UNIT-V

Design of Analog Systems:

- System specification,
- Power budget,
- Bandwidth budget

Design of Digital Systems:

- System specification,
- Rise time budget,
- Power budget,
- Receiver sensitivity.

Applications:

- Telephony,
- Telemetry,
- Video distribution,
- Military applications,
- Passive and active sensing.

DESIGN OF DIGITAL SYSTEM:

POINT-TO-POINT LINKS:

A P-T-P link has a transmitter on one end and receiver on the other. The three major optical link building blocks are transmitter, receiver & optical fiber.

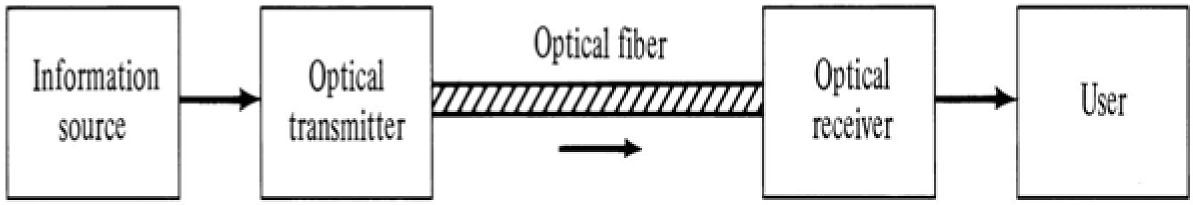


Fig. 5.1: simplex point-to-point link.

Performance and cost constraints are very important factors in OFC links. It is necessary to carefully choose the components to ensure that the desired performance level can be maintained over expected system life time.

The following key system requirements are needed in analyzing a link.

1] Desired transmission distance 2] Data rate or channel BW 3] The bit error rate [BER].

To fulfil these requirements the designer has a choice to choose the following components and their associated characteristics.

Multimode or single mode optical fiber:

[a] core size [b] core RIP's [c] BW [d] attenuation [e] NA

LED or Laser diode optical source:

[a] emission wavelength [b] spectral line width [c] output pattern [d] Effective radiating area [f] emission pattern.

Pin or APD:

[a] operating wave length [b] responsivity [c] speed [d] sensitivity

Two analyses ensure the system performance. They are [1] Link power budget [2] System rise-time-budget.

SYSTEM CONSIDERATIONS:

First it is necessary to decide at which wavelength to transmit & choose the components according to that wavelength. If short distance, then choose 800 to 900 nm. If long distance, then choose 1300 to 1550 nm.

After choosing wavelength, it is necessary to choose 3 major building blocks: receiver, transmitter & fiber.

If the components have been over or under specified, design iteration may be needed.

Photo detector: Photo detector may be chosen based on [a]optical source [b] how much data can be transmitted over a particular fiber before amplifier is needed [c] minimum optical power that must fall on photo detector to satisfy BER.

PIN: Simple, more stable, less expensive, bias voltage required is 5v.

APD: Bias voltage required is 40v, but it has increased sensitivity than PIN.

LED or Laser Diode: Spectral width of LD is narrower than LED. LED is generally used for short distance communication, operated on 800-900nm. LD is generally used for long distance communications, operated on 1300-1550nm. LD delivers 10 to 15dB more power than LED.

Optical Fiber: Single-mode or Multi-mode fibers. Multi-mode fibers are used when light source is LED.

LINK POWER BUDGET:

The optical power received at the photodetector depends on amount of light coupled into the fiber and the losses occurring in the fiber and at the connectors and splices. The link loss budget is derived from the sequential loss contributions of each element in the link.

Each of these loss elements is expressed in decibels (db) as

Loss=10log p_{out}/p_{in}

The link loss budget simply considers the total optical power loss P_T that is allowed between the light source and the photodetector and allocates this loss to cable attenuation, connector loss, splice loss, and system margin. Thus, if P_S is the optical power emerging from the end of a fiber fly lead attached to the light source or from a source-coupled connector, and if P_R is the received sensitivity, then $P_T=P_S-P_R = 2l_c + \alpha L$ + system margin. Here, l_c = connector loss, α = fiber attenuation [dB/Km], system margin is normally taken as 6 dB.

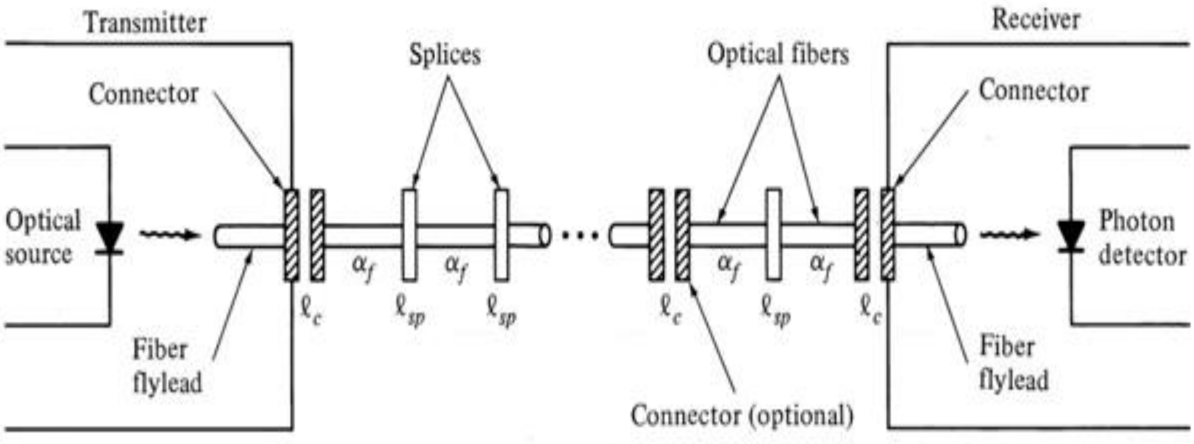


Fig. 5.2: Optical power loss model for point-to-point link.

RISE-TIME BUDGET ANALYSIS:

It is a convenient method to calculate dispersion limitations of an optical fiber link. The total rise time t_{sys} of link is root sum square of rise times from each contributor t_i to the pulse rise time degradation. $t_{sys} = [\sum^{N}_{i=1} t_i^2]^{1/2}$

The system speed is limited by [i] Transmitter rise time t_{tx} [ii] Group velocity dispersion rise time [GVD] t_{GVD} of fiber [iii] Model dispersion rise time t_{mod} of fiber [iv]Receiver rise time t_{RX}.

The transmitter rise time is primarily due to light source and its driver circuitry.

The response of receiver front end is given by $g(t) = [1-\exp(-2\pi B_{RX}t)]u(t)$. where u(t)= unit step function, B_{RX} = 3dB electrical BW of receiver. The rise time t_{RX} of receiver is $t_{RX} = 350/ B_{RX}$

The fiber rise time resulting from GVD & Modal dispersion. The rise time resulting from GVD is $t_{GVD}= [/D/]L\sigma_\lambda$. Where σ_λ= half-power spectral width of the source, D= dispersion, L= length.

