37 Optical Fibres in Power Systems

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37.1 Introduction

In the 1980s when optical fibres were in their infancy, they were primarily used by the telecommunications industry to replace the copper lines normally used in telephone networks and the long-haul coaxial trunk links between telephone exchanges. Nowadays, this cost-effective medium with its high transmission bandwidth, low attenuation and relative immunity to ElectroMagnetic Interference (EMI) has become increasingly advantageous in the fields of data communications, Local Area Networks (LANs), Urban Broadband Service Networks (UBSNs), Community Antenna TeleVision (CATV), and control applications. Fibre (especially in digital communications) overcomes the problems of different earth potentials between locations, is unaffected by the electric fields found in high-voltage environments, lightning strikes and other electromagnetic interference (e.g. the high magnetic fields caused by transformers and motors etc.). As the data transfer rates of local area networks increase, fibre becomes increasingly attractive and more economically viable. In terms of pence per metre per unit bandwidth, in an increasing number of applications, fibre as a transmission medium is the obvious choice.

In the electrical power industry, these advantages have meant that fibre optics and the technology of fibre optics has replaced normal cable systems and is now widely used for a variety of purposes. The adoption of fibre optics by the telecommunications technology is already well advanced and the realisation of reliable optical data transmission for protection and control has been convincingly demonstrated. Furthermore, research into optical fibre based parameter sensing has reached the stage that properly engineered systems are now available and their integration into optical fibre networks has produced a purely optical monitoring and transmission system.

This chapter of the *Electrical Engineers' Reference Book* contains a brief introduction to optical propagation in fibres followed by a description of the technology of cabling and interconnecting fibres. The present status of communication and telemetry along high voltage transmission lines is discussed and progress towards the optical fibre monitoring of power equipment in substations and elsewhere on a power system is described.

37.2 Optical fibre fundamentals

37.2.1 Optical propagation in fibres: ray theory

Strictly speaking, one should not use the term 'light' when referring to most optical fibre transmission systems. Normally, near infra-red radiation (with a wavelength in the range 780–1550 nm), derived from a light-emitting diode (LED) or semiconductor laser, is employed and as such, the radiation is not usually visible to the naked eye. However, 'light' is the term commonly employed, and is used here.

Light propagation through an optical fibre depends upon total internal reflection at the interface between two transparent materials with high and low refractive indices. *Figure 37.1* shows that as a ray approaches a boundary within a transparent medium, it can be totally internally reflected at the high–low refractive index interface, and will be guided along the high refractive index medium. As the angle at which the approaching ray increases, a critical value (θ_2) may be reached beyond which light 'leaks' out of both media.

The most basic type of optical fibre can be developed from the above principle by using a cylindrical geometry. Rays beyond the critical angle are trapped within the fibre core and travel down the fibre.

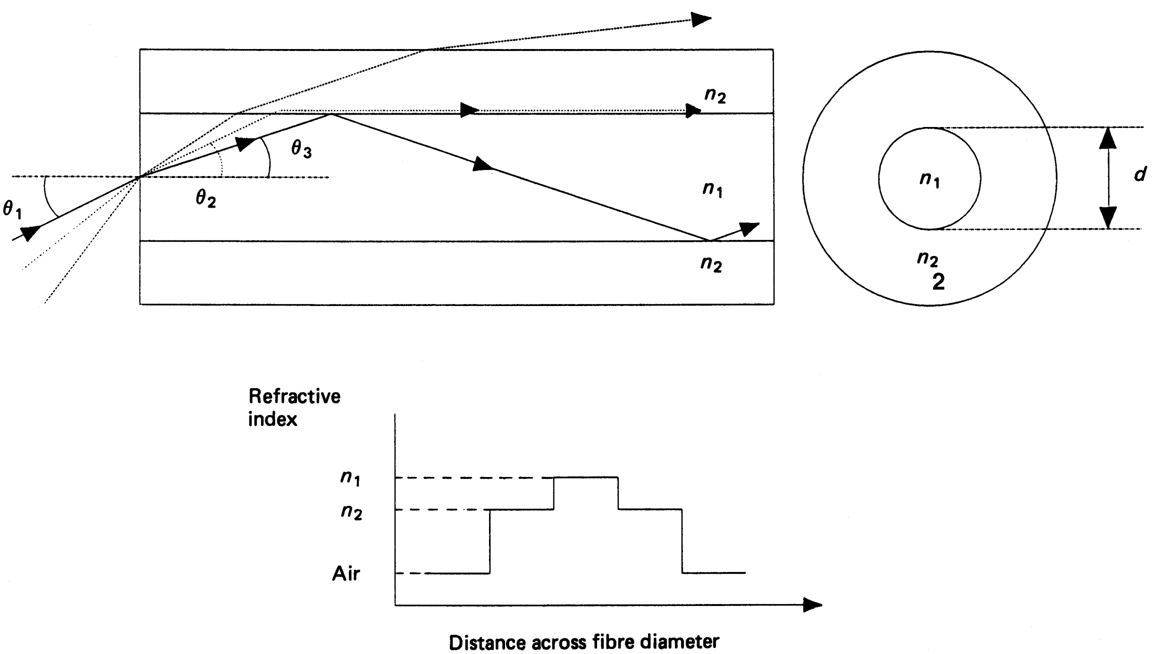

Figure 37.1 Ray diagram for multimode step index fibre

37.2.2 Acceptance angle and numerical aperture

The acceptance angle is a function of the refractive indices of the core and the cladding materials. The sine of the acceptance angle is called the numerical aperture.

Consider the fibre illustrated in *Figure 37.1*, having a circular core of diameter *d*, and a uniform refractive index n_1, surrounded by a cladding layer of uniform refractive index n_2. Light launched into the core at angles θ_1 will be propagated within the core at angles θ_3 up to a maximum value θ_2 to the axis. Light at angles greater than θ_2 will not be internally reflected and will be refracted into the cladding. The maximum launch or acceptance angle θ_1 can be expressed as a function of the Numerical Aperture (NA), where:

$$\mathrm{NA} = (n_1^2 - n_2^2)^{1/2} = \sin\theta_1 = n_1 \sin\theta_2 \qquad (37.1)$$

Note that reciprocity dictates that what is true for light entering the core of a fibre is also true for light exiting. The fibre core diameter (d), the NA, and the operating wavelength (λ) are often used together in a single parameter, known as the normalised frequency, waveguide parameter, or fibre parameter (V), which is of importance in characterising all fibres:

$$V = \frac{\pi d}{\lambda} \cdot \mathrm{NA} \qquad (37.2)$$

37.2.3 Basic fibre types, modes, mode conversion and bandwidth

Two types of fibre are used for optical transmission (step-index and graded-index) and two modes (single-mode and multimode).

37.2.3.1 Single-mode fibre

Single-mode fibre (also referred to as fundamental or mono-mode fibre) will permit only one mode to propagate and, as such, cannot suffer mode delay differences. Single-mode fibres are capable of wide bandwidths (e.g. >40 GHz) and are, therefore, ideally suited for long-haul and high capacity circuits. Single-mode fibre are used almost universally in telecommunications over 1 km or so and are generally used at the 1300 nm and 1550 nm wavelengths where attenuation is low and sources and detectors are available.

37.2.3.2 Multimode fibre

In comparison to single-mode fibre, multimode fibre has a relatively large core (typically 50–60 µm) and a high numerical aperture. As the name implies, multimode fibres are capable of propagating more than one mode at a time and they are ideally sited for high bandwidth (i.e. a few GHz) and medium haul applications. Multimode fibre has become increasingly popular in the last decade and is now widely used in high-speed (e.g. 100 Mbit/s) local area networks, and 62.5/125 (core/cladding diameters in µm) fibre was specified as the first choice for the ANSI X3T9.5 committee Fibre Distributed Data Interface (FDDI) standard.

37.2.3.3 Step index fibre

A small glass fibre in air has a large critical angle of approximately 42°. This enables propagation along paths that are much longer than the axial route but attenuation and dispersion losses are substantially increased. By making the fibre core extremely narrow (e.g. 150 µm) and enclosing it in a cladding material whose refractive index is only slightly lower than the fibre, will not only reduce the critical angle but also reduce the losses.

