DATA COMMUNICATION THROUGH OPTICAL FIBRE

QUALITATIVE ANALYSIS

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QUALITATIVE ANALYSIS OF OPTICAL FIBRE COMMUNICATION

Chapter 1

Introduction to Optical Fibre Communication

1.1 INTRODUCTION :

The concept of guided lightwave communication along optical fibres has stimulated a major new technology years. During this period tremendous advances have been achieved with optical fibres and components as well as with the associated optoelectronics. As a result this new technology has reached the threshold of large scale commercial exploitation. Installation of optical fibre communication systems is progressing within both telecommunication networks and more localized data communication and telemetry environments.

Furthermore, optical fibre communication has become synonymous with the current worldwide revolution in information technology. The relentless onslaught will undoubtedly continue over the next decade and the further predicted developments will ensure even wider application of optical fibre communication technology in this "information age".

On the part of fibre, huge reductions in the material attenuation have been obtained. It has been established that as compared to metal system, size for size, optical fibres offer greater information capacity arising from a higher carrier frequency and lower material costs.Starting from the simple communication systems, the optical fibres now find the use from telecommunications to broadband and computers, and from sensors applications in production industry to applications in military defence.

1.2 HISTORICAL PERSPECTIVE :

Communications using light occurred early when human beings first communicated by using hand signals.This is obviously a from of optic communication; it does not work in darkness.During the day, the sun is the source of light for this system. The information is carried from the sender to the receiver on the sun's radiation.Hand motion modifies,or modulates, the light. The eye is the message detecting device and the brain processes this message. Information transfer for such a system is slow, the transmission distance is limited,and the chances of error are great. A later optic system, useful for longer transmission paths,was smoke rising from a fire. This pattern was again carried to the receiving party by sunlight. This system required that a coding method be developed and learned by the communicator and receiver of the message. This is comparable to modern digital system that use pulse codes.

In 1880 Alexander Graham Ball invented a light communication system, the photophone. He used sunlight reflect from a thin voice-modulated mirror to carry conversation. At the receiver, the modulated sunlight fell on a photo-conducting selenium cell, which converted the message to electrical current.A telephone receiver completed the system. The photophone never achieved commercial success, although it worked rather well.

In 1960, a major breakthrough that led to high capacity optic communication was the invention of the laser. The laser provided a narrow-band source of optic radiation suitable for use as a carrier of information. Lasers are comparable to the radio frequency sources used for conventional electronics communications. Unguided optic communication systems (non fibre) were developed shortly after the discovery of laser. Communication over light beams traveling through the atmosphere was easily accomplished.The disadvantages of these systems include dependence on a clear atmosphere, the need for a LOS path between transmitter and receiver, and the possibility of eye damage to persons who unknowingly look into the beam.

In the 1960's the key element in a practical fibre system was missing .... an efficient fibre. Although it had been established that light could be guided by a glass fibre, those available attenuate light by far too large an amount.

In 1970 the first truly low-loss fibre was developed and fibre optic communication became practical. This occurred just 100 years after John Tyndall, a British physicist, demonstrated to the Royal Society that light can be guided along a curved stream of water. Guiding of light by a glass fibre and by a stream of water are evidence of the same phenomenon (total internal reflection).

1.3 BASIC DEFINITION OF OPTICAL COMMUNICATION :

Optical communication is the transmission of signals over a specified distance by modulation of an optical wave, either in air, in vacuum or in a transparent dielectric medium, which is known as optical fibre. Basically the processing (i.e. amplification, modulation, demodulation etc.) of the signal is done by conventional electronic circuitry but the modulated signal is transmitted in the form of light, and hence at the transmitter side just conversion of electrical signal into optical signal takes place by laser diode, conventional high intensity) LEDs etc. and correspondingly at the receiver side, the conversion of optical signal into electrical signal takes place by a photo transistor etc.

1.4 THE BASIC COMMUNICATIONS SYSTEM:

An optical fibre communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Fig. 1.1., the function of which is to convey the signal from the information source over the transmission medium to the destination. The communication system therefore, consists of a transmitter of modulator linked through the information source, the transmission medium,and a receiver or demodulator at the destination point. In electrical communication, the information source provides an electrical signal usually derived from a message signal which is not electrical (e.g.sound), to a transmitter comprising electrical and electronics components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved by modulating a carrier which may be electromagnetic wave.

The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down of a pair which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination.

In every transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise as well possible distortions imposed by mechanisms within the medium itself. Therefore, in any, communication system there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication. For long- haul applications these factors necessitate the installation of repeaters or line amplifiers at intervals, both to remove signal distortion and to increase signal level before transmission is continued down the link.

For optical fibre communications system in Fig. 1.1.(a), the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which provides the electrical-optical conversion may be either a semiconductor laser or LED.

The transmission medium consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Phothdiodes (p-n,p-i-n or avalanche) and in some instances, phototransistor are utilized for the detection of the optical signal or the optical-electrical conversion.

Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.

The optical carrier may be modulated using either analog or digital information signal. In the system show in Fig.1.1.(b) analog modulation involves the variation of the light emitted from the optical source in a continuous manner. with digital modulation, however, discrete changes in the light intensity are obtained (i.e.on-pulses). Although often simpler to implement, analog modulation with an optical fibre communication system is less efficient, requiring a far higher SNR at receiver than digital modulation.

Also the linearity needed for analog modulation is not always provided by semiconductor optical sources, specially at high modulation frequencies. For these reasons,analog optical fibre communication links are generally limited to shorter distances and lower bandwidths than digital links.

Fig.1.2. shows a block schematic of a typical digital optical fibre link. Initially the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence the digital optical signal is launched into the optical fibre cable. The avalanche photodiode (APD) detector is followed by a front- amplifier and equalizer or filter to provide gain as well as linear signal processing and noise

bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information.

The generalized diagram of an optical communication link useful for guided data transmission is shown in Fig.1.3.In this general from it applies to both digital and analog system. The signal to be transmitted from a system input point to an output point will travel through the following stages:

(a) Signal-shaper encoder:

The electrical signal is fed into signal-shaper encoder. In an analog system this element provides predistortion.

(b) Source driver:

The signal shaped by the signal-shaper encoder is applied to the source driver. The driver modulates the current flowing through the optical source to produce the desired optical signal. The use of an incoherent LED or semiconductor injection laser allows the direct modulation of the optical source.

(c) Source:

The source converts the electrical signal into a corresponding optical signal. The source may either be an incoherent LED, or a semicohernt semiconductor laser, or a coherent nonsemi-conductor.

Principle requirements for the source are faithful reproduction of the electrical signal, monomode excitation, high optical output at low current : density, small emitting area, high frequency response, and long lifetime even with high current density.

(d) Source fibre coupler:

The purpose of this coupler is the efficient introduction of the optical power into the waveguide. Its main requirements are low coupling loss and perfect match of source and fibre cross-sectional areas.

(e) Optical cable:

The optical fibre cable transmits the optical signal from the transmitter to the receiver, either over a single fibre or over a fibre bundle, consisting of either a few or upto several thousands individual fibres, which may carry either the same or different information.

Principle technical requirements center on low loss and low dispersion. Depending on the fibre, source and detector characteristics, and the total system length, it may be necessary to regenerate the optical signal either electrically or optically by use of repeaters.

(f) Repeater:

The repeater acts as a regenerative system element. It is designed to enhance the shape of the signal degraded during transmission over the optical cable. It thus consists of a photodetector, amplifying and reshaping circuitry, and an optical source. It contains practically all the circuitry associated with the source, the detector of the transmitter and the receiver elements. A repeater can therefore be considered a back to back receiver-transmitter combination.

(g) Fibre detector coupler:

The purpose of this coupler is the efficient detection by the photodetector of the optical signals coming from the fibre. It is designed to provide a match of the respective cross-sectional areas and to minimize reflective losses at the fibre detector interface.

(h) Detector:

The photodetector must be able to follow the signal emerging from the fibre both in amplitude and frequency. At short wave lengths, the achievements of this goal does not present any difficulties, and the detector is able to reproduce the optical signal faithfully an electrical signal, but at large wavelengths some problems of detection efficiency emerge.

(i) Amplifier and signal shaper decoder:

The amplifier enhances the electrical signal generated by the detector in the optical-electrical conversion process and increases it to the level at which it can be reshaped for proper further use. Again, the amplifier must be distortion free and its frequency response must match that of the signal. The signal shaper decoder finally converts the raw electrical signal as it is detected into the proper form for use.

1.5 ADVANTAGES OF OPTICAL FIBER COMMUNICATION :

Communication using an optical carrier wave guided along a glass fibre has a number of extremely attractive features, several of which were apparent when the technique was originally conceived. Furthermore, the advances in the technology to date have surpassed even the most optimistic predictions creating additional advantages. Hence, it is useful to consider the merits and special features offered by optical fibre communication over more conventional electrical communication.

(a) ENORMOUS POTENTIAL BANDWIDTH :

The optical carrier frequency in the range 10^{13} to 10^{16} Hz yields a far greater potential transmission bandwidth than metallic cable systems. At present, the bandwidth available to fibre systems is not fully utilized but modulation at several gigahertz over a few kilometers & hundreds of megahertz over tens of kilometers without intervening repeaters is possible.

Therefore, the information carrying capacity of optical fibre systems is already proving far superior to the best copper cable systems. By comparison the losses in wideband coaxial cable systems restrict the transmission distance to only a few kilometers at bandwidths over a hundred megahertz.

(b) SMALL SIZE AND WEIGHT :

Optical fibres have very small diameters which are often no greater than the diameter of a human hair. Hence, even when such fibres are covered with protective coatings copper cables. This allows for an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

(c) ELECTRICAL ISOLATION :

Optical fibres which are fabricated from glass sometimes a plastic polymer are electrical insulators & therefore, unlike their metallic counterparts, they do not exhibit earth loop and interface problems. Furthermore, this property makes optical fibre transmission ideally suited for communication in electrically hazardous environments as the fibres create no arcing or spark hazard at abrasions or short circuits.

(d) IMMUNITY TO INTERFERENCE AND CROSSTALK :

Optical fibres form a dielectric waveguide & are therefore free from electromagnetic interference(EMI), radio frequency interference (RFI), or switching transients giving electromagnetic pulses (EMP). Hence, the operation of an optical fibre communication system is unaffected by transmission through an electrically noisy environment and the fibre cable requires on shielding from EMI. The fibre cable is also not susceptible to lightning strikes if used overhead instead of underground. Moreover, it is fairly easy to ensure that there is on optical interference between fibres and hence, unlike communication suing electrical conductors, crosstalk is negligible, even when many fibres are cabled together.

(e) SIGNAL SECURITY:

The light from optical fibres does not radiate significantly &

therefore they provided a high degree of signal security. Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from a fibre in a noninvasive manner. Therefore, in theory, any attempt to acquire a message signal transmitted optically may be detected. This feature is obviously attractive for military, banking and general data transmission applications.

(f) LOW TRANSMISSION LOSS :

Fibres have been fabricated with losses as low as 0.2 dB/Km & this feature has become a major advantage of optical fibre communication. It facilitates the implementation of communication links with extremely wide repeater spacing (long transmission distances without intermediate electronics), thus reducing both system cost and complexity. Together with the already proven modulation bandwidth capability of fibre cable this property provides a totally compelling case for the adoption of optical fibre communication in the majority of long-haul telecommunication applications.

(g) RUGGEDNESS AND FLEXIBILITY:

Although protective coatings are essential, optical fibres may be manufactured with very high tensile strengths. The fibre may also be bent to quite small radii or twisted without damage.

