Pollinating Innovations Through Information

DWDM Training : *CSIR, South Africa*

27th/28th/29th/30th/31st July,2015

By

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DAY -2

DWDM Impairments :

1) Dispersion & its types-CD,PMD , Modal
2) Scattering Effects
3) Non- linearities
4) Four Wave Mixing (FWM)
5) Cross- phase Modulation (XPM)
6) Stimulated Brillouin Scattering (SBS)
7) Stimulated Raman Scattering (SRS)
8) Noise Sources: ASE, Shot, Thermal, etc.
9) Not- Return- to- Zero (NRZ) vs. Return- to- Zero (RZ) Transmission
10) The Effects of Optical Crosstalk

Analysis of Optical Components :

11. Optical Transmitters: Lasers
12. Optical Couplers
13. Polarizer and Rotators
14. Beam Splitters
15. Optical Multiplexers and Demultiplexers

DWDM Impairments

DWDM Impairments : is a symptom of reduced quality or strength and it effects signal propagation and limit transmission distances in fibers.

Impairments are :-

1) Attenuation
2) Scattering
3) Dispersion(Chromatic Dispersion(CD and PMD)
4) Fiber Non- Linearities (These are another serious impairments at High rates for Long-Haul systems that affect communication) such as –

a. SPM (Self - Phase modulation of Optical signal by itself)
b. XPM (Adjacent Signal on some adjacent wavelength)

And,

c. FWM
d. Raman
e. Brillouin effects

These 3 are the further more non-linear effects that affect communication.

1. **Attenuation** : is the most fundamental impairment that affects signal propagation.

It is quite standardized and is given as a specification for a particular Fiber Type.

Attenuation is a property of the fiber, and it is a result of the –

various material,
structural and ,
modular impairments in a fiber.

Fiber attenuation can be defined as the *optical loss that is accumulated from a source to sink along a fiber link.*

It consists of two components:

1. an Intrinsic fiber loss and
2. an Extrinsic Bending loss

An Intrinsic fiber loss - Intrinsic loss can be further characterized by two components :-

a Material Absorption loss
b. Raleigh Scattering

Material Absorption loss : - is caused by the Imperfections & Impurities in the Fiber.

Example- The -OH molecule has an absorption peak at 2.73 µm in the optical spectrum, which means that wavelengths near 2.73 µm have "high attenuation".

Correspondingly, the –OH molecule yields harmonics at 0.95 and 1.4 µm.

As per the attenuation graph shown in Figure 1-10, the 1.4 μm peak is a severe hindrance to commercial optical communication.

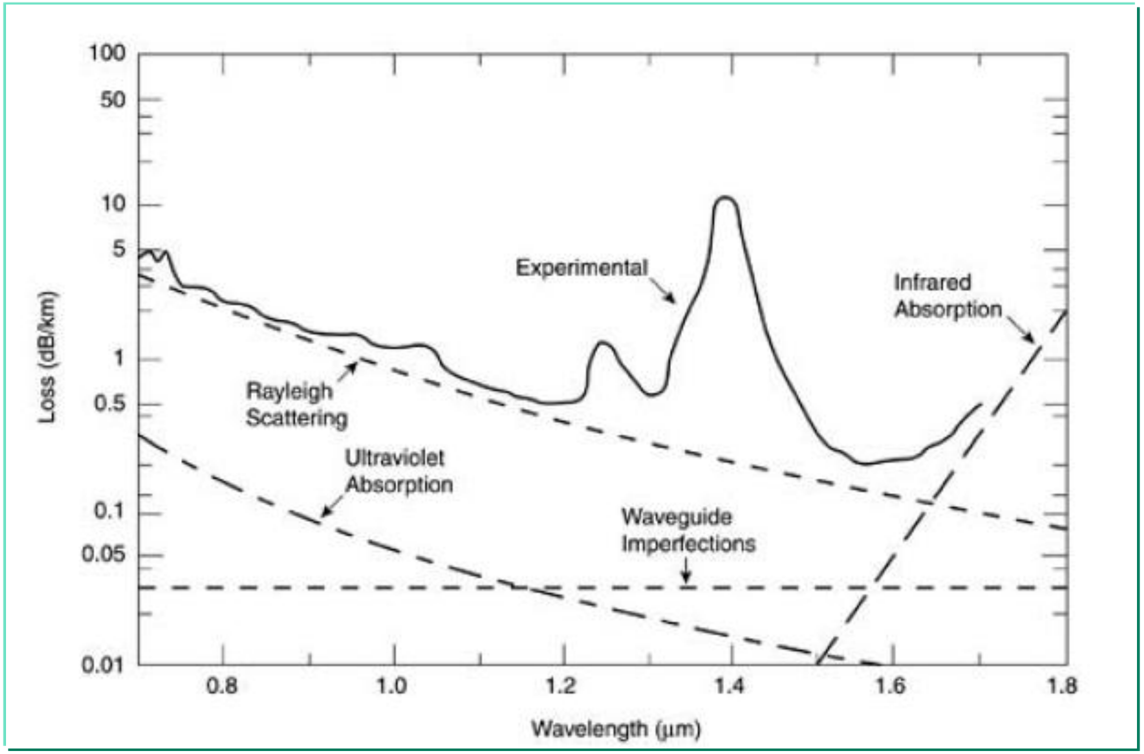


Figure 1-10. Attenuation Curve in a Fiber (Reprinted from IEEE Electronics Letters, 1979)

Absorption also occurs as a result of group 3 (transition) elements being present in the fiber.

Lucent Technologies and Corning use a *unique manufacturing process to develop fiber types that do not have an -OH peak, which almost eliminates the -OH molecule.*

These types of fibers (such as AllWave from Lucent and SMF-28e from Corning) extend the range from 1250 nm to 1700 nm, resulting in more capacity.

Attenuation that results from absorption , limits the use of wavelengths above 1.7 μm for optical communications.

Raleigh Scattering - Light scatters due to dense fluctuations in the core leading to a core causing scattering in more than one direction where some light propagates forward & some deviates and escapes from the core.

Among scattering phenomena, Raleigh scattering is the most prominent in optical fibers, and its profile follows a unique wavelength distribution.

The amount of Raleigh scattering a signal is subject to **is inversely proportional to the fourth power** of wavelength $(R \propto \lambda^{-4})$.

Therefore, short wavelengths are scattered more than longer wavelengths.

As signal rates increase, dispersion becomes a serious impairment, although *dispersion* does not attenuate the signal as such, it *causes severe pulse spreading*, leading to difficulty at the receiver end in trying to decode the signal.

Any wavelength that is below 800 nm is unusable for optical communication because attenuation due to Raleigh scattering is high.

At the same time, propagation above 1.7 µm is not possible due to high losses resulting from infrared absorption.

An Extrinsic Bending loss : is also two types –

i. Micro-Bending and
ii. Macro-Bending

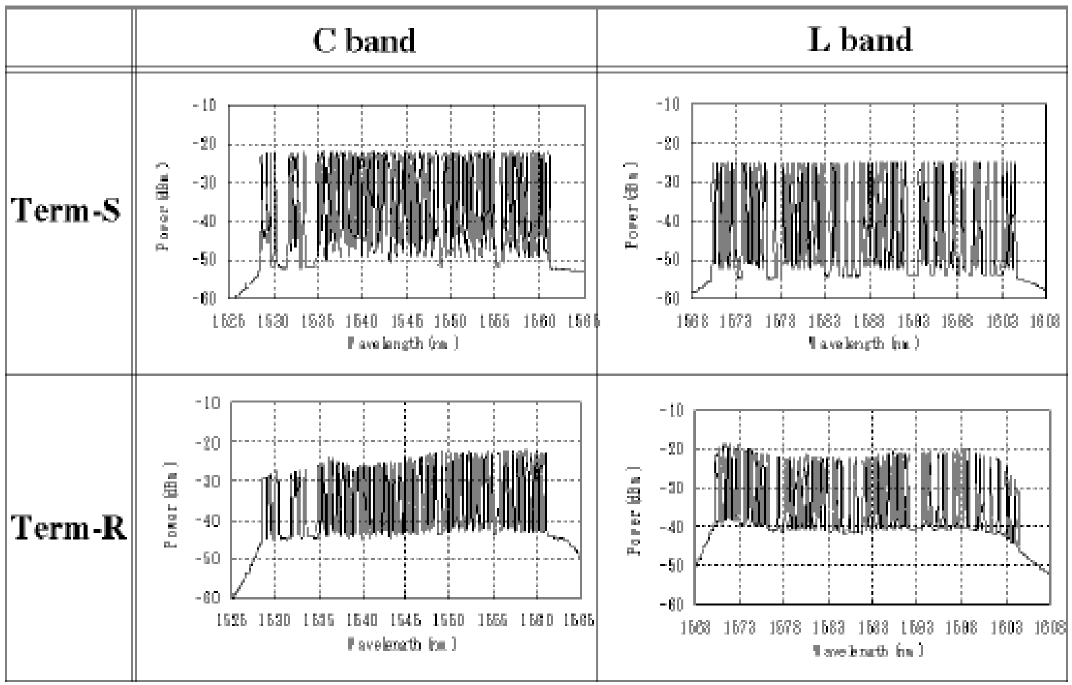
Micro-Bending :- is caused by Imperfection of cylindrical Geometry

Macro-Bending :- is caused by bending of fibers in small Radius.

Nonlinear OSNR Impairments

Impairments on the DWDM route cause changes in the Optical Signal-to-Noise Ratio that can be compensated for by proper use of pre emphasis.

Figure below shows the composite DWDM signal before the application of pre emphasis.



Before Pre emphasis

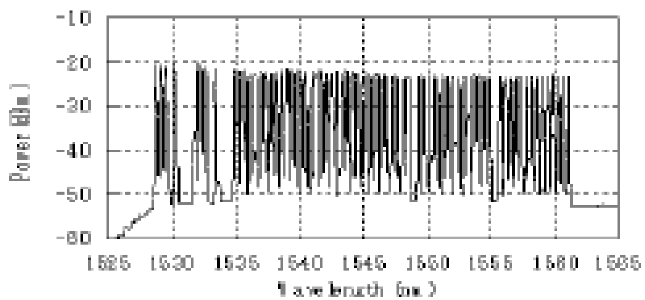
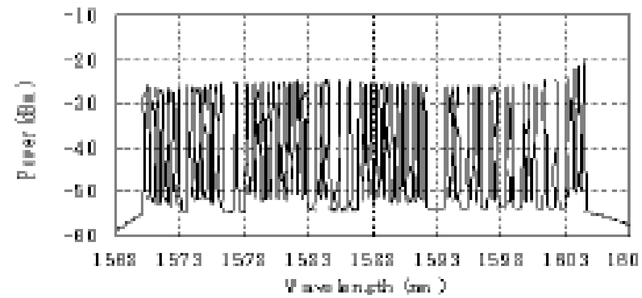
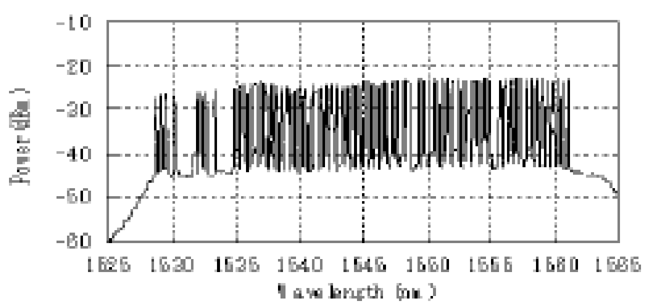
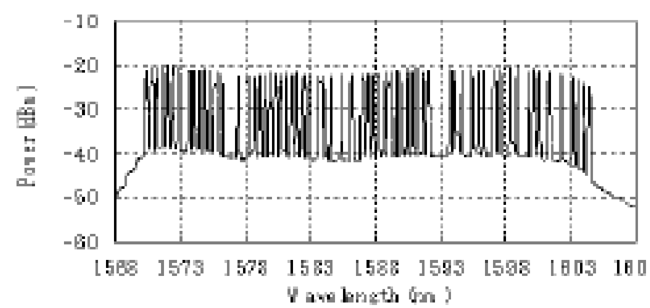
The transmit power levels (S) are flat, but the receive OSNRs (R) are not flat.

To optimize optical signals for transmission, **Equalization** is used to adjust the signal across the complete network, as shown in Figure.

This is called Pre -Emphasis which adjusts the transmit powers to optimize the receiver signal-to-noise ratios.

Spectrum after Pre emphasis : Received signals are smoother as a result of pre emphasis, as Figure illustrates.

After the insertion of pre emphasis, the receive OSNRs are the same, however the transmission powers vary.

	C band	L band
Term-S		
Term-R		

After Pre emphasis

Distance Limitations :

In the long-distance network, the majority of embedded fiber is standard single-mode (G.652) with high dispersion in the 1550-nm window, which limits the distance for OC-192 Transmission.

Dispersion can be mitigated to some extent, and at some cost, using Dispersion Compensators and Non-zero Dispersion-Shifted fiber (DSF) can be deployed for OC-192 transport, but higher optical power introduces nonlinear effects.

In the *Short-Haul network*, PMD and nonlinear effects are **not so critical** as they are in long-haul systems, where higher speeds (OC-192 and higher) are more common.

DWDM systems using optical signals of 2.5 Gbps or less are not subject to these nonlinear effects at short distances.

In (DWDM) the nonlinear effects plays important role where system offers

1. Component Reliability
2. System Availability and
3. System Margin.

As DWDM system carries different channels, hence Power level carried by fiber **increases** which generates nonlinear effect such as SPM, XPM, SRS, SBS and FWM.

What is Scattering :

It is a general physical process where some forms of radiation, such as light , sound or moving particles, are forced to deviate from a straight trajectory by one or more paths due to localized non-uniformities in the medium through which they pass.

In conventional use, this also includes deviation of reflected radiation from the angle predicted by the law of reflection.

Reflections that undergo scattering are often called diffuse reflections and unscattered reflections are called specular (mirror-like) reflections.

There are **two types** of nonlinearities----- one is scattering phenomenon that arise from scattering and described as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS).

Another is refractive index phenomenon that arise from :-

1. Optically induced changes in the refractive index, and result either in phase modulation such as [self-phase modulation (SPM) and cross phase modulation (XPM)] **or**

2. In the mixing of several waves and the generation of new frequencies [modulation instability (MI) and Parametric processes, such as four wave Mixing (FWM)].

Stimulated Brillioun Scattering(SBS)- In SBS , the phonons are acoustic phonons where Pump and Stokes waves propagate in opposite directions and it does not typically cause interaction between different wavelengths.

It creates distortion in a single channel and depletes the transmitted signal.

The opposite travelling Stokes wave means the transmitter needs an isolator.

This non-linear phenomenon can be considered in terms of three waves in optical fiber.

Consider an incident wave propagating along an optical fiber.

If this incident wave reaches a *threshold power, it will* excite an *acoustic wave within the fiber.*

Although this threshold power may vary, *the phenomenon of* acoustic wave excitation is unavoidable.

This acoustic wave alters the optical properties of the fiber, including the refractive index. This fluctuation in refractive index scatters the incident wave, creating a *reflected wave that propagates in the opposite direction.*

This scattering is known as Brillouin Scattering.

