Chapter 3 Introduction to Optical Fibres

3.0 INTRODUCTION

The idea of communicating using optical wavelengths (or light waves) has been around for a long time. The first modern system was devised in 1880 by Alexander Graham Bell. This system used a voice-modulated mirror to vary the light intensity directed toward a selenium photocell. The device was not a commercial success.

The idea of communicating with light waves was to remain merely a curiosity for nearly a century because of two reasons:

- The optical sources available during that time (such as incandescent, fluorescent, and arc lamps) could be modulated only at low speeds. This made their data rate very low.
- The optical attenuation between the transmitter and receiver sights was high (spreading losses as in open-air systems or high material losses as in dielectric waveguides).

Renewed interest in light-wave technology was aroused in the 1960s and 1970s by two inventions:

- The invention of laser, which provides a nearly single wavelength optical source that could be modulated at high data rates.
- The development of low-loss silica glasses that could be formed into optical fibres.

3.1 ADVANTAGES OF OPTICAL FIBRES OVER THE CONVENTIONAL COPPER SYSTEM

1. *Low transmission loss and wide bandwidth*
   Optical fibres have lower transmission losses and wider bandwidths than copper wires. This will allow longer transmission distance before the attenuated signals be regenerated and amplified again.
2. *Small size and less weight*
   The size of the fibre itself is very small and the weight is less compared with heavy copper wire system.
3. *Immunity to interference*
   This will ensure that the optical waveguides/optical fibres have immunity to electromagnetic interference.
4. *Electrical isolation*
   Basically, optical fibres are made of glass or silica, which provides electrical isolation from external electrical sources.
5. *Signal security*
   The transmission of light or infrared signals in the optical fibre makes it quite impossible to be tapped or identified easily.
6. *Abundant raw material*
   The raw material such as silica, used to make optical fibre is abundant and inexpensive.

7. *Wide usable bandwidth*
   The usable bandwidth of a typical optical fibre is approximately 25,000 GHz. In the past, the communication channel between two electronic systems was often the low speed bottleneck that limited the overall system performance. But with optical fibres, the electronic systems themselves are often the low-speed bottleneck.

3.2 BASIC COMPONENTS OF AN OPTICAL COMMUNICATION SYSTEM

Figure 1 shows the basic components of a typical fibre-optic communication system: the optical source, the optical channel, and the receiver.

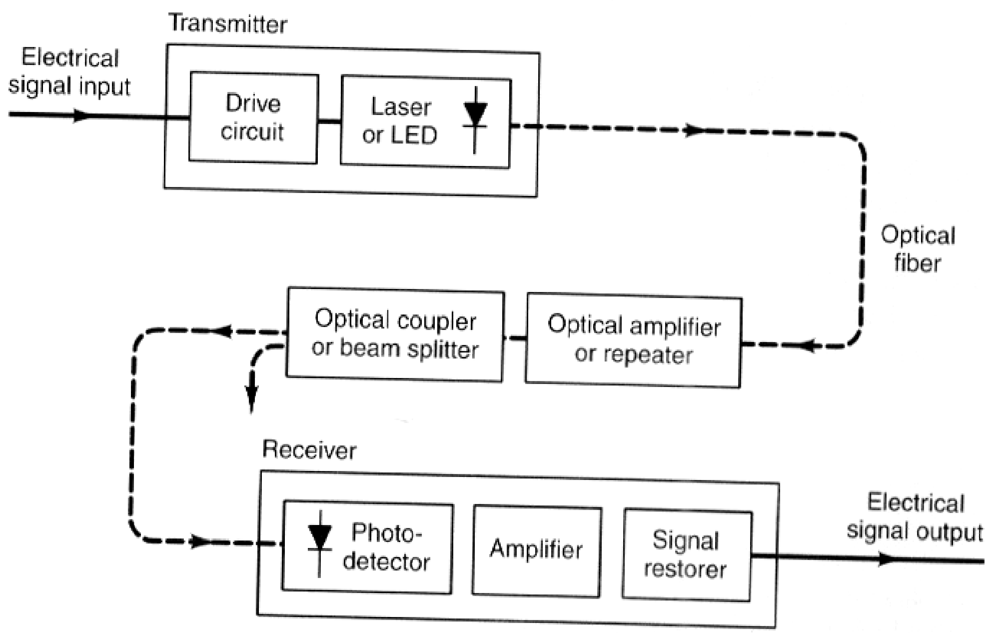

Figure 1

The optical source is usually a laser or an LED whose output is modulated by the electrical signal that contains the message. Common modulation techniques are amplitude shift keying (ASK), phase shift keying (PSK), and frequency shift keying (FSK).

In simple systems, the optical channel consists solely of an optical fibre. In more complicated systems, the optical channel also includes connectors, couplers, optical amplifiers, and repeaters.

The receiver consists of a photodetector (usually a pin diode) that converts the optical signal into an electrical signal, followed by amplifiers and demodulators.

3.3 REVIEW OF SOME BASIC CONCEPTS

Figure 2 shows rays from a point source in glass falling on a glass-air interface. As the angle of incidence, θ is increased, we reach a situation at which the refracted ray points along the surface, the angle of refraction being 90^0. For angles of incidence larger that this *critical angle,* there is no refracted ray, and we speak of *Total Internal Reflection* Therefore, critical angle is that angle of incidence for which the angle of refraction is 90^0.