Furthermore,cable structures have been developed which have proved flexible, compact and extremely rugged. Taking the size and weight advantage into account, these optical fibre cables are generally superior in terms of storage, transportation, handling and installation than corresponding copper cables whilst exhibiting atleast comparable strength and durability.

(h) SYSTEM RELIABILITY AND EASE OF MAINTENANCE:

These features primarily stem from the low loss property of optical fibre cables which reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength. Hence with fewer repeaters, system reliability is generally enhanced in comparison with conventional electrical conductor systems.

(i) POTENTIAL LOW COST:

The glass which generally provides the optical fibre transmission medium is made from the sand.... not a scarce resource. So, in comparison with copper conductors, optical fibres offer the potential for low cost line communication. As yet this potential has not been fully realized because of the sophisticated, and therefore expensive, processes required to obtain ultra-pure glass, and the lack of production volume. At present, optical fibre cable is reasonably competitive with coaxial cable, but not with simple copper wires (e.g. twisted pairs). However, it is likely that in the future it will become as cheap t use optical fibres with their superior performance than almost any type of electrical conductor.

Moreover, overall system costs when utilizing optical fibre communication on long-haul links are generally reduced to those for equivalent electrical line systems because of the low loss and wideband properties of the optical transmission medium. Although, the reduced cost benefit gives a net gain for long-haul like this is not usually the case in short-haul applications where the additional cost incurred, due to the electrical-optical conversion, may be a deciding factor. Nevertheless, there are other possible cost advantages in relation to shipping, handling, installation and maintenance as well as features indicated in (c) & (d) which may prove significant in the system choice.

The low cost potential of optical fibre communication not only provides strong competition with electrical line transmission systems, but also with microwave and millimeter wave radio transmission systems. Although these systems are reasonably wideband the relatively short span line of sight transmission necessitates expensive aerial towers at intervals no greater than a few tens of kilometers.

Many advantages are therefore provided by the use of a lightwave carrier within a transmission medium consisting of an optical fibre.

1.6 LIMITATIONS:

Basically there are three fundamental limitations that restrict the maximum pulse rate and hence the upper bandwidth of the fibre optics systems. These operations are limited by:

(a) Detector noise.

(b) Pulse dispersion.

(c) Delay distortion.

Their severity increases with the length of the waveguide.

(1) DETECTOR NOISE LIMITATIONS:

Because of waveguide signal attenuation, the amplitude of light input pulse will suffer diminution as the pulse propagates alongwith the waveguide. Ultimately the amplitude becomes so small that it is indistinguishable from noise & the receiver is unable to make a zero-or-one decision within the specified probability of error. In this case the amplitude of the pulse, rather than the spread resulting from dispersion, will limit the communication capability of the system.

(2) WAVEGUIDE AND MATERIAL DISPERSION LIMITATIONS:

Waveguide dispersion is a consequence of the apparent changes in fibre dimension (in units of wavelength)with frequency. This results in a frequency-dependent phase & group velocity.

Material dispersion is a consequence of the variation in the refractive index of the fibre with frequency. Both waveguide and material dispersion cause a pulse, propagating along the waveguide, to spread because of the different component velocities. Because of pulse spreading, the receiver will eventually be unable to distinguish between two adjacent pulses that tend to overlap after having experienced dispersion. Consequently, the receiver will be unable to decide whether the given time slot contains a zero or a one. In this case, the widening of the pulse, rather than its loss in amplitude will limit the communication capability of the system.

(3) DELAY DISTORTION LIMITATIONS:

If a waveguide supports several modes with different phase and group velocities, energy, in the respective modes will arrive at the detector at different times. Most optical sources, particularly LEDs, excite many modes; if they are able to propagate through the waveguide, distortion will occur. The degree of distortion depends upon the amount of energy in the modes arriving at the detector input which in turn, depends upon the difference in attenuation between the modes & the degree of modemixing. In this case, the ability of the waveguide to suppress undesirable modes or to convert their energy to a desirable mode is the limiting factor for the communication capability of the system.

Chapter 2

Optical Fibre Waveguide

2.1 RAY THEORY TRANSMISSION:

(a) Total internal reflection:

Fibre optics is based on the phenomena of total internal reflection. To consider the propagation of light within an optical fibre utilizing the ray theory model it is necessary to take account of refractive index of the dielectric medium.

The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum too the velocity of light in the medium. A ray of light travels more slowly in an optically dense medium than in one that is less dense and the refractive index gives a measure of this effect.

When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass, air), refraction occurs as illustrated in Fig.2.1.

It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index N1 and is at an angle of 1 tot the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index which is less than N1 then the refraction is such that the ray path in this lower index medium is at an angle 2 to the normal, where $\phi 2$ is greater than $\phi 1$.

The angles of incidence 1 and refraction 2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that

$$N1 \sin \phi 1 = N2 \sin \phi 2$$

or $$\sin \phi 1 / \sin \phi 2 = N2 / N1 \text{ ---------- (A)}$$

Referring Fig.2.1 (a) that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As N1 is greater than N2, the angle of refraction is 90o. This is the limiting case of refraction and the angle of incidence is now known as the critical angle c as shown in Fig.2.1 (b).

From eq. # A, the value of the critical angle is given by:

$$\sin \phi c = N2 / N1 \text{ ----------------- (B)}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99%). Hence it may be observed in Fig. 2.1 (c). that total internal reflection occurs at the interface between two dielectrics of differing refractive indices when light on the dielectric of lower index from the dielectric of higher index, and the angle of incidence of the ray exceed the critical value. This is the mechanism by which light at a sufficiently shallow angle (less than 90o - c) may be considered to propagate down an optical fibre with low loss.

Fig.2.2 illustrates the transmission of a light in an optical fibre via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray has an angle of incidence at the interface which is grater than the critical angle and is reflected at the same angle to the normal.

The light ray shown in Fig. 2.2 is known as a meridional ray as it passes through the axis of the fibre core. the light transmission illustrated in Fig.2.2. assumes a perfect fibre, and any discontinuties or imperfections at the core-cladding interface would probably result in refraction rather than total internal reflection with a subsequent loss of the light ray into the cladding.

(b) ACCEPTANCE ANGLE:

Having considered the propagation of light in an optical fibre through total internal reflection at the core-cladding interface, it is useful to enlarge upon the geometric optics approach with reference to light rays entering the fibre. Since only rays with a sufficiently shallow grazing angle (i.e. within angle to the normal greater than c) at the core-cladding interface are transmitted by total internal reflection, it is clear that not all rays entering the fibre will continue to be propagated down its length.

The geometry concerned with launching a light ray into an optical fibre is shown in Fig. 2.3. which illustrates a meridional ray A at the critical angle c within the fibre at the core-cladding interface. It may be observed that this ray enters the fibre core at an angle a to the fibre axis and is refracted at the air-core interface before transmission to the core-cladding interface at the critical angle. Hence, any rays which are incident into the fibre core at an angle greater than a will be transmitted to the core-cladding interface at an angle less than c, and will not be totally internally reflected. This situation is also illustrated in Fig.2.3 where the incident ray B at an angle greater than a is refracted into the cladding and eventually reflected into the radiation. Thus for rays to be transmitted by total internal reflection within the fibre core they must be incident to the fibre core within an acceptance cone defined by the conical half angle a. Hence a is the maximum angle to the axis that light may enter the fibre in order to be propagated and is often referred to as the acceptance angle for the fibre.

If the fibre has a regular cross section (i.e. the core-cladding interfaces are parallel and there are no discontinuties) an incident meridional ray at greater than the critical angle will continue to be reflected and will be transmitted through the fibre. From symmetry consideration it may be noted that the output angle to the axis will be equal to the input for the ray, assuming the ray emerges into a medium of the same refractive index from which it was input.

(c) NUMERICAL APERTURE:

The relationship between the acceptance angle and the refractive indices of the three media, namely the core, cladding and air is given by a more generally used term, the numerical aperture (NA) of the fibre.

Consider meridional rays within the fibre. Fig.2.4 shows a light ray incident on the fibre core at an angle 1 to fibre axis which is less than the acceptance angle for the fibre a. The ray enters the fibre from a medium (air) of refractive index N0, and the fibre core has a refractive index N1, which is slightly greater than the cladding refractive index N2.

Assuming the entrance face at the fibre core to be normal to the axis, then considering the refraction at the air-core interface and using Snell's law:

$$N0 \sin \theta 1 = N1 \sin \theta 2 \text{ -------(a)}$$

From the Fig.2.4,

$$\phi = 90^{o} - 2$$

where is greater than the critical angle at the core-cladding interface. Hence eq.# (a) becomes

$$No = \sin \theta 1 = N1 \cos \theta \text{ ------ (b)}$$

Eq. # (b) can be written as

$$N0 \sin \theta_1 = N1 \, (1 - \sin^2 \theta)^{1/2} \text{ -------- (c)}$$

hen the limiting case for the total internal reflection is
nsidered becomes equal to the critical angle c for the
re-cladding interface and is given by:

$$\sin \theta_c = N2 \, / \, N1$$

lso in this limiting case 1 becomes acceptance angle for the
brea. Combining these limiting cases into eq.# (c) gives:

$$N0 \sin \theta_a = (N1^2 - N2^2)^{1/2} \text{ ------ (d)}$$

q.# (d), apart from relating the acceptance angle to the
efractive indices, serves as the basis for the an optical fibre
parameter, the numerical aperture (NA). Hence the numerical
aperture is defined as :

$$NA = N0 \sin \theta_a = (N1^2 - N2^2)^{1/2} \text{----- (e)}$$

Since the NA is often used with the fibre in air where N0 is
unity, it is simply equal to sin a. It may also be noted that

incident meridional rays over the range $0 \leq 1 \leq \theta a$ will be propagated within the fibre.

The relationship given in eq.# (e) for the NA is very useful measure of the light-collecting ability of a fibre. It is independent of the fibre core diameter and will hold for diameters as small 8 micrometer.

When interference phenomena are considered it is found that only rays with certain discrete characteristics propagate in the fibre core. Thus the fibre will only support a discrete number of guided modes. This becomes critical in small core diameter fibres which only support one or few modes. Hence electromagnetic mode theory must be applied in this case.

(d) SKEW RAYS:

Apart from meridional rays in the optical waveguide, there is another category of ray exists which is transmitted without passing through the fibre axis. These rays, which greatly outnumber the meridional rays, follow a helical path through the fibre as illustrated in Fig.2.5 and are called skew rays.

It is not easy to visualize the skew ray paths in two dimensions but it may be observed from Fig.2.7(b) that the helical path traced through the fibre gives a change in the direction of 2Y at each reflection where is the angle between the projection of the ray in two dimensions and the radius of the fibre core at the point of emergence of skew rays from the fibre in air will depend upon the number of reflections they undergo rather than the input conditions to the fibre. When the light input to the fibre is nonuniform, skew rays will therefore tend to have a smoothing effect on the distribution of the light as it is transmitted, giving a more uniform output. The amount of smoothing is dependent on the number of reflections encountered by the skew rays.

2.2 OVERVIEW:

Two characteristics of optical waveguides of primary importance are signal attenuation and dispersion. Generally speaking, attenuation (or loss) determines the distance over which a signal can be transmitted without becoming indistinguishable from noise, and dispersion determines the number of bits of information that can be transmitted over a given fibre in a specified time period.

Optical waveguides generally have to meet the following requirements at the optical wavelength of interest:

(a) Low transmission loss,

(b) High transmission bandwidth and data rate,

(c) High mechanical stability,

(d) Easy and reproducible fabrication methods,

(e) Low optical and mechanical degradation under all anticipated operational conditions,

(f) Easy interface with peripheral system components without performance degradation,

These and a few other factors can provide substantial advantages for fibre in comparison with more conventional coaxial waveguides and electric transmission media.