Since the scattering effect is caused by the **incident light wave**, the process is known as *Stimulated Brillouin Scattering (SBS).*

The incident wave is often referred to as the pump wave, while the reflected wave is also known as the *Stokes wave.*

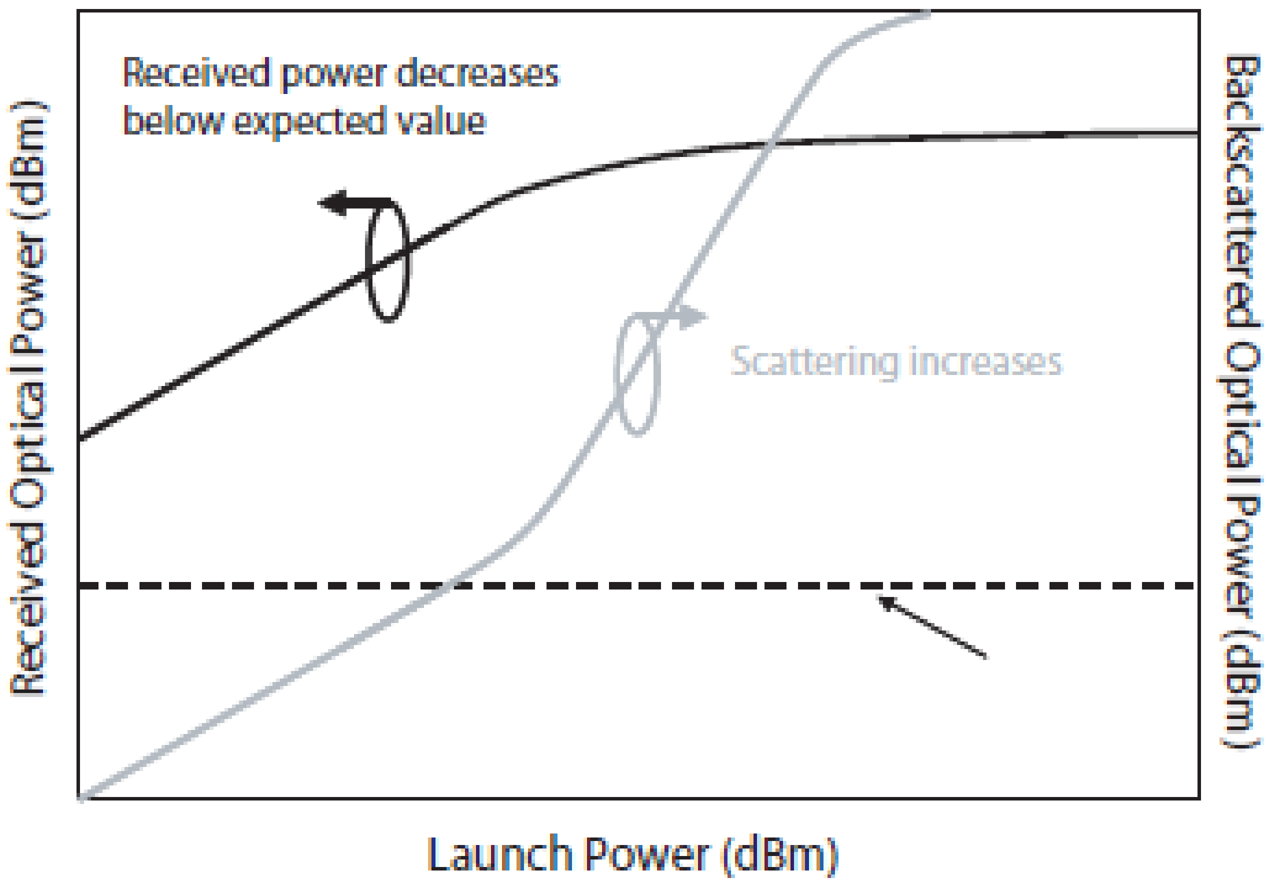


Figure 1 Received and Backscattered Power vs. Launch PowerDnS

This effect can occur in single channel or multiple channel systems at threshold powers of just a few milli-watts in single-mode fiber.

The scattering effect transfers power from the incident wave to the reflected wave.

The lost energy is absorbed by molecular vibrations in the fiber.

Due to this loss of energy, the reflected wave has a lower frequency than the incident wave.

The frequency shift is approximately 11 GHz (0.09 nm) in optical fiber.

For typical WDM and DWDM systems, this small frequency shift does not create crosstalk with other channels.

The harmful effects of SBS can be classified into **three categories:**

– Attenuation

– Power Saturation

– Backward-Propagation

Attenuation of the incident signal occurs when power is lost to the acoustic and reflected waves.

Furthermore, SBS limits the maximum amount of power that can be transmitted over a fiber.

After a certain point, an increase in incident power no longer leads to an increase in received power.

The backward propagating wave can create noise in transmitters and saturate amplifiers.

Isolators are required to limit these effects to a single span.

Stimulated Raman Scattering (SRS)-

Here, if two or more signals at different wavelengths are injected into a fiber, it causes power to be transferred from the lower wavelength channels to the higher-wavelength channels.

It has a broadband effect (unlike SBS) while in SRS there are both forward and reverse travelling Stokes waves.

SRS causes a signal wavelength to behave as a **"pump"** for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light.

The shorter wavelengths are attenuated by this process, which amplifies longer wavelengths.

Hence, SRS takes place in the transmission of fiber.

Self Phase Modulation (SPM)- In this Phenomenon , the intensity modulation of an optical beam results in the modulation of its own phase **via** modulation of the refractive index of the medium.

It is a phenomenon that leads to spectral broadening of optical pulses.

Cross Phase Modulation (XPM) is a similar effect to SPM, but it involves two optical beams instead of one.

In XPM, the intensity modulation of one of the beams is in a phase modulation of the other.

However,
Because the total intensity is the square of a sum of two electric-field amplitudes, the spectral broadening caused by XPM is twice as large as in SPM.

Kerr Effect -- It is a nonlinear interaction of light in a medium with an instantaneous response, related to the nonlinear electronic polarization.

The Kerr effect is ***a nonlinear optical*** effect occurring when intense light propagates in :

1. Crystals
2. Glasses, and also in other media
3. Such as Gases.

Four-wave mixing refers to the nonlinear combination of two or more optical signals in such a way that they produce new optical frequencies.

The interaction of two or more light waves can lead to a second kind of χ (3) nonlinearities which involve an energy transfer between waves and not simply a modulation of the index seen by one of them due to the other.

This interaction is often referred to as **"parametric,"** where these nonlinearities lead to parametric processes.

In WDM system using the angular frequencies ω1,ω2, …ωn the intensity dependence of the refractive index not only induces phase shifts with in a channel but also gives rise to signals at new frequencies such as 2ωiωj and ωi+ωjωk.

This phenomenon is called four wave mixing.

In contrast to SPM and XPM, which are significant mainly for high bit rate systems, the four wave mixing effect is independent of the bit rate but is critically dependent on he channel spacing and fiber dispersion.

Decreasing the channel spacing increases the four wave mixing effect, and so does decreasing the dispersion.

In general the signals generated by four wave mixing have lower powers due to the lack of perfect phase matching and the attenuation of signals due to fiber loss.

The frequency components thus generated are known as FWM products.

If these four wave Mixing products happen to coincide with a signal channel, the interference causes a distortion of the signal amplitude.

As many channels of the WDM system generate FWM products at the frequency of the distorted channel, the interference can be regarded as random.

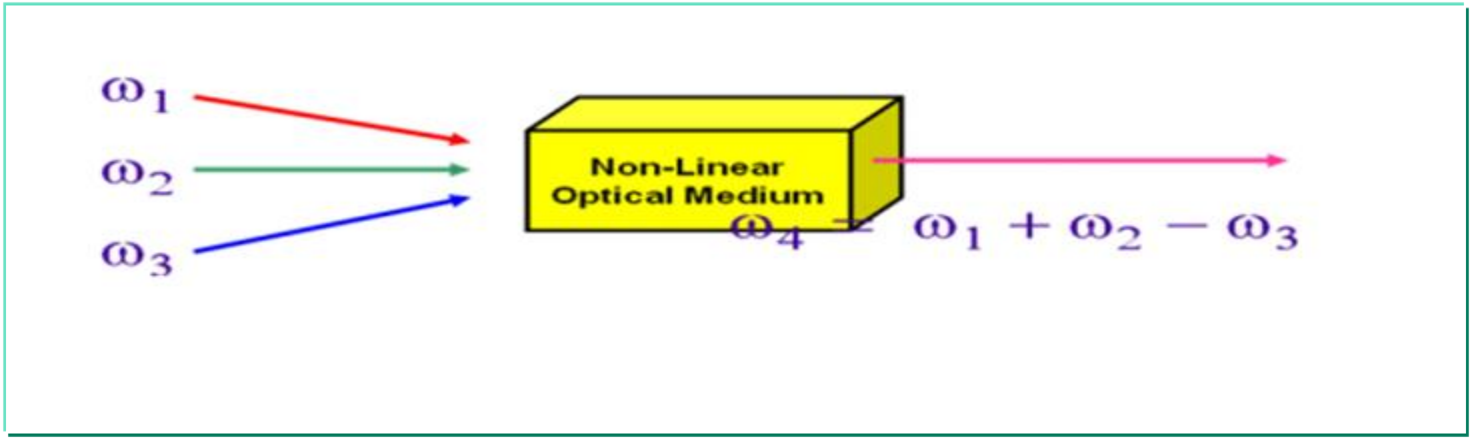


Figure 1 – Formation of Fourth Spurious Component

Hence,

Four wave mixing (FWM) is one of the most troubling issues where three signals combine to form a fourth spurious or mixing component, hence the name four wave mixing, shown in Figure 1 in terms of frequency w.

Effects of Four wave mixing (FWM)-- is one of the most troubling issues.

Three signals combine to form a *fourth spurious or mixing component*, hence the name four wave mixing. Spurious components cause following problems:

- Interference between wanted signal(cross)
- It generates additional noise and degrades system performance
- Power is lost from wanted signals into unwanted spurious signals

The total number of mixing components increases dramatically with the number of channels. The total number of mixing components, M is calculated from the equation 2.

$$\boxed{M = (\tfrac{1}{2})\, N^2\, (N-1)}$$

Thus three channels create 9 additional signals and so on. As N increases, M increases rapidly. Where N is no. of channels.

Effect of Dispersion and Channel Spacing on FWM –

As dispersion increases effect of four wave mixing decreases.

For dispersion of 16ps/nm , FWM effect reduces but chromatic dispersion increases.

At zero dispersion FWM effect is more hence fiber having dispersion 4ps/nm is used where FWM effect is less and fiber is called Non-Zero dispersion shifted fiber.

Due to equal spacing some FWM components overlap DWDM channels , but in unequal spacing there is no overlapping of DWDM channels and wavelength conversion occurs.

Minimization of FWM Effects :

Traditional non-multiplexed systems have used dispersion shifted fiber (DSF)at 1550nm to reduce chromatic dispersion.

Unfortunately operating at the dispersion minimum increases the level of FWM.

Conventional fiber (dispersion minimum at 1330 nm) suffers less from FWM but chromatic dispersion rises .

Solution is -

To use "Non-Zero Dispersion Shifted Fiber" (NZ DSF) which is a compromise between DSF and conventional fiber (NDSF, Non-DSF).

ITU-T standard G.655 is defined for non-zero dispersion shifted single mode fibers.

So, by ***using unequal spacing*** between DWDM channels , effect of FWM decreases.

What is Noise ?

Noise is defined as the deviation from an ideal signal, and is usually associated with random processes.

By definition it corrupts the information content and fidelity of the signal, particularly at low levels.

In Optical Amplifiers, noise is due to spontaneous light emission of excited ions, which we will further explore.

Following Noise sources are follow as:

- ASE
- THERMAL Noise
- SHOT Noise

Amplified Spontaneous Emission(ASE):- is also known as S**uper luminescence** which is light, produced by spontaneous emission, that has been optically amplified by the process of stimulated emission in a gain medium. It is inherent in the field of random lasers.

ASE is produced when a Laser gain medium is pumped to produce a population inversion.

Feedback of the ASE by the laser's optical cavity may produce laser operation if the lasing threshold is reached.

Excess ASE is an unwanted effect in lasers, since it is not coherent, and limits the maximum gain that can be achieved in the gain medium.

ASE creates serious problems in any laser with high gain and/or large size.

In this case, a mechanism to absorb or extract the incoherent ASE must be provided, otherwise the excitation of the gain medium will be **depleted** by the incoherent ASE rather than by the desired coherent laser radiation.

ASE is especially problematic in lasers with short and wide optical cavities, such as disk Lasers (active mirrors).

Thermal noise is due to the resistive elements in the receiver amplifier.

The Thermal noise is *independent* to the optical signal level but increase with the temperature.

The thermal noise power is given by,

$$\langle i_T^2 \rangle = 4K_B T_o B / R_L$$

where, T_o is the absolute temperature in Kelvin and K_B is the Boltzman constant and R_L is the receiver load impedance.

Since the light is composed of photons, which are discrete packets of energy, thus, the randomness of the arrival time of each photon generates a random noise component at the output current of the photo diode which is referred to as the quantum or shot noise.

The shot noise is proportional to the average value of the optical signal.

For a PIN diode, the shot noise power is given by

$$\langle i_Q^2 \rangle = 2q\Re P_o B = 2qI_P B$$

where, P_o is the optical power at the detector, q is the charge of an electron, B is the bandwidth of interest and $\Re$ is the photo diode responsivity. The detector current, which is denoted by I_p, is responsivity times P_o. That is $I_p = \Re P_o$.

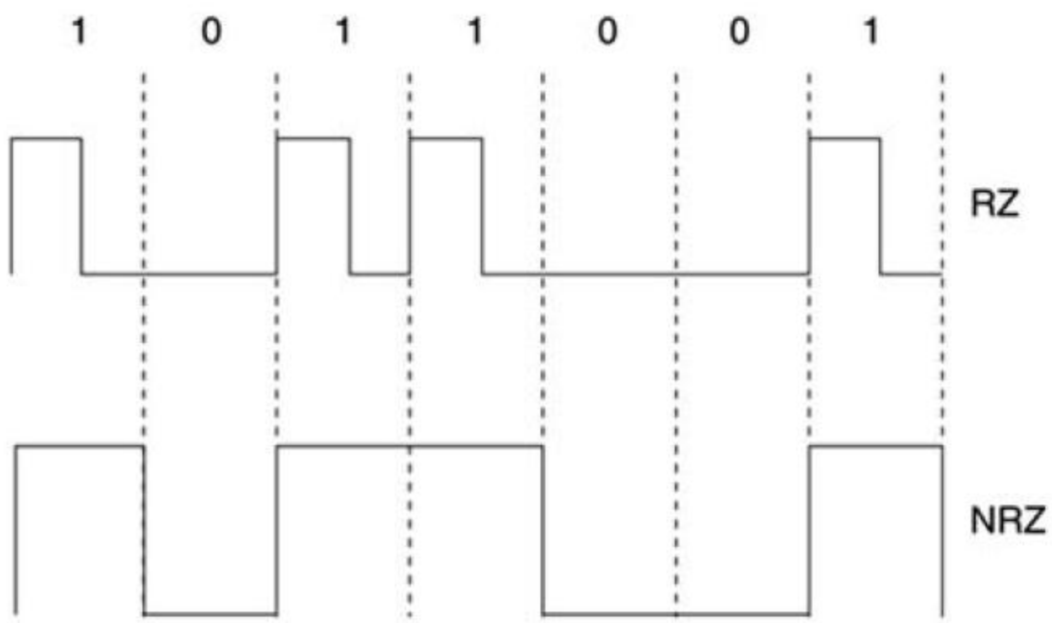
For avalanche photodiodes,

$$\langle i_Q^2 \rangle = 2qI_P BM^2 F(M)$$

where, M is the avalanche noise and F(M) is the excess noise (or noise figure). Both these are unity for PIN diodes.

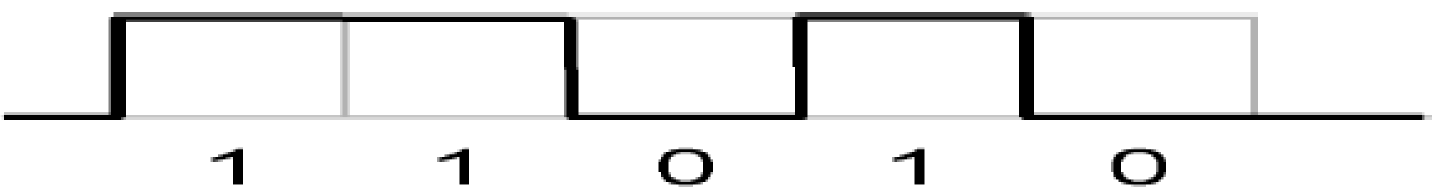
The electrical signals that carry different kinds of information are encoded when converted to optical signals for transmission, and decoded at the optical receiver and then converted back to an electrical signal.

These types include non-return to zero (NRZ), return to zero (RZ), optical duo binary and carrier-suppressed return-to-zero(CS-RZ).



Non-return to zero (NRZ) is a method of transmission where the signal does not return to zero between bits .

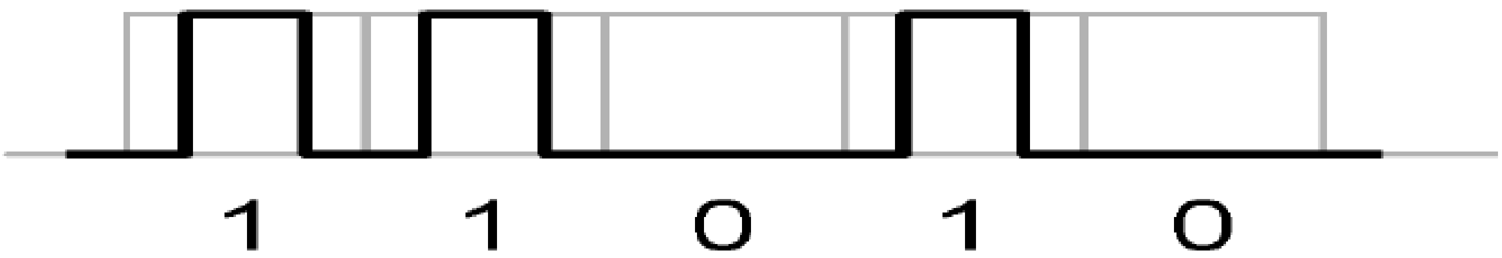
NRZ has the following attributes:
• A 1 represents light signal present for a complete bit period.
• A 0 is no light for a complete bit period.
• NRZ is more tolerant to dispersion effects.