The BW B_M in a link of length L can be expressed by $B_M(L) = B_O/L^q$. where B_O= BW of 1km length of cable, q=0.5 to 1. The rise time resulting from modal dispersion $t_{mod} = 0.44/ B_M$ $= 0.44\ L^q/ B_O$. If t_{mod} expressed in nsec & B_M in MHz then $t_{mod} = 44o/ B_M = 440L^q/ B_O$

Therefore $t_{sys} = [t_{tx}^2 + [440L^q/ B_O]^2 + [D\ L\sigma_\lambda\ ]^2 + [350/ B_{RX}]^2]^{1/2}$.

In 800 to 900 nm region, D is about 0.07 which is principally a material dispersion. $t_{GVD}^2=t_{mat}^2$.

POWER PENALTIES:

When there is any impairments effects are present in a link, there is a reduction in the signal-to-noise ratio (SNR) of the system from the ideal case.

The reduction in SNR is known as the power penalty. It is expressed in decibels.

$PP_X = -10 \log [SNR_{impair}/SNR_{ideal}]$

Chromatic dispersion penalty:

Chromatic dispersion originates from the fact that each wavelength travels at a slightly different velocity in a fiber, and thus they arrive at different times at the fiber end. Therefore the range of arrival times at the fiber end of the spectrum of wavelengths will lead to pulse spreading.

The accumulated chromatic dispersion increases with distance along a link. A basic estimate of what limitation chromatic dispersion imposes on link performance can be made by specifying that the accumulated dispersion should be less than a fraction of the bit period $T_b = 1/B$, where B is bit rate.

Polarization mode dispersion penalty:

Polarization mode dispersion (PMD) results from the fact that light-signal energy at a given wavelength in a single mode fiber actually occupies two orthogonal polarization. PMD arises because the two fundamental orthogonal polarization modes travel at slightly different speeds owing to fiber birefringence. The resulting difference in propagation times between the two orthogonal polarization modes will result in pulse spreading. PMD is not a fixed quantity but fluctuates with time due to factors such as temperature variations and stress changes on fiber.PMD varies as the square root of distance and thus is specified as a maximum value in units of ps / square root of KM.

To have a power penalty less than 1.0db, the pulse spreading result from PMD

$\Delta T_{PMD} <$ 10% of bit period T_b. i.e., $\Delta T_{PMD} = D_{PMD} [L]^{1/2} < 0.10\, T_b$

Extinction ratio penalty:

The extinction ratio r_e in a laser is defined as the ratio of the optical power level P_1 for a logic 1 to the power level P_o for a logic 0, that is $r_e = p_1/p_0$. Ideally one would like the extinction ratio to be infinite, so that there would be no power penalty from this condition. In this case, if P_{ave} is the average power then $P_o=0$ and $p_1=2p_{ave}$. Letting p_{1-er} and p_{0-er} be the 1 and 0 power levels, respectively, with a non-zero extinction ratio , and defining $r_e = p_{1-er}/p_{0-er}$,

the average power is $p_{ave} = [p_{1-er} + p_{0-er}]/2$

$$p_{ave} = P_{0-er} [[r_e+1]/2]$$

$$p_{ave} = P_{1-er} [[r_e+1]/2r_e]$$

When receiver thermal noise dominates, then the 1 and 0 noise powers are equal and independent of the signal level. In this case $P_0=0$ & $P_1 = P_{ave}$. Power penalty is given by $PP_{ER} = -10 \log([r_e-1]/[r_e+1])$.

ERROR CONTROL:

In any digital transmission system, errors are likely to occur even when there is a sufficient SNR to provide a low bit error rate. To control the errors, first it is necessary to be able to detect the errors and then either to correct them or retransmit the information.

Error detection methods encode the information stream to have a specific pattern. If segments in the received data stream violate this pattern, then errors have occurred.

The 2 basic schemes for error correction are repeat request [ARQ] & forward error correction [FEC].

ARQ technique uses a feedback channel between the receiver and the transmitter to request message retransmission in case errors are detected at the receiver. Since each retransmission adds at least one round-trip time of latency.

FEC avoids the shortcomings of ARQ for high bandwidth optical networks requiring low delay. In FEC technique, redundant information is transmitted along with original information. If some of the original data is lost or received in error, the redundant information is used to reconstruct it.

An error in a data stream can be categorized as a single bit error or a burst error.

LINEAR ERROR DETECTION CODES:

The single parity check code is one of the simplest error detection methods. This code forms a code word from the combination of K information bits and a single added check bit. If the K information bits contain an odd number of 1 bits, then the check bit is set to 1; otherwise it is set to 0. This procedure ensures that the code word has an even no. of ones, which is called having an even parity.

If the received code word contains an even number of errors, this method will fail to detect the errors. The single parity check code is called a linear code. POLYNOMIAL CODES:

Polynomial codes are used for error detection. The information symbols, the code words, and the error vector are represented by polynomials with binary coefficients. The encoding process generates check bits by means of a process called a cyclic redundancy check [CRC].

ANALOG LINKS:

The transmitter contains either an LED or a laser diode optical source. The simplest form for optical fiber links is direct intensity modulation, wherein the optical output from the source is modulated simply by varying the current around the bias point in proportion to the message signal level.

In relation to the fiber-optic elements, one must take into account the frequency dependence of the amplitude, phase, and group delay in the fiber. Thus the fiber should have a flat amplitude and group-delay response within the pass band required to send the signal free of linear distortion.

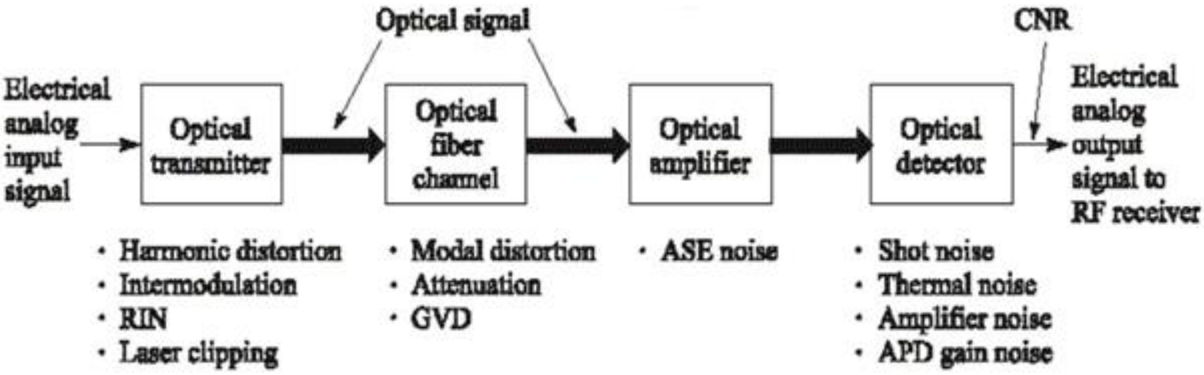


Fig.5.3 : **basic elements of an analog link and the major noise contributors**

The fiber attenuation is also important, since the carrier-to-noise performance of the system will change as a function of the received optical power.

