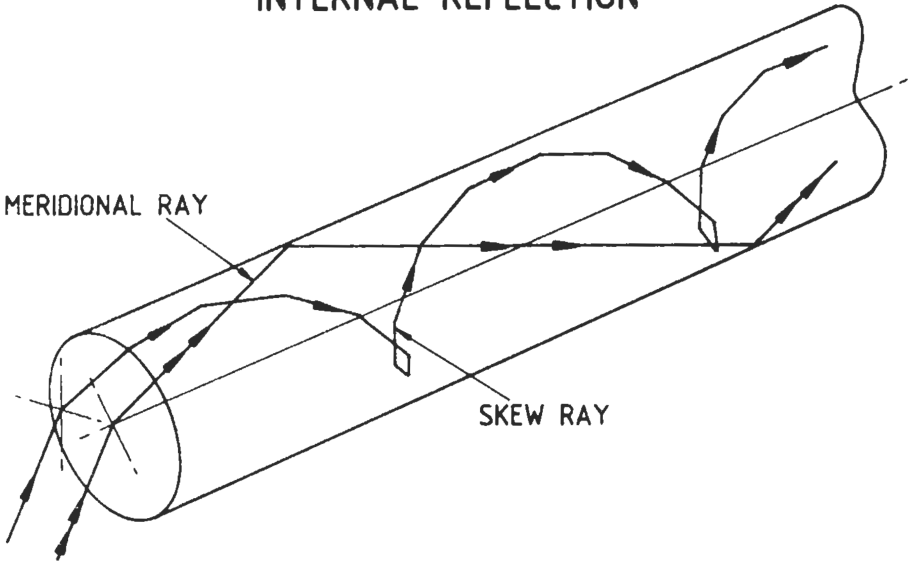


FIG 8.6 TRANSMISSION WITHIN A GLASS ROD

32 A cylindrical glass fibre behaves in a similar manner, except that the majority of rays travel in a stepped helical manner by many such reflections at the circumference.

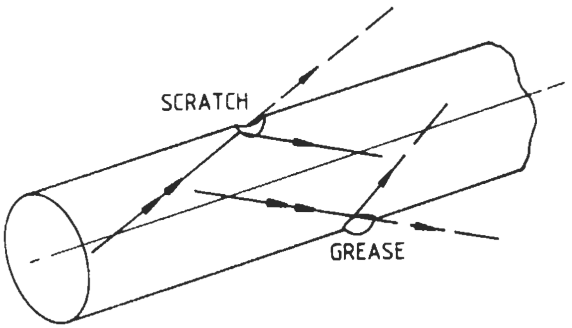
33 Since this is difficult to visualise in two dimensions, it is usual to consider only those rays which lie in a plane through the fibre axis (meridional rays), even though these are greatly outnumbered by the helical, or skew rays.

Optical Cladding

34 An essential requirement for total internal reflection is that the external medium should possess a lower refractive index than the fibre. Although this condition is satisfied by a simple glass-air interface, in practice this is easily damaged, and light then escapes by two principal mechanisms, both of which alter the effective angle of incidence at the interface:

(1) Inclusions or scratches.

(2) Surface contaminants (eg grease).



