DWDM Training : *CSIR, South Africa*

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By

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Nex-G Skills

DAY-3

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An Optical Cross-Connect (OXC), as the name implies, is a cross-connect that is built on some optical technology .

This cross-connect can switch any wavelength from one port to any other port, where , this kind of switch also needs wavelength conversion at the ingress or egress ends to be able to support fixed channel-spaced AWG multiplexer sections at the extreme ends.

These are key routing and switching elements in backbone wavelength-division multiplexed (WDM) networks and enable optical networks to be reconfigurable on a wavelength-by-wavelength basis to match changing traffic patterns and to recover from network failures.

Among the **three types of FBG-based OXCs**, namely the P-type, S-type and N-type, the N-type OXCs have comprehensive better performance.

Opaque OXCs (electronic switching) -

One can implement an OXC in the electronic domain where all the input & optical signals are converted into electronic signals after they are de-multiplexed by de-multiplexers.

The electronic signals are then switched by an electronic switch module.

Finally, the switched electronic signals are converted back into optical signals by using them to modulate lasers and then , the resulting optical signals are multiplexed by optical multiplexers onto outlet optical fibers.

This is known as an "*OEO" (Optical-Electrical-Optical) design.*

Optical add-drop multiplexer (OADM) :

These are used to separate / route different Optical add-drop multiplexer wavelength channels.

They can be used at different points along the optical link to insert/remove or route selected channels increasing the network flexibility.

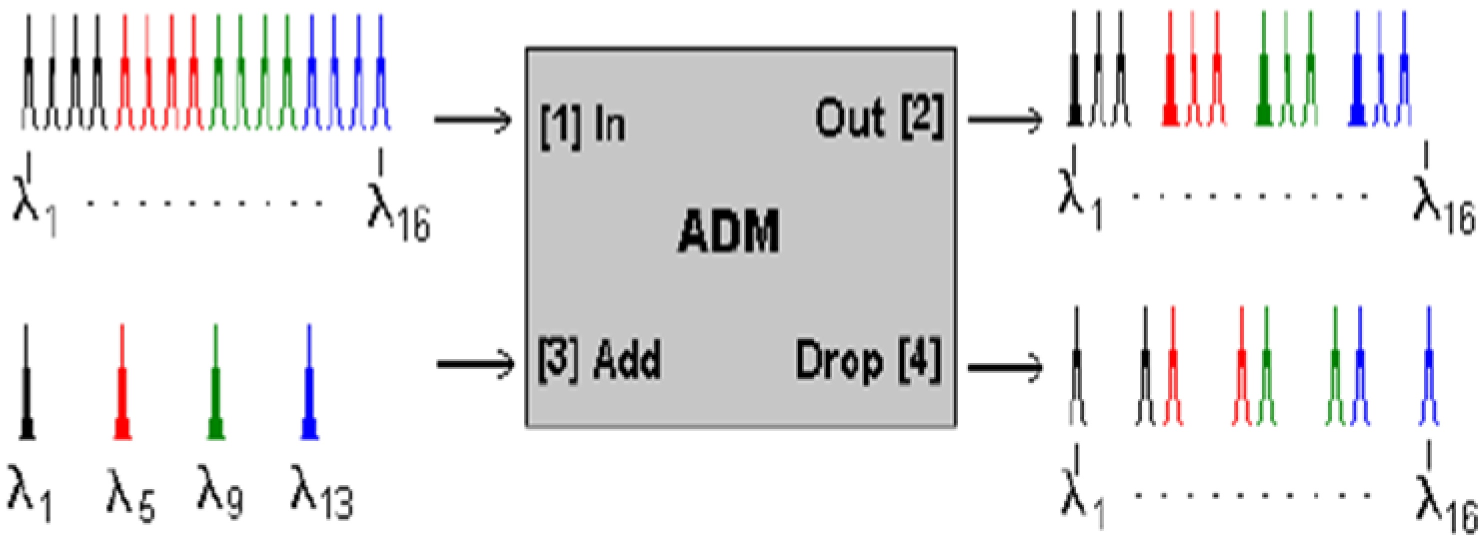
This feature is particularly important in Metropolitan WDM light wave services where offices or sites can be connected by different Add-Drop channels , for example in an inter-office ring.

Additionally there is a flexibility of transmitting different data rates in different WDM channels according to the capacity needs.

The Figure illustrates the basic operation of an add-drop multiplexer where a stream of 16 channels with central wavelengths λ_1 through λ_{16} are launched into the input (port 1) and 8 channels are dropped at port 4, the rest go through port 2.

Simultaneously, 4 channels are launched into port 3 and added to the signal stream at port 2.

The channels that are added or dropped at that node depend on that network requirements.



Basic operation of an optical add-drop multiplexer.

There are two main types of OADM that can be used in WDM optical network;

1. Fixed OADMs- that are used to drop or add data signals on dedicated WDM channels, and

2. Reconfigurable OADMs - that have the ability to electronically alter the selected channel routing through the optical network.

The main features of the second type of OADM is to provide flexibility in rerouting optical streams, bypassing faulty connections, allowing minimal service disruption and the ability to adapt or upgrade the optical network to different WDM technologies.

Summary - Hence, **OADM** is a device used in WDM systems for multiplexing and routing different channels of light into or out of a (SMF).

This is a type of optical node, which is generally used for the construction of optical telecommunications networks.

"Add" and "drop" here refer to the capability of the device to add one or more new wavelength channels to an existing multi-wavelength WDM signal, and/or to drop (remove) one or more channels, passing those signals to another network path.

An OADM may be considered to be a specific type of optical cross-connect.

A Traditional OADM consists of three stages: -

- An Optical Multiplexer
- An Optical De-multiplexer and
- Between them a method of reconfiguring the paths between the de-multiplexer, the multiplexer and a set of ports for adding and dropping signals.

The reconfiguration can be achieved by a fiber patch panel or by optical switches which direct the wavelengths to the multiplexer or to drop ports.

The multiplexer multiplexes the wavelength channels that are to continue on from de-multiplexer ports with those from the add ports, onto a single output fiber.

In DWDM transmission, optical gain equalization is required because the DWDM signals eventually become unequal in power.

This is because the gain characteristic of amplifiers and filters is not flat, because –

- Optical cross-connects do not have the same loss characteristics for all channels
- Dispersion is not the same for all channels

In addition, as dropping and adding wavelengths takes place, the wavelengths added most likely will not have the same amplitude as those passing through.

The end result is that all DWDM channels in the fiber do not arrive at the same optical strength at the receiver.

Optical gain equalization improves the *signal-to-noise ratio*, and thus it enhances the performance of optical amplifiers and allows for longer fiber spans between amplifiers.

Therefore, ***Gain equalization is a key function in long-haul applications*.**

Optical gain equalizers monitor each wavelength channel and selectively make amplitude adjustments on each channel to flatten the optical power spectrum within a fraction of a decibel.

They may be static or dynamic.

Static equalizers consist of filters with specific gain profile that counteract the gain variability of channels in the DWDM system.

Such static equalizers, although inexpensive, are applicable to networks that are not expected to (substantially) change.

As system and/or network scalability may alter the gain level, dynamic equalization is able to adjust to this changing environment.

A dynamic gain equalizer is an opto-electronic feedback control sub-system that incorporates several components.

Among them are :-

1. An Optical de-multiplexer and multiplexer
2. Power Splitters per channel
3. Variable Optical Attenuators (VOA) per channel
4. Optical Power measuring mechanism , and
5. A Microprocessor which according to an algorithm performs per channel real-time gain management and VOA adjustments.

Based on this, the DWDM signal is de-multiplexed, each signal is monitored and adjusted for gain with the VOA, and then all signals are multiplexed again.

Clearly, the key component in this method is the transfer function and accuracy of variable attenuators and how well they integrate with the mux/demux.

Variable attenuators may be solid state or variable intensity filters; either technology requires voltage to control attenuation.

Figure 4.25 illustrates a regenerator with dispersion compensation and gain equalization modules

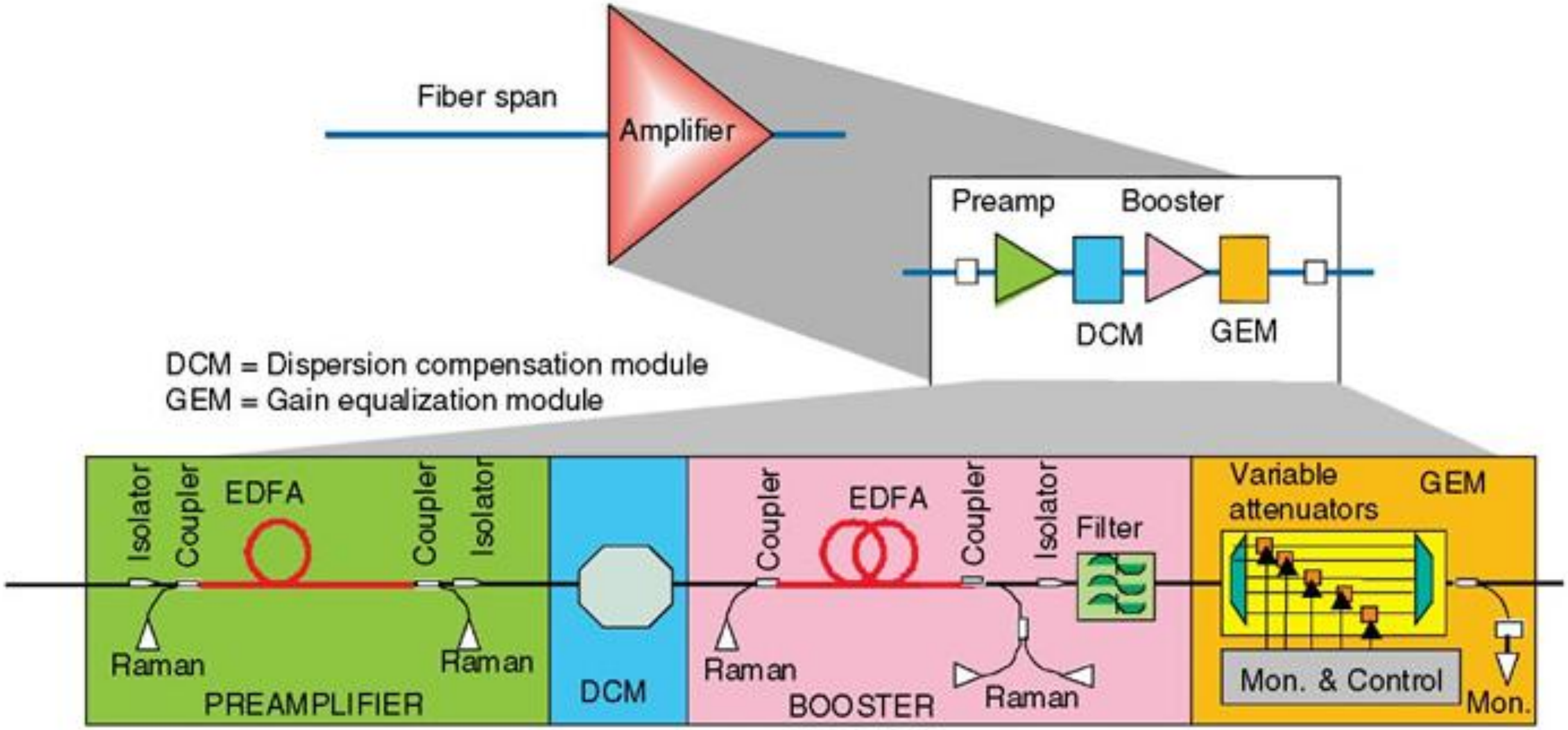


Figure 4.25 A regenerator with dispersion compensation and gain equalization modules.

Light Amplification by Stimulated Emission of Radiation – is a beam of radiation produced from a laser, used in :

1. Surgery
2. Communications
3. Weapons systems
4. Printing
5. Recording and
6. Various Industrial Processes.

Fiber nonlinearities , such as Stimulated Raman Scattering or Four-Wave Mixing can also provide gain and thus ***serve as gain media*** for a fiber laser.

❖ Light emitters and light detectors are active devices at opposite ends of an optical Transmission System.

❖ Light sources, or light emitters, are transmit-side devices that convert electrical signals to light pulses and the process of this conversion, or modulation, can be accomplished by externally modulating a continuous wave of light or by using a device that can generate modulated light directly.

❖Light detectors perform the opposite function of light emitters as they are receive-side opto-electronic devices that convert light pulses into electrical signals.

Light Detectors **:** The signals transmitted at different wavelengths on the fiber which is necessary to recover at the receiving end.

Because photo detectors are wideband devices by nature , the optical signals are de-multiplexed before reaching the detector.

Two types of Photo Detectors are widely deployed i.e,

1. Positive-Intrinsic-Negative (PIN) Photodiode
2. Avalanche Photodiode (APD).

Where,

- PIN photodiodes work on principles similar to, but in the reverse of LEDs. i.e. light is absorbed rather than emitted, and photons are converted to electrons in a 1:1 relationship.

- APDs are similar devices to PIN photodiodes, but provide gain through an amplification process.i.e. one photon acting on the device releases many electrons.

PIN photodiodes have many advantages including low cost and reliability, but APDs have higher receive sensitivity and accuracy.

However, APDs are more expensive than PIN photodiodes, they can have very high current requirements, and they are temperature sensitive.

Light Emitters—LEDs and Lasers :

The light source used in the design of a system is an important consideration because it can be one of the most costly elements.

Its characteristics are often a strong limiting factor in the final performance of the optical link.

Light emitting devices used in optical transmission must be –

1. Compact
2. Monochromatic
3. Stable and
4. long-lasting.

Generally two types of light emitting devices are used in optical transmission- light-emitting diodes (LEDs) and laser diodes/semiconductor lasers.

LEDs are relatively slow devices, suitable for use at speeds of less than 1 Gbps, they exhibit a relatively wide spectrum width, and they transmit light in a relatively wide cone.

These inexpensive devices are often used in multimode fiber communications.

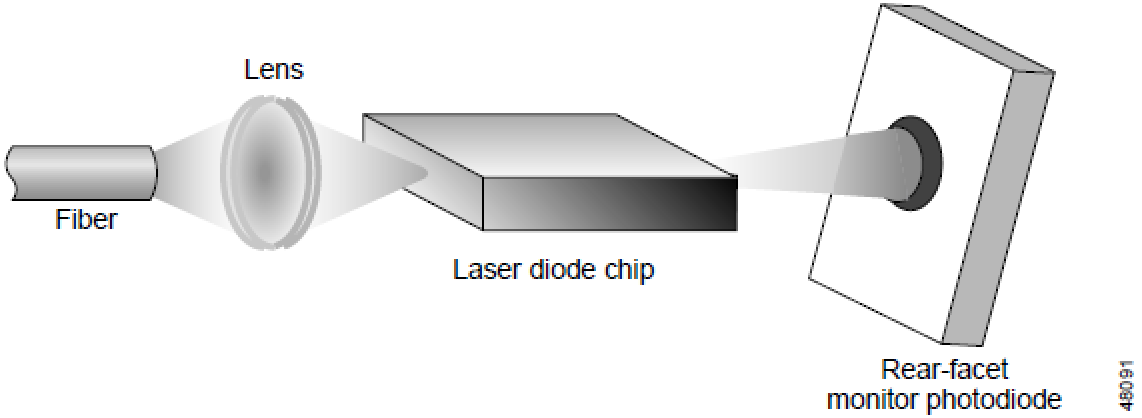
Semiconductor lasers, on the other hand, have performance characteristics better suited to single-mode fiber applications.