Carrier-to-noise ratio (CNR):

CNR is defined as the ratio of rms carrier power to rms noise power at the input of the RF receiver following the photo detection process. This is known as CNR.

The total CNR is given by CNR = Carrier power / [source + photo diode + amplifier + inter modulation noises] --------→ [1]

For a sinusoidal received signal, the carrier power C at the output of the receiver is

$C = [1/2] (mRM\bar{P})^2$ -----------→ [2]

where m = modulation index, R = unit gain responsivity of the photodetector, M = photodetector gain & $\bar{P}$ is the average received optical power.

The photodiode noises are given by

$\langle i_N^2 \rangle = \sigma_N^2 = 2q(I_p + I_D)M^2F(M)B_e$ ---------→ [3]

Where I_p = primary photo current = $R_0\bar{P}$

I_D = detector bulk dark current, M = photo diode gain with F(M) being its associated noise figure, B_e = receiver band width.

The CNR for the photodetector only is $CNR_{det} = C / \sigma_N^2$.

The preamplifier noise is given by

$\langle i_T^2 \rangle = \sigma_T^2 = [4k_BT/R_{eq}]B_eF_t$ ---------------------→ [4]

Where R_{eq} = equivalent resistance of the photodetector load and preamplifier and F_t = noise factor of preamplifier.

The CNR for the preamplifier only is $CNR_{preamp} = C/ \sigma_T^2$

The Relative Intensity Noise [RIN]: within a semiconductor laser, fluctuations in the amplitude or intensity of the output produce optical intensity noise. These fluctuations could arise from temperature variations or from spontaneous emission contained in the laser output. The noise resulting from the random intensity fluctuations is called RIN, which may be defined in terms of mean square intensity variations. The resultant mean square noise current is given by

$\langle i_{RIN}^2 \rangle = \sigma_{RIN}^2 = RIN(R\bar{P})^2B_e$ ---------------------→[5]

The CNR due to laser amplitude fluctuations only is $CNR_{RIN} = C/ \sigma_{RIN}^2$

Substituting [2], [3], [4] & [5] in equation [1]

$[C/N] = [[1/2] (mRM\bar{P})^2] / RIN(R\bar{P})^2B_e + 2q(I_p + I_D)M^2F(M)B_e + [4k_BT/R_{eq}]B_eF_t$

MULTICHANEEL TRANSMISSION TECHNIQUES:

In broadband analog applications, such as cable TV [CATV], super trunks etc,. One needs to send multiple analog signals over the same fiber. This can be done by employing a multiplexing technique where a no. of baseband signals are superimposed electrically on a set of N subcarriers that have different frequencies $f_1, f_2, - - - f_N$

These modulated subcarriers are then combined electrically through FDM to form a composited signal that directly modulates a single optical source.

VSB-AM, FM, subcarrier multiplexing methods is adopted to modulate the optical source. Of these AM is simple & cost effective, but its signal is very sensitive to noise and non-linear distortion.

FM requires large BW then AM; it provides higher SNR & is less sensitive to source non-linearity.

Subcarrier multiplexing [SCM] operates at higher frequency than AM & FM.

MULTICHANNEL AMPLITUDE MODULATION:

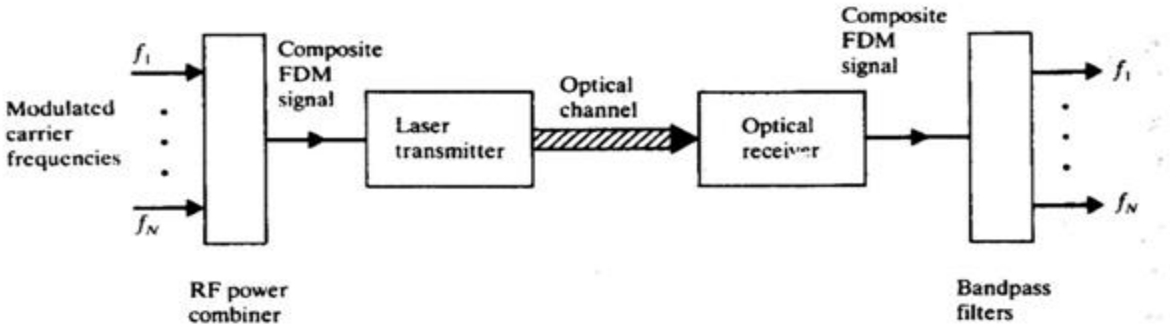


Fig.5.4: frequency division multiplexing of N independent information bearing signals.

In broadband analog applications, such as cable television (CATV) super trunks, one need to send multiple analog signals over the same fiber.

A multiplexing technique where a number of baseband signals are superimposed electronically on a set of N subcarriers that have different frequencies f_1, f_2....f_N.

An information bearing signal on channel i amplitude modulates a carrier wave that has a frequency f_i , were i=1,2,.....N.

An RF power combiner then sums these N amplitude – modulated carriers to yield a composite frequency-division-multiplexed(FDM) signal which intensity modulates a laser diode.

Following the optical receiver, a bank of parallel band pass filters separates the combined carriers back into individual channels. For N channels the optical modulation index m is related to the per-channel modulation index m_i by

$$m=[\sum_{=1} \quad]^{1/2}$$

If each channel modulation index m_i has same value m_c then $m = m_c N^{0.5}$.

MULTICHANNEL FREQUENCY MODULATION:

The use of AM-VSB signals for transmitting multiple analog channels is straight forward & simple. But C/N requirement is 40db for each AM channel which places very stringent requirements on laser and receiver linearity.

Alternative technique is FM.

Each subcarrier is frequency-modulated by a message signal. This requires a wider bandwidth (30 MHZ versus 4 MHZ for AM), but yields a SNR ratio improvement over the carrier-to-noise ratio.

The S/N at the output of an FM detector is much larger than the C/N at the input of the detector. The improvement is given by

$$[S/N]_{out} = [C/N]_{in} + 10\log\left[\frac{3}{2}\frac{B_e}{f_v}\left(\frac{\Delta f_{PP}}{f_v}\right)^2\right] + w$$

where B_e=required bandwidth,Δf_{pp} = peak-to-peak frequency deviation of the modulator, f_v = highest video frequency, w is weight factor for non-uniform response of the eye pattern to white noise in video.

SUB CARRIER MULTIPLEXING:

The term subcarrier multiplexing (SCM) is used to describe the capability of multiplexing both ***multichannel analog*** *and* ***digital*** signals within the same system.