Waveguide theory shows that the total number of modes which can be sustained in a step index fibre is given by

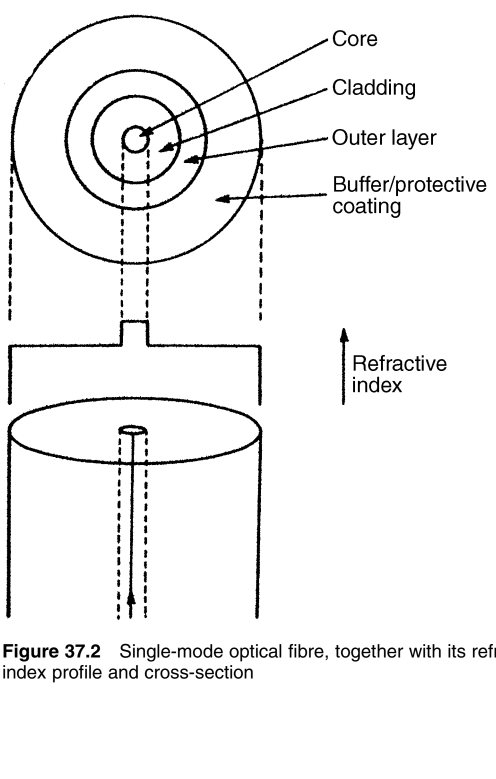

Figure 37.2 Single-mode optical fibre, together with its refractive index profile and cross-section

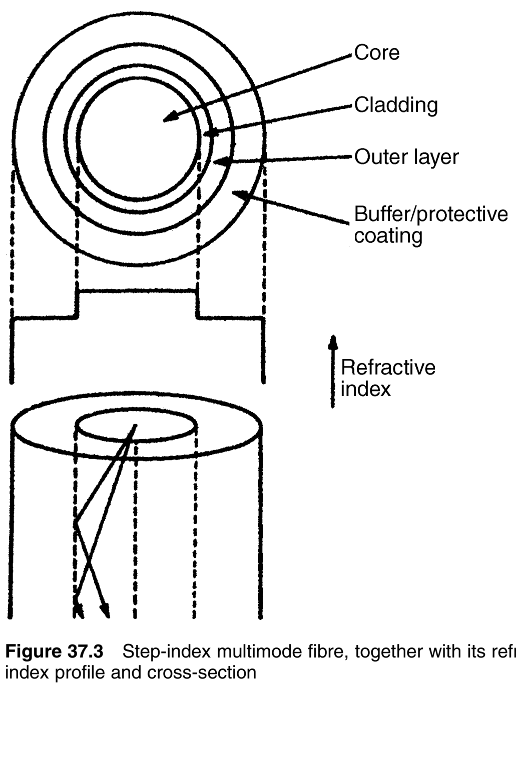

Figure 37.3 Step-index multimode fibre, together with its refractive index profile and cross-section

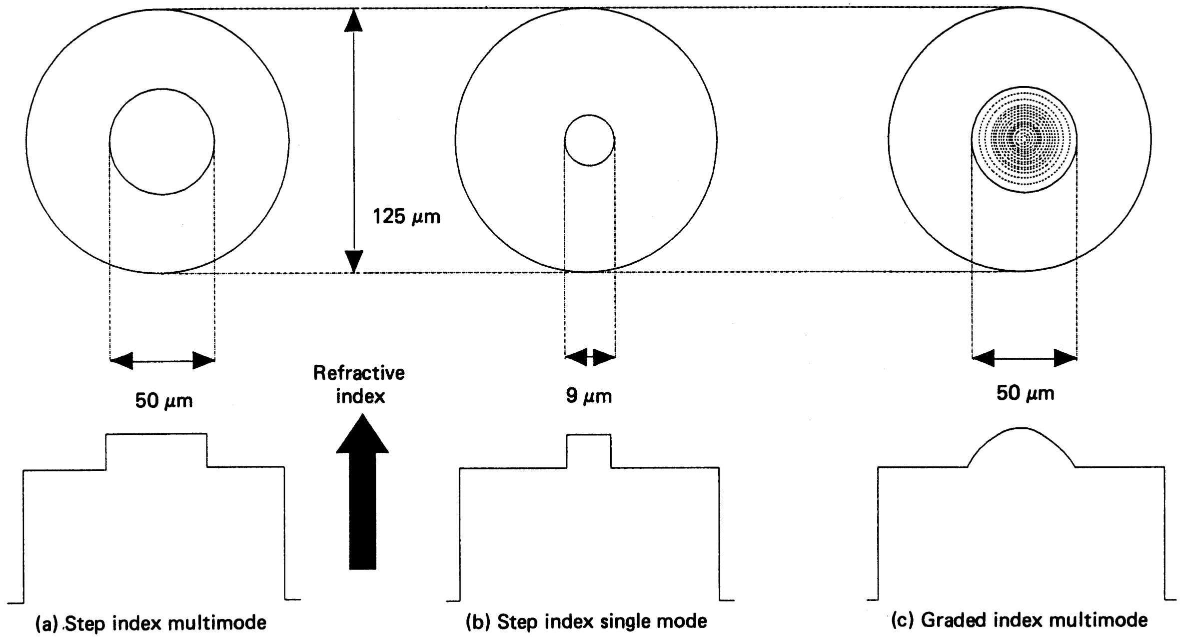

Figure 37.4 Refractive index profiles (typical dimensions shown)

$N = V^2/2$. Modes can be visualised as rays propagating at differing angles to the fibre core. Discrete and definable modes only can propagate because of the geometrical constraints of the fibre, and are analogous to modes in hollow metallic waveguides used at microwave frequencies (ca. 1–100 GHz). Typical multimode fibres, with core diameters of 50–200 μm propagate 100–1000 modes. It is not necessary for the general user of fibres, however, to understand the mathematics of propagation.

In a multimode step index fibre (*Figure 37.4*(*a*)), no matter however careful one is to launch a single mode, conversion between modes or ray angles is inevitable because of bending and fibre imperfections. This is a great drawback for such fibres, because different modes travel at different speeds down the fibre, causing different arrival times at the receive end. The difference in transit time between the extreme ray paths for a multimode step index fibre of length L is given by:

$$\Delta T_{\text{intermodal}} = \frac{L}{c}(n_1 - n_2) \qquad (37.3)$$

where c is the velocity of light. The difference in transit times causes a sharp pulse of launched light to become spread at the distant end, limiting the bandwidth of a system. Typically, for an all-silica based fibre of NA ≈ 0.2, pulse spreading is of the order of 50 ns/km, and is inversely proportional to the length of the system; the longer the system, the lower the bandwidth.

As V is reduced, less guided rays or modes can be supported, and when $V < 2.405$, only a single waveguide mode can propagate. Such single mode fibres have a core diameter which is comparable with the wavelength of light (d is commonly 8–10 μm for telecommunications fibres see *Figure 37.4*(*b*)), making fibre-fibre and fibre-device interconnection more difficult and generally less efficient than for multimode fibres. Intermodal dispersion does not occur, and bandwidths can be very high.

It should be noted, however, that a fibre which is single mode at, say, 1300 nm will not necessarily be single mode at 850 nm or below. V increases as the wavelength decreases, and will generally be greater than 2.405 at 850 nm. A wavelength known as the cut-off wavelength is an important manufacturing parameter defining the onset of multimode behaviour.

Simple ray optics cannot describe the propagation of energy through a single mode fibre very well as it is difficult to depict a single ray being guided. Mathematical modelling of single and multimode fibre may be achieved by solving Maxwell's equations with boundary conditions defined by fibre geometry and wavelength. This involves Bessel functions and is beyond the scope of this introduction. One of the important results of mathematical modelling, however, is that optical power is not confined to the core alone, but extends appreciably into the cladding region—the power distribution is approximately Gaussian. The extent of cladding penetration is dependent primarily on refractive index difference and wavelength.

37.2.3.4 Graded index fibre

In an effort to overcome bandwidth and connection difficulties, a fibre type (known as graded index fibre) was developed as an intermediate step between index multimode and step index single mode Although previously only used for long-haul (i.e. trunk) networks, graded index fibres are nowadays frequently being employed in local networks at the 850 and 1300 nm wavelengths.

The principle behind graded index fibre is shown in *Figure 37.4*(*c*). Here, the refractive index profile is graded, and ray paths are curved as the rays are continually refracted (*Figure 37.5*). Rays which travel closer to the core-cladding boundary are in a region of lower refractive index, and will, therefore, travel faster than those in the denser central core area. The overall effect, given the appropriate refractive index profile, is that rays travelling

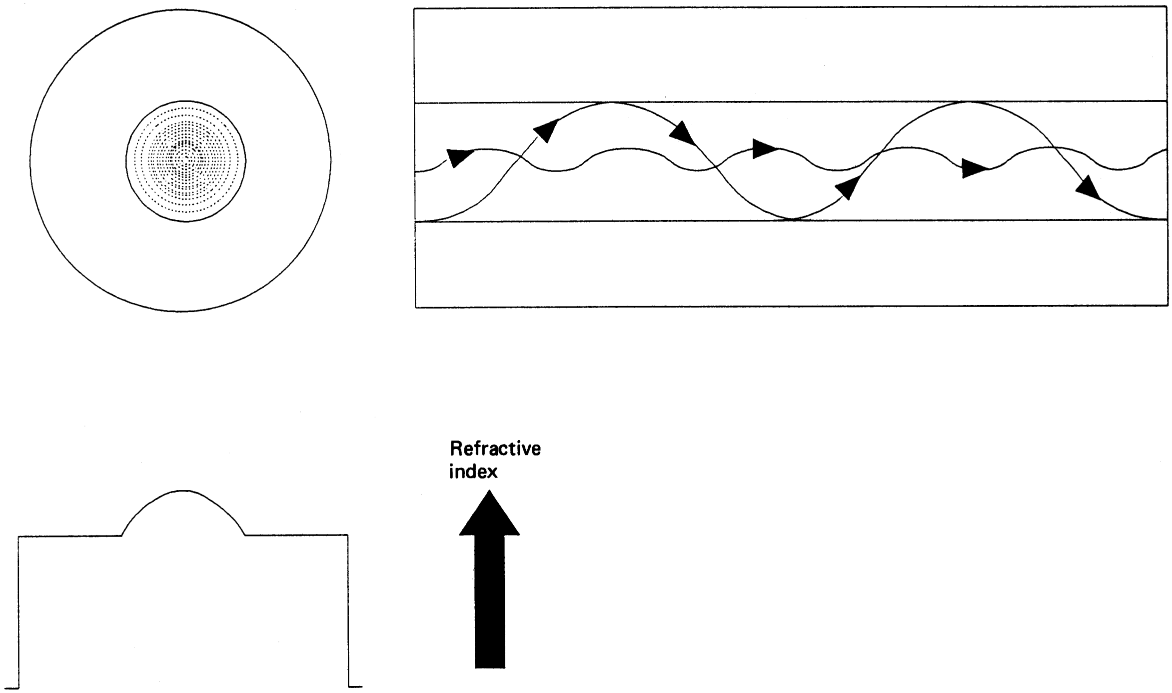

Figure 37.5 Typical ray paths for graded index fibre

different paths arrive at the far end at approximately the same time. The exact index profile to minimise dispersion effects is dependent on the composition of the fibre and the operating wavelength, but is approximately parabolic.

