Unit: 05

Optical technologies: Wavelength division multiplexing (WDM) concepts: Operational principles of WDM, passive optical star coupler, isolators, circulators, and Active optical components: MEMS technology, variable optical attenuators, tunable optical filters, dynamic gain equalizers, polarization controller, and chromatic dispersion compensators. Optical amplifiers: Basic applications and types of optical amplifiers, Erbium Doped Fiber Amplifiers (EDFA): amplification mechanism, architecture, power conversion efficiency and gain. Amplifier noise, Optical SNR, System applications. Performance Measurement and monitoring: Measurement standards, basic test equipment, optical power measurements, optical fiber characterization, eye diagram tests, optical time-domain Reflectometer, optical performance monitoring.

5.1 Operational Principles of WDM

The technology of combining a number of independent information carrying wavelengths onto the same fiber is known as Wavelength Division Multiplexing or (WDM).A characteristic of WDM is that discrete wavelengths form an orthogonal set of carriers which can be separated, routed and switched without interfering with each other. This isolation between channels holds as long as the total optical power intensity is kept sufficiently low to prevent nonlinear effects such as stimulated brillouin scattering and four wave mixing processes from degrading the link performance.

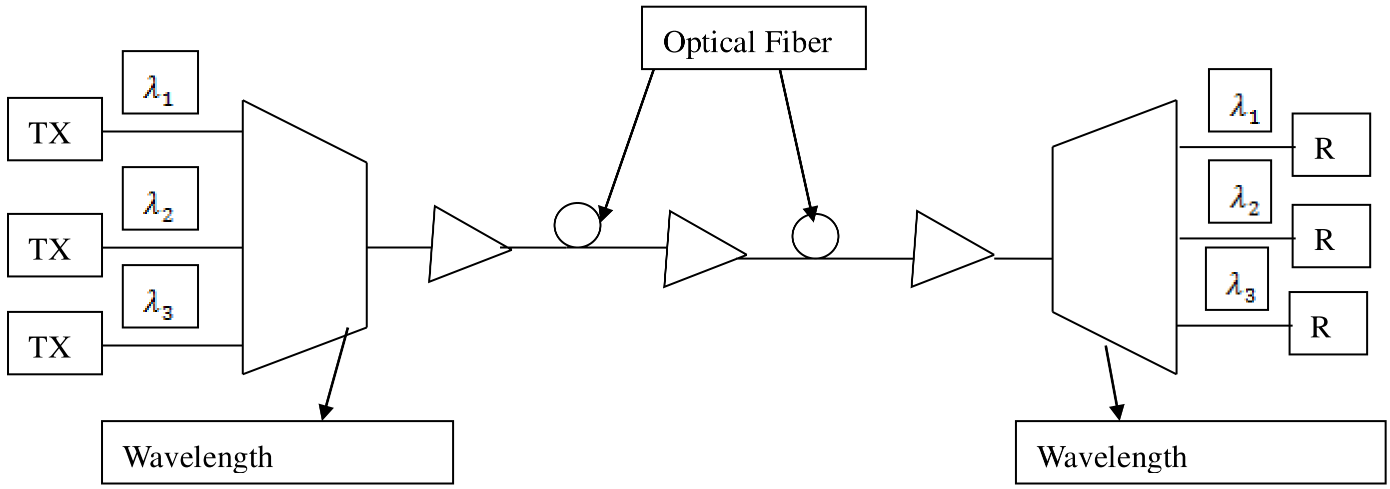


Fig.5.1 Implementation of a typical WDM Network containing various types of optical Amplifiers

Figure 5.1 shows the implementation of active and passive components in a typical WDM link containing various types of amplifiers. At the transmitting end there are several independently modulated light sources, each emitting signals at a unique wavelength. Here a multiplexer is needed to combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber. At the receiving end a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing.