Figure 2-15 shows the general principles of launching laser light into fiber.

The laser diode chip emits light in one direction to be focused by the lens onto the fiber and in the other direction onto a photodiode.

The photodiode, which is angled to reduce back reflections into the laser cavity, provides a way of monitoring the output of the lasers and providing feedback so that adjustments can be made.

Figure 2-15 Typical Laser Design



Requirements for lasers include precise wavelength, narrow spectrum width, sufficient power, and control of chirp (the change in frequency of a signal over time).

Semiconductor lasers satisfy nicely the first three requirements.

Chirp, however, can be affected by the means used to modulate the signal.

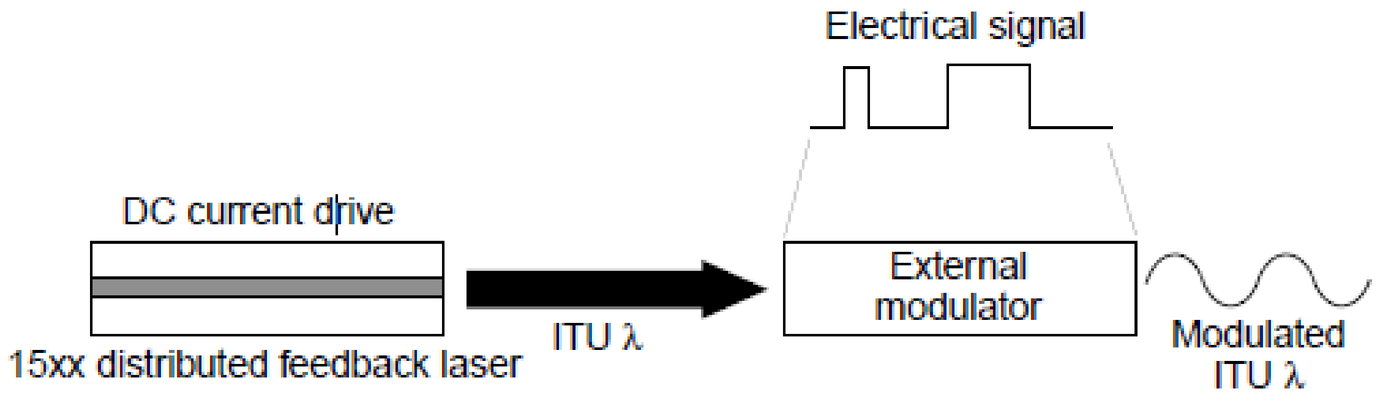
In directly modulated lasers, the modulation of the light to represent the digital data is done internally.

With external modulation, the modulation is done by an external device.

When semiconductor lasers are directly modulated, chirp can become a limiting factor at high bit rates (above 10 Gbps).

External modulation on the other hand, helps to limit chirp depicted in Figure 2-16.

Figure 2-16 External Modulation of a Laser



Two types of semiconductor lasers are widely used -monolithic Fabry-Perot lasers, and distributed feedback (DFB) lasers.

The latter type (DFB) is particularly well suited for DWDM applications, as it emits a nearly monochromatic light which is capable of high speeds and has a favourable signal-to-noise ratio along with the superior linearity.

DFB lasers also have center frequencies in the region around 1310 nm, and from 1520 to 1565 nm..

The latter wavelength (from 1520 to 1565 nm) range is compatible with EDFAs.

There are many other types and subtypes of lasers.

Narrow spectrum tuneable lasers are available, but their tuning range is limited to approximately 100-200 GHz.

Under development are wider spectrum tuneable lasers, which will be important in dynamically switched optical networks

One of the main elements to allow optical interconnect is the optical modulator, converting efficiently an electrical signal into an optical version at high bit rates (10-40Gbps).

Today's commercially available high-speed optical modulators at >10Gb/s are based on ***electro-optic materials*** such as lithium niobate and semiconductors.

These devices have demonstrated modulation capability as high as 40Gb/s achieving fast modulation in silicon was a challenging task.

So, by designing DWDM networks are based on size and performance using external modulators.

Typically, two kinds of modulators are available:

1. Electro-absorption modulators (EAMs)
2. Mach-Zehneder Interferometer (MZI) modulators.

Where, Mach-Zehneder interferometers are more common.

Demonstrations up to 40 Gbps have been made, but 10 Gbps technology is more common.

EAM lasers have the advantage of size over the MZI counterpart because they are much smaller than MZIs.

The single biggest advantage of having external modulators is the reduced chirp, which means that the signal occupies less bandwidth.

Typically, *MZI modulators are known to have twice the bit rate as their bandwidth.*

This also means that the spacing between adjacent channels in a WDM system can be greatly reduced.

When two dissimilar systems are connected, certain wavelengths (using wavelength converters) **must be** converted to others, and the signal level must be equalized to meet receiver requirements.

Transponders convert optical signals from one incoming wavelength to another outgoing wavelength suitable for DWDM applications.

Transponders are *optical-electrical-optical* (O-E-O) wavelength converters.

A transponder performs an O-E-O operation to convert wavelengths of light thereby converting the optical signal back to an electrical signal (O-E) and then performs either 2R (re-amplify, reshape) or 3R (re-amplify, reshape, and retime) functions.

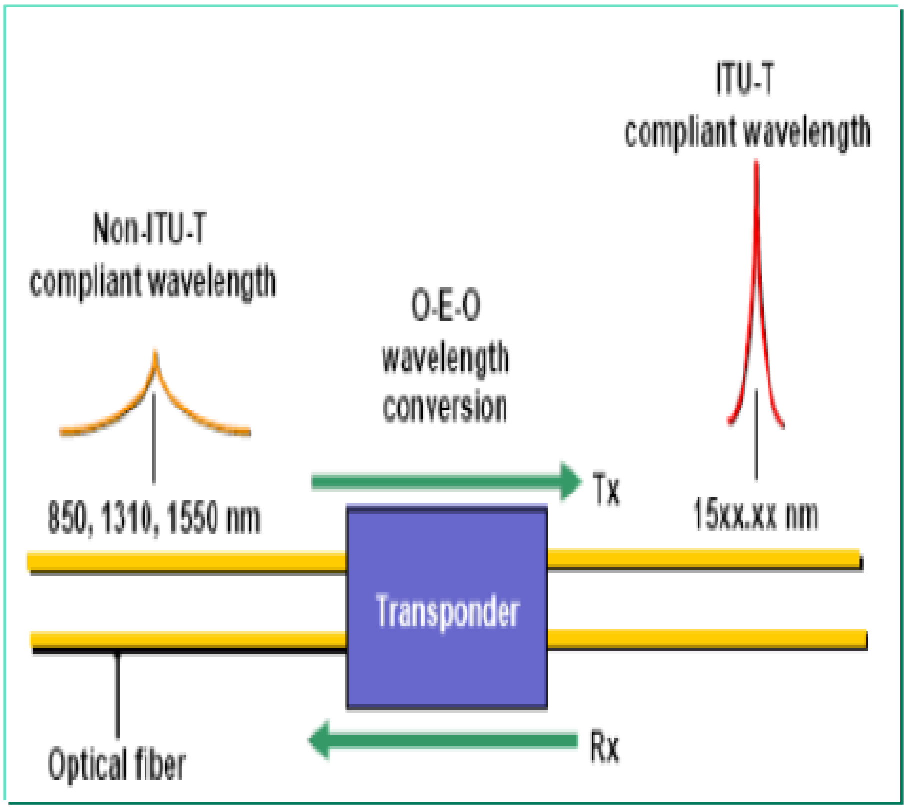
The block diagram given below shows bi-directional transponder operation.

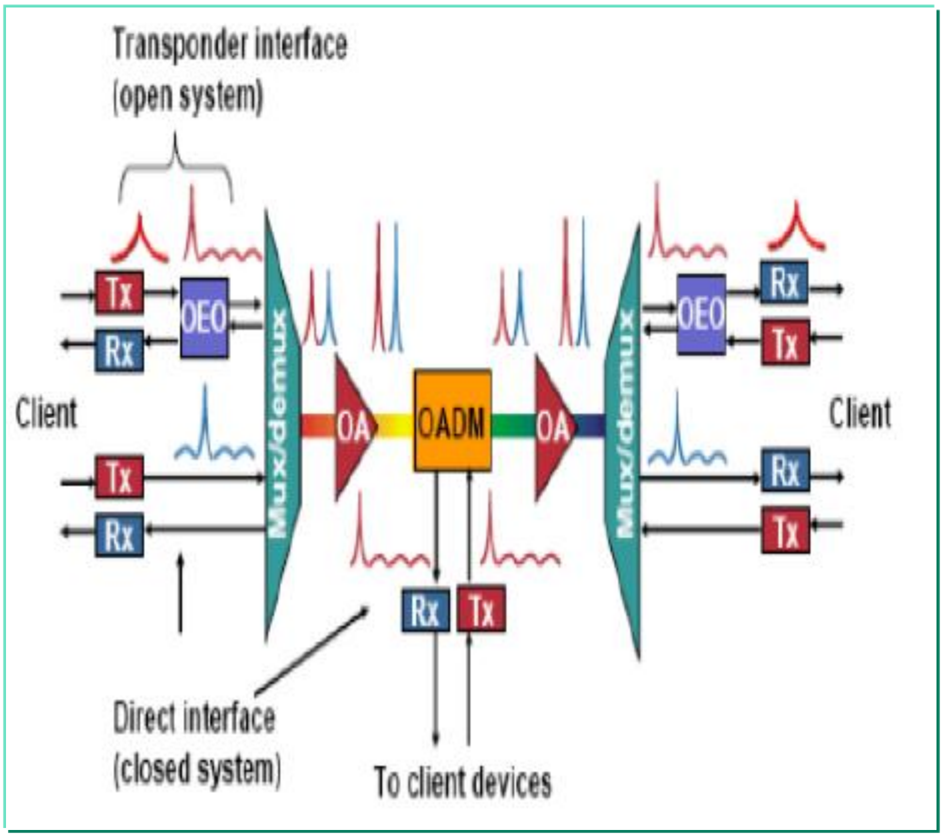
A Transponder is located between a client device and a DWDM system.

From left to right, the transponder receives an optical bit stream operating at one particular wavelength (1310 nm).

The transponder converts the operating wavelength of the incoming bit stream to an **ITU-** compliant wavelength and it transmits its output into a DWDM system.

On the **receive side** (right to left), the process is reversed such as the transponder receives an ITU-compliant bit stream and converts the signals back to the wavelength used by the client device.


ITU-T
compliant wavelength
Non-ITU-T
compliant wavelength
O-E-O
wavelength
conversion
Tx
850, 1310, 1550 nm
15xx.xx nm
Transponder
Optical fiber
Rx


Transponder interface
(open system)
Tx
Rx
OEO
Mux/demux
OA
OADM
Client
Direct interface
(closed system)
To client devices

In the mid-1990s, however, wavelength converting transponders rapidly took on the additional function of signal regeneration.

Signal regeneration in transponders quickly evolved through 1R to 2R to 3R and into overhead-monitoring multi-bit rate 3R regenerators.

These differences are outlined below:

1R(Retransmission)-- Basically, early transponders were "**garbage in garbage out**" in that their output was nearly an analogue "copy" of the received optical signal, with little signal cleanup occurring.

This limited the reach of early DWDM systems because the signal had to be handed off to a client-layer receiver (likely from a different vendor) before the signal deteriorated too far.

Signal monitoring was basically confined to optical domain parameters such as received power.

2R(Re-time and re-transmit)- Transponders of this type were not very common and utilized a quasi-digital Schmitt-triggering method for signal clean-up.

Some rudimentary signal-quality monitoring was done by such transmitters that basically looked at analogue parameters.

3R(Re-time, re-transmit, re-shape)- 3R Transponders were fully digital and normally able to view SONET /SDH section layer overhead bytes.

Currently in the C band as well as L band, the ITU allots wavelengths with 0.8 nm or 100 GHz as well as 0.4 nm or 50 GHz separations.

Many systems will offer 2.5 Gbit/s transponders, which will normally mean the transponder is able to perform 3R regeneration on OC-3/12/48 signals, and possibly gigabit Ethernet.

In practice, the signal inputs and outputs will not be electrical but optical instead (typically at 1550 nm).

This means that in effect we need wavelength converters instead, which is exactly what a transponder is.

A *Transponder* can be made up of two transceivers placed after each other: the **first transceiver** converting the 1550 nm optical signal to/from an electrical signal, and the **second transceiver** converting the electrical signal to/from an optical signal at the required wavelength.

Transponders that don't use an intermediate electrical signal (all-optical transponders) are in development.

Hence, the Wavelength convertor converts the optical signal to new wavelength channel that is available in the path and routes it to the destination.

In a service provider network, it is necessary to have all light paths or wavelengths specified by the ITU standard but in practice, most service provider networks use C and sometimes L bands.

However, a client to the service provider might not use a standard wavelength on his light path.

Essentially, Transponders have a functionality that allows them to receive any wavelength but transmit only an ITU-compliant wavelength.

Furthermore, this functionality can be increased so that transponders transmit a range of ITU-defined wavelengths instead of just one fixed wavelength.

Hence, Transponders essentially are wavelength converters that use O-E-O as a means to convert the ingress wavelength to the egress wavelength.

An **Optical Attenuator** , or fiber optic attenuator, is a device used to reduce the power level of an optical signal, either in free space or in an optical fiber.

The basic types of optical attenuators are –

1. Fixeds
2. Step-wise variable and
3. Continuously variable.

It is mainly used in measuring -

1. The index of an optical fiber system
2. A short-distance telecommunication system’s signal attenuation and
3. A system test.

An ideal optical attenuator will be –

1. Light
2. Small
3. Precise
4. Stable and
5. Easy to Operate.

The basic types of optical attenuators are –

1. *Fixed*
2. *Step-wise variable* and
3. *Continuously variable*.

A continuously variable optical attenuator is usually used in optical measurement, when measures the sensitivity of a light receiver, it is placed near the input end of a light receiver and use it to adjust the power level of the receiving light.

Optical attenuators are **often** used in optical communication systems , in which the attenuation , also called transmission loss, helps with the long-distance transmission of digital signals.

The most common optical attenuator types include fixed and continuously variable attenuators.

Optical Signal-to-Noise Ratio (OSNR) - is the ratio of optical signal power to noise power for the receiver in a given bandwidth.

Most commonly a reference bandwidth of 0.1 nm is used.

This bandwidth is independent of the modulation format **for the frequency** and the receiver.

For instance an OSNR of 20dB/0.1 nm could be given, even the signal of 40 GBit .

An OSNR value may be targeted greater than 15 dB to 18 dB at the receiver, but this value will depend on many factors need to be taken into account, including :-

1. Modulation format
2. Data rate
3. Location in the network
4. Type of network and the target BER level.

Here are a few initial guidelines:

Dependency on the location :- the required OSNR will be different for different locations in the light path.

Closer to the transmitter, the OSNR requirement will be higher.

Closer to the receiver, the OSNR requirement will be lower.

