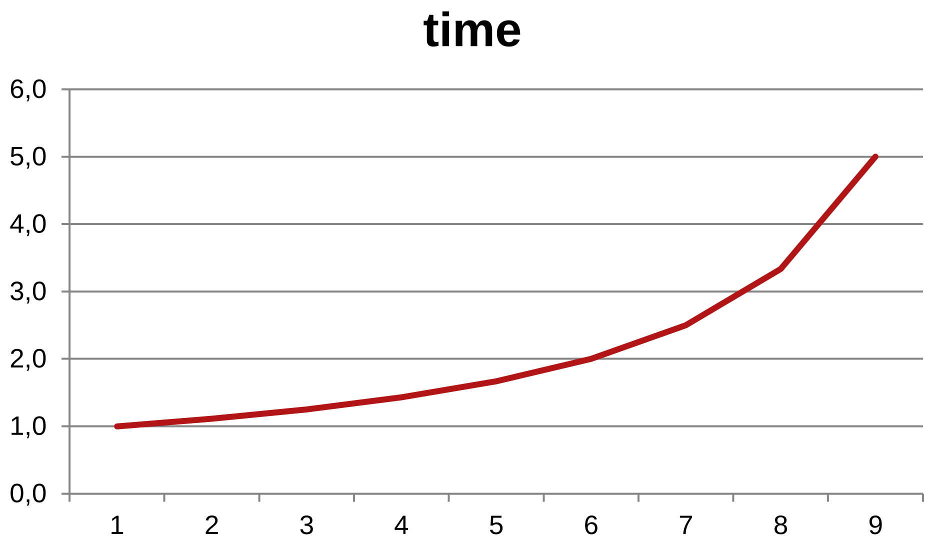
Fiber optics non linear effects

Non linear medium

A medium is non linear when its response is not proportional to excitation

Example: time to transit an avenue in function of traffic demand



In optical fibers we speak of non-linearities related mainly to the optical power In the fiber

A Fibra óptica é um meio linear ?

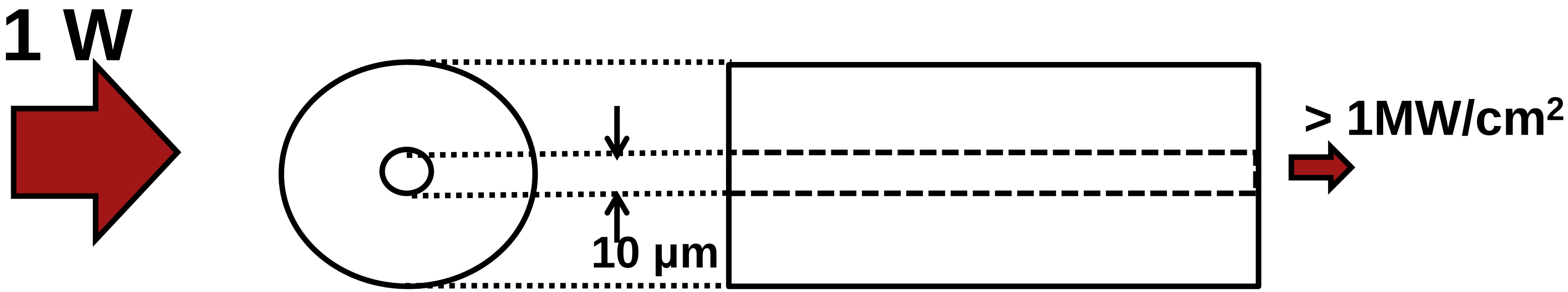
Sim, para sinais de baixa potência.

Deve haver uma limitação para a potência que pode se transmitida por uma fibra óptica.

A distância e a taxa de bits são fatores que implicam em maior potência óptica.

Em consequência é preciso levar em consideração os efeitos não lineares em sistemas ópticos de alta desempenho.

High power coupling



Non linear effects are power and distance dependents. The longer the fiber, the more the non linear effects adds up.

Fiber parameters subject to non- linearities are attenuation and refractive index.

Non linear effects

Single channel effects: the signal in one channel affects itself, independently of other channels

Self-Phase Modulation (SPM) (índice de refração)

Stimulated Brillouin Scattering (SBS) (atenuação)

Multiple channel effects

Four Wave Mixing (FWM) (índice de refração)

Cross Phase Modulation (XPM) (índice de refração)

Stimulated Raman Scattering (SRS) (atenuação)

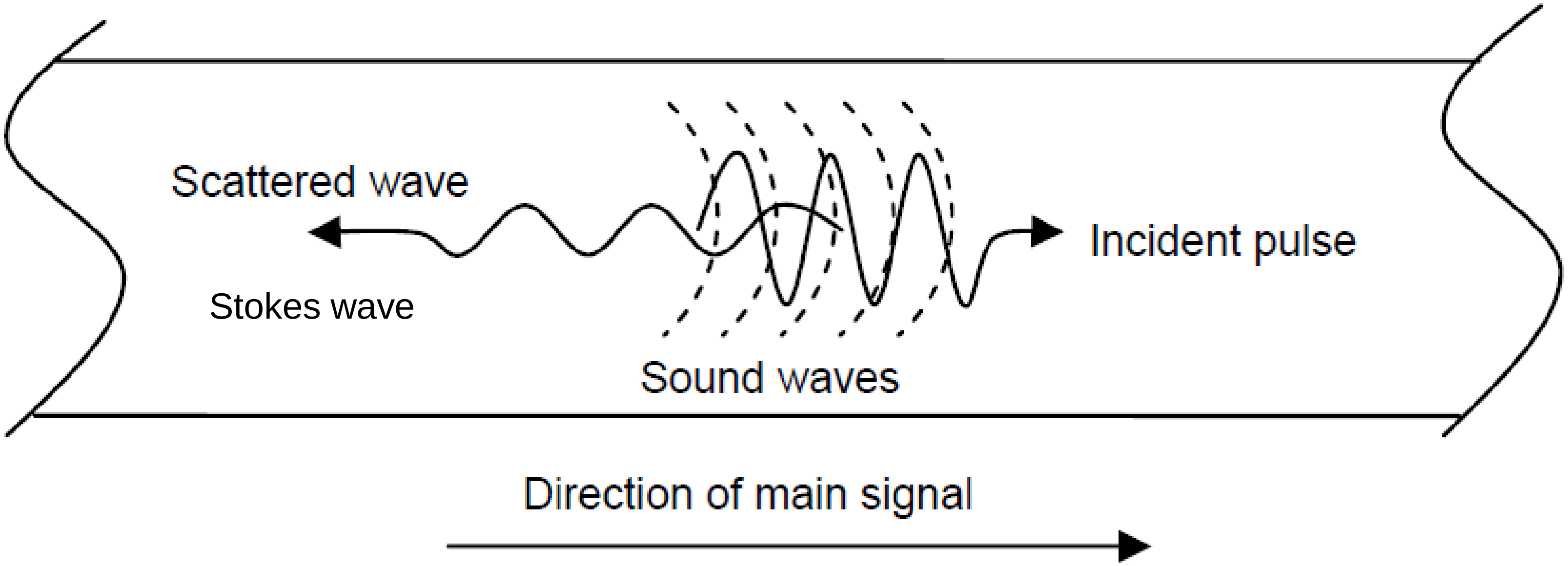
Stimulated Brillouin Scattering (SBS)

This is a phenomenum of high frequency waves being scattered by low frequency waves (mechanical vibrations).

SBS was analysed by Brillouin, a french physics that emigrated to USA during Second World War.

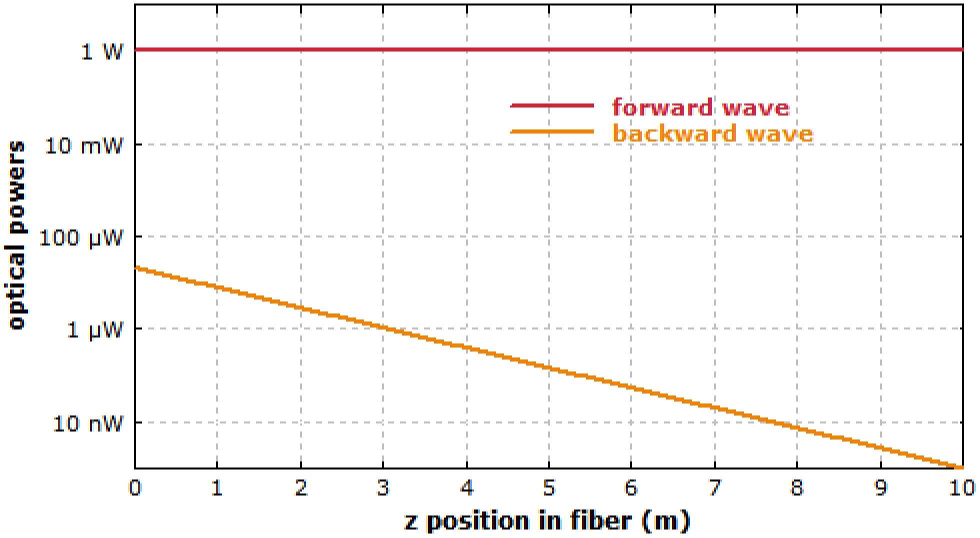
This kind of scattering is called stimulated because lattice vibrations can be produced by a high power light wave (above 10mW)

How SBS works



SBS can be seen as a Doppler effect produced by interaction between incident wave and vibrating cristal lattice.