LOSS OF LIGHT AT SURFACE IMPERFECTIONS

THE SOLUTION - AN OPTICAL CLADDING

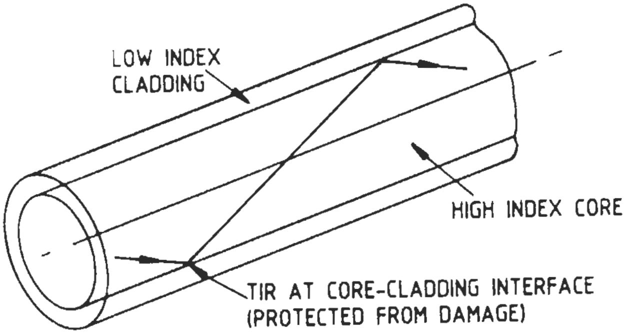


FIG 8.7 LOSS OF LIGHT AT SURFACE IMPERFECTIONS

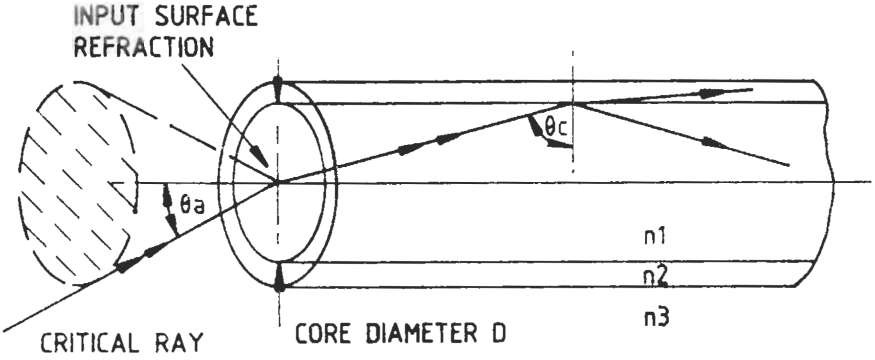
35 Grease has a refractive index which is similar to that of glass and hence, to the approaching ray, appears as an extension of the glass surface.

36 These defects are avoided by the provision of an optical cladding. This is a region of lower refractive index surrounding the central zone (core). Total internal reflection can now take place at the protected core-cladding interface.

37 The development of clad optical fibres represents one of the most significant steps forward in the technology of fibre optics.

Numerical Aperture

38 Since only those rays with a sufficiently low grazing angle at the core-cladding interface are transmitted by total internal reflection, rays must approach the input surface of the fibre within a similarly limited cone angle.



NUMERICAL APERTURE (NA)

NA = SIN $\theta a = \frac{1}{n3}\sqrt{n_1^2 - n_2^2}$ (FOR AIR n3 = 1)

FROM LARGE, WIDE ANGLE LIGHT SOURCES
LIGHT ACCEPTED BY FIBRE α (NA x D)2

FIG 8.8 LIGHT ACCEPTANCE CONE
OF AN OPTICAL FIBRE

39 The half angle Θa of this cone, within which rays will be transmitted, is called the acceptance angle and is related to the refractive indices of the three media - core, cladding and air. The index of air is approximately 1. Note that a refraction occurs at the input surface.

40 The expression sinΘa is a measure of the light collecting ability of the fibre and is called the numerical aperture (NA). Rays at greater angles to the fibre axis than Θa will not be transmitted by total internal reflection. Since many light sources emit over a wide range of angles, it follows that fibres with large NAs will collect a greater proportion of that light (in proportion to NA^2). Similarly, large diameter fibres are to be preferred if the light source is large compared with the fibre.

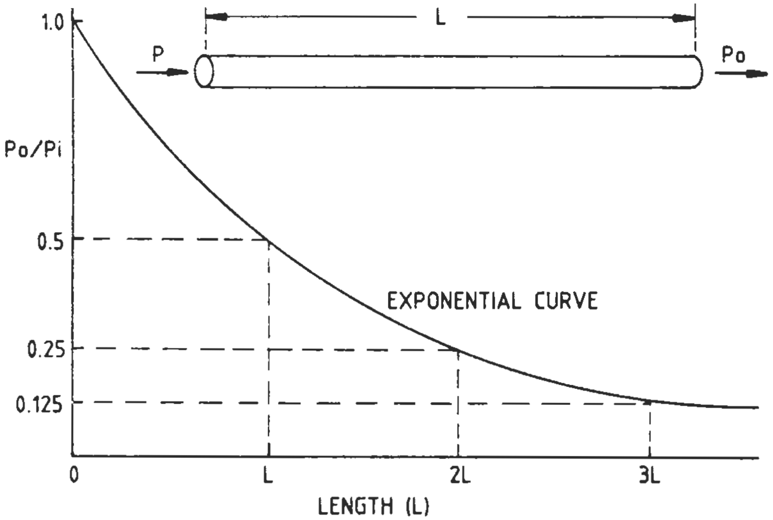
Typical fibres have diameters ranging from 30 µm - 600 µm, and NAs from 0.15 to 0.5.

Optical Loss

41 The amount of light emerging from the end of a fibre is always less than that entering due to losses caused by scattering and absorption in the core, and by imperfect reflection at the optical interface. This loss is dependent on the length of the fibre, and, like many natural phenomena, produces an exponential decay, which means that repeated equal increments of length always cause the same proportional decrease in power.

42 This is an inconvenient law to use for mental calculations, but can be converted into a linear function of length by expressing the exit/input power ratio (Po/Pi) in terms of its logarithm.

