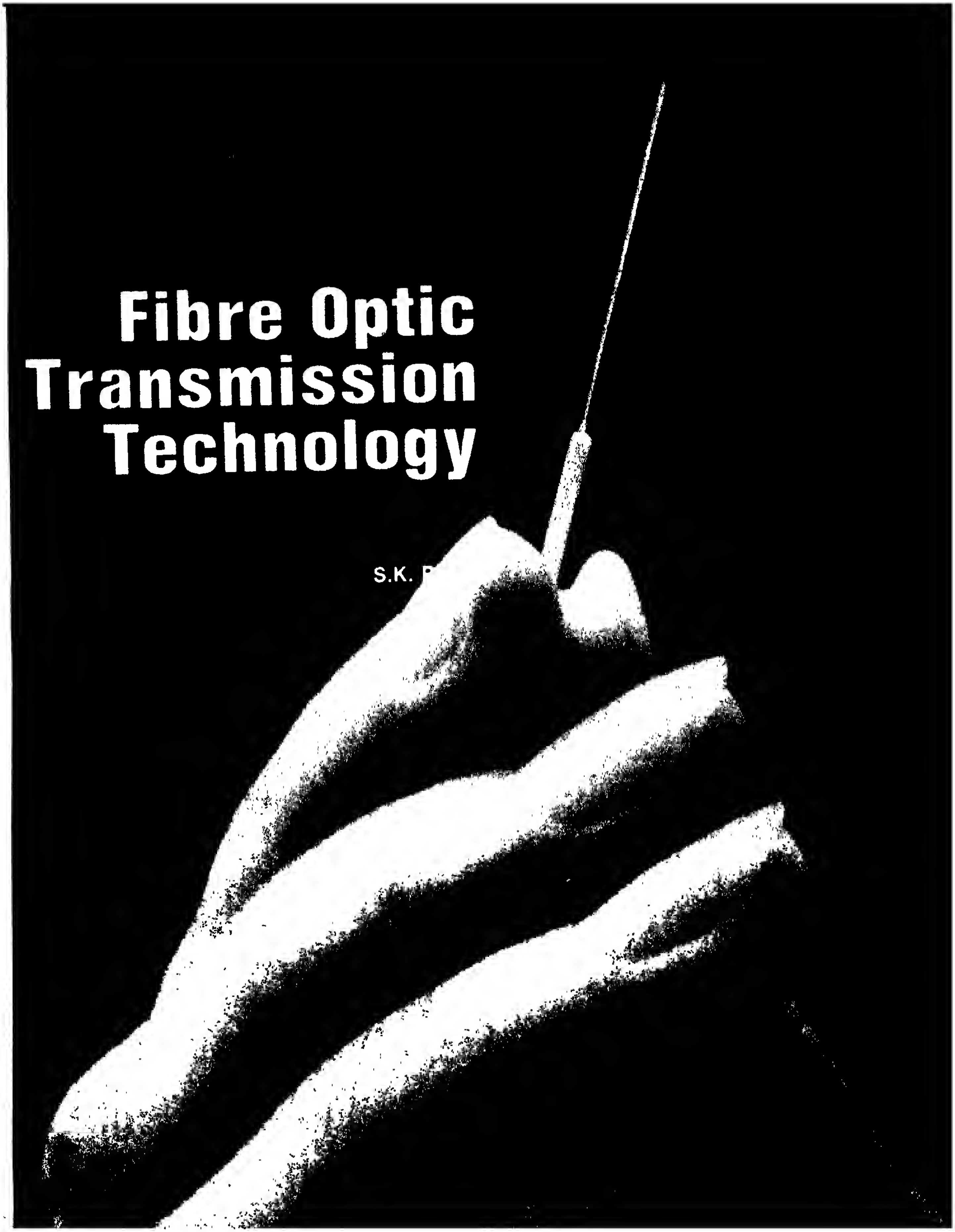
Fibre Optic Transmission Technology



S.K. P

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Fibre optic transmission technology has made great progress as one of the leading forces towards a more advanced information society. The low transmission loss, noise immunity and wide bandwidth of optical fibres now make it possible to realise cost effective and highly reliable systems in a broad spectrum of applications transmission of audio, video, high speed digital and analogue signals in local exchanges and long-haul communication systems, instrumentation, local area networks, distributed computer control systems and also in special purpose systems.

Fibre optic transmission technology owes its origin to two epoch-making scientific breakthroughs made in 1970: one, the success of Corning Glass Works in the large-scale reduction of transmission loss in optical fibre and two, Bell Laboratories' achievement of continuous operation of a semiconductor laser at room temperature. Since then, this technology has developed very rapidly and today finds wide scale industrial and commercial applications. It has exceeded the expectations of even the most optimistic forecasts in market projections

Advantages

Fibre optic cables compare favourably with HF symmetrical and coaxial cables. Optical fibre systems offer a number of advantages.