Optical Power for Pump and Stokes Waves



Importance of SBS

The frequency difference between incident and scattered waves in silica is ≈10 GHz, with bandwidth for energy transfer is as tight as 20 MHz.

This value is small, and owing to this SBS does not shows crosstalk in DWDM systems.

The problem is attenuation. O SBS introduce an extra attenuation that increase with signal power. The consequence is fiber saturation.

Beyond that, reflected light make troubles in some transmitters like DFB lasers (Distributed Feedback)

Raman Stimulated Scatering (SRS)

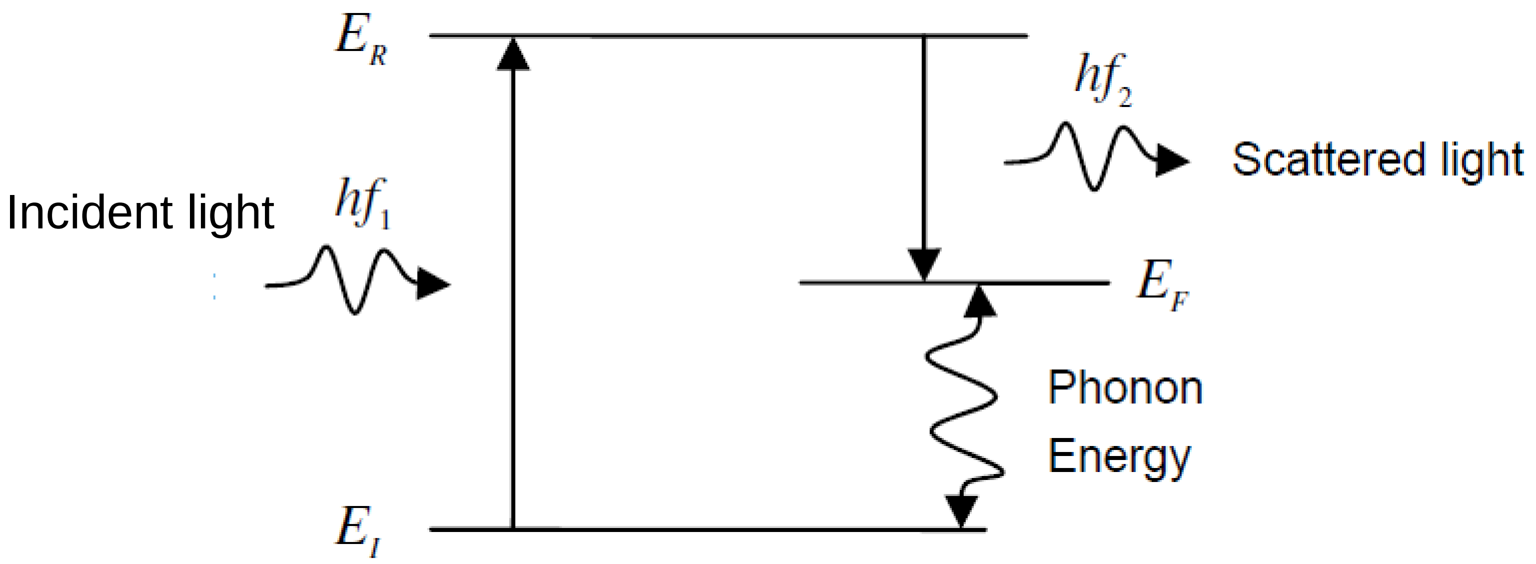
It is a phenomenum related to inelastic scatering of light in matter.

The effect was analysed by indian physics Chandrasekhar Venkata Raman in 1923 (Nobel prize of 1930)

SRS is unimportant as a loss mechanism because it occurs only with high powers, above 500 mW.

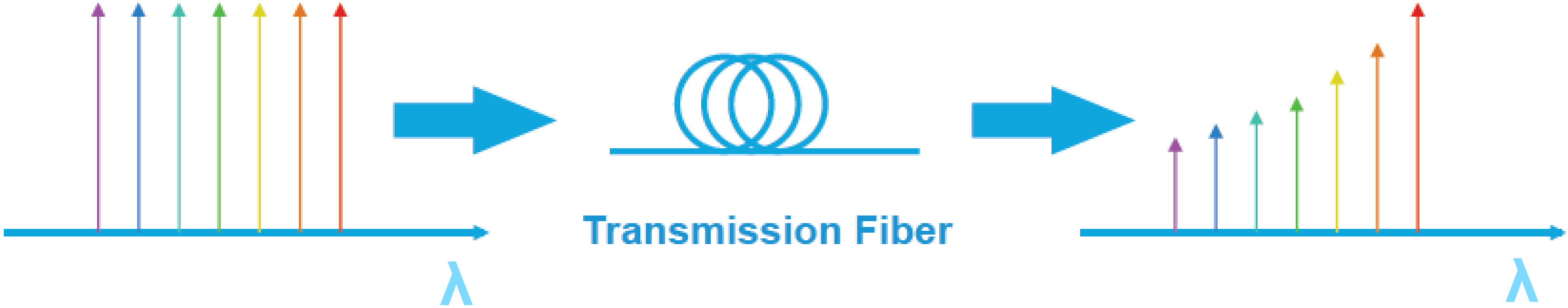
The higher frequency photon energy is transferred to lower frequency photons. Remember that photon energy is proportional to its frequency.

How SRS occurs



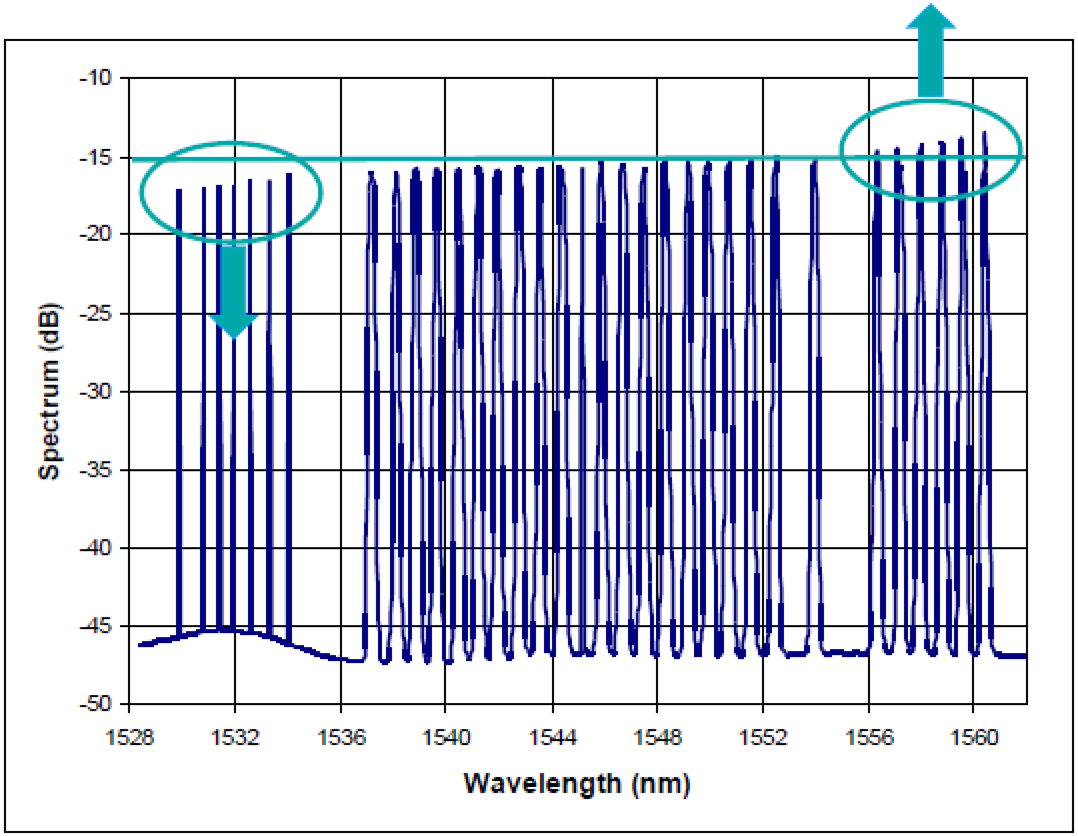
In silica, scattered light spectrum rises almost linearly below f_1 and reaches a maximum at 13 THz, falling quickly after that.