Chapter 3

Transmission Characteristics of Optical Fibres

3.1 INTRODUCTION:

The transfer of information in the form of light propagating within an optical fibre requires a successful implementation of an optical fibre communication system. This system, in common with all other systems, is composed of a number of a discrete components which are connected together in a manner that enables them to perform a desired task. The reliability and security of such a transmission system depends upon the communication technique used and the choice of components. The choice of components in turn depends upon the requirements of the system's the basic characteristics of the optical fibre and components themselves.

The factors which affect the performance of optical fibres as a transmission medium, i.e. transmission characteristics, are of utmost importance when the suitability of optical fibres for communication purposes is investigated. The transmission characteristics of most importance are those of attenuation (or loss) and dispersion.

3.2 ATTENUATION:

The attenuation or transmission loss of optical fibres has proved to be one of the most important factors in bringing about their wide acceptance in telecommunications. As channel attenuation largely determined the maximum transmission distance prior to signal restoration, optical fibre communications became especially attractive when the transmission losses of fibres were reduced below those of the competing metallic conductors (less than 5 dB/km).

Signal attenuation within optical fibres, as with metallic conductors, is usually expressed in the logarithmic unit of the decibel. The decibel which is used for comparing two power levels may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power Pi into a fibre to the output (received) optical power Po from the fibre

nos. of decibel (dB) = $10 \log_{10} Pi / Po$

In optical fibre communications the attenuation is usually expressed in decibels per unit length (i.e. dB/km) following:

$$a_{dB} L = 10 \log_{10} Pi / Po$$

here a_{dB} is the signal attenuation per unit length in decibels and is the fibre length.

ignal attenuation is a major factor in the design of any ommunication system. All receivers require that their input ower be above some minimum level, so transmission losses mit the total length of the path. There are several points in an ptic system where losses occur. These are at the channel input oupler, splices and connectors, and within the fibre itself. herefore a no. of mechanisms are responsible for the signal ttenuation within optical fibres. These mechanisms are nfluenced by the material composition, the preparation and urification technique, and the waveguide structure. They may e categorized within several major areas which include material bsorption, material scattering (linear and nonlinear scattering), nicrobending losses, mode coupling radiation losses and losses ue to leaky modes.

.3 MATERIAL ABSORPTION LOSSES:

aterial absorption is a loss mechanism related to the material omposition and the fabrication process for the fibre, which esults in the dissipation of some of the transmitted optical power heat in the waveguide. The absorption of light may be intrinsic caused by the interaction with one or more of the major omponents of the glass) or extrinsic (caused by impurities within e glass).

a) INTRINSIC ABSORPTION:

ven the purest glass will absorb heavily within specific vavelength regions. This is intrinsic absorption, a natural roperty of the glass itself. Intrinsic absorption is very strong in he short wavelength ultraviolet portion of the electromagnetic pectrum. The absorption, due to strong electronic and nolecular transition bands, is characterized by peak loss in the ltraviolet and diminishing loss as the visible region is approached. The ultraviolet is far removed from the region where fibre systems are operated, so this loss is unimportant. The tail end of UV absorption probably extends into the visible

3.3 MATERIAL ABSORPTION LOSSES:

Material absorption is a *loss mechanism related to the material* composition and the fabrication process for the fibre, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of light may be intrinsic (caused by the interaction with one or more of the major components of the glass) or extrinsic (caused by impurities within the glass).

(a) *INTRINSIC ABSORPTION:*

Even the purest glass will absorb heavily within specific wavelength regions. This is intrinsic absorption, a natural property of the glass itself. Intrinsic absorption is very strong in the short wavelength ultraviolet portion of the electromagnetic spectrum. The absorption, due to strong electronic and molecular transition bands, is characterized by peak loss in the ultraviolet and diminishing loss as the visible region is approached. The ultraviolet is far removed from the region where fibre systems are operated, so this loss is unimportant. The tail end of UV absorption probably extends into the visible gion, but is generally considered to contribute very little loss at s point.

trinsic absorption peaks also occur in the infrared. The infrared ss is associated with vibrations of chemical bonds such as the icon oxygen bond.

hus we conclude that intrinsic losses are mostly significant in a ide region where fibre systems can operate, but these losses hibit the extension of fibre systems toward the ultraviolet as ell as toward longer wavelengths. However, these effects can e minimized by suitable choice of both core and cladding omposition.

) EXTRINSIC ABSORPTION:

practical optical fibres prepared by conventional melting chniques, a major source of signal attenuation is extrinsic bsorption from transition metal element impurities. Another ajor extrinsic loss mechanism is caused by the absorption due water (as hydroxyl or OH ion).

etal impurities, such as Fe, Cu, V, Mn, and Cr, absorb strongly the region of interest and must exceed levels of a few parts r billion to obtain losses below 20 dB/km. Such purity has en achieved for high silica-content fibres, so little loss is tually observed.

e loss mechanism in the metals involves incompletely filled ner electron shells. Absorption of light causes electrons to ove from a lower-level shell (low-energy state) to a higher-vel one (higher-energy state). The added electron energy is otained from the incident light. The allowed transition energies rrespond to photons whose frequencies are in the region of terest for fibre communications.

om a practical point of view, the most important impurity to inimize is the OH ion. The loss mechanism for the OH ion is e stretching vibration, just as for the absorption of the S10 ond. The oxygen and hydrogen atoms are vibrating due to the ermal motion. The Oil impurity must be kept to less than a few arts per million. Special precautions are taken during the glass anufacture to ensure a low level of OH impurity in the finished roduct. Dry fibres have particularly low OH levels; wet fibres t a bit more. Within the low intrinsic loss region, OH sorption dictates which wavelength must be avoided for most cient propagation.

4 LINEAR SCATTERING LOSSES:

near scattering mechanisms cause the transfer of some or all of e optical power contained within one propagating mode to be ansferred linearly (proportionally to the mode power) into fferent mode. This process tends to result in attenuation of the ansmitted light as the transfer may be to a leaky or radiation ode which does not continue to propagate within the fibre ore but is radiated from the fibre. With all linear processes there no change of frequency on scattering.

near scattering may be categorized into two major types:

ayleigh and Mie scattering. Both result from the nonideal hysical properties of the manufactured fibre which are difficult nd in certain cases impossible to eradicate at present.

(a) RAYLEIGH SCATTERING:

Rayleigh scattering is the dominant intrinsic loss mechanism in the low absorption window between the ultraviolet and infrared absorption tails. it results from inhomogeneities of random nature occurring on a small scale compared with the wavelength of the light. These inhomogeneitis manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing-in of the density inhomogeneities are fundamental and cannot be avoided.

(b) MIE SCATTERING:

Linear scattering may also occur at inhomogeneities which are comparable in size to the guided wavelength. These from the nonperfect cylindrical structure of the waveguide and may be caused by the fibre imperfections such as irregularities in the core-cladding interface, core-cladding refractive index difference along the fibre length, diameter fluctuations, strains and bubbles.

ne scattering created by such inhomogeneities is mainly in the rward direction and is called Mie scattering. Depending upon ne fibre material design and manufacture, Mie scattering can ause significant losses. The inhomogeneities may be reduced by:

a) removing imperfections due to the glass manufacture process;

b) carefully controlled extrusion and coating of the fibre;

c) increasing the fibre guidance by increasing the relative refractive index difference.

y these means it is possible to reduce Mie scattering to nsignificant levels.

3.5 NONLINEAR SCATTERING LOSSES:

Optical waveguides do not always behave as completely linear hannels whose increase in output optical power is directly roportional to the input optical power. Several nonlinear effects occur, which in the case of scattering cause disproportionate ttenuation, usually at high power levels. This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same or other modes, at a different frequency. It depends critically upon the optical power density within the fibre and hence only becomes significant above threshold power levels. The most important types of nonlinear scattering within optical fibres are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single mode fibers. These scattering mechanisms infact give optical gain but with a shift in frequency thus contributing to attenuation for light transmission at a specific wavelength.

3.6 FIBRE BEND LOSS:

Optical fibres suffers radiation losses at bends or their paths. This is due to the energy in the evanescent fields at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fibre. An illustration of this situation is shown in Fig.3.1.

he part of the mode which is on the outside of the bend is equired to travel faster than that on the inside so that a vavefront perpendicular o the direction of propagation is naintained. HEnce part of the mode in the cladding needs to ravel faster than that the velocity of light in that medium. As this s not possible, the energy associated with this part of the mode s last through radiation. There are two types of bends, nacroscopic and microscopic.

Macroscopic refers to large scale bending, such as that which occurs intentionally when wrapping the fibre on a spool or pulling it around a corner. Fibres can bend with radial of curvature as small as 10 cm with negligible loss. Typically, breaking will not occur unless the bend radius is less than 150 times the fibre diameter.

Bending loss can be explained as follows:

In Fig.3.2, a trapped ray proceeds through a SI fibre, striking the core-cladding interface at an angle 1 greater than c (critical angel), so that total internal reflection occurs. This same ray enters the bend and strikes the interface at an angle 2, which is clearly less than 1, and which may be less than critical. The ngle 2 diminishes as the bend decreases. At some bend radius, 2 becomes smaller than the critical angel, total internal reflection does into occur, and a portion of the wave is radiated.

Microscopic bending often occurs when a fibre is sheathed within a protective cable. The stresses set up in the cabling process cause small axial distortions (microbends) to appear randomly along the fibre. The microbends couple light between the various guided modes of the fibre and cause some of the light to couple out of the fibre. Because of this effect, a fibre having a certain attenuation when unsheathed often has an increased loss after the cabling process.

3.7 DISPERSION:

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibres. When considering the major implementation of optical fibre transmission which involves some form of digital modulation, then dispersion mechanisms within the fibre cause broadening of the transmitted light pulses as they travel along the channel. The phenomenon is illustrated in the Fig.3.3(a) where it may be oserved that each pulse broadens and overlaps with its eighbors, eventually becoming indistinguishable at the receiver put. The effect is known as inter symbol interference (ISI). Thus increasing number of errors may be encountered on the gital optical channel as the ISI becomes more pronounced. The ror rate is also a function of the signal attenuation on the link nd the subsequent signal to noise ratio (SNR) at the receiver. owever, signal dispersion alone limits the maximum possible andwidth attainable with a particular optical fibre to the point here individual symbols can no longer be distinguished.

or no overlapping of light pulses down on an optical fibre link e digital bit rate B_T must be less than the reciprocal of the roadened (through dispersion) pulse duration (2t). Hence:

$$B_T \leq 1 / 2t$$

his assumes that the pulse broadening due to the dispersion on e channel is which dictates the input duration which is also t. ig.3.3(b) shows the three common optical fibre structures, ultimode step index, multimode graded index and single mode index, whilst diagrammatically illustrating the respective e broadening associated with each fibre type. It may be erved that the multimode step index fibre exhibits the test dispersion of a transmitted light pulse and that the timode graded index fibre gives a considerably improved ormance. Finally, the single mode fibre gives the minimum e broadening and thus is capable of the greatest transmission dwidths which are currently in the Gigahertz range, whereas smission via multimode step index fibre is usually limited to dwidths of a few tens of Megahertz. However, the amount of se broadening is dependent upon the distance the pulse els within the fibre and hence for a given optical fibre link the riction on usable bandwidth is dictated by the distance ween regenerative repeaters (i.e. the distance the light pulse vels before it is reconstituted). Thus the measurement of the persive properties of a particular fibre is usually stated as the lse broadening in time over a unit length of the fibre (i.e. ;/km).

ence, the number of optical signal pulses which may be ansmitted in a given period, and therefore the information arrying capacity of the fibre is restricted by the amount of pulse ispersion per unit length. In the absence of mode coupling or ltering, the pulse broadening increases linearly with fibre length nd thus the bandwidth is inversely proportional to distance.