5.2 Passive Optical Star Coupler

Star coupler combines the light streams from two or more input fibers and divide them among several output fibers. In general splitting is done uniformly for all wavelengths, so that each of each of N outputs receives 1/N of the power entering the device as shown in Figure 5.2.It is a device with two inputs and two outputs hence called 2X2 coupler. In general NXM coupler has N inputs and m outputs. The techniques for creating star couplers include fused fibers, gratings, micro-optic technologies, and intergrated optic schemes.

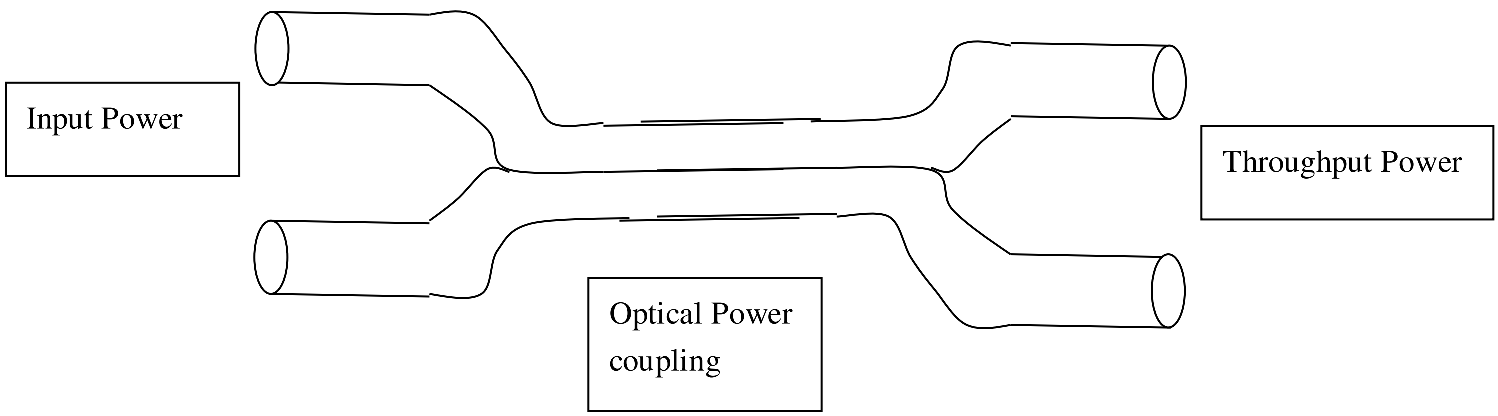


Fig 5.2 Cross-sectional view of fiber coupler

5.3 Isolators and Circulars

In number of applications it is desirable to have a passive optical device that is nonreciprocal, that is, it works differently when inputs and outputs are reversed. Two examples of such devices are isolators and circulators. Optical Isolator: Are devices that allow light to pass through them only in one direction as shown in Fig. 5.3. This is important in a number of instances to prevent scattered or reflected light from travelling in the reverse direction. Simple design configuration of isolator depends on the state of polarization of the input light. However, such a design results in 3dB loss when un polarized light is passed is passed through the device.