DECAY OF OPTICAL POWER IN LONG FIBRES



FIBRE ATTENUATION IS A LINEAR FUNCTION

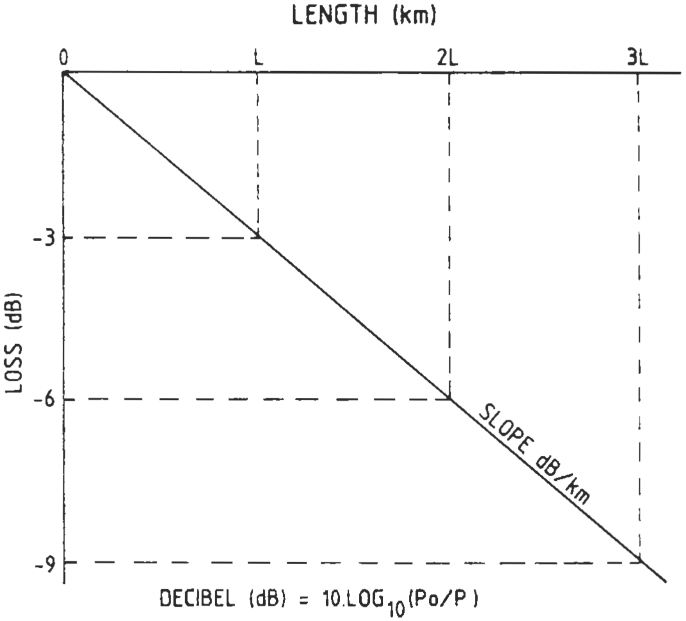


FIG 8.9 DECAY OF OPTICAL POWER IN LONG FIBRES

The name bel is given to this raio when using logarithms to the base 10. In practice this is too large for convenience, and a smaller unit one tenth the size has been termed the decibel (dB):

Thus, loss in dB = 10 x log10(Po/Pi).

43 Fibre losses are normally expressed in terms of attenuation (in dB) per unit length (km). For example, values range from less than 1 to in excess of 1000 dB/km.

Spectral Response

44 Visible light is a small region of the electro-magnetic spectrum covering wavelengths in the range 0.4-0.7 micron. Many of the light sources used in optical communications emit at wavelengths either just inside the visible spectrum (red) or just outside (near infra-red), say from 0.6 to 1.2 μm wavelength.

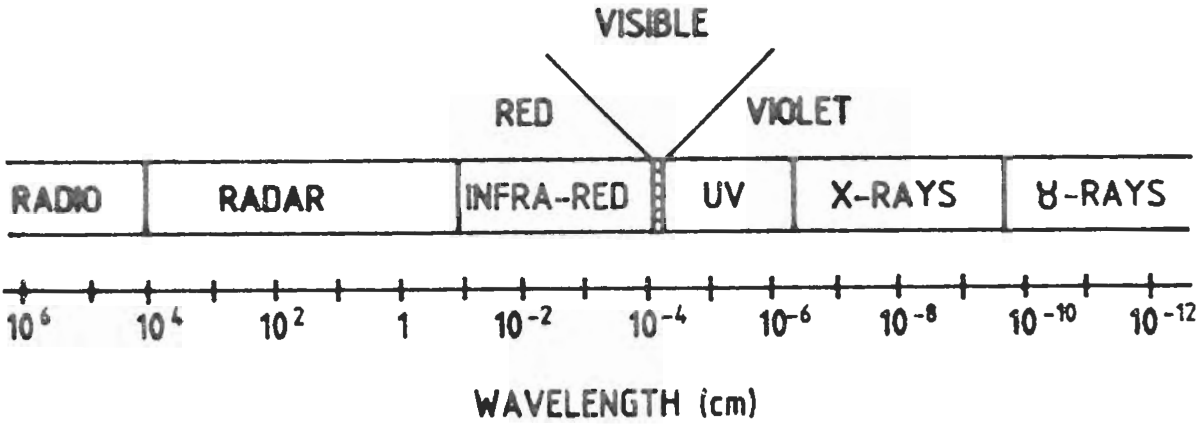


FIG. 8.10 THE ELECTROMAGNETIC SPECTRUM

45 All glasses scatter light due to frozen in thermal fluctuations of constituent atoms. These cause density and hence refractive index variations within the material. It is believed that this intrinsic Rayleigh scattering represents the fundamental minimum limit to fibre attentuation. Since Rayleigh Scattering is found to vary inversely as the 4th power of wavelength (ie λ^{-4}) it follows that lower fibre attenuation occurs at longer wavelengths, and ideally light sources should be selected accordingly, consistent with adequate detector response.