37.2.3.5 Material dispersion

As the refractive index of a glass prism varies with wavelength, different wavelengths (from an LED and even a narrower linewidth laser source) travelling at different velocities down the fibre will arrive at different times. This causes an energy loss which is called material dispersion, and which predominates in single-mode fibres. The speed of light propagating in the fibre is inversely proportional to the refractive index of the propagating medium, and the refractive index of silica drops from 1.46 to 1.44 between 600 and 200 nm, approximately. The variation of the material dispersion parameter $M(\lambda)$ with respect to wavelength is given by

$$M(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_1}{d\lambda^2} \text{ (ps/nm/km)} \qquad (37.4)\Leftarrow$$

and is shown for silica in *Figure 37.6*. Pulse broadening in a particular case can be calculated by multiplying the value of $M(\lambda)$ by both the length of fibre in question and the linewidth of the source in nanometres. An LED source, for example, operating at 850 nm, and with a linewidth of 40 nm will give pulse spreading of some 4 ns/km, and this spreading may be significantly reduced by using a laser source with much reduced linewidth of typically 4 nm or less. The bandwidth length product is generally specified for multimode telecommunications and data communications grade fibres, and is generally of the order of a few hundred megaherz-kilometre product.

Note that $M(\lambda)$ goes through zero at approximately 1300 nm. First generation telecommunication systems operated with multimode fibre in the region of 850 nm, called the first window (where many sources and detectors were available, and fibre losses were acceptable at approximately 3 dB/km or greater), but second generation (or second window) systems operate at 1300 nm and can exploit the dispersion zero to give high bandwidths. At 1300 nm, losses can also be substantially below 1 dB/km, giving far greater transmission distances before regeneration is required. A third window at 1550 nm, at which attenuation can be less than 0.2 dB/km, is now widely used throughout the telecommunications industry. *Figure 37.7* shows nominal attenuation

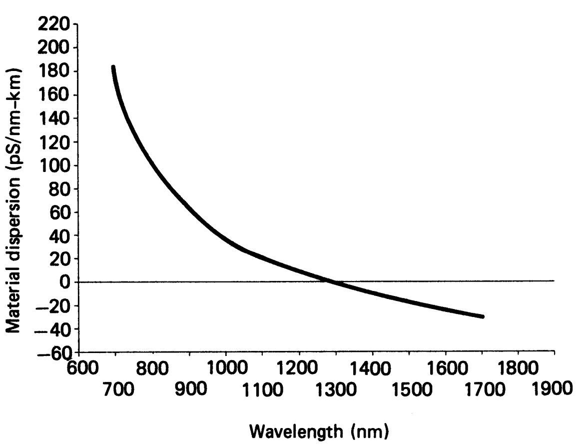

Figure 37.6 Material dispersion versus wavelength for silica

Table 37.1 Fibre types

Type	*Core/cladding diameter* (μm)	*Typical attenuation* (dB/km)	*Typical bandwidth* (MHz/km)	*Applications*
All silica				
Step index multimode	50/125–200/300	3–10 at 850 nm	20	Data links
Graded index multimode	50/125–100/140	3 at 850 nm <1 at 1300 nm	200–1000	Telecommunications, data links
Single mode	5/125–10/125	<0.5 at 1300 nm <0.25 at 1550 nm	>1000	Telecommunications, high speed data links
Other				
PCS	50/125–200/300	5–50 at 850 nm	20	Data links
All plastic	50/100–50/1000	>100	<20	Light pipes, electrical isolation, short data links

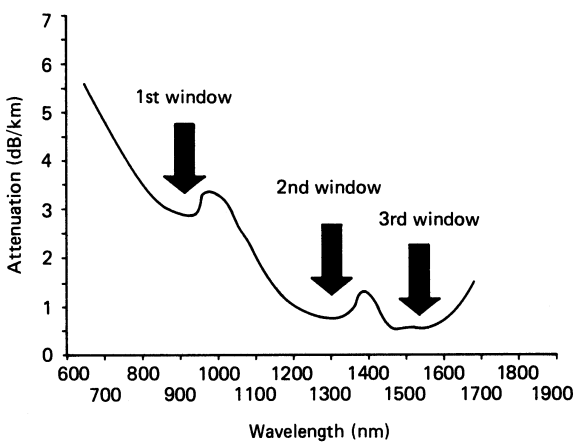

Figure 37.7 Nominal attenuation versus wavelength for silica fibre (showing operating windows)

versus wavelength for all-silica fibre, and indicates operating windows.

By modifying the chemical composition of single-mode fibre, and the geometry of the core and cladding, the zero of $M(\lambda)$ can be moved to 1550 nm (the third window), which gives further advantages in terms of attenuation, as is explained in the next section. $M(\lambda)$ can also be flattened to give near zero dispersion at both 1300 and 1550 nm, but this is achieved only at the expense of an attenuation penalty and is not common practice. (High-bandwidth systems are generally achieved by using very narrow spectral linewidth lasers.)

The above treatise generally refers to all-silica fibres which are widely used in the telecommunications industry. The two other common types are Plastic-Clad-Silica (PCS) and all-plastic fibres.

PCS fibres have an all-silica core and a polymer based cladding (commonly a silicone resin) which also serves as a protective layer. They are generally less expensive to manufacture, but are characterised by higher attenuation and lower bandwidth (as they have a step index) than all-silica fibres, but are used for relatively short data links.

All-plastic fibres, generally manufactured from Poly-Methyl-MethAcrylate (PMMA) are the least expensive type. They currently have the highest attenuation of commonly available fibres, and are generally step index. They have application as 'light pipes' over short distances (i.e. a few metres).

37.2.4 Fibre protection

37.2.4.1 Microbending losses

If a fibre is subjected to mechanical stress, local discontinuities can be introduced. Curvatures of the fibre involving axial displacements of a few millimetres may cause a light ray on the outside radius of a bend to approach or exceed the optical angle and light may be lost through the cladding and also result in additional attenuation losses. These are referred to as microbending losses, or in the case of macroscopic axial deviation of the fibre from a straight line, macrobending losses. To overcome these problems, high-density laser diodes are frequently used.

A guide to the susceptibility to microbending of a particular multimode fibre type can be made by using the following 'figure of merit' (this is based on step-index analysis but can be used as a general guide):

$$\gamma = K \frac{d_{\text{core}}^4}{\text{NA}^6 d_{\text{cladding}}^6} \qquad (37.5)$$

An optical fibre must therefore be protected against radial forces. This is accomplished by mechanically decoupling the fibre from its immediate surroundings, and is commonly achieved by surrounding the fibre with a very low-elastic modulus material such as a silicone rubber followed by an extruded polymer layer (termed a 'tight' packaged fibre), or by encapsulating the fibre loosely within a polymer tube ('loose' packaging). The type of protection depends upon the particular application.

Note that the pristine surface of an all-silica fibre is always protected during manufacture by a thin UltraViolet (UV) radiation or heat cured polymer layer.

37.2.5 Fibre strength

37.2.5.1 Proof testing

Silica is, to all intents and purposes, purely elastic and has no plastic deformation prior to tensile failure. The strain at which a fibre breaks is dictated by its surface condition.

Minute flaws, 1 µm or less in size, and generally at the surface, act as stress raising points and the effective stress at the flaws may be much higher than that directly imposed. The flaws are generally created during fibre fabrication, and are caused by (inevitable) contamination. Although all manufacturers take immense care to produce fibre in scrupulously clean conditions, some particles (from the hot furnace element, for example) inevitably reach the fibre. A flaw 1 µm deep will cause failure at about 1% strain.

The stress intensity at a crack flaw tip can be explained by classic Griffith crack theory. Local stress intensification can be described by an intensification factor K_1, which reaches a critical value K_{IC} when fracture occurs:

$$\sigma_f = \frac{K_{IC}}{Ya^{1/2}} \tag{37.6}$$

where σ_f is the applied stress, a the crack depth, and Y is a geometric factor. σ_f is always less than the theoretical breaking stress for the material in question.

Flaws can be introduced easily, and that is one reason why fibres are coated, within seconds of being drawn from the melt, with a UV curing polyurethane acrylate or a thermally curing silicone material to a diameter of 250 µm.