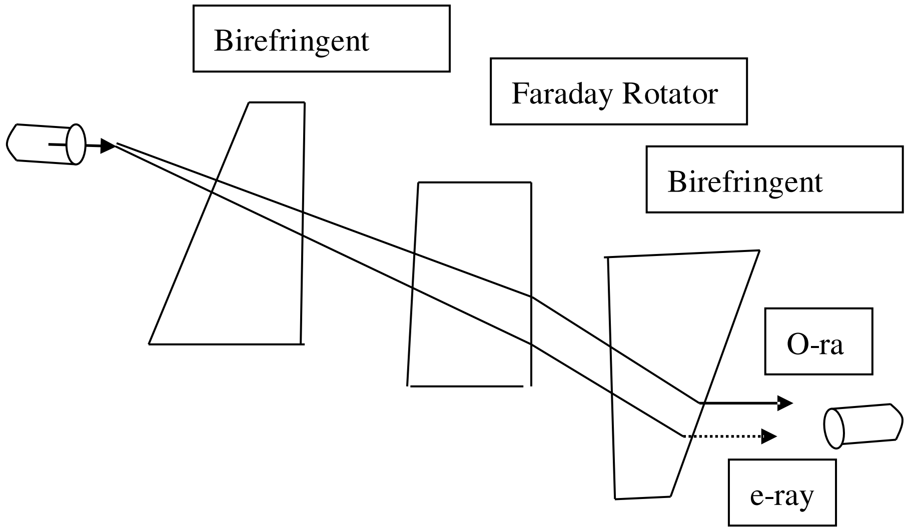


Fig. 5.3 Design of Polarization independent Isolator

Optical Circulator: An optical circulator is a non-reciprocal multiport passive device that directs light sequentially from port to port in only one direction. This device is used in optical amplifiers, add / drop multiplexes, and dispersion compensation modules. The operation of circulators is similar to that of an isolator except its construction is more complex. Typically it consist of number of walk-off polarizers, half wave plates and faraday rotator and has three or four ports. Here an input port 1 is sent out out on port2, an input port2 is sent out on port 3 and input port 3 is sent out on port 1.

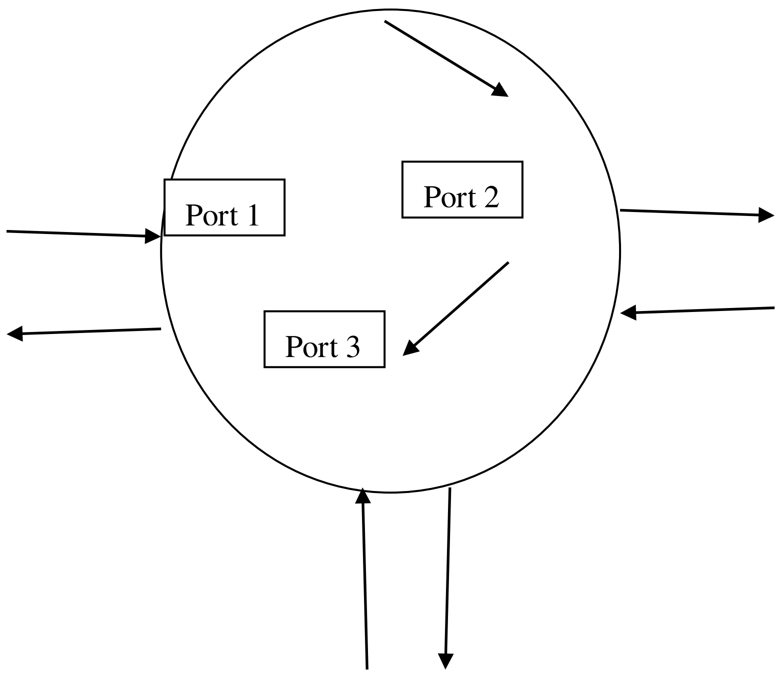


Fig. 5.4 Operational Concept of three port circulator

5.4 MEMS Technology

MEMS is the acronym for micro electro-mechanical systems. These are miniature devices that can combine mechanical, electrical and optical components to provide sensation and actuation functions. MEMS devices are fabricated using integrated circuit compatible batch-processing techniques and range in size from micrometers to millimetres. To control the actuation of a MEMS device is done through electrical, thermal or magnetic means such as micro gears or movable levers, shutters or mirrors. The devices are used widely in automobile air-bag deployment systems, in ink-jet printer heads, for monitoring mechanical shock and vibration during transportation of sensitive goods, for monitoring the condition of moving machinery for preventative maintenance. And in biomedical applications for patient activity monitoring and pacemakers. MEMS technology are also finding applications in light wave systems for variable optical attenuators, tunable optical filters, tunable lasers, optical add-drop multiplexers etc.