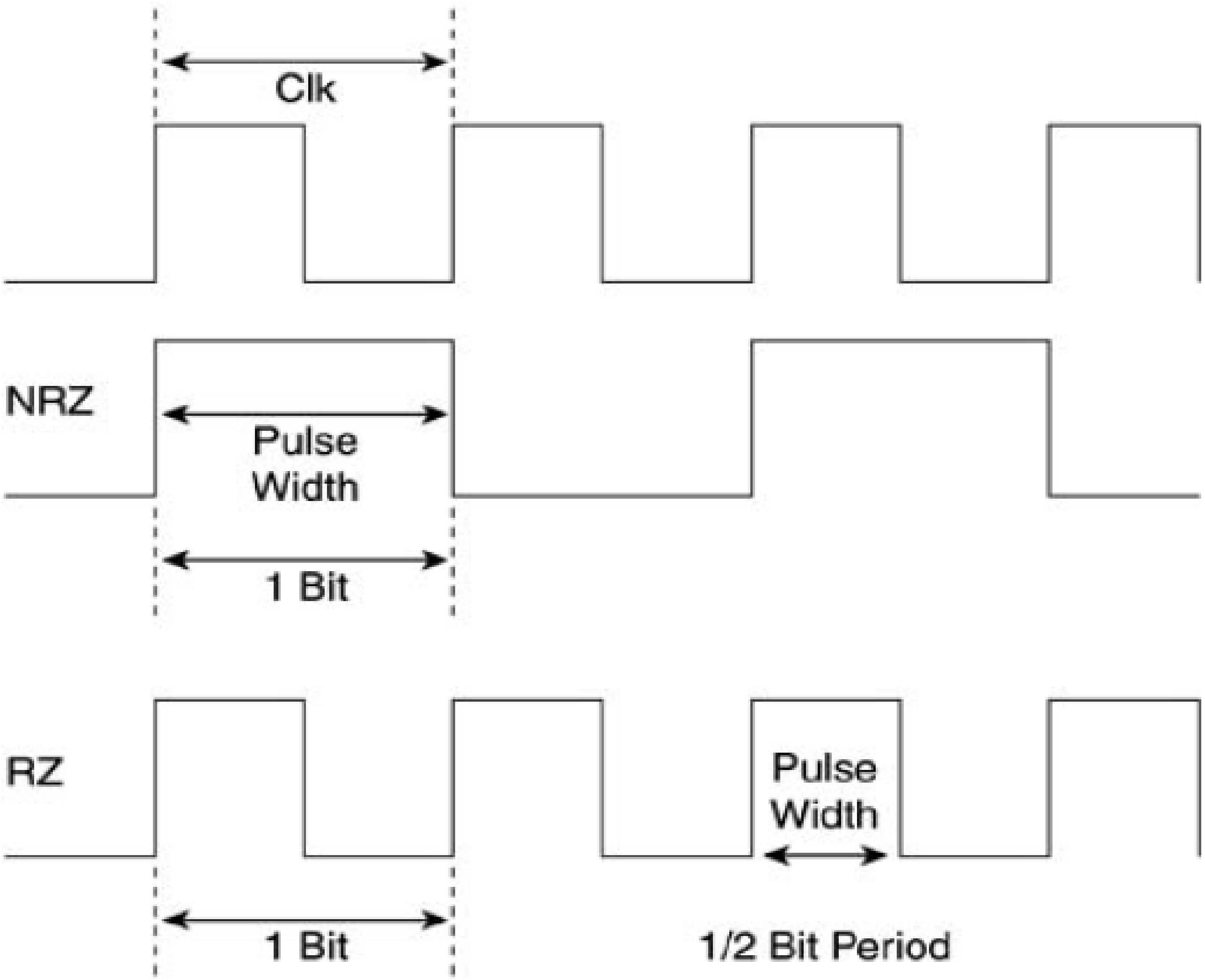
Non-Return to Zero

Return to Zero:- is a method of transmission where the signal does return to zero between bits. RZ has the following attributes.

• A 1 results from the presence of light for one-half a bit period.
• A 0 is no light for a complete bit period.
• Less tolerant to dispersion.



Return to Zero


Clk
NRZ
Pulse Width
1 Bit
RZ
Pulse Width
1 Bit
1/2 Bit Period

In RZ format for the logical 1 bit, the power level returns to 0 after half the period (pulse slot), whereas for the 0 bit, the power level is 0 continuously.

In NRZ, the 1 bit has a signal that is in the high power level throughout the 1-bit period and a 0 power level throughout the 0-bit period .

NRZ is the preferred waveform format in optical WDM networks.

The RZ signal is half the pulse width of NRZ, which means it takes twice the bandwidth and twice the switching time than that required for NRZ.

Even though it is costly and more difficult to build RZ-based components, they do help to overcome other challenges, such as chromatic dispersion (CD) and polarization mode dispersion (PMD).

For a 40 Gbps signal, the bit period is only 25 picoseconds in duration (NRZ).

CD- and PMD based design are challenging at 10 Gbps and even harder at 40 Gbps.

With the RZ format, dispersion is less likely to cause an RZ pulse to interfere with subsequent pulses.

Note: In particular, it has been demonstrated numerically and experimentally that the conventional non return-to-zero (NRZ) modulation format is superior compared to the return-to-zero (RZ) modulation when dealing with large WDM systems.

What is a CROSSTALK ?

Crosstalk is a measure of how well the channels are separated, and channel separation refers to the ability to distinguish each wavelength.

Optical Crosstalk severely limit the number of optical interconnects in the system in spite of many different technologies can be compared, including

1. Blocking
2. Non blocking and
3. Wavelength converting (using cross-gain, cross-phase, four-wave mixing, and opto-electronic technologies).

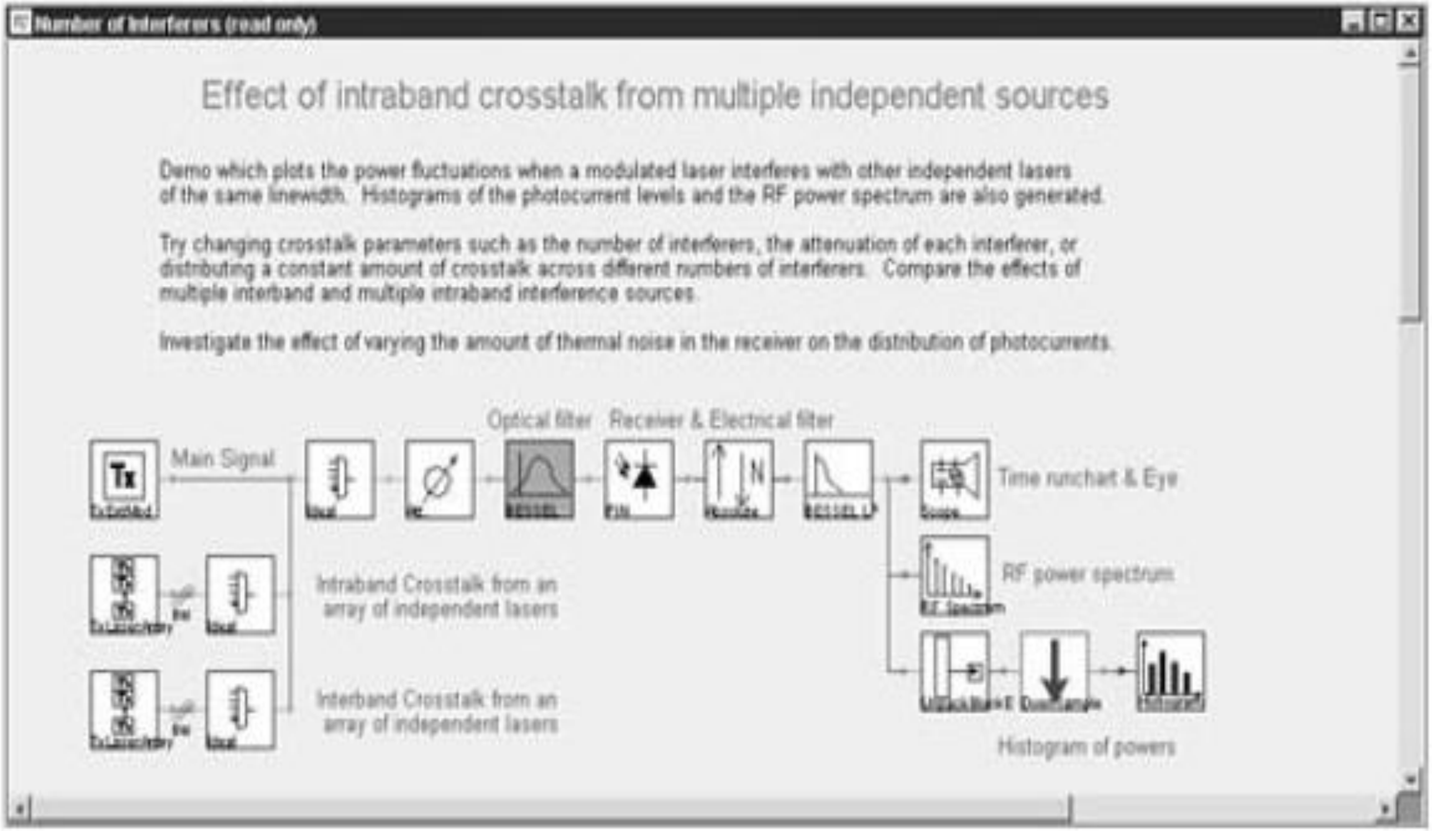
Figure 10-8 shows a simulation that illustrates and quantifies the effects of optical cross-talk.

The severity (hardness, strictness)of the crosstalk depends on whether the interfering carrier lies within the signal bandwidth of the desired signal.

If it does, the cross-talk produces a strong beat signal that lies within the electrical bandwidth of the receiver.

The interference is often called *coherent because* its severity depends on the addition of the optical fields rather than the optical powers.

Figure 10-8. Simulation to Assess Coherent and Incoherent Cross-Talk Effects



The histogram of Figure 10-9 shows the electrical signal levels at the sample time of the receiver.

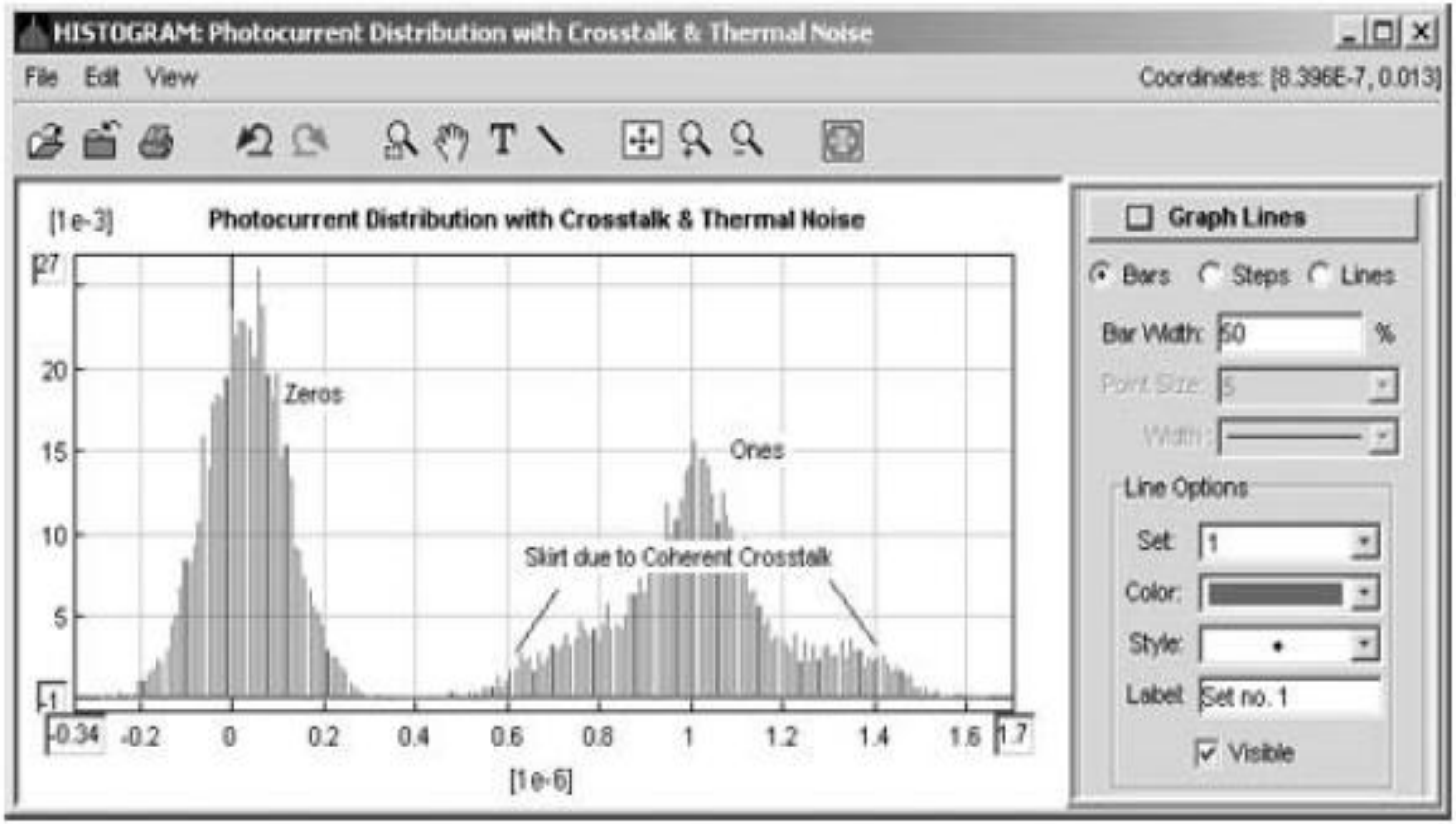
For a low BER, the distributions of the 1s and 0s should be well separated.

The coherent cross-talk causes a large spread in the 1-bit signal levels because the fields for 1 bits are higher than those for 0 bits.

Thermal noise and incoherent cross-talk cause the spread in the 1 bits.

Figure showing – the Probability Distribution of Powers in the 1 and 0 bits .

The skirts on the 1s distribution indicate coherent (or Homodyne) optical cross-talk.

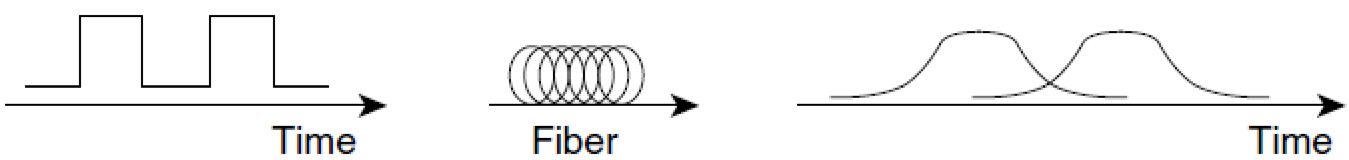


Dispersion - is the spreading of light pulses as they travel down optical fiber and results in distortion of the signal, which limits the bandwidth of the fiber.

Types:

- ❖ Chromatic Dispersion
- ❖ Polarization Mode Dispersion

Dispersion compensation is a useful technique for long haul as well metropolitan area networks, especially at high data rates .



Principle of Dispersion

The total dispersion that occurs in an optical fiber is a combination of several types of dispersion, including modal, chromatic, polarization, waveguide, and material dispersion.

Modal dispersion, which can be the largest contributor to total fiber dispersion, is not present in single-mode applications.

Modal dispersion :

Modal dispersion(ns/km*nm) occurs in multimode optical fiber.

This phenomenon is linear; i.e. , if the distance of the optical fiber doubles, the pulse spreading also doubles.

So , to eliminate modal dispersion, switch to single-mode fiber.

In general, modal dispersion is the most detrimental (harmful) to system performance.

Using Maxwell's equations it can be shown that any given fiber geometry can support a finite number of hybrid and transverse modes.