Wider bandwidth. Existing optical fibre systems transmit hundreds of MB/sec over thousands of kilometres. AT&T's latest system can handle 6000 simultaneous telephone calls on each pair of fibres (a pair is required: one to transmit and another to receive the signal). This capacity will increase four-fold by 1988. An experimental system that should be commercially available within a few years transmits 2 billion bits/sec over 100 repeaterless kilometres. At this rate, the entire text of the 30 volumes of 'Encyclopedia Britanica' could be transmitted in less than a second.

Attenuation. Repeater span of over 100 kms has been achieved with 2 dB/km attenuation at 1.5um wavelength, resulting in increased system reliability as well as lower initial and maintenance cost.

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Noise immunity. Optical fibres are inherently immune to radiation and electromagnetic and electrostatic interference such as lightning, motors, EHT (extra high tension) power lines, radio frequency and crosstalk, irrespective of data rate.

Size and weight. The greater signal carrying capacity is accompanied by its smaller size and lesser weight. A copper cable carrying 36,000 channels has a diameter of 7.5 cm and weighs 11 kg/m. By contrast, a fibre cable carrying 50,000 channels is only 1.25 cm in diameter and weighs just 1.2 kg/m. This saves in shipping, storage and installation costs.

Compatibility with conventional electronics. Fibre optic systems match perfectly with the present day electronic communication systems utilising digital CMOS/TTL integrated circuit and large scale integrated circuit technology.

Modular design. With their modular design, each component of fibre optic system can be upgraded individually, without the need for an overhaul of the entire network.

Security. It is extremely difficult to tap a glass fibre without detection. This makes it ideal for military and other sensitive applications.

No scarcity of raw material. It is made of silica, available on earth in abundance.

Safety. There is no sparking or short circuit in optical fibres. It can be used in hazardous environment.

Insulating medium. Its dielectric property is advantageously utilised in several applications.

The fibre optic transmission system can be divided into three main functional units: (i) the transmitter or the source; (ii) the receiver or detector; and (iii) the propagating medium.

Transmitter or source

The electrical signal input to the transmitter is converted into light signal output which in turn is launched into the fibre cable through suitable coupling. The transmitter consists of a modulator or coder, a driver circuit and a temperature compensating circuit and a transducer.

Transmitters are available in sizes as small as 1.5 cm × 3.7cm, 24-pin, dual-in-line modules. Integrated circuitry is used for coder, driver and compensation circuits. Input of the module matches the electronic communication circuits delivering the input electrical signal to the transmitter.

The transducer for converting electrical energy into light should be a small, bright, fast, monochromatic source for efficient, long distance, fast data transmission with low dispersion and high reliability. Light emitting diodes (LED) and laser (light amplification through stimulated emission of radiation) diodes (LD) are used for this purpose. Both can operate in either the short-wave or long-wave spectrum. Early developments were confined to the operation of source transducers in the short wavelength region.

LEDs (typically 50μW output/100mA driving current/2.5V operating voltage) and LDs (typically 5mW output/70mA threshold current/0.5ns rise and fall time) of GaAlAs/GaAs double heterogenous structure are used for 0.76-0.89μm and GaAsP/InP/buried-heterojunction type LDs (typically 3mW/30mA threshold current/0.5ns rise and fall time) are used for 1.2-1.6μm wavelengths.

LED is a low-cost, simple, reliable long-life device with linear input/output characteristics. On the other hand, the laser diode is not a very stable device. Due to the strong dependence of its threshold current on temperature, the laser diode should be operated at some fixed temperature within the operating range. The temperature is controlled by peltier cooling elements.

Fabrication of LED and LD is done with a double heterojunction, liquid phase, epitaxial growth process. Due to wave guiding characteristics of the recombination layer, energy is emitted in a narrow cone in the plane perpendicular to the plane of the junction. LDs and LEDs are provided with factory assembled fibre pigtails so as to avoid the need for field alignment of fibre to the devices.

Receiver or detector

It receives the optical signals from the transmission link and converts them into electrical output signals. The receiver consists of transducer, amplifier, threshold detector, comparator, error detector and decoder or demodulator. Receivers are also available in sizes as small as 1.5cm × 3.7cm, DIL module. Integrated circuit technology is used for the various receiver circuits.

Major receiver transducer requirements are high efficiency, high speed response, low noise and low operating voltage. Photodiodes, used as receiver transducers, are of two types PIN (P, N and I intrinsic) and APD (avalanche photodiode). In response to the light signal received from the transmission link, reverse biased detector delivers electric current to the load resistor. PIN diodes require about 5 to 20 volts and APDs as much as several hundred volts.

APDs have internal amplification due to the avalanching (multiplication by collision) of free charges. Gains up to several hundred are obtainable, making an APD receiver more sensitive than a PIN diode receiver. High cost and the need for large power supplies are the disadvantages of an APD. Silicon photodiodes are suitable for short wavelength region and have a peak responsivity of about 0.5 A/W at 0.85 μm. Germanium (Ge) and indium gallium arsenide (InGaAs) photodiodes have responsivities close to 0.7 and 1.1 A/W respectively in the 1.3 to 1.55μm range.