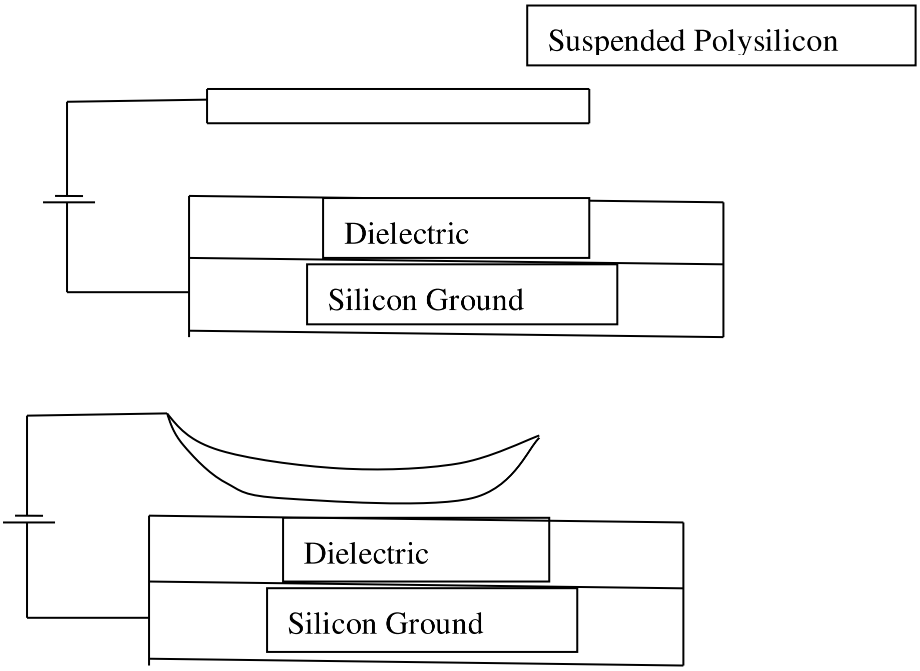


Fig.5.5 MEMS actuation method. The top shows an “off “position and bottom shows an “on” position

Figure 5.5 shows a simple example of a MEMS actuation method. At the top of the device there is thin suspended polysilicon beam that has typical length of 80µm, 10µm and 0.5µm respectively. At the bottom there is silicon ground plane which is covered by an insulator material. There is a gap of nominally 0.6µm between the beam and the insulator. When a voltage is applied between the silicon ground plane and polysilicon beam, electric force pulls the beam down so that it makes contact with lower structure. Current MEMS devices are made with highly compliant polymeric materials that are as much as six orders of magnitude less stiff than silicon.

5.5 Variable Optical Attenuators

A Variable optical attenuator (VOA) offers dynamic signal level control. This device attenuates optical power by various means to control signal levels precisely without disturbing the properties of a light signal. That means they should be polarization independent, attenuate light independent of wavelength, and have low insertion loss. The control methods include mechanical, thermo-optic, MEMS, or electro-optic techniques. The mechanical methods are reliable but have a low dynamic range.

5.6 Tunable Optical Filters

The key technologies to make a tunable filter are MEMS- based and bragg –grating based devices. MEMS actuated filters have the advantageous characteristics of a wide tunning range and design flexibility. The MEMS based devices consists of two sets of epitaxially grown semiconductor layers that form a single fabry perot cavity. The device operation is based on allowing one of the two mirrors to be moved precisely by an actuator. This enables the change in the distance between the two cavity mirrors, there by resulting in the selection of different wavelengths to be filtered.

5.7 Dynamic Gain Equalizers

A dynamic gain equalizer (DGE) is used to reduce the attenuation of the individual wavelengths within a spectral band. These devices are also called dynamic channel equalizers (DCE) or dynamic spectral equalizers. The function of DGE is equivalent to filtering out individual wavelengths and equalizing them on a channel by channel bases. Their applications include flattening the non linear gain profile of an optical amplifier (such as EDFA or raman amplfier), compensation for variation in transmission losses on individual channels across the given spectral band within a link, and attenuating , adding or dropping selective wavelengths.

5.8 Polarization Controllers

Polarization controllers offers high speed real time polarization control in a closed loop system that includes a polarization sensor and control logic. These devices dynamically adjust any incoming state of polarization to an arbitrary output state of polarization. For example, the output could be a fixed, linearly polarized state. Normally, this is done through electronic control voltages and are applied independently to adjustable polarization-retardation plates. Application of polarization controllers include polarization mode dispersion (PMD) compensation, polarization scrambling, and polarization multiplexing.