SRS Effect

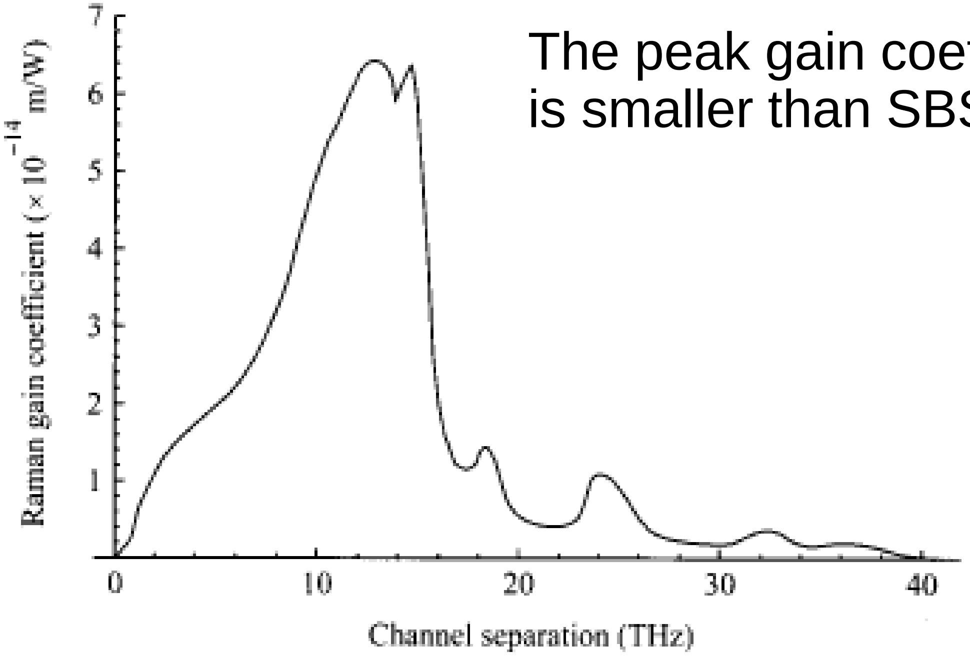


Raman effect is many times wished as an amplification of optical signals. In that case high frequency light operates as a pump of lower frequency signals.

SRS impact on DWDM systems



Raman gain versus frequency separation



The peak gain coefficient (6.10^{-14}) is smaller than SBS coefficient

SRS causes coupling in both directions (direct and reverse)

Kerr Effect

The optical Kerr effect is the phenomenon in which the refractive index of the medium changes when the electron orbit is deformed by a strong eletric field.

$n = n_0 + n_2|E^2|$ n_0 is the linear refractive index and n_2 is the Kerr coefficient.

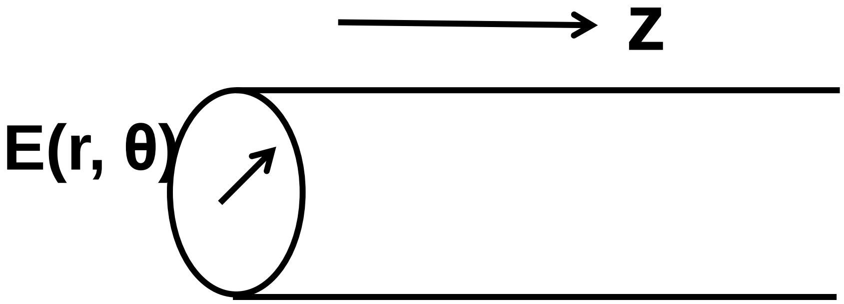
$n_0 = 1{,}46$ $n_2 = 3{,}18\ .10^{-20}\ m^2/W$ (para fibra de vidro)

Kerr effect produces: (1) optical solitons; (2)optical pulse compression; (3) modulations instabilities

Self Phase Modulation (SPM) – prop. linear

It is a direct consequence of Kerr effect: if propagation index changes, then propagation speed also changes, and angular frequency changes accordingly.

Let’s consider time and z-axis propagation



$$e = E(r,\theta)e^{j(\omega t-\beta z)}$$

$$\eta = \frac{c}{v} \qquad v = \frac{\omega}{\beta} \qquad \Rightarrow \qquad \eta = \frac{c\beta}{\omega}$$

The frequency of the pulse changes where the eletrical field is more strong.

SPM – Propagação não linear

No meio não linear a constante de propagação é dada por:

$$\beta = \frac{\omega_0}{c}\left(\eta + \frac{3}{8\eta}\chi^{(3)}E^2\right)$$

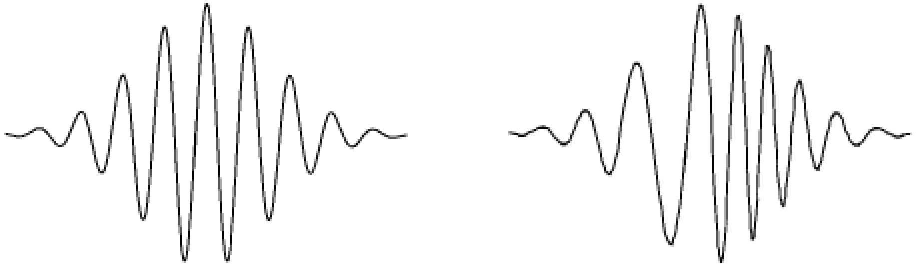
Então o campo elétrico $E(z,t) = E\cos(\omega_0 t - \beta z)$ é uma senoide cuja fase varia com o quadrado do campo elétrico. Este fenômeno é a SPM.

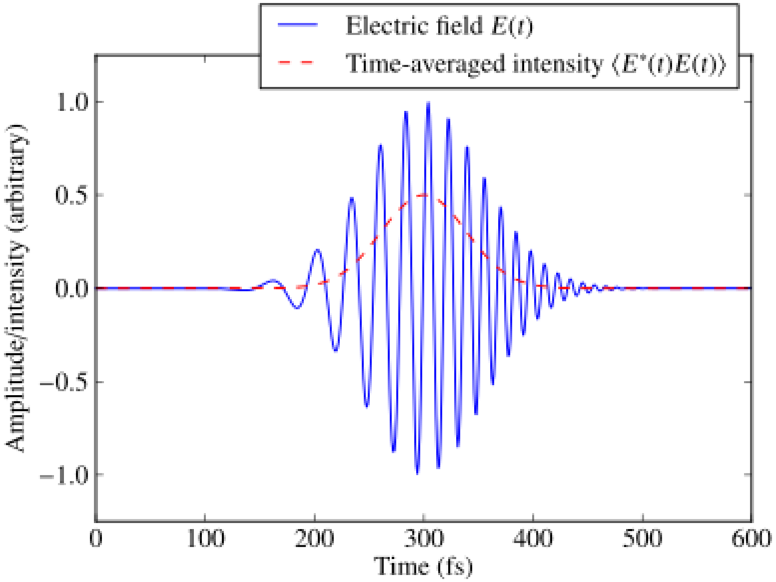
O valor do índice de refração costuma ser expresso em função da intensidade do campo elétrico como: $\eta(E) = \eta_0 + \check{n}I$

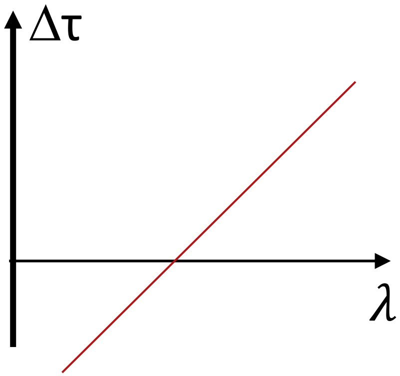
A fase do campo elétrico contém um termo proporcional à intensidade do campo elétrico, mas a intensidade do campo elétrico não é constante nos pulsos e, portanto, a mudança de fase é diferente nas diferentes partes do pulso.

Note que o sinal da mudança de fase devido à SPM é negativo.