Chapter 4

Optical Fibres & Cables

4.1 TYPES OF OPTICAL FIBRE:

(a) STEP INDEX FIBRES:

The optical fibre with a core of constant refractive index N1 and a cladding of a slightly lower refractive index N2 is known as step index fibre. This is because the refractive index profile for this fibre makes a step change at the core-cladding as indicated in Fig.4.1. which illustrates the two major types of step index fibre. The refractive index profile may be defined as:

$$N(r) = \begin{cases} N1 & r < a \quad \text{(core)} \\ N2 & r \geq a \quad \text{(cladding)} \end{cases}$$

in both cases.

Fig.4.1 (a) shows a multimode step index fibre with a core cladding diameter of around 50 micrometer or greater which is large enough to allow the propagation of many modes within the fibre core. This is illustrated in Fig.4.1 (a) by many different possible ray paths through the fibre.

Fig.4.1 (b) shows a single mode or monomode step index fibre which allows the propagation of only one transverse ectromagnetic mode, and hence the core diameter must be of rder of 2 - 10 micrometer. The propagation of a single mode is ustrated in Fig.4.1 (b) as corresponding to a single ray path usually shown as the axial ray) through the fibre.

he single mode step index fibre has the distinct advantage of ow inter modal dispersion (broadening of transmitted light ulses), as only one mode is transmitted, whereas with nultimode step index fibre considerable dispersion may occur lue to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with nultimode step index fibres, especially when compared with ingle mode fibres. However, for lower bandwidth applications nulti mode fibres have several advantages over single mode ibres.

They are:

1) The use of spatially incoherent optical sources (e.g. most light emitting diodes) which cannot be efficiently coupled to single mode fibres.

2) Larger numerical apertures, as well as core diameters,

facilitating easier coupling to optical sources.

Lower tolerance requirements of fibre connectors.

) GRADED INDEX FIBRES:

ne graded index (GRIN) fibre has a core material whose fractive index varies with distance from the fibre axis. This ructure, illustrated in the Fig.4.2(a) appears to be quite different om the SI fibre. We will show how the GRIN fibre guides light y trapping rays, not unlike the operation of SI waveguide. The idex variation is described by

$$N(r) = N1\,(1 - 2\,(r/a)^{\alpha}\,\Delta)^{1/2} \qquad r \leq a \text{ ---- (C)}$$

$$N(r) = N1\,(1 - 2\Delta)^{1/2} = N2 \qquad r > a \text{ ---- (D)}$$

vhere

N1 = refractive index along the fibre axis.

N2 = refractive index outside the core (cladding radius).

a = core radius.

α = parameter describing the refractive index profile variation.

Δ = parameter determining the scale of the profile change.

nt rays travel through the fibre in the oscillatory fashion of 4.2 (b). The changing refractive index causes the rays to be ntinually redirected towards the fibre axis, and the particular riations in eq. C and eq. D causes them to be periodically focused.

is redirection can be illustrated by modeling the continuous ange in refractive index by a series of small step changes as own in Fig.4.2(c). This model can be as accurate as desired by creasing the number of steps. Many GRIN fibre resemble this ep model because their cores are fabricated in layers. The ending of the rays at each small step follows Snell's Law (eq. A).

he rays are bent away from the normal when traveling from a igh to a lower refractive index. Considering this, the ray trace in ig.4.2(c) becomes reasonable. A ray crossing the fibre axis strikes a series of boundaries, each time traveling into a region of ower refractive index, and thus bending farther towards the horizontal axis. At one of the boundaries away from the axis, the ray angle exceeds the critical angle and is totally reflected back towards the fibre axis. Now the ray goes from low to higher index media, thus bending towards the normal until it crosses the re axis. At this point, the procedure will repeat. In this manner, e fibre traps a ray, causing it to oscillate back and forth as it opagates down the fibre.

MULTIMODE STEP INDEX FIBRES:

ultimode step index fibres may be fabricated from either ulticomponent glass compounds or doped silica. These fibres n have reasonably large core dias and large numerical pertures to facilitate efficient coupling to incoherent light ources such as LEDs. The performance characteristics of this ore type may vary considerably depending on the materials sed and the method of preparation; the doped silica fibres xhibit the best performance.

typical structure for a glass multimode step index fibre is hown in Fig.4.3.

STRUCTURE:

Core dia:	50 -- 400 micro meter
Cladding dia:	125 -- 500 micro meter
Buffer jacket dia:	250 -- 500 micro meter
Numerical aperture:	0.16 -- 0.5

ERFORMANCE CHARACTERISTICS:

ttenuation:	40 -- 50 dB/km
andwidth:	6 -- 25 MHz km
pplication:	These fibres are best suited for short haul, limited bandwidth & relatively low cost applications.

l) MULTIMODE GRADED INDEX FIBRES:

hese fibres which have a graded index profile may also be ıbricated using multicomponent glasses or doped silica. The erformance characteristics of multimode graded in dex fibres re generally better than those for multimode step index fibres ue to index grading and lower attenuation. Multimode graded ndex fibres tend to have small core diameters than multimode tep index fibres although the overall diameter including the uffer jacket is usually about the same. This gives the fibre reater rigidity to resist bending.

typical structure is shown in Fig.4.4

STRUCTURE:

Core dia:	30 -- 100 micro meter
Cladding dia:	100 -- 150 micro meter
Buffer jacket dia:	250 -- 1000 micro meter
Numerical aperture:	0.2 -- 0.3 micro meter

PERFORMANCE CHARACTERISTICS:

Attenuation:	2 -- 10 dB/km
Bandwidth:	150 MHz km -- 2 GHz km
Application:	These fibres are best suited for medium - haul, medium to high bandwidth applications using incoherent multimode sources.

(e) SINGLE MODE FIBRES:

Single mode fibres can have either a step index or graded index profile. They are high quality fibres for wideband, long-haul transmission and are generally fabricated from doped silica (silica-clad-silica) in order to reduce attenuation.

ough single mode fibres have small core diameter to allow
gle mode pròpagation, the cladding diameter must be at least
times the core diameter to avoid losses from the evanescent
ld.

ence, with a buffer jacket to provide protection and strength,
ngle mode fibre have similar overall diameters to multimode
ore.

typical example of a single mode step index fibre is shown in
g.4.5.

TRUCTURE:

ore dia:	3 -- 100 micro meter
ladding dia:	50 -- 125 micro meter
uffer jacket dia:	250 -- 1000 micro meter
lumerical aperture:	0.08 -- 0.15 micro meter

ERFORMANCE CHARACTERISTICS:

Attenuation:	2 -- 5 dB/km. (lower losses are possible in the longer wavelength region.)
Bandwidth:	Greater than 500 MHz km.

plication: These fibres are ideally suited for high bandwidth very long haul application using single mode injection.

PLASTIC CLAD FIBRES:

astic clad fibres are multimode & have either a step index or a raded index profile. They have a plastic cladding and a glass ore which is frequently silica (PCS fibres). The PCS fibres exhibit ower radiation induced losses than silica clad silica fibres. Plastic lad fibres are generally slightly cheaper than the corresponding lass but usually have more limited performance characteristics.

A typical structure for a step index clad fibre is shown in Fig.4.6.

STRUCTURE:

Core dia:	Step index	100 -- 500 micro meter
	Graded index	50 -- 100 micrometer
Cladding dia:	Step index	300 -- 800 micro meter
	Graded index	125 -- 150 micrometer
Buffer jacket dia:	Step index	500 -- 1000 micro meter
	Graded index	250 -- 1000 micrometer

Numerical aperture:	Step index	0.2 -- 0.5
	Graded index	0.2 -- 0.3

PERFORMANCE CHARACTERISTICS:

Attenuation:	Step index	5 -- 50 dB/km
	Graded index	4 -- 15 dB/km
Bandwidth:	Step index	5 -- 25 MHz km
	Graded index	200 -- 400 MHz km
Application:	These fibres are generally used on lower bandwidth, shorter haul links where fibre cost need to be limited. They also have the advantage of easier termination over glass clad multimode fibres.	

4.2 OPTICAL FIBRE CABLES:

If optical fibres are to be alternatives to electrical transmission lines it is imperative that they can be safely installed and maintained in all the environments e.g. underground cables in which metallic conductors are normally placed. Therefore, when optical fibres are to be installed in a working environment their mechanical properties are of prime importance. In this respect he unprotected optical fibre has several disadvantages with regard to its strength and durability. Bare glass fibres are brittle and have small cross-sectional areas which makes them very susceptible to damage when employing normal transmission line handling procedures. It is therefore necessary to cover the fibres to improve their tensile strength and to protect them against external influences. This is usually achieved by surrounding the fibres by a series of protective layers which are referred to as coating and cabling. The initial coating of plastic with high elastic modulus is applied directly to the fibre cladding. it is then necessary to incorporate the coated and buffered fibre into an optical cable to increase its resistance to mechanical strain and stress as well as adverse environmental conditions.

The functions of the optical cable may be summarized into four main areas. These are:

(a) FIBRE PROTECTION:

The major function of the optical cable is to protect against fibre damage and breakage both during installation and throughout the life of the fibre.

(b) STABILITY OF THE FIBRE TRANSMISSION CHARACTERISTICS:

The cabled fibre must have good stable transmission characteristics which are comparable with the uncalled fibre. Increases in optical attenuation due to cabling are quite usual and must be minimized within the cable design.

(c) CABLE STRENGTH:

Optical cables must have similar mechanical properties to electrical transmission cables in order that they may be handled in the same manner. These mechanical properties include tension, torsion, compression, bending, squeezing and vibration. Hence, the cable strength may be improved by incorporating a suitable strength number and by giving the cable a properly designed thick outer sheath.

(d) IDENTIFICATION AND JOINTING OF THE FIBRES WITHIN THE CABLE:

This is especially important for cables including a large number of optical fibres. If the fibres are arranged in a suitable geometry it ay be possible to use multiple jointing techniques rather than ointing each fibre individually.

XAMPLES OF FIBRE CABLES:

Many different cables have been proposed and a large number have been adopted by different organizations throughout the world. At present there are no definite standards for optical fibre cables incorporating either a particular number of fibres or for specific application. However, there is a general consensus on the overall design requirements and on the various materials that can be used for cable construction.

Fig.4.7 shows two examples of cable construction for single fibres. In Fig.4.7(a), a tight buffer jacket of Hytrel is used to surround a layer of Kevlar for strengthening. In this construction the optical fibre cable itself acts as a central strength member.

The cable construction illustrated in the Fig.4.7 (b) uses a loose tube buffer around the central optical fibre. this is surrounded by a Kevlar strength member which is protected by an inner sheath or jacket before the outer sheath layer. the strength members of single optical fibres are not usually incorporated at the centre of ne cable but are placed in the surrounding cable form as shown n Fig.4.7 (b).

able designs for multifibre cables may also take this general orm with the strength member surrounding the fibres at the entre of the cable. Examples of this construction are illustrated n Fig.4.8.

ig.4.8 (a) shows seven fibres at the cable centre surrounded by a helically laid Kevlar strength member.

Fig.4.8 (b) shows a ribbon cable configuration with a strength member of polypropylene yarns in the surrounding cable form. it may also be noted that this design utilizes armoring of stainless steel wires placed in the outer sheath.

Two more cable designs which allow the incorporation of a large number of fibres are shown in Fig.4.9.

