Pollinating Innovations Through Information

DWDM Training : *CSIR, South Africa*

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

By

ABHISHEK AGARWAL

Nex-G Skills

DAY-5

DWDM Span Engineering

1. Nonlinear Effects (SPM, XPM, FWM, Raman)
2. Polarization Dependent Effects (PDL and PMD)
3. Signal Crosstalk

DWDM Testing, Measurements and OAM & P

4. Optical Waveform Analysis
5. Complete DWDM End- to- End
6. Component conformance tests
7. Engineering a DWDM link
8. Power Budget Design

The terms linear and nonlinear (Figure 1), in optics, mean intensity independent and intensity-dependent phenomena respectively.

Nonlinear effects in optical fibers occur due to -

1. Change in the refractive index of the medium with optical intensity and,
2. Inelastic scattering phenomenon.

ie, the power dependence of the refractive index is responsible for the Kerr-effect., and depending upon the type of input signal, the Kerr-nonlinearity manifests itself in three different effects such as –

1. Self-Phase Modulation (SPM),
2. Cross-Phase Modulation (CPM)
3. Four-Wave Mixing (FWM).

At high power level, the inelastic scattering phenomenon can induce stimulated effects such as Stimulated Brillouin-Scattering (SBS) and Stimulated Raman-Scattering (SRS).

The intensity of scattered light grows exponentially if the incident power exceeds a certain threshold value.

The difference between Brillouin and Raman scattering is that the Brillouin generated phonons (acoustic) are coherent and give rise to a macroscopic acoustic wave in the fiber , while in Raman scattering the phonons (optical) are incoherent and no macroscopic wave is generated.

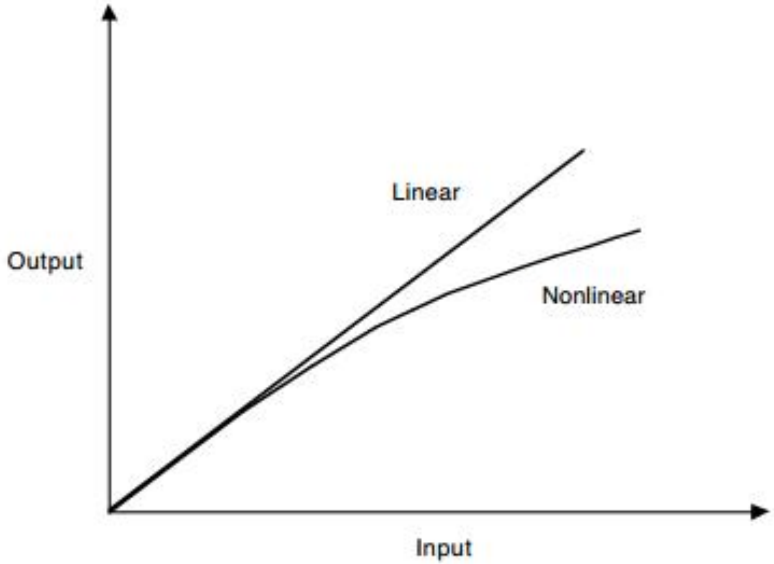
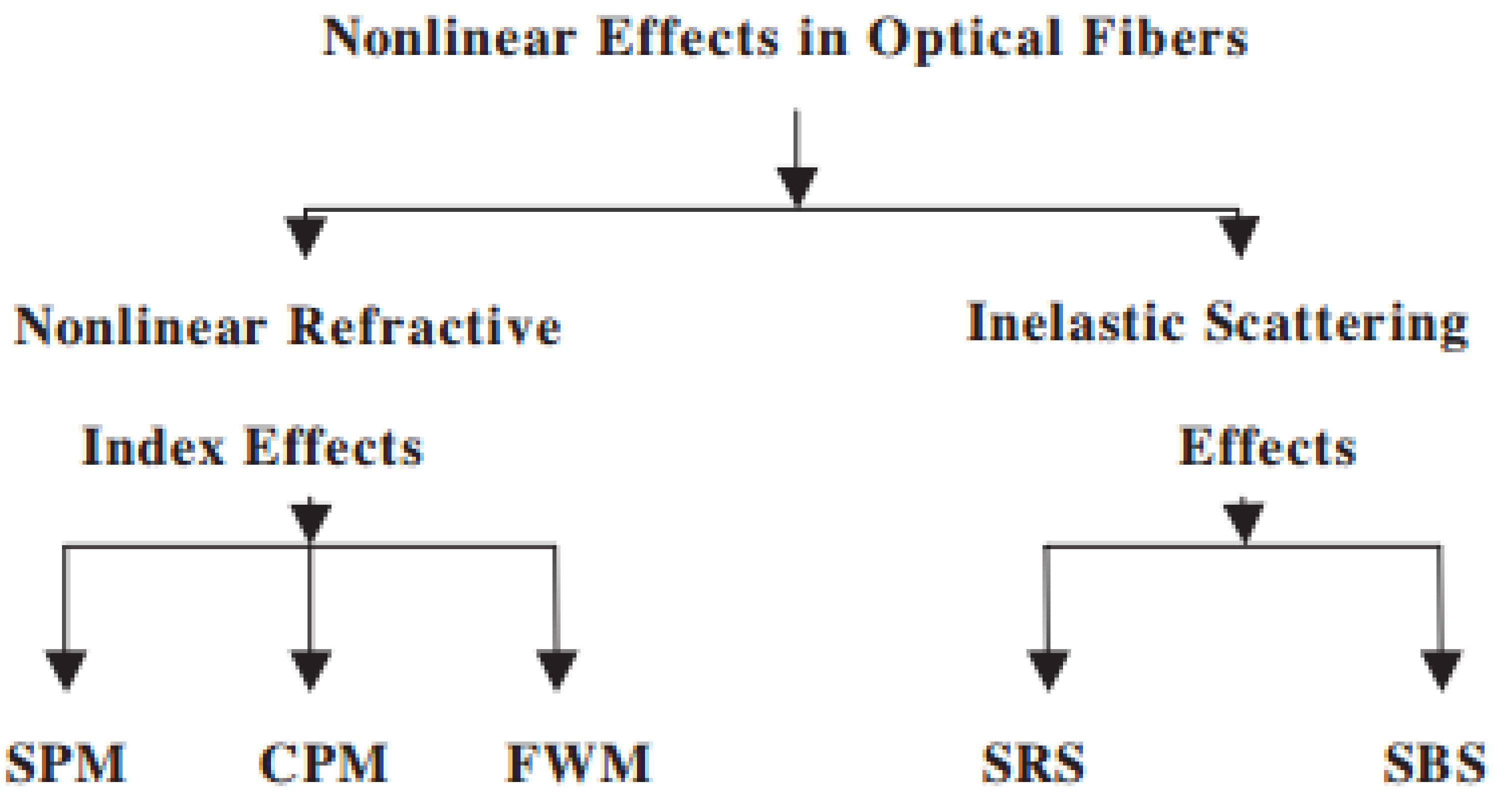


Figure 1. Linear and nonlinear interactions.

Table 1. Nonlinear effects in optical fibers.


Nonlinear Effects in Optical Fibers
Nonlinear Refractive Index Effects
Inelastic Scattering Effects
SPM
CPM
FWM
SRS
SBS

So, it is important to consider the effects of nonlinearities, When the optical communication systems operated at higher bitrates such as 10 Gbps and above and/or at higher transmitter powers , but *in the case of WDM systems*, nonlinear effects can become important even at moderate powers and bitrates.

At sufficiently high optical intensities, non-linear refraction occurs in the core (Kerr effect), which is the variation of the index of refraction with light intensity.

This makes Nonlinear Impairments a critical concern in optical networks since long-haul transmission commonly relies on high power lasers to transmit optical pulses over long spans to overcome attenuation.

Nonlinear Impairments depend mainly on the fiber type and length and can be placed into two categories.

The first includes the nonlinear effects that affect the *energy* of an optical pulse and includes:

- Stimulated Brillouin Scattering (SBS)
- Stimulated Raman Scattering (SRS)
- Four-wave mixing (FWM)

Nonlinear effects that affect the *shape* of an optical pulse include :

- Self-Phase Modulation (SPM)
-Cross-Phase Modulation (XPM)

1 Stimulated Brillouin Scattering (SBS):

SBS is a narrow band effect relative to the data channels operating in the THz range resulting in *shorter wavelengths amplifying longer wavelengths* by depleting themselves.

The result is that power from the optical signal can be scattered back towards the transmitter.

SBS involves the interaction of incident light with acoustic waves in the silica glass generating down-shifted scattered light in a manner similar to Stimulated Raman Scattering (SRS) , presented below.

Hence, SBS is a narrowband process that affects each channel in a DWDM system individually, but which is even more pronounced in STM–64/OC–192 systems, due to the greater power levels required for their transmission.

The SBS has a relatively low threshold (lower that that for the SRS) and can be detrimental for fiber-optic transmission systems.

However, the SBS finds applications in *Brillouin lasers and Amplifiers*.

2.Stimulated Raman Scattering (SRS):

If two or more signals at different wavelengths are injected into a fiber, SRS causes power to be transmitted from lower wavelength channels to the higher wavelength channels.

If two or more signals at different wavelengths are injected into a fiber, (SRS) causes power to be transferred from the *lower wavelength channels* to the *higher-wavelength channels*.

SRS and SBS are similar except that SRS scatters in both forward as well as reverse directions, whereas SBS scatters in reverse only.

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.

SRS takes place in the transmission fiber.

In both SRS and SBS, a wave called *Stoke's wave* is generated due to the scattering of energy by amplifying wave of high energy.

The gain obtained by using such a wave creates Raman and Brillouin amplification.

The Raman gain can extend most of the operating band (C and L band) for WDM networks.

3. Self Phase Modulation (SPM) :

In a single mode fiber, even a single light wave can be affected by this non-linearity since its phase is modulated by optical intensity fluctuations in the same wave.

This effect is called Self-Phase Modulation (SPM).

SPM together with GVD effect make the different spectral components of optical pulse propagate at different speed.

This make the pulse broaden temporally and therefore leads to overlapping between adjacent bits and resulting in an increase in bit error rate.

4. Cross-phase modulation (XPM):

The innovation (WDM) enables multiple signals to be transmitted on the same fiber.

In a WDM system the optical intensity or power fluctuations of a optical wave propagating in an optical fiber modulates the phase of the other co-propagating optical signals through a phenomenon called Cross phase modulation (XPM).

XPM arises from the same phenomenon as SPM, but the effect of XPM is more relevant for multi channel transmission while SPM effect is only significant in single channel transmission systems.

XPM can impose more limitations than SPM for WDM systems since there are presumably many other channels to generate the phase shift and intensity fluctuations.

XPM results from the different carrier frequency of independent channels, including the associated phase shifts on one another.

XPM is severely harmful and is twice as powerful as Self phase modulation , SPM .

In multichannel WDM systems, XPM causes intensity-based modulation to adjacent frequency channels.

XPM causes fluctuations in pulse propagation due to the effect of other channels. Furthermore, if adjacent channels are travelling at the same bit rate, XPM effects are more pronounced.

One way to avoid XPM is by carefully selecting bit rates for adjacent channels that are not equal to the present channel bit rate.

When designing WDM links, we typically keep a 0.5dB power penalty margin for both FWM and XPM.

XPM has more impact on certain types of modulation formats.

Note– All 5 i.e., XPM, SPM, SRS, SBS, FWM has the loss margin of 0.5 db as shown in margin requirements table.

1. SPM is primarily due to the self modulation of the pulses and it is caused generally in single wavelength systems.

2. At high bit rates, SPM tends to cancel dispersion.

3. XPM is modulation of pulse power by adjoining pulses (at different wavelengths).

4. We can calculate XPM and dispersion in a fiber by using the split Fourier transform method, whereby the dispersion effects and the XPM effects are taken individually.

5. We also must divide the fiber into minute strips for individual computation.

6. FWM is directly dependent on the wavelength spacing in WDM systems and it is inversely proportional to the dispersion of the fiber.

7. A 1dB penalty for XPM and FWM is generally advisable.

8. SRS and SBS are comparatively unimportant effects on long-haul system design, especially at compact WDM spacing.

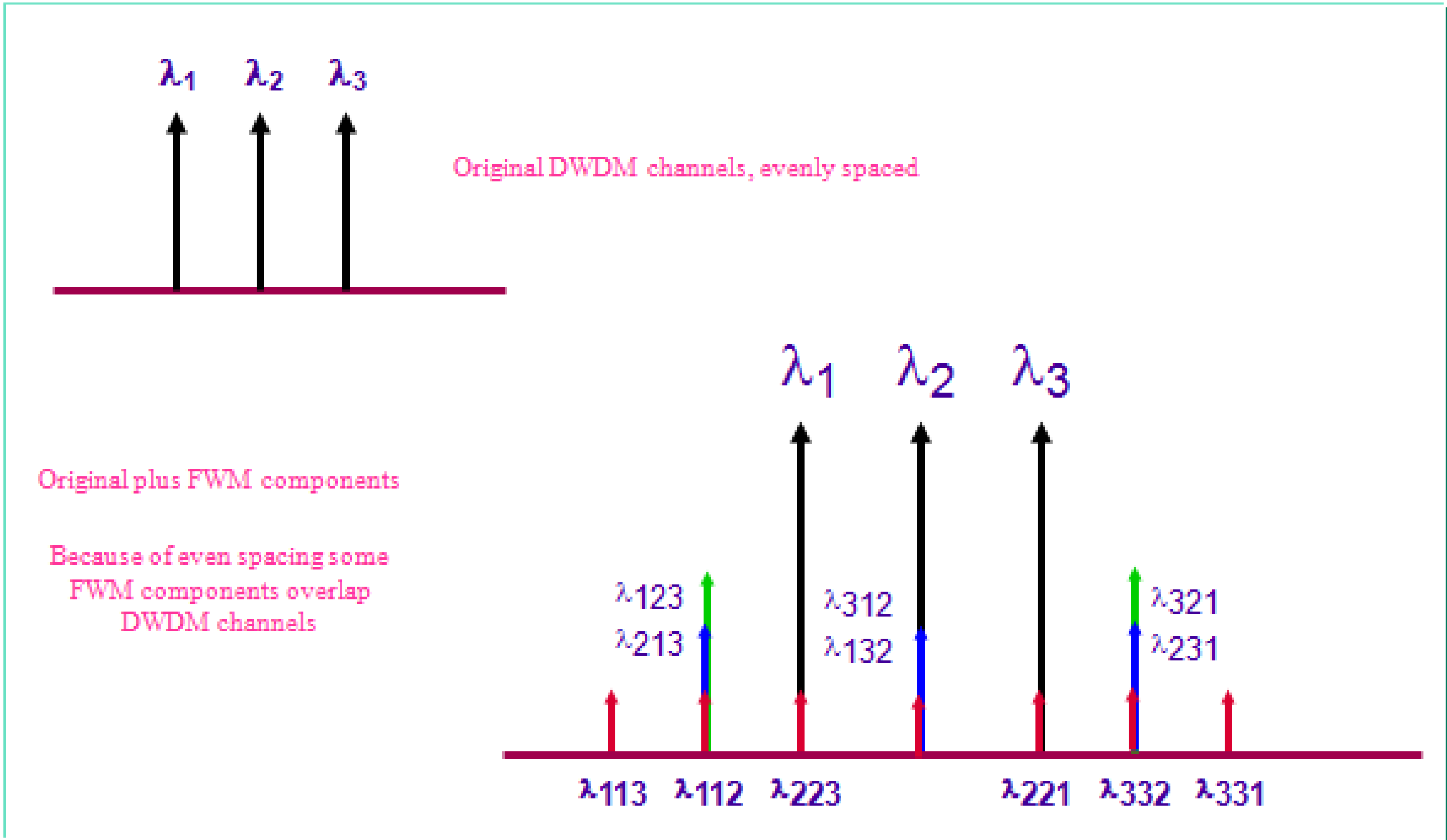
9. PMD is the big source of impairment for ultra long-haul systems due to group delay of the pulse being a function of the state of polarization (SOP) of the signal.