Chirping







É a variação da frequência ao longo do tempo. Quando a intensidade de campo aumenta a frequência diminui

Descrição Matemática de um Pulso com Chirp

$$G(t) = A_0 e^{-\frac{1}{2}\left(\frac{t}{T_0}\right)^2} cos\left(\omega_0 t + \frac{k}{2}\left(\frac{t}{T_0}\right)^2\right)$$

A amplitude de pico é A_0 e o parametro T_0 determina a largura do pulso.

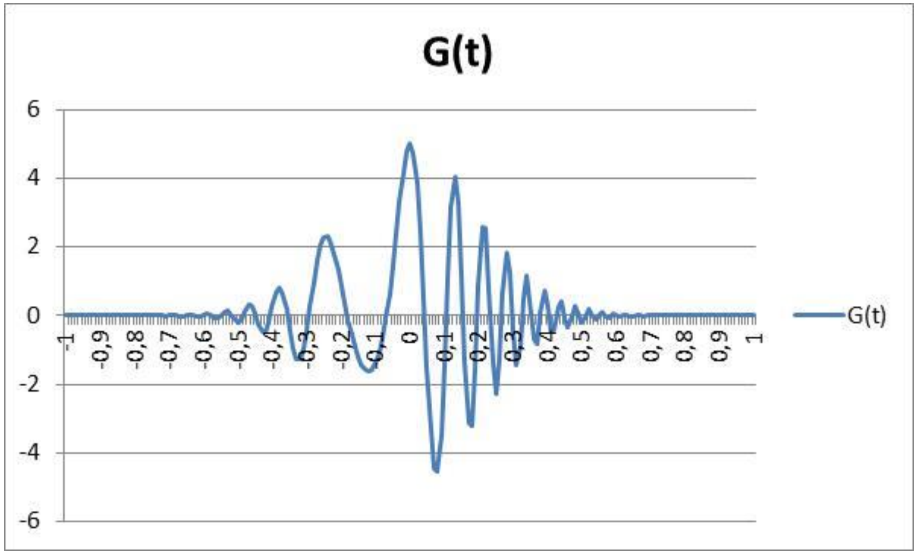
T_0 é a meia largura do pulso no ponto onde a amplitude é 1/e do valor Máximo.

A fase instantânea do pulso é: $\emptyset(t) = \omega_0 t + \frac{k}{2}\left(\frac{t}{T_0}\right)^2$

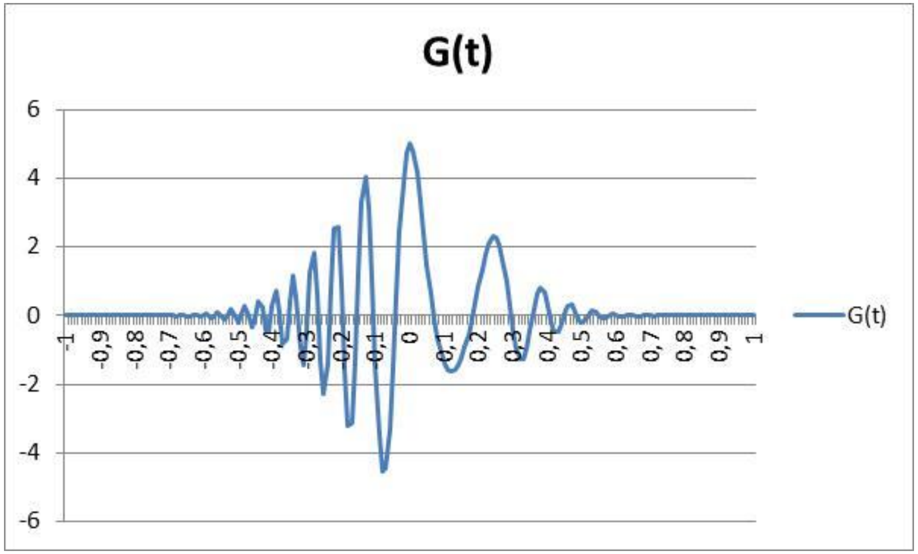
A frequência instantânea é a derivada da fase $w(t) = \omega_0 + \frac{k}{T_0^2} t$

O fator de chirping é definido como o produto de T_0^2 pela derivada da frequência instantânea. Ou seja é k.

Pulsos com Chirping



k = 10



k = -10

Chirping e Dispersão Cromática

Quando um pulso com chirping se propaga em um meio com dispersão cromática, ele se alarga ao longo do tempo.

A quantidade $T_0^2/|\beta_2|$ é chamada comprimento de dispersão (L_D).

Para sistemas com fibra padrão em 1,55µm, L_D é da ordem de 1800 km para 2,5 Gbps, mas 115 Km para 10 Gbps.

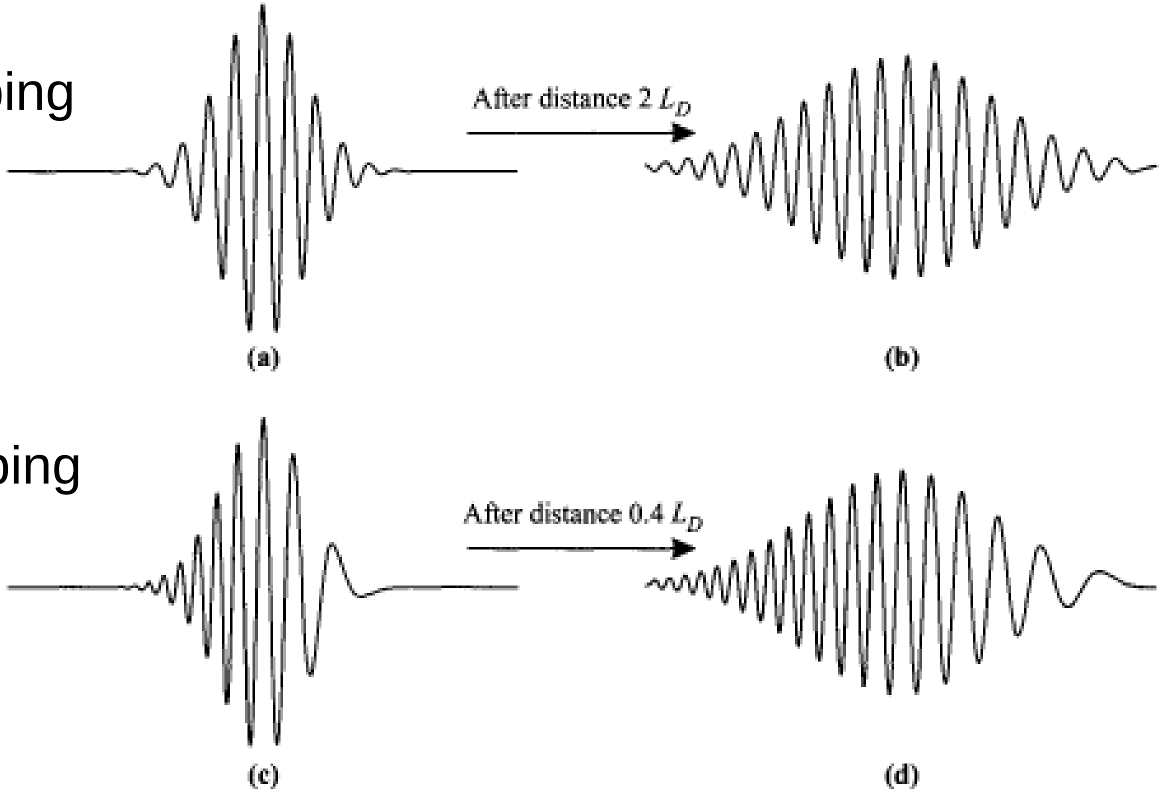
A largura de um pulso gaussiano, com chirp fator k após viajar uma distância z é dada por:

$$\frac{T_z}{T_0} = \sqrt{\left(1 + \frac{\kappa\beta_2 z}{T_0^2}\right)^2 + \left(\frac{\beta_2 z}{T_0^2}\right)^2}.$$