OSNR is measured with an optical spectrum analyzer.

It is a ratio of two powers; therefore, if a signal and noise are both amplified, system OSNR still tells the quality of the signal by calculating this ratio.

System design based on OSNR is an important fundamental design tool.

This is because optical amplifiers and ROADMs add noise, which means that the OSNR value degrades after going through each optical amplifier or ROADM.

To ensure that the OSNR value is high enough for proper detection at the receiver, the number of optical amplifiers and ROADMs needs to be considered when designing a network.

Dependency on the type of network :- For a metro network, an OSNR value of *>40 dB* at the transmitter might be perfectly acceptable, because there are not many amps between the transmitter and the receiver.

As for example, a submarine network, the OSNR requirements at the transmitter are much higher.

Dependency on the data rate :- As the data rate goes up for a specific modulation format, the OSNR requirement also increases.

Dependency on the target BER :- A lower target BER calls for a higher OSNR value.

Those were the guidelines, and now for some specifics. The OSNR values that matter the most are at the receiver, because a low OSNR value means that the receiver won't detect or recover the signal.

The exact requirements at the receiver will vary from one manufacturer to another (contact your system provider), but see the examples below for a few average OSNR figures to guarantee a BER lower than 10^{-8} at the receiver .

The ***THUMB rule*** says that the OSNR should be greater than 15 dB to 18 dB at the receiver, but also this value will depend on many factors.

10 Gbit/s NRZ: OSNR greater than approximately 11 dB
40 Gbit/s NRZ: OSNR greater than approximately 17 dB
40 Gbit/s DPSK: OSNR greater than approximately 14 dB
100 Gbit/s NRZ: OSNR greater than approximately 21 dB
100 Gbit/s DPSK: OSNR greater than approximately 18 dB

EDFA Details

Erbium-Doped Fiber Amplifier :

(EDFA) was a key enabling technology , by making it possible to carry the large loads that DWDM is capable of transmitting over long distances.

Erbium is a rare-earth element that can emit light around 1.54 micrometers, which is the low-loss wavelength for optical fibers used in DWDM.

Erbium-Doped Fiber Amplifier Design

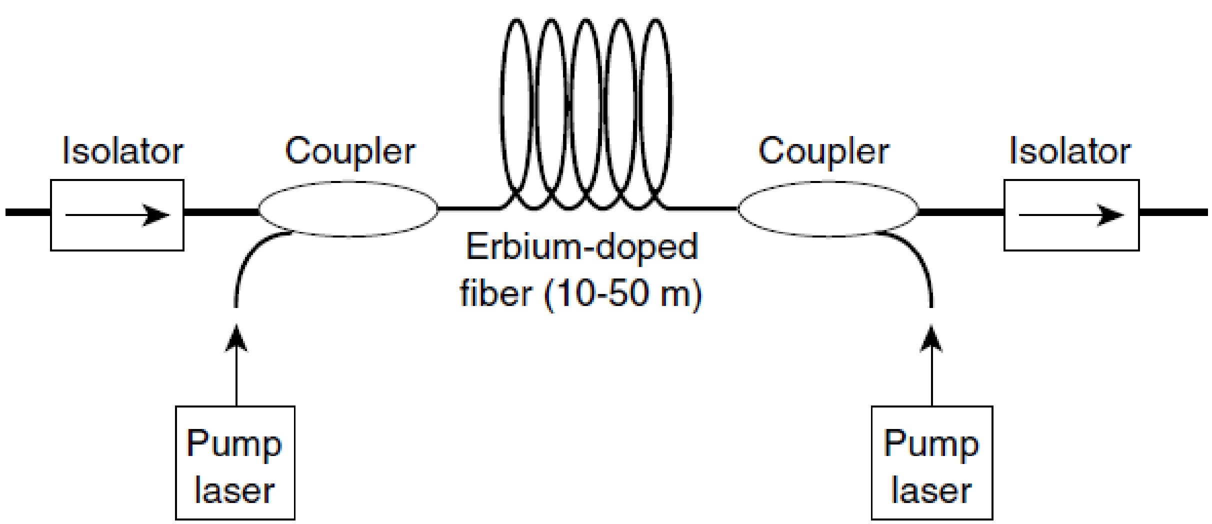


Figure shows a simplified diagram of an EDFA

A weak signal enters the erbium-doped fiber, into which light at 980 nm or 1480 nm is injected using a *pump laser*.

This injected light stimulates the erbium atoms to release their stored energy as additional 1550-nm light.

As this process continues down the fiber, the signal grows stronger and the spontaneous emissions in the EDFA also add noise to the signal, which determines the noise figure of an EDFA.

The key performance parameters of optical amplifiers are gain, gain flatness, noise level, and output power.

EDFAs are typically capable of gains of 30 dB or more and output power of +17 dB or more.

The target parameters when selecting an EDFA, however, are low noise and flat gain.

While the signal gain provided with EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters.

So, such filters are often built into modern EDFAs.

Gain should be flat, because all signals must be amplified uniformly, while the signal gain provided with EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters where such filters are often built into modern EDFAs.

Low noise is a requirement because noise, along with signal, is amplified.

Because this effect is cumulative and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated.

At longer distances of 372 mi to 620 mi (600 to 1000 km) the signal must be regenerated, because the optical amplifier merely amplifies the signals and does not perform the 3R functions (retime, reshape, regenerate).

EDFAs are available for the C-band and the L-band.

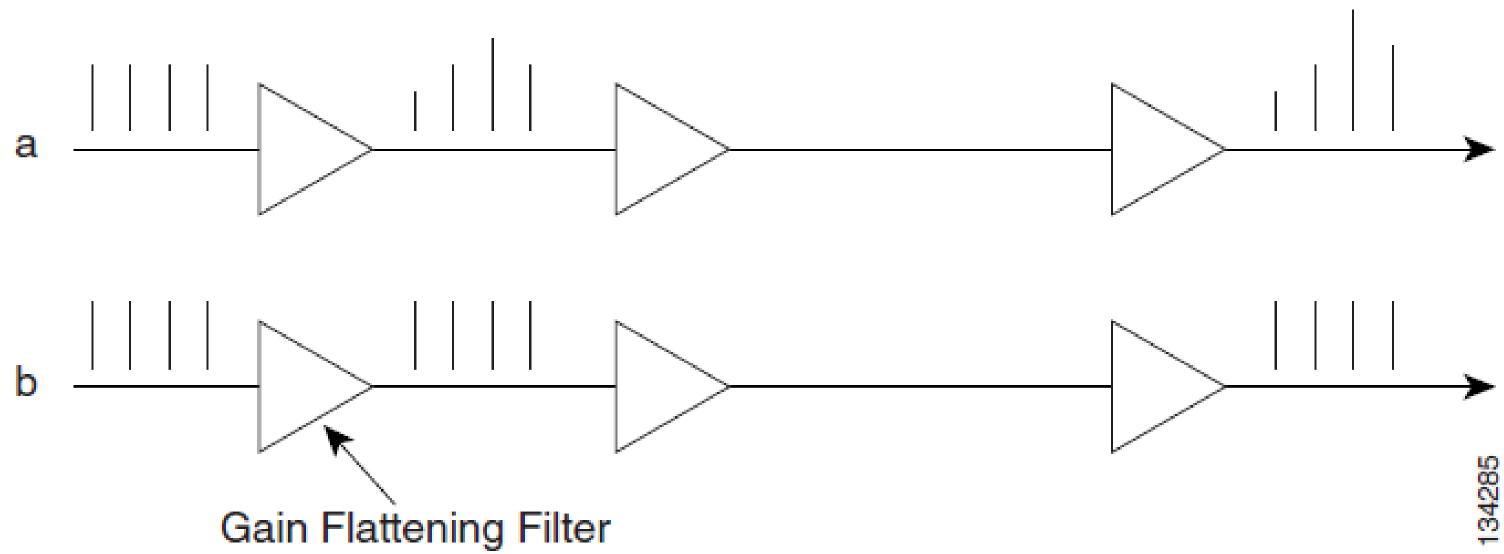
Constant Gain Mode : Constant gain mode is achieved using an automatic control circuit that adjusts pump power when changes in input power are detected.

Gain Flatness : Figure 1-15 illustrates the importance of an EDFA gain-flattening filter.

With the first fiber (a), channels having equal power going into a cascaded network of amplifiers have vastly different powers and optical signal-to-noise ratio (SNR) at the output—without a gain flattening filter.

In contrast, with the second fiber (b), the EDFAs reduce this effect by introducing a gain-flattening filter within each amplifier.

Figure 1-15 Gain Flattening Filter

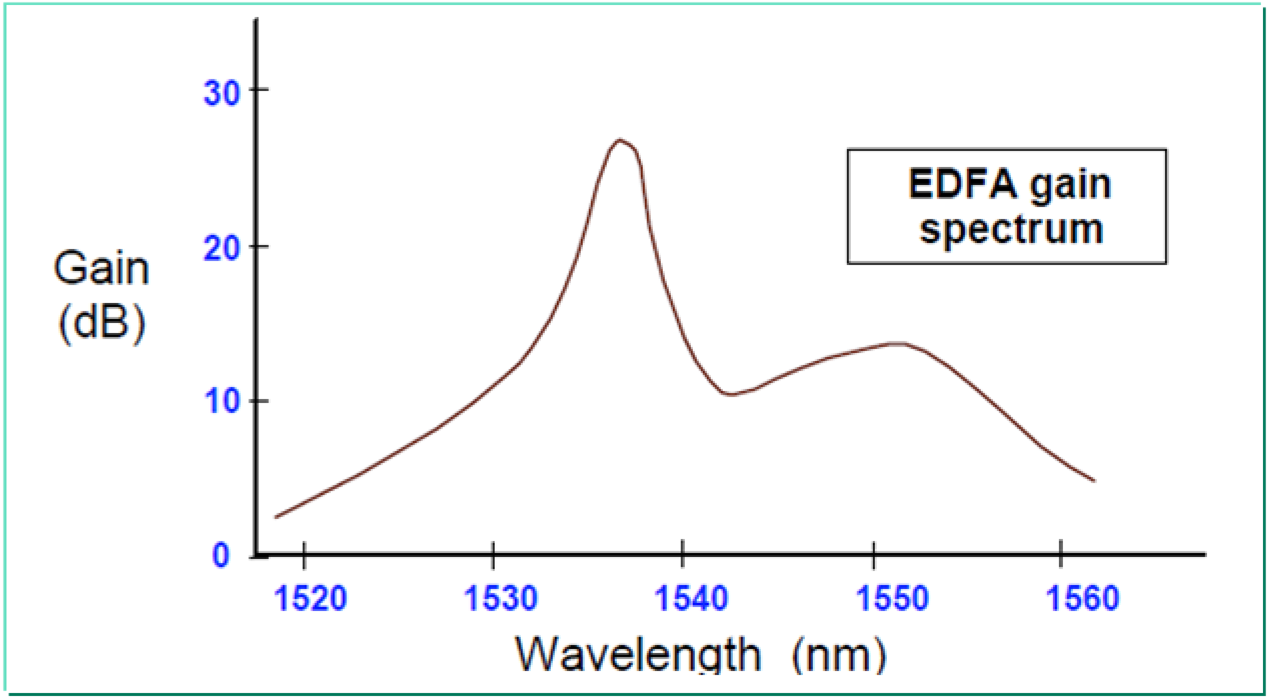


EDFA Gain Spectrum :-

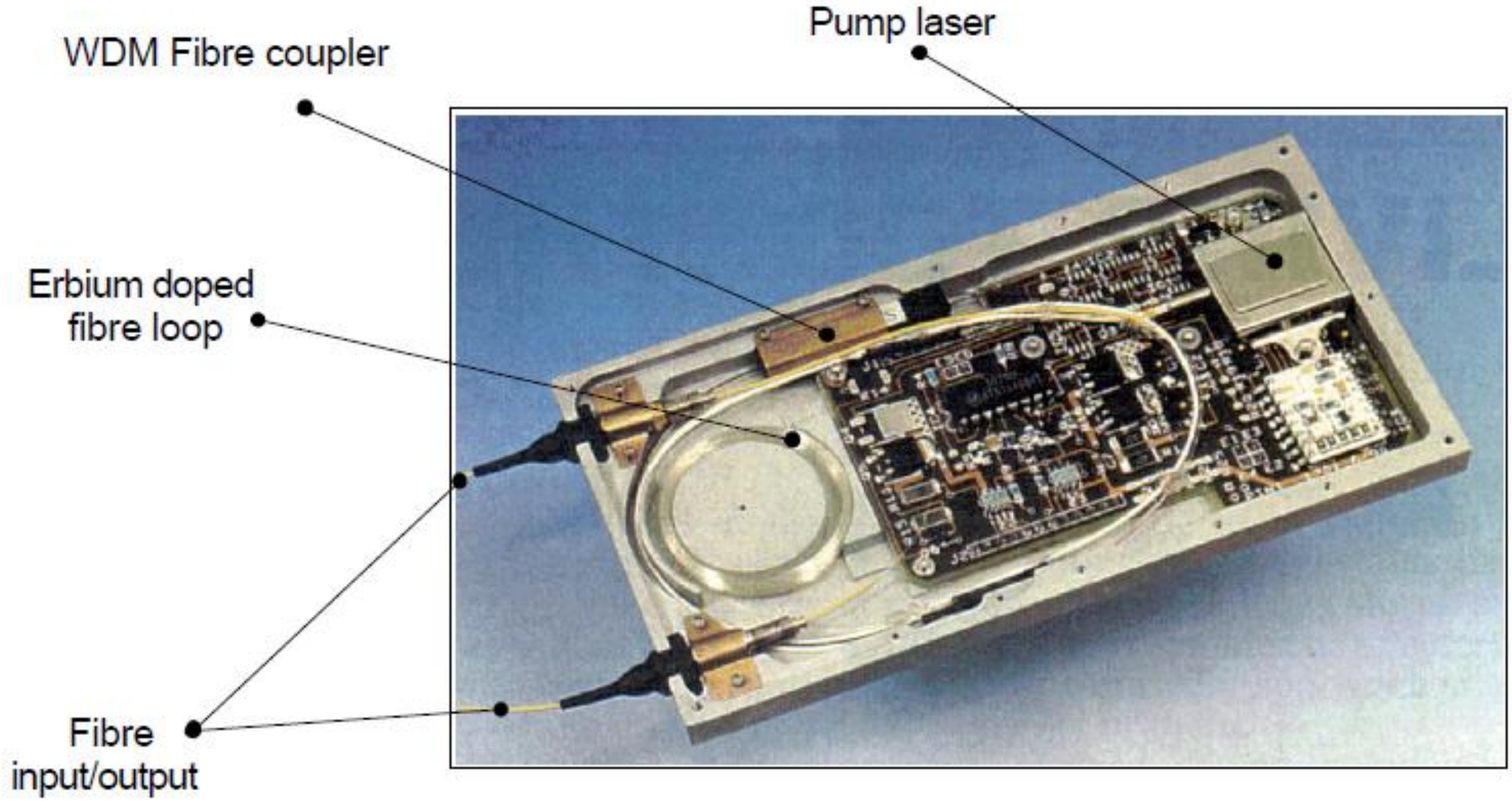
Erbium can provide about 40-50nm bandwidth, from 1520-1570 nm.