10. SPM & XPM are two common coupling problems whereas FWM, (SRS), and (SBS) are also high bit rate, high power issues.

11. On the other hand, nonlinear effects exist in which the net content of the energy is scattered into the interacting nonlinear medium.

12. SRS and SBS are inelastic scattering effects.

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



3 ITU channels 0.8 nm spacing

Channel	nm
$\lambda 1$	1542.14
$\lambda 2$	1542.94
$\lambda 3$	1543.74

Equal spacing

- For the three channels λ_1, λ_2 and λ_3 calculate all the possible combinations produced by adding two channel λ's together and subtracting one channel λ.
- For example $\lambda_1 + \lambda_2 - \lambda_3$ is written as λ_{123} and is calculated as 1542.14 + 1542.94 - 1543.74 = 1541.34 nm
- Note the interference to wanted channels caused by the FWM components λ_{312}, λ_{132}, λ_{221} and λ_{223}

FWM mixing components

Channel	nm
$\lambda 123$	1541.34
$\lambda 213$	1541.34
$\lambda 321$	1544.54
$\lambda 231$	1544.54
$\lambda 312$	**1542.94**
$\lambda 132$	**1542.94**
$\lambda 112$	1541.34
$\lambda 113$	1540.54
$\lambda 221$	**1543.74**
$\lambda 223$	**1542.14**
$\lambda 331$	1545.34
$\lambda 332$	1544.54

- Reducing FWM can be achieved by:
  - Increasing channel spacing (not really an option because of limited spectrum)
  - Employing uneven channel spacing
  - Reducing aggregate power
  - Reducing effective aggregate power within the fibre
- Another more difficult approach is to use fibre with non-zero dispersion:
  - FWM is most efficient at the zero-dispersion wavelength
  - Problem is that the "cure" is in direct conflict with need minimise dispersion to maintain bandwidth
- To be successful the approach used must reduce unwanted component levels to at least 30 dB below a wanted channel.

Four-wave mixing (FWM)-contd.

Four Wave Mixing example with 3 unequally spaced channels

3 DWDM channels

Channel	nm
λ1	1542.14
λ2	1542.94

unequal spacing

FWM mixing components

Channel	nm
λ123	1541.24
λ213	1541.24
λ321	1544.64
λ231	1544.64
λ312	1543.04
λ132	1543.04
λ112	1541.34
λ113	1540.44
λ221	1543.74
λ223	1542.04
λ331	1545.54
λ332	1544.74

- As before for the three channels λ_1, λ_2 and λ_3 calculate all the possible combinations produced by adding two channel λ's together and subtracting one channel λ.

- Note that because of the unequal spacing there is now no interference to wanted channels caused by the generated FWM components

Sample FWM problem with 3 DWDM channels

Problem:

- For the three channels λ_1, λ_2 and λ_3 shown calculate all the possible FWM component wavelengths.
- Determine if interference to wanted channels is taking place.
- If interference is taking place show that the use of unequal channel spacing will reduce interference to wanted DWDM channels.

3 channels 1.6 nm spacing

Channel	nm
λ1	1530.00
λ2	1531.60
λ3	1533.20

Solution to FWM problem

3 channels 1.6 nm equal spacing

Channel	nm
λ1	1530.00
λ2	1531.60
λ3	1533.20

FWM mixing components

Channel	nm
λ123	1528.40
λ213	1528.40
λ321	1534.80
λ231	1534.80
λ312	**1531.60**
λ132	**1531.60**
λ112	1528.40
λ113	1526.80
λ221	**1533.20**
λ223	**1530.00**
λ331	1536.40
λ332	1534.80

3 channels unequal spacing

Channel	nm
λ1	1530.00
λ2	1531.60
λ3	1533.40

FWM mixing components

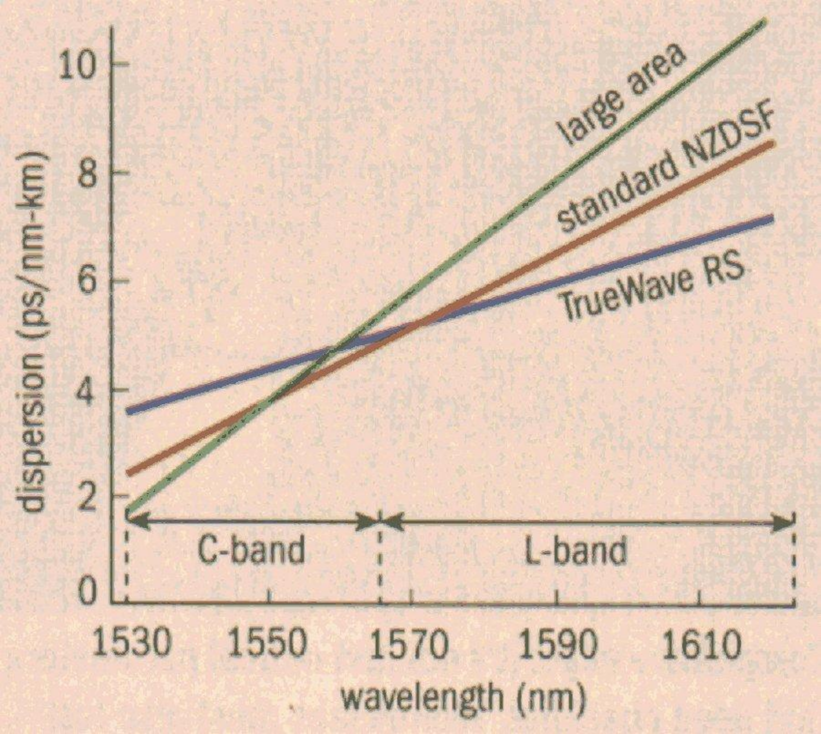
Channel	nm
λ123	1528.20
λ213	1528.20
λ321	1535.00
λ231	1535.00
λ312	1531.80
λ132	1531.80
λ112	1528.40
λ113	1526.60
λ221	1533.20
λ223	1529.80
λ331	1536.80
λ332	1535.20

Reducing FWM using NZ-DSF

- Traditional non-multiplexed systems have used dispersion shifted fibre at 1550 to reduce chromatic dispersion
- Unfortunately operating at the dispersion minimum increases the level of FWM
- Conventional fibre (dispersion minimum at 1330 nm) suffers less from FWM but chromatic dispersion rises
- Solution is to use "Non-Zero Dispersion Shifted Fibre" (NZ DSF), a compromise between DSF and conventional fibre (NDSF, Non-DSF)
- ITU-T standard is G.655 for non-zero dispersion shifted singlemode fibres

Lucent TrueWave NZDSF

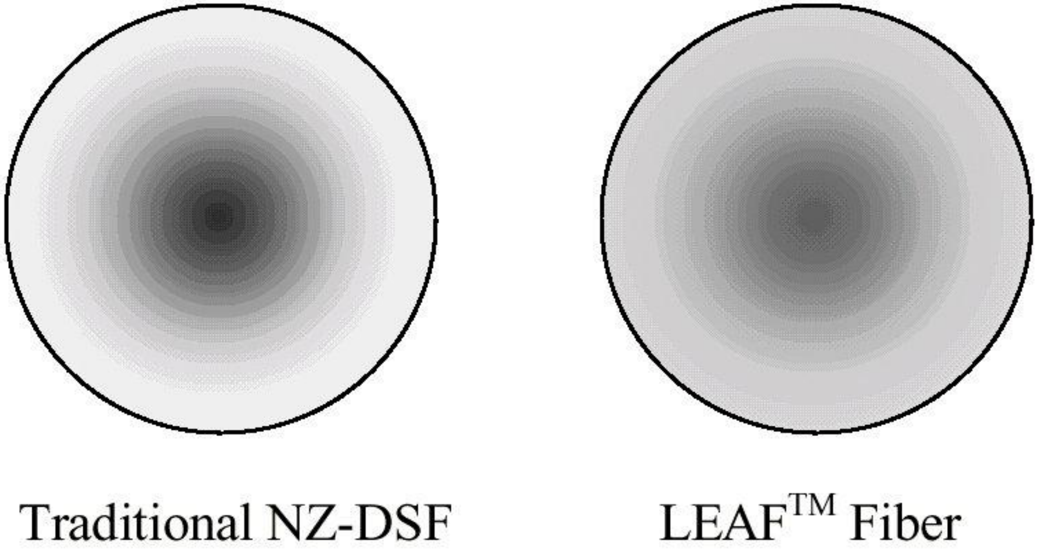
- Provides small amount of dispersion over EDFA band
- Non-Zero dispersion band is 1530-1565 (ITU C-Band)
- Minimum dispersion is 1.3 ps/nm-km, maximum is 5.8 ps/nm-km
- Very low OH attenuation at 1383 nm (< 1dB/km)



Dispersion Characteristics

Reducing FWM using large effective area Fiber NZ-DSF

- One way to improve on NZ-DSF is to increase the effective area of the fibre
- In a singlemode fibre the optical power density peaks at the centre of the fibre core
- FWM and other effect most likely to take place at locations of high power density
- Large effective Area Fibres spread the power density more evenly across the fibre core
- Result is a reduction in peak power and thus FWM



RSULTS and DISCUSSION

By varying the dispersion from 0 to 4 ps/nm/km we observed effect of dispersion on FWM. And also effect equal and unequal spacing on FWM is observed.
These effects are shown in following figs.

Effect of Dispersion (wrt) FWM :-

At input when we apply signal observed input optical spectrum as shown in Figure 4. By varying dispersion we observed the effects.

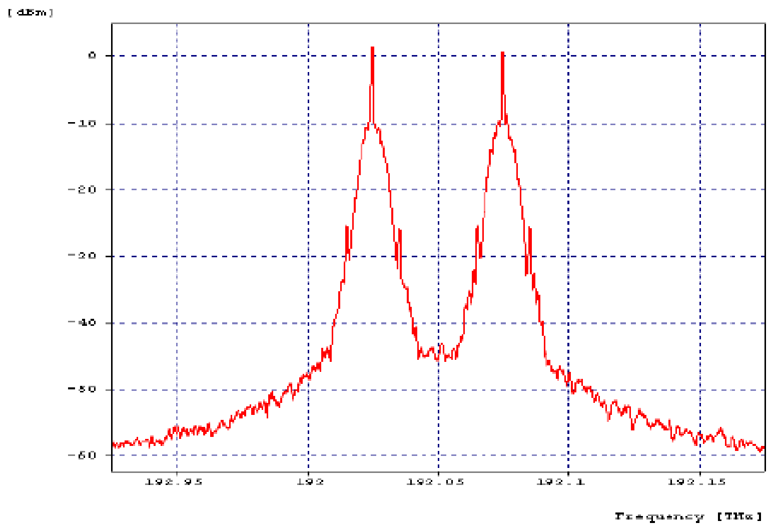


Figure 4 Input Spectrum

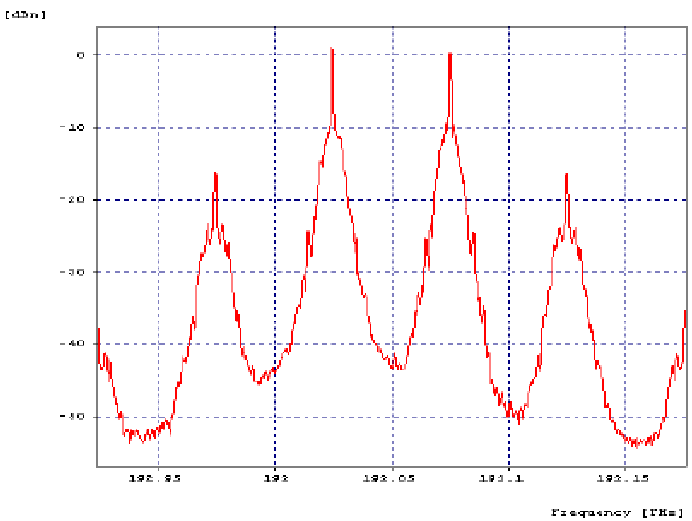


Figure 5 Output spectrum dispersion=0

Fig. 5 shows at zero dispersion FWM effect is more i.e. -15dB and as dispersion increases FWM effect decreases.

It is -25dB and -32dB as shown in Figure 6 and Figure 7 respectively.

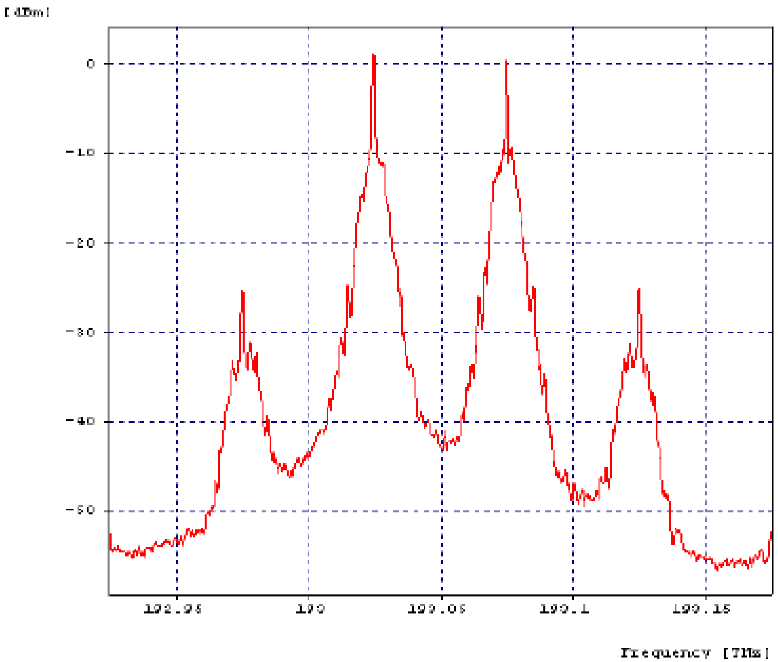


Figure 6 Output spectrum dispersion=1

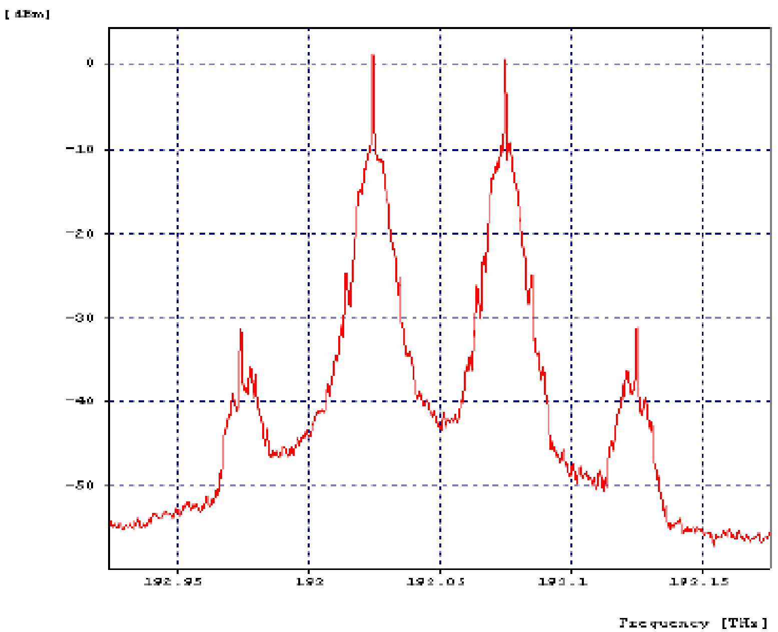


Figure 7 Output spectrum dispersion=2

Further as dispersion is 3 ps/nm/km and 4 ps/nm/km effect of FWM decreases.