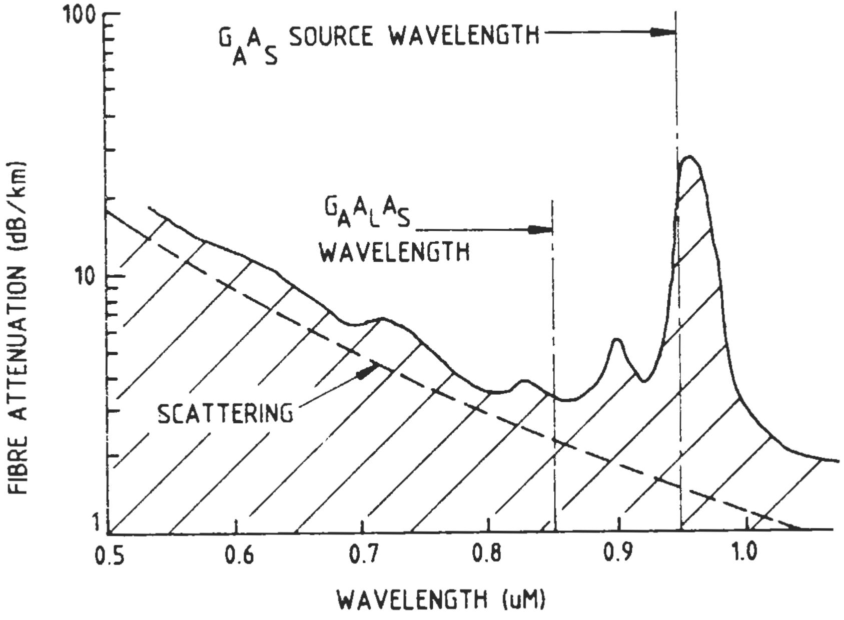


FIG 8.11 SPECTRAL RESPONSE OF A SILICA FIBRE

46 In practice, of course, other considerations often assume greater importance. For example, it is particularly important to avoid certain attenuation peaks which occur with some types of fibre. One particularly severe peak occurs close to the GaAs source wavelength. This is caused by absorption in the core by hydroxyl ions and consequently is frequently referred to as a water peak.

47 As well as the nominal operating wavelength, the spectral linewidth (range of emitted wavelengths) of the source is important since each wavelength propagates at a different velocity. As will be seen, this limits the bandwidth of high data rate systems, and consequently semiconductor lasers are preferable to light emitting diodes as sources in such cases, since these exhibit narrower linewidths.

Optical Pulse Dispersion

48 Fibre optics communication is concerned with the transmission of information by varying or modulating the intensity of the light source at appropriate intervals. Fibres are most useful if they can faithfully support a rapid modulation frequency, or high data rate.

49 Apart from electronic limitations in the transmitter and receiver, a restriction is imposed on the maximum frequency by the fibre itself.

50 Light is transmitted along a fibre by a multitude of different paths, ranging from one which is parallel to the axis to those propagating at angles close to the critical angle, with many in between. Each path at a different angle is termed a transmission mode. It is clear that the distances travelled by various modes, and hence the times taken, are not equal.