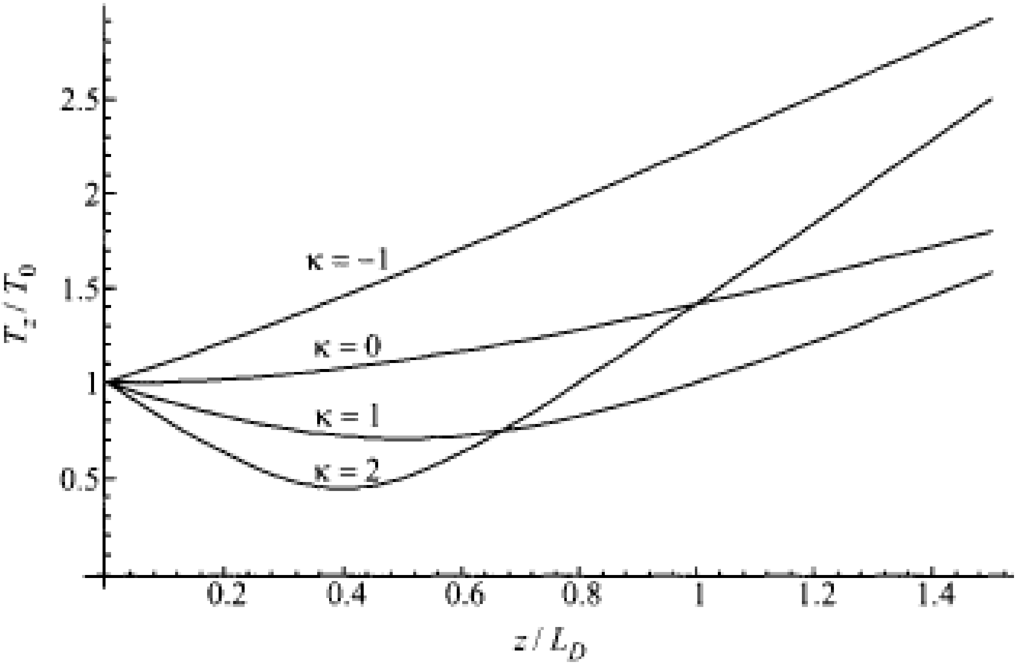
Alargamento de Pulsos

Sem chirping

Com chirping

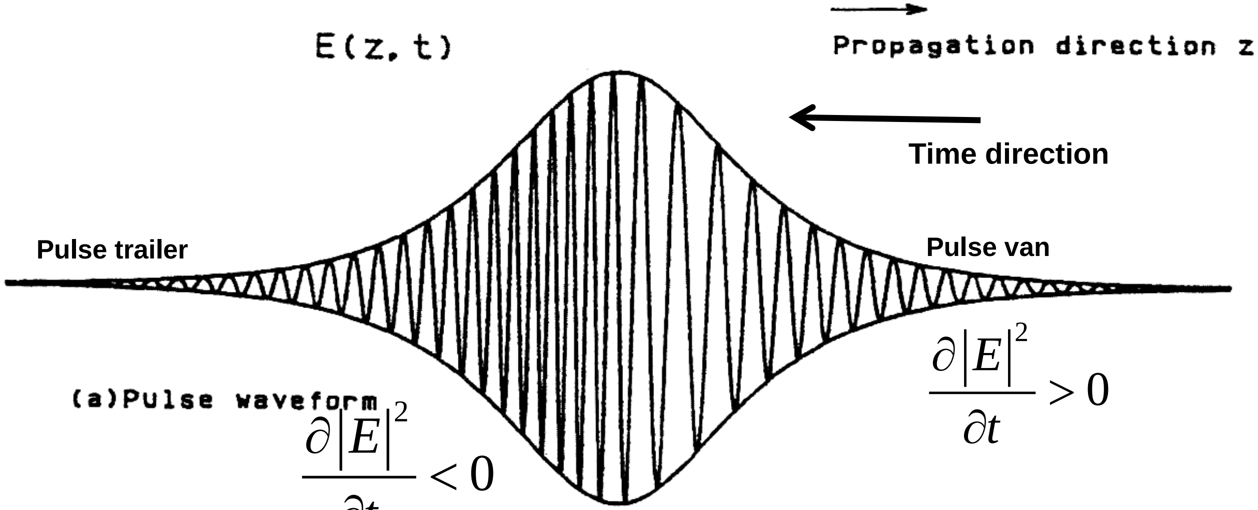


Efeito do Chirping Negativo



O efeito inicial de compressão ocorre se o produto $k\beta_2 < 0$

Self Phase Modulation



Time direction

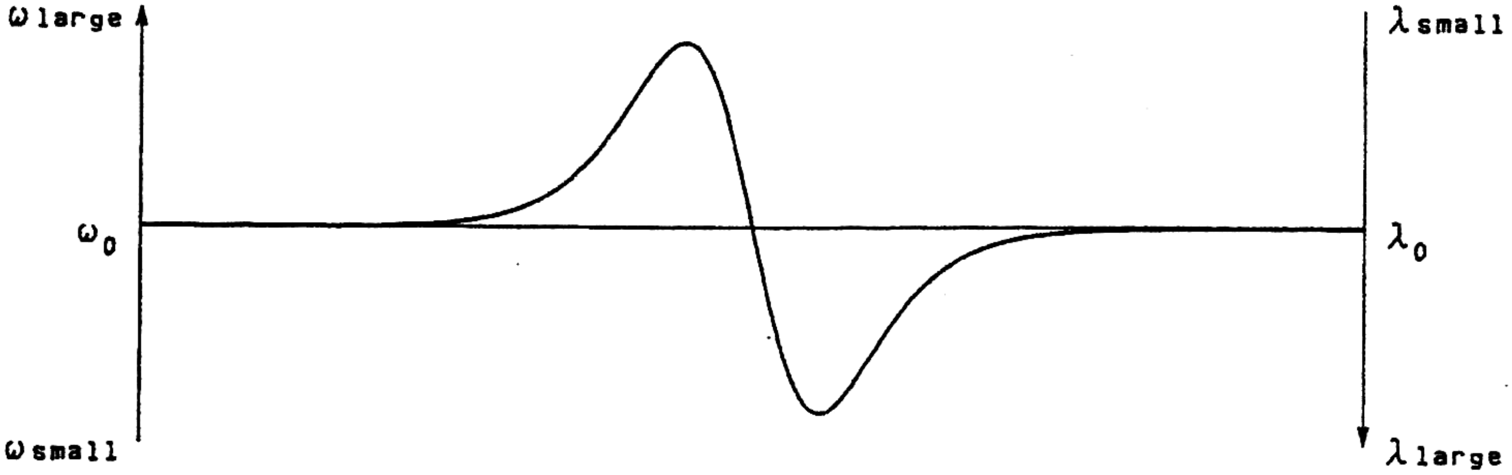
Pulse trailer

Pulse van

$$\frac{\partial |E|^2}{\partial t} > 0$$

(a)Pulse waveform

$$\frac{\partial |E|^2}{\partial t} < 0$$



(b)Frequency (wavelength) variation

Self Phase Modulation

$$\eta(\omega_0) + n_2 |E|^2 = \frac{c\beta}{\omega}$$

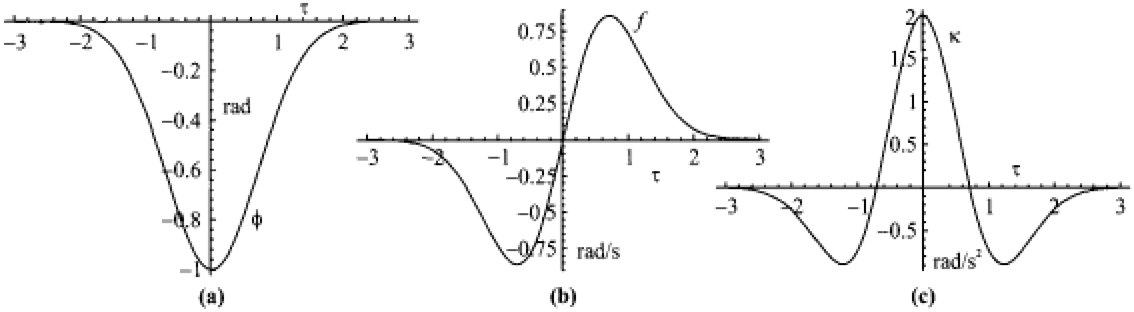
$$\Theta(t) = \omega t - \beta z$$

$$\omega(t) = \frac{\partial \Theta}{\partial t} = \omega_0 - \frac{\omega_0 n_2}{c} z \frac{\partial |E|^2}{\partial t}$$

$$\text{Se} \quad \frac{\partial |E|^2}{\partial t} > 0 \Rightarrow \omega(t) < \omega_0$$

$$\text{Se} \quad \frac{\partial |E|^2}{\partial t} < 0 \Rightarrow \omega(t) > \omega_0$$