It is -33dB and -36 dB as shown in Figure 8 and Figure 9 respectively.

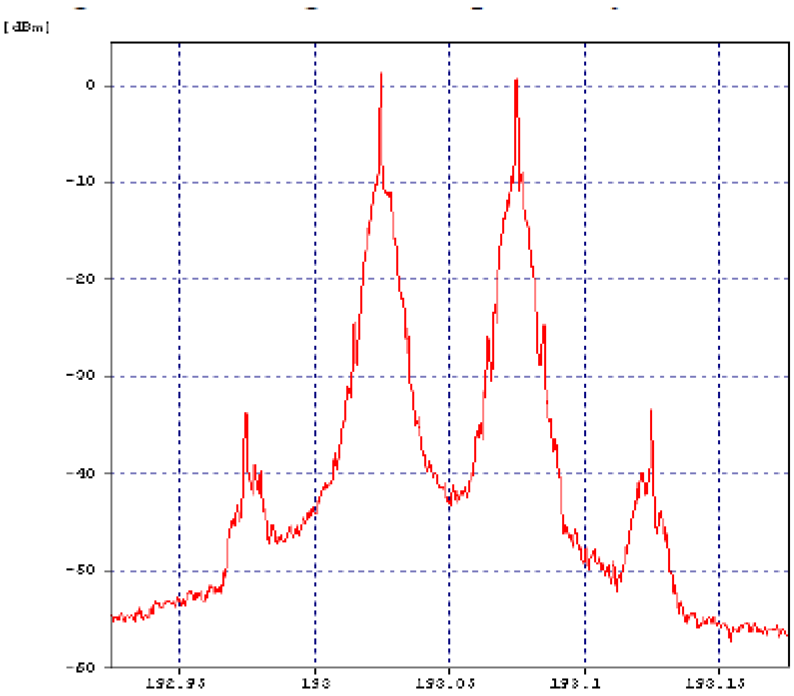


Figure 8 Output spectrum dispersion=3

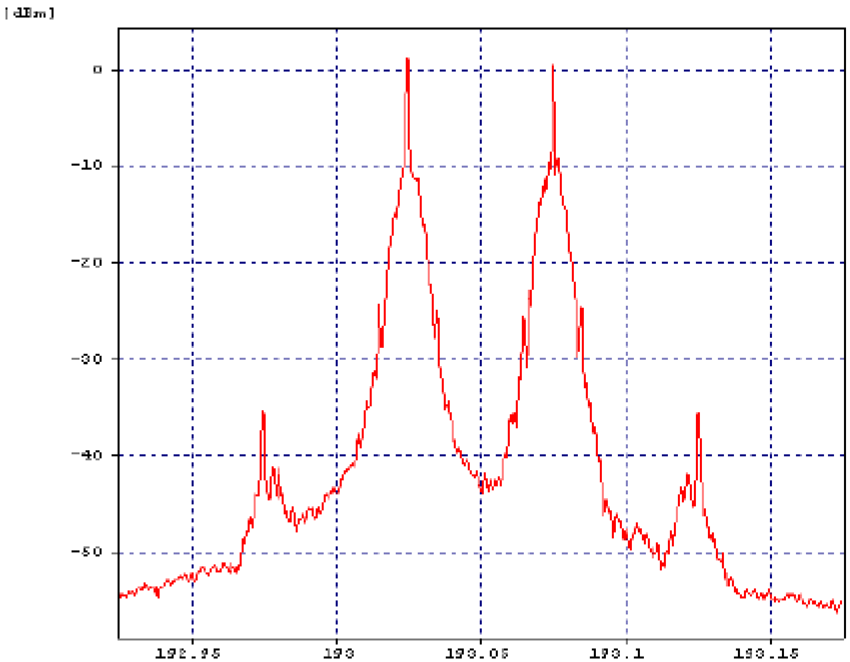


Figure 9 Output spectrum dispersion=4

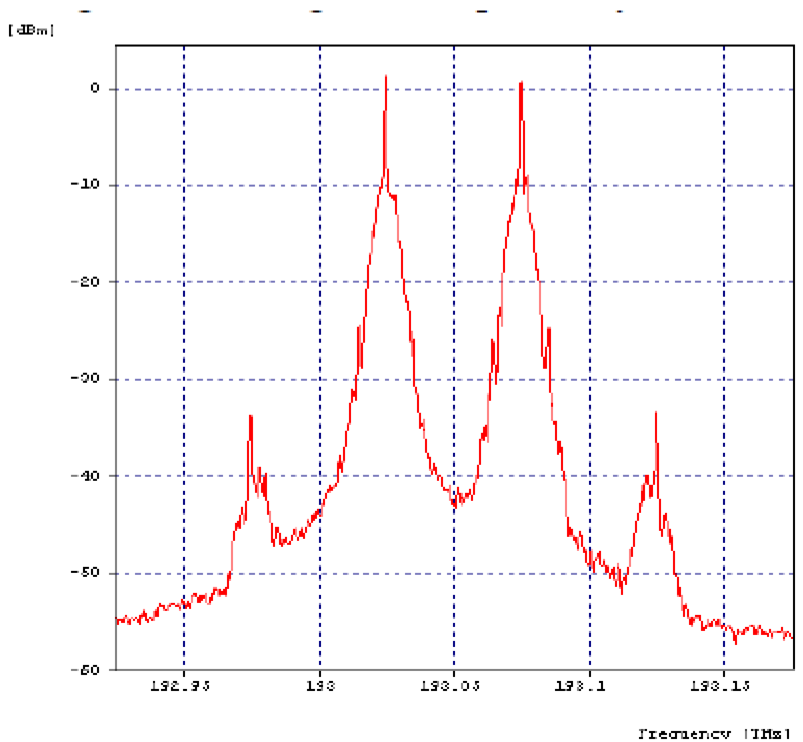


Figure 8 Output spectrum dispersion=3

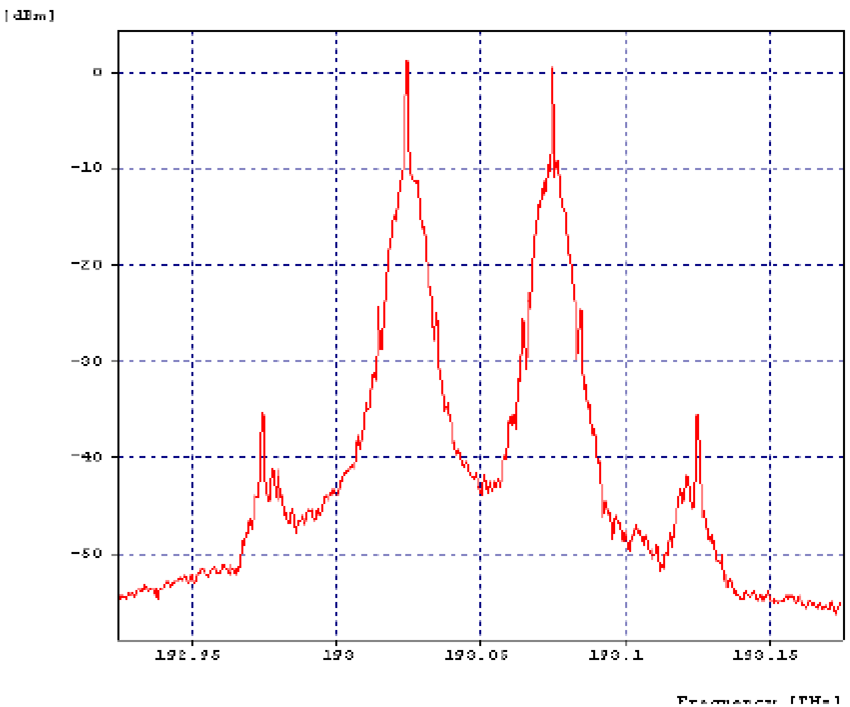


Figure 9 Output spectrum dispersion=4

Effect of Channel Spacing

Figure 10 shows Optical spectrum and Figure 11 shows eye spectrum for equal spacing of 0.2 nm.

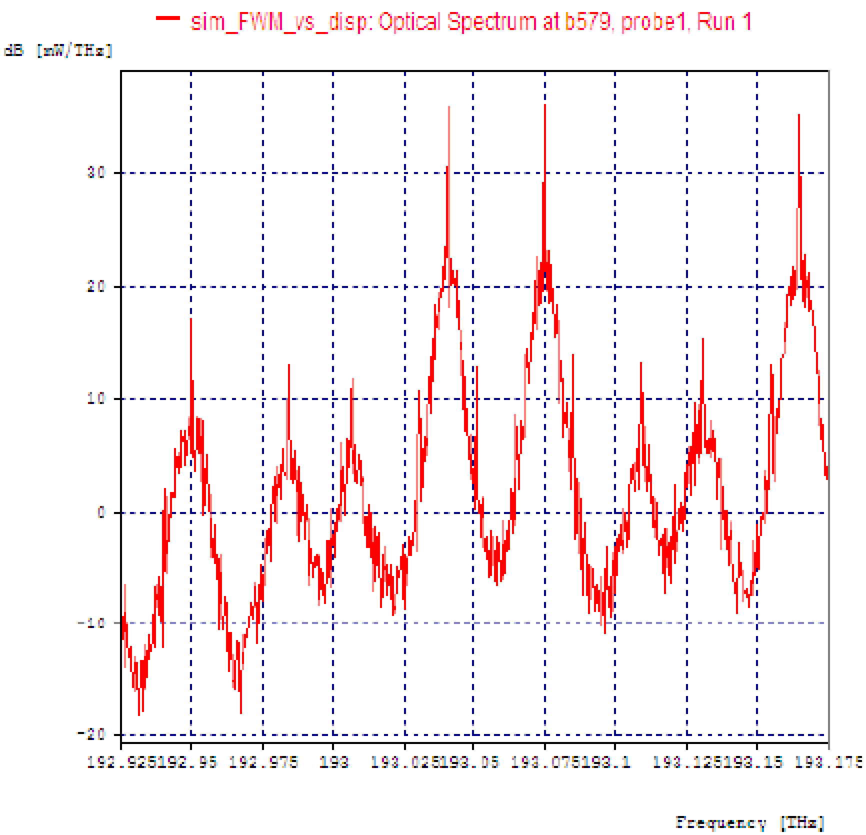


Figure 10 Optical spectrum

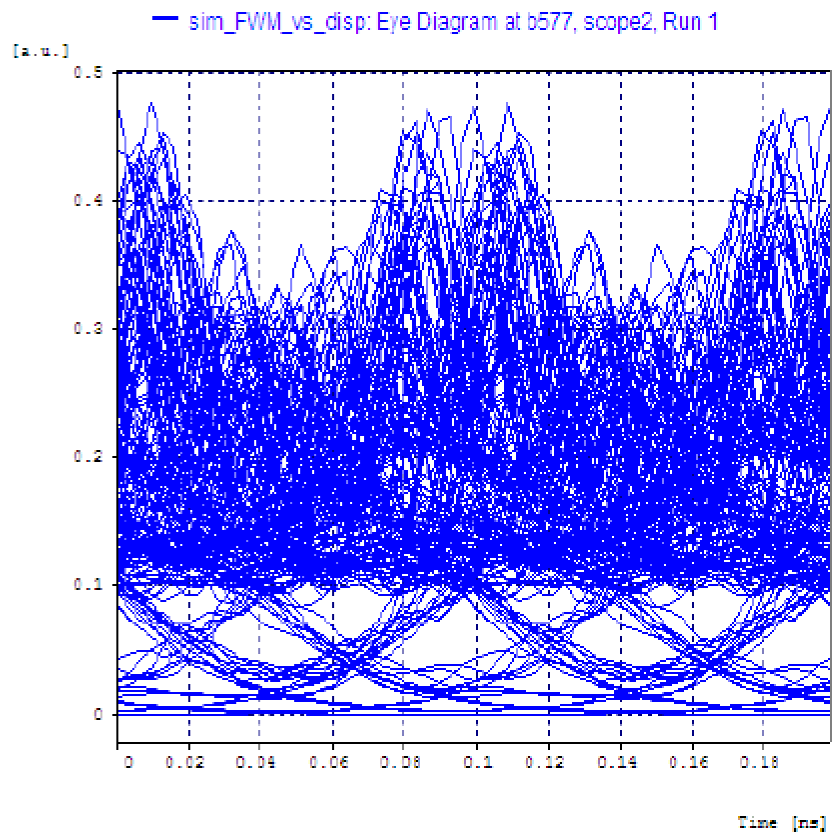


Figure 11 Eye spectrum

As shown in fig 11, eye spectrum is distorted.

For *equal spacing* effect of FWM is **more ,** but for *unequal spacing* effect of FWM **decreases**.

For this spacing's are 0.1, 0.2, 0.1 and 0.2 nm. Figure 12 and Figure 13 show effect of unequal spacing.