Strength is guaranteed by subjecting all delivered fibre to a proof or screen test, commonly 0.5–1% strain. The strain is applied after production by passing the fibre continuously through two capstans, and loading the section in between.

Fibre manufacturers will generally specify the minimum radius to which a fibre should be bent (about 50 mm for telecommunications fibres). There are two reasons; a bend causes tensile strain on the outer edge, and severe bending will cause light leakage.

37.2.5.2 *Static fatigue*

Static fatigue is caused by the combined action of tensile stress and moisture on a fibre surface, and causes weakening over time. Because glass is a supercooled liquid, it has an amorphous or non-crystalline structure. The lattice is quite open and water (in the form of OH^- ions), if it reaches the fibre surface, destroys silica–silica surface bonds. The energy for this to happen is supplied by external (tensile) stress, and the rate increases with the applied stress.

Although there has been much research on the phenomenon, it is still not fully understood. The generally accepted model is for a growth law of the form:

$$V = AK_I^n \tag{37.7}$$

where V is the velocity of crack growth, K_I is the stress intensification factor mentioned above, and A and n are constants. If the above is combined with the Griffith equation and integrated, the following result is achieved:

$$t = BS_I^{n-2}\sigma_f^{-n} \tag{37.8}$$

where t is the time to failure, S_I is the inert strength of the material (the stress required to produce instant failure or failure in the absence of crack growth), B is a constant related to both a and n, and σ_f is the applied stress.

The time to failure is thus finite and inversely proportional to the nth power of the applied stress or strain. Values of n usually lie in the range 14–30, the higher the better. The lowest value corresponds to 100% relative humidity and higher values to dry laboratory conditions. The time to failure is thus extremely sensitive to changes in both σ_f and n, and accurate values are needed to enable cable lifetime to be reliably extrapolated. During cable design, manufacturers take account of static fatigue; to ensure that design lifetimes are achieved, maximum installation and service loads must be adhered to.

37.3 Optical fibre cables

37.3.1 General

Unlike copper cables, where the performance of conductors is largely immune to bending and tensile forces, optical cables are designed to protect the contained fibres. This does not suggest that properly designed fibre cables are fragile, but merely that care has been taken during both design and manufacture. Optical cables have and are being installed in environments that are as harsh as those experienced by copper cables—for example, sub-sea, between high-voltage electricity pylons, and in the military environment.

Suppliers of optical cables use many different manufacturing techniques and, although it is beyond the scope of this introduction to include them all, the most common types encountered in data communications and telephony are covered.

37.3.2 Low fibre count cables

The requirement for low fibre count cables is generally for a cost-effective, compact construction which provides a package with ample mechanical protection. Typical uses are for inbuilding telephony, data and control links, rack-to-rack links, and electrical isolation.

Both 'tight' and 'loose' designs of cable are used. 'Tight' designs utilise fibre which has been packaged in a closely fitting polymer jacket, commonly nylon, PolyVinyl Chloride (PVC), polypropylene, or polyester elastomer, the outer diameter of which is between 0.5 and 1.0 mm. One or more individually jacketed fibres are generally positioned at or near the neutral bend axis of the cable, with a peripheral tensile strength member. The simplest design is for a single jacketed central fibre provided with stranded polyaramid yarns (e.g. Kavlar and Twaron) for axial reinforcement, and an overall sheath. Similar designs are available for 'loose' packaged fibre with a tube outer diameter of 1.5–3.0 mm, but these may have an increased overall diameter.

'Tight' fibre designs have the advantage that, once broken out of the cable, the fibre still maintains some measure of protection, and may be routed over short distances without a splice. Utilisation of this approach can be cost-effective and will generally keep overall losses to a minimum. *Figure 37.8* shows a typical single-fibre cable design.

37.3.3 High fibre count cables

As the fibre count increases, suppliers generally encounter a cost and overall diameter trade-off between centrally and peripherally positioned fibres. The break point varies between manufacturers and manufacturing methods, but is typically between 8 and 20 fibres.

The approach adopted in most cases is to bundle the fibres together in some form of unit packaging or element. This may take the form of tubes containing one or more loose fibres, placing the fibres in a grooved or slotted former, using fibre ribbons akin to copper ribbon cabling

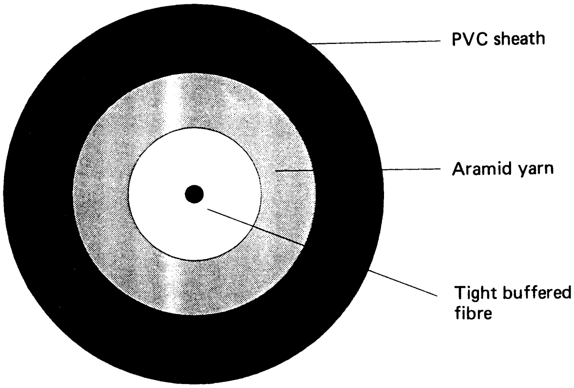

Figure 37.8 Single-fibre cable

(but with much reduced dimensions), or a combination of the above.

An extruded thermoplastic sheath is then applied to elements stranded helically or in an oscillating fashion (commonly called 'S-Z' stranding) around a central axial strength member. In external cables, interstitial filling compounds and/or an aluminium-polymer laminate barrier are used to prevent moisture reaching the fibres and exacerbating static fatigue effects. *Figures 37.9* and *37.10* show typical high fibre count cable designs.

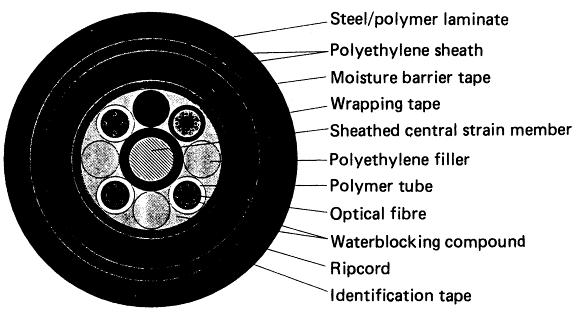

Figure 37.9 Loose tube type cable

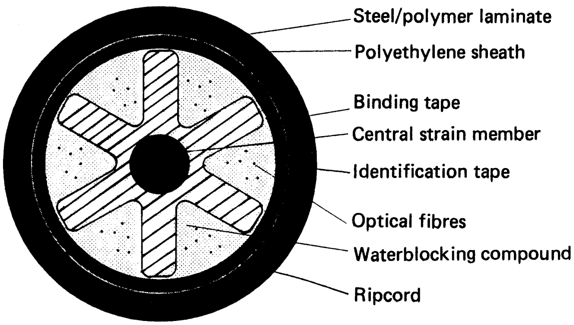

Figure 37.10 Slotted core type cable

37.3.4 Cable protection

37.3.4.1 Ruggedisation

Ruggedisation of the cable can be achieved by utilising some form of strength member (e.g. Kavlar) which is either laid helically or braided around the fibre coating. This is then surrounded by a tough outer sheath to provide the required environmental and mechanical protection. *Figures 37.11* and *37.12* show two examples of ruggedised optical fibre cables.

37.3.4.2 Armouring

Sometimes even ruggedising an optical cable is insufficient for some environments, especially where the cable is liable to mechanical radial forces (caused by digging implements) and rodents. In these cases the optical cable will need to be armoured. The most usual forms of armour are stranded steel wires, polymer laminated tapes, Kavlar and corrugated steel tape, the latter being particularly effective against rodent bites. The steel must, of course, be protected against corrosion by moisture.

37.3.4.3 Fire safety (internal cables)

As the fire safety properties of a cable are dependent on both the materials and the construction, cables which are to be sited within buildings require constructions which make them safe to use in the event of fire. Polyethylene, used commonly as a sheathing compound for external cables, has poor fire safety properties, and flame retardant PVC sheaths have been and are used for internal (electric) power and data cables. For more demanding applications, for example at sites where the public has common access, it is prudent to use cables which in a fire will:

- resist the spread of flame (flame retardance);
- produce minimal smoke; and
- produce minimal toxic emissions.

37.3.4.4 Environmental considerations

The service environment of a cable will, again, affect both the materials and the construction used. Principal considerations will be temperature, aggressive gaseous and liquid chemicals, radiation, electric fields, and extreme mechanical and other forces such as hydrostatic pressure.