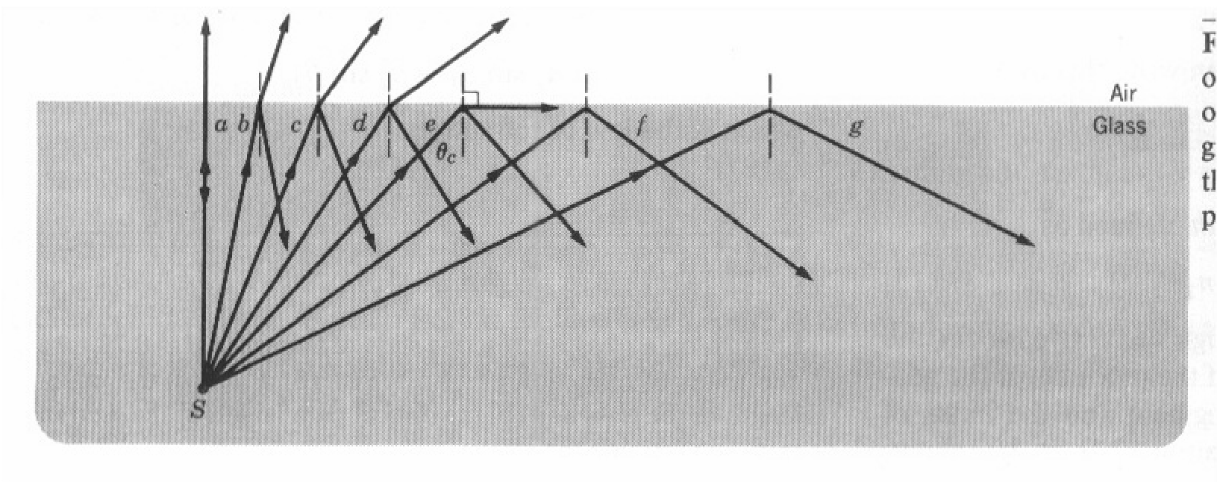

Figure 2

From Snell's Law of Refraction,

$$n_1 \sin\theta_C = n_2 \sin 90^0$$

or

$$\theta_C = \sin^{-1}\frac{n_2}{n_1}$$

The sine of an angle cannot exceed unity, so that we must have $n_2 < n_1$. This tells us that *Total Internal Reflection* cannot occur when the incident electromagnetic energy is in the medium of lower index of refraction. The word *total* means that the reflection occurs with no loss of intensity. In ordinary, reflection there is a loss of intensity.

3.4 OPTICAL FIBRE MODES AND CONFIGURATIONS

An optical fibre is a dielectric waveguide that operates at optical frequencies. The guided electromagnetic waves are propagating waves in the fibre in certain modes. These modes are those electromagnetic waves that satisfy the homogeneous wave equation in the fibre and the boundary condition at the waveguide interface.

The basic structure of an optical fibre is shown in the Figure 3. The core is where the waves will propagate and has a refractive index $n_1 = n_f$ and is surrounded by a solid dielectric cladding. The cladding has a refractive index $n_2 = n_c$.

The cladding is required for:

- providing additional mechanical strength to the fibre;
- reducing scattering loss due to the dielectric discontinuities at the core surface;
- protecting the core from being exposed to contaminants.

Low- and medium-loss fibres are generally glass and high-loss fibres contain plastic core. Optical fibres are usually divided into two classes: ***multimode fibres*** and ***single-mode fibres***.

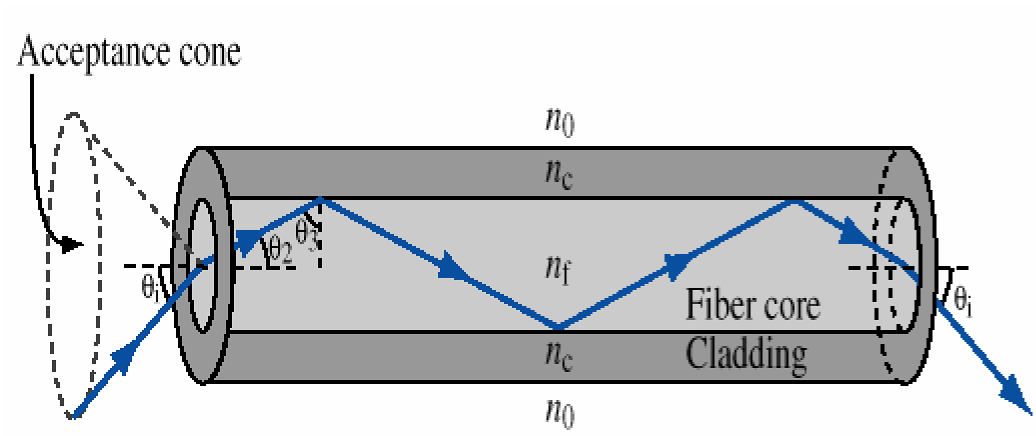

Figure 3

3.4.1 Multimode Fibres

There are two principal types of ***multimode fibres*** in common use: **step-index** and **graded-index fibres**. The index profiles of these fibres are shown in the Figure 4.

3.4.1.1 Step-Index Fibre

The refractive index of the core is uniform throughout and undergoes an abrupt change at the cladding boundary, as shown in Figure 4.