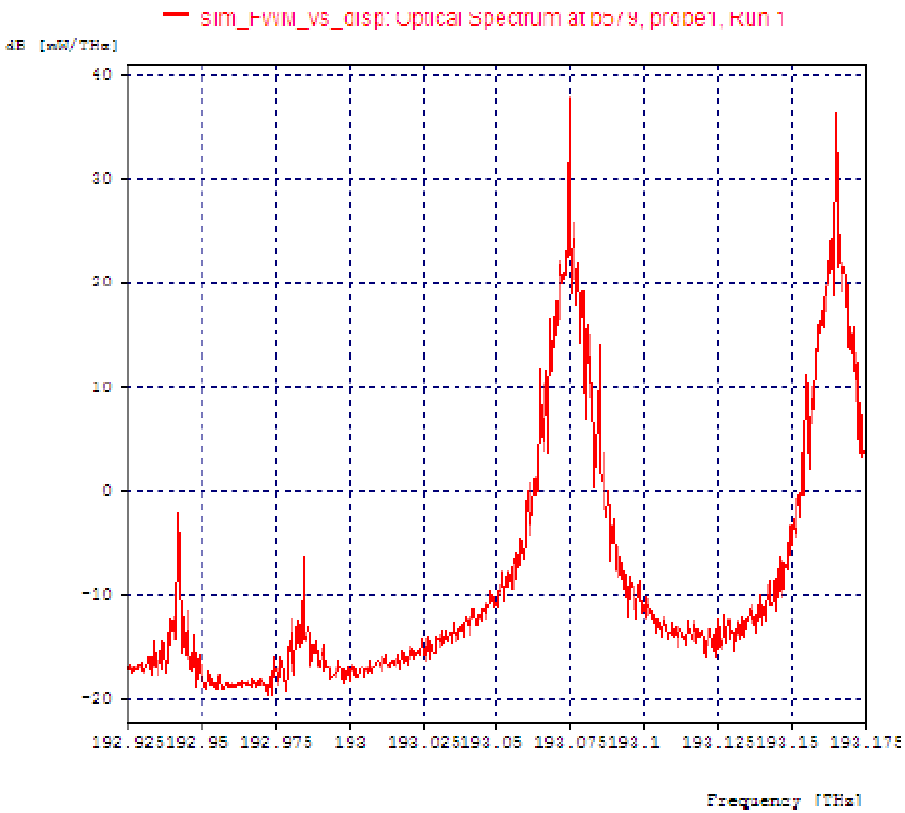


Figure 12 Optical spectrum

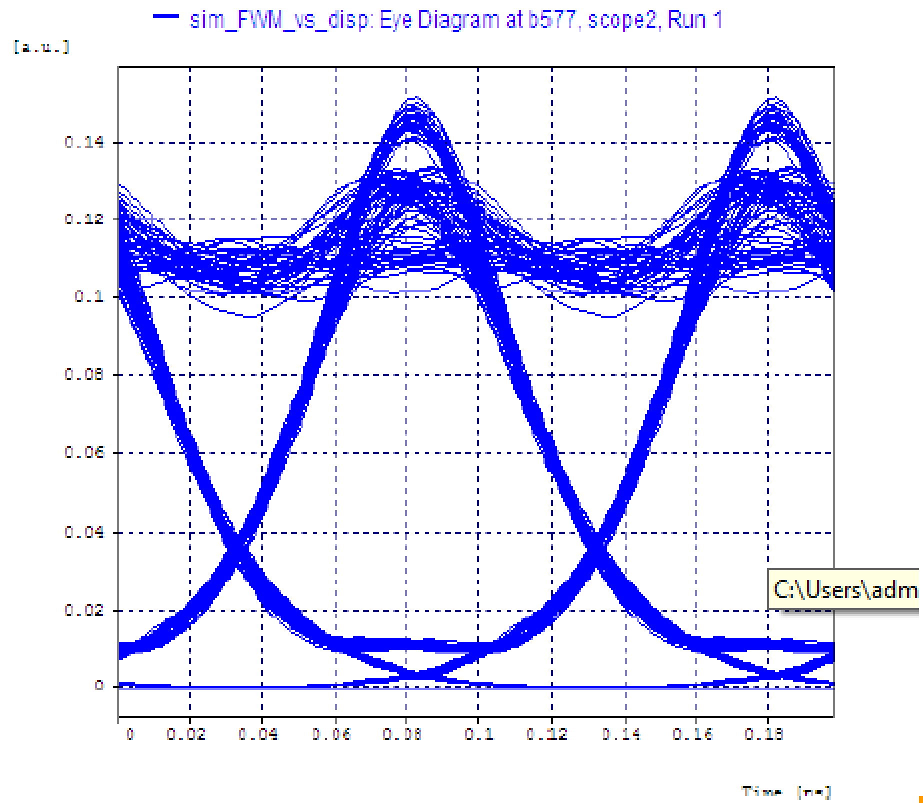


Figure 13 Eye spectrum

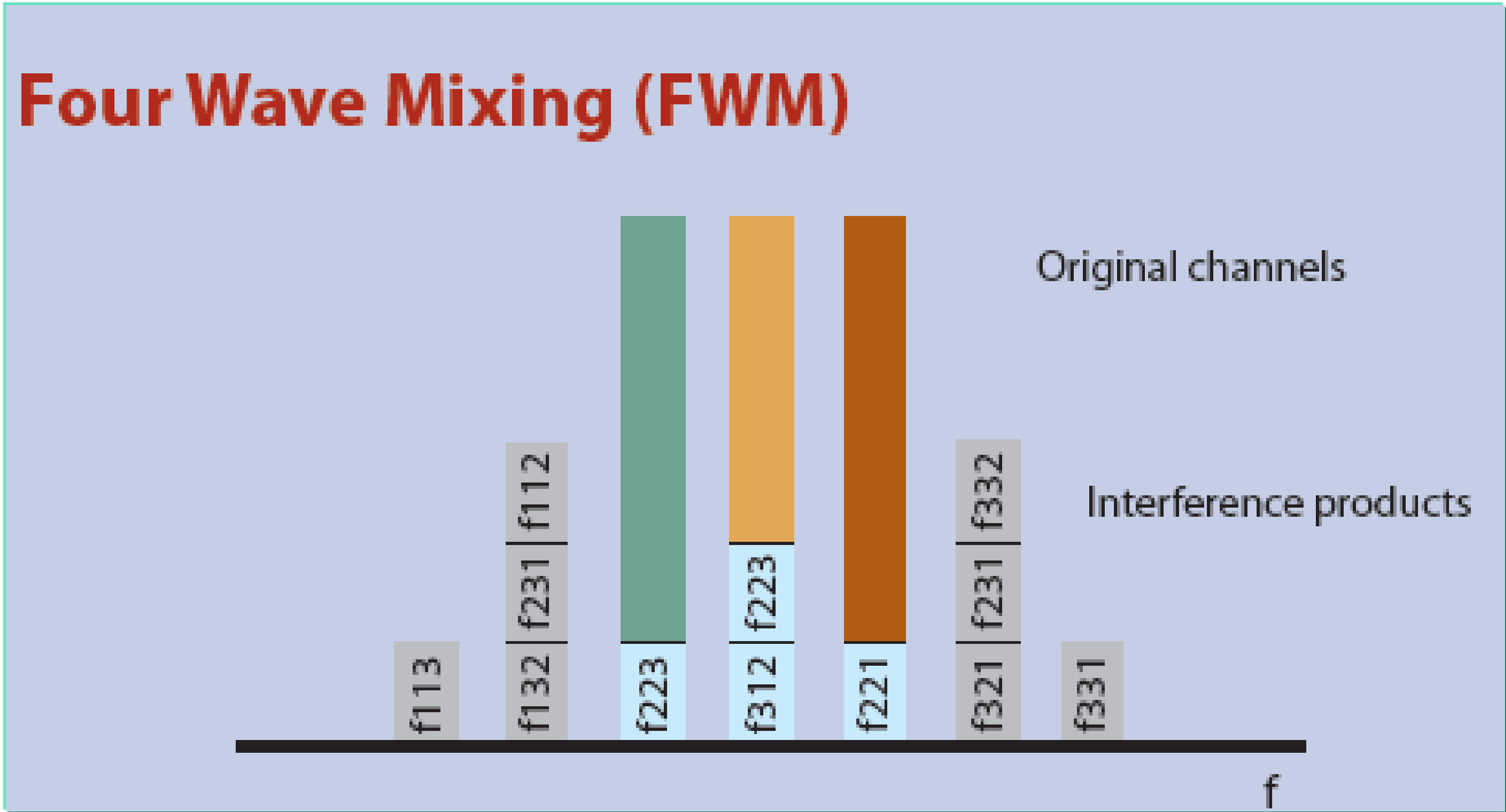
CONCLUSION

FWM leads to inter channel crosstalk in DWDM systems.

It generates additional noise and degrades system performance.

By using non zero dispersion shifted fiber i.e. fiber having 4 ps/nm/km and using unequal spacing among channels FWM effect can be reduced.

On other hand FWM can be used beneficially for parametric amplification, demultiplexing of OTDM channels, wavelength conversion of WDM channels.


Four Wave Mixing (FWM)
Original channels
Interference products
f113
f132
f231
f112
f223
f312
f223
f221
f321
f231
f332
f331
f

This interference phenomenon produces unwanted signals from three frequencies (fxyz = fx + fy − fz) known as ghost channels.

As three channels automatically induce a fourth, the term four wave mixing is used.

FWM is problematic in systems using dispersion-shifted fibers (DSF).

Wavelengths travelling at the same speed at a constant phase over long periods increase the effect of FWM.

Effects:
Power transfer to new signal frequencies (harmonics), channel crosstalk, and bit errors.

Solutions: use of fibers with CD and irregular channel spacing.

Polarization and Its Measurements :

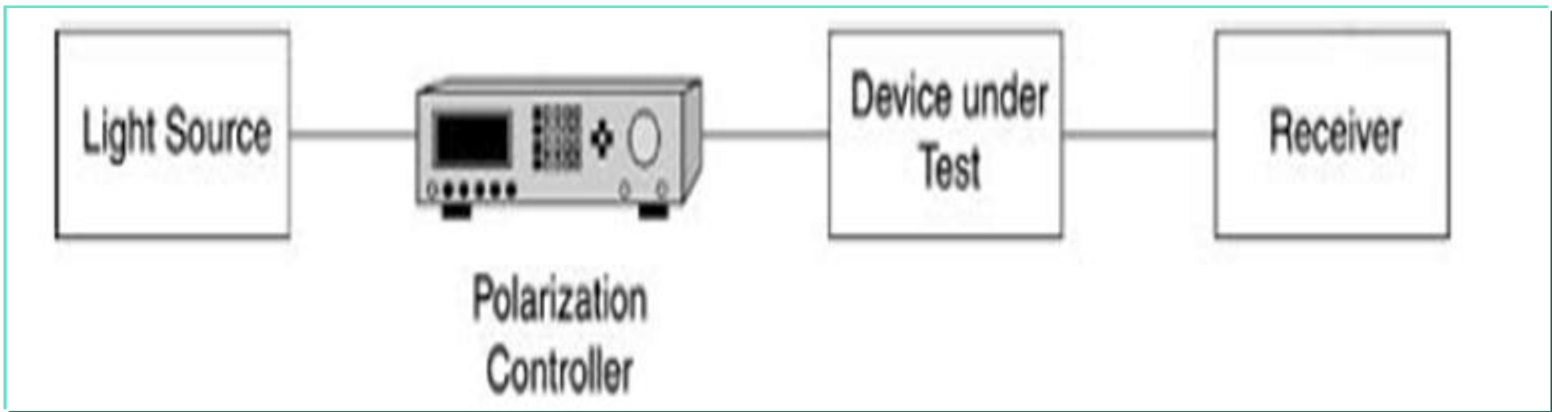
After chromatic dispersion is compensated, the system data rate in an optical system is limited by polarization mode dispersion (PMD).

The polarization dependent loss affects the system by selectively degrading certain *States of polarization (SOPs*).

Polarization dependent loss (PDL) can be measured in several different ways, out of which the *Jones method (measures* PDL from the Jones matrix) and the *Muller matrix method (simulates a test path with four known* SOPs) are most widely used.

A Polarimeter is used to calculate the SOP of input light. (The output of a polarimeter is a normalized Stokes' parameters.)

Figure 9-15 shows a conceptual setup to measure the polarization dependent loss of the device under test.



Polarisation controller(Reproduced with Permission, courtesy of Agilent Technologies,Inc.

Polarization dependent loss can be defined –as the difference in the maximum and minimum variation in loss (transmission/insertion) of an optical device over all states of polarization (SOP) and is expressed in dB.

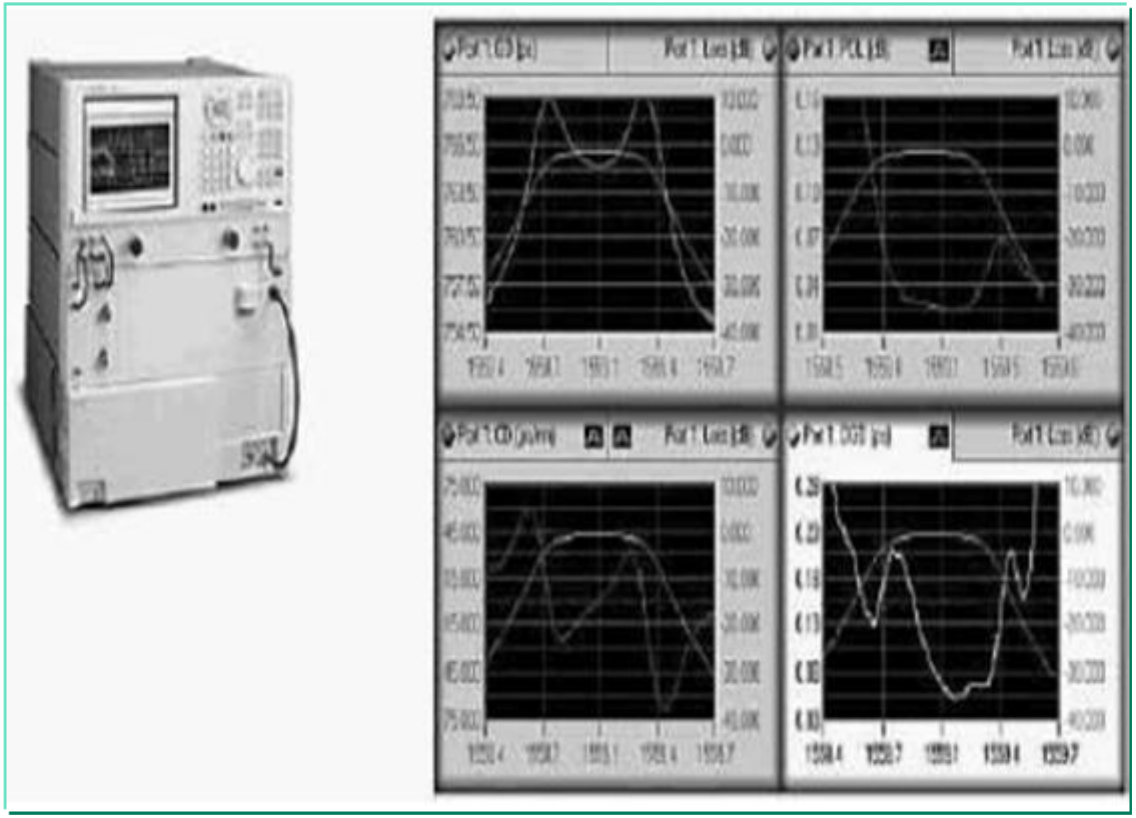
A Typical PDL for an optical connector is less than 0.05 dB and varies from component to component.

The complete polarization characterization of optical signals and components can be accomplished using a polarization analyzer.

Chromatic dispersion can be measured using optical dispersion analyzers.

NOTE-- Modern analyzers can *simultaneously measure* chromatic dispersion, polarization mode dispersion and polarization dependent loss.

The Agilent 86038A Optical Dispersion Analyzer (ODA) (shown in Figure 9-16) can simultaneously measure CD, PMD, group delay, insertion loss, and PDL with a single connection.



Agilent 86038A Can Be Used to Measure CD, PMD, PDL,

Group Delay, and Insertion Loss (Reproduced with Permission, Courtesy of Agilent Technologies, Inc.)

What is crosstalk ?

The term crosstalk refers to any phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel.

Crosstalk is usually caused by –

1. Undesired Capacitive
2. Inductive or
3. Conductive Coupling from one circuit or part of a circuit to another.

Crosstalk **occurs** in devices that filter and Separate Wavelengths.

A small proportion of the optical power that should have ended up in a particular channel (on a particular filter output) actually ends up in an adjacent (or another) channel.

Crosstalk is critically important in WDM systems.

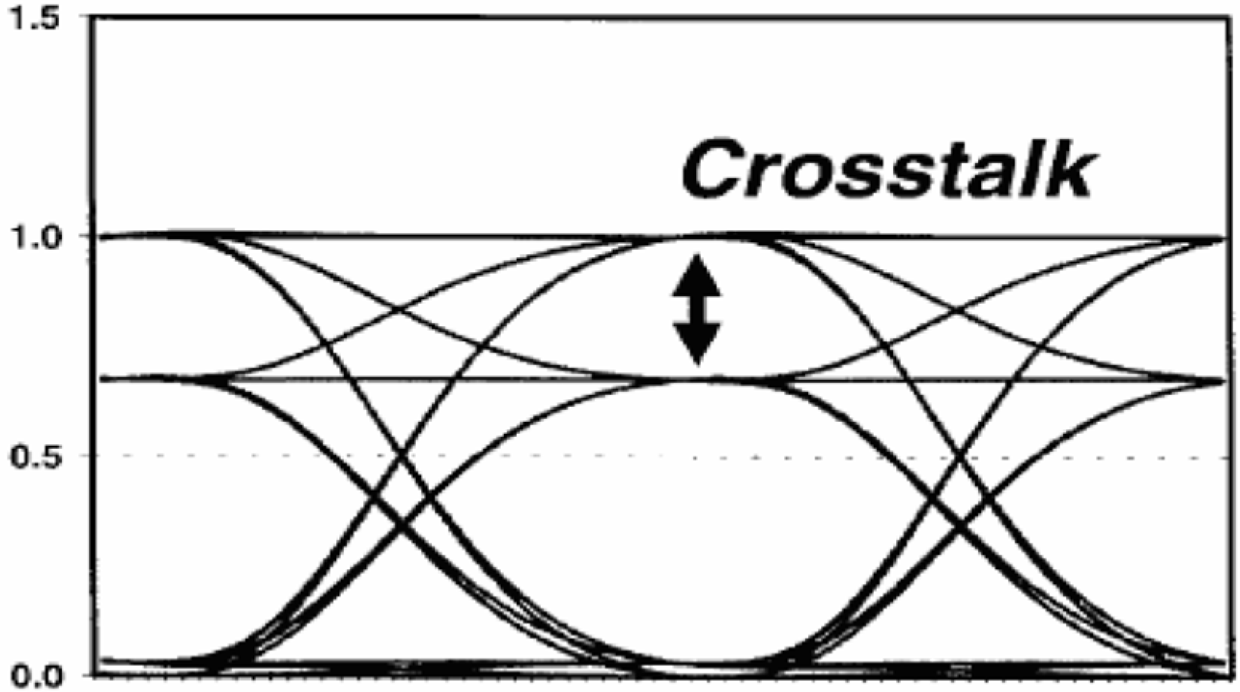
When signals from one channel arrive in another they become noise in the other channel. This can have serious effects on the signal-to-noise ratio and hence on the error rate of the system.