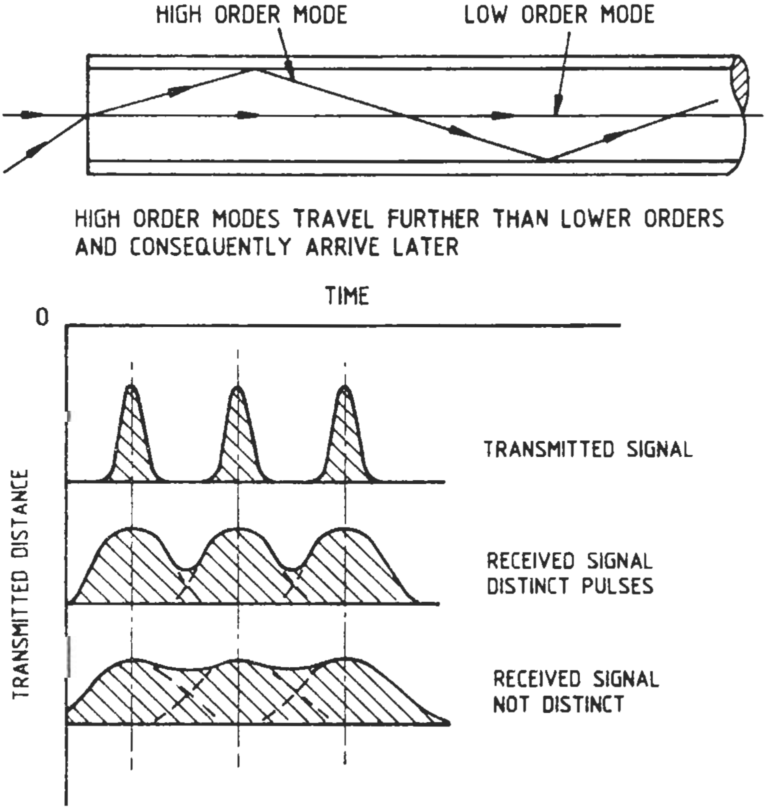
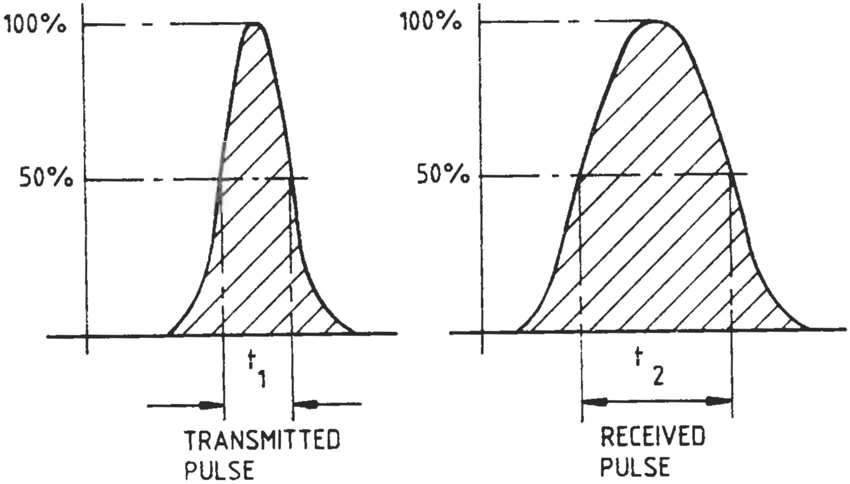


FIG 8.12 SIGNAL DISPERSION CAUSED BY MULTIPLE RAY PATHS (MODES)

52 Consequently, a short pulse of light, launched simultaneously into many modes, will have various transmission delays, and will arrive at the exit dispersed over an extended period of time.

53 This limits the maximum data rate, since a rapid train of pulses will merge into one another and may not be distinguishable. There will also be a reduction in amplitude caused by the pulse spreading. This is referred to as intermodal dispersion.



DISPERSION = $(t_1 - t_2)$ nS

$$\text{FIBRE BANDWIDTH (MHz.km)} = \frac{310}{\text{DISPERSION (nS/km)}}$$

FIG 8.13 THE MEASUREMENT OF DISPERSION

54 The usual measure of dispersion is the increase in width of a Gaussian shaped pulse, measured at the half amplitude level. This is dependent on both the length and the NA of the fibre under test. Values are often quoted in ns/km.

55 Sometimes a fibre bandwidth is specified, corresponding to the upper frequency at which dispersion reduces the signal modulation amplitude by 3 dB. Typical values for a 0.5NA fibre are 50 ns/km or 7.75 MHz km.

Mode Conversion

56 In real fibres, bends and minor irregularities at the core-cladding interface lead to conversion between high and low order modes, ie changes in ray angle.