Gain Spectrum depends on the glass used . Eg- silica or zblan glass.

Gain Spectrum is not Flat, significant gain variations.



Interior of an Erbium Doped Fibre Amplfier (EDFA)



Power Input to an EDFA :

On the left-hand side of the above *figure* we see an example of coupling two different wavelengths into the same output fiber.

At the input of an EDFA you want to mix the (low level) incoming signal light with (high level) light from the pump.

Typically the signal light will be around 1550 nm and the pump will be 980 nm.

In this case it is possible to choose a coupling length such that **100%** of the signal light and 100% of the pump light leaves on the **same fiber**.

A major advantage of this is that there is very little loss of signal power in this process.

	EDFA	RAMAN	SOA
Gain	~30 dB	~20-25 dB	~ 10-20 dB
Output power	High	High	Low
Input power	Moderate	High	High
Crosstalk	Low	Low	Very high
Gain tilt	High gain tilt	Low	High
Application	Metro, long haul	Typically long haul	Short haul, single channel, wavelength converters

Amplifier Comparison

Advantages

1. EDFA has high pump power utilization (>50%)
2. Directly and simultaneously amplify a wide wavelength band (>80nm) in the 1550nm region, with a relatively flat gain
3. Flatness can be improved by gain-flattening optical filters
4. Gain in excess of 50 dB
5. Low noise figure suitable for long haul applications

Disadvantages

1. Size of EDFA is not small.
2. It can not be integrated with other semiconductor devices.

Wavelength Selective Coupler(Splitters) : These are used to either combine or split light of different wavelengths with minimal loss.

Light of two different wavelengths on different input fibers can be merged (combined) onto the same output fiber.

In the reverse direction, light of two different wavelengths on the same fiber can be split so that one wavelength goes to one output fiber and the other wavelength is output onto the other output fiber and hence, this process can be performed with very little loss.

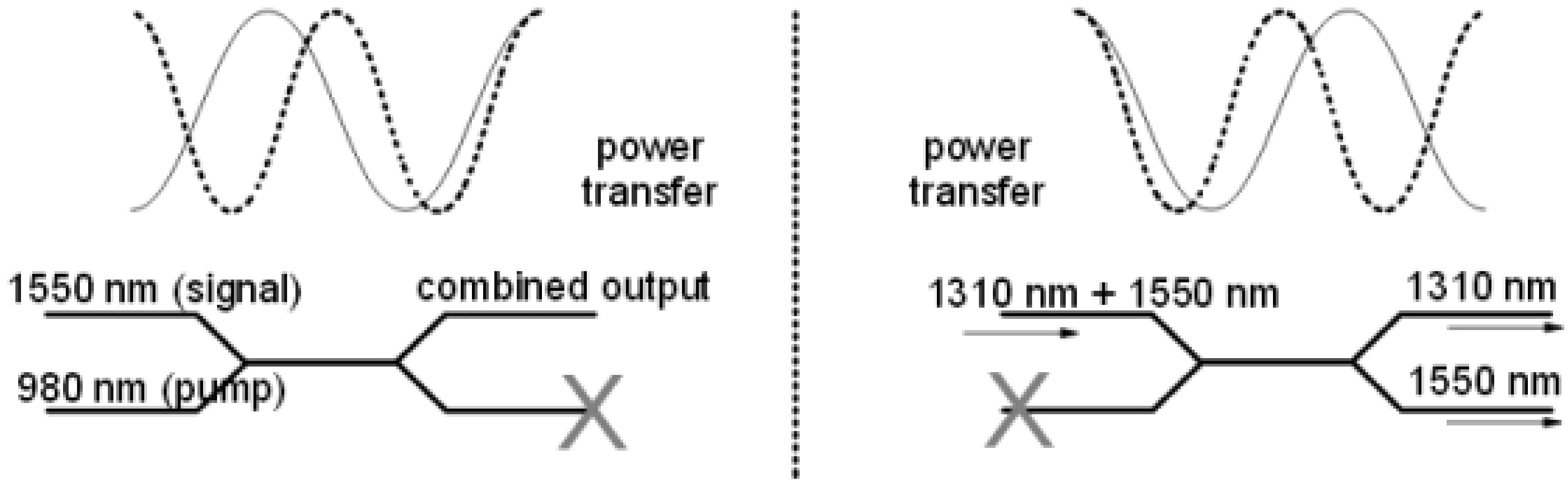
As the coupling length is wavelength dependent, the shifting of power between the two parallel waveguides will take place at different places along the coupler for different wavelengths.

All we need to do is choose the coupling length carefully and we can arrange for loss free wavelength combining or splitting.

These functions are shown in the figure below.

The graph of power transfer shows how power input on one of the fibers shifts back and forth between the two waveguides.

The period of the shift is different for the two different wavelengths.



Thus in the left-hand section of the diagram (combining wavelengths) there will be a place down the coupler where all of the light is in only one waveguide.

If we make the coupler exactly this length then the signals have been combined.

On the right-hand side of the diagram the reverse process is shown where two different wavelengths arrive on the same input fiber.

In fact both the processes described above are performed in the same coupler—the process is Bi-Directional.

Thus the coupler on the left can operate in the opposite direction and become a splitter and the splitter on the right can operate in the opposite direction and become a coupler (combiner).

Note that each coupler or splitter must be designed for the particular wavelengths to be used.

Commercial devices of this kind are commonly available and are very efficient.

The quoted insertion loss is usually between 1.2 and 1.5 dB and the channel separation is quoted as better than 40 dB.

“Wavelength flattened” couplers or splitters of this kind operate over quite a wide band of wavelengths. i.e,

in a given device may allow input over a range of wavelengths in the 1310 nm band up to 50 nm wide and a range of wavelengths in the 1550 nm band also up to 50 nm wide.

Adding the Management Channel in DWDM Systems :

In DWDM systems where many channels are carried in the 1550 nm band there is often a requirement to carry an additional relatively slow rate channel for management purposes.

A convenient way to do this is to send the management information in the 1310 nm band and the mixed DWDM stream in the 1550 band.

Wavelength selective couplers are commonly used for this purpose.

A management signal (a single wavelength) in the 1310 band is coupled onto a fiber carrying many wavelengths between 1540 nm and 1560 nm.

Another similar device (wavelength selective splitter) is used to separate the signals at the other end of the link.

Networking with DWDM

Modulation can be defined as ***superimposing a data stream onto a carrier signal by altering one*** of the virtues of the carrier signal with respect to a change in the data stream.

In other words, you can make a binary data stream superimpose on a carrier frequency.

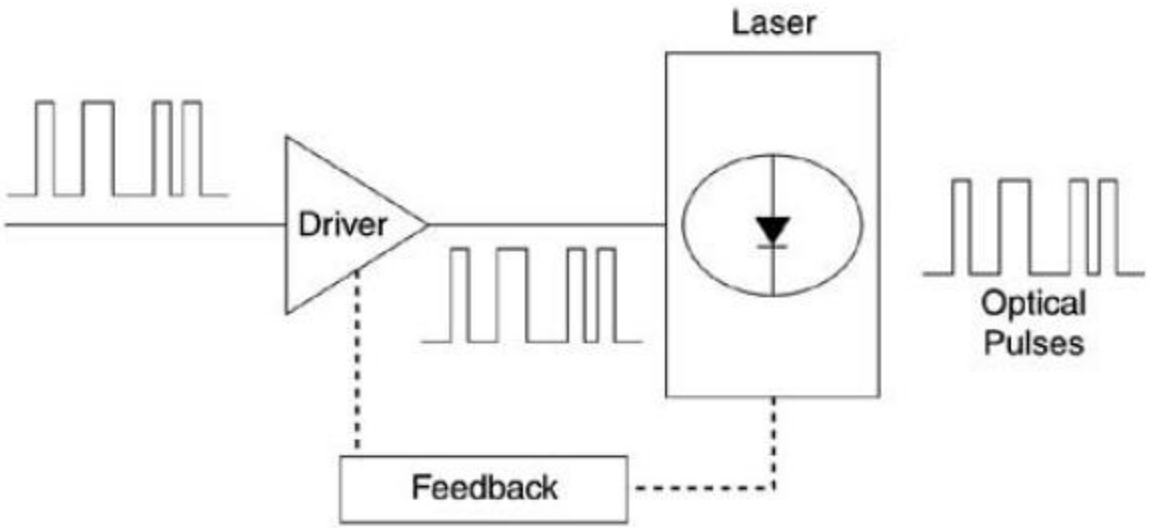
The motive behind modulation is to enable transport of data efficiently and without many errors.

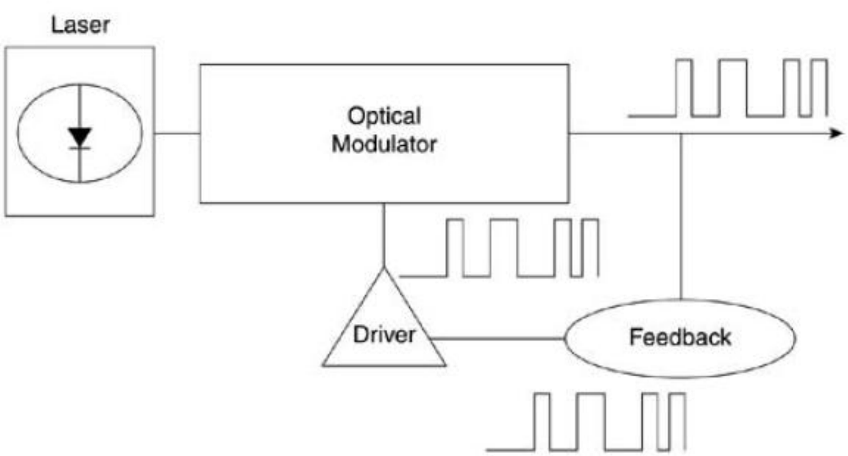
In an optical WDM network, data is modulated onto the light that a laser diode emits.

One way of modulation is to make the output optical power of a laser diode proportional to the binary sequence of the data stream.

You can use two techniques for modulation by using optical lasers: direct modulation, as shown in Figure, and external modulation, as shown in Figure.

Direct Modulatior





External Modulation Technique

Here, the laser drive current that is needed to cause stimulated emission which is varied with the data stream which causes the output optical power to fluctuate as per the data stream.

In other words, a stream of binary data, when made proportional to the optical power, creates a series of isomorphism optical pulses.

So, this modulation technique is termed *direct modulation* *because the data is directly coupled with the laser drive current.*

Drawback : Direct modulation has severe drawbacks at ***high data rates*** as it cannot be used at bit rates that are greater than 2.5 Gbps.

Also, Direct modulation—creates non-linearity's especially self phase modulation (SPM).

Direct modulation also *increases the laser chirp.*

Typically, a binary data stream is made to modulate a laser diode; therefore, the optical power fluctuates between high and low.

Due to the return-to-zero type of modulation format, the laser diode switches between ON and OFF for a logical 1 and logical 0 respectively, such that turning the laser ON and OFF introduces time dependence and so as a result, the bit rate that is transmitted using direct modulation having a maximum limit.

Limitation : Direct modulated lasers are limited more by distance than by bandwidth Drawbacks and for short ranges, **they are cost effective** and useful, especially for **metro-optical operations.**

External Modulation

When a laser source is not directly modulated to feed the data stream, but the output optical frequency is modulated in a separate section by other means, this kind of optical modulation technique is called external modulation.

External modulation avoids nonlinearity's and excessive chirp.

The function of an **Optical Receiver** is to decode and interpret the optical signals and generate an electrical data stream proportional to the received optical signal.

The main component of an optical receiver is **a** ***photo detector***, which converts the optical power into electrical current.

Photo detectors need to meet stringent(**exact**) requirements to achieve desirable performance, where these requirements include good responsivity **(sensitivity)** to a wide range of wavelengths used for transmission .

1. (usually in the 850 nm, 1300 nm, or 1550 nm region)
2. low noise characteristics
3. low or zero sensitivity to temperature variations
4. low cost and
5. Extended operating life.

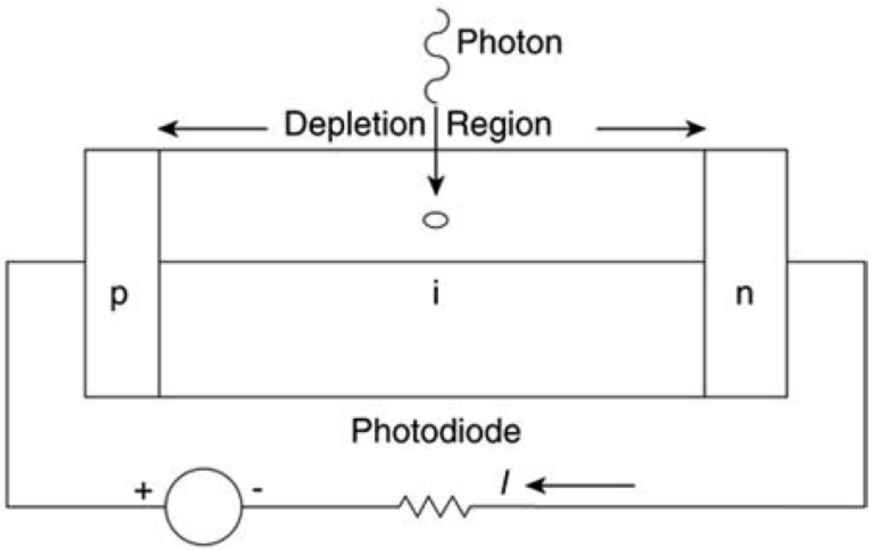
Even though several types of photo detectors are available, semiconductor-based photo detectors (photodiodes) are used exclusively for optical communications such as PIN photo detectors and Avalanche Photo Detectors (APDs), due to their

1. Small size
2. Fast response
3. High photo-sensitivity and
4. Comparably low costs.

The PIN Photo Detector : The PIN diode is an extension of the P-N junction diode, in which slightly doped intrinsic material (I stands for intrinsic) is inserted in between the P-N junction, thereby increasing the depletion width (region) of the P-N junction.