Crosstalk is usually quoted as the “worst case” condition.

This is where the signal in one channel is right at the edge of its allowed band.

Crosstalk is quoted as the loss in dB between the input level of the signal and its (unwanted) signal strength in the adjacent channel.

A figure of 30 dB is widely considered to be an acceptable level for most systems.



Crosstalk in DWDM System

Sources of crosstalk:

- Coherent crosstalk
- Non Coherent crosstalk
- Crosstalk due to filtering
- Linear crosstalk
- Non-linear crosstalk

Coherent Crosstalk

The crosstalk is called coherent crosstalk if the total crosstalk is dominated by this beat.
It is seen that coherent crosstalk is less harmful to system performance than incoherent crosstalk.

Non Coherent Crosstalk

If this beat term is very small compared with the total crosstalk, it is called incoherent. This difference will be illustrated hereafter.

Linear Crosstalk :

- Space switches crosstalk
- Homo wavelength crosstalk
- Hetero wavelength crosstalk

Both arises due to non-ideal wavelength filtering, occurring in multiplexer, Demultiplexers, filter and space switches.

Non-linear Crosstalk :

- Four wave mixing: Wave mixing gives rise of new frequency.
- Cross phase modulation: Intensity dependent refractive index.
- Scattering: Transfer of power between propagation modes.

Space switches crosstalk :

In a N x N switch, there are N^2 combination of cross points which will introduce crosstalk

- Intra-band crosstalk
- Inter-band crosstalk

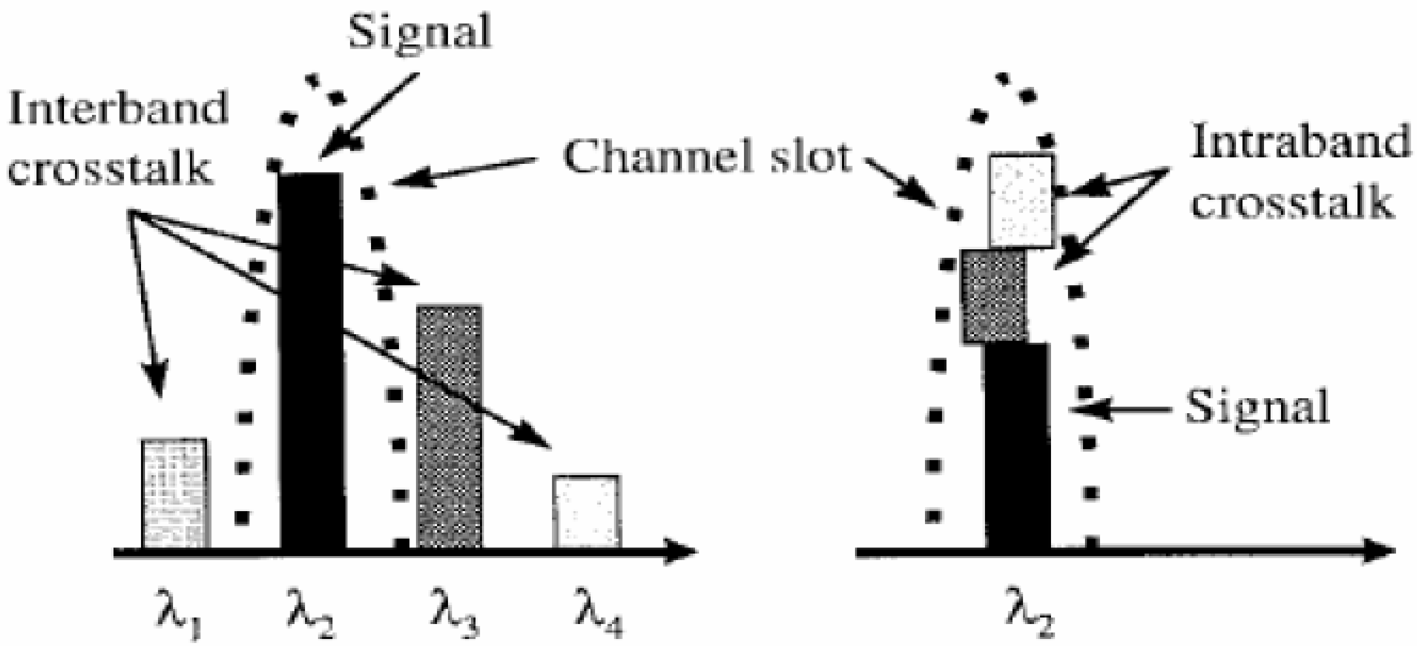


Figure2.5: Interband Crosstalk and Intraband Crosstalk

Crosstalk point of the path will introduce crosstalk since it involve the same wavelength transverse of path may occur randomly.

Blocking may occur if two wavelengths transverse to the same destination receiver

Homo wavelength Crosstalk

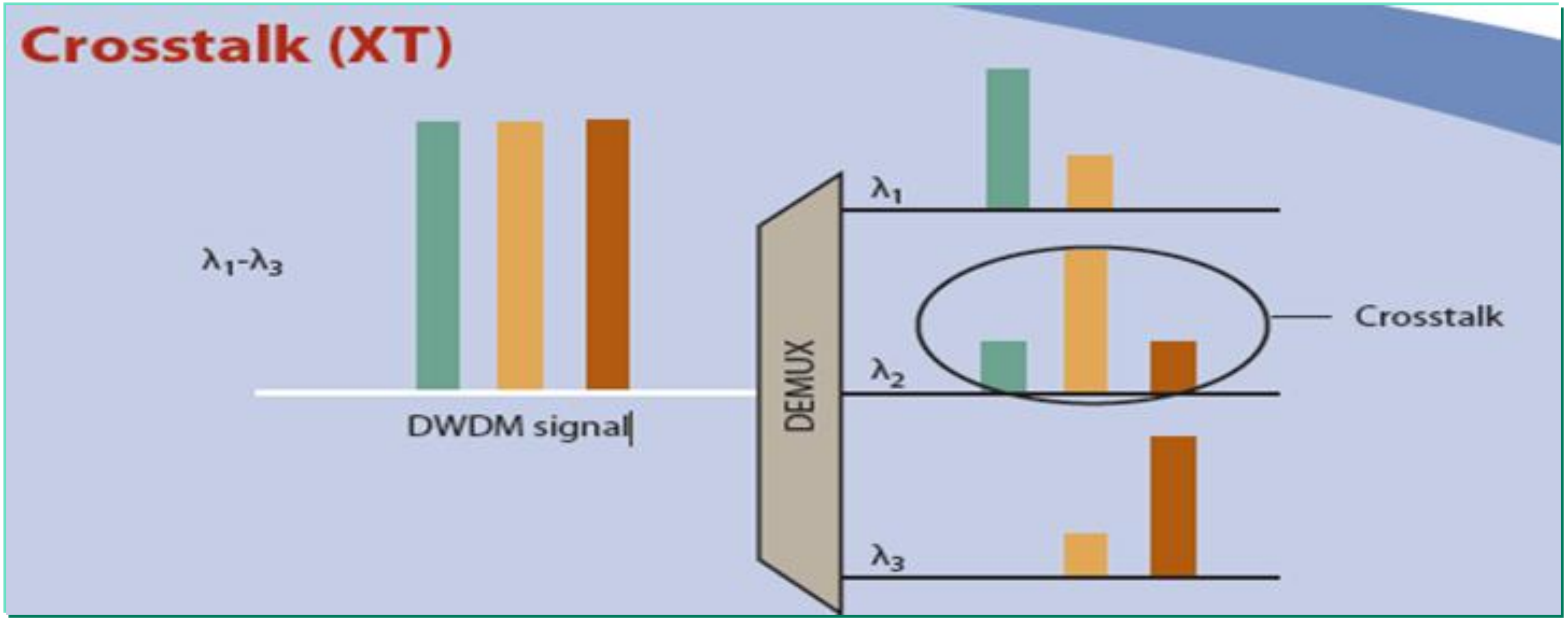
Different fiber route and each channel occupy the same wavelength as the desired signal.

Crosstalk element occupy the same frequency as the desired signal, thus can not be removed once coupled and accumulate through the network.

Crosstalk element will beat with signal and results in complex impairment showing a serious limitation to the system performance.

Heterowavelength Crosstalk : Same fiber route but each channel operating at different wavelength.

- Note that secondary crosstalk element is negated(ie, Nullified).



Crosstalk occurs in devices that filter and separate wavelengths.

A Proportion of optical power intended for a specific channel is found in an adjacent or different channel.

Effects:

Generation of additional noise affecting optical signal to noise ratios (OSNR), leading to bit errors.

Solutions: use appropriate optical channel spacing, for example 0.4 nm → 10 Gbps.

The main terms that describe the performance of optical passive components are discussed here.

The measurements of these parameters are important to evaluate total end-to-end system or network performance :

Nominal wavelength— This is the wavelength for which the system is designed to operate.

DWDM systems have more than one nominal operating wavelength.

Channel spacing determines the wavelength spacing of the nominal wavelength(s).

The ITU proposed standard is followed.)

Peak wavelength— This is the wavelength measure at the output of an optical device with the minimum loss between the input and output (refer to Figure 9-17).

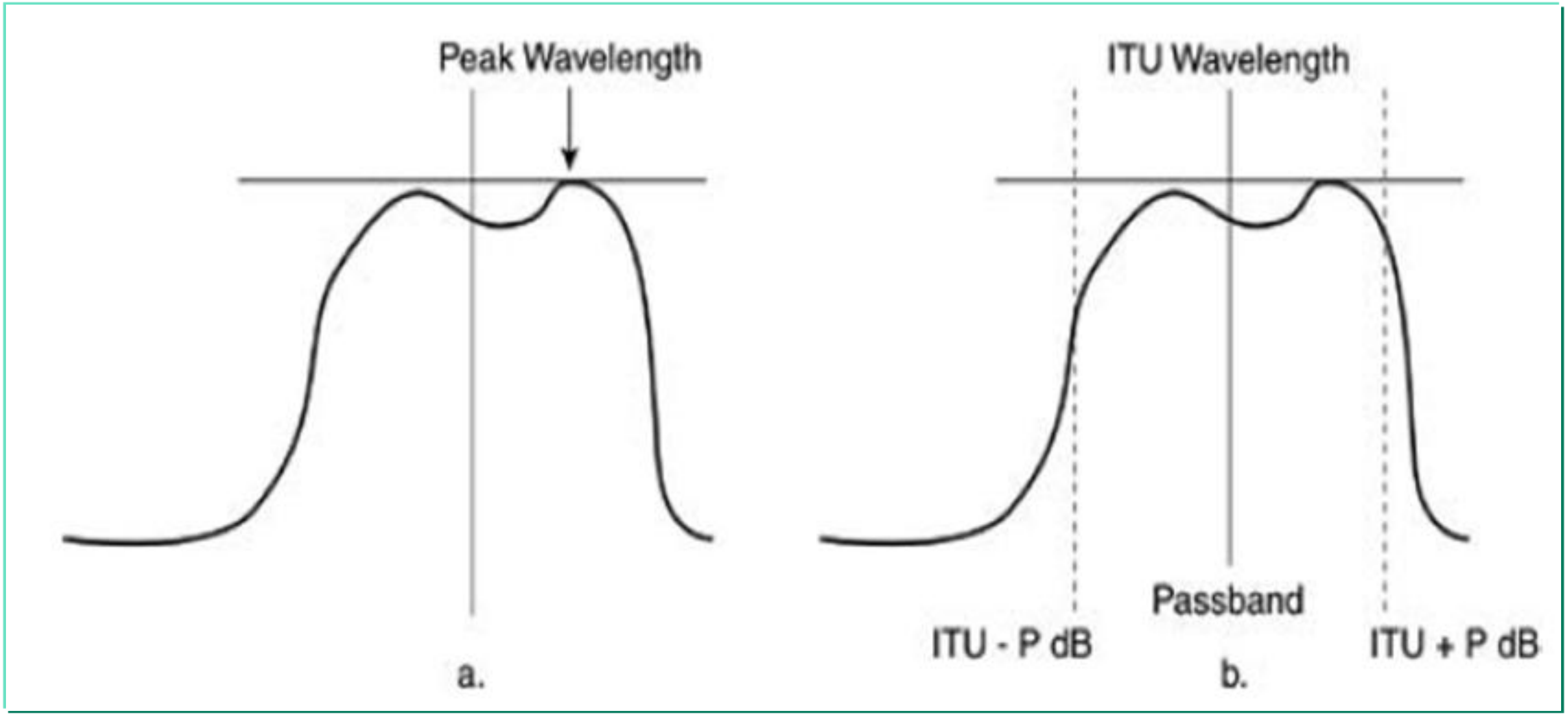


Figure 9-17- (a) Peak Wavelength, (b) Pass Band

Mean centre wavelength- This is the mean value of the wavelength measured at the edges of the Band. (Band Edges are the wavelengths below 1 dB peak).

In ideal cases, nominal wavelength should be the Same.

Bandwidth(BW)- This is the width of a fiber at a specified level below the maximum Peak.

Pass band- This is the reference point upon which measurements are taken. It refers to the useable operating bandwidth and is always in reference to ITU-defined wavelengths.

If a pass band is expressed as P, then the pass band is mean central wavelength+P and mean central wavelength (refer to figure 9-17b).

Pass band shape- This is the shape of the spectral response within the pass band.
Flat response, Gaussian response and Lorentzian response are the three most commonly known Response Types.

Insertion Loss- This is the difference in power at the input and the output of the device under test. It is usually expressed in decibels.(This is per channel loss on a DWDM system)

Cross-Talk – This specifies how much power is received from the adjacent channels.
It is the worst case difference between the minimum inband power of the channel under test into an adjacent channel passband and the maxmimum insertion loss within the passband of the channel under test.

Return Loss- It is the ratio of incident power and the reflected power and can also depend on the wavelength and it refers to the portion of the original input power that is reflected back.

PDL- This is difference in the maximum and minimum variation in the loss(transmission/insertion) of an optical device over all SOPs and expressed in decibels.
PDL also adds the Insertion loss and crosstalk of the device.

Best and worst case loss- If we consider all previously defined parameters , there will be a combination of wavelength and state of polarization, where the loss of the device under test reaches its maximum and minimum.

This maxima and minima represents the best and worst case losses.

An eye pattern technique is used to analyze signals and verify that the signals have enough quality to support the communication system.