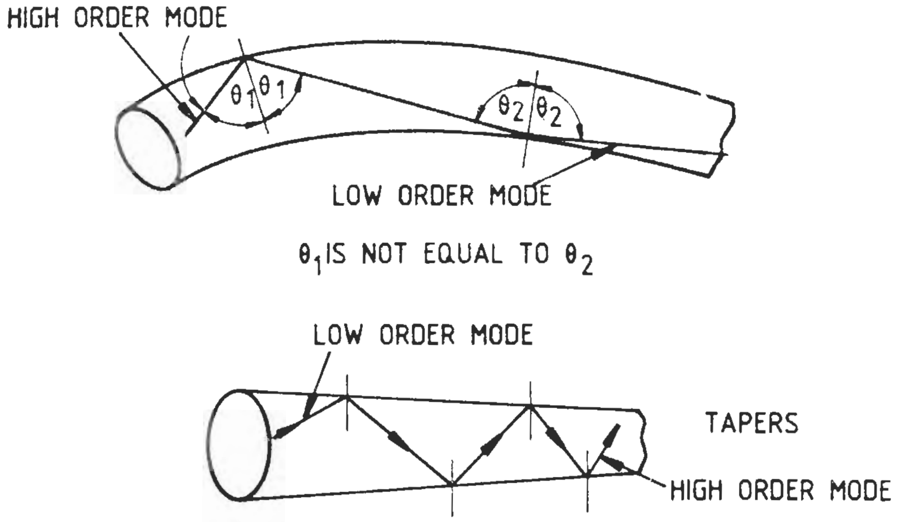


FIG 8.14 MODE CONVERSION REDUCES DISPERSION

57 Thus, to some extent, dispersion is reduced since all rays travel by high and low order paths along the fibre. This is particularly noticeable in longer lengths of fibre and in such cases dispersion may be assumed to increase in proportion to the square root of length rather than a linear function.

58 For low frequency applications, dispersion is usually insignificant and maximum length will be limited by fibre attentuation. However, for long haul high bandwidth telecommunications, fibre dispersion may be predominant, and different fibre constructions have been evolved to ease the problem.

Step and Graded Index Fibres

59 The fibres considered so far exhibit a distinct change in refractive index between the core and cladding, and are called step index fibres for this reason.

60 Imagine a fibre constructed with many such changes in refractive index, with larger values towards the centre. A ray crosses the axis, approaching the circumference ...

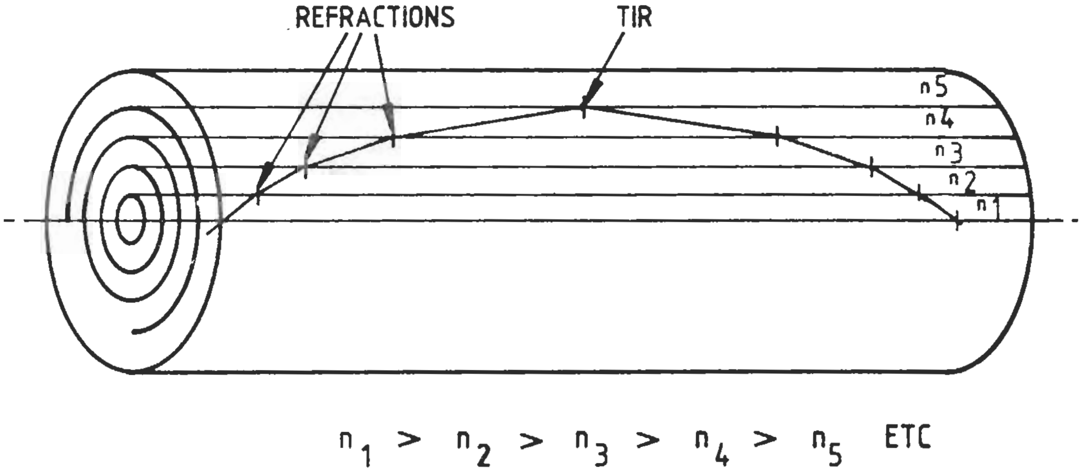
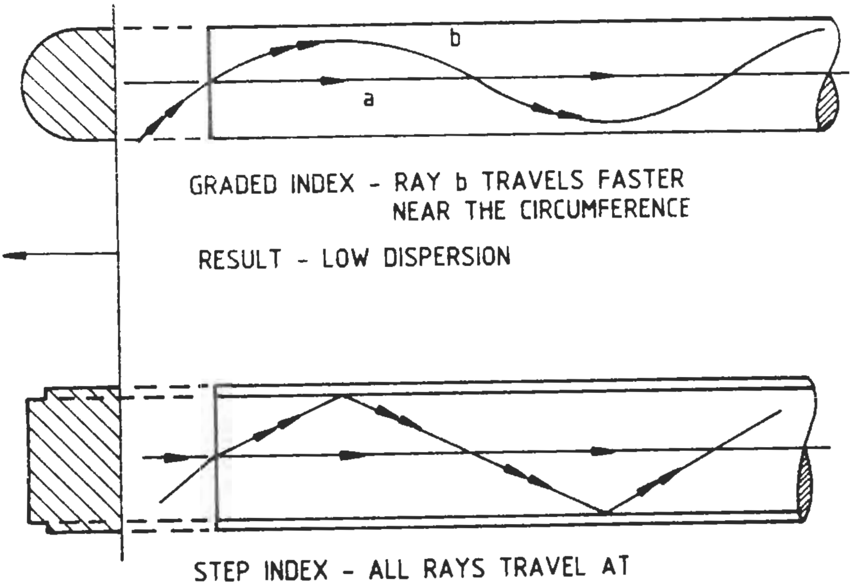