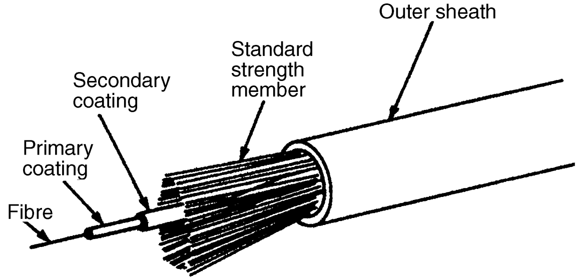

Figure 37.11 Construction of a single-fibre ruggedised optical fibre cables

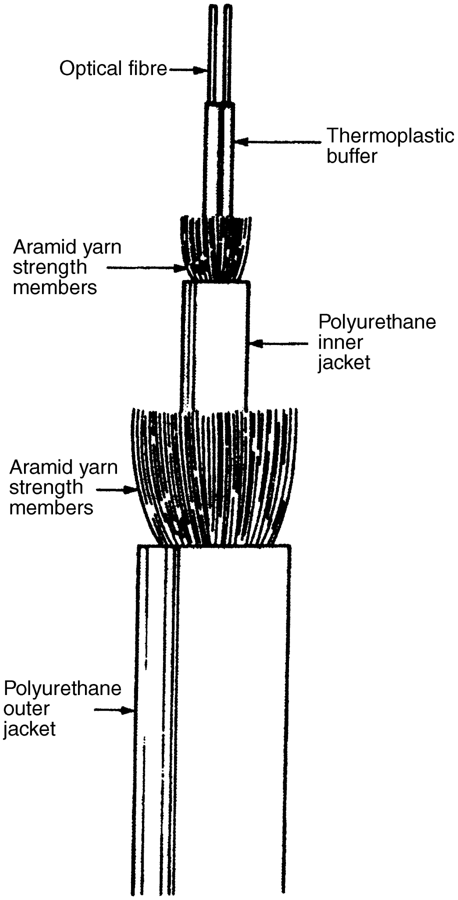

Figure 37.12 Construction of a multi-fibre ruggedised optical fibre cable, suitable for harsh, military environments

37.3.5 Cable usage

Optical fibre cables, because of their mechanical strength and low weight, can be pulled into ducts, ploughed in, cleated to walls, installed in vertical runs of over 1000 m in length (particularly important in multistorey office blocks and mines etc.) placed on cable trays and planer shelves (or PVC conduit) installed aerially, attached to supporting wires (e.g. high-voltage cables), or even immersed in water (oceanographic systems).

The technique used, of course, not only depends upon the environment but on the length of cable to be installed. Today, one of the most practised methods of installing short lengths into highly populated duct systems is to use compressed air to inject an auxiliary rope. This will then be connected to a winch rope which in turn will be connected to the cable.

37.3.5.1 In buildings

In buildings, cables tend to be of the 'tight' type, for two main reasons. Firstly, they allow for connectors to be directly mounted on to buffered fibre, minimising the number of splices and 'pig-tails' (i.e. factory assembled single-fibre cables with a connector at one end). This is generally a more cost-effective means of installation, and also keeps route losses to a minimum. Secondly, the tight construction relieves axial fibre stress in vertical runs due to its own weight (i.e. the fibre is continually supported by the cable strength member along its entire length).

37.3.5.2 External

In external applications, it is important to keep moisture away from the fibre surface, and to minimise fibre stress. 'Loose' cable types prevail, generally using a combination of filling or flooding compounds designed to displace water, plus an aluminium–plastic–laminate moisture barrier. Axial strength is provided by a stranded steel or glass reinforced member, and/or polyaramid yarns.

Because optical fibre cables are very light they can be incorporated into overhead power line routes without any additional stress being exerted onto the existing mast. In addition, as the optical fibre cable is completely non-metallic, any problems associated with inductive interference are eliminated.

The process is very similar to installing normal copper aerial cables and the optical fibre is merely lashed to the phase conductors or ground wires of the overhead power line. This is further explained in Section 37.5.

37.3.6 Splices and connectors

When an optical fibre cable is damaged it can be repaired either by splicing a new piece of cable into the existing line or, if sufficient cable is available, by cutting out the damaged portion and splicing the two ends together. This process is referred to as concatenation.

Most techniques for joining fibres rely on accurate geometry. The core/cladding concentricity is also very important in all-silica fibres where alignment of the cores usually depends on alignment of the outside surfaces of the cladding. In any optical system, there is likely to be a mix of splices and connectors for active device to fibre interconnection and for fibre to fibre interconnection (e.g. external cable to in-building cable, or for patching).

Both splices and connectors require the achievement of fibre end faces which are flat and at 90° to the fibre axis. Two methods (or a combination of both) are commonly used; cleaving, and cut-and-polish. Tools for either method are commonly available.

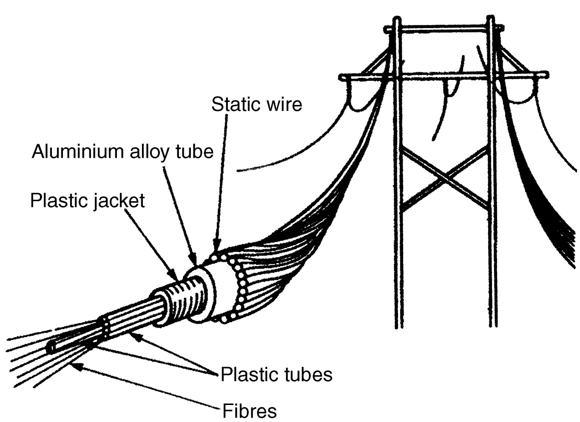

Figure 37.13 Ground wire, incorporating optical fibres, mounted on the top of a pylon power line structure

37.3.6.1 Splices

A number of techniques for permanently and temporarily splicing optical fibres are available, including fusion, V-groove (now largely obsolete), and sleeve splices. Sleeve splices have obvious mechanical advantages for single-fibre jointing in the field, but have the disadvantage of 'slop', due to the clearance required to insert the fibres in the sleeve. Fusion splices are attractive but they require precise external alignment of the fibres to be joined. The fusion type is permanent, but some sleeve splices can be demounted and re-used.

In a typical sleeve splice, an elastomeric tube is used to locate the fibre ends which are simply inserted into the sleeve, together with a small amount of index adhesive to fuse the two fibre ends together. Alternatively, the splice connector can be crimped to the optical fibre cable. Supports are available to house the sleeve and to clamp the fibre/cable. An insertion loss of 0.2 dB is typical for both single and multimode fibres, and the elastomeric tube can be re-used up to 50 times.

Fusion splicing for silica fibres has been developed by numerous companies world-wide. In this technique, the fibres to be joined are visually or automatically aligned using micromanipulator movements. The aligned fibres are then fused together using a suitable localised heat source. Electric arcs are most common, but for high-strength splices, an oxy-gas torch is sometimes used. Losses less than 0.1–0.2 dB are routinely and reliably achieved for both multi- and single-mode fibres. Alignment is commonly achieved by locally injecting light in one fibre and detecting in the other, using a severe bend to cause core/cladding mode coupling. Fusion is activated when the locally detected signal is maximised.

Fibres are usually protected from the environment after splicing by some type of reinforced heat shrink tube, or by coating reinstatement.

Splice losses Splice losses can be due to variations in the outer diameter of the fibre core, differences in index profile, differences in the ellipticity of the core, misalignment of the fibre ends, poor quality of the refractive index match at fibre ends, waveguide imperfections, etc.

In practice, splice losses of about 0.5 dB are typical for fusion-spliced multimode fibres while single-mode fibres (because of the narrowness of the core diameter) are not as much (e.g. 0.1 – 0.2 dB). Mechanical splicing, whilst still being more lossy than fusion-splicing, is nevertheless appreciably less than that of a connector.

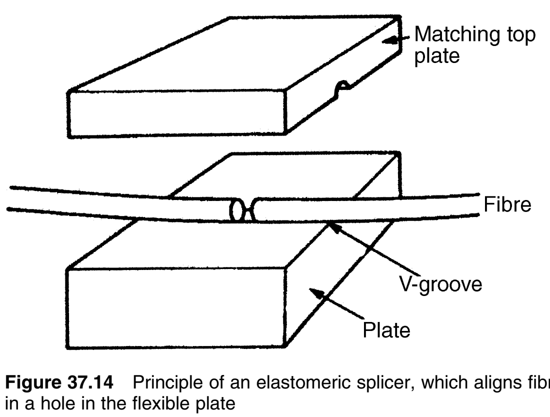

Figure 37.14 Principle of an elastomeric splicer, which aligns fibres in a hole in the flexible plate

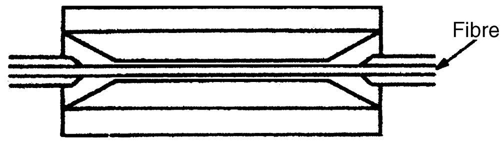

Figure 37.15 Principle of an elastomeric splicer, which aligns fibres in a hole in the flexible plate

37.3.6.2 Connectors

Demountable connectors for optical fibre (cables) need to perform several functions. The primary function is to couple light from one fibre to another efficiently and repeatably. If a connector is to operate satisfactorily it must also protect the fibre ends from damage which may occur due to handling, to protect against environmental factors such as moisture and dust, and to carry tensile loads on the cable, whilst allowing rapid connection and disconnection when required. For optimum performance in hostile environments the cable and connector must be considered as an integral unit.

An optical fibre connector can usefully be considered in three parts:

(1) Fibre terminations which protect and locate the fibre end;
(2) Alignment guides which position the pair of fibre terminations for optimum coupling; and
(3) Connector shells which protect the optical contacts from the environment, hold the alignment guides and fibre terminations in place, and terminate the cable sheath and strain member.

There are two main categories of demountable optical connector. The first is the butt joint in which the prepared ends are close to each other and are aligned so that their fibre axes coincide. The second major category uses the expanded beam technique. In this approach the diameter of the transmitted beam is increased by one half of a connector and this expanded beam is reduced again to a size compatible with the core of the receiving fibre by the second half of the connector.

This expansion can be achieved by tapering the fibre, but generally lenses are used.