This method has long been used in digital copper transmission systems to evaluate performance.

The same technique is used now in optical systems to analyze the effects of waveform in fiber-optic transmission systems.

The eye diagram measurements are done in a time domain and displayed on an oscilloscope (sampling oscilloscope).

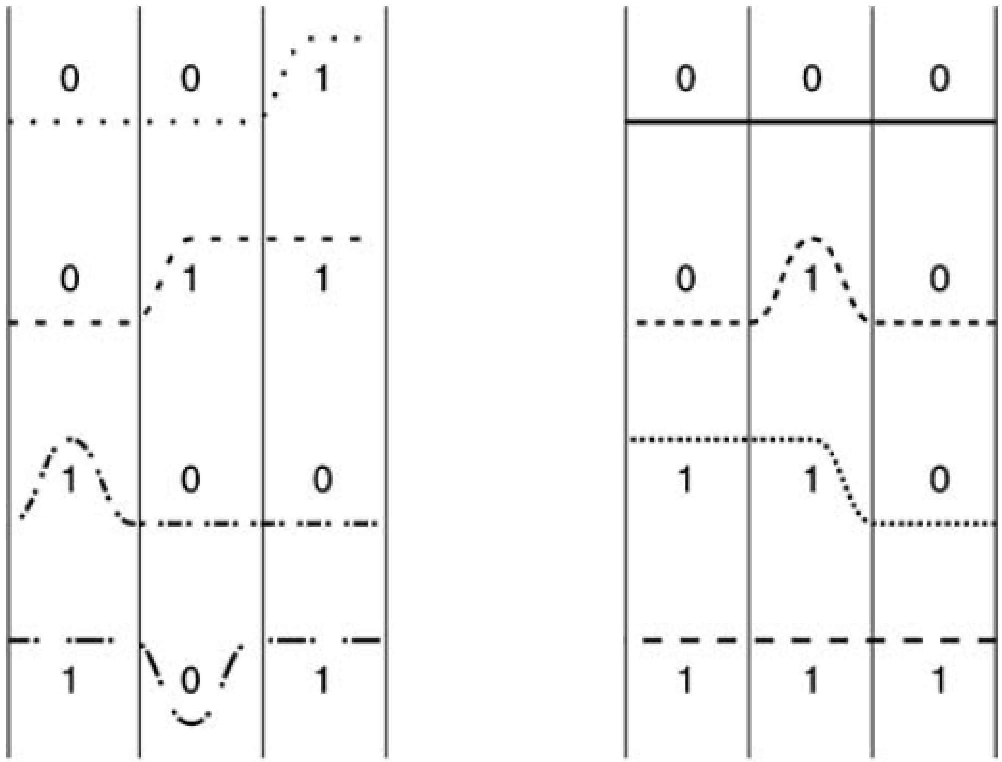
The eye pattern is constructed by superimposing the various bit sequences on top of each other.

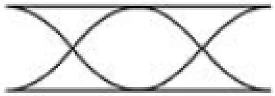
Consider all eight possible combinations of 3-bit sequences :
000, 001, 010, 011, 100, 101, 110, and 111 (see Figure 9-25).

If we superimpose all the combinations and display them on an oscilloscope, we get an eye diagram or eye pattern, as shown in Figure 9-25.

An eye pattern gives us information about the signal distortion, pulse rise time, and jitter, and also helps us calculate extinction ratio, Q factor, and laser chirp.

Figure 9-25. Formation of Eye Diagram





Eye Pattern

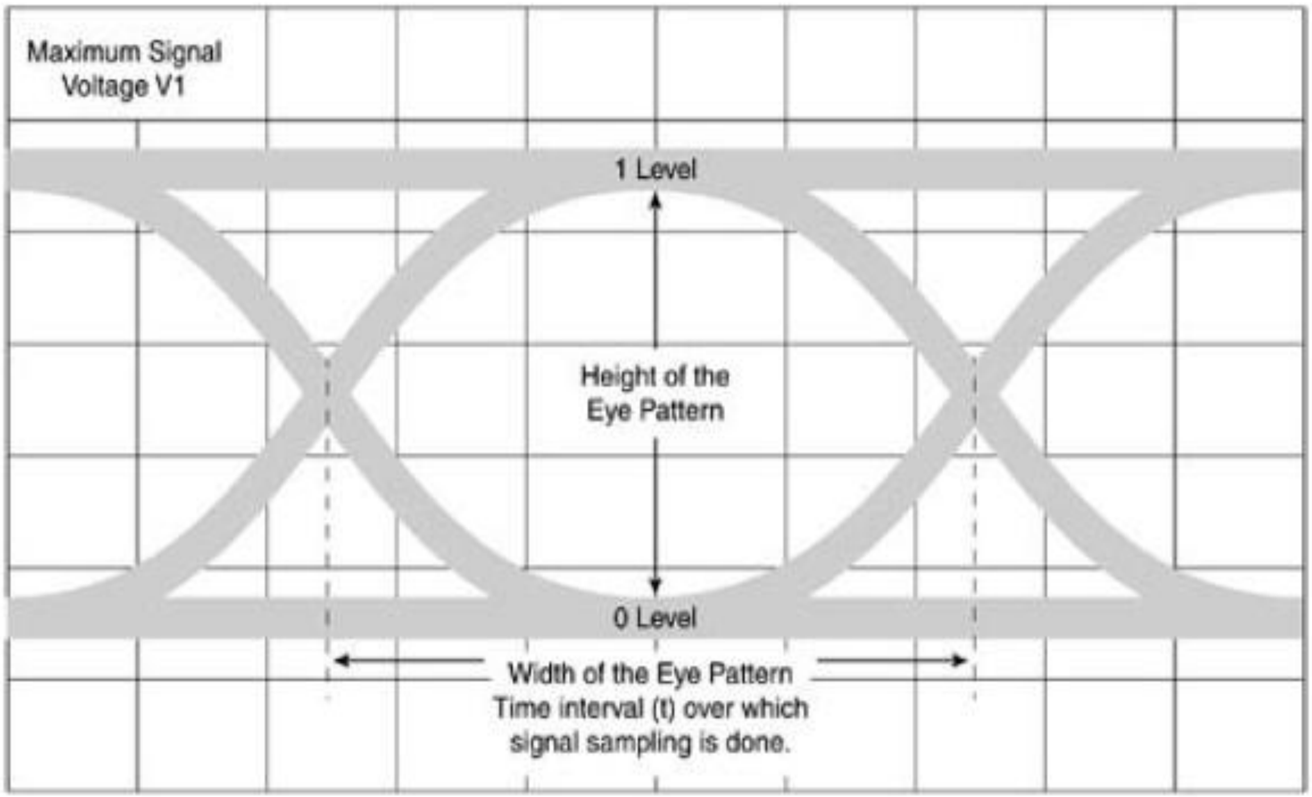
An eye diagram shows a relative performance of the signal.

The horizontal and vertical openings of the eye provide valuable information about the ability of the receiver to detect a 1 bit and a 0 bit correctly.

Figure 9-26 shows the characteristics of the eye diagram.

The vertical *eye opening* (height) shows the ability to distinguish between a 1 and 0 bit, and the width or the horizontal opening gives the time period over which the signal can be sampled without any errors.

Figure 9-26. Eye Pattern of Optical Signal as Viewed Using Sampling Oscilloscope



For a good transmission system, the eye opening should be as wide and open as possible.

The eye diagram also displays information such as maximum signal voltage, rise and decay time of pulse, and so on.

The extinction ratio *(ratio of a 1 signal level to a 0 signal level) and* Q factor *(ratio of peak-to peak* signal strength to total noise in electrical domain) are also calculated from eye diagrams.

To determine whether a transmitter is conforming to the standards and is capable of error-free transmissions, the eye diagram is tested for correct shape (eye mask test) and proper extinction ratio.

A basic setup for measuring an eye pattern is shown in Figure 9-27.

Because data is random in nature, the best approach is to generate a random sequence of data.

A pseudo-random binary sequence (PRBS) generator is used to generate data for test purposes.

A PRBS can generate data patterns o 2^N x 1, where N can be any integer.

Typical values of N can be 7,9,13, and 31

After the limit is reached, the data sequence repeats.

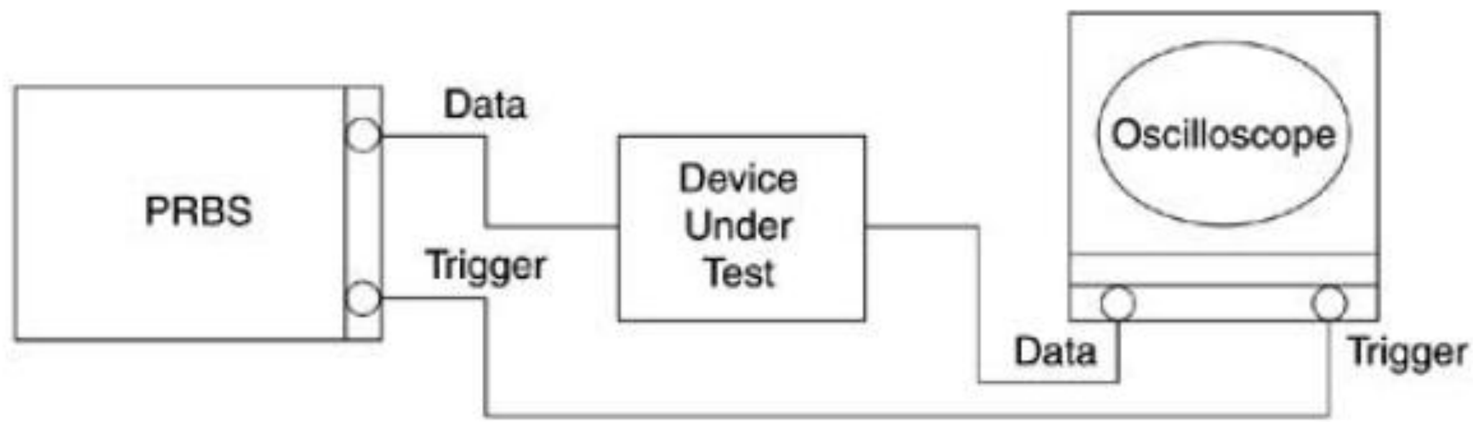


Figure 9-27. Typical Setup for Viewing Eye Pattern

A Typical setup for measuring eye pattern is shown in Figure 9-27.

In this setup, the method of triggering an analyzer has an impact on how the data will be displayed.

The ideal approach is to use the clock signal that is synchronized with data.

Data can be used as a trigger if this clock signal is unavailable.

During the jitter measurements, triggering using the clock source is more accurate than using data.

Jitter is the variation in the location in the time of the rising and falling edge of the signal.

In the eye diagram, this is shown as the thickness (spread) of the crossing point.

(In the photonic layer, jitter accumulation is not a primary verification parameter as compared to the SONET/SDH and Gigabit [Layer 2] verifications.)

To measure optical signals and to display the eye diagram, an optical-to-electrical conversion is needed.

Such a device is used to emulate the effect of an optical oscilloscope.

Because the analysis is done in a wide range of frequencies, the frequency response of the instrument used to analyze this is important.

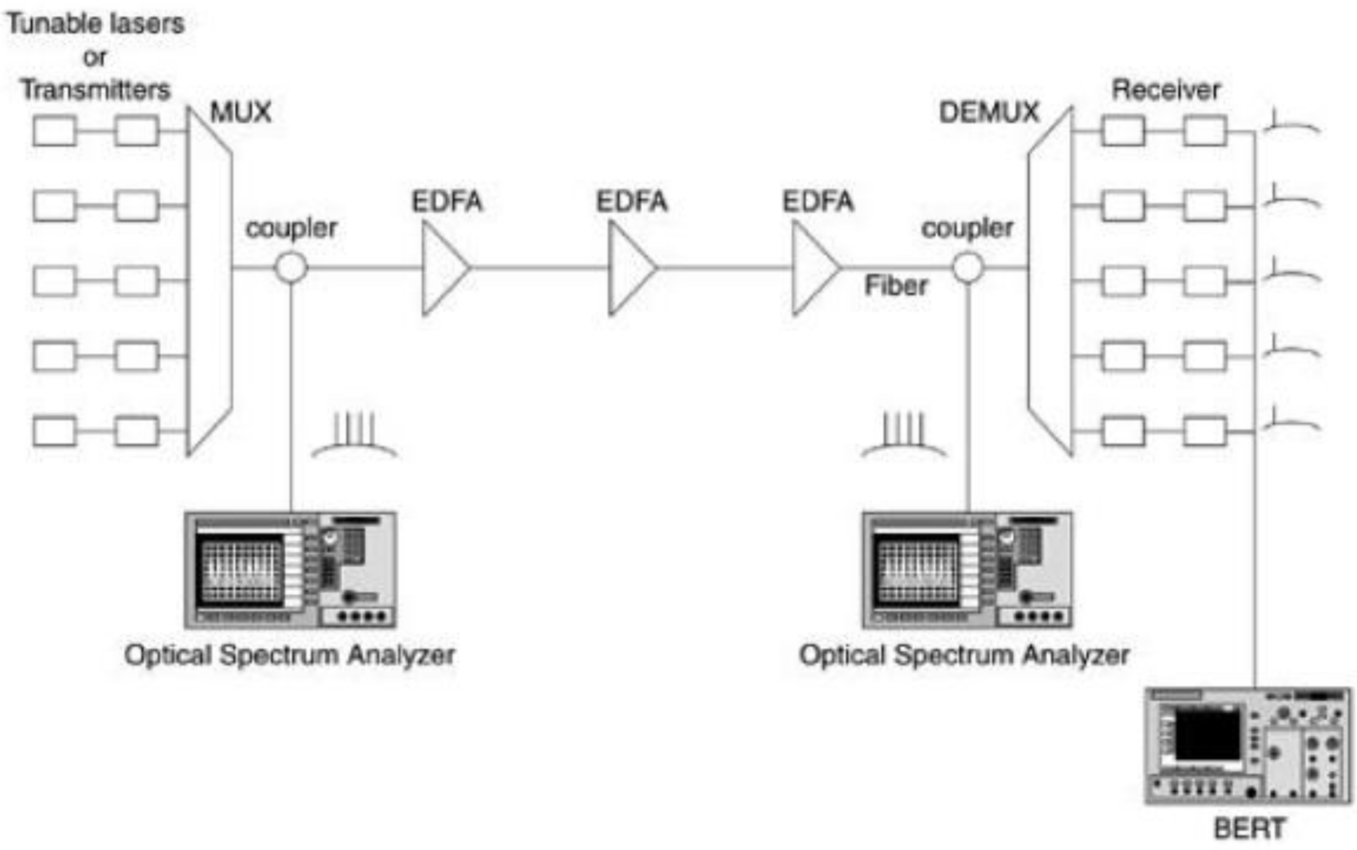
A reasonable combination of frequency, bandwidth, and noise characteristics are essential for accurate display of optical signals in an oscilloscope.

A complete point-to-point DWDM system that includes the transport units, multiplexer/de multiplexer, EDFA, and cables is shown in Figure 9-32.

The testing of this system ensures that the whole system works and conforms with margin requirements (based on system design parameters) before it can carry live traffic.

The deployment of the system is usually stage-by-stage; in other words, the WDM system is never fully loaded initially; rather, channels are added according to the requirement.

Figure 9-32. WDM End-to-End Testing



WDM Link Acceptance Testing

Optical spectrum analyzers are employed to analyze each wavelength that is used in the system.

A power meter can also be used in this case, depending on the level of analysis.

A bit analyzer is used to analyze errors in the system.

WDM Provisioning Test

The following procedure simulates the provisioning exercise to verify whether the system is behaving according to the specifications:

1. Add a channel .
2. Check to ensure that all existing channels indicated zero errors when the channel was added.
3. Measure the tilt, power level, and OSNR using an OSA as each channel is configured.

