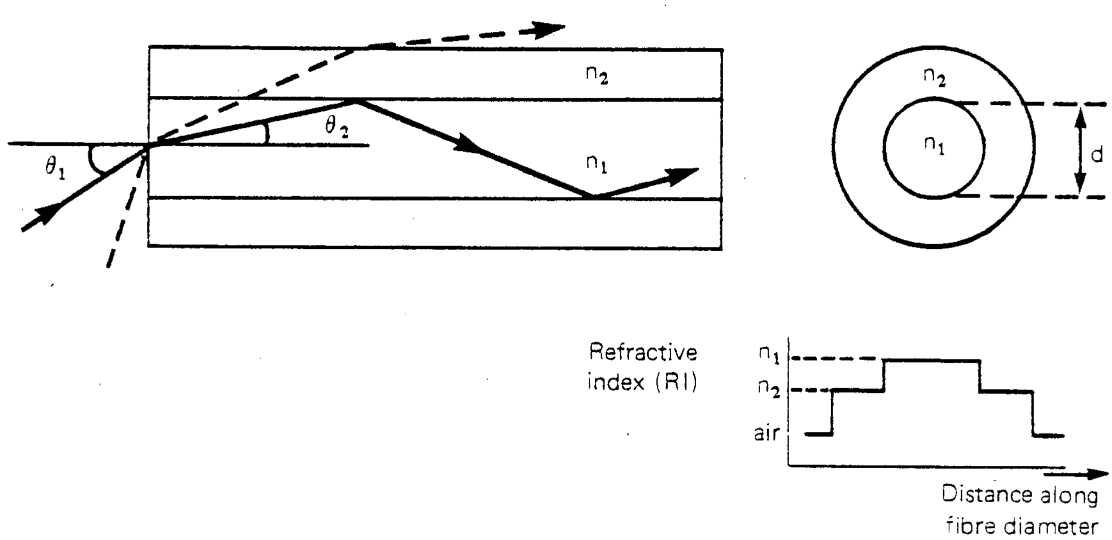
NOTES ON THE BASIC PRINCIPLES AND PROPERTIES OF OPTICAL FIBRES

Transmission Principles

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 1 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

Fig. 1 Ray Diagram for Multimode Step Index Optical Waveguide



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

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

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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.

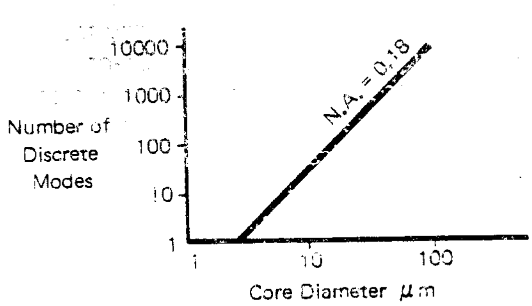
The number of discrete modes, N, for light having a wavelength of λ is given by:

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

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 2 illustrates this point.

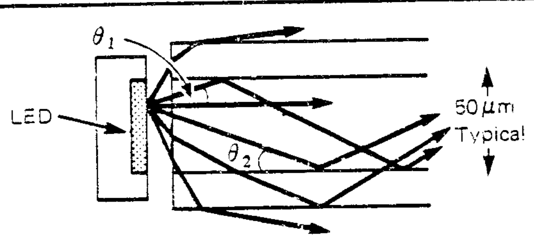
Fig. 2 Graph Showing Reduction in Number of Modes with Reduction in Core Diameter (λ = 850 nm)



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 3 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/mm²) which can be coupled into a fibre butted up against a source radiating uniformly is given by:

Fig. 3 Simple Ray Diagram Showing Launching Conditions with an LED Source and Multimode Fibre



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

where R = radiance (watts/steradian)

A = core or emitting area, whichever is the smaller (mm²)

Multipath Dispersion

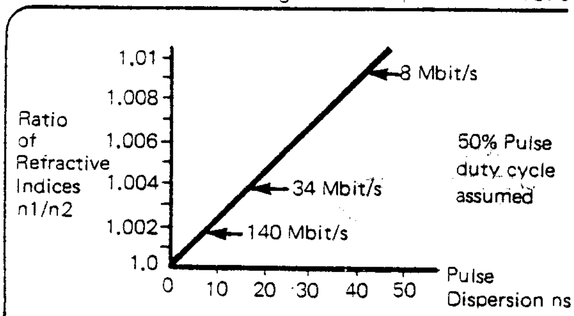
Unfortunately there is a disadvantage in having a high numerical aperture because it means that a fairly large number of modes can propagate along the length of the fibre. (See equation 2.) Now different modes will travel different distances along the fibre and they therefore arrive at the far end at 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:

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

Where Δt is known as the multipath 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 4. From Equation 1, there is a direct relationship between NA and refractive index ratio. It

Fig. 4 Graph Showing Variation of Pulse Dispersion with Refractive Index Ratio n1/n2 for 1km Length of Step Index Fibre



follows that the multipath pulse dispersion increases with increase in numerical aperture, or in other words the bandwidth decreases with increase in numerical aperture.

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.

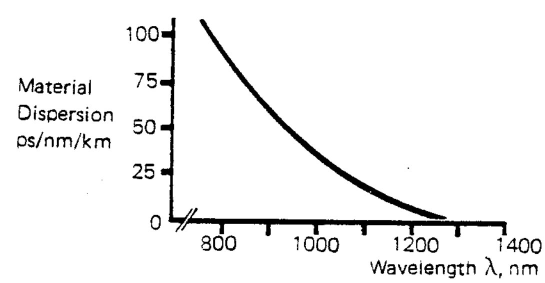
Material Dispersion

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 5. The advantages of systems operating at wavelengths around 1300 nm are quite apparent.