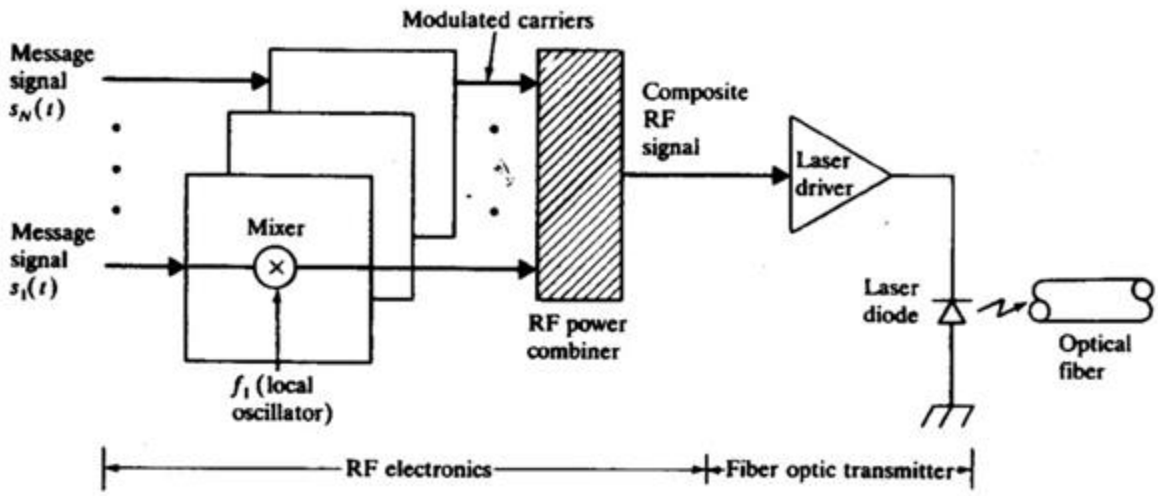


Fig. 5.5: subcarrier multiplexing

The input to the transmitter consists of a mixture of N independent analog and digital baseband signals. Each incoming signals $S_i(t)$ is mixed with a local oscillator (LO) having a frequency f_i. The local oscillator frequencies employed are in the 2-to-8-GHZ range and are known as subcarriers. Combining the modulated subcarriers gives a composite frequency-division-multiplexed signal which is used to drive a laser diode.

At the receiving end, the optical signal is directly detected with a high speed wideband InGaAs pin photodiode and converted to a microwave signal.

RF OVER FIBER:

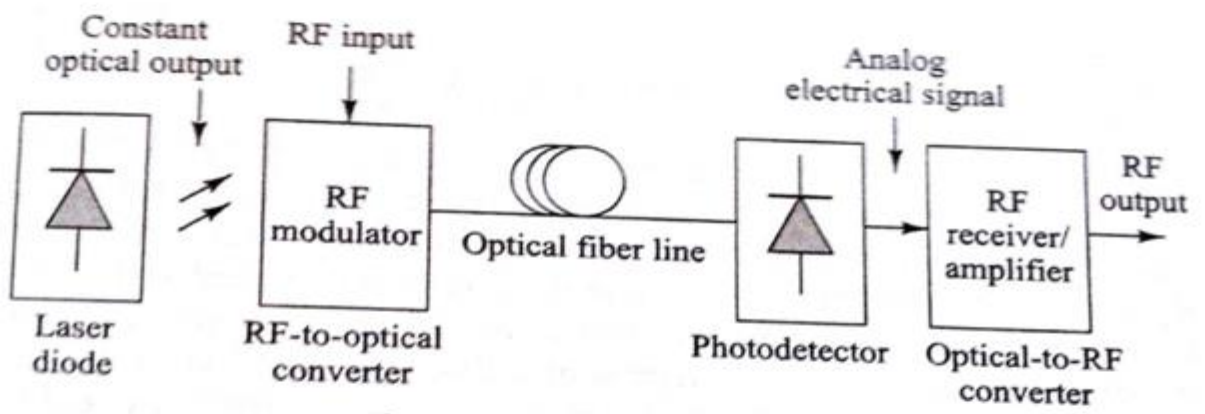


Fig 5.6: Basic constituents of a generic RF over fiber link

Radio frequency (RF) signals at microwave and millimetre –wave frequencies are used in applications such as radars, satellite links, broadband terrestrial radios and cable television networks.

The three major modules are, RF-to optical signal converting device at the transmitting end. Optical-to-RF signal converting device at the receiving end. An optical fiber that joint these two modules

The parameters used to characterize the RF performance is Link gain: It is defined as the ratio of the RF power P_{out} generated in the photodetector load resistor to the RF power input P_{in} to the laser transmitter. Thus for a directly modulated link the gain is

$$G = \frac{POut}{Pin}$$

Noise figure: It represents a measure of the degradation in the signal-to-noise ratio (SNR) between input and output of the link

$$NF=10\log \frac{SNR_{in}}{SNR_{OUT}}$$

RADIO-OVER-FIBER LINK:

The application of RF-over-fiber technology is in broadband wireless access networks for interconnecting antenna base station (BSc) with the central controlling office.

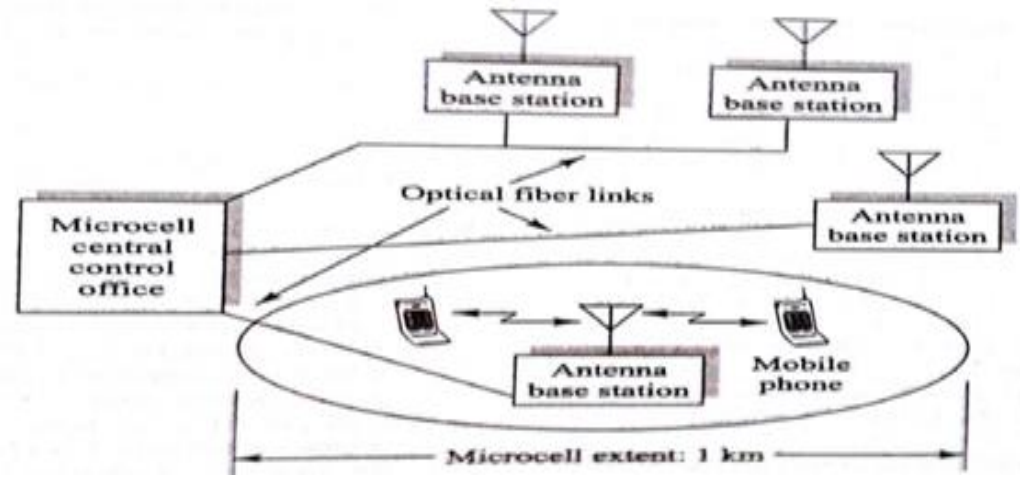


Fig 5.7: Radio over fiber broadband wireless access network.

Here a collection of antenna base stations provide wireless connectivity to subscribers by means of millimetre wave frequencies. Subscribers are located up to 1 KM from a local base station. The transmission range around a BS is called a microcell [diameter less then 1Km] or a picocell or hotspot.

The BSc are connected to a microcell control station (cs) in the central office, which is responsible for functions such as RF modulation and demodulation, channel control, and switching and routing of customer calls.