NOTE : Repeat this process until all wavelengths are operational.

WDM Stress Test : The following procedure simulates the WDM stress test to verify the system is behaving according to the specifications :

- **Start the BER test.**
- **Check the power, tilt, and OSNR using the OSA.**
- **Check the BER performance**

Repeat until the system margins have been verified(BER vs. OSNR)

Conformance means -whether a product or system meets some specified standard.

A typical optical fiber network is composed of many passive and active components working in conjunction to form a complete communication system where the performance characteristic of each component (subsystem) affects the total performance of the entire system.

So, the system engineer needs to know the exact characteristics of the components to design the smooth system such as :

1. *The Attenuation and dispersion characteristics of a fiber change during the installation Phase.*
2. *Limit the maximum distance ,and*
3. *Bandwidth of the fiber.*
4. *Cracks* in fiber wich can degrade the overall performance, whereas breaks in the fiber distort the entire communication channel along with measuring and testing other parameters such as **attenuation, dispersion**, and so on.

Therefore, the test and measurement requirements for system engineers/installers are different from vendor's testing needs.

A System designer needs to know the characteristics of each component in the network. These **passive and active** components should operate in a given optical spectrum without degradation in performance.

Optical network is made up of *Passive* Components as:

1. Splitters
2. Connectors and
3. Couplers.

Active Components are:

1. Transmitter
2. Receiver
3. Optical amplifiers

The operators/installers need to monitor or troubleshoot problems :

1. If there is any break in the fiber
2. If the transmitter is launching enough power into the fiber
3. If Attenuation is well within the specifications and
4. Status of amplifiers in the link

Hence, A System designer/installer needs to measure/test the system during the troubleshooting phase.

A Typical WDM network is shown in Figure 9-1 is composed of :

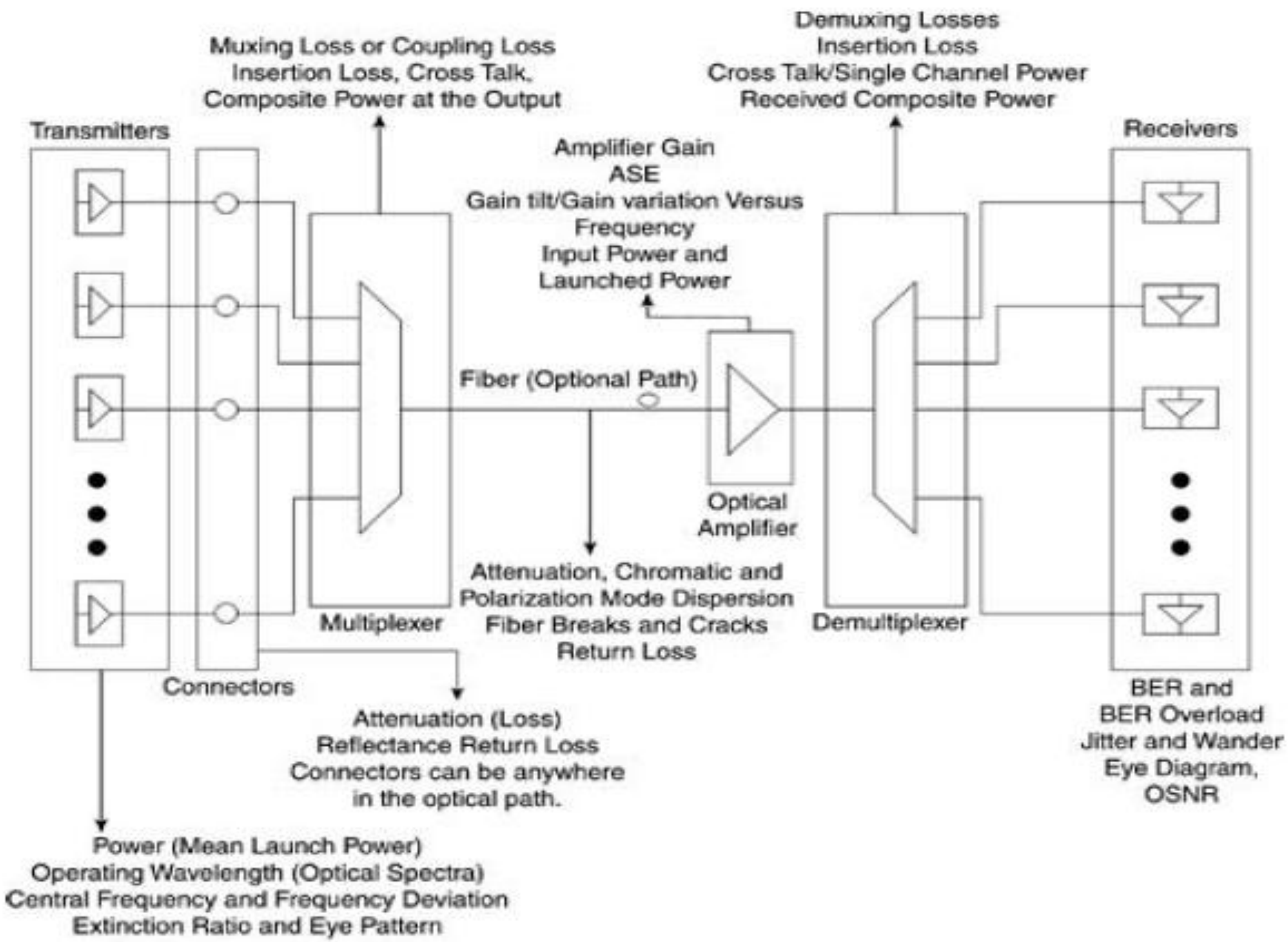
- Transmitters (source/transponders)
- Connectors (to connect different subsystems)
- Splices
- Couplers/multiplexers/demultiplexers
- Optical fibers, amplifiers (EDFAs etc.)

and Receivers like :

- Photodiode/Transponders

Figure 9-1 also shows the characteristics/parameters that need to be tested for performance or Conformance analysis.

Figure 9-1 WDM Network Parameter That Needs to Be Tested


Muxing Loss or Coupling Loss
Insertion Loss, Cross Talk,
Composite Power at the Output
Demuxing Losses
Insertion Loss
Cross Talk/Single Channel Power
Received Composite Power
Transmitters
Receivers
Amplifier Gain
ASE
Gain tilt/Gain variation Versus
Frequency
Input Power and
Launched Power
Fiber (Optional Path)
Optical
Amplifier
Attenuation, Chromatic and
Polarization Mode Dispersion
Fiber Breaks and Cracks
Return Loss
Multiplexer
Demultiplexer
Connectors
Attenuation (Loss)
Reflectance Return Loss
Connectors can be anywhere
in the optical path.
BER and
BER Overload
Jitter and Wander
Eye Diagram,
OSNR
Power (Mean Launch Power)
Operating Wavelength (Optical Spectra)
Central Frequency and Frequency Deviation
Extinction Ratio and Eye Pattern

The whole network is divided into multiple sub-elements, and need to be individually conform to support an *end-to-end system*.

After the performance and conformance of individual network sub-elements are complete, the final step is to perform a **system-level test** or **network-level test**.

This is usually done by testing the **:-**

1. Bit error rate (BER) 10^{-8} to 10^{-12})
2. Receiver sensitivity at
3. Optical Signal-to-Noise Ratio (OSNR)
3. Spectral analysis and
4. Eye-masking analysis.

DWDM Span Engineering

(DWDM Link Design and Power Budget Calculation)

The DWDM system considered here is designed to carry 80 channels in 1550nm band.

The amplifiers used to boost the signal power are fixed gain amplifiers.

The power measurement at each component of DWDM system is calculated separately.

Calculations are accounted to the 80 channel DWDM system and calculations are done with respect to the individual channels.

Insertion loss of the network elements and attenuation through the fiber link are considered during calculation.

The relationship between the optical power at input and output of each component in DWDM system is discussed, and is made feasible to carry all 80 channels without violating the power requirements and constraints for the amplifiers and other components used in the network.

The key to network design is Optical Power Budget, which is the amount of light available to make a fiber optic connection.

The allocation of power losses between optical source and detector is referred to as the power budget.

The power budget with various losses in an optical fiber, as shown in figure 1, is obtained by first determining the optical power emitted by the source, usually expressed in dBm, and subtracting the power (expressed in same units, e.g., dBm) required by the detector to achieve the design quality of performance (Receiver Sensitivity).

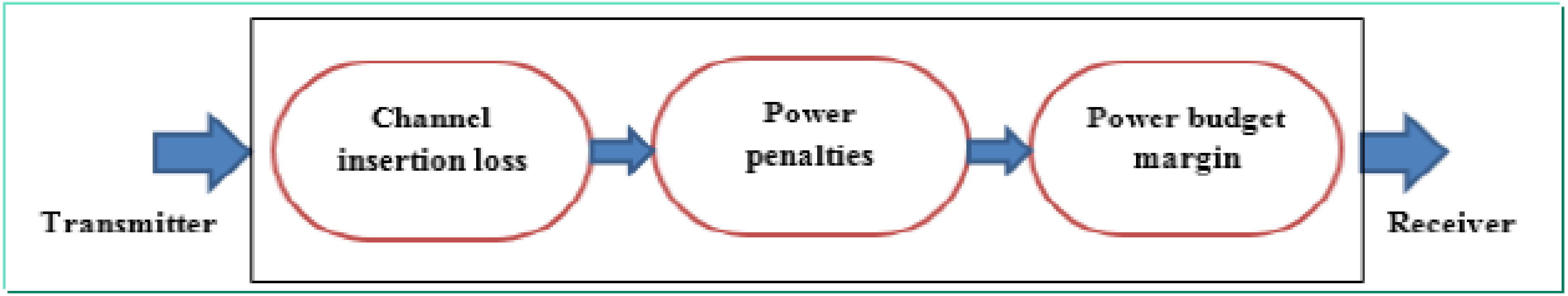


Figure-1. Link Power Budget

Link Power Budget = Min Transmit Power - Min Receiver Sensitivity---(1)

Equation (1) can be used to calculate the link power budget that can be used to decide length of the fiber span such that the loss through the span is manageable to have optimal power value at the receiver.

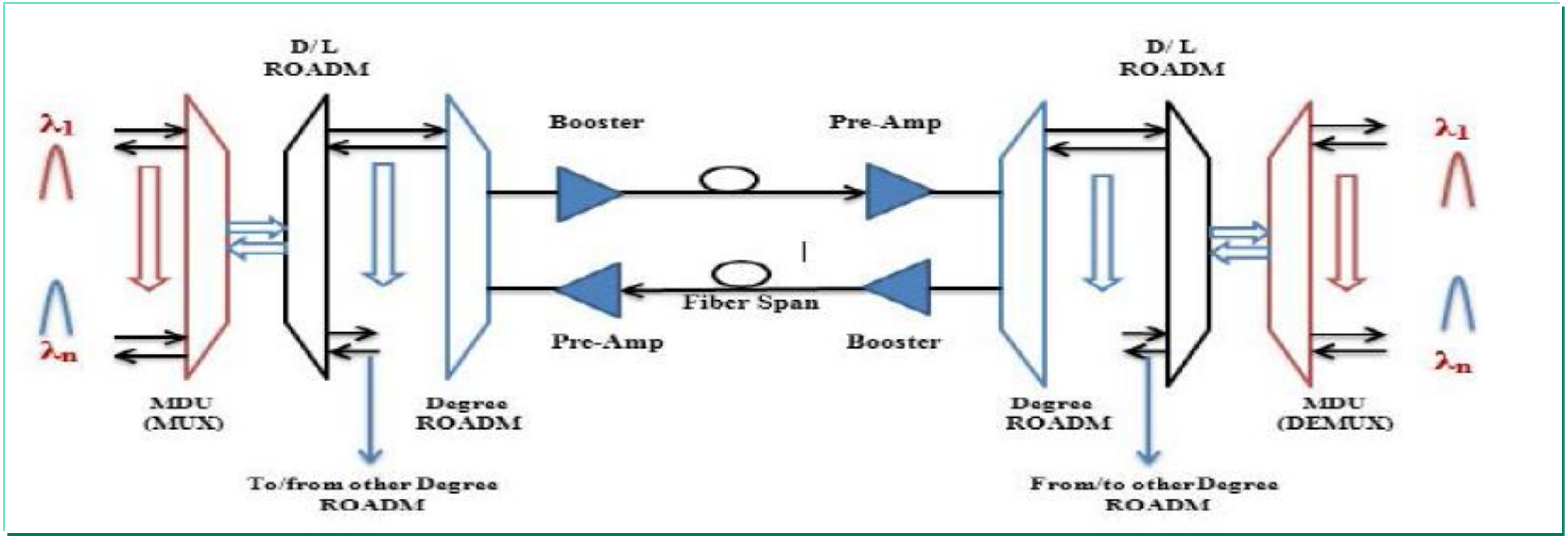


Figure-2.DWDM Link

Another important component in the link design is DCM, which has to be placed at ROADM or EDFA sites to manage dispersion of the signal travelling over longer distance through fiber.

Preferable location of DCM placement is before the EDFA node, because DCMs also add up good amount of insertion loss and EDFAs after DCMs can take care of the losses.

Finally at the receiver end the de-multiplexer part of MDU splits the incoming composite signal into individual wavelengths and feeds to the respective receivers.

A very important point in link power budget is that, the power received at the receiver should be well within the range of receiver sensitivity.

So, MDU, ROADM, Fiber and CDMs are the major part of the network that adds up to the power loss through the link in the form of attenuation and insertion loss, whereas EDFAs are the gain components in the form of Boosters, Line and Pre amplifiers.

Link engineering involves placement of Optical amplifiers (OAs) and DCMs for each fiber link to ensure sufficient minimization of all optical impairments.

A fiber link starts and ends at a central office containing a ROADM site with intermediate sequence of fiber spans with known losses and lengths.

Intermediate endpoints of spans are pass through ROADMs, OAs and DCMs.

The overall goal is to minimize equipment cost and power losses.

This paper focuses on DWDM network design for 80 channels with each channel carrying 10 Gbps of data.

Considering per channel calculations, the output power of an amplifier per channel in an N channel DWDM network is obtained by considering below formula.

Pout (dBm) = Pin (dBm) + Gain (dB) (2)
Pout /ch = Maximum output power – 10*log10 (N) (3)

With N = 80 channels:

Pout /ch = 20 – 10*log10 (80) = 1 dBm.

Per channel output power can be given as:

Pin (dBm) + Gain (dB) = 1 dBm.

Therefore, in 80 channel DWDM link, for single channel calculation the maximum output should be 1 dBm.

In order to maintain 1 dBm output power per channel, the gain has to be adjusted w.r.t the input power of the EDFAs.

And gain should be in the range of 15 to 30 dB with a typical NF of 5.5 dB.

OSNR is an important parameter to be taken into consideration before deciding the placement of the amplifier and setting the gain.

The minimum OSNR value for 10 Gbps transmission is 17 dB.

Lower the input power of an amplifier stage, better is the OSNR.

But this is a trade-off between OSNR improvement and number of amplifier components used throughout the link.

If amplifier is place at a point to have less input power (i.e. at a lesser distance), this will increase the OSNR, but the distance covered will be less, and in order to compensate for the whole span, more amplifiers are needed, which will have reduced input power, but will increase the design cost.

Formula used for OSNR calculation at (i + 1) stage of EDFA is:

$$OSNR_{(i+1)} = \frac{1}{\frac{1}{OSNR(i)} + \frac{NFh\nu\Delta f}{Pin}}$$

In equation ,"NF" is the noise figure of (i + 1th) amplifier. "ν" represents optical frequency (193 THz), "Δf" is the bandwidth (0.1 nm = 12.5 GHz) that measures the noise figure NF and "h" is the Planks Constant (6.626 x 10 -34 J. s).