This would not be a problem if each mode travels at a different speed through the fiber.

Modal dispersion can be eliminated by using single mode fibers (SMF) which is done by simply extruding (pushing out) a fiber with a relatively small core radius.

Chromatic dispersion is a measure of fiber delay for different wavelengths where different wavelengths travel at different velocities through fiber.

Hence, The difference in velocity is called **“delay”** or chromatic dispersion of the signal.

The effect of chromatic dispersion increases as the square of the bit rate.

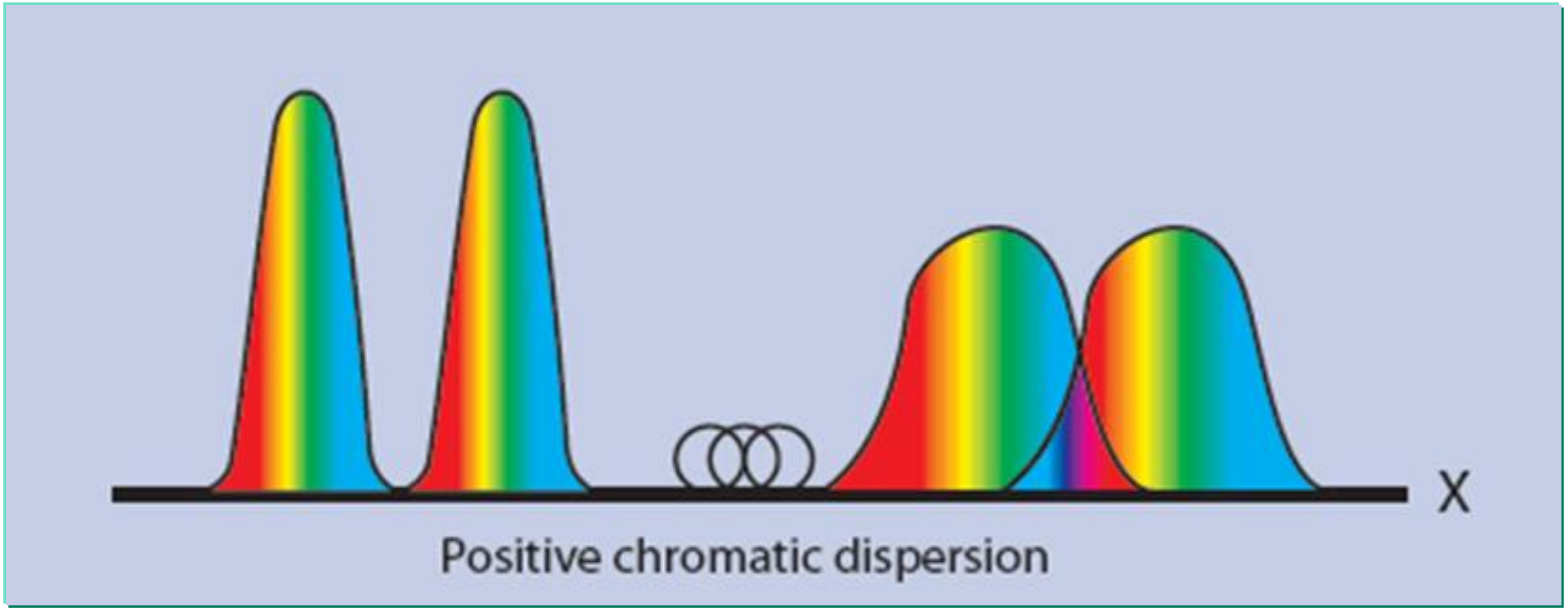
In single-mode fiber, *chromatic dispersion* has two components:-

- ❖ Material dispersion
- ❖Waveguide dispersion.

Material dispersion: occurs when wavelengths travel at different speeds through the material.

A light source, no matter how narrow, emits several wavelengths within a range.

Thus, when this range of wavelengths travels through a medium, each individual wavelength arrives at a different time.


X
Positive chromatic dispersion

CD refers to the phenomenon when different wavelengths of an optical pulse travels at different velocities along a fiber and arrive at different times in the receiver.

Effects-

1. Decreases of Peak Power
2. Pulse Broadening
3. Bit Errors

Solutions –

1. Use of fibers or modules with reverse CD values(DCF/DCM)

Waveguide dispersion : The second component of chromatic dispersion is waveguide dispersion , occurs because of the different refractive indices of the fiber's core and cladding.

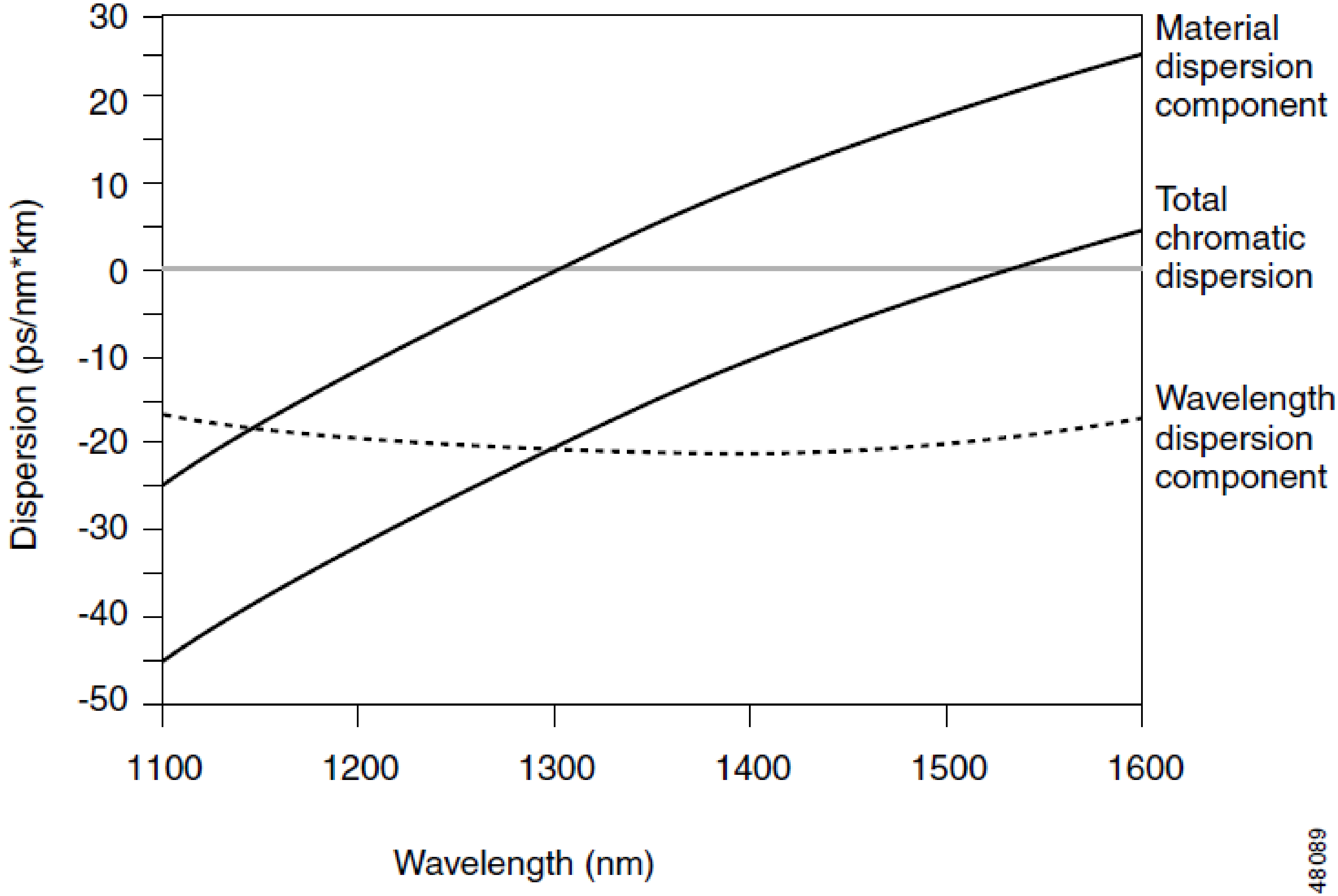
The effective refractive index varies with wavelength, as follows:

- At short wavelengths, the light is well confined within the core. Thus the effective refractive index is close to the refractive index of the core material.

- At medium wavelengths, the light spreads slightly into the cladding. This decreases the effective refractive index.

- At long wavelengths, much of the light spreads into the cladding. This brings the effective refractive index very close to that of the cladding.

This result of waveguide dispersion is a propagation delay in one or more of the wavelengths.


30
20
10
0
-10
-20
-30
-40
-50
Dispersion (ps/nm*km)
1100
1200
1300
1400
1500
1600
Wavelength (nm)
Material dispersion component
Total chromatic dispersion
Wavelength dispersion component
48089

Total Chromatic Dispersion, along with its components, is plotted by wavelength for dispersion-shifted fiber(DSF).

For non dispersion-shifted fiber, the zero dispersion wavelength is 1310 nm.

Though chromatic dispersion is generally not an issue at speeds below OC-48, it does increase with higher bit rates due to the spectral width required.

New types of zero-dispersion-shifted fibers greatly reduce the effects of chromatic dispersion and it can also be mitigated with ***dispersion compensators.***

Note : Most single-mode fibers support two perpendicular polarization modes, a vertical one and a horizontal one.

Because these polarization states are not maintained, an interaction between the pulses causes a smearing of the signal.

Scientists and Engineers for years have always fear that as Optical Networking systems get faster and sends signals for longer distances, major Physics related problems would become a limiting force.

The Technology for years had been given a free ride as it grew from 90Mbps to 270 Mbps to 435 Mbps to 2.5 Gbps.

A problem began to manifest itself in 10 Gbps systems and threatens major Dislocation at 40 Gbps networking. for the first time, the Fiber Optics Industry had faced with networking killer.

The problem which itself was not discovered untill the early 1990's is PMD, which can

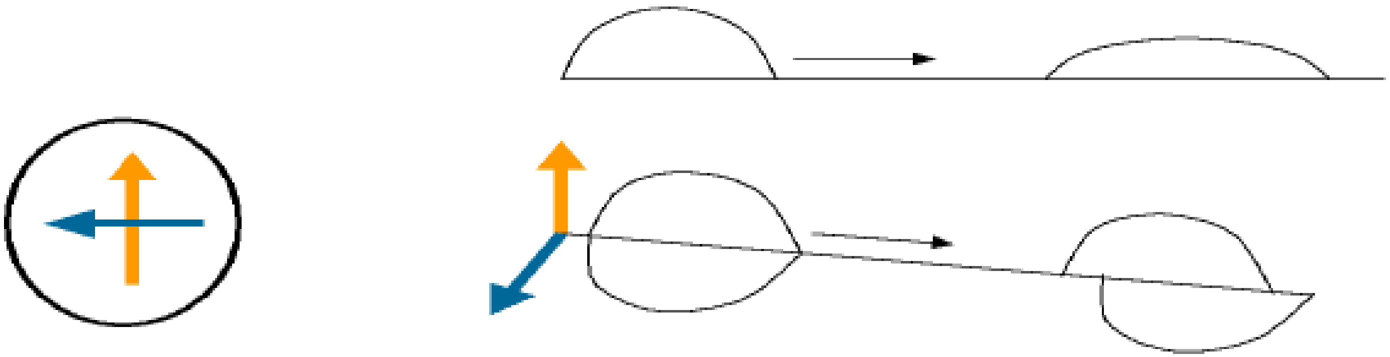
-distort the signals,
-Render bits inaccurate and
-Destroy the integrity of a network.

Approx, 20%-30% of the SMF manufactured before the mid 1990's has a property that has become more Problematic as BIT-Rates & Span – Length Increase due to which creates the problem in the Fiber core was not "Perfectly ROUND".

Of course, no fiber's core is perfectly symmetrical, but this fiber is OFF by enough that it causes Dispersion to the degree that it renders signals unreadable.

Polarization Mode Dispersion :

As light has polarization, where some light is vertical and some is horizontal, as depicted in Figure .



Polarization Mode Dispersion

Different polarizations travel at different velocities, because fiber is not perfectly round.

Different velocities cause dispersion.

As light is refracted within the fiber, slight changes in the polarization of the light may occur.

Light which takes different paths within the fiber, will have polarization differences resulting in "dispersion".

When Light travels down a single mode fiber toward the receiver, it has two polarization modes that follow the path of two axes.

They move toward the receiver at right angles to each other.

When the core of the fiber that bounds the light is Asymmetrical, the light travelling along One polarization axis move slower or faster than the light polarized along the other Axis.

Hence, This effect can spread the pulse enough to make it overlap with other pulses or change its own shape enough to make it undetectable at the receiver.

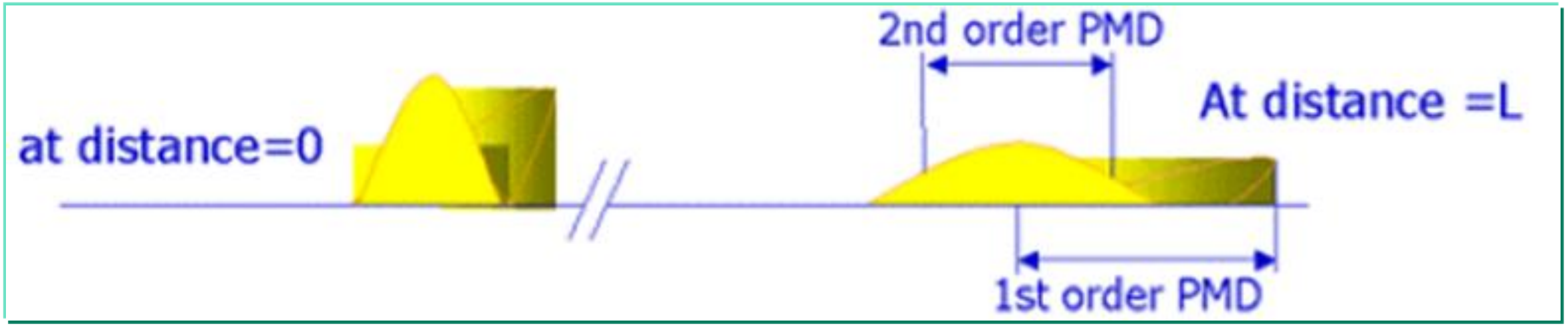
The Optical Pulse and its constituent photons travels from the source, or transmitter at distance =0, along the single fiber mode optical fiber.

At some distance after PMD has affected the pulse, the Polarized energy is separated by some time.

This times is known as Differential group Delay(DGD).

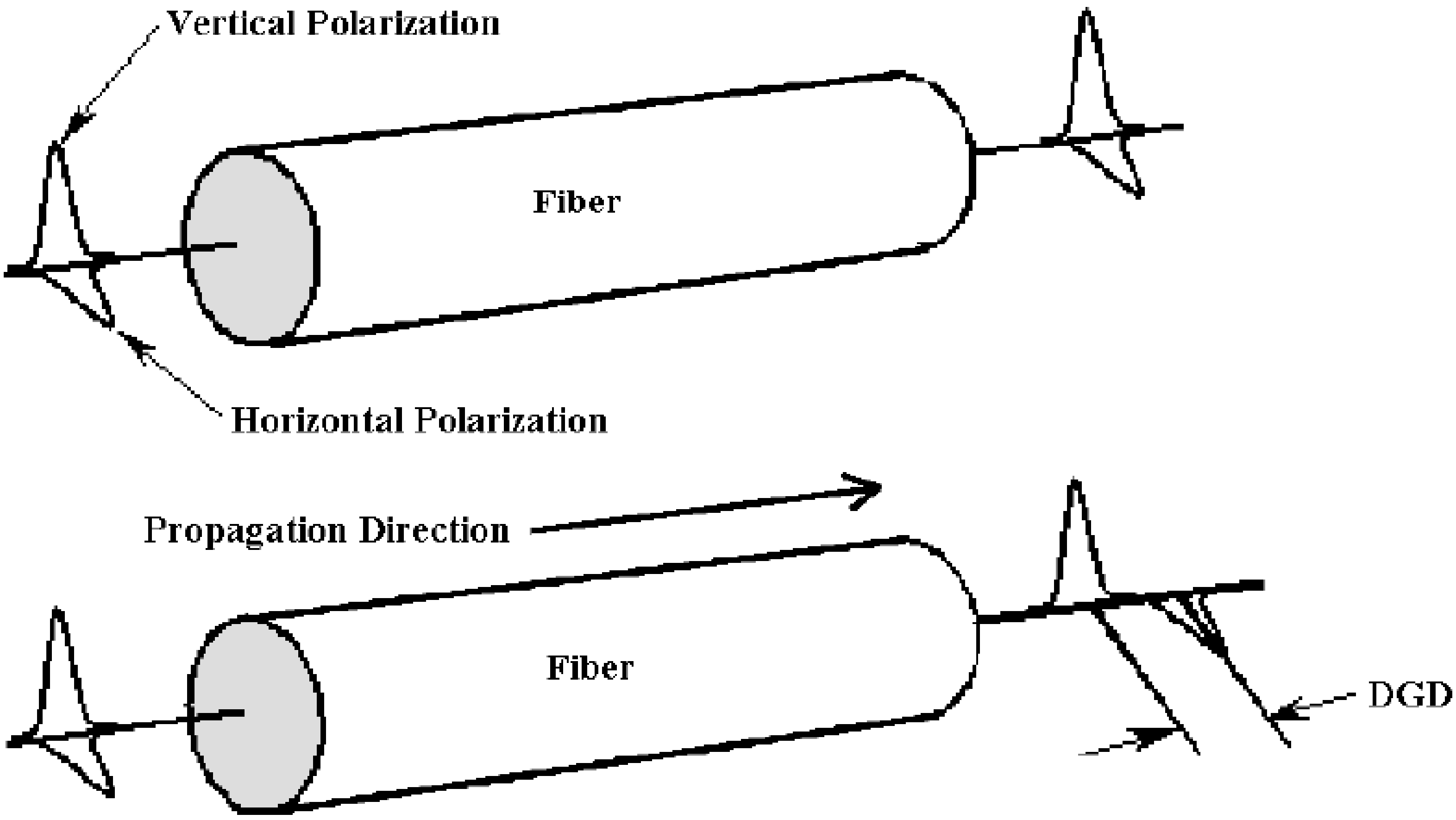
DGD is the fundamental measure of PMD and is measured in Picoseconds.