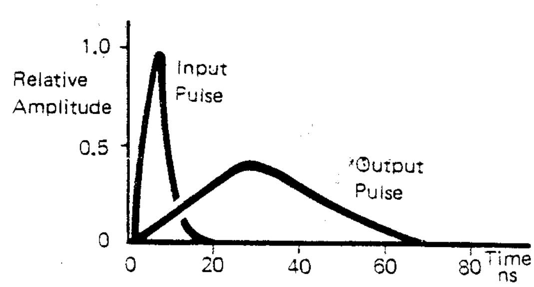
To illustrate the mechanism of material

Fig. 5 Relationship Between Material Dispersion and Wavelength for a Typical Fibre



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 6.) Fortunately this can be

Fig. 6 Pulse Dispersion for Typical 1km Length of Multimode Step Index Fibre



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 more. The material dispersion bandwidth is given by:

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

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.

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 7a. It is possible however to construct an optical waveguide by using a graded continuous index profile as shown in Figure 7b. 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:

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

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

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

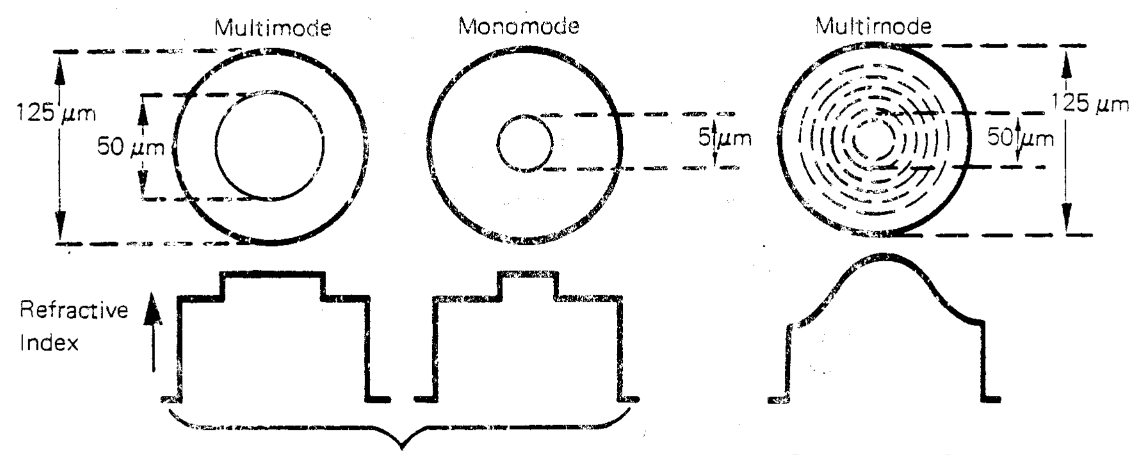
r = distance from fibre axis

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.

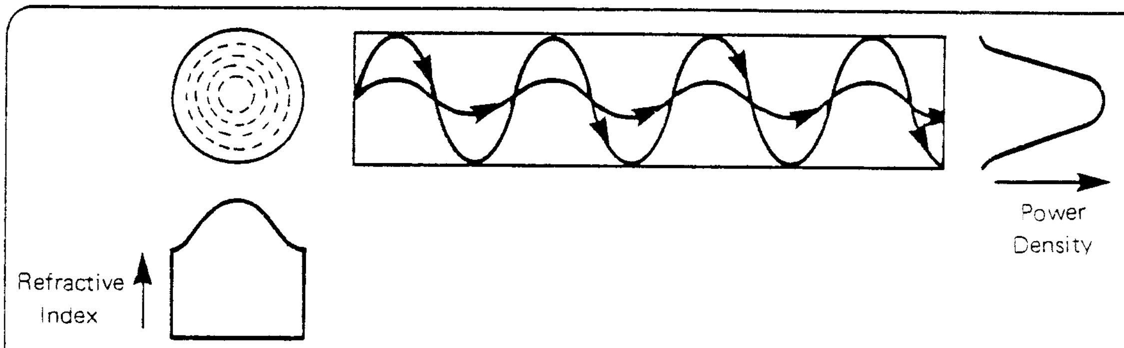
Fig. 7 Refractive Index Profiles
(Typical Dimensions shown)



a) Step Index Profiles b) Graded Index Profile

With this type of profile many modes can propagate. Two of these are illustrated in Figure 8. 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. 8 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 multi-mode 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:

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

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 multi-mode 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 4 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.

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.

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.

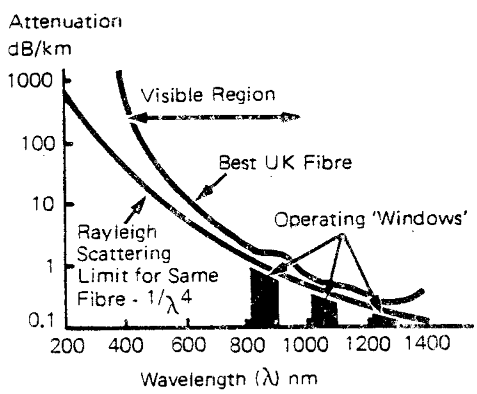
i. Absorption Loss

Absorption losses in glasses are mainly due to the presence of impurity ions. 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. 9 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 9. 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 9 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 5 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 9. 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 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 λ = 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.