Block diagram for dual-in-line, 24-pin transmitter and receiver modules are shown in Figs 1 and 2 respectively. Specifications of the transmitter module in Fig. 1 are as follows:

1. 0-2MB/sec data rate
2. 27dBm light output (80μm cone)
3. 800-900nm wavelength
4. GaAlAs LED light source
5. +5 ±0.25V voltage supply
6. TTL compatible
7. -20° to +70°C operating temperature

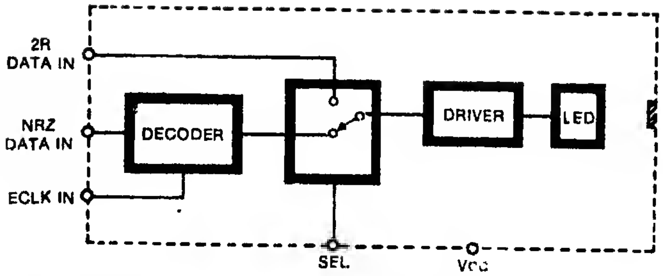

Fig. 1: Block diagram of transmission module.

8. 7.5mm × 10mm × 37mm size.

The receiver module in Fig. 2 has the following specifications:

1. 0-2MB/sec data rate
2. -38dBm minimum receiving power
3. 20dB AGC range
4. Si PIN detector
5. 1-4MHz clock frequency
6. TTL code level
7. 5 ±0.25V voltage supply
8. TTL compatible
9. -20°C to +70°C operating temperature
10. 7.5mm × 15mm × 37mm size

These modules are TTL-compatible and accommodate arbitrary data formats. They provide data transmission over 2 km at a 0-2MB/sec NRZ (non-return to zero) data rate. These modules use 80μm graded, index profiled optical fibre with an attenuation of 15 dB/km. Operating on a single 5V supply, they provide timing signal transmission and automatic link monitoring signal detection to realise regenerative multi-repeating transmission.

Propagating medium

Plastic and glass fibres are used as the propagating medium of light signals from transmitter to receiver. The principle of transmission of energy along an optical fibre is similar to the concept of total internal reflection which occurs when light in a glass core strikes the boundary of the glass sheath of lower refractive index at greater than the critical angle. It is directly dependent upon the ratio of the two refractive indices. Plastic fibre cables are used in optical transmission because of their low cost, high source-fibre coupling efficiency and ease of handling. Their attenuation is high and restricts their application to short links of around 30m.

Optical glass fibre cables consist of a glass fibre clad with a sheath of different glass. The core has a higher refractive index than the sheath. The fibre glass is made of pure silicon. It should have a very low optical scattering and absorption for low losses. The transmitted energy must be optimum with regard to amplitude and phase for maximum transmission capacity.

Despite its high tensile strength, glass fibre needs protection against excessive mechanical loading forces which might occur when pulling a fibre cable through a duct or when hanging it between two poles. To minimise the effect of lateral crushing force, one or two soft plastic buffering layers normally cover the sheathed fibre. Applied shortly after production of the fibre, this buffer provides cushioning and resistance to scratches.

The buffer fibre may be placed loosely within a surrounding plastic tube. In the loose tube the fibre is isolated from external crushing forces and is relatively insensitive to cable bending. The tube may be surrounded by tensile strength member (kelvar) brading. It is further covered by a plastic sheath such as polyurethane to protect against abrasion and to ease handling (Fig. 3). Moisture protection can be provided by filling the tube with a gel. Steel or fibre glass rod is placed inside the cable for increased strength. Armouring can also be included for further protection.

The three type of fibres are: (i) step index fibres (SI); (ii) graded index fibres (GRIN); and (iii) single mode fibres.

Step index fibre

Step index fibre has an inner glass core whose refractive

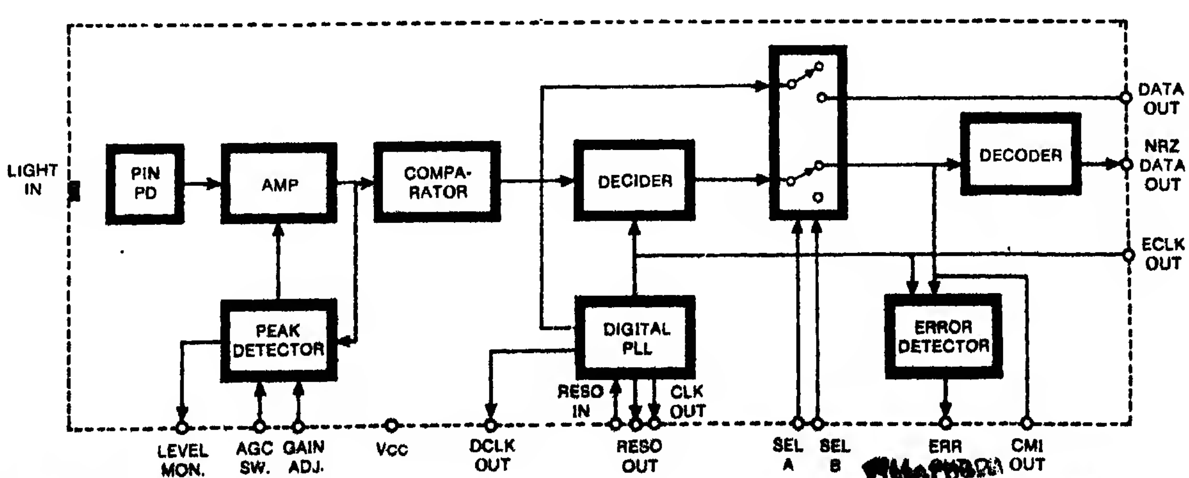

Fig. 2: Block diagram of receiver module.