FIG 8.15 STEPPED INDEX MODEL OF A GRADED INDEX FIBRE

61 At the majority of interfaces, the critical angle will be exceeded so that a refraction occurs. This, however, reduces the grazing angle, and eventually conditions will be met for total internal reflection to take place. From then on, the ray will be refracted back towards the axis in a symmetrical manner.

62 If this model is replaced by a fibre in which the refractive index is continuously graded from a maximum at the centre to a minimum at the circumference, the previously stepped path is replaced by a smooth curve. Moreover, since the same phenomenon occurs on the opposite side of the axis, light is transmitted down the fibre following a smooth oscillating path.



GRADED INDEX - RAY b TRAVELS FASTER
NEAR THE CIRCUMFERENCE

RESULT - LOW DISPERSION

STEP INDEX - ALL RAYS TRAVEL AT
THE SAME SPEED

RESULT - CONSIDERABLE DISPERSION

FIG 8.16 TRANSMISSION OF GRADED AND STEPPED INDEX FIBRES

63 There is still a path length difference between modes (a) and (b), but from the original definition of refractive index it is clear that ray (b) accelerates as it moves into the lower index medium near the circumference and generally travels faster than ray (a) in the high index centre. If the refractive index profile varies in a nearly parabolic manner, the increased speed of ray (b) exactly compensates for the greater path length, and the two rays, and consequently all rays, pass through the axis at the same instant.

64 It is difficult to fabricate fibres with the exact refractive index profile required, but a sufficiently close approximation can be made to give a useful factor of 10 or more reduction in dispersion. These fibres are called graded index fibres.

Numerical Aperture (Graded Index Fibres)

65 The numerical aperture of a step index fibre was defined earlier as:

$$NA = \sqrt{N1^2 - N2^2}$$

Where N1 = core index
N2 = cladding index
(N3 = 1)

Since there is only a very small difference in refractive index between the core and cladding (typically 1-1.5%) very little error is introduced by expressing the NA in terms of this difference Δ and the average material index N using the approximation

$$NA = N\sqrt{2\Delta} \quad \text{where } \Delta = \frac{N1-N2}{N}$$

In practice N may be taken as being equal to either N1 or N2, or the index of the raw material (say 1.4-1.5), whichever is the most convenient. Thus, for example, a fibre with an index difference of 1% exhibits an NA of about 0.2.

66 A graded index fibre with a maximum index difference Δ exhibits an identical $NA = N\sqrt{2\Delta}$ on its axis, but lower values towards the periphery in line with the reducing refractive index. For a parabolic index profile the effective NA for the total core can be shown to be

$$NAeff = N\sqrt{\Delta}$$

Thus it is clear that the total power acceptance of a graded index fibre (proportional to $NAeff^2$) is half of an equivalent step index fibre.

Limitation of Ray Theory - Monomode Fibres

67 Although the concept of a ray travelling in a straight line provides a useful and quite accurate basis for describing the transmission properties of light on a large scale, a more detailed understanding can only be achieved by considering it in terms of a wave motion.