The configuration illustrated in Fig.4.9 (a) is a standard design where the buffered fibres are arranged in one or more layers.

Alternatively Fig. 4.9 (b) shows a multi-unit design where each unit contains seven buffered fibres. In this case the design allows 49 fibres to be included within the cable.

Finally a cable design which has proved successful in installations is shown in Fig.4.10. The cable has a central copper wire for strengthening and also to provide possible electrical conduction surrounded by a plastic structure member. Upto 12 optical fibres are placed in a flat ribbon between plastic tapes and incorporated into a helical groove in the extruded plastic structural member. Another diametrically opposite groove is designed for the placement of upto seven plastic insulated metallic pairs or alternatively the incorporation of other ribbon of optical fibres. The principal strength member is a loose aluminum tube fitted over the cable core which also acts as a water barrier. This is surrounded by an inner polyethylene jacket or sheath followed by armoring consisting of corrugated steel tape with longitudinal overlap. A second polyethylene jacket acts as an outer cable sheath giving the cable an overall diameter of around 2.5 cm. The use of the aluminum tube also allows the cable to be operated under pressurized conditions which gives the additional advantages of:

(a) An alarm in the event of sheath perforation.

(b) Sheath fault location.

(c) The exclusion or reduction of water ingress at a sheath fault.

4.3 PROPAGATION ASPECTS AND FIBRE REQUIREMENTS:

In the following, the propagation aspects of optical fibres are reviewed in order to present a critical analysis of their future potential. This includes an analysis of the state of art and of the inherent limitations of fibres. The terms fibre and waveguide are used interchangeably.

Because of the central importance of fibres to the performance of a complete communication system, the requirements that the waveguide has to satisfy are rather stringent. They can be divided into technical and economic demands, both of which tend to constrain the optimization of practical systems. These requirements are specified as below:

(A) SMALL LOSS:

The fibre must have a low loss in order to prevent signal nplitude degradation over large distance; the loss minima must e at a wavelength for which suitable light sources and detectors xist or for which development can be expected.

B) SMALL DISPERSION:

he fibre must have small signal dispersion in order to prevent gnal pulse width degradation over large distances.

C) HIGH REPRODUCIBILITY:

ibre geometry as well as dopant and index profiles must be hosen such that loss and dispersion are minimized over the entire length of the fibre. this requirement implies extremely ight control over the parameters to avoid spatial and time variations which lead to performance degradation.

(D) SUPPRESSION OF UNDESIRABLE MODES:

Support of only one or a few modes with similar propagation properties is desirable to avoid variations in signal delay caused by different modes arriving at the detector at different times.

) OPTIMIZED NUMERICAL APERTURES:

is critical to select a numerical aperture whose value is mpatible with, or at least an acceptable compromise among, e normally conflicting requirements of large bandwidth, large tical acceptance angle, minimum bending loss and other rformance criterion.

) EASY IMPLEMENTATION:

sy fabrication, installation and maintenance of fibres which low economical, reproducible and reliable fabrication, field licing and other implementation of connectors, as well as easy andling under all anticipated conditions are major criteria in electing an appropriate fibre.

G) ENVIRONMENTAL RESISTANCE:

ibre protection against environmental influences such as stress nd strain, torsion, bending, humidity, shock, vibration and rradiation without a significant degradation compared to the characteristics in the naked state are of practical importance in most applications.

H) COMPATIBILITY WITH OTHER COMPONENTS:

ompatibility in geometry and characteristics with other omponents of the system may severely constrain the choice of bres and another components.

he best fibres fabricated to date have attained loss and ispersion characteristics that approach the theoretical limits. This orresponds to attenuation of approximately 1 dB/km and ispersion of less than 1 ns/km.

Chapter 5

eliability of Optical Fibres, Cables and Splices

INTRODUCTION:

since the success of the early field trials, fibre optic smission has gained wide acceptance in such diverse cations as telephony, instrumentation, computer, CATV & military. As a matter of fact, in telephony trunking & more ntly in new feeder applications, it has become the smission system of choice. The availability of optimized gn for the specific application, correct installation practices long-term reliability and maintainability have been the equisites for broad use of fibre optic transmission systems.

eneral, installed fibre optic cable systems have an enviable rd for reliability, although failures have been reported. nsic fibre reliability & the effects of cabling have been studied nsively. The limitations are well understood & the design iples for any given set of environmental & installation itions are known.

r as the user is concerned, the reliability of the entire cable m is of importance. In this context, the cable system is ed as the fibre optic transmission medium between the fibre *istribution frames or between transmitter and receiver.* Cable ystem reliability is influenced by the reliability of the system components, namely; the input/output connectors/pigtails, *splices and the cables themselves, whose reliability in turn is imited by that of the fibres.*

.2 INSTALLED CABLE RELIABILITY:

eferring to Table I, the 312 sheath km consists of approximately 4 percent underground duct, 26 percent direct buried, and 20 ercent aerial plant. The study covered the period from January 977 to July 1982. For purposes of the study, failure was defined s performance outside the specified limits and failures were assified into three categories:

a) Extrinsic
b) Avoidable extrinsic
c) Intrinsic

xtrinsic failures include uncontrollable breaks such as those due o digups, breaking poles, collapsing ducts etc. All types of cable, ibre or copper, are subject to such failures.

voidable extrinsic failures are those due to improper installation.

ntrinsic failures are fibre failures that occurred while the cable was handled, installed, and operated within specifications.

he largest number of incidents (10 out of a total of 14) were in he "uncontrollable extrinsic" category. The breakdown is as ollows:

) 5 cuts, backhoe, direct buried.

) 1 rodent direct buried.

) 3 shotgun, aerial.

) 1 duct, served, underground.

Not unexpectedly, the underground duct environment seems the east susceptible to uncontrollable failures. Avoidable failures are usually due to placement errors and can be reduced by training and following established practices. The one and only intrinsic failure, a factory splice, occurred in 1978. Factory splices are arbitrarily classified as fibre failures instead of field splice failures.

More recent data from MCI are summarized in Table II. No intrinsic fibre/cable failures were reported. The 18 incidents are all extrinsic and are dominated by cable cuts. The failure rate is one incident per year per 146 sheath. km of cable. This number is in the same order of magnitude as the one calculated form the number of hits/year/(sheath.km) for long-distance coaxial transmission systems. A 30 percent improvement can be achieved by improving parallel construction practices.

In addition to the typical incidents described in table II, reported failures include those due to a tunnel fire, burst stream pipes, ducts cut by piles being driven through them, and clam dredger cutting underwater cable.

5.3 DISCUSSION OF SPECIFIC FIBRE CABLE FAILURE MODES AND MECHANISMS:

(1) FIBRE STRENGTH:

The easiest way to minimize cable failures due to fibre strength is to follow correct installation practices. When placing underground cable, tension monitoring is essential so that the short-term maximum rating of the cable is not exceeded.

urthermore, the residual tension in the cable after installation nust decrease to a level below the long-term tensile rating.

2) HYDROGEN EFFECTS:

The implications of the effects of hydrogen on optical fibres will lepend on the concentration of hydrogen which can build up nside cables. This, in turn, depends on the materials used in able manufacturing and the cable construction. In one trial ystem, fibre loss increases were observed after two years. The oss increase for the multimode, high P concentration fibres amounted to 0.15 dB/km at 1300 nm, whereas the value at 1500 nm was 1.5 dB/km. There are two other field-related ncreases of multimode fibre loss where the most probable cause was hydrogen. In the case of a terrestrial system, the attenuation at 1270 nm increased by 0.7 dB/km over a period of two years.

For today's low phosphorous, conventional single mode fibres, hydrogen pressures in well-designed cables are predicted to be sufficiently low such that background effects will not cause any deterioration in the long-term performance of systems operating at 1.3 or 1.55 micro meter.

3) LIGHTNING:

Historically, metallic shielded telecommunication cables buried in earth have been damaged by transient energy associated with lightning discharge. The typical damage is pinholes due to arcing in the cable shield, but on occasion, additional crushing damage occurs. The classical explanation of this phenomenon has been termed the "steamhammer" effect. Recent work suggests that mechanical crushing of armored cables is more likely the result of magnetic fields generated by lightning passing over or in near proximity of cables. Results showed that cables with shields or armor with circumferential conductivity are subject to severe damage, while those without suffer little or no damage.

Thus, bare metallic tapes or solid tubes used for shield or armor functions may be very poor performers in the natural environment, while shields and armor made from longitudinally applied plastic coated metal tapes having dielectric coatings will be virtually undamaged.

There has not been any reported fibre optic cable damage due to lightning because most optic fibre cables are filled and pinhole damage is not likely to impair the transmission properties of bres. Furthermore, all dielectric cables and those with metallic entral members are not susceptible to magnetic crush. Finally, nost armored fibre optic cables are also magnetic crush resistant.

4) RODENTS:

Many cable parameters influence the effects of rodent attack. The major considerations in cable design and placement for best rodent protection are cable size, placing depth and sheath material. Tests have shown that for cables in excess of 53 mm in diameter, gopher attack is rarely observed. On the other hand, cables below 20 mm in diameter (most fibre optic cables fall into this category) are subject to the most severe attack because certain rodents are able to bite directly down on the cable.

Another important consideration in reducing the risk of rodent attack is cable placement. Studies have shown that the probability of rodents digging to 1.2 m is only 15 percent.

For rodent protection, stainless steel tape armoring 125 micro meter thick or greater appears to be necessary to provide protection against rodent attack.

e users in areas of dense rodent population and high ning incidence have opted for extruded innerduct cable use if its larger outside diameter and its all-dielectric truction.

following cable failures due to rodent damage have been orted: buried all-dielectric cable,k dielectric cable in erground duct, inner-duct cable, buried cable in corrugated er duct. There are no failures of steel armored cables orted. Appropriate steel armoring is effective. Considering that ain types of metallic armor are resistance to lightening, and no lightning damage has been reported, it appears that the ferred choice is armored cable, with longitudinally applied tic coated steel tape, in areas of dense rodent population, n in areas of high lightning incidence.

SHOTGUN DAMAGE:

rial installed telecommunication cables are subject to shotgun sts resulting in damage by shotgun pellets. The rural areas are re likely to sustain cable damage due to recreational hunting.

aerial fibre optic cables, this is the most frequent failure
hanism.

FACTORY SPLICES:

ing cable manufacturing, it is sometimes convenient and
nomical to include factory splices in the cables. Because of
and reliability considerations, these splices are invariably
le by fusion. Early studies had shown that the primary source
he low strength of fusion splices was the damage done to the
e by the fibre stripping process.

now factory splicing techniques have improved to the point
they do not constitute a failure mode. The results of one
dy are shown in Table III.

4 RESTORATION:

maintain systems in service, it is clear that troubleshooting
d repair procedures have to be established. A study of working
re systems conducted in 1982 indicated that fibre cable-
ated troubles constituted less than 10 percent of the total

ber of troubles, the majority of total plant clearing time was t on repairing fibres. The average plant clearing time per cable incident was 2145 min. These long clearing times e attributed to the relative newness of the technology in 2, and it was expected that the experience factor should rove these figures considerably.

TROUBLESHOOTING:

ubleshooting is an obvious prerequisite to restoration. Once it etermined that the trouble is in the cable, the problem fibres accessed with an optical time domain reflectometer. Cable ts, increased attenuation, and failed splices or connectors are dily identifiable.

SPLICE REPAIR:

ed on the data, it appears that splice reliability is more than quate to meet service needs. Failures in all instances were ted to one or two fibre splices and were repairable by ntering the closures. As long as the system is protected or re are a few spare fibres, service is not affected.