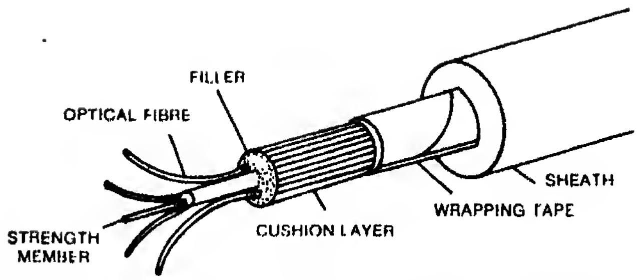

Fig. 3: Long wavelength, four-core layer type optical fibre cable structure.

index is slightly greater than that of the surrounding glass cladding. Variations include a glass core with plastic cladding and a plastic core with plastic cladding. It is called step index fibre because of the rapid change in refractive index at the core-cladding boundary, giving rise to a step-like profile. Refractive index remains constant from the core centre to the core boundary.

The core traps rays of light by a phenomenon called total internal reflection. Light rays which strike the core-cladding interfere at an angle greater than the so-called critical angle and undergo 100 per cent reflection. The equation $\sin \phi = n2/n1$ determines the critical angle, where n1 and n2 are the refractive indices of the core and cladding respectively.

The wave guiding process consists of light rays zigzagging down the fibre, continually reflecting at the core cladding interface. While medium bending does not seriously disturb the transmission process, excessive bending will cause some rays to fall below the critical angle, resulting in leakage of the light out of the core into the surrounding medium.

Information carrying capacity of a transmission line is proportional to its bandwidth. For fibres, the bandwidth is conventionally included in its characteristic bandwidth-length product (B × L). Step index fibres have a bandwidth-length product value of 25 to 30 MHz/km.

Graded index fibre

Graded index fibre has a refractive index which decreases continually from the core axis to the outer edge. The refractive index variation causes light rays to follow sinusoidal paths along the length of the fibre rather than undergoing abrupt reflections, as in the case of the step index fibre.

The higher order modes travel longer distances faster so that all modes arrive at the receiver nearly at the same time. Graded index fibre has a bandwidth-length product value of 600 MHz/km or more.

The bandwidth capacity arises from signal attenuation. Thus, system design requires the following two separate calculations to determine the suitability of a fibre for prescribed bandwidth and length:

1. A calculation of total attenuation to ensure that sufficient power reaches the receiver to clearly detect the intended message.

2. A calculation to ensure that the bandwidth-length product is not exceeded.

Typical fibre cores (50 to 200μm diameter) greatly exceed the operating wavelengths making these fibres multimode waveguides. This means that the light injected into one end of the fibre breaks up into many different patterns for transmission to the other end.

In step index fibre, the different modes correspond to rays travelling at slightly different angles as they zigzag down the fibre. Numerous modes also exist in large GRIN fibres. The differences between the modes of these fibres are difficult to describe in a simple manner. Nevertheless, many different patterns of light are possible in a multimode GRIN fibre.

For both SI and GRIN fibres, different modes travel with different velocities. This causes distortion of the modulated wave shapes. The amount of distortion increases as the wave travels through fibre. It is primarily this effect which limits the bandwidth of multimode fibres.

Single or mono mode fibres

Single mode fibres improve the above situation. Limiting the core diameter to a small size of 0.005 to 0.006 mm in single mode fibre helps propagation in the axial mode only. As the multimode distortion is eliminated, these fibres have much higher bandwidth capacities ranging up to several thousand MHz/km.

Since different wavelengths travel at different velocities, material dispersion for single mode fibres contributes most heavily to signal distortion. Material dispersion manifests itself when white light is decomposed into various colours by a glass prism. The different velocities lead to an unequal amount of bending of ray sources which emit light over a small but significant range of wavelength. The accompanying range of wave velocities occurring in the dispersive fibre results in signal wave shape distortion. Dispersive distortion would disappear if the source emitted perfectly coherent, i.e. single frequency, light. Since dispersions in glass disappear around 1.3μm, single mode fibres have extremely large bandwidth capacities at this wavelength. It has a bandwidth-length product value of 10 GHz/km.

Single mode fibres are difficult to use because of their thin core. Precision connectors are expensive and splicing must be performed carefully. Single mode fibres operating in a low loss, small dispersion, long wavelength region provide the capability for constructing long, high data rate links.

The system designer must choose between step index, graded index, multimode and monomode fibres, specifying the operating wavelength.

Connectors/coupling

For connecting fibre cables to the attached devices, optical connectors are required. These can be repeatedly connected and disconnected without affecting the system performance. Similarly, connectors are required for connecting cable to cable. Precision machine parts are used for coupling. Available connectors are moderately successful in minimising losses. Typical high quality connectors have losses less than 1 dB.