The depletion region is the region in the p-n junction that is formed by some of the electrons from the n type moving over and depleting the holes in the p type, thereby creating a region of neutral charge, upon condition of reverse bias, as shown in the figure –

Figure 2-11. PIN Photo-Diode



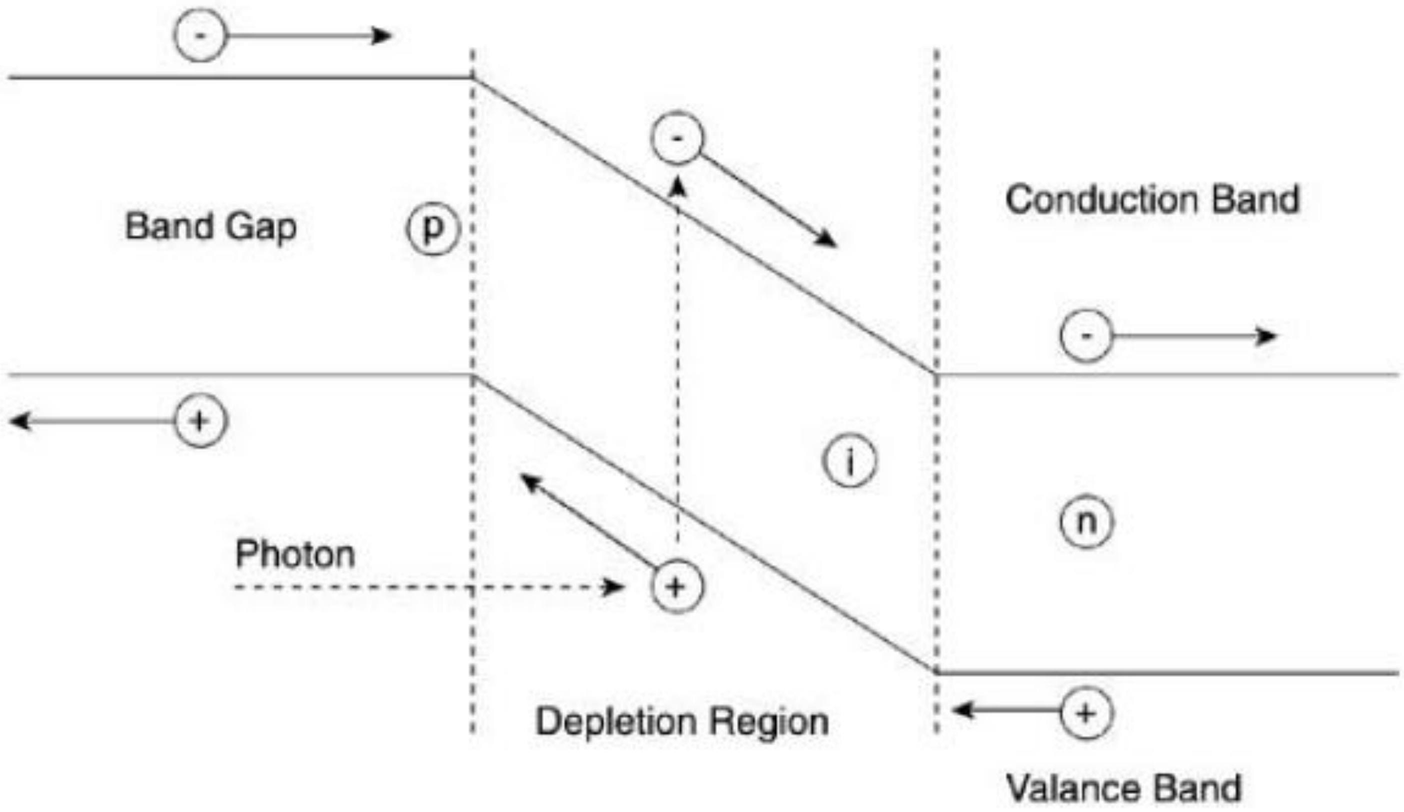
A high reverse-biased voltage is applied across the PIN diode so that the intrinsic region is completely depleted and figure above represents the normal operation of a PIN diode with reverse bias applied across the p-i-n junction.

When light (photons) is incident on a semiconductor material, electrons in the valence band **absorb it.**

As a result of this absorption, the photons transfer their energy and excite electrons from the valance band to the conduction band, leaving holes in the valance band.

The design of the PIN photodiode is optimized in such a way that electron hole pairs are generated mostly in the depletion region (see **Figure 2-12**).

Energy Band Diagram for Photodetector



After the application of voltage across the depletion region, the formed electron hole pairs induce an electric current flow (also known as *photocurrent) in an external circuit.*

Each electron hole pair generates one electron Flow.

To generate the photocurrent, we must ensure that the energy of the incident photon is equal to or greater than the band gap energy.

Avalanche Photodiodes :

When light is absorbed by a PIN photo detector, only a single electron hole pair is generated per photon.

You can increase the sensitivity of the detectors if more electrons are generated, which means that you need less power for photo detection and that the signal can travel longer.

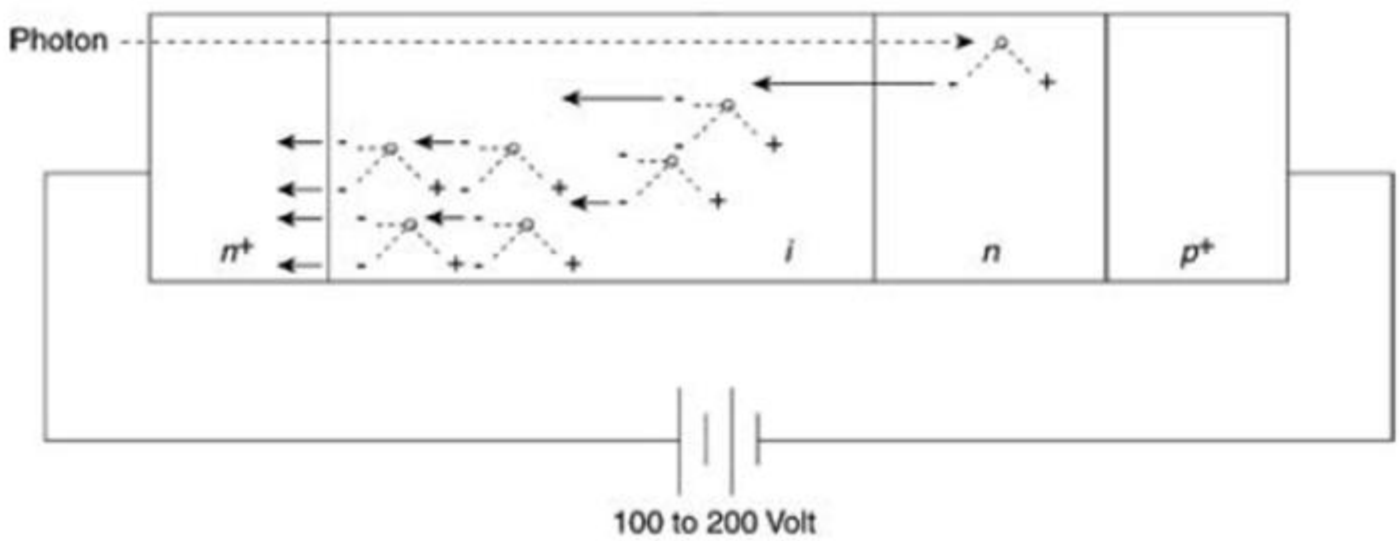
If a high electric field is applied to the generated electrons, enough energy is procured to excite more electrons from the valence band to the conduction band.

This, in turn, results in more electron hole pairs being generated.

These secondary electron hole pairs that are generated by the preceding process can produce more electron hole pairs if they are subjected to a high electric field (Avalanche effect).

This process of multiplication of electron-hole pairs is called *Avalanche multiplication, which is* demonstrated in Figure 2-13. The photodiode that is designed to achieve this kind of electron hole pair multiplication is known as **Avalanche photodiode (APD).**

Figure 2-13. Avalanche Multiplication Process



In practice, the avalanche effect is a statistical phenomenon.

In other words, electron hole pairs generated by the primary electrons are randomly distributed.

The statistical value is termed as *multiplicative factor, or multiplicative gain (Mf),*

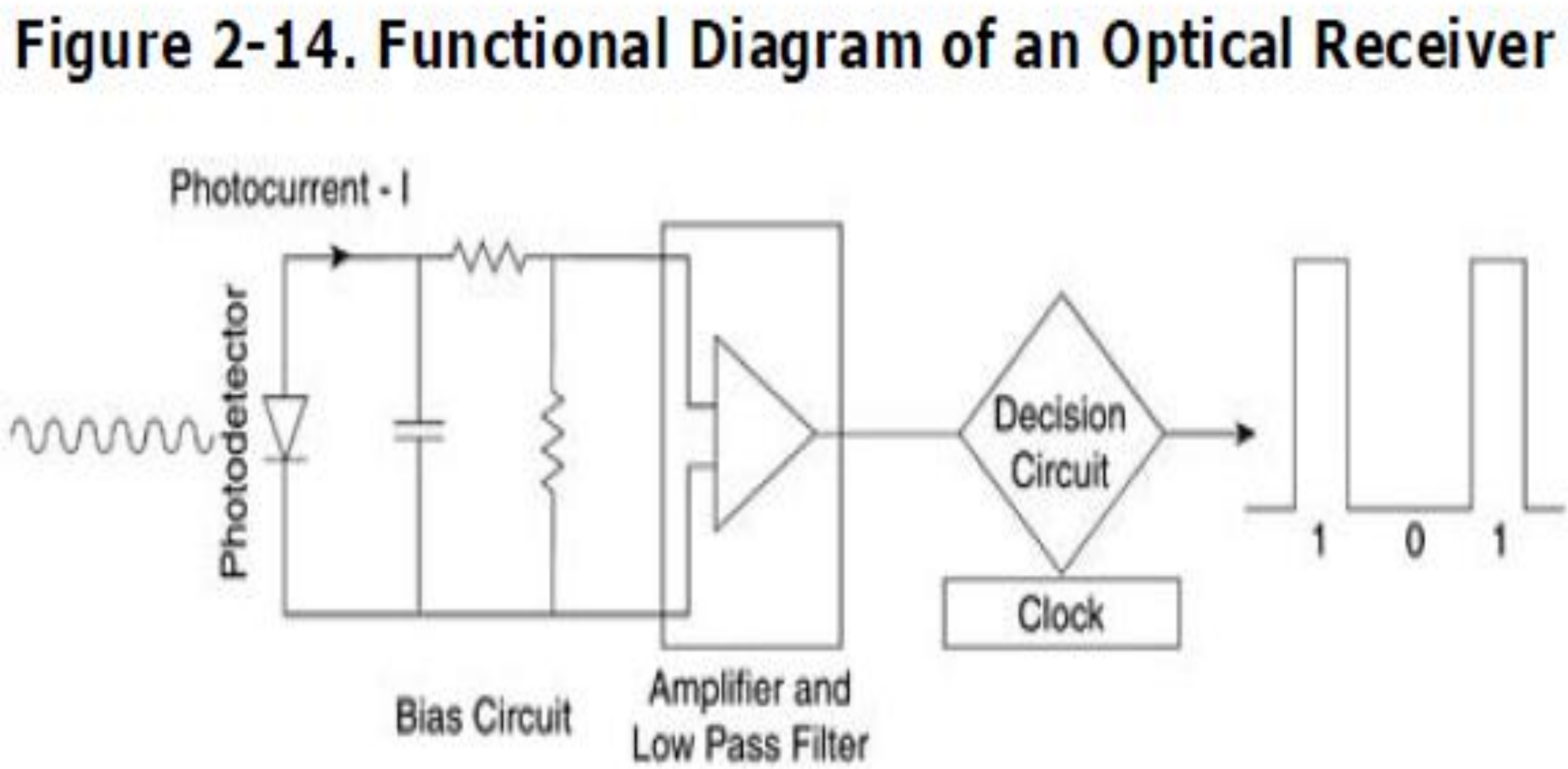


Figure 2-14. Functional Diagram of an Optical Receiver
Photocurrent - I
Photodetector
Bias Circuit
Amplifier and
Low Pass Filter
Decision
Circuit
Clock
1
0
1

An optical receiver consists of a photo detector followed by a preamplifier which is used to amplify the photocurrent for further processing.

The next stage consists of a high-gain amplifier and a low-pass filter.

An amplifier gain control circuit automatically limits the amplified output to a fixed level, regardless of the optical power incident on the photo detector.

The low-pass filter reduces the noise level and shapes the pulses.

Receiver noise is proportional to receiver bandwidth, and loss-pass filters can reduce noise by having the bandwidth (BW) be lower than the bit rate (B).

The electric pulse spreads beyond the bit slot for BW < B and results in ISI, which interferes with proper detection of nearby bits.

The final stage of an optical receiver consists of a decision circuit and a clock recovery circuit, where the decision circuit compares the output to a threshold level at sampling times that the clocking circuit defines and then decides whether the input signal pulse is a 1 bit or a 0 bit.

Optical cavities and filters are important WDM devices that can demultiplex the composite signal.

Tuneable optical filters are key building blocks that can tune to a desired wavelength and tap a channel or a band of channels.

Tuneable optical filters are inherently of two types :-

- cavity based
- thin-film based.

Cavity-based filters are the most common filters available, examples include the *Fabry Perot cavity filters* and the *Acousto-Optic Tunable Filters (AOTF).*

A filter is designed to have the following characteristics :

- A clean window of operation (pass band); in other words, minimal cross-talk with adjacent channels
- A wide tuning range that should be able to cover the entire band of operation
- A fast tuning speed that should be dynamically provisioned to facilitate changing traffic requirements
- Should not affect the polarization state of the passing signal.

Most filters are based on the principle of optical cavities, which can be tuned to a resonant frequency.

The other technology used in conjunction with optical cavities is that of thin film filters.

Fabry Perot cavity filters :

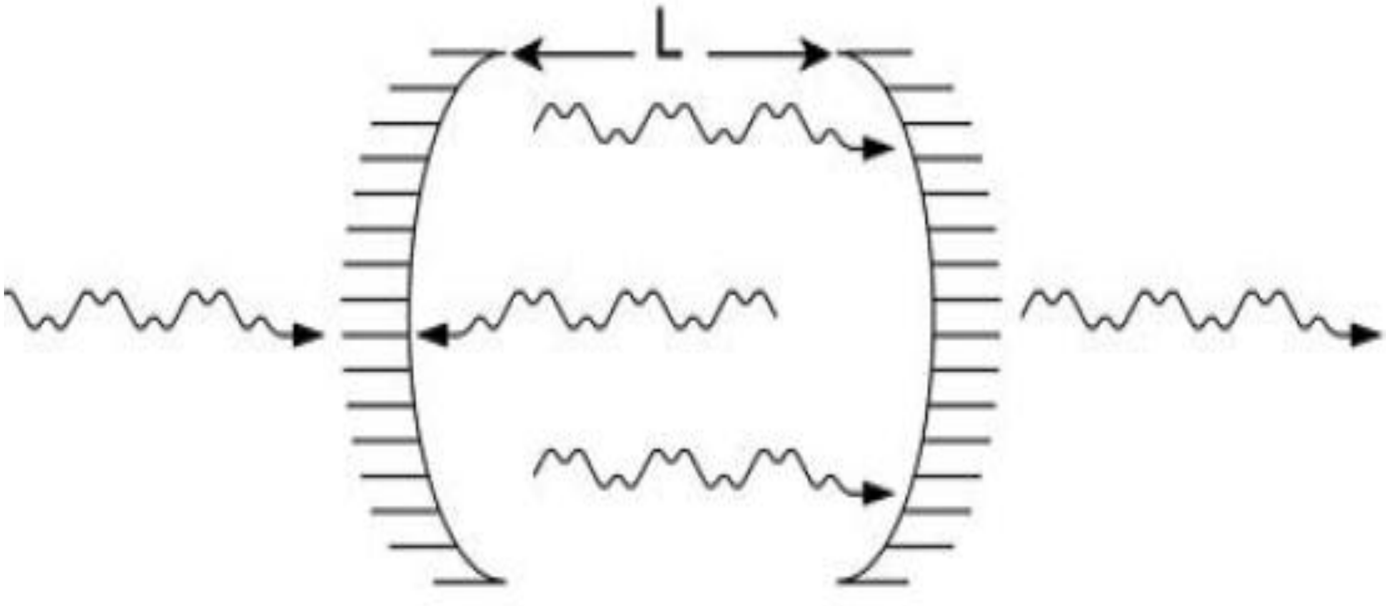
A Fabry Perot cavity consists of two *reflective surfaces* that are separated by a hollow region.