If DGD is SEVERE, the receiver at some distance L cannot accurately decode the optical pulse, and bit error s can result.



Graphical representation of the effect of PMD on an optical pulse

There is no PMD in a "perfect" fiber (top). Real optical fibers have some core assymetries which results in DGD (bottom).



Causes of PMD –

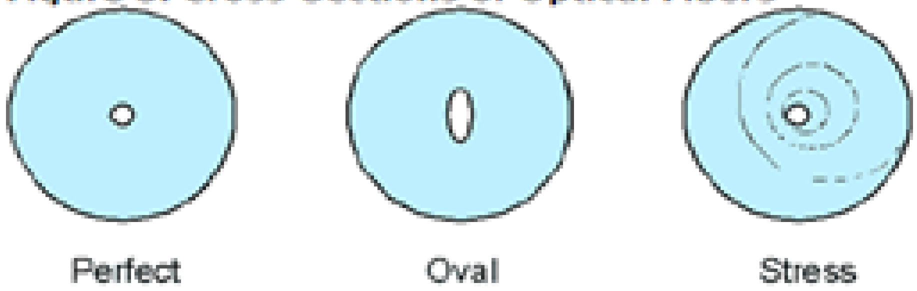
The major cause of the PMD is the Asymmetry of the fiber-optic strand.

Asymmetry is simply the fact that the fiber core is slightly out of round, or oval.

Fiber Asymmetry may be inherent in the fiber from the manufacturing process ,or it may be a result of mechanical stress on the deployed Fiber.

The inherent asymmetries of the fiber are fairly constant over time, while the mechanical stress due to the movement of the fiber can vary, resulting in a dynamic aspect to PMD.

Figure 3. Cross-Sections of Optical Fibers



There are several technologies that can be utilized to compensate for the effects of PMD.

These Technologies have included the following :

Mechanical devices that actually squeeze a portion of the Fiber in order to re-align the polarization pulses of the optical bit.

In other words, a mechanical PMDC " counter-stresses" the Fiber.

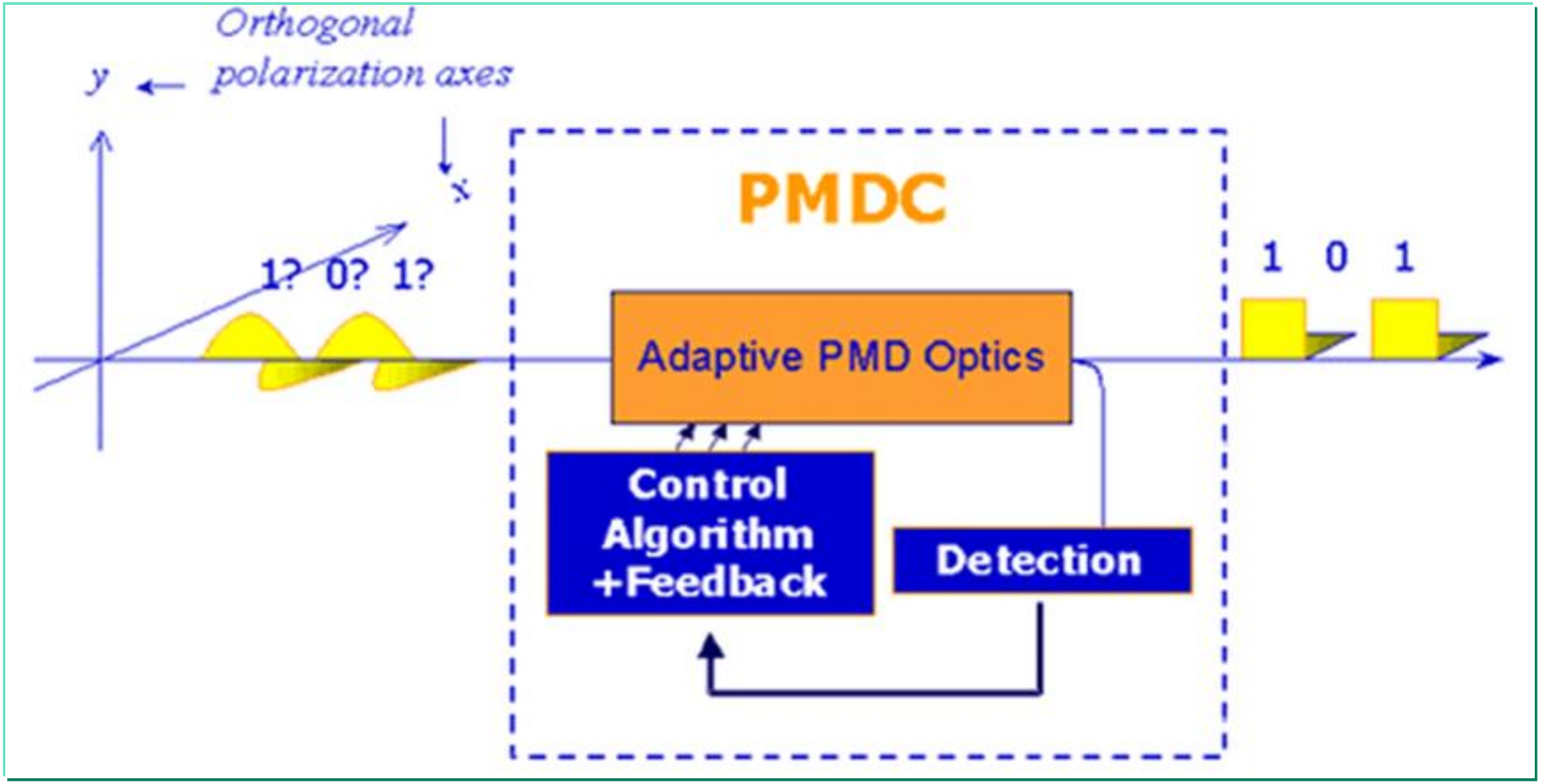
The Primary drawback of this method is that mechanical devices are more Prone to Failure over long Durations ; eg, the original mechanical "step" switches of 64 early voice networks, a technology of the early 2oth century , demanded frequent maintenance and were prone to the problems.

Electronic devices that work after the receiver decoder\ manipulating electrons in order to reduce bit errors.

The primary drawback to this method is the difficulty in correcting an optical problem at the electronic Layer.

The most reliable and efficient PMDC technology is the use of adaptive optics to re-align and correct the pulses of dispersed optical bits.

The high-level concept of adaptive optic technology is shown in Figure.


Orthogonal
polarization axes
y
x
1? 0? 1?
PMDC
1 0 1
Adaptive PMD Optics
Control
Algorithm
+Feedback
Detection

The Figure shows how dispersed optical bits from the fiber network are corrected by the PMDC.

Before correction, the polarised pulses of the bits have been separated and dispersed by PMD.

The PMDC re-aligns and re-shapes the optical bits before they are decoded by the receiver (Rx).

The adaptive optics of the PMDC are controlled by an intelligent algorithm that is driven by analyses of the optical bit.

Note -

Polarization mode dispersion (PMD) is caused by the quality of the fiber shape or from external stresses.

Because stress can vary over time, PMD is subject to change over time, unlike chromatic dispersion.

PMD is generally not a problem at speeds below OC-192.

Fiber Dispersion Characteristics

Fiber Type	Manufacturer	Chromatic Dispersion [ps/(nm x km)]	PMD ($ps/km^{1/2}$)
SMF-28	Corning	17.0	<0.2 (0.1 typical)
E-LEAF	Corning	2.0 – 6.0 (1530 – 1565)	<0.1 (0.04 typical)
TrueWave RS	Lucent	2.6 – 6.0 (1530 – 1565)	<0.1

NOTE :

Chromatic dispersion is a rather

1 Stable
2. Linear effect
3. Making compensation relatively easy

but , PMD is a linear effect that is time-varying in fiber links, making compensation difficult.

PMD is very stable in components and unlike chromatic dispersion, the effects of PMD are dependent on the launched polarization state.

In high-bit-rate systems, PMD may introduce errors as pulses spread into one another.

Analysis of Optical Components

The role of the optical transmitter is to convert the electrical signal into optical form and to launch the resulting optical signal into the optical fiber.

It consists of --

1. An Optical Source
2. An Electrical Pulse Generator and
3. An Optical Modulator.

The **launched power** is an important design parameter, as it indicates how much fiber loss can be tolerated and expressed in units of dBm with 1 mW

Lasers are used as optical sources for emitting modulated data into an optical fiber, where these lasers have a distinct property whereby they can emit a narrow beam of light with a small optical spectra (line width), while having a high output optical power (concentrated beam of photons of approximately the same phase and frequency).

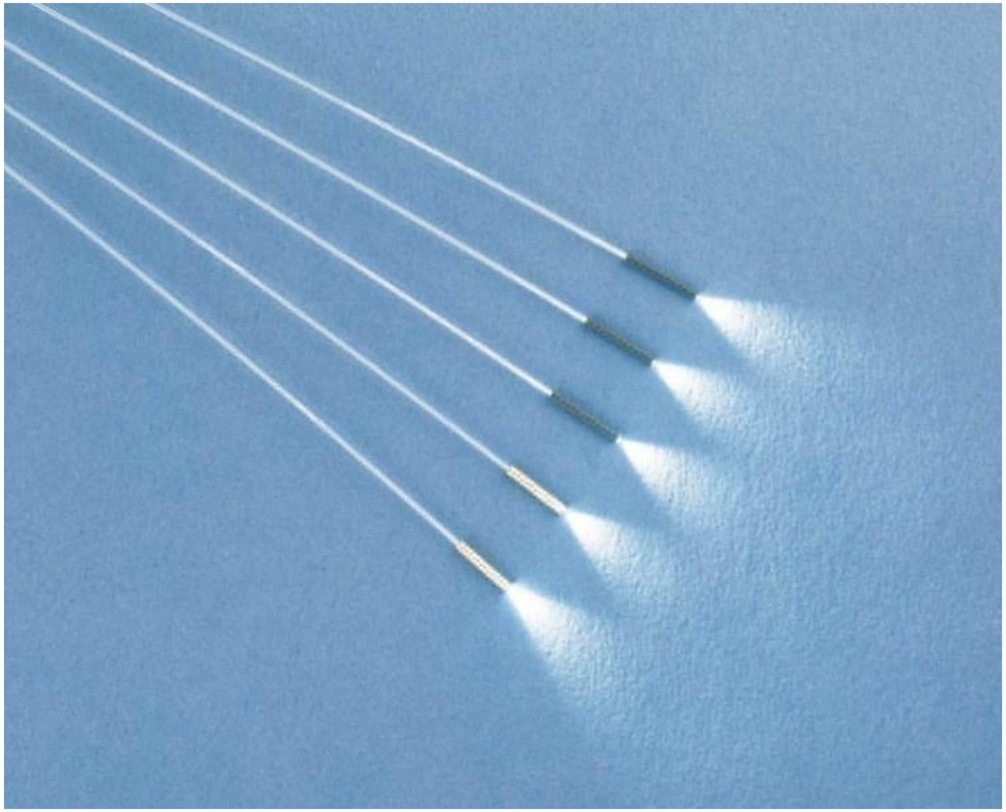
A laser is a semiconductor device (for optical purposes at least, although different forms of lasers do exist) that has an operation based on the population inversion condition.

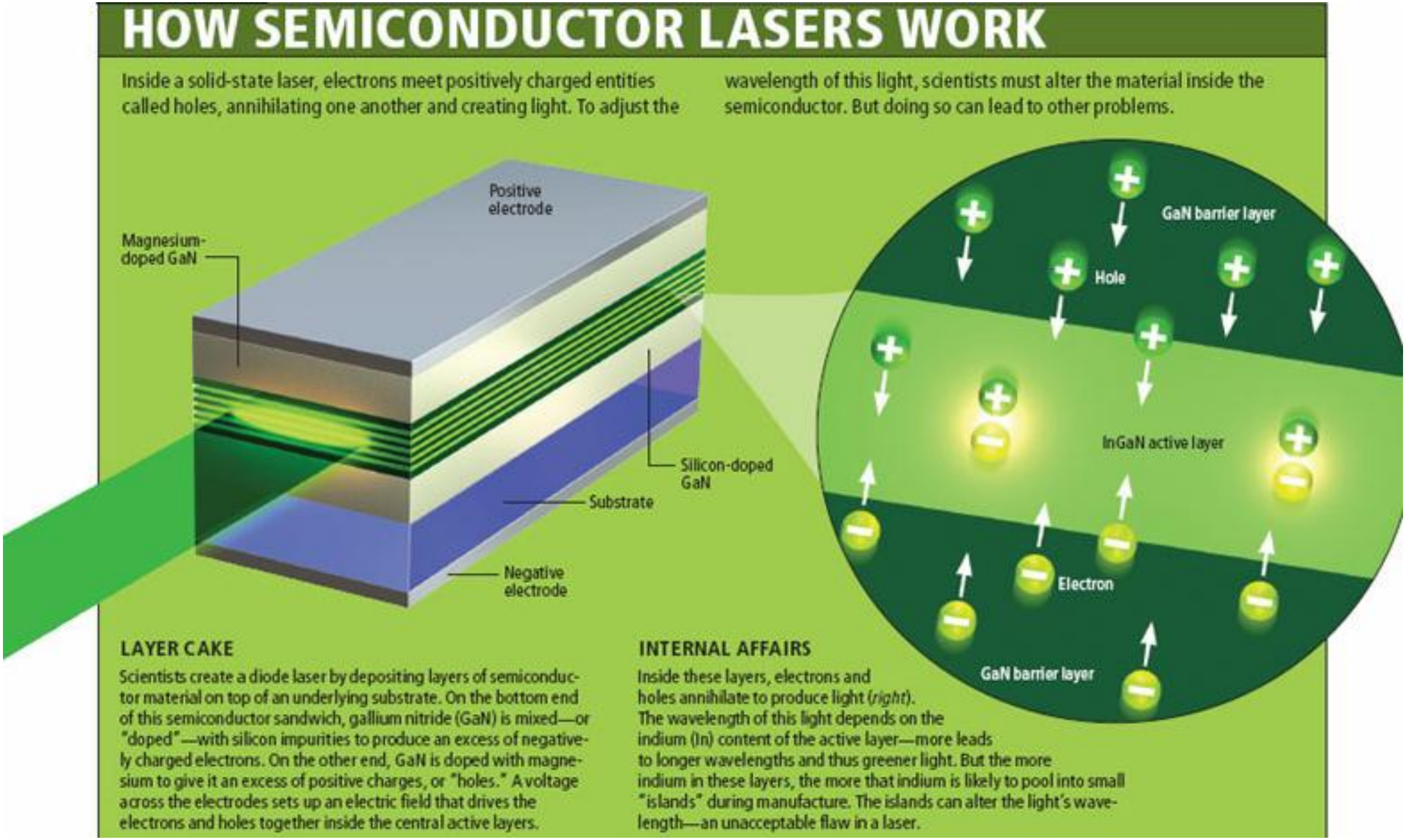
This population inversion condition specifies the numerical superiority in volume of the electrons in the excited state (formed by absorption of energy by normal state electrons) over the electrons in the ground state in a semiconductor junction device.

laser that is used in optical networking operations should have a **narrow spectral line width**, in addition to fast response (tenability) and be able to couple a significant amount of optical power into the fiber waveguide.