Due to the advantages of optical fibers [low loss, high immunity to electromagnetic interference and a wide band width], they used to connect base stations to central office.

Individual BSs can be connected independently to the microcell CS through WDM techniques by using a separate unique wavelengths for each BS.

APPLICATIONS:

The primary advantages obtained using optical fibers for line transmission can be summarized as follows:

- Enormous Potential BW
- Small size & Light Weight
- Electrical Isolation
- Immunity to interference and crosstalk
- Signal Security
- Low Transmission loss
- Ruggedness & Flexibility
- Low cost

TELEMETRY:

The trunk or toll N/W is used for carrying telephone traffic between major Conurbations. Hence there is generally a requirement for the use of transmission systems which have a high capacity in order to minimize cost per circuit.

Optical fiber systems with their increased BW and repeater spacing's offer a distinct advantage.

The local and rural N/W or subscriber loop connects telephone subscribers to the local switching center or office. Possible N/W configurations are shown in figure and include a ring, tree and star topology from local switching center.

Ring N/W – any information fed into n/w by a subscriber passes through all n/w nodes and hence number of transmission channels must be provided between all nodes. In this case only information addressed to a particular subscriber is taken from N/W at that particular subscriber node.

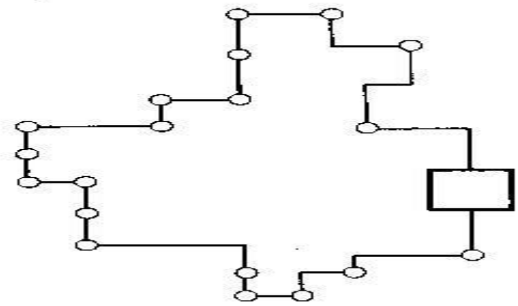


Figure: Ring N/W

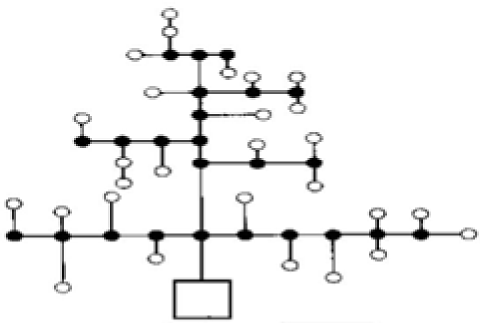


Figure: tree n/w topology

TREE N/W TOPOLOGY:

It consists of several branches as shown in figure, must also provides a number of transmission channels on its common links. It has advantage of greater flexibility in relation to topology enlargement. But the number of subscribers is limited by the transmission capacity of links used.

STAR N/W TOPOLOGY:

It provides separate link for each subscriber to local switching center. Hence the amount of cable required is increased but, enhanced reliability and availability for the subscribers. In addition simple subscriber equipment is adequate and n/w expansion is straight forward. It provides wide band services [video, tv, data].

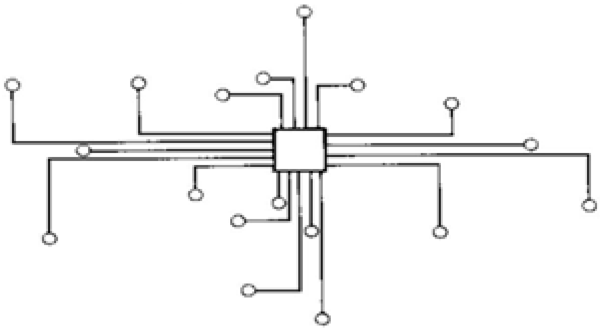


Figure: star n/w topology

In the UK a small Fibrevision (Cable TV) network has been installed in Milton Keynes using a switched star configuration [Refs. 20 and 21]. This has led to planning for the implementation of a full scale local network based on the same principles which will eventually incorporate more advanced entertainment and information services as well as an interactive capability. The topology for this multistar network is illustrated in Fig. 11.4 [Ref. 22]. It consists of three types of transmission link, namely super-primary links, primary links and secondary links. The two former link types will require high capacity and significant transmission distances (up to 20 and 5 km respectively) in order to distribute the wideband services, and hence optical fibers provide an ideal solution. The primary links service wideband switch points (WSPs) from hub sites giving access to all program material and services. In the larger

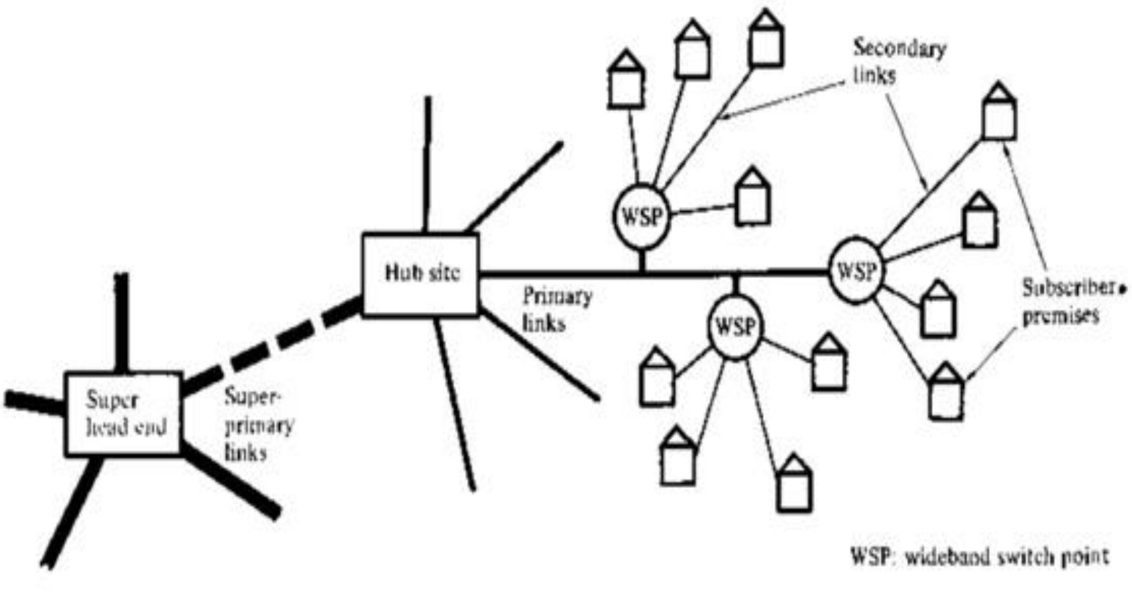


Fig. Multistar wideband local network configuration schemes these hub sites will in turn be fed from a super head end where most of the program material and services will originate. Short secondary links (up to 1 km) will fan out from the WSPs to the subscriber premises. The use of wideband switching reduces the capacity required on these secondary links. Economic considerations, especially when the cost of the optoelectronic interface equipment is included, suggest that at present coaxial cable provides the best solution, on cost grounds, for these secondary links. However, it is indicated [Ref. 22] that a large scale integration approach for the optical equipment, to give a low unit cost, may allow optical fibers to be utilized for these secondary links in the future.