5.8 Chromatic Dispersion Compensators

A critical factor in optical links operating above2.5Gb/s is compensating for chromatic dispersion effects. This phenomenon causes pulse broadening which leads to increased bit error rates. The device for compensating is referred to as Dispersion compensating Module (DCM).This module can be tuned manually, remotely, or dynamically, Manual tuning is done by a network technician prior to or after installation of module in telecommunications racks. Dynamic tuning is done by the module itself without any human intervention.

One method of achieving dynamic chromatic dispersion is through the use of chirped fiber bragg grating (FBG). Here the grating spacing varies linearly over the length of the grating, which creates what is known as chirped grating. The relative delays induced by the grating on different frequency components of the pulse are the opposite of the delays caused by the fiber. This results in dispersion compensation, since it compresses the pulse.

5.9 Basic applications and types of amplifiers

To amplify an optical signal with conventional repeater, one performs photon-to-electron conversion, electrical amplification, retiming , pulse shaping and then electron to photon conversion. Three fundamental amplifier types Are semiconductor optical amplifiers (SOAs), Doped fiber amplifiers (DFAs), and Raman amplifiers. All optical amplifiers increase the power level of incident light through a stimulated emission or an optical power transfer process. SOAs and DFAs does not have optical feedback mechanism.

An in-line optical amplifier can be used to compensate for transmission loss and increase the distance between regenerative repeaters.

Preamplifier is used as front end amplifier for an optical receiver. There by, a weak optical signal is amplified before photodetection so that signal to noise ratio degradation caused by thermal noise in the receiver electronics can be suppressed.

Power amplifier of booster amplifier applications include placing the device immediately after an optical transmitter to boost the transmitted power.

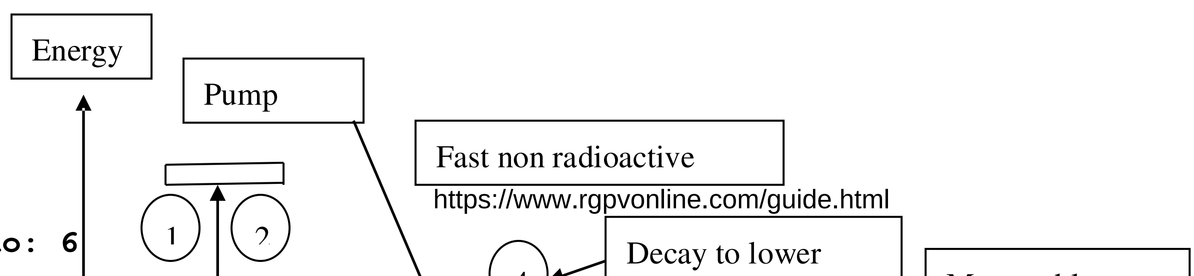
5.10 Erbium Doped Fiber Amplifiers

The active medium in an optical fiber amplifier consists of a nominally 10 t0 30 m length of optical fiber that has been lightly doped with a rare earth element, such as erbium (Er), ytterbium (Yb), thulium (Tm), praseodymium (Pr), the most fiber material can be standard silica, a fluoride- based glass, or tellurite glass. The operating regions of these devices depend on the host material and doping elements. A popular material for long haul telecommunication applications is silica fiber doped with erbium, which is known as erbium-doped fiber amplifier or EDFA. In some cases Yb is added to increase the pumping efficiency and amplifier gain. The operation of standard EDFA normally is limited to 1530 to 1560nm region. Actually the EDFA operated in this region of the C-band

5.11 Amplification Mechanism of EDFA

Whereas semiconductor optical amplifiers use external current injection to excite electrons to excite electrons to higher energy levels, optical amplifiers use optical pumping. In this process, one uses photons to directly raise electrons into excited states. The optical pumping process requires three or more energy levels. The top energy level to which electron is elevated initially must quickly lie energetically above the desired final emission level. After reaching initial excited state, the electron must release some of its energy and drop to a slightly lower energy level. A signal photon can then trigger the excited electron sitting in this new lower level into stimulated emission, whereby the electron releases its remaining energy in the form of a new photon with wavelength identical to that of signal photon. Since pumping photon must have a higher energy than signal photon, the pump wavelength is shorter than signal wavelength.