Lasers that are used in optical communications are generally of two types :

1. Semiconductor lasers
2. Fiber lasers




HOW SEMICONDUCTOR LASERS WORK
Inside a solid-state laser, electrons meet positively charged entities called holes, annihilating one another and creating light. To adjust the wavelength of this light, scientists must alter the material inside the semiconductor. But doing so can lead to other problems.
Positive electrode
Magnesium-doped GaN
Silicon-doped GaN
Substrate
Negative electrode
GaN barrier layer
Hole
InGaN active layer
Electron
GaN barrier layer
LAYER CAKE
Scientists create a diode laser by depositing layers of semiconductor material on top of an underlying substrate. On the bottom end of this semiconductor sandwich, gallium nitride (GaN) is mixed—or "doped"—with silicon impurities to produce an excess of negatively charged electrons. On the other end, GaN is doped with magnesium to give it an excess of positive charges, or "holes." A voltage across the electrodes sets up an electric field that drives the electrons and holes together inside the central active layers.
INTERNAL AFFAIRS
Inside these layers, electrons and holes annihilate to produce light (right). The wavelength of this light depends on the indium (In) content of the active layer—more leads to longer wavelengths and thus greener light. But the more indium in these layers, the more that indium is likely to pool into small "islands" during manufacture. The islands can alter the light's wavelength—an unacceptable flaw in a laser.

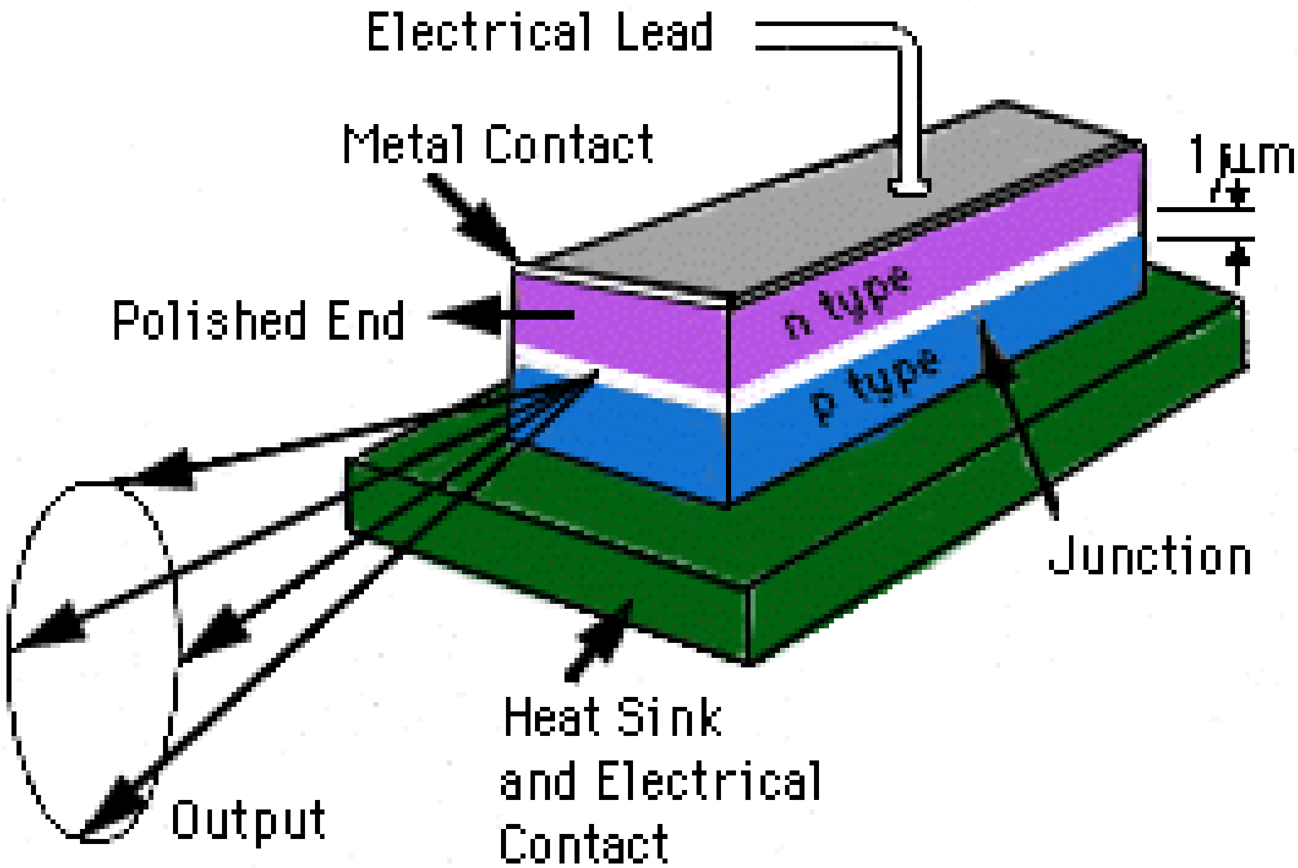


Diagram of Semiconductor Laser

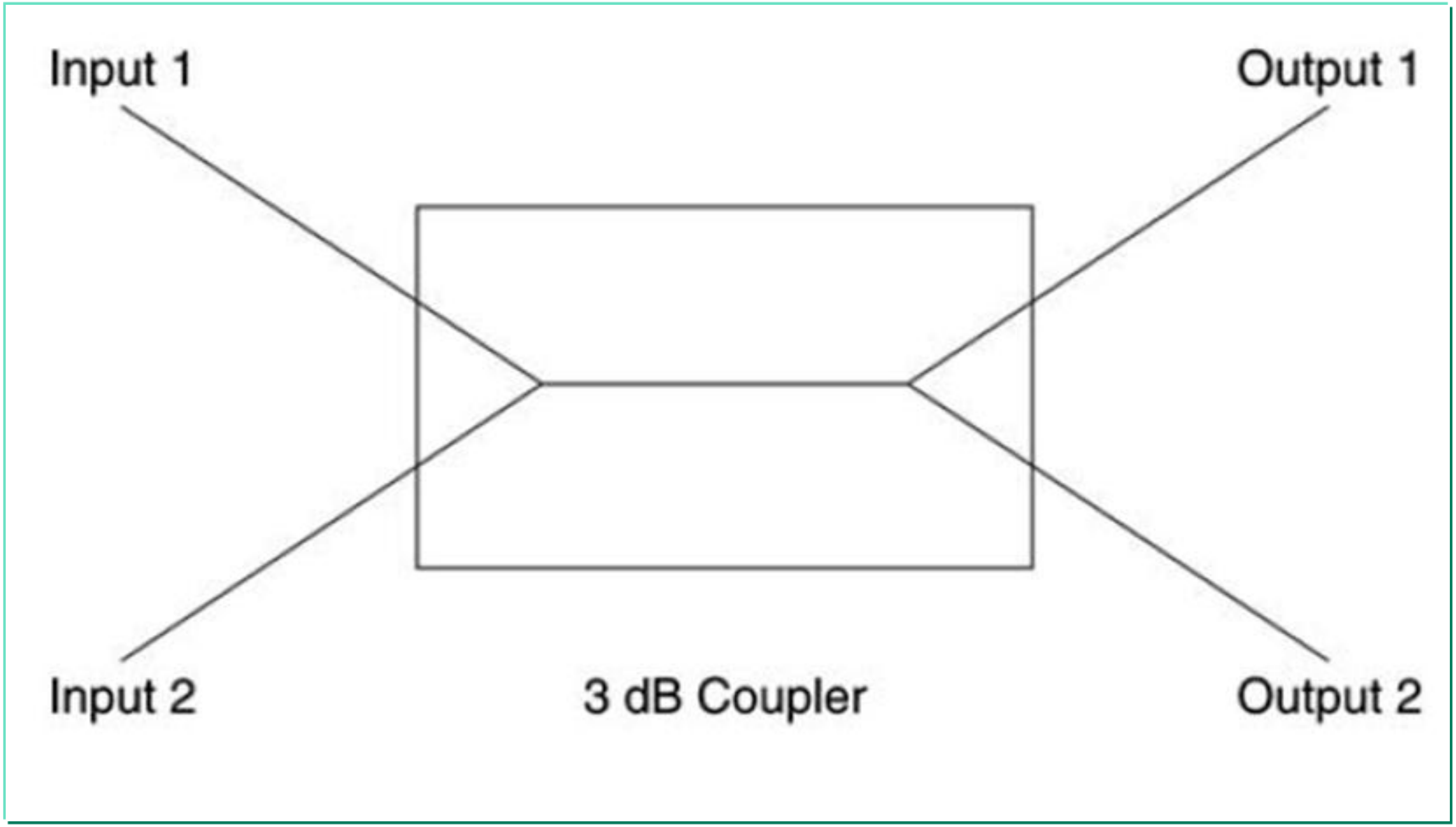
Couplers are the simplest optical devices and they are passive and completely bidirectional in nature in the sense that we can interchange the input and output ports.

Couplers are N x M, where N and M are integers.

In other words, we can have N input segments (fibers) and M output segments (fibers).

The principle (of a coupler) is to fuse the cores of the N input fibers to the cores of M output fibers so as to create a power transfer device.

Practically, 2 x 2 couplers are most common and are known as 3dB couplers because of the 3 dB loss in power at each output port due to a signal at one of the input ports. Refer to Figure 2-20.


Input 1
Output 1
Input 2
3 dB Coupler
Output 2

A Circulator is a multiport device that allows signals to propagate in certain directions based on the port that the signal came from (incident port).

The operation is based on an isolator (analogous to an optical valve), which allows unidirectional propagation only.

In Figure 2-21, the signal from port 1 moves freely to port 2; while the signal from port 2 cannot go to port 1, but it can go to port 3. Likewise, the signal from port 3 can go to port 1 but not to port 2.

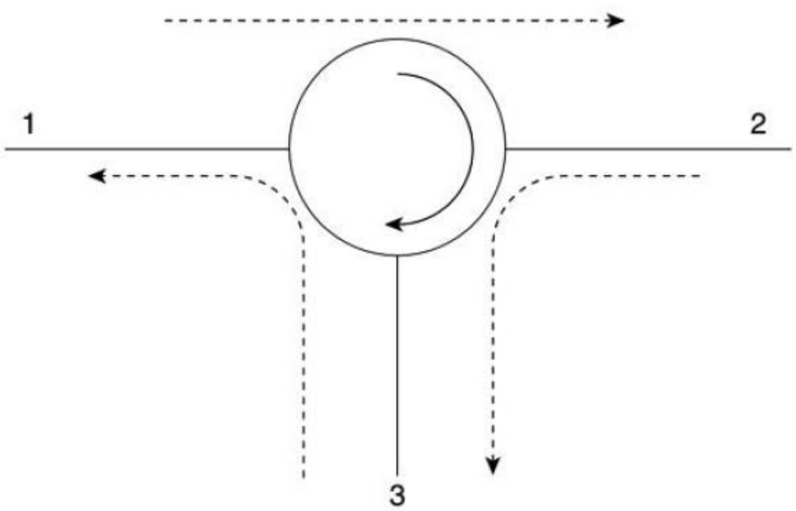


Figure 2-21. Three Port Circulators

Isolators :

These are used in Optical Amplifiers to prevent the amplifier from tuning into Laser.

Isolators are similar to an electronic diode as they transmit in only one Direction.

Two Key Parameters for Isolators are :-

1. Insertion Loss
2. PMD

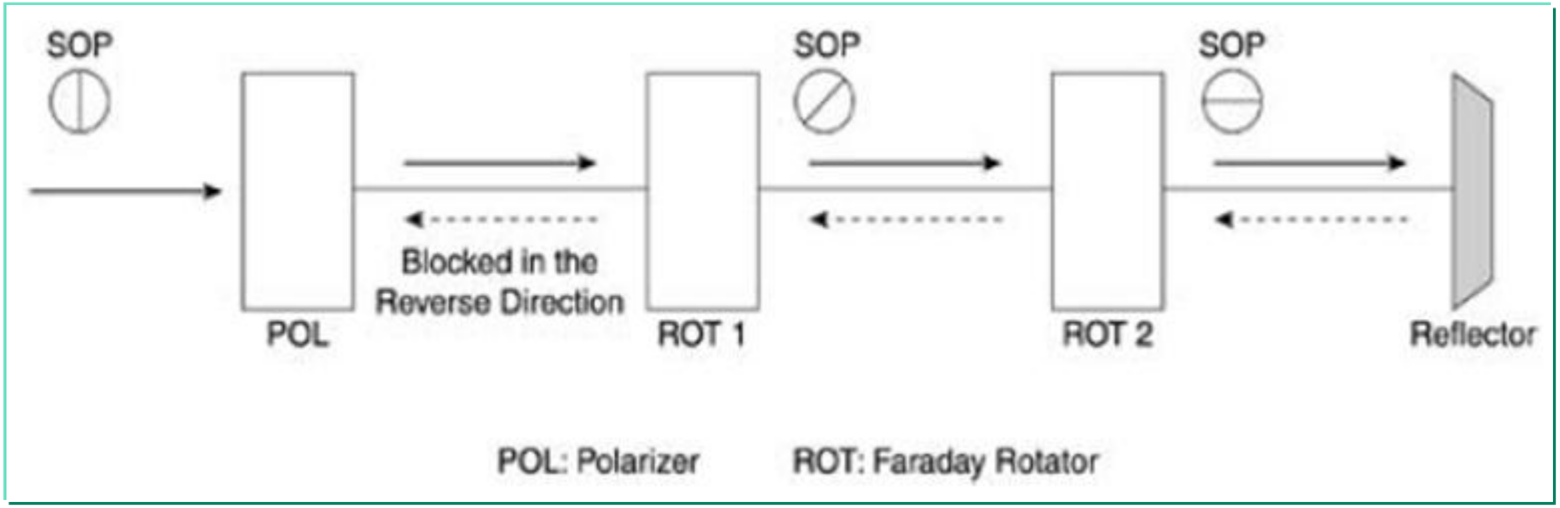
Where the need for insertion Loss is obvious but for PMD , it is a problem for HIGH bit-rate system.

A *Polarizer* is a device that allows light to pass through only if it is polarized in a certain manifestation(presented/demonstrated).

By inducing light to a polarizer, only the light that matches the phase of the polarizer passes through and subjected to a Faraday Rotator, which rotates the **state of polarization** (SOP) by 45 degrees.

A further rotation of 45 degrees by the second rotator makes the output state of polarization at the end of the second rotator 90 degrees as compared to the original input state of Polarisation(SOP).

If this light reflects back, it is blocked by the polarizer; this is because its SOP is 90 degrees out of phase with that of the polarizer as shown from the Figure shown below.



Isolator showing uni-directional optical communication analogous to optical valve

Beam Splitters :

Beam splitters are optical components used to split input light into two separate parts.

Beam splitters are common components in laser or illumination systems and are also ideal for :-

1. fluorescence Applications
2. Optical Interferometry
3. life science
4. Semiconductor Instrumentation.

The Light can be split by percentage of overall intensity, wavelength, or polarization state.

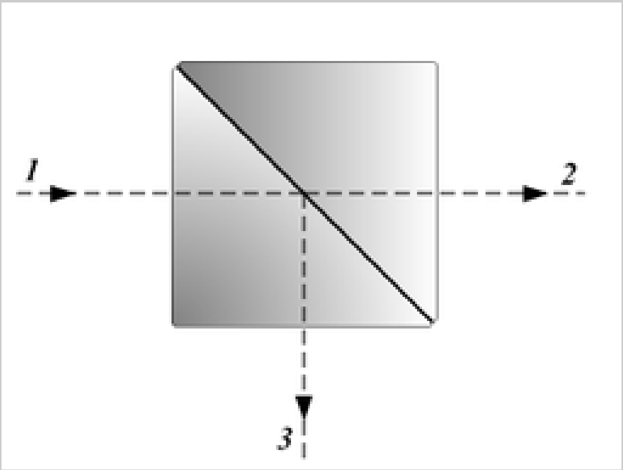
Types :

1. Standard Beam Splitters, which split incident light by a specified ratio that *is independent of wavelength or polarization state*, are ideal for illumination subassemblies or as one way mirrors.