When the core diameter is large ($\varphi > \lambda_0$), the number of modes supported by these fibres is large (excess of many thousands). So it will accept relatively high percentage of the light produced by LEDs and lasers.

The major disadvantage of step-index fibre is that they have high dispersion. This is because the propagation delays of higher order modes are larger than those of lower order modes. That is why they are ideal for short distance and local area networks.

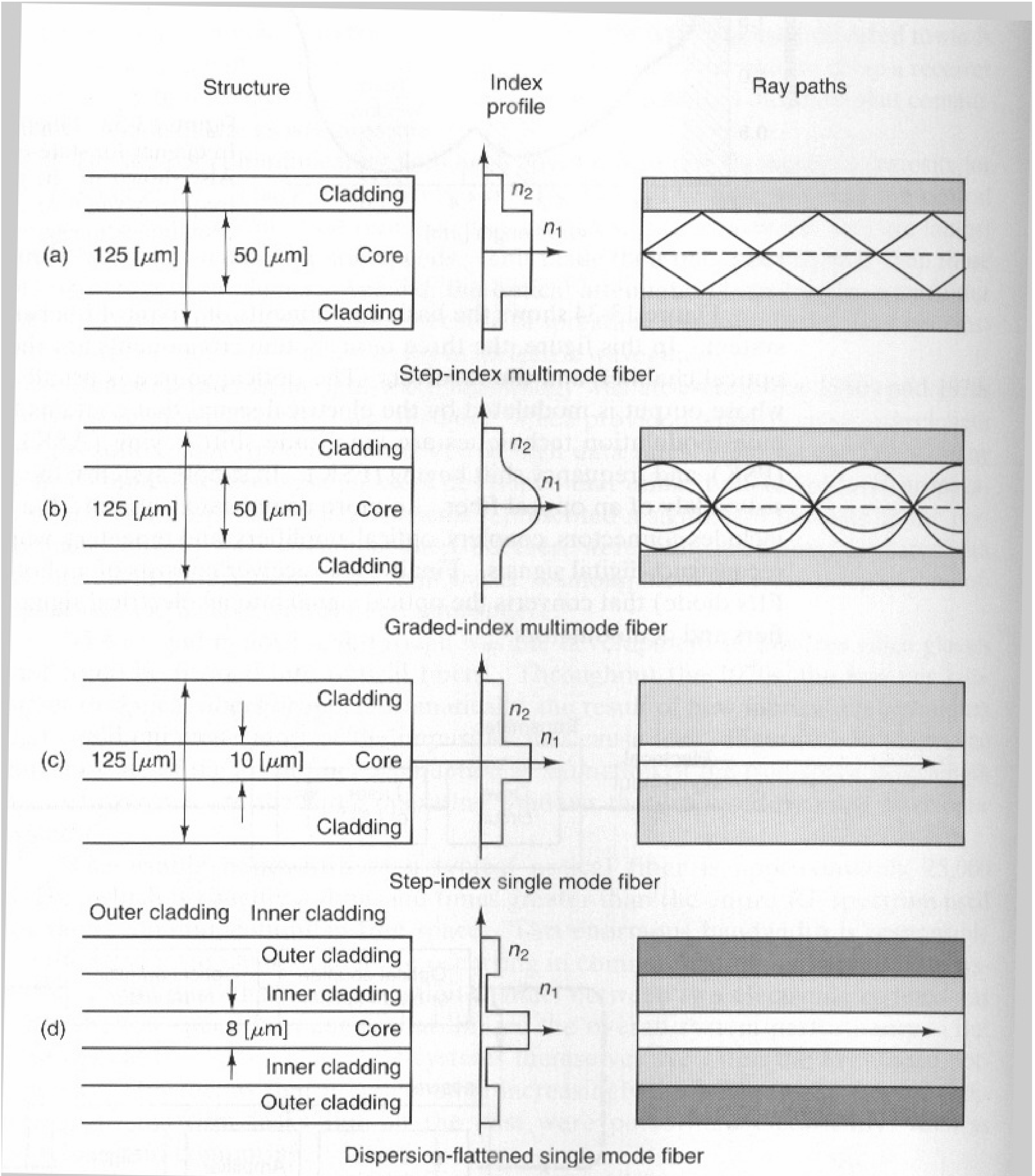
Structure
Index profile
Ray paths
Cladding
(a)
125 [μm]
50 [μm]
Core
Cladding
n_2
n_1
Step-index multimode fiber
Cladding
(b)
125 [μm]
50 [μm]
Core
Cladding
n_2
n_1
Graded-index multimode fiber
Cladding
(c)
125 [μm]
10 [μm]
Core
Cladding
n_2
n_1
Step-index single mode fiber
Outer cladding
Inner cladding
Outer cladding
Inner cladding
(d)
8 [μm]
Core
Inner cladding
Outer cladding
n_2
n_1
Dispersion-flattened single mode fiber

Figure 4

3.4.1.2 Graded-index fibre (GRINs)

The refractive index of the core varies as a function of the radial distance from the centre of the fibre. GRINs achieve *lower dispersion* by using a tapered refractive index in the core, with the highest index in the centre of the core. GRINs allows for *higher signaling rates* than can be achieved with step-index fibres.