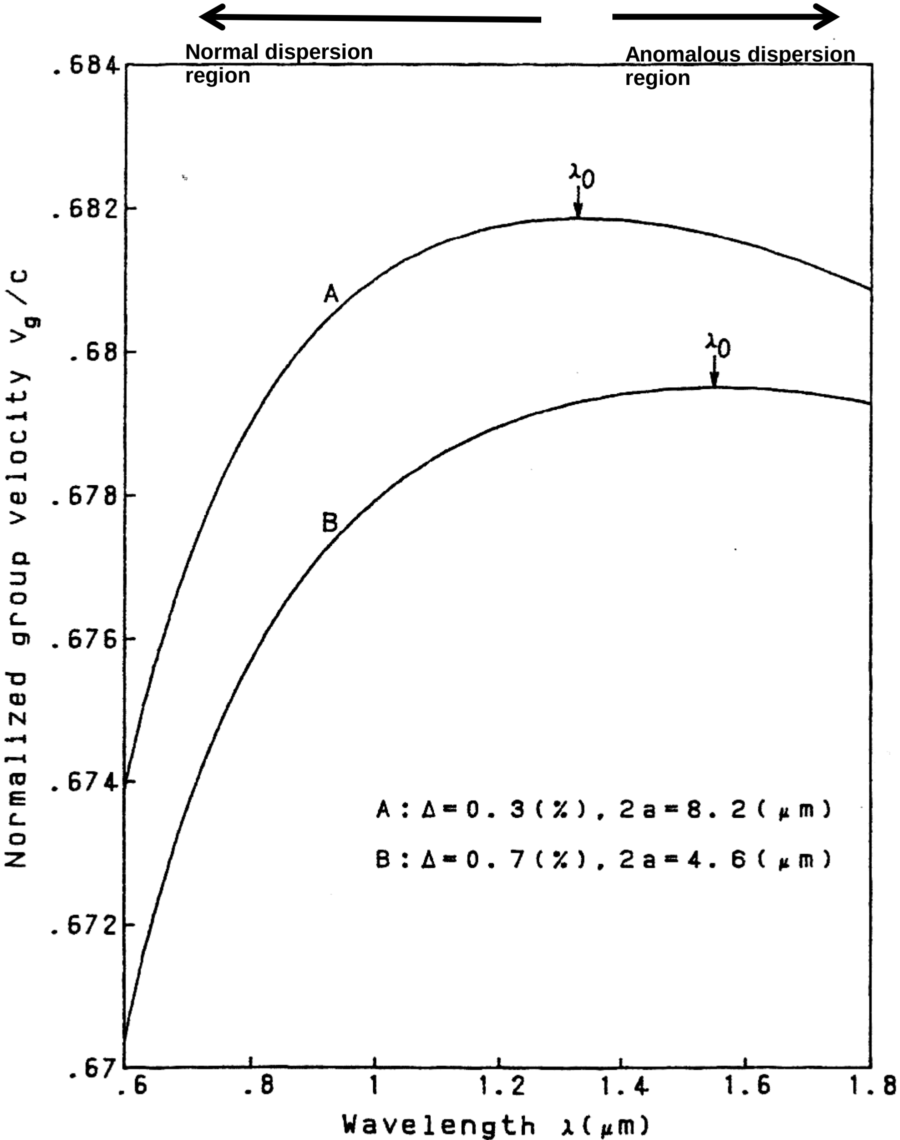
Efeito da SPM sobre pulsos



Desvio de fase Desvio de frequência Chirping

Assume-se L = Lnl

SPM and group velocity



In the anomalous dispersion region, the lower the frequency (the longer the wavelength), the smaller the group velocity.
But the frequency is lower at the preceding edge of the optical pulse.
Then the pulse is compressed

A: 1.3 μm zero-dispersion

B: 1.55 μm zero-dispersion

Solitons

If the compression of the optical pulse due to SPM balances the pulse broadening caused by dispersion, the optical pulse propagates through the fiber while maintaining its original pulse shaping.

This is called an optical soliton (more precisely, a *bright optical soliton*) and it is an ideal form of propagation.

Attenuation reduces the SPM effect, because the electrical field is weakened.

Chromatic dispersion compensates SPM when it is positive, but reinforces SPM when it is negative.

Cross Phase Modulation (XPM)

It is analogous to SPM, but here more than a pulse travels in the fiber at the same time.

One pulse, by its intensity, produces variations of the refractive index, which, by its time, causes changes in frequency of the other pulse.

XPM effects is very like a crosstalk and it is common in DWDM systems where different frequencies travel on the same fiber at the same time.

The increase of channel spacing reduces the XPM.

Is it possible also to balance XPM with adequate cromatic dispertion compensation.

Four Wave Mixing (FWM)

It is a intermodulation effect between waves that propagates in the same medium. It is due to channel non- linearities.

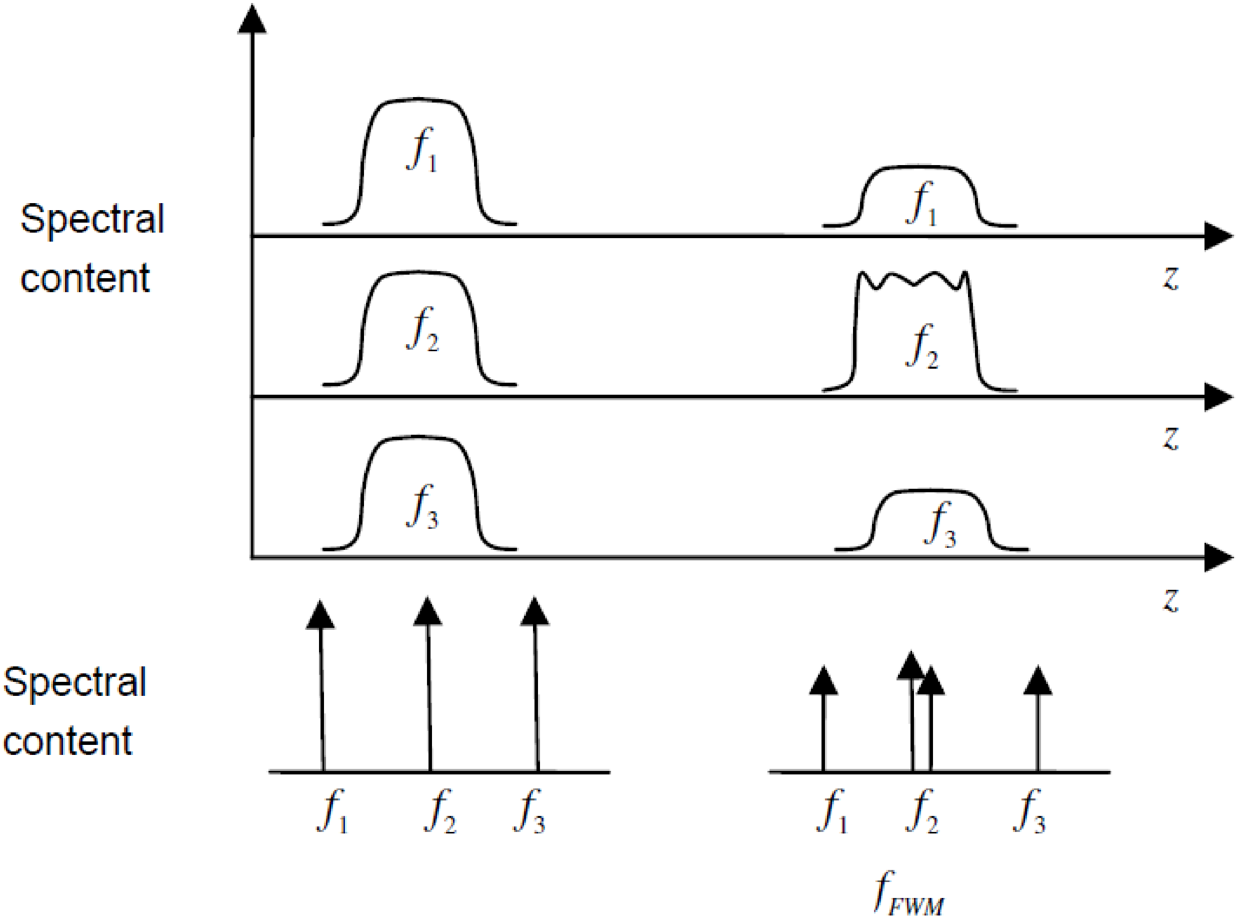
It causes attenuation of some frequencies and reinforces the others.

Dispersion reduces correlation between waves and reduces FWM. Because of this fiber with zero dispersion are not optimized to DWDM applications.

The FWM effect cannot be filtered out because it overlaps a valid channel.

Effects occur over sum and difference of channel frequencies, like $\omega_4 = \omega_1 + \omega_2 - \omega_3$

Four Wave Mixing



Four Wave Mixing

The FWM effect depends on combination of specific phase conditions between the signals.