The distance between the reflective surfaces can be made to change by changing the current associated with the transducer, responsible for creating the cavity.

In general, the cavity has two reflective surfaces with reflectivity that is a function of the operating wavelength.

The reflectivity can be made to change for different resonant wavelengths.

For a resonating cavity, the resonant wavelength is the only wavelength, and it does not suffer reflection from one of the two mirrored walls as shown in the figure.



Fabry Perot Cavity Filter

The transmission characteristics or the transitivity of an FP cavity is best for $\lambda = \lambda_{resonance}$, is generally shown as in Equation 2-43.

Equation 2-43

$$\lambda_{res} = \frac{L}{2n}$$

In the equation, n is an integer and L is the distance between the two walls of the cavity.

Two properties that are important for design of cavities are the free spectral range (FSR) and finesse.

For a mirror of reflectivity R, the finesse is provided as in Equation 2-44.

Equation 2-44

$$F = \frac{\pi\sqrt{R}}{1-\sqrt{R}}$$

In the equation, R is a ratio of incident to reflected power of a mirrored surface (reflectivity).

Therefore, R is figure of merit for a reflective surface.

Finesse of a cavity is a figure of merit that depicts the amount of fine tenability that can be achieved by using this cavity.

The FSR can be defined as the minimum range of two successive filtered peaks; it is the frequency difference between two transmission peaks. See Equation 2-45.

Equation 2-45

$$\Delta f_1 = \frac{c}{2n_g L}$$

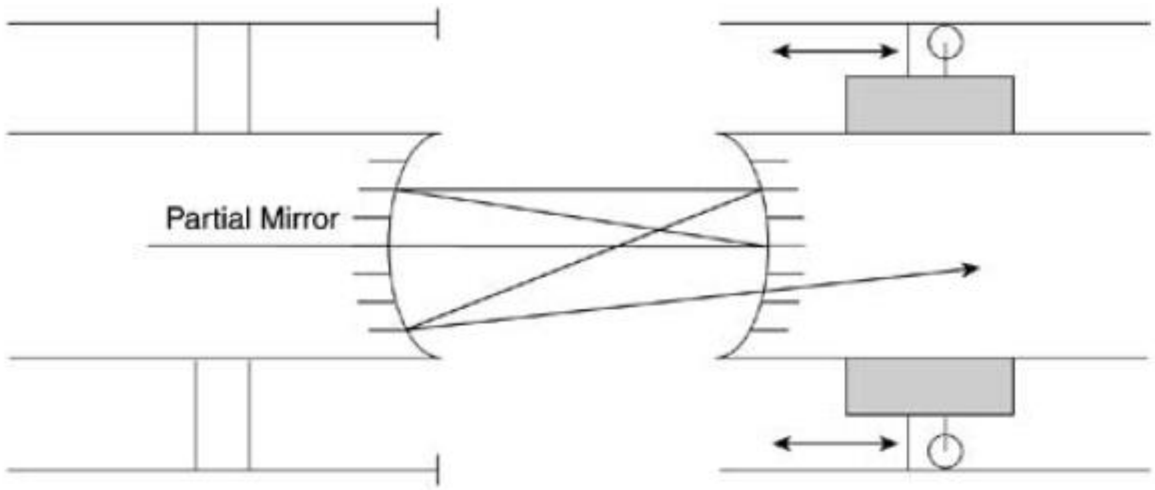
In the equation, Ng is the group index and L is the length of cavity.

The length of the cavity can be changed by applying a voltage to a transducer that mechanically shifts the mirrors (closer or further away).

The change in length for practical WDM systems is a function of the wavelength.

Moreover, the mirrors are not more than 150–200 mm apart, which makes FP cavity fabrication more difficult.

A popular approach is to utilize the air gap between the two polished surfaces of two fibers, as in Figure .



Acousto-Optical Tunable Filter

AWG Arrayed Waveguides : An AWG device consists of many waveguides of different lengths converging at the same point(s).

Signals coming through each of these waveguides travel through a length such that they interfere from the signals through the other waveguides (at the converging point) either constructively or destructively, depending on the net phase difference between the signal and its interfering counterpart(s).

Such a phased array of waveguides can be used as a multiplexer or demultiplexer (follow Figure 2-26 closely).

For de-multiplexing, the composite WDM signal is coupled into an array of waveguides using a 1 x N coupler.

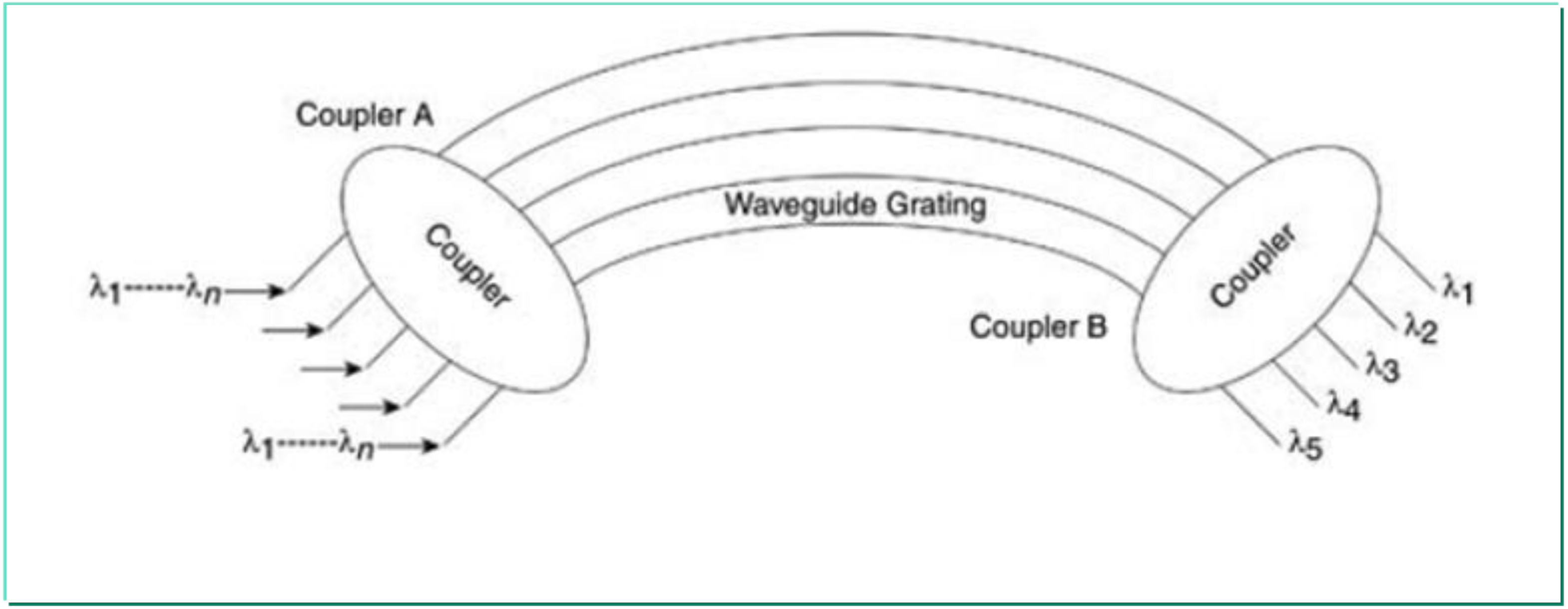
Each signal in the waveguides gets a different phase shift because of different lengths of each waveguide.

The amount of phase shift induced depends on the wavelength.

The interference caused at the second coupler (see Figure -2-26) can be controlled such that each channel is separated into each of the output fibers.

This is due to the spatial diversity induced by the interference of phase-shifted signals.

In this way, a composite signal consisting of many wavelengths can be demultiplexed into individual wavelengths, one in each of the output fibers (ports).



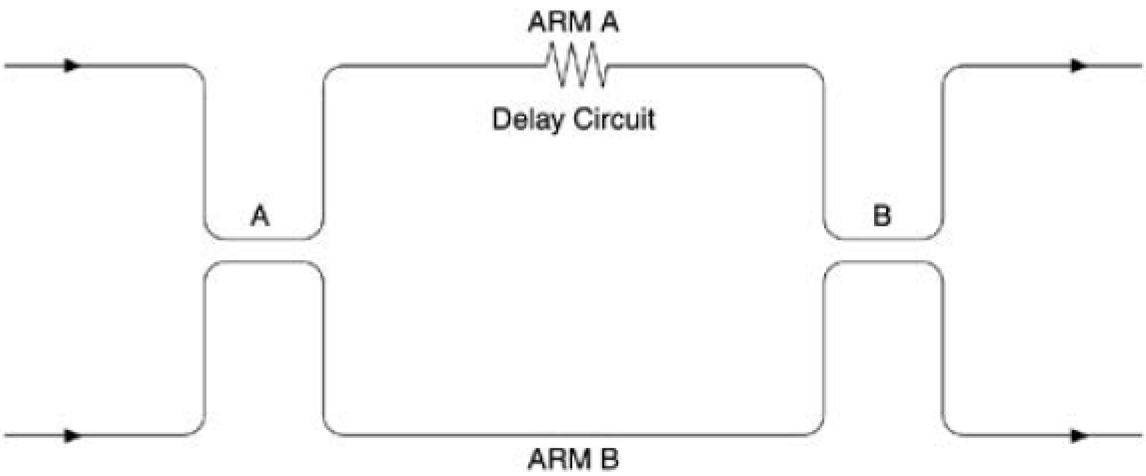
Array Waveguide

Mach Zehneder Interferometer and Filter : A *Mach Zehneder Interferometer (MZI) is a two-arm device, such that the signals in the two* arms interact with each other twice.

Physically, an MZI can be constructed by connecting two passive 2 x 2 couplers in tandem.

The couplers are equibalanced; in other words, input power is equally split into the two arms. The first coupler (A) divides the signal into two (see Figure 2- 27).

Figure 2-27. MZI- Mach Zehneder Interferometer



The two propagating signals can be made to obtain different phase shifts by varying the lengths of the two arms.

The signals, upon interfering with each other at coupler B, might have constructive or destructive interference.

The MZI is built on silica substrate, and these kinds of optical circuits are called *planar light wave circuits (PLC)* because of their planarity of the substrate.

A more mature technology is Indium Phosphide substrate or Lithium Niobate substrate.

The issue of Grating filters discussed previously cannot be dynamically tuned with ease to drop or add any channel now can be solved by creating dynamic gratings by using acoustic waves.

By creating a series of acoustic (sound) waves inside a waveguide, an acoustic grating is formed.

Light passing through such a disturbance has the same effect as passing through a grating.

The interaction of light with the acoustic waves is termed as the *photon-phonon interaction given by an effect known as the photo-elastic effect.*

AOTF can be fabricated best by using Lithium Niobate ($LiNbO_3$) waveguides, producing small polarization-independent filters.

AOTFs are characterized by a tuning range in the excess of 100 nm covering both C and L bands.

One limitation is channel cross-talk, which is currently being investigated.

By definition, a *Transponder is a device that enables end-users to access the WDM channels and it can* detect optical signals at various wavelengths and convert them to ITU grid wavelengths.

(The ITU is a standardizing body & is responsible for allocating fixed wavelengths in a WDM network known as ITU-grid wavelengths).

Transponders are considered complex WDM components because they consist of several subsystems—such as lasers and photo detectors—in addition to filters.

Different versions of transponders are available depending on the requirement where the simplest is the reshape and reamplify (2R) version in which **protocol-independent** conversion and detection of the optical signal is carried out.

The more complex and expensive version is the reshape , retime, and reamplify (3R) transponder, which is **protocol dependent** and such transponders are needed for high bit rate signals.

For example, an OC-192 transponder card will not work for a 10 GigE card for the simple reason of protocol incompatibility even though the line rates are almost the same.

Currently in the C-band as well as L-band, the ITU allots wavelengths with 0.8 nm or 100 GHz as well as 0.4 nm or 50 GHz separations.

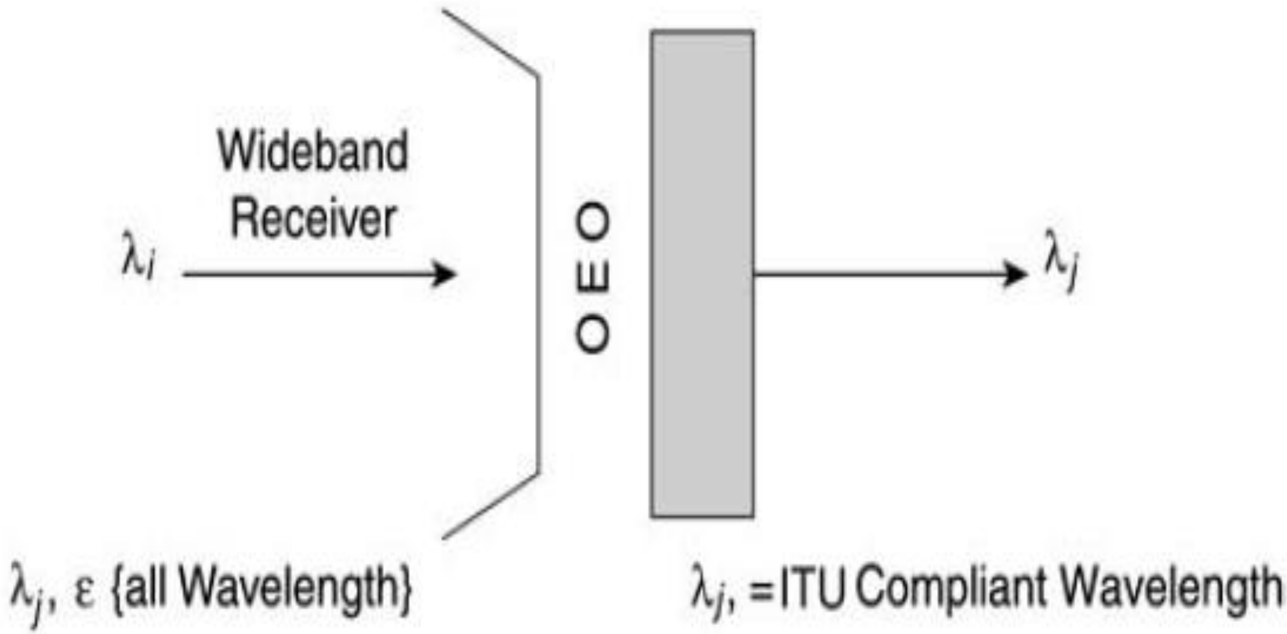
In a service provider network, it is necessary to have all light paths or wavelengths specified by the ITU standard but in practice, most service provider networks use C and sometimes L bands.

However, a client to the service provider might not use a standard wavelength on his light path.

Essentially, transponders have a functionality that allows them to receive any wavelength but transmit only an ITU-compliant wavelength.

Furthermore, this functionality can be increased so that transponders transmit a range of tuneable (ITU-defined) wavelengths instead of just one fixed wavelength.