REPAIR OF PARTIALLY FAILED CABLES:

le failures which impair the transmission performance of a all fraction of the fibres in a cable can be handled without vice interruption as long as the damaged area is accessible. s is normally the situation in aerial or direct buried plants and manholes. It is relatively straight forward to open the cable ath, repair the damaged fibres, and repair the sheath without turbing the good fibres.

EMERGENCY RESTORATION:

ce most fibre cable failures are uncontrollable, emergency toration procedures are necessary. The essential requirements emergency repair are rapid temporary restoration and the lity to transition to permanent repair without disturbing any of e fibres other than the one being worked on.

alysis of case histories of actual cable restoration emphasizes e importance of advance planning. The major difficultly countered proved to be the location of the necessary rdware.

OFFSET BREAKS:

ny restoration, it is of great concern where the fibre breaks relative to the actual cable break. In any freely suspended optic cable subjected to tensile forces acting axially, fibres break at randomly distributed points over the cable length n pulling forces exceed specified values. In case of a cable k, there is no correlation between the location of the cable k and the location of the fibre breaks.

nost installations the cable breaks occur very differently from ve. The cables are not freely suspended, are restricted to ve either by friction or lashing, and cable breaks are not ally caused by axial forces.

most susceptible designs are cables with high tensile rating, fibres located in the center of the cable. On the other hand, nded filled loose tube cables are the least susceptible.

5 CONCLUSIONS:

alled fibre systems have excellent reliability. Most of the ures to date were i n the "uncontrollable extrinsic category"

the majority of these were due to complete cable cuts. It is
cted that existing data on the frequency of copper cable cuts
given service area are applicable to fibre cable cuts. Splice
bility has also been found to be excellent, provided that the
opriate techniques and equipment were used.

rgency restoration procedures to deal with the dominant
e mode of cables have been established to assure a rapid
n of service. Based on data to date, it is essential that the
have an established plan for restoration.

Chapter 6

Optical Fibre Systems

INTRODUCTION:

ransfer of information in the form of light propagating within ptical fibre requires the successful implementation of an al fibre communication system. This system, in common all systems, is composed of a number of discrete ponents which are connected together in a manner that les them to perform a desired task. Hence, to achieve ble and secure communication using optical fibres it is ntial that all the components within the transmission system compatible so that their individual performances, as far as sible, enhance rather than degrade the overall system ormance.

principal components of a general optical fibre system for er digital or analog transmission are shown in the system ck schematic of Fig.6.1. The transmit terminal equipment sists of an information encoder or signal shaping circuit ceding a modulation or electronic driver stage which rates the optical source. Light emitted from the source is nched into an optical fibre incorporated within a cable which nstitutes the transmission medium. The light emerging from r end of the transmission medium is converted back into an rical signal by an optical detector positioned at the input of receive terminal equipment. This electrical signal is then ified prior to decoding or demodulation in order to obtain nformation originally transmitted.

THE OPTICAL TRANSMITTER CIRCUIT:

unique properties and characteristics of the injection laser light emitting diode (LED) make them attractive sources for cal fibre communication.

JRCE LIMITATIONS:

POWER:

electrical power required to operate LEDs is generally with cal current levels of between 20 and 300 mA, and voltage ps across the terminals of 1.5 -- 2.5 V. The optical output ver against current characteristic for the two devices varies siderably as is indicated in Fig.6.2. The injection laser is a eshold device which must be operated in the region of

nulated emission (i.e. above the threshold where continuous
cal output power levels are typically in the range 1 - 10 mill
t.

ction lasers are capable of launching between 0.5 and several
/s of optical power into a fibre. LEDs are capable of similar
ical output power levels to injection lasers depending on their
icture and quantum efficiency. The optical power coupled into
bre from an LED can be 10 - 20 dB below that obtained with
ypical injection laser. The power advantage gained with the
ction laser is a major factor in the choice of source, specially
en considering a long-haul optical fibre link.

LINEARITY:

earity of the optical output power against current
racteristic is an important consideration with both the
ction laser and LED. It is especially pertinent to the design of
log optical fibre communication systems where source
nlinearities may cause severe distortion of the transmitted
nal.

first the LED may appear to be ideally suited to analog ısmission as its output is approximately proportional to the ve current. However, most LED display some degree of ılinearity in their optical output against current characteristic ause of junction heating effects which may either prohibit ir use, or necessitate the incorporation of a linearizing circuits hin the optical transmitter. Certain LEDs do display good arity, with distortion products between 35 and 45 dB below signal level.

alternative approach to obtaining a linear source characteristic o operate an injection laser in the light generating region ve its threshold, as indicated in Fig.6.2 This may prove more able for analog transmission than would the use of certain Ds. However, gross non linearities due to mode instabilities y occur in this region. Therefore, many of the multimode ction lasers have a limited use for analog transmission without litional linearizing circuits within the transmitter.

ernatively, digital transmission is far less sensitive to source ılinearities and is therefore often preferred when using both ction lasers and LEDs.

THERMAL:

thermal behaviour of both injection lasers and LEDs can limit r operation within the optical transmitter. The variation of ction laser threshold current with the device junction perature can cause a major operating problem. Any ificant increase in the junction temperature may cause loss of g and a subsequent dramatic reduction in the optical output ver. This limitation cannot usually be overcome by simply ing the device on a heat sink, but must be taken into ount within the transmitter design, through the incorporation ptical feedback, in order to obtain a constant optical output ver level from the device.

optical output from an LED is also dependent on the device tion temperature. Most LEds exhibit a decrease in optical out power following an increase in junction temperature, ch is typically around - 1% per degree centigrade. this mal behaviour, however, although significant is not critical to operation of the device due to its lack of threshold. ertheless, this temperature dependence can result in a tion in optical output power of several decibels over the perature range 0-70C. It is therefore a factor within system gn considerations which, if not tolerated, may be overcome providing a circuit within the transmitter which adjusts the drive current with temperature.

RESPONSE:

speed of response of the two types of optical source is ely dictated by their respective radiative emission hanisms. Spontaneous emission from the LED is dependent the effective minority carrier life time in semi conductor erial. The rise time of the LED is atleast twice the effective ority carrier lifetime. The rise times for currently available s lie between 2 and 50 ns, giving 3 dB bandwidths of around at best 175 MHz. Therefore, LEDs are inherently restricted ower bandwidth applications, although suitable drive circuits maximize their bandwidth capabilities (i.e. reduce rise times).

ulated emission from injection lasers occurs over a much ter period giving rise times of the order of 0.1 - 1.0 ns, thus ving 3 dB above 1 giga hertz. However, injection laser ormance is limited by the device switch-on delay. To achieve highest speeds it is therefore necessary to minimize the h-on delay:

SPECTRAL WIDTH:

finite spectral width of the optical source causes pulse dening due to material dispersion on an optical fibre munication link. This results in a limitation on the dwidth-length product which may be obtained using a cular source and fibre. The incoherent emission from an LED lly displays a spectral linewidth of between 20 and 50 nm width at half power points) when operating in the 0.8 - 0.9 ometer wavelength range. The overall system bandwidth for ptical fibre link over several kilometers may be restricted by erial dispersion rather than the response time of the source.

rnatively, an optical source with a narrow spectral linewidth be utilized in place of the LED. The coherent emission from njection laser generally has a linewidth of 1 nm or less HP). Use of the injection laser greatly reduces the effect of erial dispersion within the fibre, giving bandwidth length ducts of 1 GHz km at 0.8 micrometer, and far higher at er wavelengths. Hence, the requirement for a system ating at a particular4 bandwidth over a specific distance will ence both the choice of source and operating wavelength.

THE OPTICAL RECEIVER CIRCUIT:

eiver noise is of great importance within optical fibre munications as it is the factor which limits receiver sensitivity therefore can dictate the overall system design.

e we consider different possible circuit arrangements which be implemented to achieve low noise preamplifier as well as her amplification (main amplification) and processing of the ected optical signal.

lock schematic of an optical fibre receiver is shown in Fig.6.3. owing the linear conversion of the received optical signal into electrical current at the detector, it is amplified to obtain a able signal level. Initial amplification is performed in the amplifier circuit where it is essential that additional noise is ot to a minimum in order to avoid corruption of the received nal. As noise sources within the preamplifier may be minant, its configuration and design are major factors in ermining the receiver sensitivity. The main amplifier provides litional low noise amplification of the signal to give an reased signal level for the following circuits.

hough optical detectors are very linear devices and do not mselves introduce significant distortion onto the signal, other mponents within the optical fibre communication system may hibit nonlinear behaviour. For instance, the received optical nal may be distorted due to the dispersive mechanisms within optical fibre.

ernatively, the transfer function of the preamplifier-main plifier combination may be such that the input signal becomes torted. Hence, to compensate for this distortion and to ovide a suitable signal shape for the filter, an equalizer is often luded in the receiver. It may precede or follow the main plifier, or may be incorporated in the functions of the plifier and filter.

Fig.6.3 the equalizer is shown as a separate element following amplifier and preceding the filter.

e function of the final element in the receiver, the filter is to ximize the received signal to noise ratio whilst preserving the ential features of the signal. In digital systems the function of er is primarily to reduce intersymbol interference, whereas in alog systems it is generally required to hold the amplitude and ase response of the received signal within certain limits. The er is also designed to reduce the noise bandwidth as well as in nd noise levels.

ally, the general receiver consisting of the elements depicted Fig.6.3 is often referred to as a linear channel because all erations on the received optical signal may be considered to mathematically linear.

4 SYSTEM DESIGN CONSIDERATION:

any of the problems associated with the design of optical fibre mmunication systems occur as a result of the unique operties of the glass fibre as a transmission medium. However, common with metallic line transmission systems, the dominant sign criteria for a specific application using either digital or alog transmission distance and the rate of information transfer.

hin optical fibre communications these criteria are directly ted to the major transmission characteristics of the fibre, nely optical attenuation and dispersion. Unlike metallic ductors where the attenuation (which tends to be the ninant mechanism) can be adjusted by simply changing the ductor size, entirely different factors limit the information sfer capability of optical fibres. Nevertheless, it is mainly se factors, together with the associated constraints within the ninal equipment, which finally limits the maximum distance may be tolerated between the optical fibre transmitter and eiver. Where the terminal equipment is more widely spaced n this maximum distance, as in long-haul telecommunication lications, it is necessary to insert repeaters at regular intervals hown in Fig.6.4. The repeater incorporates a line receiver in er to convert the optical signal back into the electrical regime ere, in the case of analog transmission, it is amplified and alized before it is retransmitted as an optical signal via a line smitter. When digital transmittion techniques are used the eater also regenerates the original digital signal in the trical regime before it is retransmitted as a digital optical

l. In this case the repeater may additionally provide alarm, rvision and engineering order wire facilities.

installation of repeaters substantially increases the cost and plexity of any line communication system. Hence a major gn consideration for long-haul telecommunication systems is maximum distance of unrepeatered transmission so that the nber of intermediate repeaters may be reduced to a imum. In this respect optical fibre systems display a marked rovement over alternative line transmission systems using allic conductors. However, this major advantage of optical e communications is somewhat reduced due to the present uirement for electrical signal processing at the repeater.

ore any system design procedures can be initiated it is ential that certain basic system requirements are specified. ese specifications include:

Transmission type; digital or analog.

Acceptance system fidelity generally specified in terms of the received BER for digital systems or the received SNR and signal distortion for analog systems.

Required transmission bandwidth.

Acceptance spacing between the terminal equipment or intermediate repeaters.

Cost

Reliability

en the desired result is a wideband, long-haul system then it necessary to make choices by considering factors such as lability, reliability, cost and ease of installation and operation ore specifications (a) - (d) can be fully determined.

milar approach must be adopted in lower bandwidth, shorter-l applications where there is a requirement for the use of cific components which may restrict the system performance.