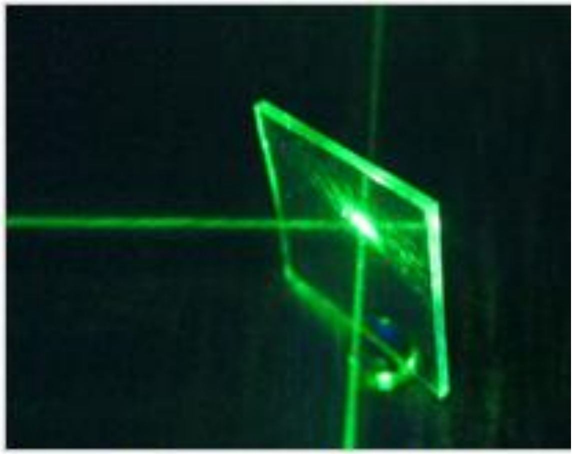
2. Dichroic Beam splitters, which split light by wavelength, are often used as laser beam combiners or as broadband hot or cold mirrors.

3. Non-Polarizing Beam splitters, ideal for laser beam manipulation, split light by overall intensity.

4. Polarizing Beam splitters, often used in photonics instrumentation which split light by polarization state. Edmund Optics' anti-reflection coatings are designed for the Ultraviolet (UV), Visible, of Infrared (IR).



Schematic illustration of a beam splitter cube.
1 - Incident light
2 - 50% Transmitted light
3 - 50% Reflected light
In practice, the reflective layer absorbs some light.



Aluminum coated beam splitter.

Beam splitters

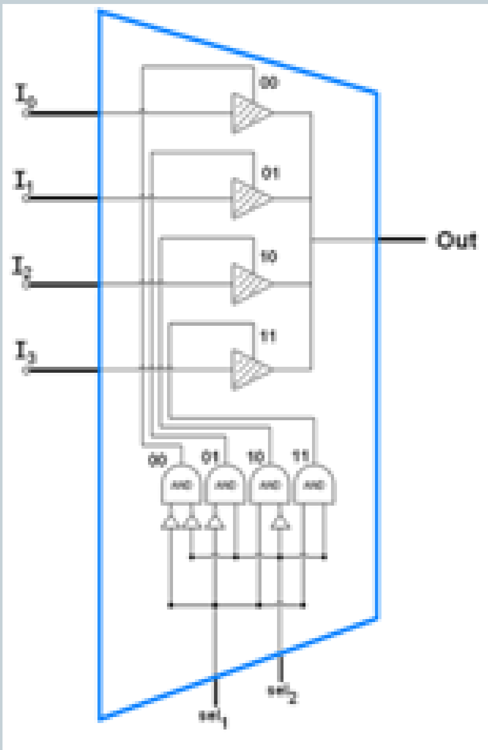
- What are Multiplexers?

  Multiplexers are hardware components that combine multiple analog or digital input signals into a single line of transmission.

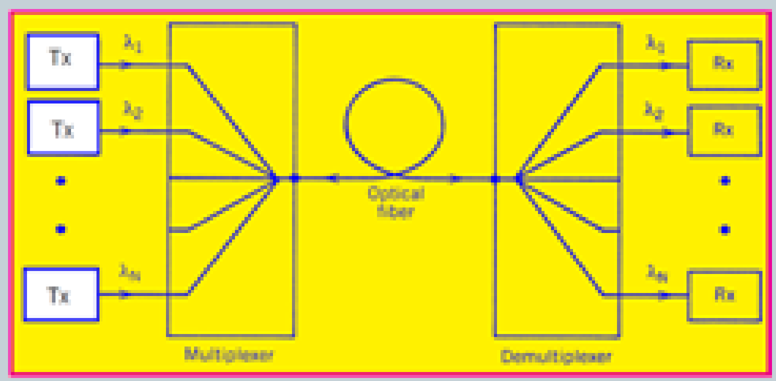
  And at the receiver's end, the multiplexers are known as de-multiplexers – performing reverse function of multiplexers.

- Multiplexing is therefore the *process of combining two or more input signals into a single transmission.*
- At receiver's end, the combined signals are separated into distinct separate signal.
- Multiplexing enhances efficiency use of bandwidth.

Multiplexer

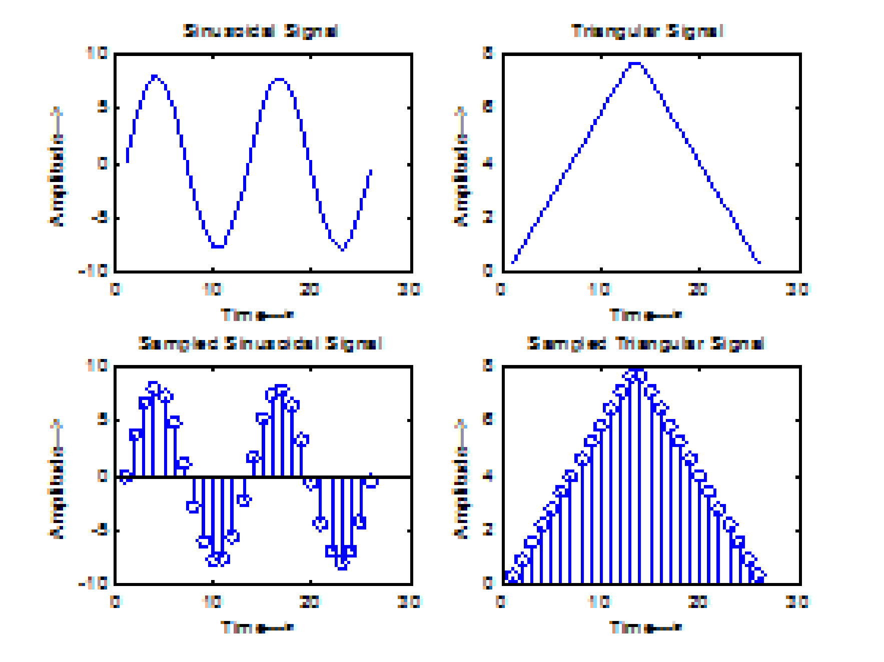


http://en.wikipedia.org/wiki/File:Telephony_multiplexer_system.gif



Multiplexing Example

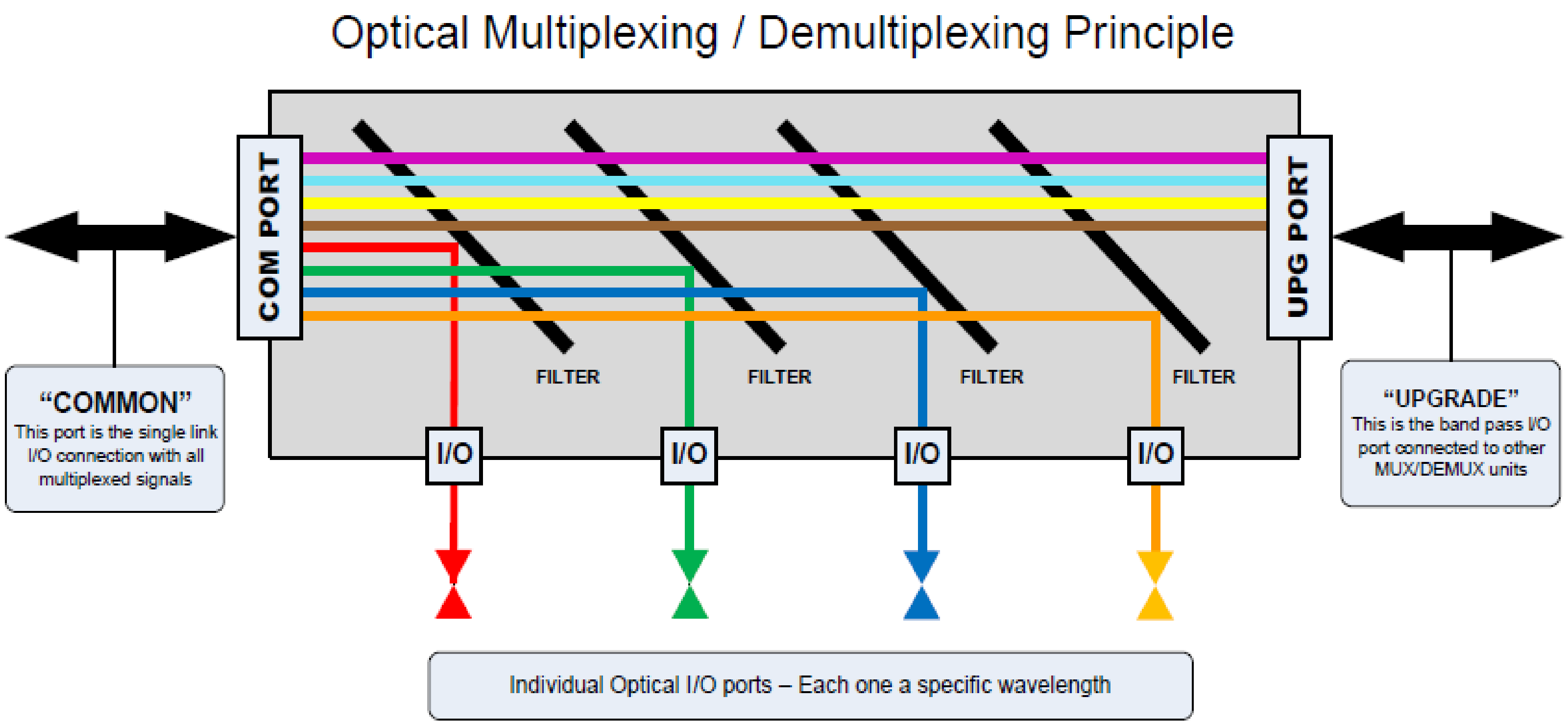
- MATLAB simulation example:
  - Sampled in time:
    - Quantization
    - Digitization



- Optical multiplexer and de-multiplexer are required to multiplex and de-multiplex various wavelengths onto a single fiber link.
- Each specific I/O will be used for a single wavelength.
- One optical filter system can act as both multiplexer and de-multiplexer
- Optical multiplexer and de-multiplexer are basically passive optical filter systems, which are arranged to process specific wavelengths in and out of the transport system (usually optical fiber).
- Process of filtering the wavelengths can be performed using:
  - Prisms
  - Thin film filter
  - Dichroic filters or interference filters

The filtering materials are used to selectively reflect a single wavelength of light but pass all others transparently.

Each filter is tuned for a specific wavelength.

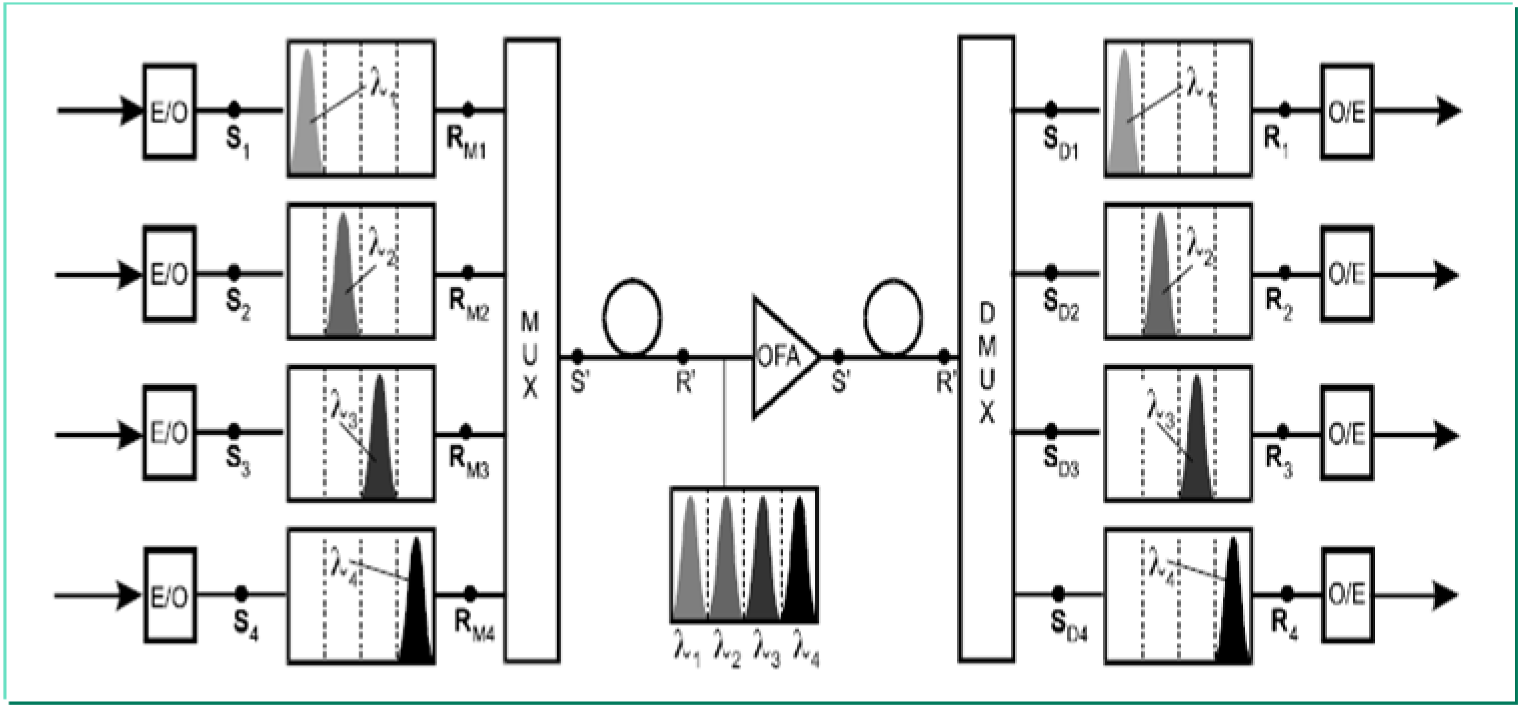


In a DWDM system , the light of laser diodes with wavelengths recommended by the ITU is launched into the inputs of a wavelength multiplexer (MUX).

At the output of the wavelength multiplexer all wavelengths are then combined and coupled into a single mode fiber (fig. 2) in next slide.

At the end of the transmission link the optical channels are separated again by means of a wavelength Demultiplexers (DMUX) thereby giving the different outputs.

In long Transmission links, it is necessary that the DWDM signals are *optically amplified* by an optical fiber amplifier (OFA).



MUX: wavelength multiplexer **DMUX:** wavelength demultiplexer **OFA:** optical fiber amplifier

E/O: transmitter **O/E:** receiver

Set-up of a DWDM system (4 channels) with recommended points for reference measurements

Multiplexer and Demultiplexers :

Multiplexes and De-multiplexers are key components in each DWDM system.

Multiplexers (MUX) provide n optical inputs where each input is equipped with a selective filter for a certain wavelength.