3.4.1.3 Advantages of Multimode

- Contains many modes of propagation.
- Larger core radii of multimode fibres make it easier to launch optical power into the fibre.
- Easier connection between similar fibres.
- LED light source can be used to launch light to the fibre. LEDs have less optical output power, easier to make, less expensive, less complex circuitry, longer lifetimes.

3.4.1.4 Disadvantages of Multimode

Intermodal dispersion problem, where optical pulse launched into the fibre, will propagate at multiple modes, which travel at slightly different speed. This will lead to the *dispersion of the pulse signal*. The use of graded-index profile can reduce this problem.

3.4.1.5 Numerical Aperture

A figure of merit that is often used to describe the multimode fibres is the ***numerical aperture***, which indicates the light gathering of the fibre. Figure 5 shows a plane wave approaching the end of a step-index fibre at an angle θ_0 with respect to the optical axis.

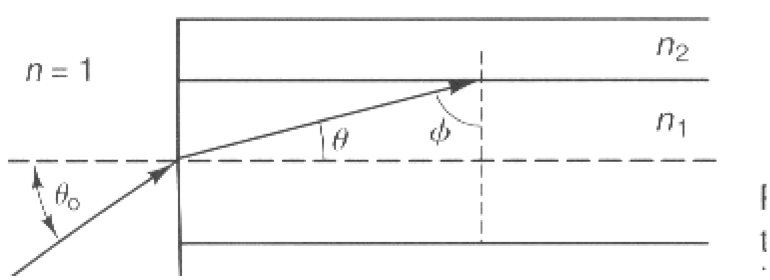

Figure 5

As this ray enters the core, it makes an angle θ with the optical axis, and the angle of incidence at the core cladding is ϕ. Using Snell's law, we get

$$\sin\theta_0 = n_1 \sin\theta = n_1\sqrt{1-\sin^2\phi}$$

The maximum entrance angle $\theta_{0,max}$ occurs when $\phi = \sin^{-1}(n_2/n_1)$, which is the critical angle for the core-cladding interface. The sine of $\theta_{0,max}$ is the *numerical aperture*, **NA**.

For a step index fibre,

$$\mathbf{NA} = \sin\theta_{0,max} = \sqrt{n_1^2 - n_2^2}$$

The larger the **NA** of a fibre, the more optical power it can capture from a source. A typical value of **NA** for a step-index multimode fibre is in the range from 0.19 to 0.25.

Since the refractive index is not constant inside the core of graded-index fibres, $\theta_{0,max}$ depends upon the radial position at which the ray enters the fibre. GRIN fibres tend to accept less light than step-index fibres with the same core diameters.

3.4.2 Single-Mode Fibres.

Multimode fibres are popular for short-haul communication networks, where high optical power levels are necessary to distribute signals to a large number of users. But due to its high dispersion, they cannot be used for long-haul systems. In such case, single mode fibres are used because of their low-dispersion characteristics.

In a single mode:

- Only one mode of propagation;
- Laser diodes are used to launch light into the fibre;
- Do not have intermodal dispersion problem since there is only one mode.

There are many kinds of single mode fibres. The simplest one is step-index fibres with very small core. An exact analysis of the modes in these fibres shows that single-mode operation is attained when the core radius satisfy the inequality

$$\frac{a}{\lambda_0} < \frac{2.405}{2\pi\sqrt{n_1^2 - n_2^2}}$$

3.5 DISPERSION

The phenomenon of spreading of a pulse of light as it travels down an optical fibre is called dispersion. It is a consequence of the variation of refractive index with optical frequency.

Clearly, any optical energy propagating in a material medium will comprise a range of wavelengths (frequencies). It is not possible to devise a source of radiation which has zero spectral width. Consequently, in the face of optical dispersion in the medium, different parts of the propagating energy will travel at different velocities; and if that energy is carrying information (i.e. it has been modulated in some way), that information will become distorted by the velocity differences. The further it travels, the greater will be the distortion; the greater the wavelength spread, the greater will be the distortion; the greater the dispersion power of the medium, again the greater will be the distortion. For good communications we need, therefore, to choose our sources, wavelengths and materials vary carefully, and in order to make these choices, we must understand the processes involved.

In optical fibres and in all other optical waveguides, there are three types of dispersion: ***modal dispersion*** (in multimode guides only), ***material dispersion*** and ***waveguide dispersion***.

The effect of dispersion in a waveguide is to limit its communications-carrying capacity, i.e., its bandwidth. This is seen most readily by considering a digital communications system, that is, one which transmits information by means of a stream of pulses.