COMPONENT CHOICE:

e system designer has many choices when selecting nponents for an optical fibre communication system. In order exclude certain components at the outset it is useful if the erating wavelength of the system is established. This decision

largely be dictated by the overall requirements for the
em performance, the ready availability of suitable reliable
nponents and cost. Hence, the major component choices are:

OPTICAL FIBRE TYPE AND PARAMETERS:

ltimode or single mode, size, refractive index profile,
enuation, dispersion, mode coupling, strength, cabling, jointing
.

SOURCE TYPE AND CHARACTERISTICS:

er or LED; optical power launched into the fibre, rise and fall
e, stability etc.

TRANSMITTER CONFIGURATION:

sign for digital or analog transmission; input impedance,
pply voltage, dynamic range, optical feedback etc.

DETECTOR TYPE AND CHARACTERISTICS:

, p-i-n, or avalanche photodiode; responsivity, response time, tive diameter, bias voltage, dark current etc.

RECEIVER CONFIGURATION:

eamplifier design (low impedance, high impedance or nsimpedance front end), BER or SNR, dynamic range, etc.

MODULATION AND CODING:

urce intensity modulation; using pulse modulation techniques either digital or analog transmission.

cision in the above areas are interdependent and may be ectly related to the basic system requirements. The potential oices provide a wide variety of economic optical fibre mmunication systems. However, it is necessary that the oices are made in order to optimize the system performance a particular application.

) MULTIPLEXING:

order to maximize the information transfer over an optical e communication link it is usual to multiplex several signals o a single fibre. It is possible to convey these multichannel nals by multiplexing in the electrical time or frequency main, as with conventional electrical line or radio mmunication, prior to intensity modulation of the optical irce. Hence, digital pulse modulation schemes may be ended to multichannel operation by TDM narrow pulses from ltiple modulators under the control of a common clock. Pulses m the individual channels are received and transmitted uentially, thus enhancing the bandwidth utilizing of a single e link.

ernatively, a no. of baseband channels may be combined by M. In FDM the optical channel bandwidth is divided into a no. nonoverlapping frequency bands and each signal is assigned of these bands of frequency. The individual signals can be racted from the combined FDM signal by appropriate ctrical filtering at the receive terminal. Hence FDM is generally formed at the transmit terminal prior to intensity modulation single optical source.

wever, it is possible to utilize a no of optical sources each erating at a different wavelength on the single fibre link. In this chnique, often referred to as wavelength division multiplexing 'DM), the separation and extraction of the multiplexed signals e. wavelength separation) is performed with optical filters (e.g. erference filters, diffraction grating filters, or prism filters).

ally, a multiplexing technique which does not involve the plication of several message signals onto a single fibre is known space division multiplexing (SDM). In SDM each signal annel is carried on a separate fibre within a fibre bundle or ultifibre cable form. The good optical isolation offered by fibres eans that cross coupling between channels can be made gligible. However, this technique necessitates an increase in e no of optical components required (e.g. fibre, connectors, urces, detectors) within a particular system and therefore not dely used.

.4 DIGITAL SYSTEMS:

e shift towards digitizing the telecommunication network llowed the introduction of digital circuit techniques and pecially, integrated circuit technology which made the smission of discrete time signals both advantageous and nomic. Digital transmission systems generally give superior formance over their analog counterparts as well as providing ideal channel for data communications and compatibility with ital computing techniques.

tical fibre communication is well suited to baseband digital nsmission in several important ways. For instance, it offers a mendous advantage with regard to the acceptable signal to se ratio (SNR) at the optical fibre receiver over analog nsmission by some 20-30 dB for practical systems. Also the e of baseband digital signaling reduces problems involved with tical source and sometimes detector, nonlinearities and nperature dependence which may severely affect analog nsmission.

common with electrical transmission systems analog signals g. system may be frequency fire transmission utilizing pulse de modulation (PCM). Encoding the analog signal into a digital pattern is performed by initially sampling the analog signal at equency in excess of the Nyquist rate (i.e. greater than twice e maximum signal frequency). Hence, the amplitude of the

stant width sampling pulses varies in proportion to the sample
es of the analog signal known as pulse amplitude modulation
M) as indicated in Fig. 6.5. The sampled analog signal is then
ntized into a number of discrete levels, each of which are
ignated by a binary code which provides the PCM signal. This
lustrated in Fig.6.5. using a linear quantizer with eight levels
seven steps so that each PAM sample is encoded into three
ary bits. The analog signal is thus digitized and may be
nsmitted as a baseband signal or alternatively demodulated by
plitude, frequency or phase shift keying. However, in practical
M systems for speech transmission, nonlinear encoding is
nerally employed over 256 levels giving eight binary bits per
mple. Hence, the bandwidth requirement for PCM
nsmission is substantially greater then the corresponding
seband analog transmission. This is not generally a case with
tical fibre communications because of the wideband nature of
e optical channel.

nlinear encoding may be implemented using a mechanism
own as companding where the input signal is compressed
fore transmission to give a nonlinear encoding characteristic
d expanded again at the receive terminal after decoding.

mpanding is used to reduce the quantization error on small nplitude analog signal levels when they are encoded from PAM PCM. The quantization error (i.e. the rounding off to the arest number discrete level) is exhibited as distortion or noise the signal (often, called a quantization noise). Companding bers the step size, thus reducing the distance between levels r small amplitude signals whilst increasing the distance between vels for higher amplitude signals. This substantially reduces the antization noise on small amplitude signal at the expense of ghtly increased quantization noise, in terms of signal amplitude, r larger signal levels. The corresponding SNR improvement for nall amplitude signals significantly reduces the overall signal gradation of the system due to the quantization process.

block schematic of a simplex (one direction only) baseband CM system is shown in Fig.6.6. The optical interface is not own but reference may be made to Fig.6.1. which illustrates e general optical fibre communication system. It may be noted om Fig.6.6.(a) that the received waveform is decoded back to AM via the reverse process to encoding, and then simply ssed through a low pass filter to recover the original analog gnal. The conversion of a continuous analog waveform into a crete PCM signal allows a no. Of analog channels to be TDM simultaneous transmission down one optical fibre link as strated in Fig.6.6(b). The encoded samples from the different annels are interleaved within the multiplexer to give a single mposite signal consisting of all the interleaved pulses. This nal is then transmitted over the optical channel. At the receive minal the interleaved samples are separated by a synchronous itch or demultiplexer before each analog signal is constructed from the appropriate set of samples.

M a no. of channels onto a single link can be used with any m of digital transmission and is frequently employed in the nsmission of data as well as with the transmission of digitized alog signals. However, the telecommunications networks imarily designed for the transmission of analog speech signals hough the compatibility of PCM with data signals has couraged the adoption of digital transmission systems.

Chapter 7

pplications and Future Developments

1 INTRODUCTION :

e of the most important technological developments during e 1980s has been the emergence of optical fibre nmunication as a major international industry. The period of id expansion in the worldwide fibre optics industry has ently slowed, as most of the need for new long-haul ecommunication capacity has already been satisfied and in ne areas a situation of overcapacity already exists. More of the us within the industry is now on markets which require orter cable lengths, with many observers feeling that local area works and wideband subscriber loops represent the next jor opportunities for dramatic growth.

hough telecommunication is the rationale for most of the rent interest in fibre optics, this was not the case during the ly days of the technology. The researchers who produced the t clad glass optical fibres in the early 1950s were not thinking using them for communications; they wanted to make them aging bundles for endoscopy. During the 1950s and 1960s, ethods for making fibre optic bundles were developed; oherent bundles for illumination, and coherent bundles for age transmission. Automobile instrument panel illumination, corative lighting, cathode ray tube faceplates, cockpit displays aircraft, and medical endoscopes were among the commercial plications.

e first low-loss (20 dB/km) silica fibre was described in a blication which appeared in October of 1970. The date of this blication is sometimes cited as the beginning of the era of fibre mmunication. Although this development did receive nsiderable attention in the research community at the time, it as far from inevitable that a major industry would evolve. The) dB/km loss figure was still too high for long-haul lecommunication systems. The fibres were fragile, and a way to otect them would have to be found. There were no suitable ght sources. Connectors with much closer mechanical lerances than their electrical or microwave counterparts would e needed and researchers did not know whether field rmination and splicing of optical cables would ever be practical. nally, there were serious doubts as to whether these omponents could ever be produced economically enough for e technology to play a major role in the marketplace.

though the technological barriers appeared formidable, the conomic potential was very significant. As a sequence, research nd development activity expanded rapidly, and a number of nportant issues were resolved during the early 1970s. Success material purification and the use of new core dopants led to rther dramatic loss reductions in silica fibres. Development of raded-index multimode fibres provided a favorable combination f transmission bandwidth and source coupling efficiency. esearchers learned to protect the fibres with polymer coatings nd to cable them without breakage. Diode lasers were operated ontinuously at room temperature for the first time and high diance LEDs, capable of efficient coupling to multimode fibres, ere produced. The arc fusion method for splicing fibres and a ariety of connector designs were proved in practice.

uring the middle and late 1970's, the rate of progress towards arketable products accelerated as the emphasis shifted from esearch to engineering. Fibres with losses approaching the ayleigh limit of 2 dB/km at a wavelength of 0.8 micrometer, 0.3 B/km at 1.3 micrometer and 0.15 dB/km at 1.55 micrometer ere produced in the laboratory. Microbend problems were vercome through the use of improved fibre coatings and cabling nniques. Rugged cables and multifibre connectors were duced for field installation. Room temperature threshold rents for gallium aluminum arsenide (GaAlAs) lasers operating he 0.8 micrometer to 0.85 micrometer spectrum region were luced to the 20 - 30 mA range, and projected lifetimes in the 0,000 to 1,000,000 hour range were claimed for both lasers d LEDs. Light sources and improved photodetectors which erated hear 1.3 micrometer were developed to take advantage the low fibre loss and dispersion in this "longer wavelength gion". Encouraging data on the reliability for longer wavelength sers and LEDs fabricated in the indium gallium arsenide osphide (InGaAsP) quartenary alloy system were also obtained.

nprovements in component performance, cost and reliability by 980 led to major commitments on the part of telephone ompanies. Fibre soon became the preferred transmission edium for long-haul trunks. Some early installations used 0.8 icrometer light sources and graded-index multimode fibre, but y 1983, designers of intercity links were thinking in terms 1.3 icrometer, single mode systems. The single mode fibre, used in onjunction with a 1.3 micrometer lasers provides a bandwidth dvantage which translates into increased. repeater spacings for igh-data-rate systems.