To get understanding how an EDFA works, we need to look at the energy level structure of erbium as shown in figure 5.6 . The erbium atoms in silica are Er^{3+} ions, which are erbium atoms that have lost three of their outer electrons. The two principal levels for telecommunication applications are metastable level and pump level. The term metastable means that the life times for transitions from this state to the ground state are very long compared with the life times of the states that led to this level. In normal operation a pump laser emitting 980nm photons is used to excite ions from the ground sate to the pump level. These excited ions decay very quickly from pump band to metastable band . Within the metastable band, the electrons of the excited ions tend to populate the lower end of the band. Some of the ions sitting at the metastable level can decay back to the ground state in the absence of an externally stimulating photon flux as shown in transition process 5. This decay phenomenon is known as spontaneous emission and adds to the amplifier noise. Two more types of transitions occur when a flux of signal photons that have energies corresponding to the band gap energy between ground state and metastable level passes through the device. First, a small portion of external photons will be absorbed by the ions in the ground state, which raises these ions to metastable level as shown by transition process 6. Second, in the stimulated emission process (transition process 7) a signal photons triggers an excited ion to drop to the ground state, thereby emitting a new photon of same energy, wavevector, and polarization as incoming signal photon.



https://www.rgpvonline.com/guide.html

Fig. 5.6 Energy level Diagrams and various transition process of Er^{3+} ions

5.12 EDFA Architecture

An optical amplifier consist of a doped fiber, one or more pumped lasers, a passive wavelength coupler, optical isolators and tap couplers. The diachronic (two-wavelength) coupler handles either 980/1550nm or 1480/1550nm wavelength combinations to couple both pump and signal optical powers efficiently into the fiber amplifier. The pump light is usually injected from the same direction as the signal flow. This is known as co directional pumping. It is also possible to inject the pump power in the opposite direction to the signal flow, which is known as counter directional pumping.

5.12 EDFA Power Conversion efficiency and Gain

As is the case with any amplifier, as the magnitude of any output signal from an EDFA increase, the amplifier gain eventually starts to saturate. The reduction in gain in an EDFA occurs when the population inversion is reduced significantly by large signal thereby yielding the typical gain-versus power performance curve. The input and output powers of an EDFA can be expressed in terms of principle of energy conservation.

$$P_{s,out} \leqslant P_{s,in} + \frac{\lambda_p}{\lambda_s} P_{p,in}$$

Where $P_{p,in}$ is the input power and λ_p and λ_s are the pump and signal wavelengths, respectively. The power conversion efficiency is defined as

PCE= $\frac{P_{s,out} - P_{s,in}}{P_{p,in}}$ is less than unity. The maximum theoretical value of PCE is $\frac{\lambda_p}{\lambda_s}$. For absolute reference purposes, it is useful to use the quantum conversion efficiency (QCE), which is wavelength independent and is defined by.

QCE=$\frac{\lambda_p}{\lambda_s} PCE$

5.13 Amplifier Noise

The dominant noise generated in an optical amplifier is called amplified spontaneous emission (ASE) noise. The origin of this noise is spontaneous recombination of electrons and holes in the amplifier medium.This recombination occurs over a wide range of electron-hole energy differences and thus give rise to broad spectral background of noise photons that get amplified along with the optical signal as they travel through the EDFA.

5.14 Optical SNR

When analyzing a transmission link that has a series of optical amplifiers in it, an important point is that the light signal entering the optical receiver may contain a significant level of ASE noise that has been added to the cascade of optical amplifiers. In this case one has to evaluate the optical signal to noise Ratio (OSNR). This parameter is defined as the ratio of EDFA optical signal ouput power P_{out} to the unpolarized ASE optical noise power P_{ASE} In decibel OSNR is

OSNR (dB)=10 log$\frac{P_{out}}{P_{ASE}}$

In practice OSNR can be measured with an Optical spectrum analyzer (OSA).