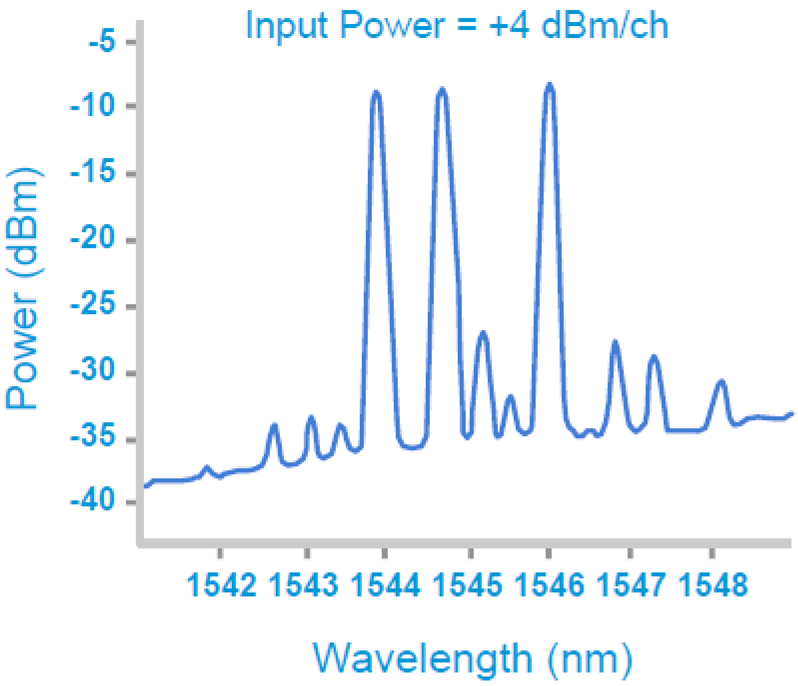
Signal frequency must be alike and propagation constant (β) must be the same

When those conditions are met, FWM increases along the fiber, imposing a fiber length limitation.

For instance, in a system with 32 channels, 0,5 mW per channel, 50 GHz of channel spacing, with DSF fiber is limited to 100 Km

Introducing dispersion, that is, with non DSF fiber, FWM can be irrelevant up to 5000 Km of fiber length.

FWM Example



The figure shows power in a DSF fiber after 25 Km

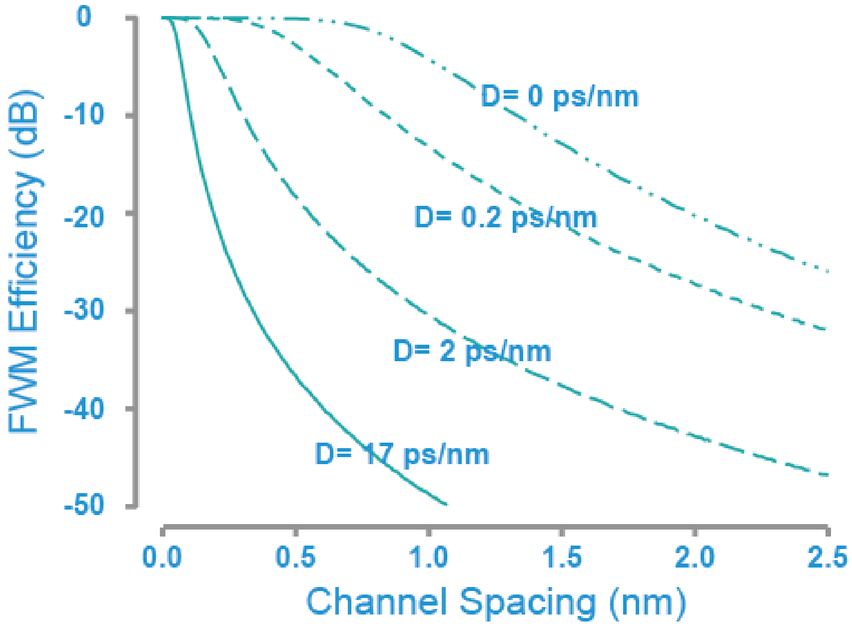
Four Wave Mixing

$$
\begin{aligned}
\mathcal{P}_{NL}(\mathbf{r}, t) &= \epsilon_0 \chi^{(3)} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} E_i \cos(\omega_i t - \beta_i z) E_j \cos(\omega_j t - \beta_j z) E_k \cos(\omega_k t - \beta_k z) \\
&= \frac{3\epsilon_0 \chi^{(3)}}{4} \sum_{i=1}^{n} \left(E_i^2 + 2 \sum_{j \neq i} E_i E_j \right) E_i \cos(\omega_i t - \beta_i z) && (2.28) \\
&\quad + \frac{\epsilon_0 \chi^{(3)}}{4} \sum_{i=1}^{n} E_i^3 \cos(3\omega_i t - 3\beta_i z) && (2.29) \\
&\quad + \frac{3\epsilon_0 \chi^{(3)}}{4} \sum_{i=1}^{n} \sum_{j \neq i} E_i^2 E_j \cos((2\omega_i - \omega_j)t - (2\beta_i - \beta_j)z) && (2.30) \\
&\quad + \frac{3\epsilon_0 \chi^{(3)}}{4} \sum_{i=1}^{n} \sum_{j \neq i} E_i^2 E_j \cos((2\omega_i + \omega_j)t - (2\beta_i + \beta_j)z) && (2.31) \\
&\quad + \frac{6\epsilon_0 \chi^{(3)}}{4} \sum_{i=1}^{n} \sum_{j > i} \sum_{k > j} E_i E_j E_k \\
&\qquad \Big(\cos((\omega_i + \omega_j + \omega_k)t - (\beta_i + \beta_j + \beta_k)z) && (2.32) \\
&\qquad + \cos((\omega_i + \omega_j - \omega_k)t - (\beta_i + \beta_j - \beta_k)z) && (2.33) \\
&\qquad + \cos((\omega_i - \omega_j + \omega_k)t - (\beta_i - \beta_j + \beta_k)z) && (2.34) \\
&\qquad + \cos((\omega_i - \omega_j - \omega_k)t - (\beta_i - \beta_j - \beta_k)z) \Big). && (2.35)
\end{aligned}
$$

How to avoid FWM

The planned introduction of cromatic dispersion avoid phase combinations. It is possible to introduce dispersions with opposite signals, in order to keep total dispersion as near zero as possible

Different spacing between channels avoid frequency pairing.

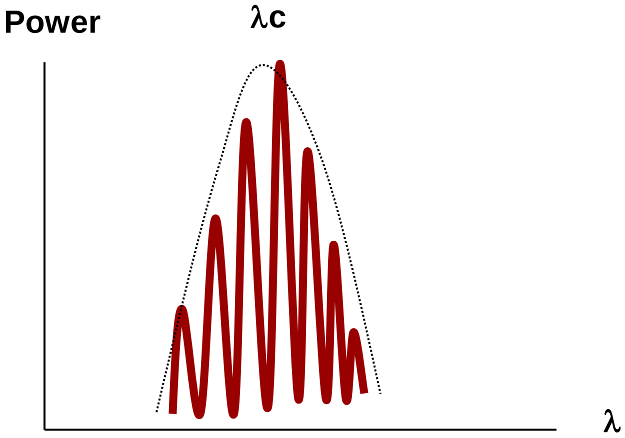


$$P_{FWM} \propto \frac{P.n_2}{A_{eff}.D}$$

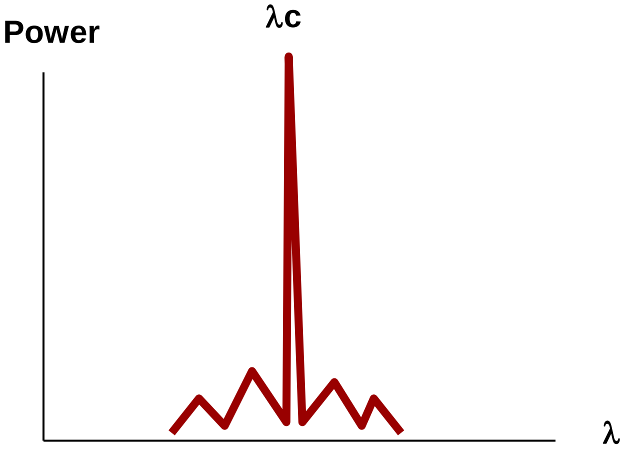
Generation and Transmission of Optical Signals