Butt jointing In a butt joint, a ferrule usually protects the fibre. The main types are jewelled, ceramic, and tri-ball. A typical jewelled metal ferrule is manufactured with an accurate outside diameter and a 1 mm counterbore at one end. A standard watch jewel, with a hole size closely matching the diameter of the fibre to be used, is press-fitted into the counterbore giving a fibre size hole which is accurately concentric with the outside diameter of the ferrule. The close diameter and concentricity tolerances of the fibre hole are achieved more easily and cheaply by drilling a 1 mm hole and using a watch jewel than by drilling a small hole directly into the end of the metal ferrule.

To terminate a fibre in a jewelled ferrule, the protective coating is removed over a short length from the end, and the fibre is fed into the ferrule filled with a suitable adhesive and through the close fitting jewel hole at the front. The fibre is then polished back flush with the ferrule end. Typical concentricity errors between the fibre core and the outside diameter of the ferrule are 2–6 μm. The termination technique has been developed for silica and plastic-clad-silica fibres.

Another similar technique uses a precision ceramic rod with a central hole, and has fast become the standard for most fibre connectors as the rods can be manufactured very cost effectively.

Another technique uses three precision balls (as used in the bearing industry) to locate a fibre centrally within a conical hole.

Butt joint connectors are by far the most common; those regularly encountered are SMA, bi-conic (both types for multimode all-silica fibres), ST (for both multimode and single mode), and FC/PC (for single mode).

Expanded beams The expanded beam method uses a different mechanism to achieve alignment. When a prepared fibre end is fixed at the focus of a convex lens, a collimated beam, with a diameter greater than the fibre core diameter, emerges from the lens. When two of these terminations are aligned an optical connector is produced. The fibre must be positioned at the focus with the same accuracy as two fibres in a butt joint since the receiving fibre is in effect forming a butt joint with the image of the transmitting fibre. At first sight this may appear to forfeit the advantages of this technique; however, since the accurate positioning of the fibre in the lens termination unit is only required once, it would normally be done in a factory. Making and breaking of the connection occurs between the two lenses. The required connection tolerances are reduced since the increased beam diameter allows greater lateral misalignment than with a simple butt. Owing to the collimation of the beam, a small separation of the terminations, and/or angular misalignment can be tolerated without significantly increasing attenuation.

The increased beam diameter reduces the effect of dust on the connector loss. The separation of the terminations minimises the risk of permanent damage arising from grit scratching or chipping the optical surfaces when the connector is inadvertently coupled in a dirty condition. For these reasons, this type of connector is useful in harsh environments.

Alignment and connector shells For accurate alignment of two fibres within the connector shell, precision holes are used. Watch jewels are used for fibre guidance as well as precision bores, bioconical systems, and helical springs. In the FC/PC type (used for single mode), a factory set keying system is used to optimise connector angular orientation to optimise connector angular orientation to optimise connector loss. Springs overcome the need for a sliding fit tolerance by using the fact that as they are unwound, the inner diameter increases; at this stage the two ferrules are inserted, and then the spring relaxed.

Many connector bodies or shells are available, generally using bayonet or screw threads to mate. Hermaphroditic types are also available. The shell may be for a single connection, or for multiple fibres.

Connectors tend to be very specific to the type of cable which they will accept and the need to clamp onto the cable strength member rather than the fibre itself for strain relief is always advisable.

37.4 British and International Standards

Listed below are current British (BS), American (ANSI) and international (ISO) standards that concern optical fibres and Fibre Distributed Data Interface (FDDI).

ANSI X3.139 (1997)—INFORMATION SYSTEMS—FIBER DISTRIBUTED DATA INTERFACE (FDDI)—TOKEN RING MEDIA ACCESS CONTROL (MAC)

Describes Media Access Control, lower sublayer of Data Link Layer for FDDI, which provides high-bandwidth (100 Mbits/s), general-purpose interconnection among computers and peripheral equipment using fibre optics in ring configuration.

ANSI X3.148 (1999)—INFORMATION SYSTEMS—FIBER DISTRIBUTED DATA INTERFACE (FDDI)—TOKEN RING PHYSICAL LAYER PROTOCOL (PHY)

Describes Physical Layer Protocol standard, upper sublayer of Physical Layer, for FDDI which provides high-bandwidth (100 Mbit/s), general interconnection among computers and peripheral equipment using fibre optics. Coverage includes definitions, conventions, coding, symbol set, line states, coding overview, general organization, smoothing function, repeat filter and ring latency. Also gives detailed diagrams and tables.

ANSI X3.166 (1995)—FIBER DISTRIBUTED DATA INTERFACE (FDDI) PHYSICAL LAYER MEDIUM DEPENDENT (PMD)

Gives a specification for Physical Layer, Medium Dependent (PMD) requirements for the FDDI high-bandwidth (100 Mbit/s) general purpose interconnection among peripheral and computer equipment that use fibre optics as the transmission medium.

ANSI X3.263 (1995)—FIBRE DISTRIBUTED DATA INTERFACE (FDDI)—TOKEN RING TWISTED PAIR PHYSICAL LAYER MEDIUM DEPENDENT (TP-PMD)

Defines Twisted Pair Physical Layer Medium Dependent (TP-PMD) criteria for FDDI high-bandwidth, (100 Mbit/s) general purpose interconnection among computers and equipment using fibre optics and twisted pair as the transmission media. It can be shaped to support a sustained data transfer rate of 80 Mbit/s or more, and allows connection for nodes distributed over distances of several kilometres. Default values are calculated on the basis of 1000 physical links and total fibre path of 200 km in length. (Typically corresponding to 500 nodes and 100 km of dual fibre cable.)

BS 6004 (1995)—SPECIFICATION FOR PVC-INSULATED CABLES (NON-ARMOURED) FOR ELECTRIC POWER AND LIGHTING

Specifies requirements and dimensions for non-armoured PVC insulated cables for fixed installation and for operation at voltages up to and including 450 V to earth and 750 V a.c. between conductors. Coverage includes: voltage designation, conductors, insulation, core identification, sheath, marking, electrical requirements and fillers and extruded inner covering. Also gives definitions, tables, diagrams and annexes.

BS EN 186000 PT1 (1994)—HARMONIZED SYSTEM OF QUALITY ASSESSMENT FOR ELECTRONIC COMPONENTS. GENERIC SPECIFICATION: CONNECTOR SETS FOR OPTICAL FIBRES & CABLES—REQUIREMENTS, TEST METHODS AND QUALIFICATION APPROVAL PROCEDURES

Applies to fibre optic connector sets for optical fibres and cables. Coverage includes definitions, environmental category, gauges, corrosion resistance, component marking, package marking, spectral loss, cable torsion, cable pulling, static load, nuclear radiation, solar radiation, spectral loss, axial compression and industrial atmosphere.

BS EN 187000 (1997)—GENERIC SPECIFICATION FOR OPTICAL FIBRE CABLES

Applicable to optical fibre cables to be used with telecommunication equipment and devices having similar techniques and combining optical fibres and electrical conductors.

IEC 60793-1 (1992)—OPTICAL FIBRES—GENERIC SPECIFICATION

Applies to primary coated or primary buffered optical fibres for use in telecommunication equipment and in devices employing similar techniques. Establishes uniform requirements for the geometrical, optical, transmission, mechanical and environmental properties of optical fibres and includes measuring methods for dimensions, transmission and optical characteristics. A guide for fibres for short distance links is in Annex A.

IEC 60793-1.1 (1999)—OPTICAL FIBRES—GENERIC SPECIFICATION—GENERAL

Applies to primary coated or buffered optical fibres for use in telecommunication equipment and in devices employing similar techniques and defines categories of optical fibres as well as packaging.

IEC 60793-1.2 (1996)—OPTICAL FIBRES—GENERIC SPECIFICATION—MEASURING METHODS FOR DIMENSIONS

Gives the measuring methods applicable to environmental tests of optical fibres. The methods are to be used for inspection of optical fibres for commercial purposes. They establish uniform requirements for geometrical characteristics of optical fibres.

IEC 60793-1.3 (2000)—OPTICAL FIBRES—PART 1–3: GENERIC SPECIFICATION—MEASURING METHODS FOR MECHANICAL CHARACTERISTICS

Applicable to the tests of mechanical strength, ease of handling or the recognition of physical defects or primary coated or primary buffered optical glass fibres. The methods are to be used for inspecting fibres for commercial purposes. The aim of this part is to establish uniform requirements for mechanical characteristics of optical fibres.

IEC 60793-1.4 (1998)—OPTICAL FIBRES—GENERIC SPECIFICATION—MEASURING METHODS FOR TRANSMISSION AND OPTICAL CHARACTERISTICS

Applies to the practical measurements of transmission and optical parameters of fibre. The methods are to be used for inspection of fibres and cables for commercial purposes to establish uniform requirements.

IEC 60793–1.5 (1995)—OPTICAL FIBRES—GENERIC SPECIFICATION—MEASURING METHODS FOR ENVIRONMENTAL CHARACTERISTICS

Describes measuring methods which apply to environmental tests of optical fibres. The methods are to be used for inspection of optical fibres.