5.15 System Applications

For Power amplifiers, the input power is high, since the device immediately follows an optical transmitter. High pump powers are required for this application. In-Line Amplifiers are used for long distance transmission, they are needed to periodically restore the power level after it has decreased due to attenuation in the fiber.

5.16 Measurement Standards

Three basic classes of standards exist for fiber optics are primary, component testing and system standards. Primary standards referred to measuring and characterizing fundamental physical parameters such as attenuation, bandwidth, mode- field diameter for single mode fibers and optical power. In united states the main group involved in primary standards is the national Institute of Standards and technology (NIST). Other national organizations include the National Physical laboratory (NPL) in united kingdom and PHysikalisch-Technische Bundesanstalt (PTB) in germany.

Several International organizations are involved in formulating component and system testing standards. The measure organizations that deal with measurement methods for links and networks are the Institute of Electricals and Electronics engineers (IEEE) and the telecommunication union (ITU-T). Component testing standards define relevant test for fiber optic component performance, and they establish equipment-calibration procedure. A key organization for component testing is the Telecommunication industry association (TIA) in association with electronic Industries Alliance (EIA).

System standards refers to measurement methods for links and networks. The major organizations involved here are American National Standards Institute (ANSI), IEEE and ITU-T.

5.17 Basic Test Equipment

As optical signals pass through the various parts of an optical link, they need to be measured and characterized in terms of the three fundamental areas of optical power, polarization and spectral content. The basic instruments for carrying out such measurements on optical fiber components and systems include optical power meters, attenuators, tunable laser sources, spectrum analyzers and optical time domain reflectometers.

5.18 optical power Measurements

Optical power measures rate at photons arrive at a detector. Thus it is measure of energy transfer per unit time. Since the rate of energy transfer varies with time, the optical power is function of time , It is measured in watts or joules per second (J/s). radiance (or brightness) is measure, in watts, of how much optical power radiates into a solid angle per unit solid angle per unit emitting surface. The two standard classes of power measurements are 1) peak power is a maximum power level in a pulse. 2)Average power is a measure of power level averaged over relatively long time period compared to the duration of individual pulse. Optical power meters are used for power measurement, they measure power in terms of dBm (where 0dBm=1mW).

5.19 optical Fiber Characterization

Various types of equipment for factory use have been developed to characterize the physical and performance parameters of these fibers. These parameters include mode field diameter, attenuation, cut-off wavelength, refractive index profile, effective area, geometric properties of core and cladding diameters. Two basic measurement methods used by this specialized equipment are the refracted near field techniques which determines refractive index profile and transmitted near field techniques which measures mode field diameters. Mode field diameter is important since it describes the radial optical field distribution across the fiber core. Detailed information of MFD enables one to calculate characteristics such as source to fiber coupling efficiency, splice and joint losses, micro bending loss and dispersion.

5.20 optical Time- Domain Reflectometer

An Optical time reflectometer is a versatile portable instrument that is used widely to evaluate the characteristics of an installed optical fiber link. In addition to identifying and locating faults or anomalies within a link, this instrument measures parameters such as attenuation, length, optical connector and splice losses and light reflectance. OTDR operates by periodically launching narrow laser pulses into one end of a fiber under test by using either a directional coupler or a circulator. The properties of optical fiber link then are determined by analyzing the amplitude and temporal characteristics of the waveform of the reflected and back scattered light. A typical OTDR consist of a light source and receiver, data acquisition and processing modules, an information storage unit for retaining data either in the internal memory or in an external disk , and a display. Figure 5.7 shows principle of an OTDR using an optical circulator. The backscattered waveform has four distinct features:

1) A large initial pulse resulting from Fresnel reflection at the input end of the fiber.
2) A long decaying tail resulting from Rayleigh scattering in the reverse direction as input pulse travels along the fiber.
3) Abrupt shift in the curve caused by optical loss at joints or connectors in the fiber line.
4) Positive spikes arising from Fresnel reflection at far end of the fiber, at fiber joints and at fiber imperfections