Data rates for installed fibre optic systems have recently moved nto the gigabit per second range. Such systems use the pectrally pure distributed-feedback lasers to minimize fibre ispersion effects. Fibres design for low dispersion at the 1.55 nicrometer wavelength, which corresponds to minimum fibre oss, are now commonly used in long distance transmission. The use of wavelength multiplexing o further increase the fibre nformation capacity is becoming more wide spread. Undersea ibre optic cables have linked Japanese Islands for several years, and the first transoceanic fibre systems will soon be put into service.

n contrast to the recent expansion in long-haul systems, the potential of fibre optics in other areas is only beginning to be realised. After a slow start, fibre optic networks for computer systems and offices are becoming more prominent. Fibre optics is now used in numerous military systems. In the telephone system, the use of fibre optics for interconnecting central offices within a metropolitan area and for lower areas in the switching h hierarchy is still increasing rapidly. Fibre links to the home ve only been used in demonstration projects, since economics l favours conventional electrical wire and cable. However, any observers believe that national telephones systems will entually be upgraded to handle video bandwidths by using re optics. These wideband subscriber loop systems would ovide access on a switched basis to services such as cturephone, video entertainment, electronic components, must crease considerably before wide spread installation of these oadband services will become economically feasible.

order to appreciate the many areas in which the application of ntwave transmission via optical fibres may be beneficial, it is eful to review the advantages and specie features provided by s method of communication. The primary advantages obtained ing optical fibres for line transmission are summarised as lows:

- enormous potential bandwidth;
- small size and weight;
- electrical isolation;
- immunity to interface and crosstalk;
- signal security;

(f) low transmission loss;

(g) raggedness and flexibility;

(h) system reliability and ease of maintenance;

(i) potential low cost;

Although this list is very impressive, it is not exhaustive and several other attributes associated with optical fibre communications have become apparent as the technology has developed. Perhaps the most significant are the reduced power consumption exhibited by optical fibre systems in comparison with their metallic cable counterparts and their ability to provide for an expansion in the system capability often without fundamental and costly changes to the system configuration. For instance, a system may be upgraded by simply changing from an LED to an injection laser source, by replacing a p-i-n photodiode with an APD detector, or alternatively by operating at a longer wavelength without replacing the fibre cable.

The use of fibres for optical communication does have some drawbacks in practice. Hence to provide a balanced picture these disadvantages must be considered. They are:

(a) The fragility of the bare fibres;

b) The small size of the fibres and cables which create some difficulties with splicing and forming connectors;

c) Some problems involved with forming low T-couplers;

d) Some doubt in relation to the long term reliability of optical fibres in the presence of moisture;

e) And independent electrical power feed is required for any repeater;

f) New equipment and field practices are required;

g) Testing procedures tend to be more complex.

A number of these disadvantages are not just inherent to optical fibre systems but are always present at the introduction of a new technology. Furthermore, both continuing developments and exercise with optical fibre systems are generally reducing the other problems.

The combination of the numerous attributes and surmountable problems makes optical fibre transmission a very attractive proposition for use within national and international telecommunication networks.

o date applications for optical fibre systems in this area have roved the major impetus for technological developments in the eld.

n this chapter we consider current and potential applications of ptical fibre communication systems together with some likely iture developments in the general area of optical transmission nd associated components. the discussion is primarily centered round application areas including the public networks, civil and onsumer, industrial and computer systems.

.2 PUBLIC NETWORK APPLICATIONS:

he public telecommunications network provides a variety of pplications for optical fibre communication systems. It was in nis general area that the suitability of optical fibres for line ransmission first made an impact. The current plans of the major dministrations around the world feature the installation of ncreasing numbers of optical fibre links as an alternative to oaxial and high frequency pair cable systems.

a) **TRUNK NETWORK:**

The trunk or toll network is used for carrying telephone traffic between major contributions. Hence there is generally a requirement for the use of transmission systems which have a high capacity in order to minimize cost per circuit. The transmission distance for trunk systems can vary enormously from 20 km to over 3000 km, and occasionally to as much as 1000 km. Therefore, transmission systems which exhibit low attenuation and hence give a maximum distance of unrepeated operations are the most economically viable. In this context optical fibre systems with their increased bandwidth and repeater spacings offer a distinct advantage.

It is also observed that optical fibre systems show a significant cost advantage over coaxial cable systems and compete favorably with millimetric waveguide systems at all but the highest capacities.

b) **JUNCTION NETWORK:**

The junction or interoffice network usually consists of routes within major conurbations over distances of 5 - 20 km. However the distribution of distances between switching centers (telephone exchanges) or offices in the junction network of large urban areas varies considerably for various countries. It may be observed that the benefits of long unrepeated transmission distances offered by optical fibre systems are not as apparent in the junction network due to the generally shorter link lengths. Nevertheless optical fibre junction systems are often able to operate using no intermediate repeaters whilst alleviating duct congestion in urban areas.

c) LOCAL AND RURAL NETWORKS:

The local and rural network or subscriber loop connects telephone subscribers to the local switching centre or office. Possible network configurations are shown in Fig.7.1 and include a ring, tree and star topology from the local switching centre.

In a ring network shown in Fig.7.1(a) any information fed into the network by a subscriber passes through all the network nodes and hence a number of transmission channels must be provided between all nodes. This may be supplied by TDM ystem utilizing a broadband transmission medium. In this case nformation addressed to a particular subscriber node.

he tree network, which consists of several branches as indicated n Fig.7.1(b), must also provide a number of transmission hannels on its common links. However, in comparison with ring network it has advantage of greater flexibility in relation to opology enlargement. Nevertheless in common with the ring network, the number of subscriber is limited by the transmission capacity of the links used.

n contrast, the star network illustrated in Fig.7.1(c) provides a separate link for every subscriber to the local switching center. Hence the amount of cable required is considerably increased over the ring or tree network, but is offset by enhanced reliability and availability for the subscribers. In addition simple subscriber equipment is adequate (i.e. no TDM) and network expansion is straight forward. Thus virtually all local and rural telephone networks utilize a star configurations based on copper conductors (twisted pairs) for full duplex speech transmission.

There is substantial interest in the possibility of replacing the existing narrowband local and rural network twisted pairs with optical fibres. These can also be utilized in the star configuration to provide wideband services (videophone, television, stereo, hi-fi, data etc.) to the subscriber together with the narrowband speech channel. This would reduce the quantity of fibre cable required for subscriber loops. Furthermore, it is predicted that the cost of optical fibre cable may be reduced towards the cost of copper twisted pairs with the large production volume required for the local and rural networks.

d) SUBMERGED SYSTEMS:

Undersea cable systems are an integral part of the international telecommunications network. They find application on shorter routes. On longer routes, the provide route diversity in conjunction with satellite links. The no. of submerged cable routes and capacities are steadily increasing and hence there is a desire to minimize the cost per channel. In this context digital optical fibre communication systems appear to offer substantial advantage over current analog FDM and digital PCM coaxial cable systems.

High capacity coaxial cable systems require high quality, large diameter cable to overcome attenuation, and still only allow repeater spacings of around 5 km. By comparison, it is predicted that a single mode optical fibre systems operating at 1.3 or 1.55 micrometer will provide repeater spacings of 25 - 50 km and eventually even longer.

7.3 MILITARY APPLICATIONS:

In these application, although economies are important, there are usually other, possibly overriding, consideration such as size, weight, deployability, survivability (in both conventional and nuclear attack) and security.l The special attributes of optical fibre communication systems therefore often lend themselves to military use.

(a) MOBILES:

One of the most promising areas of military application for optical fibre communications is within military mobiles such as aircraft, ships and tanks. The small size and weight of optical fibres provide an attractive solution to space problems in these nobiles which are increasingly equipped with sophisticated electronics.

b) COMMUNICATION LINKS:

The other major area for the application of optical fibre communications in the military sphere includes both short and long distance communication links.

Short distance optical fibre systems may be utilized to connect closely spaced items of electronic equipment in such areas as operations rooms and computer installations.

There is also a requirement for long distance communication between military installations which could benefit from the use of optical fibres. In both these cases advantage may be gained in terms of bandwidth, security and immunity to electrical interference and earth loop problems over conventional copper systems.

Other long distance applications include torpedo and missile guidance, information links between military vessels and maritime, towed sensor arrays. In these areas the available andwidth and long unrepeatered transmission distances of ptical fibre systems provide a solution which is not generally vailable with conventional technology.

n summary, it appears that confidence is being established in his new technology such that its widescale use in military pplications in the future is ensured.

7.4 CIVIL AND CONSUMER APPLICATIONS:

(a) CIVIL:

The introduction of optical fibre communication systems into the public network has stimulated investigation and application of these transmission techniques by public utility organizations which provide their own communication facilities over moderately long distances, e.g. these transmission techniques may be utilized on the railways and along pipe and electrical power lines. In these applications, although high capacity transmission is not usually required, optical fibres may provide a relatively low cost solution; also giving enhanced protection in harsh environments.

Optical fibres are eminently suitable for video transmission. Thus optical fibre systems are starting to find use in commercial television transmission. These applications include short distance links between studio and outside broadcast vans, links between studios and broadcast or receiving aerials, and close circuit television (CCTV) links for security and traffic surveillance.

In addition, the implementation of larger networks for cable and common antenna television (CATV) has demonstrated the successful use of optical fibre communications in this area where it provides significant advantages, in terms of bandwidth and unrepeatered transmission distance, over conventional video links.

7.5 INDUSTRIAL APPLICATIONS:

Optical fibre systems offer reliable telemetry and control communications for industrial environments where EMI and EMP cause problems for metallic cable links.

Furthermore, optical fibre systems provide a far safer solution than conventional electrical monitoring in situation where explosive or corrosive gases are abundant. Hence, the increasing utomation of process control, which is making safe, reliable communication in problematical environments essential, in providing an excellent area for the application of optical fibre communication systems.

(a) **SENSOR SYSTEMS:**

It has been indicated that optical fibre transmission may be advantageously employed for monitoring and telemetry in industrial environments. The application of optical fibre communications to such sensor systems has stimulated much interest, especially for use in electrically hazardous environments where conventional monitoring is difficult and expensive.

There is a requirement for the accurate measurement of parameters such as liquid level, flow rate, position, temp. and pressure in these environment which may be facilitated by optical fibre systems.

Electro-optical transducers together with optical fibre telemetry systems offer significant benefits over purely electrical systems in terms of immunity to EMI and EMP as well as intrinsic safety in the transmission to and from the transducer. However, they still utilize electrical power at the site of the transducer which is also often in an electrically problematical environment.

(b) CONSUMER:

A major consumer application for optical fibre systems is within automotive electronics. Work is progressing within the automotive industry toward this end together with the use of microcomputers for engine and transmission control of convenience features such as power windows and seat controls. Optical fibre communication links in this area provide advantages of reduced size and weight together with the elimination of EMI.

Furthermore, it is likely they will reduce costs by allowing for an increased number of controls signals in the confined space presented by the steering column and internal transmission paths within the vehicle through multiplexing of signals onto a common optical highway.

Other consumer applications are likely to include home appliances where together with microprocessor technology, optical fibres may be able to make an impact by the late 1990's. However, as with all consumer equipment, progress is very dependent on the instigation of volume production and hence low cost. This is the factor which is likely to delay wider application of optical fibre systems in this area.

7.6 COMPUTER APPLICATIONS:

Modern computer systems consist of a large number of interconnections. These range from lengths of a few micrometers to perhaps thousands of kms for terrestrial links in computer networks. The transmission rates over these interconnections also cover a wide range from around 100 bit/s for some teletype terminals are several to hundred M bits/s for the on-chip connection.

Optical fibres are starting to find application in this hierarchy where secure, interference free transmission is required.

At present, a primary potential application for optical fibre communications occurs in inter equipment connections. These provide noise immunity, security and removal of earth loop problems, together which increased bandwidth and reduced cable size in comparison with conventional coaxial cable computer systems interconnections.

The interequipment connection topology for a typical mainframe computer system (host computer) is illustrated in Fig.7.2. The I/O to the host computer is generally handled by the processor, often called a data channel, which is attached to the main storage of the host computer. It service all the I/O requirements for the system allowing concurrent instruction processing by the CPU. Each data channel coatings an interface to a no. of I/Ok control units. These, in turn, controls the I/O devices (e.g. teletypes, visual display units, and printers).

When metallic cables are used, the interface between the data channel and the control units comprises a large no of parallel coaxial lines incorporated into cables. An attractive use of optical fibre interconnection is to serialize this channel interface using a multiplex system. This significantly reduces cable and connector bulk and improves connection reliability.