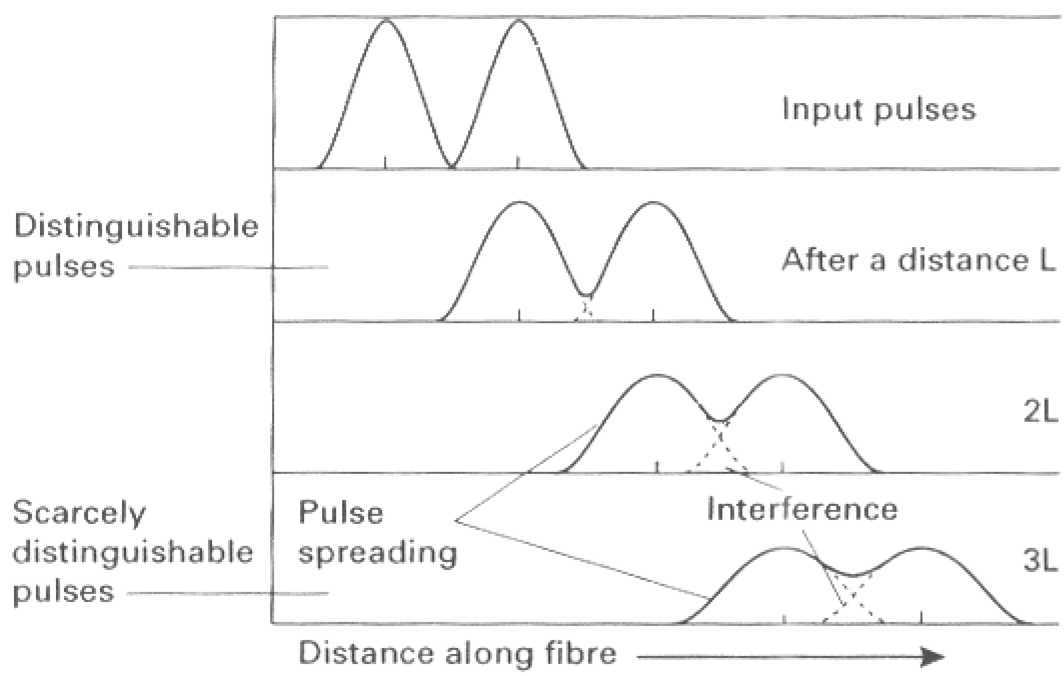

Figure 6

The presence of a pulse indicates a '1', the absence of one indicates a '0' and the stream thus comprises a digital coding of the information to be transmitted. A stream of clear, distinct pulses is launched into the fibre (for example) by modulating a laser source. As the pulses propagate down the fibre, the spread of optical wavelengths of which they are comprised will be acted upon by the dispersive effects in the fibre, and the result will be a broadening of the pulses. When the broadening has become so great that it is no longer possible to distinguish between two successive pulses, the communication link fails.

Clearly, for a given dispersive power, the broadening will increase linearly with distance. Hence,

$$\Delta T / L = \text{constant}$$

where ΔT is the broadening (in time) of the pulse over a fibre length L. Now, the 'bit-rate', effectively the digital bandwidth, which the fibre length L can carry will be $1/\Delta T$, since the spacing between pulses, ΔT, will be closed up by the dispersion when the broadening is equal to ΔT.

Hence, we have

$$BL = \text{constant} \qquad (1)$$

where B is the allowable bit-rate in pulses (or bits) per seconds. It gives a good idea of the capacity of modern optical communications systems to know that this bit-rate is usually quoted in megabits/second or gigabits/second.

The result of dispersion is thus to impose a 'bandwidth $\times$distance' limitation: the greater the distance the smaller is the bandwidth which can be transmitted for a given fibre, and vice versa.

3.5.1 Modal Dispersion

Modal Dispersion exists only in multimode fibres and it results from the differing velocities of the range of modes supported by the fibre. Optical energy is launched into the fibre and will be launched into many, perhaps all, of the modes supported by the fibre.

The effect of modal dispersion clearly will depend on how the propagating energy is distributed among the possible modes, and this will vary along the fibre as the energy redistributes itself according to local conditions (e.g. bends, joints, etc). In order to get a 'feel' for its order of magnitude, however, we can very easily calculate the difference in time of flight, over a given distance, between the fastest and slowest modes supported by the fibre.

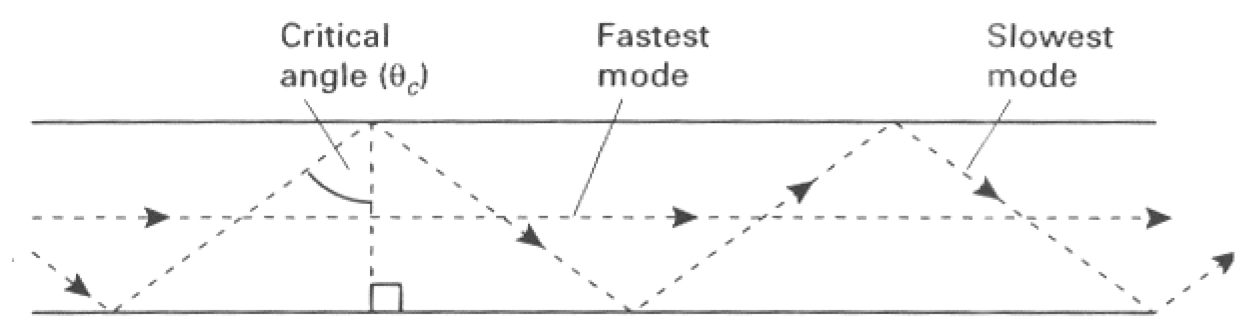

Figure 7

The fastest mode will be that which travels (almost) straight down the fibre, along the axis. This will have the velocity of the unbounded core medium, c/n_1.

The slowest mode will be that which is represented by a ray and is incident on the core/cladding boundary as shown in the Figure 7. Clearly, this ray travels at velocity $(c/n_1)\sin\theta_c$, where θ_c is the critical angle.