A fibre does not transmit all the rays of light incident upon its face. It efficiently guides only those rays which strike it within a small angular range. Rays within this range undergo total internal reflection for index fibre. They are preferably redirected periodically towards the core axis for GRIN fibres. Incident rays falling outside the acceptance range are eventually lost by transmission into the fibre cladding and buffer.

The fibre numerical aperture (NA) is given by $NA = \sin\theta$, where θ (called the acceptance angle) is the maximum incident ray angle (measured from the fibre's axis) that will result in efficient transmission. Manufacturers' data sheets always include this important fibre characteristic. Numerical apertures of typical fibres range from 0.1 to 0.5. The corresponding acceptance angles vary from 5.7^0 to 30^0.

Most light sources emit rays over a wide angular range, normally much larger than the fibre's acceptance angle. Due to this the source to fibre coupling efficiency can be quite low. For surface emitting LEDs, the coupling efficiency into a multimode step index fibre is $(NA)^2$. This is applicable when mounting the LED directly against fibre end.

For example, if NA is 0.2, the efficiency is only 0.04 or 4 per cent. This represents a 14dB power loss in transferring light from the source to the fibre. The surface emitter radiates light over a cone whose full apex angle is 120^0, while the fibre in this example only collects light over a 23^0 core angle corresponding to an 11.5^0 acceptance angle.

Edge emitting LEDs concentrate their light a bit more than surface emitters so that the coupling efficiency improves a few dB in relation to the results predicted by the preceding equation. Laser diodes concentrate their radiation even more. Laser diode coupling losses of 3 to 5 dB into a 0.2 NA fibre are possible. In system design, one of the first considerations is the source-to-fibre coupling glass.

Lenses are often used to collimate the light radiated by a source. This improves the source coupling efficiency by decreasing the divergence of the emitted light rays. Coupling light from the fibre into the detector is relatively easy. The fibre simply butts against the detector's surface. Due to the detector's insensibility to ray direction, nearly all the detector's active surface is larger than the fibre's core.

Cabling and splicing

Cable laying is easy. Fibre optic cable can be laid directly in the ground or in ducts, or erected on utility poles. Both permanent and temporary fibre connections need to be made in fibre links. Low loss connections require (i) smooth and parallel fibre end faces, (ii) minimum air gap between the fibres, (iii) angular alignment of the two fibre axes, and (iv) axial alignment of the two fibres. These conditions are met with varying amount of success by a number of connectors and splicing schemes.

Flat ends are obtained by several methods. In one, the fibre is scribed lightly with a sharp, hard (diamond or sapphire) blade and then pulled apart. Tools are commercially available to perform this operation. Rubbing the fibre with a fine sand paper and polishing compound also help. Mechanical alignment performed by connector bodies is not a simple task because of the small diameter of most fibres. For example, a $50\mu m$ fibre has a loss of about 0.6 dB if the axial misalignment is only $5\mu m$.

Permanent connections between fibres are most easily produced using fusion splicers. The two fibres fuse together when heated in an electric arc. Losses of 0.1 dB are common.

Developments and future trends

Initial optical fibre development was confined to a multimode technology. 1982 saw its commercial development and initial installations of single mode fibres. Single mode is superior to multimode technology as its more concentrated power allows for longer distances before the optical signal needs to be regenerated.

Today graded index fibres are made in commercial quantity. With an attenuation of less than 4 dB/km to a wavelength of $0.80\mu m$, single polarisation optical fibre will find use in coherent optical communications of the future and optical sensing equipment. This low-loss fibre has excellent polarisation retention properties, even with disturbances such as bending, vibration, thermal changes. It thus transmits the phase information as well as optical energy. Attenuation as low as 2 dB/km at $1.5\mu m$ wavelength has been achieved which is close to the theoretical minimum at that frequency.

Development is progressing on a new and original technique for fibre production called the root accumulation method. This technique guarantees excellence in quality and performance features. Infrared fibres such as fluoride glass is being developed. Ultra-low loss of 10^{-3} dB/km at $2\text{-}4\mu m$ is expected to be achieved practically.

Since the optical fibre exhibits a natural minimum signal attenuation of around 1.3 and 1.5 microns, recent device development has focused on laser diode and LED operation in that area. BH-type (buried-heterojunction type) $1.3\mu m$ long wavelength band laser diode has been developed. It is excellent for use in long-haul transmission in view of its low threshold power and single mode oscillation characteristics.

Fibre optic transmission system

The first generation of fibre optic systems (whose installations began around 1976) operated in the short wavelength region because of the availability of suitable light sources and detectors. This region will always be popular because of the relatively low cost of these devices.

Second generation systems utilise the lower loss, long wavelength region. Fibres have greater information carrying capacity in this region.

Third generation systems combine single mode fibres with highly coherent laser diodes in the long wavelength region.

Exceptionally high data rates and extremely long transmission paths have resulted.