MILITARY APPLICATIONS:

In these applications, although economics are important, there are usually other, possibly overriding, considerations such as size, weight, deployability, survivability (in both conventional and nuclear attack [Ref. 26]) and security. The special attributes of optical fiber communication systems therefore often lend themselves to military use.

MOBILES:

One of the most promising areas of military application for optical fiber communications is within military mobiles such as aircraft, ships and tanks. The small size and weight of optical fibers provide an attractive solution to space problems in these mobiles which are increasingly equipped with sophisticated electronics. Also the wideband nature of optical fiber transmission will allow the multiplexing of a number of signals onto a common bus. Furthermore, the immunity of optical transmission to electromagnetic interference (EMI) in the often noisy environment of military mobiles is a tremendous advantage. This also applies to the immunity of optical fibers to lightning and electromagnetic pulse (EMP) within avionics. The electrical isolation, and therefore safety, aspect of optical fiber communications also proves invaluable in these applications, allowing routing through both fuel tanks and magazines.

The above advantages were demonstrated with preliminary investigations involving fiber bundles [Ref. 3] and design approaches now include multiterminal data systems [Ref. 27] using single fibers, and use of an optical data bus [Ref. 28]. In the former case, the time division multiplex system allows ring or star configurations to be realized, or mixtures of both to create bus networks. The multiple access data highway allows an optical signal injected at any access point to appear at all other other access points. An example is shown in Fig. 11.5 [Ref. 5] which illustrates the interconnection of six terminals using two four-way star couplers. These devices give typically 10 dB attenuation between any pair of ports.

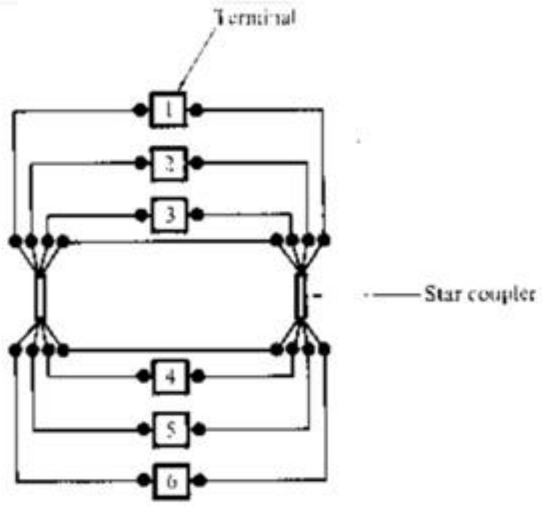


Fig. Multiple access bus showing the interconnection of six terminals using two four-way star couplers

COMMUNICATION LINKS:

The other major area for the application of optical fiber communications in the military sphere includes both short and long distance communication links. Short distance optical fiber systems may be utilized to connect closely spaced items of electronic equipment in such areas as operations rooms and computer installations. A large number of these systems have already been installed in military installations in the UK. These operate distances from several centimeters to a few hundred meters at transmission rates between 50 bauds and 4.8 Kbit s^{-1} [Ref. 29]. In addition a small number of 7 MHz video links operating over distances of up to 100 m are in operation. There is also a requirement for long distance communication between military installations which could benefit from the use of optical fibers. In both these cases **advantages** may be gained in terms of bandwidth, security and immunity to electrical interference and earth loop problems over conventional copper systems.

Other long distance applications include torpedo and missile guidance, information links between military vessels and maritime, towed sensor arrays. In these areas the available bandwidth and long unrepeatered transmission distances of optical fiber systems provide a solution which is not generally available with conventional technology. A fiber guided weapons system is illustrated in Fig. 11.6 whereby a low loss, high tensile strength fiber is used to relay a video signal back to a control station to facilitate targeting by an operator.

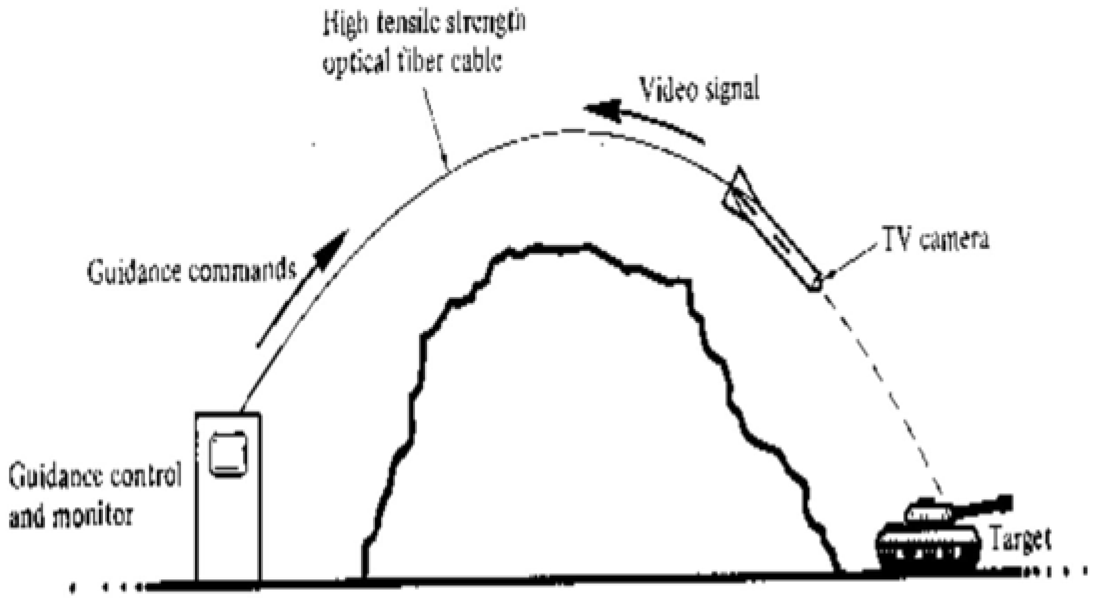


Fig. A fiber guided weapons system.

VIDEO SIGNAL TRANSMISSION:

It was indicated in that optical fibers are eminently suitable for video transmission. Thus optical fiber systems are starting to find use in commercial television transmission. These applications include short distance links between studio and outside broadcast vans, links between studios and broadcast or receiving aerials, and close circuit television (CCTV) links for security and traffic surveillance. In addition, the implementation of larger networks for cable and common antenna television (CATV) has demonstrated the successful use of optical fiber communications in this area where it provides significant advantages, in terms of bandwidth and unrepeatered transmission distance, over conventional video links.

One of the first commercial optical fiber video systems was installed in Hastings, UK, in 1976 by Rediffusion Limited for the transmission of television signals over a 1.4 km link for distribution to 34,000 customers. Another early optical fiber CATV field trial was the Hi-OVIS project carried out in Japan [Ref. 36]. The project involved the installation of an interactive video system, plus FM audio and digital data to 160 home subscribers and 8 local studio terminals in various public premises. The system operated over a 6 km distribution cable consisting of 36 fibers plus additional branches to the various destination points: no repeaters were used in this entire network.