Fresnel reflection occurs when light enters in a medium having a different index of refraction. For a glass- air interface, when light of power P_o is incident perpendicular to the interface, the reflected power is P_{ref} is

$$P_{ref} = P_o \left(\frac{n_{fiber-n_{air}}}{n_{fiber+n_{air}}}\right)^2$$

Where n_{fiber} and $n_{n_{air}}$ are the refractive indices of core and air, respectively. Two important performance parameters of an OTDR are dynamic range and measurement range. Dynamic range is defined as the difference between the initial back scatter level at the front connector and the noise level peak at the far end of the fiber. It is expressed in decibels of one way fiber loss. Dynamic range provides information on the maximum fiber loss that can be measured and denotes the time required to measure a given fiber loss. Measurement range deals with how far away an OTDR can identify events in the link, such as splice points, connection points, or fiber breaks. The maximum range R_{max} depends on the fiber attenuation α and the pulse width, that is on the dynamic range D_{OTDR}.

$$R_{max} = \frac{D_{OTDR}}{\alpha}$$

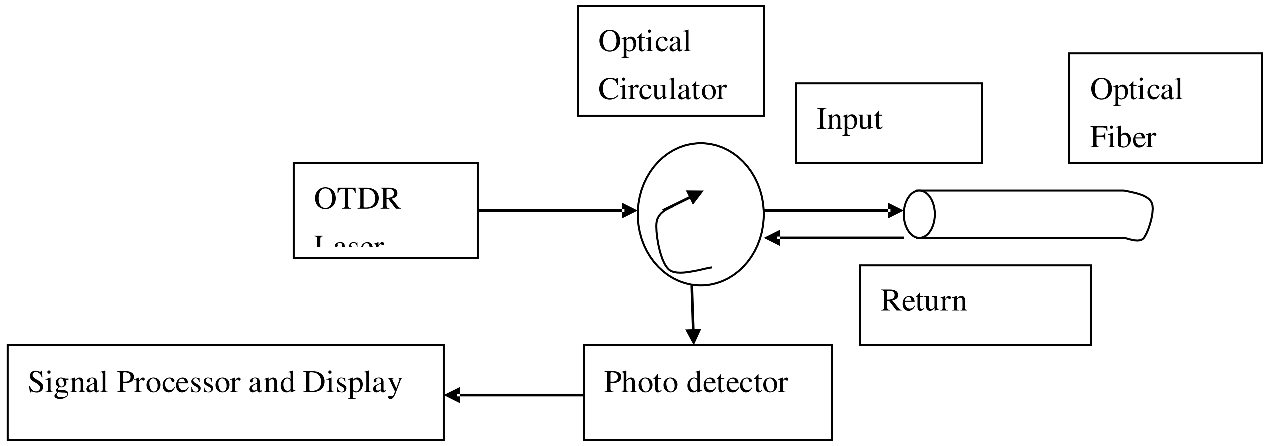


Fig.5.7 Operational principle of OTDR using optical Circulators

5.21 optical Performance Monitoring

To offer services with an extremely high degree of reliability, operators need to have a means to monitor the health and status of all parts of their network continuously. Basically network health is assessed by means of a continuous in-line-BER measurement. In addition another standard network management function is fault monitoring, which checks to see where and why a network failure has occurred or is about to take place. The network management console is a specialized workstation that serves as the interface for the human network manager. Management software modules, called agents, residing in a microprocessor within the elements continuously gather and compile information on the status and performance of managed devices. The agent stores this information in a management information base(MIB), and then provide data to the management entities within a network management system (NMS) that resides in the management workstation. The information transfer from the MIB to the MNS is done by a network management protocol such as the widely used simple network management protocol (SNMP).When agent notices problems in the element they are monitoring (for example link or component faults, wavelength drifts, reduction in the optical power levels, or excessive bit error rates), they send alerts to the management entities. Upon receiving an alert, management entities can initiate one or more action such as operator notification, event logging, system shutdown, or automatic attempts at fault isolation or repair.