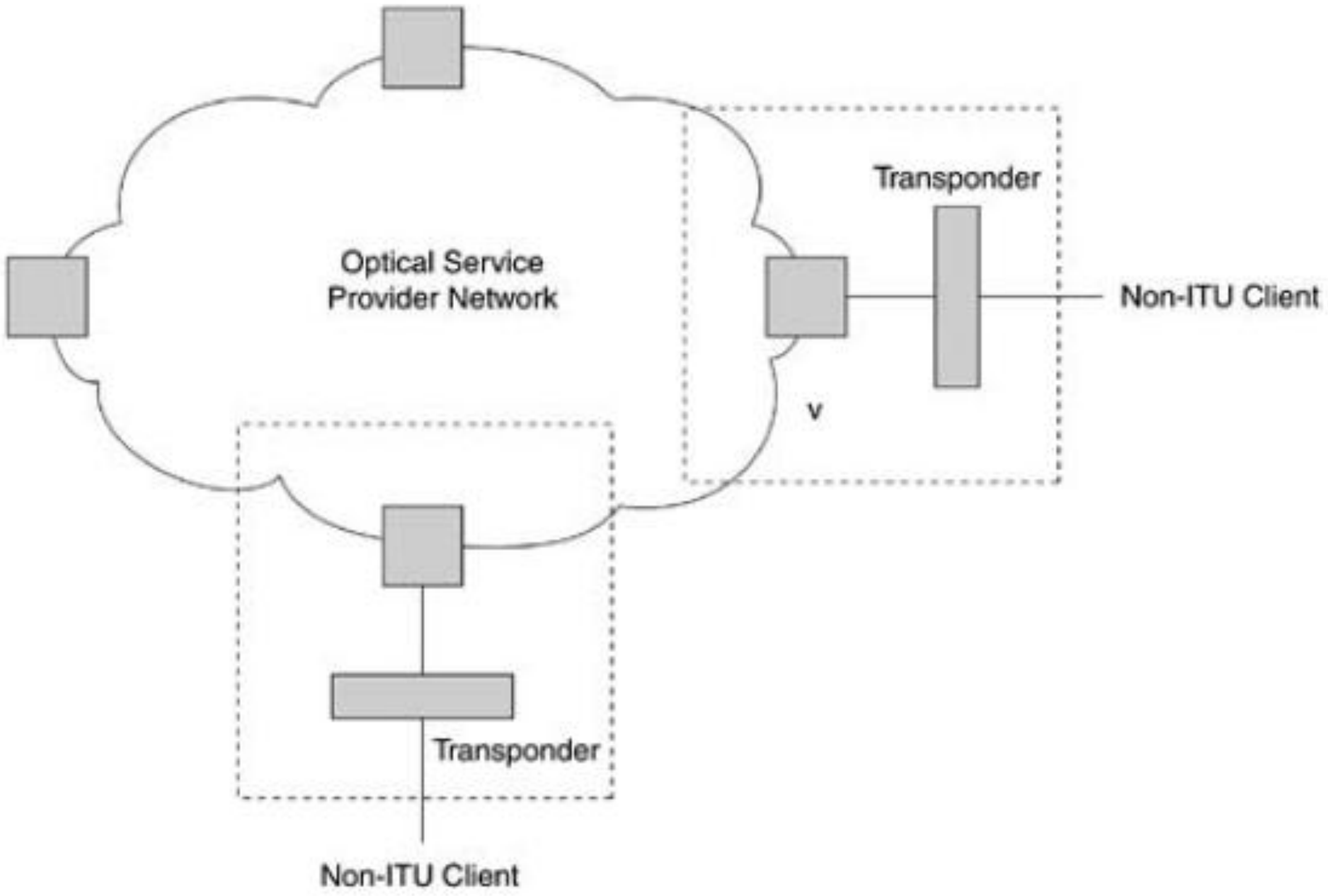
Transponders essentially are wavelength converters that use **O-E-O** as a means to convert the ingress wavelength to the egress wavelength.



Because of the **O-E-O** symmetry, transponders usually perform 3R regenerations, but 2R generations are also possible. (3R transponders are not bit-rate transparent.)

Transponder-based WDM systems are considered close systems due to the compatibility with the installed client base (SONET/SDH/IP) and they allow the legacy client equipment to feed directly into the transponder system.

Hence, The transponders allow a variety of client interfaces over WDM networks (Ethernet over WDM; storage area network (SAN) over WDM; and so on) as refer to Figure :



Typical Transponder-Based Network

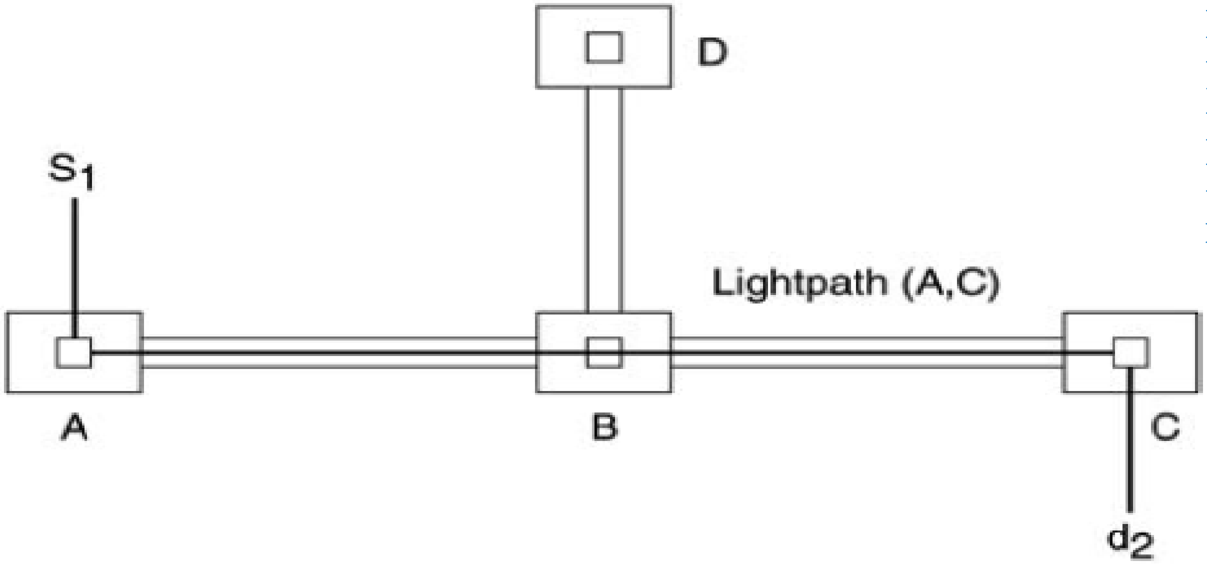
Optical switches represent the single-most dynamic element in a WDM network.

Traditionally, switches can switch data between different ports of a network element by catering two types of data: circuits and packets.

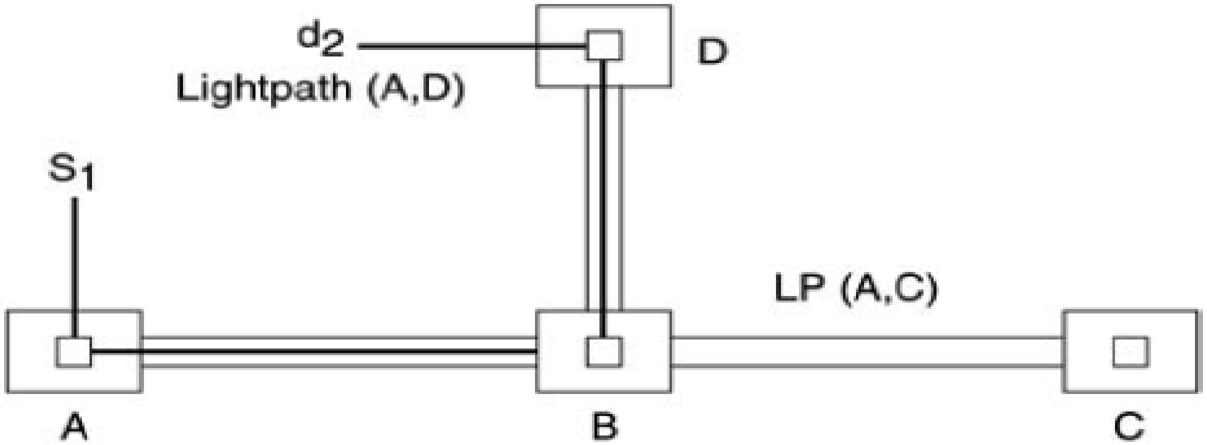
A Circuit or a light path (in the optical domain) is an end-to-end connection (source-destination pair) over which data flows and , Packets are discrete messages/data grams of short sizes.

Current technology facilitates circuit switching where a light path between a particular source and destination pair can be established for a sufficiently long period of time.

Light path may be switched optically from this destination to another using an optical switch, as shown in Figure Below :



Light path Switching: Predominant in Today's Networks.
Note the switch at node B is reconfigured.



In Packet-switched networks, individual packets are switched between source –destination pairs.

Packet Switching is more dynamic than Circuit Switching.

Considering the present form of theInternet, packet switching is more desirable than circuit switching because data traffic is currently more dominant than voice.

However, Packet switching in the optical domain is currently only an academic exercise—it's far from being feasible.

So, the Circuit switching in the optical layer is more feasible and is known as *light path switch*.

Optical switches consist of two types:

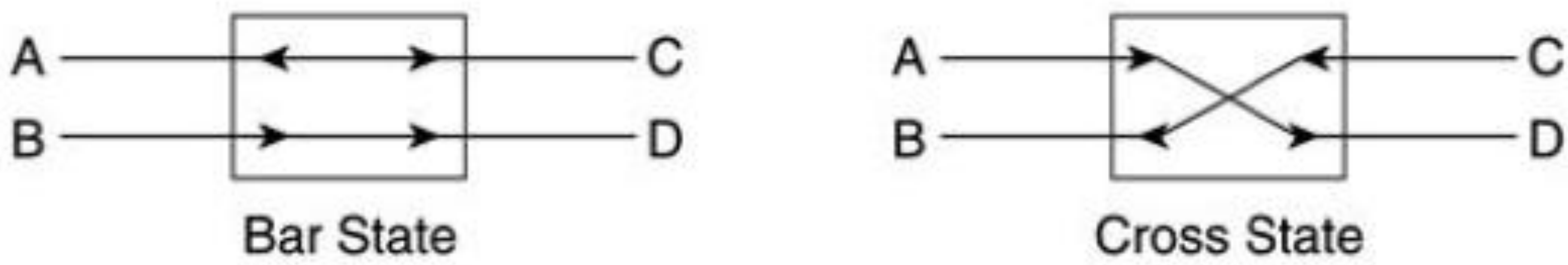
- Add-drop switches
- Optical cross-connect

Micro-mechanical switches, as shown in Figure .have become a mature technology for switching light paths.

Switches of small degree (for example, 2 x 2) work by mechanically moving a pair of fibers between corresponding output ports.

Due to the mechanical movements involved, such switches are typically slow (5–10 ms).

The movements also create dynamic loss variations where such switches have high insertion loss of about 1–2 dB(that could be negligible).

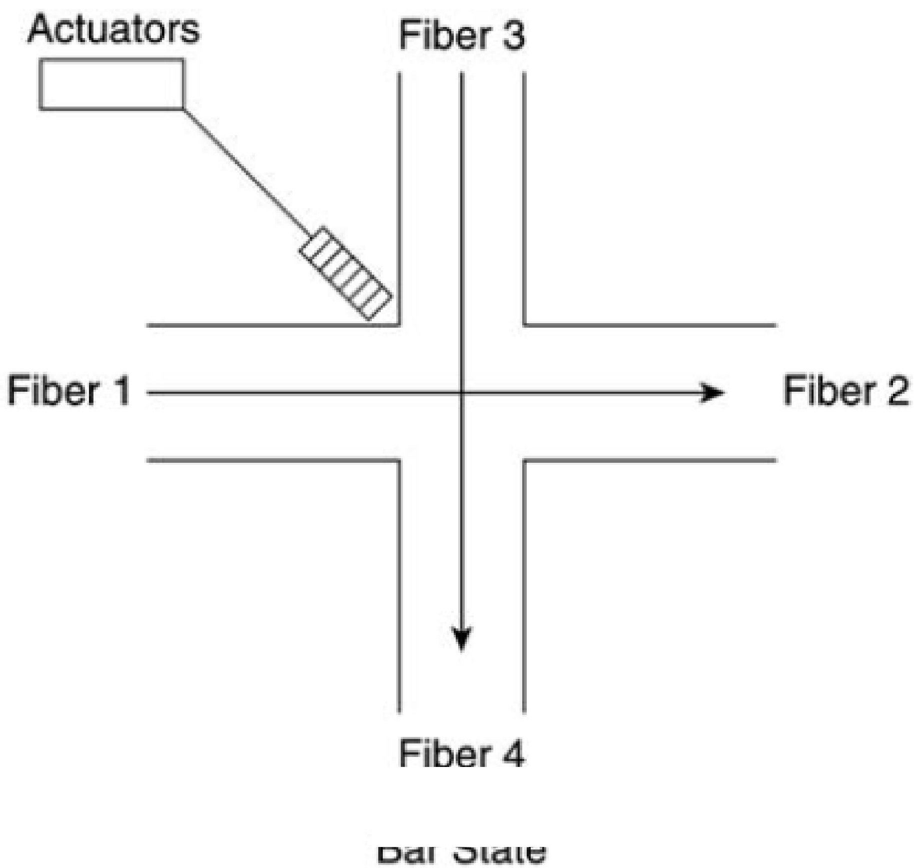


Mechanical Switches: Logical Connection Diagram

The advantage that micro-mechanical switches offer is that they are fairly robust and inexpensive and comparative performance.

These switches have negligible wavelength dependent loss and work quite the same for different wavelengths.

Micro-electro-mechanical systems (MEMS) is a fascinating innovation that is applied to optical networking & can be deployed to perform certain switching functions in the optical domain.

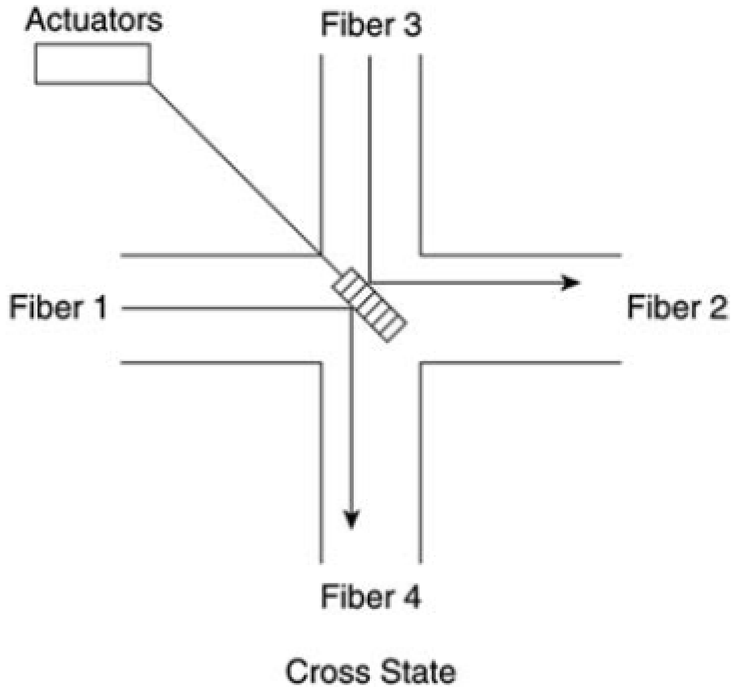


2D MEMS (Bar State)

Here, Four fibers (1, 2, 3, and 4) are coupled together to form a 2 x 2 cross-connect.