Since we have

$$\sin\theta_c = n_2/n_1,$$

it is easily seen that the two times of flight along a distance L of fibre are:

$$T_f = \frac{L}{c/n_1} = \frac{Ln_1}{c} \text{ and}$$

$$T_s = \frac{Ln_1}{c\sin\theta_c} = \frac{Ln_1^2}{cn_2}$$

Hence

$$\Delta T = T_s - T_f = \frac{Ln_1}{cn_2}(n_1 - n_2)$$

And since $n_1 \approx n_2$,

then $$\Delta T \approx L\Delta n/c \qquad (2)$$

where Δn is the difference in refractive index between core and cladding. Equation (2) is a clear specific example of the general equation (1), for we have, from (1):

$$\Delta T/L = \Delta n/c\,; \quad B = 1/\Delta T$$

3.5.2 Material Dispersion

In monomode fibres inter-modal dispersion is absent and the dominant cause of pulse broadening is *material* or *chromatic* dispersion. Material dispersion is a consequence of the variation of refractive index with the wavelength (frequency) of light. To understand this phenomenon better, the concepts of group and phase velocity have to be understood.

Consider two travelling waves having equal amplitude and slightly different angular frequencies $\omega_0 + \Delta\omega$ and $\omega_0 - \Delta\omega$ $(\Delta\omega << \omega_0)$. The phase constants, being functions of frequency, will also be slightly different. Let the phase constants corresponding to the two frequencies be $k_0 + \Delta k$ and $k_0 - \Delta k$. We have

$$E(z,t) = E_0\cos\{(\omega_0 + \Delta\omega)t - (k_0 + \Delta k)z\} + E_0\cos\{(\omega_0 - \Delta\omega)t - (k_0 - \Delta k)z\}$$
$$= 2E_0\cos(\Delta\omega t - \Delta kz)\cos(\omega_0 t - k_0 z)$$

Since $\Delta\omega << \omega_0$, the expression in the above equation represents a rapidly oscillating wave having an angular frequency ω_0 and an amplitude that varies slowly with angular frequency $\Delta\omega$. This is shown in Figure 8.

The wave inside propagates with a *phase velocity* found by setting $\omega_0 t - k_0 z$ =constant:

$$v_p = \frac{dz}{dt} = \frac{\omega_0}{k_0} \text{ (metres per second)} \qquad (1)$$

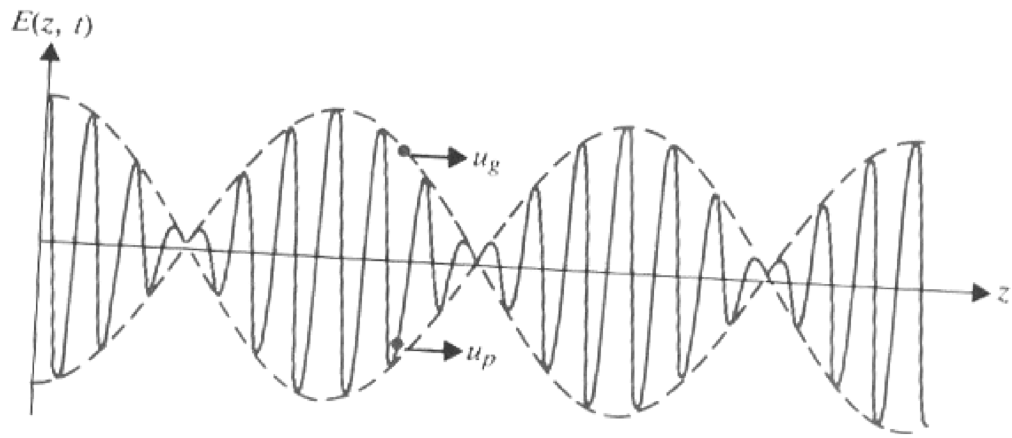

Figure 8

The velocity of the envelope, the *group velocity,* can be determined by setting the argument of the first cosine factor in the above equation equal to a constant:

$$\Delta\omega t - \Delta k z = \text{constant},$$

from which we obtain

$$v_g = \frac{dz}{dt} = \frac{\Delta\omega}{\Delta k} = \frac{1}{\frac{\Delta k}{\Delta\omega}}$$

In the limit that $\Delta\omega \to 0$, we have the formula for computing the group velocity in a dispersive medium:

$$v_g = \frac{1}{\frac{dk}{d\omega}} \qquad \text{(metres per second)} \qquad (2)$$

This is the velocity of a point on the envelope of the wave packet, as shown in the Figure 8.

A general relation between the group and the phase velocities may now be obtained. From our study of uniform plane waves we know that the phase velocity of a wave with frequency ω and wave number (phase constant) k is defined as

$$v_p = \frac{\omega}{k} \qquad (3)$$

Substituting (3) in (2), we yield

$$\frac{dk}{d\omega} = \frac{d}{d\omega}(k) = \frac{d}{d\omega}\left(\frac{\omega}{v_p}\right) = \frac{1}{v_p} - \frac{\omega}{{v_p}^2}\left(\frac{dv_p}{d\omega}\right)$$

Substituting the above equation in equation (2), we get

$$v_g = \frac{1}{\left(\frac{dk}{d\omega}\right)} = \frac{{v_p}^2}{v_p - \omega\frac{dv_p}{d\omega}} = v_p\left[\frac{1}{1 - \frac{\omega}{v_p}\left(\frac{dv_p}{d\omega}\right)}\right]$$

Thus it can be seen that if $\frac{dv_p}{d\omega} = 0$, then $v_p = v_g$ and there is no dispersion.