However, digital transmission of video signals is not always economic, owing to the cost and complexity of the terminal equipment. Hence, optical fiber systems using direct intensity modulation often provide an adequate performance for a relatively small system cost. For example, a block schematic of a long distance analog baseband video link for monitoring railway line appearances such as road crossings, tunnels and snowfall areas is shown in Fig. 11.7 [Ref. 41]. Video signals from TV cameras installed at monitoring points C_i are gathered to the concentrating equipment through local transmission lines. These signals are then multiplexed in time, frequency or wavelength on to the main transmission line to the monitoring center.

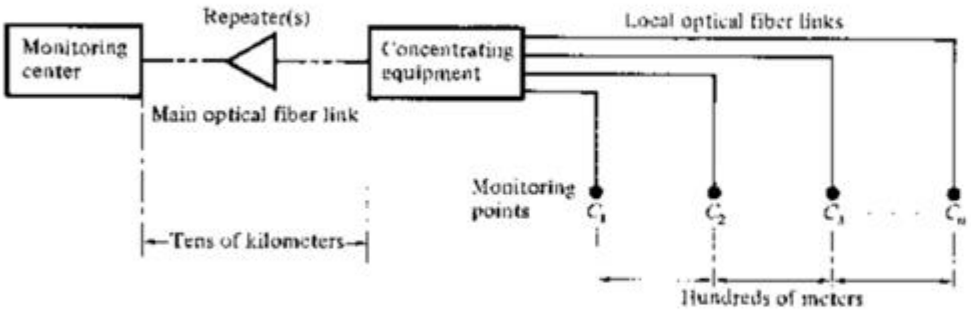
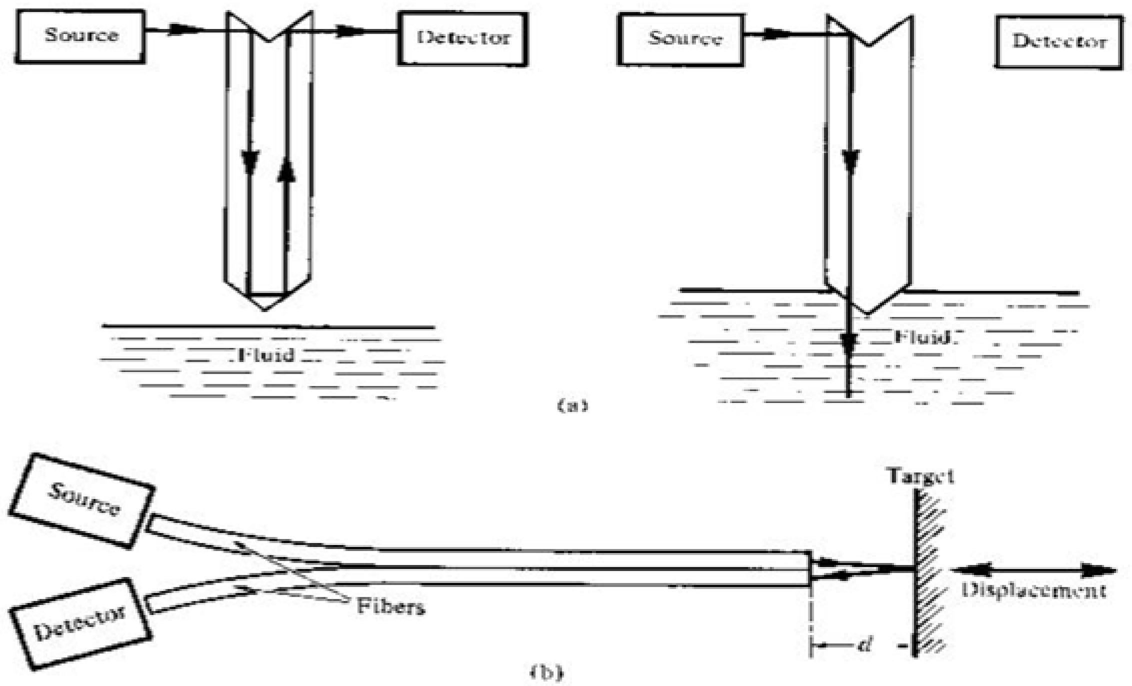


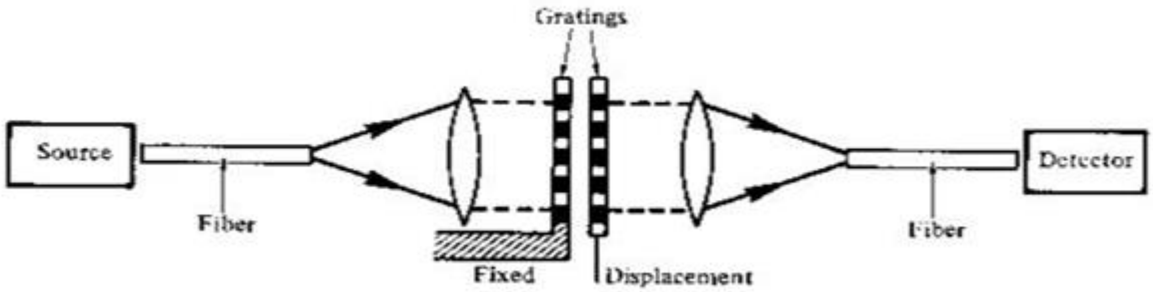
Fig. Block schematic of an optical fiber baseband video system for railway line monitoring

It has been indicated that optical fiber transmission may be advantageously employed for monitoring and telemetry in industrial environments. The application of optical fiber communications to such sensor systems has stimulated much interest, especially for use in electrically hazardous environments where conventional monitoring is difficult and expensive. There is a requirement for the accurate measurement of parameters such as liquid level, flow rate, position, temperature and pressure in these environments which may be facilitated by optical fiber systems. Early work in this area featured electrical or electro-optical transducers along with optical fiber telemetry systems. A novel approach of this type involved a piezoelectric transducer which was used to apply local deformations to a single fiber highway causing phase modulation of the transmitted signal [Ref. 50]. The unmodulated signal from the same optical source was transmitted via a parallel reference fiber to enable demodulation of the signals from various piezoelectric transducers located on the highway. This technique proved particularly useful when a number of monitoring signals were required at a central control point.