In this paper cost effective design is considered.

Thus the unnecessary placement of EDFAs is ignored.
The detailed explanation of this scenario is carried out in next section with an example link.

Consider a DWDM link with two ROADM sites at transmitter and receiver ends with an intermediate pass-through ROADM as shown in fig 3.

ROADM sites at Tx and Rx are of degree 2 and pass-through ROADM had degree equal to 4.

Link has two spans with fiber of type SMF having lengths L1 and L2 .

As mentioned earlier, ROADMs are usually accompanied with Booster and Pre amplifiers.

B1 and B2 are Booster amplifiers whereas P1 and P2 are Pre-amplifiers.

Input given to Mux is 0 dBm which is given form the transponder.

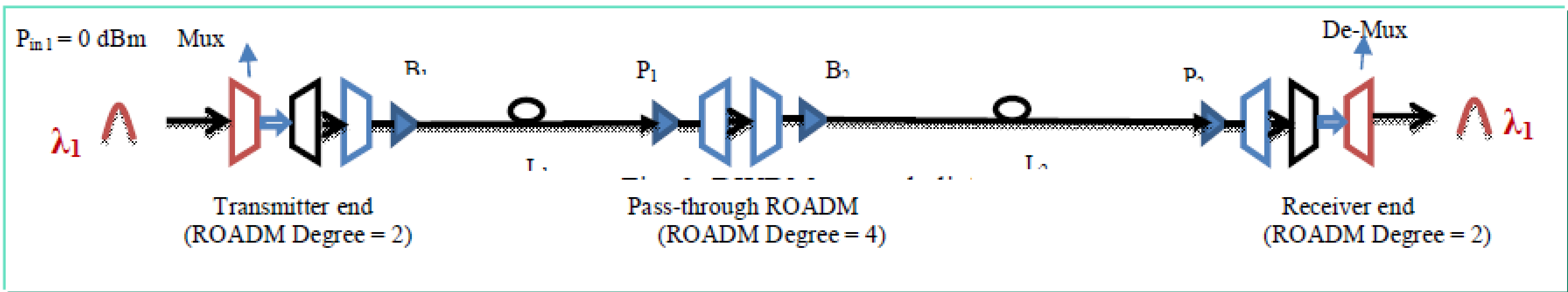


Figure-3.DWDM Link

Let L1 = 80 Km and L2 = 120 Km SMF fiber.

Insertion losses w.r.t MDU, D/L ROADM and Degree ROADM are specified in table 2 and 3.
Fiber Attenuation loss = α x Length
L1 Loss = 0.257 dB/km x 80 km = 22 dB
L2 Loss = 0.275 dB/km x 120 km = 33 dB

B. Dispersion Compensation

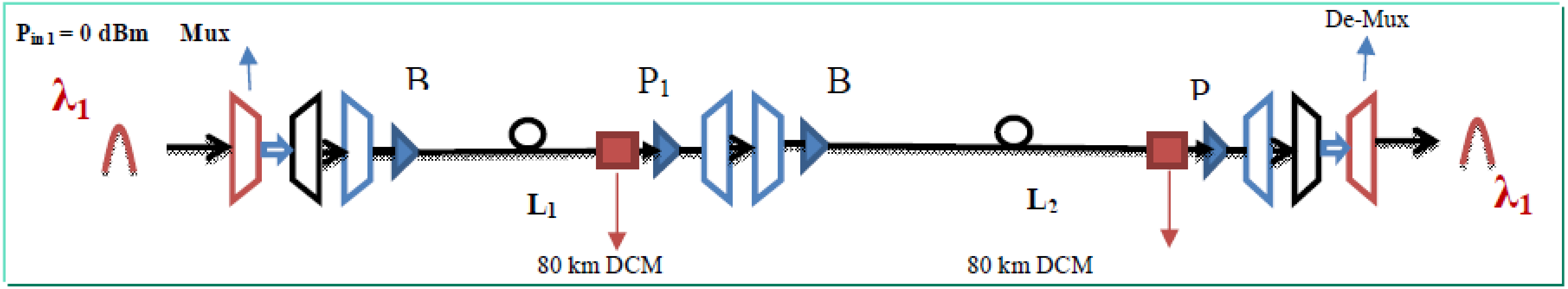
Dispersion = Length x Dispersion coefficient
L1 Dispersion = 80 Km x 17 ps/nm- km = 1360 ps/nm
L2 Dispersion = 120 Km x 17 ps/nm- km = 2040 ps/nm
Total Link Dispersion = 1360 ps/nm + 2040 ps/nm = 3440 ps/nm (> 1020 ps/nm)

Insertion Losses From Add/Drop Port to Common

ROADM Degree	Node Loss Parameters		
	MDU (dB)	Directionless ROADM (dB)	Degree ROADM (dB)
2	14	4	4
4	14	7	7
8	14	7	7

Insertion Losses from Common to Add/Drop Port

ROADM Degree	Node Loss Parameters		
	MDU (dB)	Directionless ROADM (dB)	Degree ROADM (dB)
2	7	7	7
4	7	9	9
8	7	11	11



DWDM Link with DCM Placement

Figure-4.DWDM Link

To compensate for this high dispersion of 3440 ps/nm, an 80 Km DCMs are placed at the end of L1 and. Fig.4. shows link with DCM placement at the end of L1 and L2.

Therefore the dispersion now with DCMs at the receiver node is;

Residual Dispersion = 3440 ps/nm – (2 x 80 km x 17ps/nm-km)
= 680 ps/nm (-510 ps/nm < 680 ps/nm < 1020 ps/nm)

C. EDFA Placement

Placement of EDFA depends on the span loss. Maximum gain for an EDFA is 30 dB, i.e. to have an output power of 1 dBm per channel, minimum input power will be -29 dBm (-29 dBm + 30 dB = 1 dBm). Since B1, B2, P1 and P2 are all EDFAs, their outputs need to be maintained at 1 dBm / ch.

Gain calculation of B1:

B1 I/P power = (Pin1 – MDU Loss – D/L ROADM Loss – Degree ROADM Loss) = 0 – 14 – 4 – 4 = -22 dBm.

Therefore B1 Gain = 23 dB (15 dB < 23 dB < 30 dB)

Gain calculation of P1:

P1 I/P power = B1 O/P power – Span 1 Loss

Span 1 Loss = (L1 Loss + (2 x Connector Loss) + DCM Loss) = 22 + 1 + 4 = 27 dB

P1 I/P power = 1 – 27 = -26 dBm

Therefore P1Gain = 27 dB (15 dB < 27 dB < 30 dB)

Gain calculation of B2:

B2 Input Power = (P1 O/P power – Degree ROADM 1 – Degree ROADM 2) = 1 – 7 – 9 = -15dBm,

Therefore B2 Gain = 16 dB (15 dB < 16 dB < 30 dB).

Gain calculation of P2:

P2 I/P power = B2 O/P power – Span 2 Loss

Span 2 Loss = L2 Loss + (2 x connector Loss) = 33 + 1 = 34 dBm

P2 I/P Power = 1 – 34 = -33 dBm

Therefore P2 Gain = 34 dB (> 30 dB)

By observing the gain value needed for P1 EDFA, it becomes clear that power budget exceeds the limit and an extra Line amplifier is necessary for second span of the link.

Now it becomes important to decide at what point Line amplifier has to be placed.

Placement of amplifier must be such that –

- no more unnecessary line amplifiers must be needed further in the span, and
- OSNR value at the receiver must be good enough and within the limit.

Fig 5. represents second span of the DWDM link split into L11 and L22 on either sides of the Line Amplifier (LA) along with the 80 km DCM at the end of L22.

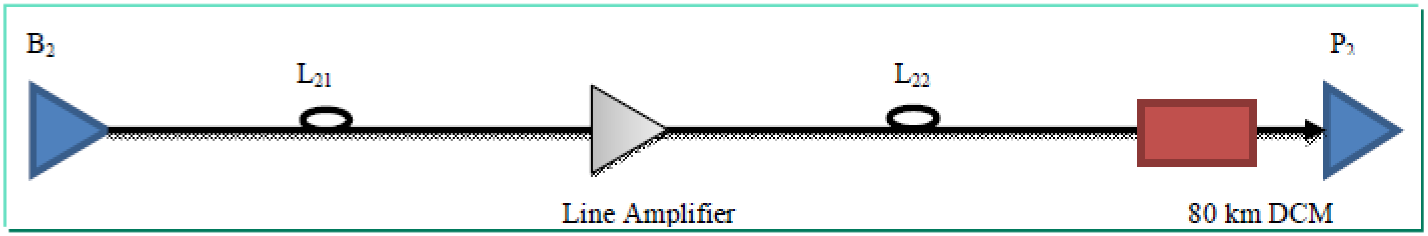


Fig. 5: Span 2 with Line Amplifier

Amplifier is placed at a point where minimum gain can be achieved i.e. 15 db.

This implies;

Line Amp O/P power = Gain – Span Loss (Line Amp) = 1dBm
If Gain = 15 dB, then Line Amp I/P power = 14 dBm
L21 Loss = (LA I/P power – (2 x Connector Loss) + B2 O/P power = 14 – 1 + 1 = 14 dB

Thus,
L22 = L2 – L21 = 120 – 50.9 = 69.1 km

Therefore,

Length L21 = L21 Loss (dB) / α (dB/km) = 14 / 0.275 = 50.9 km
L22 Loss = 69.1 x 0.275 = 19 dB

Total span loss of L22 = L22 Loss + DCM Loss + (2 x Connector Loss) = 19 + 4 + 1 = 24 dB
P2 I/P power = LA O/P power – Total Span Loss of L22 = 1 – 24 = -23 dBm

Thus Gain of P2 = 24 dB (15dB < 24dB < 30dB)

After calculating I/P, O/P and gain power values for EDFA the last step remaining is calculating the input power at the receiving XFP connected to the De-Mux.

I/P to XFP = (P2 O/P power – Degree ROADM Loss – D/L ROADM Loss – MDU Loss)
= 1 – 7 – 7 – 7
= -20 dBm (> -25 dBm).

Complete DWDM link design with the DCM and Line Amplifier placement is shown in figure 6.

Numbers ranging from 1 to 19 are the node names at i/p and o/p of each component in the link.

D. OSNR Measurements:

OSNR calculation is another important criteria to check for the network efficiency.

OSNR should be above 17 dBm for 10 Gbps transmission data rate.

The DWDM Link defined in figure 6 altogether includes 5 EDFAs and 2 DCMs after placement of DCMs and Line Amplifier.

Using the formula from equation (4) OSNR at each amplifier stage has been Calculated.

With all the above work procedure, optimized DWDM link design is obtained with Link power budget calculation at all spans of the Link.

The calculations considered here are calculated for ideal cases, without considering fiber nonlinearities.

A Typical DWDM component set up for multiple wavelength propagation with ROADMs.

DWDM link is an example link considered to describe the DWDM network design and power budget analysis. Fig 4 and 5 show the placement of DCM and EDFAs in the link with proper compensation for dispersion and power loss respectively.

Fig 6. gives a complete view of modified example link with all the required component placement.

Table 6 (Shown at the end)gives detailed result values for Power, OSNR and Dispersion at each node point.

The power calculation results are obtained for single channel.

The design is optimized such that the system can be upgraded to support 80 number of wavelengths through a single fiber with a capacity of 10 Gbps/channel.

Complete DWDM link design with the DCM and Line Amplifier placement .

Numbers ranging from 1 to 19 are the node names at i/p and o/p of each component in the link.

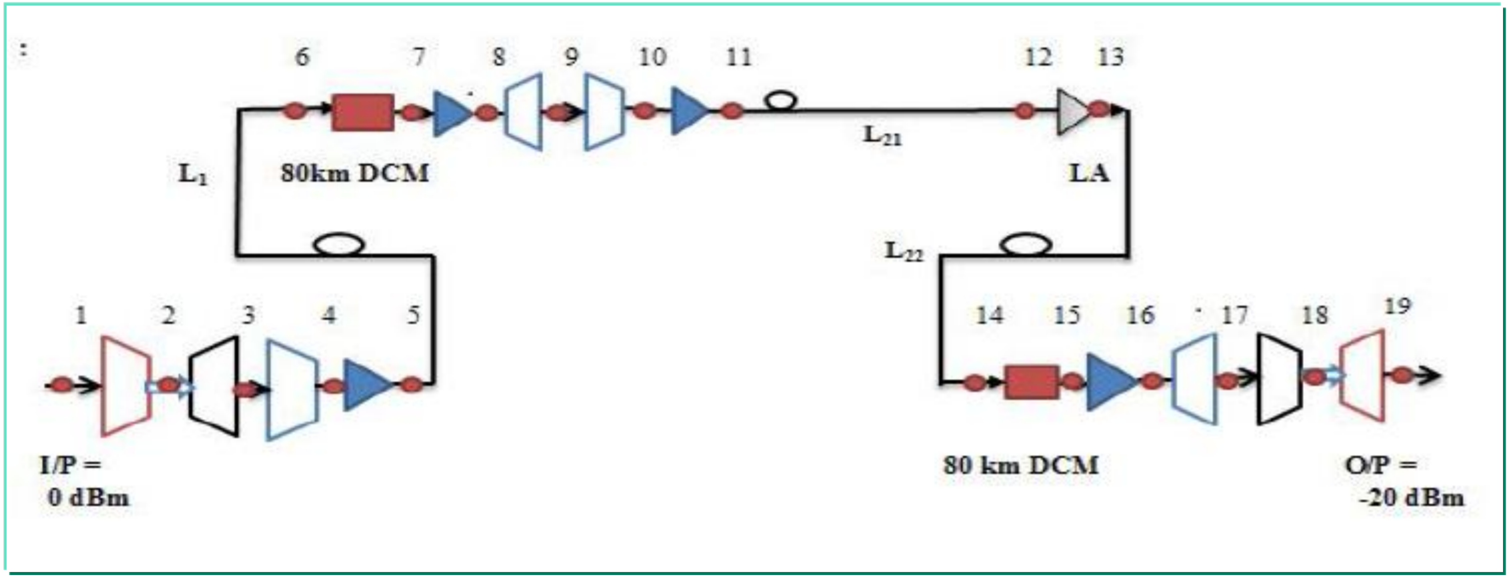


Fig 6: DWDM Link with DCM and EDFA Placement

Node Numbers	Power (dBm)	OSNR (dB)	Dispersion (ps/nm)
1	0	NA	0
2	-14	NA	0
3	-18	NA	0
4	-22	NA	0
5	1	30.4628	0
6	-22	30.4628	1360
7	-26	30.4628	0
8	1	25	0
9	-6	25	0
10	-15	25	0
11	1	24.766	0
12	-14	24.766	865.3
13	1	24.584	865.3
14	-19	24.584	2040
15	-23	24.584	680
16	1	23.361	680
17	-6	23.361	680
18	-13	23.361	680
19	-20	23.361	680

Table.6. Calculation Results For Example DWDM Link With Single Channel

For DWDM network design it is very necessary to obtain optimized power values at the EDFA nodes that are well within the range specified.

Output power at the OAs should correlate to the number of channels passing through them.

Dispersion compensation is also very much necessary so that signal is efficiently detectable at the receiver.

OSNR has to be maintained above 17 dB to obtain improved BER at the receiver.

The design procedure discussed in this paper gives the idea of DWDM link design and power budget calculation.

Procedure followed here gives idealistic results that are independent of power penalties caused due to non-linear effects in the fiber.

The DWDM System is capable of accommodating all the 80 wavelengths, thus upgrading the system capacity.

THANK YOU