Equivalent results are obtained if we consider the variation of the refractive index of a medium with frequency. For a wave travelling in a medium of refractive index *n*

$$v_p = c/n = \omega/k\ ,$$

where *c* is the velocity of light in free space. If *n* varies with frequency, we have

$$\frac{d\omega}{dk} = \frac{c}{n}\left[1 - \frac{k}{n}\left(\frac{dn}{dk}\right)\right]$$

or, in terms of wavelength λ

$$v_g = \frac{d\omega}{dk} = \frac{c}{n}\left[1 + \frac{\lambda}{n}\left(\frac{dn}{d\lambda}\right)\right]$$

If *n* does not vary with wavelength, then

$$\frac{dn}{d\lambda} = \frac{dn}{dk} = 0$$

$$\frac{d\omega}{dk} = v_g = \frac{c}{n} = v_p$$

However, if $\frac{dn}{d\lambda} \neq 0$, i.e. the medium is dispersive, then $v_g \neq v_p$ and the envelope travels at a different velocity from the carrier optical wave.

3.5.3 Waveguide Dispersion

Waveguide dispersion occurs because a single-mode fibre only confines about 80 percent of the optical power to the core. Dispersion thus arises, since the 20 percent of the light propagating in the cladding travels faster than the light confined to the core. The amount of waveguide dispersion depends on the fibre design.

Mathematically,

$$P_{Core} / P_{Cladding} = V^2$$

where $$V = \frac{2\pi a}{\lambda\sqrt{\left(n_1^{\ 2} - n_2^{\ 2}\right)}}$$

Hence, as λ rises, the power in the core increasingly transfers to the cladding.

Waveguide dispersion can, in fact, be very useful, for it can be arranged to oppose the material dispersion. The waveguide dispersion depends upon the fibre geometry, so, by choosing the geometry appropriately, the dispersion minimum for the fibre can be shifted from its value defined by material dispersion to another convenient (but quite close) wavelength. Fibre which has been 'adjusted' in this way is called 'dispersion-shifted' fibre, and this stratagem is used to move the wavelength of the dispersion minimum from its 'unrestricted' value of 1.28μm to 1.55μm.

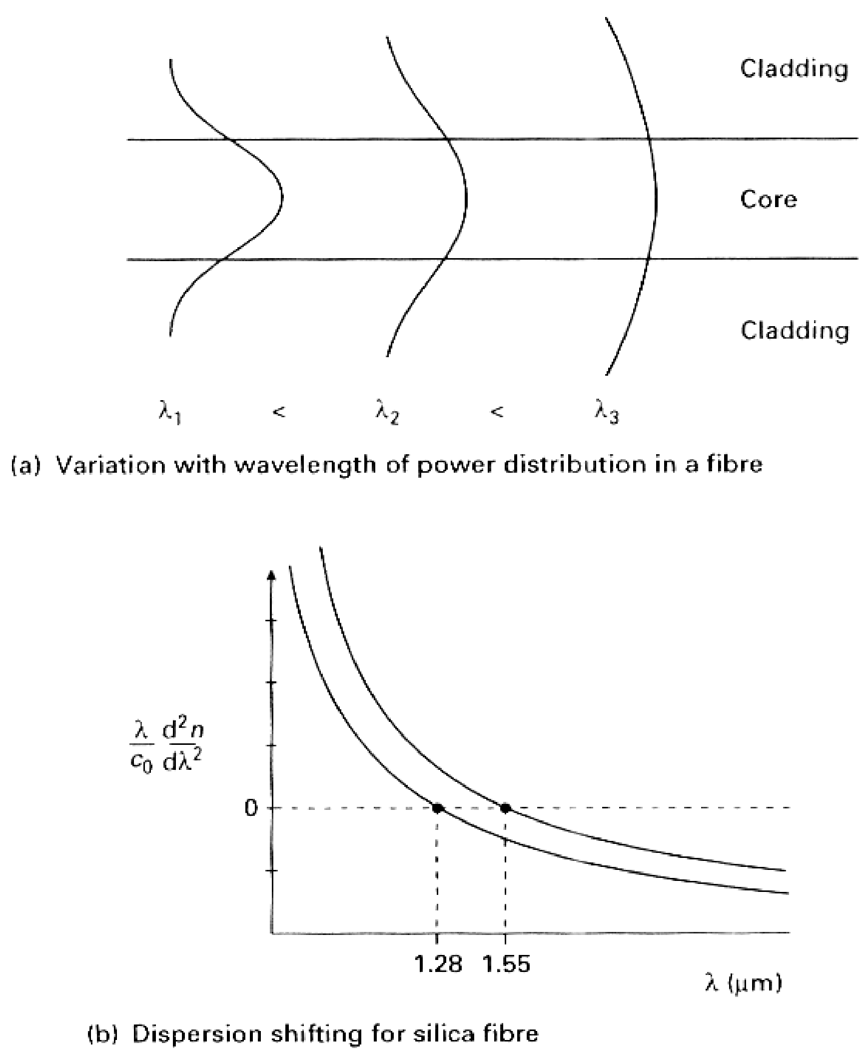

Figure 9

3.5.4 Polarisation Dispersion

Polarisation dispersion occurs when different polarisation states travel at different velocities as a result of linear and/or circular asymmetries.