IEC 61218 IEC (1993)—FIBRE OPTICS—SAFETY GUIDE

An interpretation of IEC 825 with respect to fibre optic transmission systems. Some additions have been made in this guide wherever IEC 825 and its amendment do not cover a specific fibre optic subject. Applies to the wavelength range of 400 nm–10 (to the power 5) nm. IEC 825 addresses equipment based on lasers only.

IEC 61292-1 (1998)—FIBRE OPTICS—PARAMETERS OF AMPLIFIER COMPONENTS

Applicable to optical components of Optical Fibre Amplifiers (OFAs). Provides information on the most relevant parameters of OFA optical components, but does not define included definitions as these require more research.

IEC 61930 (1998)—FIBRE OPTIC GRAPHICAL SYMBOLOGY

Applicable to graphical symbols that are used in IEC publications dealing with fibre optics. The aim is to give uniform graphical symbols for the various fibre optic elements and devices.

IEC TR 61282-1 (2000)—FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES—PART 1: SINGLE-MODE DIGITAL AND ANALOGUE SYSTEMS

Gives guidance for system design methodology for users and suppliers of fibre optic transmission systems for telecommunications and broadband video distribution applications. The function of the systems is to interconnect signals between defined digital and analogue interfaces via a fibre optic link. Generally, fibre optic systems are built-up from Basic Fibre Optic Systems (BFOS).

ISO 9314-1 (1989)—INFORMATION PROCESSING SYSTEMS—FIBRE DISTRIBUTED DATA INTERFACE (FDDI)—TOKEN RING PHYSICAL LAYER PROTOCOL (PHY)

Specifies the Physical layer protocol (PHY), for FDDI.

ISO 9314-2 (1989)—INFORMATION PROCESSING SYSTEMS—FIBRE DISTRIBUTED DATA INTERFACE (FDDI) TOKEN RING MEDIA ACCESS CONTROL (MAC)

Specifies the Media Access Control (MAC), the lower sublayer of the Data Link Layer (DLL), for an FDDI high-bandwidth (100 Mbit/s), general-purpose interconnection among computers and peripheral equipment using a transmission medium of fibre optics in a ring configuration.

ISO 9314-3 (1990)—INFORMATION PROCESSING SYSTEMS—FIBRE DISTRIBUTED DATA INTERFACE (FDDI)—PHYSICAL LAYER MEDIUM DEPENDENT (PMD)

Describes Physical Layer, Medium Dependent requirements for FDDI high-bandwidth (100 Mbit/s) general-purpose interconnection among computers and peripheral equipment using fibre optics as the transmission medium. May be configured to support a sustained transfer rate of approximately 80 Mbit/s. May not meet the requirements of all unbuffered high-speed devices. It establishes the connection among many nodes distributed over distances of several kilometres. Default values were calculated on the basis of 1000 physical connections and a total fibre path length of 200 km.

ISO 9314-13 (1998)—INFORMATION TECHNOLOGY—FIBRE DISTRIBUTED DATA INTERFACE (FDDI)—CONFORMANCE TEST PROTOCOL IMPLEMENTATION—CONFORMANCE STATEMENT (CT-PICS) PROFORMA

Gives the PICS proforma for the FDDI specified in the base standards as denoted in clause 5.

37.5 Optical fibre telemetry on overhead power lines

37.5.1 Introduction

The advent of optical fibre links has provided significant improvements in the communication facilities needed for the effective operation of power systems. Such links are well suited to the electrically noisy environments of power systems due to their immunity from electromagnetic interference. They are also free from the difficulties encountered with purely electronic systems due to local earth potential variations which may arise from the heavy earth currents that can occur during a power system fault. The wide information-carrying bandwidths of such systems leads to low costs per channel on trunk routes, can conveniently accommodate extra information transmission and provide the means for more rapid signal transmission which is important for protection and control under power system fault conditions. In addition, they are electromagnetically compatible in not generating stray or spurious interference as can be the case with microwave and power-line carrier systems.

The main uses on power systems for long-haul optical fibre links include telephony, telemetry, telecontrol, protection (the control of circuit-breakers), data transmission between computers, and possibly video signalling.

37.5.2 Fibre cable configurations

Optical fibre cables are generally available for use on overhead power lines. Such cables fall into three main generic types; (1) All-Dielectric Self-Supporting (ADSS); (2) spiral wrap-on or lashed; and (3) Optical Ground Wire (OPGW) where the optical fibres are included in the earth wire.

All-dielectric self-supporting cables require tensile members which offer a high strength-to-weight ratio such as glass reinforced plastic or aramid yarns. The presence of these cables imposes an additional load on the support structures which must be considered with regard to statutory support safety factors. An ADSS cable is inherently light and small relative to the phase conductor and earth wire which limits the effects of environmental factors such as wind and ice loads minimising any additional steel work or structural reinforcement needed. Clamping arrangements can also be chosen which allow slippage of the cable under conditions of differential loading (i.e. when one span adjacent to a support structure is loaded more or less than the other span adjacent to that support structure) further safeguarding the integrity of the supports. The optical fibre cables must also meet any ground clearance requirements imposed by the power utility. The principal benefits of ADSS cables are that they offer post-fit solutions for power utilities and can allow installation with one or both power circuits live avoiding costly supply interruptions.

Wrap-on or lashed cables can be fitted to either the earth wire or a phase conductor, although the earth wire is most common. The wrap-on cables are spirally applied to minimise the susceptibility of the resulting composite line to wind-induced vibration known as 'galloping'. Galloping is caused by light winds flowing over the cable giving rise to high and low pressure regions (similar to the action of an aircraft wing) producing up-lift or down-force depending on the orientation of the cables. By spirally applying the wrap-on cable the effective profile presented to the wind varies along the span such that consecutive spirals oppose each other cancelling any net effect.

Wrap-on or lashed cables also offer the advantage of being post-fit systems if the cable is installed on the earth wire. Live line installation of such systems on the phase conductor are being discussed.

Optical ground wire (OPGW) cables encase the optical fibres within the earth wire which is used to carry fault currents and to provide shielding from lightning. One structure of such a composite cable includes aluminium or steel strands helically wound around a hollow aluminium core carrying a polyethylene sheath which holds typically between two and four pairs of optical fibres, along with the option of a polymer tension member.

The OPGW cables offer the advantage of not imposing additional loads on the support structure as they replace the existing earth conductor. However, these cables are not post-fit solutions to the needs of power utilities for telecommunications purposes as the replacement of the existing earth wire is costly and time consuming. Therefore, such cables are generally used on new lines or when the existing earth wire is scheduled for replacement.

Any optical fibre cable used for aerial applications must be capable of operating under a range of environmental conditions without eroding the optical and power transmission characteristics or the service life of the cables and support structures.

Optical fibre cables incorporate strain relief between the strength member and the fibres to protect the optical fibres during service. Strain relief can be provided by overfeeding fibre into small polymer tubes which are then stranded around a central member or by overfeeding ribbon arrays of fibres within a slot. The amount of strain relief required is determined by relating the maximum cable strain expected during service to the maximum allowable fibre strain calculated for the required service lifetime (a function of the initial fibre proof test level) and the optical performance of the fibres when they are strained. Multiple fibres constrained in loose tubes tend to interact with each other when strained, giving increased attenuation.

The variation in cable tension and strain produced by climatic changes such as temperature, wind strength, and ice loads can be solved mathematically. The optical cable, as with the phase conductors and earth wires, adopts the shape of a catenary when suspended between two points. An initial set of known conditions (usually corresponding to those during installation) are used to determine the basic catenary and then all changes in tension due to climatic variations are related to this. The principal effect of a wind acting on the cable, apart from that on the tension in the cable, is to cause the cable to 'blow out' from the vertical.

Cable or conductor ageing must also be considered. ADSS cables generally have good self-damping characteristics which vibration in the cable and that transmitted to the support structure. Wrap-on and lashed cables tend to vibrate in harmony with the conductor or earth wire on which they are installed and hence do not produce a significant effect on the vibration behaviour of the host. OPGW cables are used instead of standard earth wires and behave in a similar fashion to those wires. Therefore, OPGW cables tend to use the same precautions (typically dampers) as earth wires.

In addition to vibration, a further consideration is a phenomenon known as 'creep' where the presence of a permanent tensile load produces a reduction in the strength of the cable or conductor leading to failure below the initial breaking load. Optical cables use strength members manufactured from materials which have been shown to be resistant to 'creep' within the operational strain window experienced during service.

The electric field in which these optical fibre cables reside can combine with onerous climatic conditions and have an effect on the sheath materials used. ADSS and wrap-on cables can be degraded by the local electric field. Careful selection of sheath materials which are resistant to dry band arcing, the phenomenon which causes sheath degradation, ensures that such cables fulfil service lifetime requirements. OPGW cables have metallic outer layers and are used for earthing purposes and so are not prone to damage from dry band arcing but can be subject to galvanic action between the dissimilar metals used in the cable construction.

37.5.3 Factors governing system design

In the UK, telephony traffic over single-mode fibre is common with bit rates up to 565 Mbit/s, and systems are installed operating at over 2 Gbit/s. The major telephony carriers use single-mode fibre only. Operation is generally at an optical wavelength of 1300 nm, with longer haul systems (e.g. intercontinental submarine links) using 1.55 μm where intrinsic fibre losses are lower (ca. 0.2 dB/km, and ca. 0.35 km at 1.3 μm). For a laser diode source with output power of typically—3 dB/m, and photodiode receiver sensitivity—50 dB/m, link lengths greater than 50 km and bit error rates of 10^{-9} are readily achieved, with a power margin to allow for component ageing and possible fibre repair splices. Such lengths generally allow for signal repeaters/regenerators to be situated within buildings.