Considering the developments in communication systems during the past several years, it is evident that applications of fibre optic communication systems are becoming more and more practical. Optical fibre networks have now been introduced in such industries as electrical power, steel, automobile as well as in long distance optical transmission systems in public telecommunication networks.

Development of fibre optic systems is associated with the development of optoelectronics. Optoelectronics has the potential of developing new communication and information processing systems by means of integrating devices and systems. In coming years, optoelectronics should play a key role in upgrading information systems and its impact on information industry will become more and more apparent.

Several transmission systems have been developed, for diversified applications such as (i) short wavelength transmission modules for the communication, (ii) long wavelength transmission modules for telecommunications, (iii) digital transmission modules, (iv) analogue modules for TV transmissions, and (v) system modules including link transmission modules for use in data loop transmission systems such as office automotion fibre loop link systems which carry voice, data and facsimile signals and highway traffic control systems.

Some of the systems slated for current and future development are:

1. Digital video transmission system that simultaneously transmits one TV channel as well as voice and data signals.
2. Bidirectional wavelength multiplexed transmissions carrying audio, data and request signals as well as video signals.
3. High resolution TV and TV telephones applications.
4. Fibre optic subscriber distribution systems.
5. International submarine optical fibre systems.

Digital and analogue transmission links are designed specifically for the fibre optic transmission systems consisting of a modular or subrack transmitter and receiver in small compact package. These systems offer the designer a choice of sensitivity, bandwidth, and other specifications making them useful in a wide variety of applications such as data transmission, high voltage optically isolated data systems, computer interface, process control and instrumentation. These small-size modules are complete functional units requiring a standard TTL data input and 5V power supply for operation at data rates of 50 MB/sec for distances over 2 km.

Fibre optics find application in a variety of modern transmission systems. Let us briefly discuss some systems developed and used for commercial applications.

Long wavelength transmission system

An optical PCM transmission system used for medium capacity communication is configured in Fig. 4. It is a 32MB/sec optical transmission system with a wavelength of about 1.3μm and repeaterless transmission distance of 35 km. The system uses GaAsP/InP LD for optical source and Ge-APD for optical detector. The matchbox-size LD module contains a peltier device and thermistor, a photodiode, three rod lenses, a beam spliter and an optical connector. Coupling loss is 3 to 7 dB. The module is a smaller device consisting of Ge-APD, a rod lense and a connector. Its coupling loss is less than 3 dB with a quantum efficiency of 70 per cent.

The two-way optical transmission equipment (OTE) is composed of the following packages: a bipolar unipolar converter (B/V), two optical transmitters (E/O), an optical directional-coupler (OPT-HYB), a modulator and demodulator (OW-SV), optical converter (U/B), an error detector (ERR-DET), and a power supply (PS). OTE is connected to a multiplexer (MUX). Bipolar code is used between the interface of the OTE and the MUX. OTE size is 250mm × 520mm × 225mm. Its subrack structure makes installation and maintenance easy.

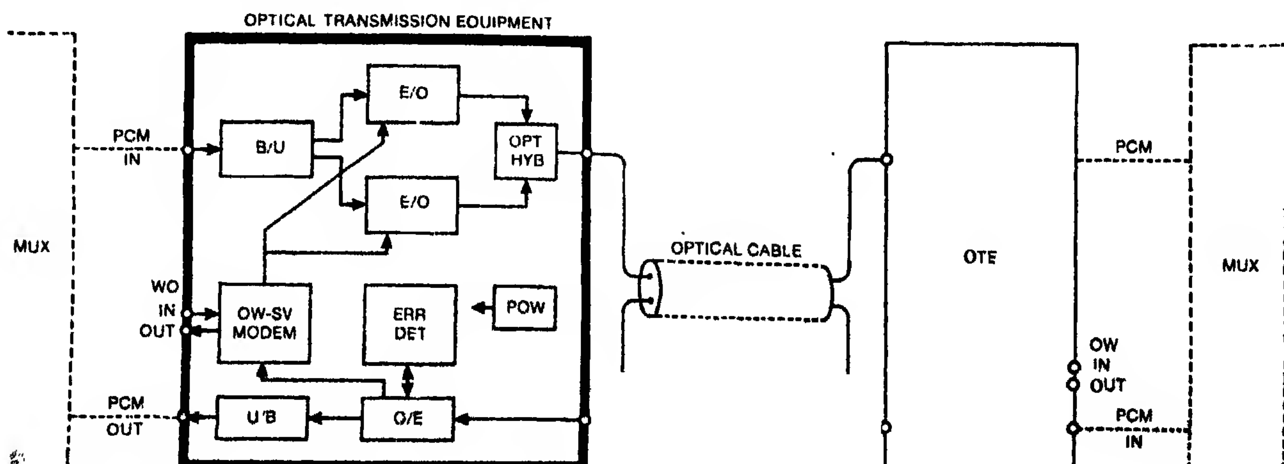

Fig. 4: Configuration of an optical digital transmission system.