In a communication fibre, light is constantly coupled back and forth amongst various polarisation modes and suffers randomly varying phase delay. This leads to Polarisation Mode Dispersion (PMD). Typically this is 1=10 *p*s/km.

3.6 LOSS IN OPTICAL FIBRES

- *Absorption loss*
  The optical power may be absorbed by the impurities inside the fibre. For example, hydroxyl ions (at 1380 nm), and metallic traces.

- *Scattering loss*
  This is due to the localized change in refractive index in the fibre and impurities, this will cause *Rayleigh Scattering*, and energy will be scattered in other directions and some may be refracted out of the fibre.

- *Reflection loss*
  This is the loss due to the reflection of optical power as the light is launched into the fibre and when the light about to leave the fibre. The discontinuity in refractive index at the boundary (for example, air/core, and core/air) will lead to the *Fresnel Reflection*.

- *Bending loss*
  Due to any sharp bend in the fibre, the optical power propagating in the fibre may be incident at the core/cladding boundary at angle smaller than the critical angle for total reflection, this energy will finally be refracted out from the fibre. This loss is normally used as a technique to build sensor and also to check whether any light source is propagating in the fibre.

3.7 ANALYSIS OF WAVE EQUATION IN OPTICAL FIBRES

There are two approaches to understanding wave propagation in optical fibres. One is geometrical optics (or ray optics), where concepts of light reflection and refraction are used to provide an intuitive picture of the propagation mechanisms (usually applied when the dimension of fibre is large compared to the wavelength).

The other approach is physical optics (or wave optics), where Maxwell's equations are used in the analysis of wave propagation in the optical fibre.

Consider an electromagnetic wave propagating in the optical fibre having the expression as

$$\vec{E} = \tilde{E}_o(r,\phi)e^{j(\omega t-\beta z)} \qquad (1)$$

and $$\vec{H} = \widetilde{H}_o(r,\phi)e^{j(\omega t-\beta z)} \tag{2}$$

where $$\widetilde{E}_o(r,\phi) = \hat{z}\,E_z(r,\phi) + \hat{r}\,E_r(r,\phi) + \hat{\phi}\,E_\phi(r,\phi) \tag{3}$$

and the magnetic field has similar expression.

In cylindrical coordinate system, the Helmholtz's equations for the longitudinal components (**E** and **H**) of the electromagnetic field are

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \phi^2} + h^2 E_z = 0 \tag{4}$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \phi^2} + h^2 H_z = 0 \tag{5}$$

Thus, both the electric and the magnetic fields have the same form of equation. When E_z=0, the modes are called transverse electric or TE modes. When H_z=0, the modes are called transverse magnetic or TM modes.

For optical fibre, it is possible to have ***hybrid mode***, where both E_z and H_z are not zero. These are called either **EH** or **HE modes**, depending on whether E_z or H_z, respectively, makes a larger contribution to the transverse field.

The fact the hybrid modes are present in optical waveguides makes their analysis more complex.

For a step index optical fibre (radius=a) which has a core refractive index of n_1 and surrounded by a layer of cladding with refractive index of n_2, consider now only the electric field, the solution of (4) is given by

$$E_z = AF_1(r)F_2(\phi) \tag{6}$$

Using the method of separation of variable, we find that

$$F_2(\phi) = e^{jn\phi} \tag{7}$$

and $$\frac{\partial^2 F_1}{\partial r^2} + \frac{1}{r}\frac{\partial F_1}{\partial r} + \left(h^2 - \frac{n^2}{r^2}\right)F_1 = 0 \tag{8}$$

Equation (8) is a differential equation for Bessel functions.

The solutions for the longitudinal components are

$$E_z(r<a) = AJ_n(h_1 r)e^{jn\phi}e^{j(\omega t-\beta z)} \tag{9}$$

$$H_z(r<a) = B\,J_n(h_1 r)e^{jn\phi}e^{j(\omega t-\beta z)} \tag{10}$$

$$E_z(r > a) = C\, K_n(h_2 r)e^{jn\phi}e^{j(\omega t - \beta z)} \tag{11}$$

$$H_z(r > a) = D\, K_n(h_2 r)e^{jn\phi}e^{j(\omega t - \beta z)} \tag{12}$$

where *A*, *B*, *C* and *D* are arbitrary constants that can be found by matching boundary conditions. $J_n(h_1 r)$ is Bessel function of the first kind, and $K_n(h_1 r)$ is modified Bessel function of the second kind.

The transverse components of **E** and **H** can be determined from E_z and H_z. For outside solution (r>a), as r→∞, the solution must decay to zero.

The exact analysis for the modes of a fibre is mathematically very complex. However, a simpler but highly accurate approximation can be used.

When $(n_1 - n_2 << 1)$, it is possible to derive weakly guided modes where approximated solutions are obtained. These modes are called *linearly polarized modes* (LP).

- Each LP_{0m} mode is derived from an HE_{1m} mode;
- Each LP_{1m} mode is derived from TE_{0m}, TM_{0m}, and HE_{2m} modes;
- Each LP_{nm} mode ($n \geq 2$) is from an $HE_{n+1,m}$ and an $EH_{n-1,m}$ mode.

For graded-index fiber, an approximated solution can be obtained using *WKB method* (named after Wenzel, Kramers, and Brillouin).