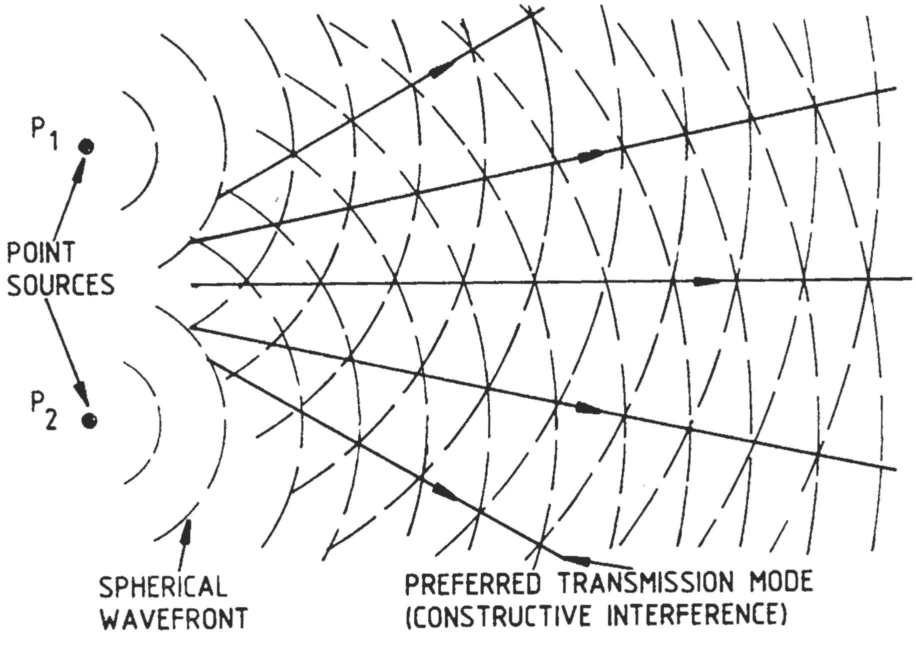


FIG 8.17 INTERFERENCE PATTERN FROM POINT SOURCES

68 We must recognise, for example, that the direct and reflected components of a wavefront interfere with one another, either constructively or destructively according to their relative phases. This defines a number of preferred ray propagation paths - transmission modes - which occur at discrete angles to the axis bounded by the numerical aperture of the fibre.

69 In other words, just like any other waveguide, the fibre is only capable of supporting a limited number of modes, this number being related to the fibre NA, its core diameter d, and the wavelength of light λ by the expressions:

$$N \simeq 0.5 \left(\frac{\pi . d . NA}{\lambda}\right)^2 \quad - \text{ step index fibres}$$

$$N \simeq 0.25 \left(\frac{\pi . d . NA^2}{\lambda}\right) \quad - \text{ graded index fibres}$$

As long as the core diameter exceeds about 10 wavelengths, the number of modes is considerable, and their distribution is virtually indistinguishable from a continuum. Such fibres are termed multimode.

70 A significant feature of the transmission modes in the simplified model illustrated is that each successively higher order mode contains some light which has been delayed by one additional complete wavelength, thus introducing signal dispersion within that mode and contributing to the dispersion of the total wavefront. Clearly reducing the number of permissible modes will result in lower dispersion and hence higher bandwidth capability.

71 This principle is equally valid in optical fibres. A reduction in NA is possible, but there is a practical limit to this, beyond which the light is insufficiently well guided and escapes at bends of even quite moderate curvature. However, reducing the core diameter also leads to a reduction in the number of modes, and in particular only one can propagate if the diameter is less than the critical value:

$$dc = \frac{2.4\lambda}{\pi NA}$$

72 This remaining mode is labelled HE11 and is significant in not being subject to intermodal dispersion. Fibres made to this criterion are called single or monomode and are capable of supporting extremely high bandwidths (potentially 50 GHz km). Bandwidth is ultimately limited by a second form of dispersion known as intramodal. This is the result of refractive index (and hence propagation velocity) variation with light source wavelength.

73 Hence for the full exploitation of monomode fibres, light sources are required which exhibit very narrow spectral linewidths. They must also be very small and bright in order to permit efficient coupling into the very small core diameters of these fibres (typically 3-5 microns).

FIBRE CONSTRUCTIONS

74 Optical fibres are commonly manufactured from either plastic, silica, or glasses containing lead, sodium or boron compounds.

Plastic Fibres

75 Fibres constructed from transparent plastic offer the advantages of large diameter (as large as 1 mm), flexibility and ease of termination (ends can be prepared by cutting with a hot razor blade). However, the high intrinsic loss of the materials used limits them to applications involving transmission distances of only a few metres, and to environments protected from extremes of temperature.