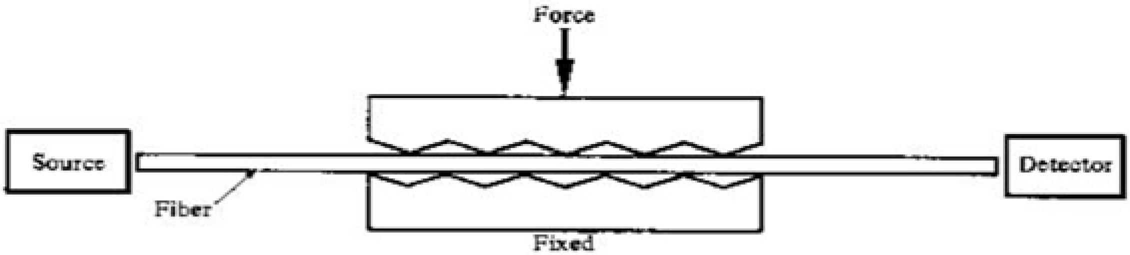
Electro-optical transducers together with optical fiber telemetry systems offer significant benefits over purely electrical systems in terms of immunity to EMI and EMP as well as intrinsic safety in the transmission to and from the transducer. However, they still utilize electrical power at the site of the transducer which is also often in an electrically problematical environment. Therefore much effort is currently being expended in the investigation and development of entirely optical sensor systems. These employ passive optical transducer mechanisms which directly modulate the light for the optical fiber telemetry link. A number of simple optical techniques which enable direct measurement are illustrated in Fig. 11.8. For instance, a fluid level may be detected by the sensor shown in Fig. 11.8(a). When the fluid, which has a refractive index greater than the glass forming the optical dipstick, reaches the chamfered end, total internal reflection ceases and the light is transmitted into the fluid. Hence an indication of the fluid level is obtained at the optical receiver. Although this system is somewhat crude and will not give a continuous measurement of fluid level, it is simple and safe for use with flammable liquids.

Optical sensor mechanisms which provide measurement of displacement are shown in Figs. 11.8(b) and (c). The former is a reflective (often called fotonic) sensor whereby light is transmitted via a fiber(s) to illuminate a target. Light reflected from the target is received by a return fiber(s) and is a function of the distance between the fiber ends and the target *d*. Hence the position of the target or displacement may be registered at an optical receiver. Figure 11.8(c) illustrates the measurement of displacement using a moiré fringe modulator. In this case the opaque lined gratings produce dark Moiré fringes. Transverse movement of one grating with respect to the other causes the fringes to move up or down. Therefore a count of the fringes as the gratings are displaced

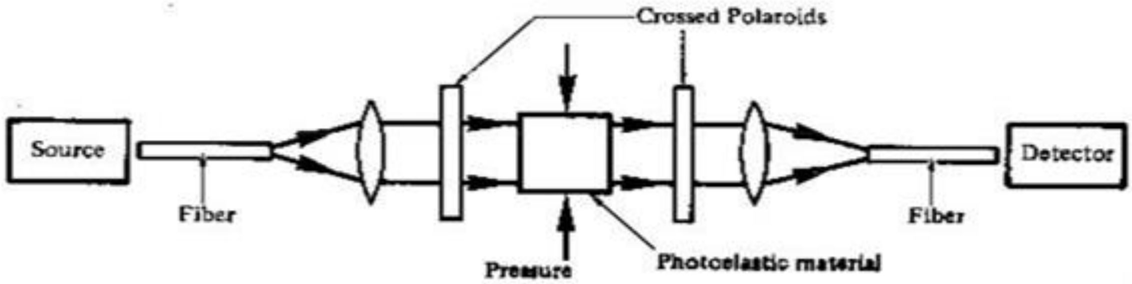




(c)



(d)



(e)

provides a measurement of the displacement. Unlike the previous techniques the Moiré fringe modulator gives a digital measurement (fringe counting) of displacement which is independent of any drift in the characteristics of the optical source. However, mechanical vibrations may severely affect the measurement accuracy and prove difficult to eradicate. Also there are problems involved with the loss of count if, for any reason, optical power to the sensor is interrupted.

The sensors shown in Figs. 11.8(d) and (e) primarily give a measurement of strain or stress. However, this may easily be converted too from a displacement, temperature or pressure. Figure 11.8(d) illustrates a microbending sensor in which the fiber is bent sharply when a force is applied to metal teeth or an array of pins. Light transmitted down the fiber is lost into the cladding due to the microbending (see Section 4.6.2) providing a measurement of the applied force. Hence changes in the applied force (e.g. strain, displacement, temperature, pressure) cause a change in light intensity of the optical receiver which may be recorded.

With the photoelastic sensor shown in Fig. 11.8(e) the light transmitted is a function of stress within the material. This phenomenon, known as birefringence, occurs with the application of mechanical stress to transparent isotropic materials (e.g. polyurethane) whereby they become optically anisotropic. An advantage of this technique is that the stress may be induced directly by pressure without the need for an intermediate mechanism (i.e. pressure to displacement). A drawback, however, is that the birefringence exhibited by photoelastic materials is very temperature-dependent making measurement of a single parameter difficult.

Figure 11.9 shows a possible optical fiber flow meter. A multimode optical fiber is inserted across a pipe such that the liquid flows past the transversely stretched fiber. The turbulence resulting from the fiber's presence causes it to oscillate at a frequency roughly proportional to the flow rate. This results in a corresponding oscillation in the mode power distribution within the fiber giving a similarly modulated intensity profile at the optical receiver. The technique has been used to measure flow rates from 0.3 to 3 m s^{-1} [Ref. 56]. However, it cannot measure flow rates below those at which turbulence occurs.

The most sensitive passive optical sensors to date employ an interferometric approach as illustrated in Fig. 11.10. These devices interfere coherent monochromatic light propagating in a strained or temperature varying fiber with light either directly from the laser source, or (as shown in Fig. 11.10) guided by a reference fiber isolated from the external influence. The effects of strain, pressure or temperature change, give rise to differential optical paths by changing the fiber length, core diameter or refractive index with respect to the
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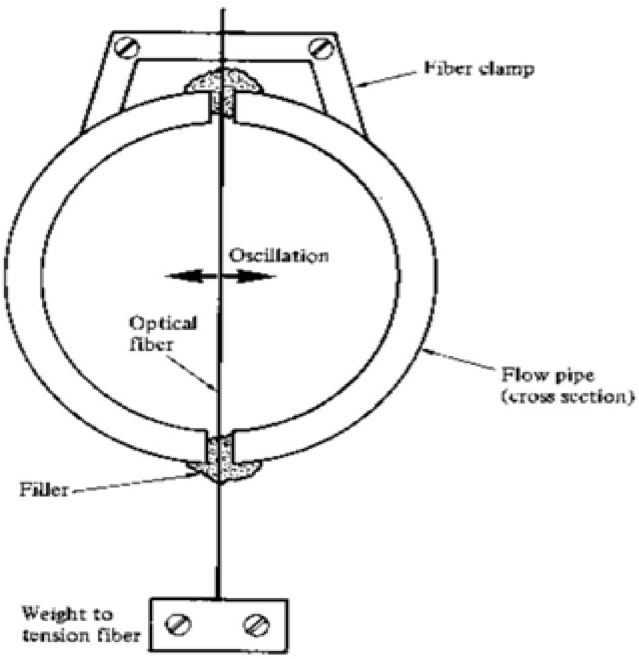

Fig. 11.9 An optical fiber flow meter