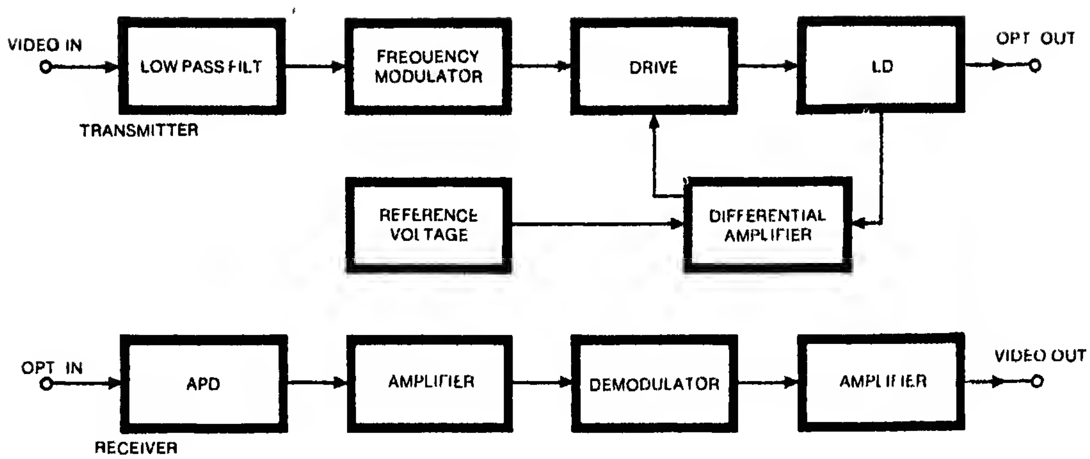

Fig. 5: PFM equipment configuration.

Analogue optical video transmission system

Higher resolution on video pictures and longer distance transmission can be realised by using optical fibre video transmission. It is superior to metallic line video transmission because of its wide bandwidth and low optical loss and less noise. It is being used increasingly in industrial television systems (ITV), video response systems, CATV and other areas.

System configuration shown in Fig. 5 is a pulse frequency modulation system (PFM) with laser diode (1.3μm wavelength) used for about 20 km long distance transmission for video monitoring (used in railway, highways etc). In this system, the carrier frequency is modulated by the video signal and the modulation output is changed to a pulse waveform. The laser diode current is driven by this pulse. At the receiver, transmitted signal is demodulated into a video signal. The SNR obtained by the system is 51 dB after 20 km transmission.

Optical fibre data free-way (DFW) system

With greater automotion and integration, local area networks have become larger and more advanced in process control and office automation areas. With its excellent properties such as low attenuation, broad bandwidth, and totally dielectric transmission medium, fibre optics can effectively realise communication subsystems like wide area, broad bandwidth network system and anti-environmental instrumentation and control systems, which are difficult to make with conventional electric transmission systems.

Fig. 6 shows a basic configuration of a 10MB/sec fibre optic data free-way system for a large-scale distributed computer control. It consists of 3R (retiming, reshaping, regeneration) repeaters, fibre cable and node control, master control and intelligent stations. By adopting the duplex configuration of the control station (CST) and each acting as a backup for the other, a reliable optical fibre DFW system is realised. The master station is connected to the host computer. Its main functions are (i) transmission control for the loop systems, (ii) data transfer control, and (iii) high speed interface control to the host computer.

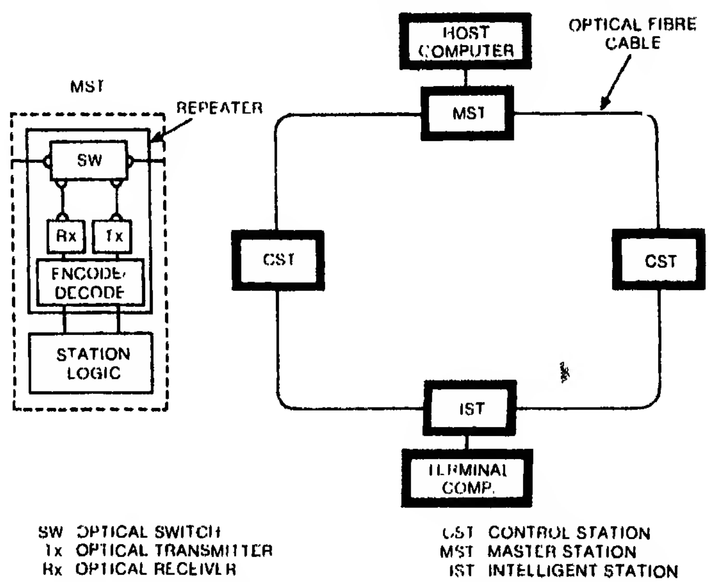

Fig. 6: Basic configuration of the DFW system.

The intelligent station is connected to a terminal computer. According to the remote command from the host computer, it performs the following functions:

1. Start, stop and reset function of the terminal computer.
2. Remote loading of data and programs (live or diagnostic) from the host computer.
3. Read-back function of programs in the terminal computers and RAS (reliability of availability and service) information.