Multimode fibre is used for data transport, analogue video transmission, etc., over short distances to approximately 2 km. Both 62.5/125 μm and 50/125 μm (core/cladding diameters) are commonly used, the former being the preferred FDDI standard. Multimode fibre, despite its higher cost, is used to allow the use of more cost-effective connectors, and launch and receive devices.

37.6 Power equipment monitoring with optical fibre sensors

37.6.1 Introduction

Although early forms of optical fibre sensing systems have illustrated the potential of such methods for power system monitoring there have been practical deficiencies which have detracted from their widespread use. The original systems were cumbersome, unreliable, costly and involved much unfamiliar optical processing and interfacing. It may be argued that insufficient attention was given to the real needs of power system monitoring. The problem has been exacerbated because the power industry has been unsure of the modes in which such novel technology might best be used whilst simultaneously a major thrust of optical fibre sensors research has been for methods which are over-sophisticated and costly for power system applications.

However, the many fundamental advantages of optical fibre sensing systems remain attractive. For instance, a major advantage is for the condition monitoring of a circuit-breaker during fault current interruption when signatures of impending faults may be more distinguishable. A further implication is that such an approach minimises supply disruption since such monitoring would be undertaken live, a capability which emerges because of such a system's electromagnetic immunity and its inherent electrical insulation properties.

This contribution examines the advantages of optical fibre monitoring for power equipment applications, reasons for limited progress in implementing such technology and possible strategies which are evolving for the site testing and evaluation of these systems.

37.6.2 Technology implementation difficulties

One objective of the realisation of optical fibre sensing in the power industry is for the implementation of an optically controlled substation system. Such an objective involves producing optical fibre sensors for monitoring a range of parameters governing the condition and operation of power equipment such as circuit-breakers and transformers. It entails interlinking the various monitoring systems with an optical fibre system and connecting these to various data stations and control units (*Figure 37.16*).

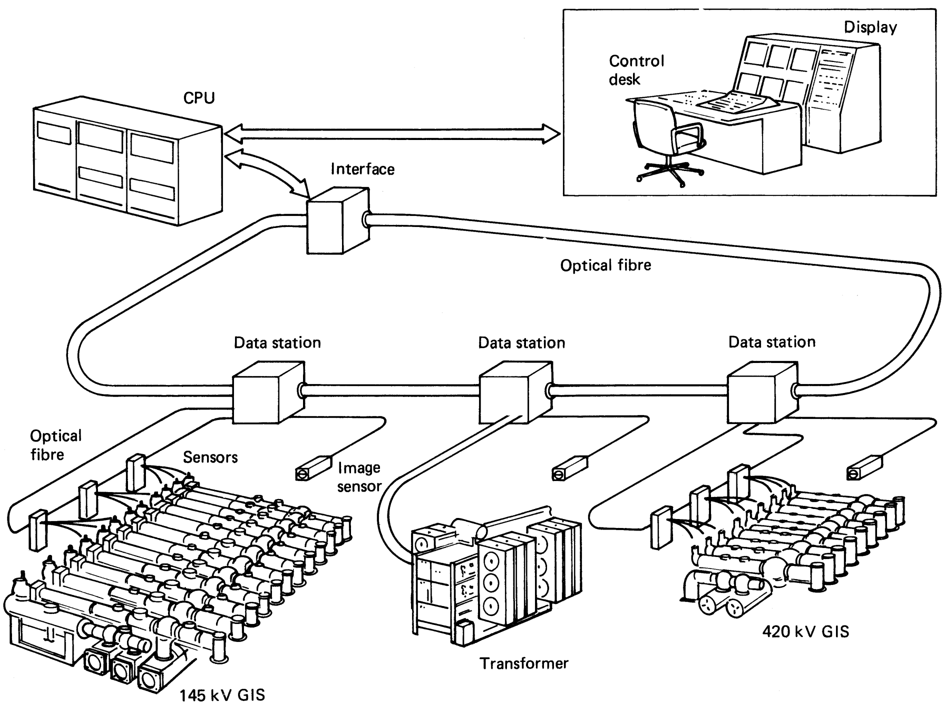

Figure 37.16 Optically monitored substation concept. (Source: Courtesy of Mitsubishi)

The attraction of optical fibre sensors for such monitoring is that their intrinsic properties offer many advantages in hostile and challenging environments. For high-voltage power apparatus applications these properties include:

- inherent isolation of electronic instruments;
- immunity from electromagnetic interference;
- geometric flexibility;
- inherent electrical insulation;
- no electrical shock hazard;
- corrosion resistance; and
- compact and lightweight.

Despite such attractive advantages, the uptake of the fibre sensing technology has been retarded because of general market penetration problems. These include:

- uncompetitive prices;
- end-user unfamiliarity;
- conservative attitude of large industries;
- range of different optical systems for monitoring various parameters;
- failure of early, immature systems; and
- absence of established markets.

Recent developments in optical fibre sensing have addressed these commercial problems. In order to appreciate the significance of the developments it is necessary to review briefly the methods available for modulating an optical signal.

The basic modulation methods involve modifying either the amplitude, phase or polarisation of the optical signal (*Figure 37.17*). Absolute amplitude monitoring is unreliable for sensing purposes because a number of external (e.g. fibre bending) and intrinsic factors (e.g. source variability) in addition to the sensor may modify the amplitude. Phase monitoring is based upon optical interferometry which involves complex instrumentation and because of its digital nature is not so attractive for situations in which the instrument power supply may be interrupted. Methods based upon monitoring changes in the plane of polarisation of an optical signal have hitherto relied upon even more complex optical systems.

Attempts to overcome the deficiencies of the amplitude modulation method by referencing a modulated signal at one wavelength (λ_1) with respect to an unmodulated signal at a second wavelength (λ_2) has met only with limited success because the referencing is not completely reliable and because of power-budget limitations.

The problem with these basic methods is that the intention with any measurement system is to seek an output (V) which is proportional to the measurand (M) via a constant which is the sensitivity S:

$$V = S \cdot M \qquad (37.9)$$

With an optical fibre system the relationship (Equation (37.10)) between the output V and modulation (by measurand) $M_1(\lambda)$ is complicated and depends upon parameters such as source power ($P(\lambda)$), fibre transmission ($T(\lambda)$), and fibre perturbation ($M_2(\lambda)$) which can be induced by external influences or age.

$$V = \int \sum_{l.m} \int_{\lambda} \left(\int [P(\lambda)T(\lambda)M_2(\lambda)\mathrm{d}l] R(\lambda) M_1(\lambda)\mathrm{d}\lambda \right)^{P} \qquad (37.10)$$

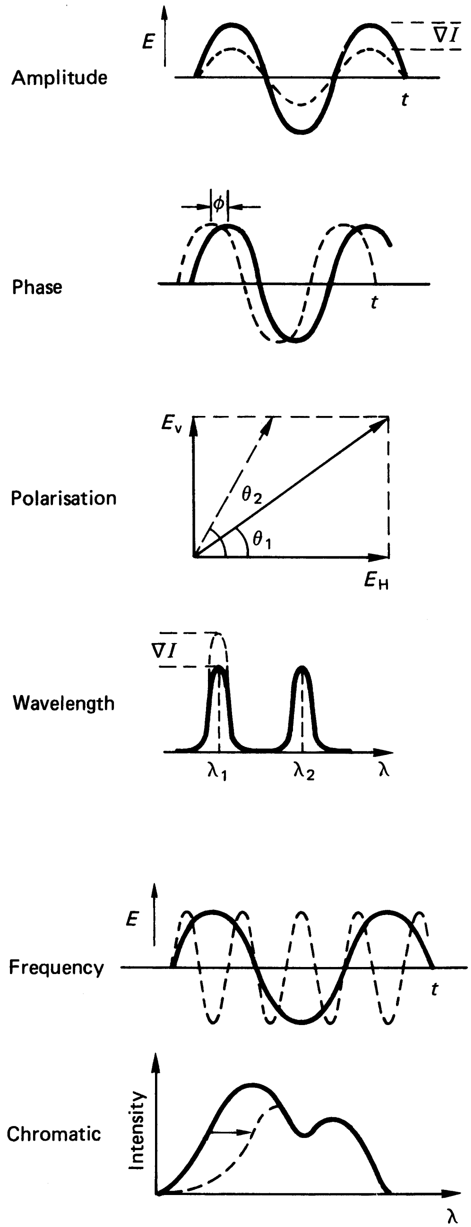

Figure 37.17 Basic optical modulation methods

It was, therefore, necessary to seek modulation methods which are less susceptible to these effects. Two main methods emerged. The first relied upon frequency modulation which was solution adopted by the telecommunication industry. The second method relied upon chromatic modulation whereby the spectral content of the optical signal is varied and the optical signal is monitored over its entire spectral range by several detectors each having a different but overlapping spectral response.

Both these methods are intensity independent and lead to practical, cost effective fibre sensing systems. The chromatic approach has the added bonus of using common instrumentation for monitoring a range of different parameters.

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