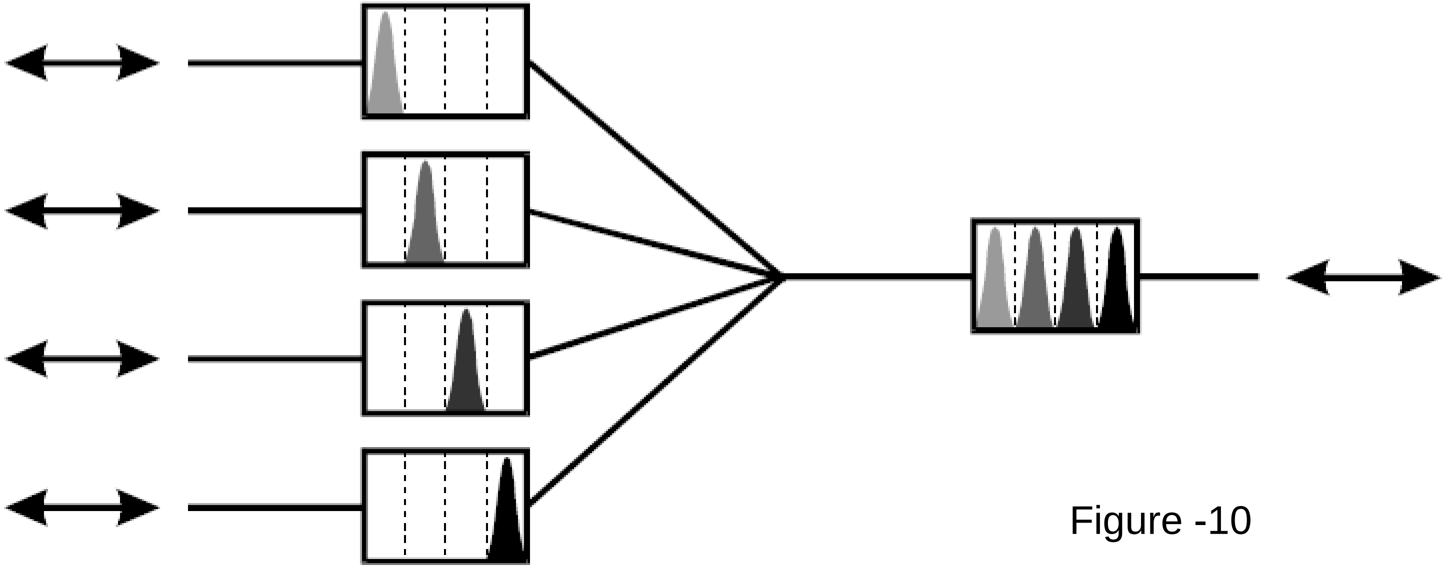


Figure -10

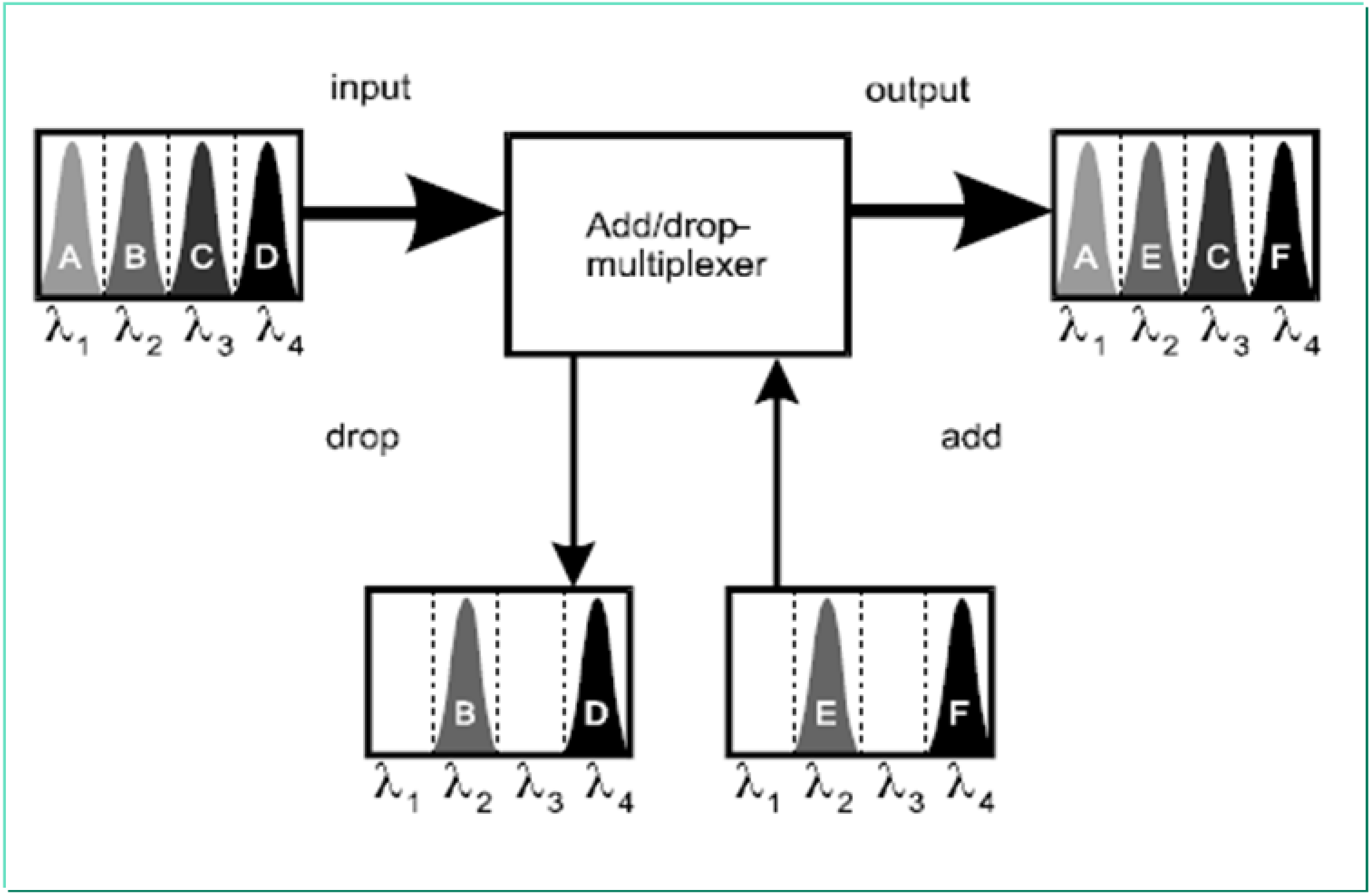
The outputs of these filters are coupled to one single mode fiber.

At the receiver, the wavelengths are separated again by a Demultiplexers (DMUX or DEMUX).

Multiplexers and De-multiplexers are identical components.

The only difference is that they are driven in opposite direction as shown above fig. 10.

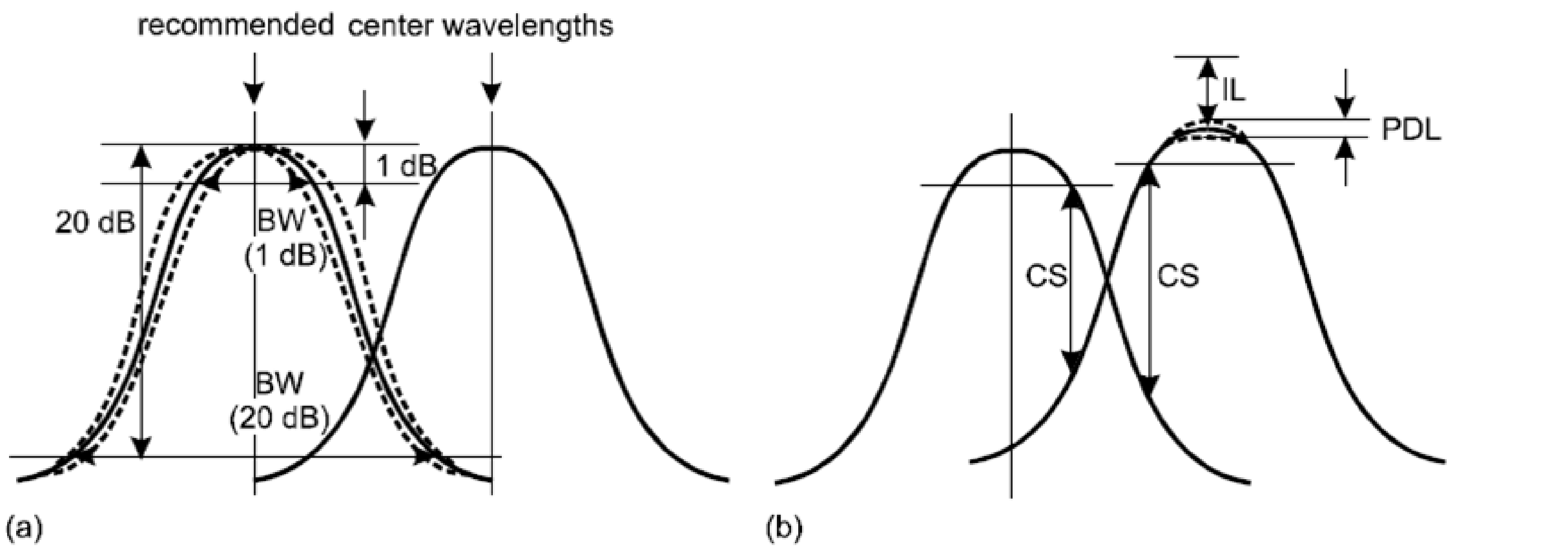
A Special type is the **add/drop-multiplexer,** where the new channels can be added to and other channels can be dropped off the transmission link (fig. 11).



Add/Drop-Multiplexer

These components are required because, in general, not all transmission channels have the same start and destination.

In future transparent optical nets the add/drop-multiplexer will be a key component, too.



Spectral behavior of two neighboring channels of a multiplexer (a) and definition of the most important parameters (b): IL: insertion loss, PDL: polarization dependent loss, CS: cross talk

The centre wavelengths of the multiplexer/demultiplexer have to be **adapted exactly to the standardized centre wavelengths.**

Within the tolerance range of the transmission channel , the optical multiplexer / Demultiplexers must have a low insertion loss, outside a high insertion loss is required.

Fig. 12 (a) shown above the spectral behaviour of two neighbouring channels of the multiplexer.

Typical parameters are the **spectral width of the** transmission band, indicated by a 1dB-drop (BW(1dB)), and the **filter slope, characterized by a 20dB-drop (BW(20dB)).**

Due to the non-ideal filter slope a defined spacing between the single channels is necessary.

The spectral width in the transmission band of the multiplexer / Demultiplexers must be wider than the total spectral range required by the laser diode according to fig. 9.

Then an insertion loss of <1dB per channel is guaranteed.

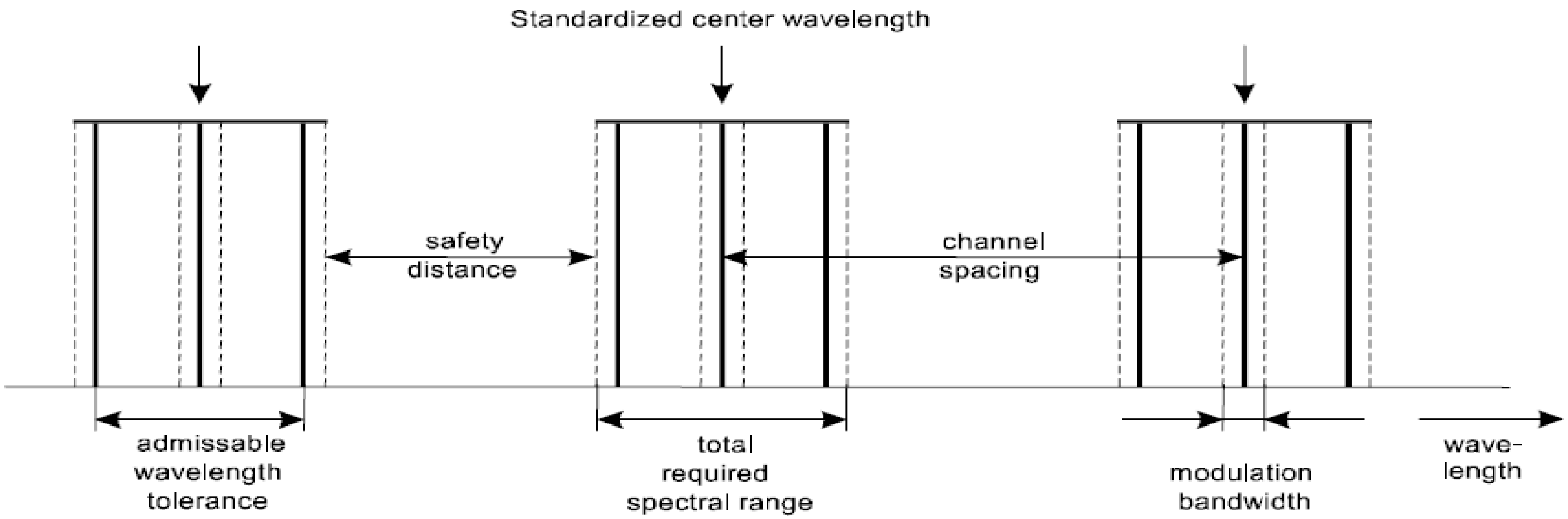


Figure 9: Wavelength grid in a DWDM system

For the examples given above, the range required by each channel was 50 % or 60 % of the channel spacing.

The ideal case for the transmission band of a multiplexer would even be 80 %. However, this cannot be realized yet.

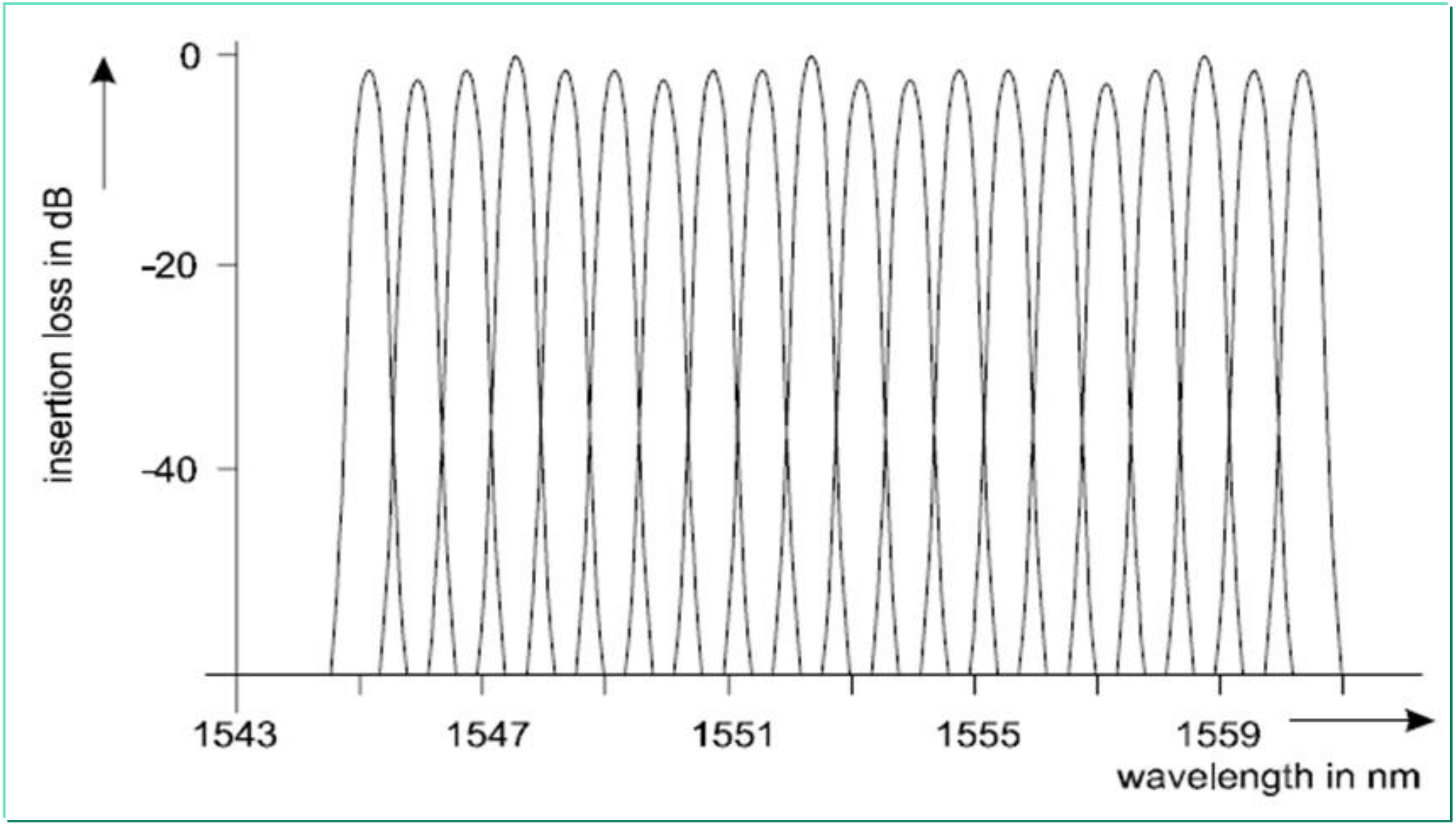
Note : In multiplexing as well as in De-multiplexing the Cross Talk (CS) plays an important role.

CS indicates that part of the power that couples over from an adjacent channel that should be as low as possible.

Since the optical receivers are broad-banded, they cannot distinguish between the information signal and the cross talk.

This may cause *interferences and lead to a higher bit BER error rate*.

De-multiplexers have cross talk values of 25dB whereas more complex networks may require up to 45dB.



Typical spectral behavior of a demultiplexer for 20 channels with 0,8nm channel spacing

Fig. above shows the spectral behaviour of a real De-multiplexer.

The **non uniformity** of the insertion losses of the single channels and the **overlapping areas are clearly visible.**

This figure illustrates the extremely high demands to multiplexers and demultiplexers, especially, if the channel spacing is very small.

Furthermore, the **polarization dependency of the attenuation of the** multiplexer / de-multiplexer should be as low as possible to avoid Polarization Dependent losses (PDL).

Multiplexers / De-multiplexers are based on Optical Gratings **(**Bragg gratings or bulk gratings) or on Integrated Optical components.

THANK YOU

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