Following are the system specifications:

1. Max. 225 stations/loop
2. Max. 2kms distance between stations
3. 10MB/sec transmission speed
4. Max. 512 bytes variable length message

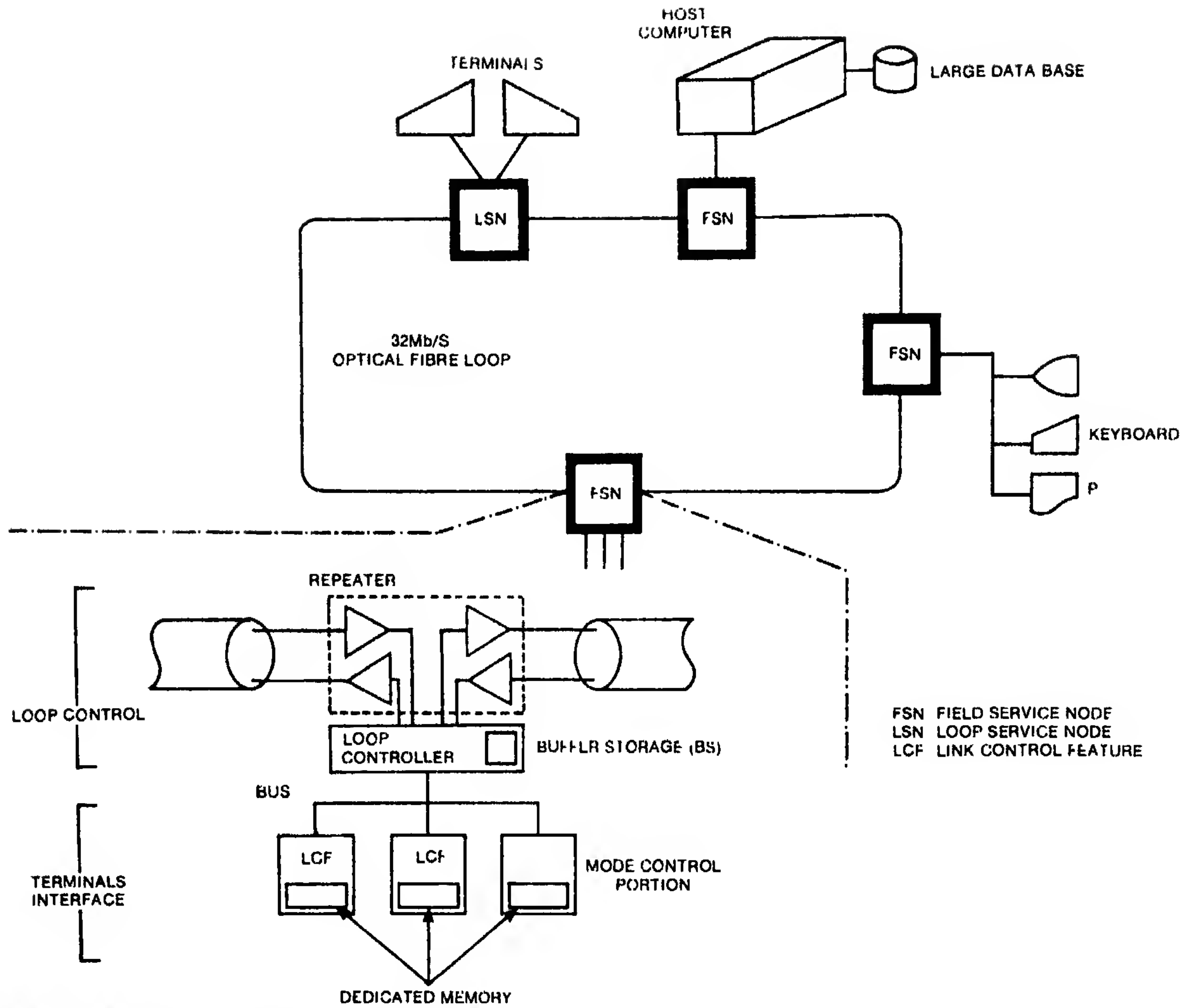

Fig. 7: System configuration of 32MB/sec loop network.

5. Automatic retransmission
6. Max. 900kB/sec channel throughput
7. 0-50°C operational temperature

Optical fibre loop network

Fig. 7 configures a 32MB/sec optical fibre loop network for application in production control, laboratory and office automation. It is a packet switching network which provides international standard packet interface CCITT × 25, to the terminals with following specifications:

1. Max. 126 nodes/loop
2. 100km max. loop length
3. Max. 2kms distance between nodes
4. NM communication mode
5. 32MB/sec transmission speed
6. Token access and loop answer method
7. LED emitter and PIN PD detector
8. 3dB/km optical fibre pair loss

Cost

There is a steady decrease in the price of cable, components and systems. Over a decade optical cable industry has experienced a 45-fold increase in the amount of cable used, and during the same period the cost of fibre cable has come down by 60 per cent. The cost of optical fibre cable is now competitive with that of copper cables.

As an infant technology, fibre optics is benefiting from the declining prices that accompany an early phase of industrial growth. It is expected that the costs of fibre optic cable and associated optoelectronics will continue to decrease at the rate of around 15 per cent a year. Copper transmission, a more mature technology, offers little promise of either advances in capabilities or downward trend in prices.