A double-sided mirror that is perpendicular to the plane of the page is present and held in position by two actuators.

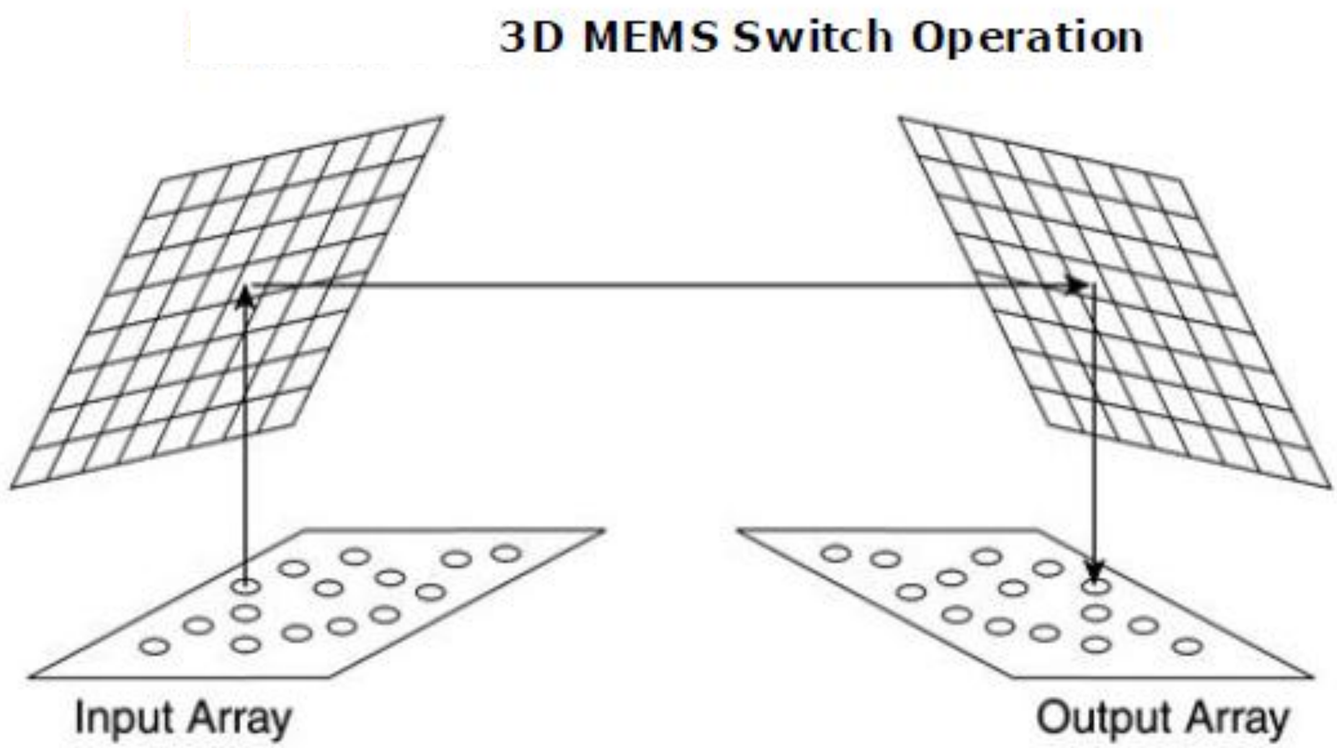
In the bar state, light from fiber 1 is coupled to fiber 2, and light from fiber 3 is coupled to fiber 4.



2 D -Cross State

So, typical switching times are in millisecond range and the insertion loss of the switch is about 1 dB per port.

So, MEMS switches can be scaled to provide an N x N cross-connect.



The one shown in Figures (Bar-state) and (cross-state) is a 2D MEMS (2-dimensional MEMS).

In contrast, the above figure is 3D MEMS switch (3-dimensional).

The incident light in 3D MEMS is switched in 3D space using collimated lens to provide efficient 3D switching; it is comparable to free space optics.

Bubble Technology

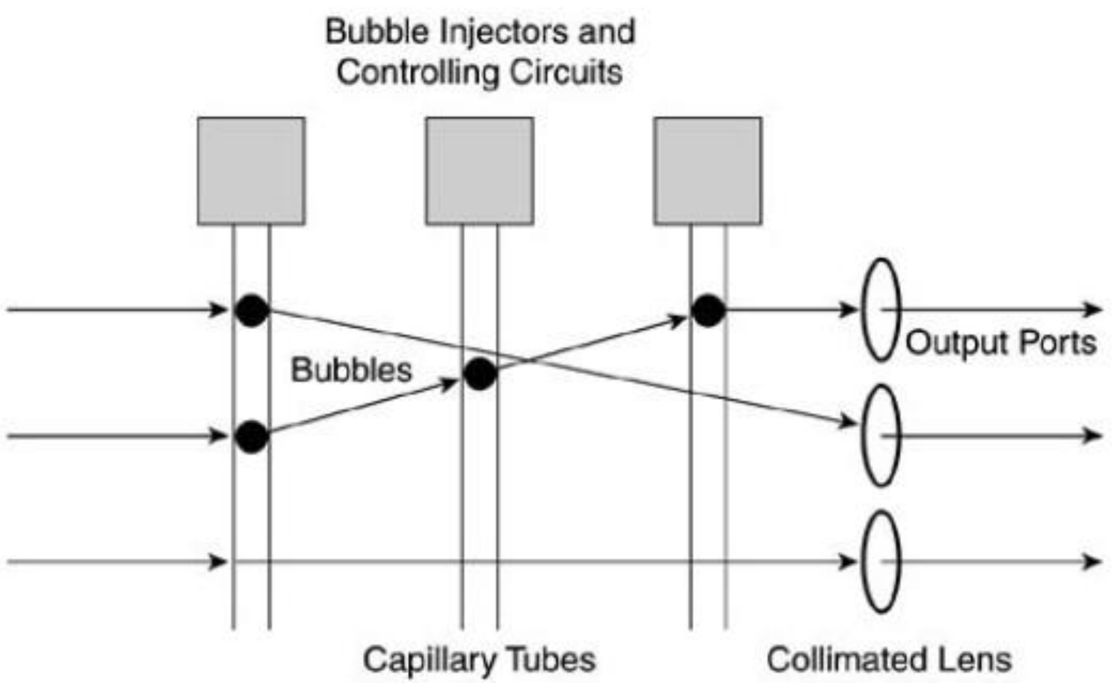
The bubble technology-based optical switch is demonstrated by AGILENT where the principle of bubble switch is demonstrated in the bubble jet printer.

In this, Micro bubbles are made to enter a region of interaction of optical beams inside capillary waveguides.

The refractive index of the bubbles can be made to vary such that optical beams refract to different ports.

Considering the figure in which the input signals are switched between output ports by introducing bubbles of refractive index that are capable of deflecting the incident beam.

These switches are leading to large loss resulting from a lossy medium and large cross-talk & have a relatively small lifetime .

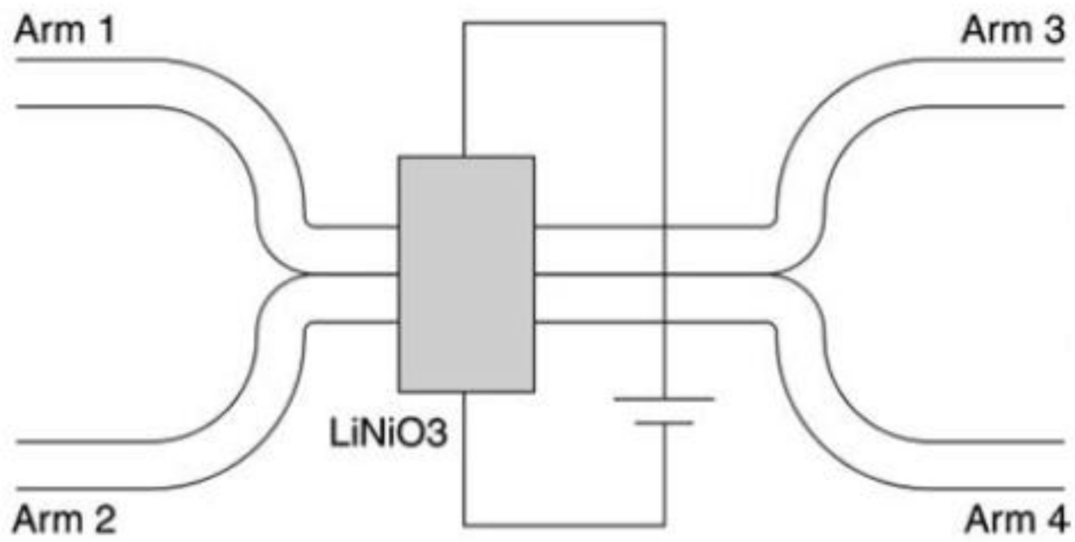


An Electro-Optic Switch is based on by using a Directional Coupler .

A 2 x 2 coupler can be made to switch from bar state to cross state by changing the refractive index inside the coupling medium leading to different coupling ratios.

As different currents are induced in a Lithium Niobate (LiNiO3) modulator region, therefore the coupling ratio can be made to change, causing the power at one of the ports to vary accordingly and switch the light paths.

Electro-Optic Switch Based on MZI (Mach Zehneder Interferometer)



Here, switching times is about 1–5 ns, but loss can be almost 2–3 dB because of imperfect coupling ratios.

Thermo-optic switches are based on MZIs.

The refractive index of one of the arms can be changed by altering the temperature, which is further controlled by current.

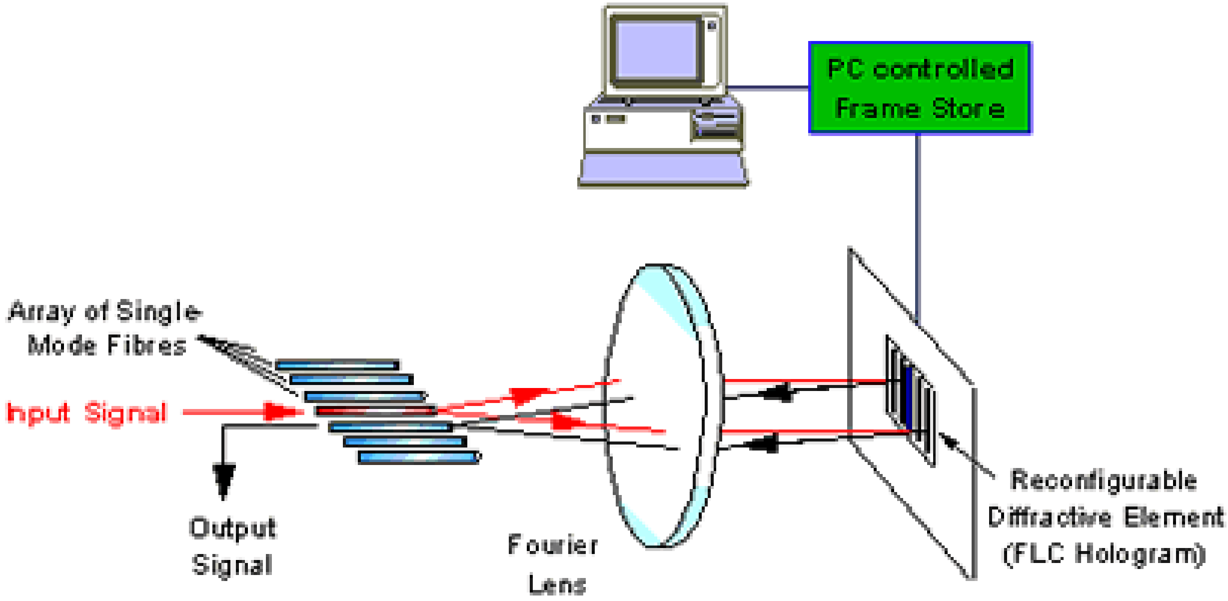
This change in length causes a phase difference associated with both arms which can be made to constructively or destructively interfere with each other, causing a similar direction coupler like- environment and the ability to switch light paths.

Characterlly , optical channels coming in on one optical fiber need to be diverted very precisely to another fiber, hence this can be achieved by using holograms as follows.

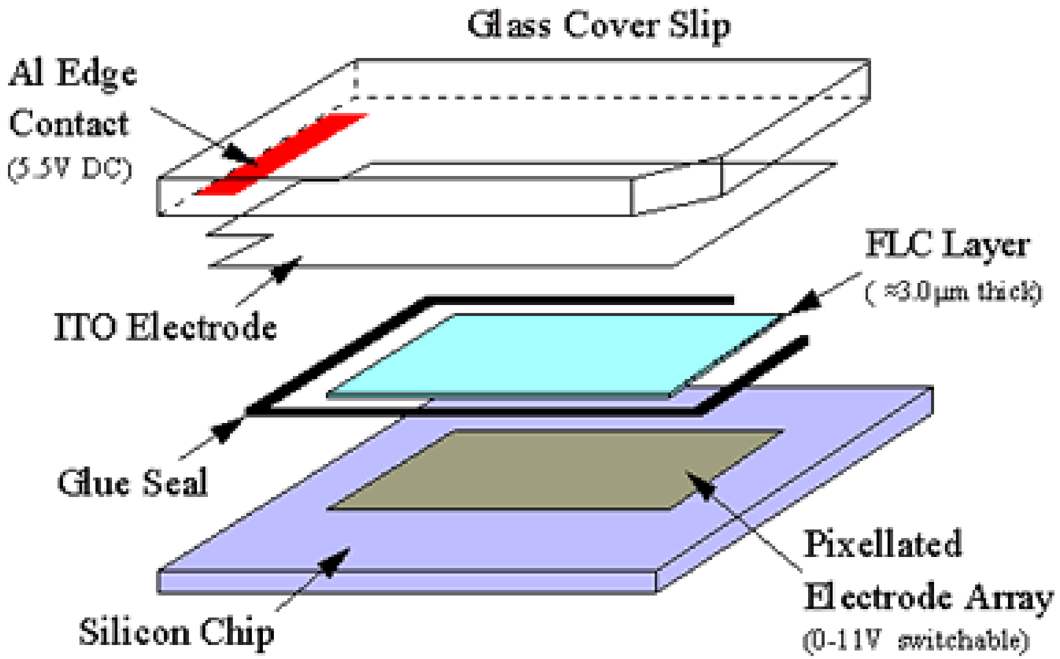
Hologram images are designed offline in a computer, and are then down-loaded onto an appropriate display device.

The holographic light switches use a similar type of technology to that used for micro displays which combines liquid crystal technology with silicon chips.

Note- Developed as part of a Link research program sponsored by the Department of Trade and Industry in conjunction with Nortel, British Aerospace and Thomas Swan, the holographic light switch is attracting a great deal of attention.



Design of a 1xN switch. The data is routed into the different single-moded output fibres by varying the angle of diffraction generated at the liquid crystal phase hologram.



Hologram device construction

Thank You

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