Laser Characteristics

Non-DWDM Laser Characteristic



DWDM Laser Characteristic



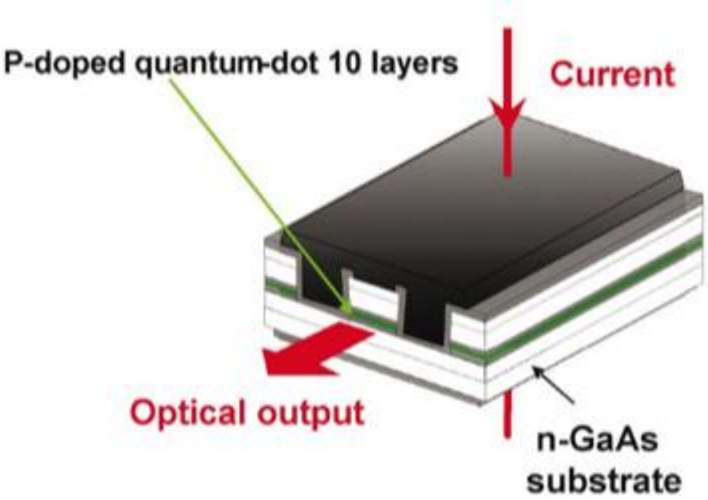
Fabry-Perot Laser

- Spectrally broad linewidth
- Unstable center/peak wavelength
- Characteristic of low-cost SR/IR optics

Distributed Feedback Laser (DFB)

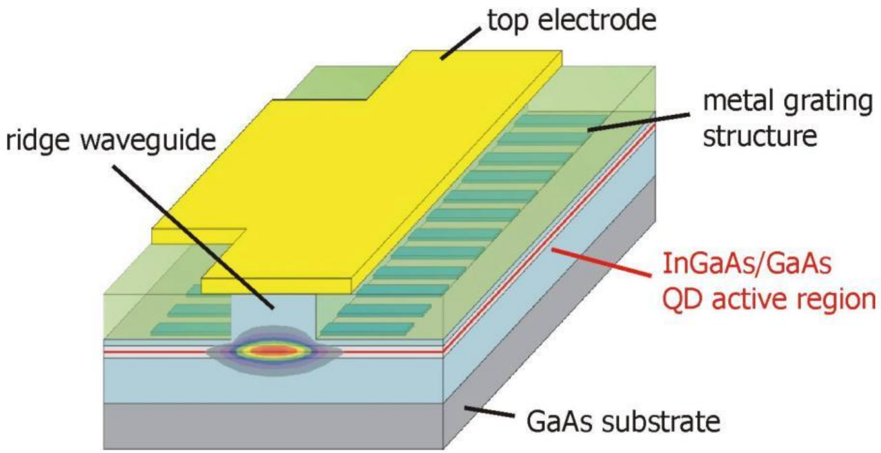
- Dominant single wavelength
- Tighter wavelength control
- Can be externally modulated
- Necessary for DWDM transmission

FP diodes



Source: toptica photonics

DFB structure

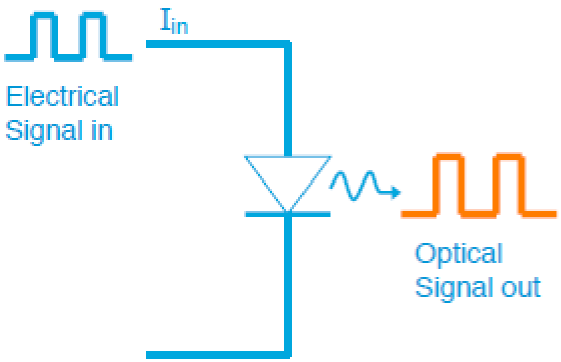


Fonte: Toptica Photonics

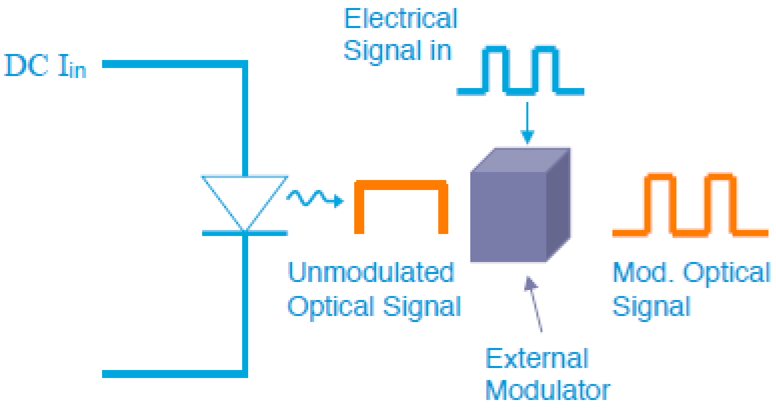
Laser Modulation

- Direct modulation
  - Directly varying the laser drive current with the information stream to produce a varying optical output power, “1” and “0”
  - Thermal difference between “1” and “0” state creates wavelength shift, induces spectral broadening of the laser spectrum… “Chirping”
  - Spectrally broad, chirped signal has *low dispersion tolerance*
- External modulation
  - High-speed system to minimize undesirable effects, such a chirping
  - Modulation achieved through
    - separate device, for example Lithium Niobate Mach-Zehnder interferometer
    - or integral part of the laser transmitter, electro-absorption
  - Spectrally narrow signal has *high dispersion tolerance*

Laser beam modulation



Direct modulation

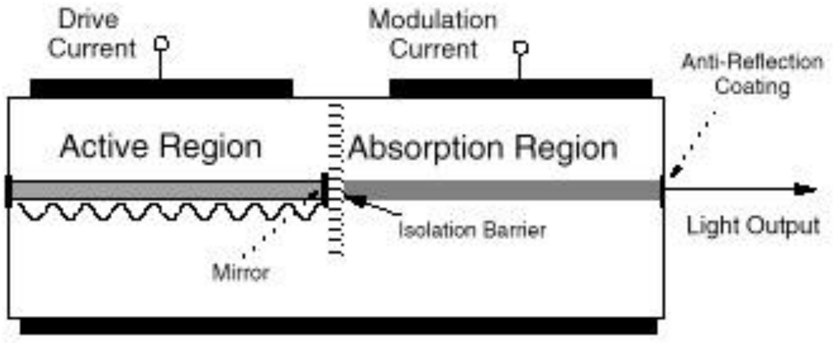


External modulation

Modulation allows information transportation, but broadens the signal spectrum.

Internal Electro-Absorption

Although the absorpting element is internal in the laser diode the modulation is considered external because power light emitted is constant.

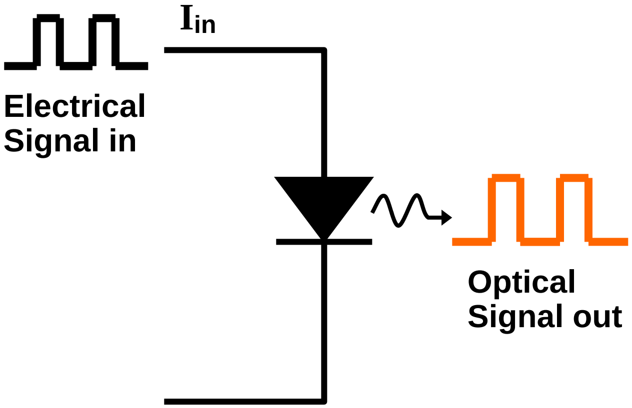


Active region produce light in a stationary way and absorption is controlled by modulation current.

Absorpting rerion is reversely polarised, owing to this leak current is small.

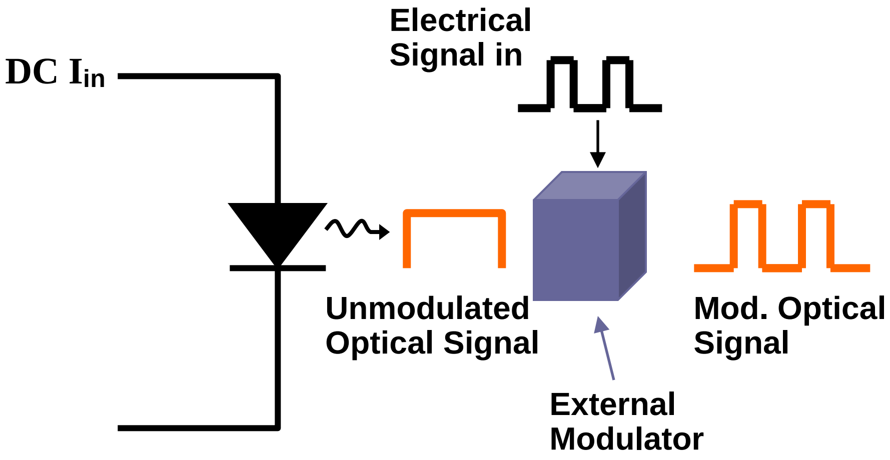
Laser Modulation

Direct Modulation



- Laser diode’s bias current is modulated with signal input to produce modulated optical output

External Modulation



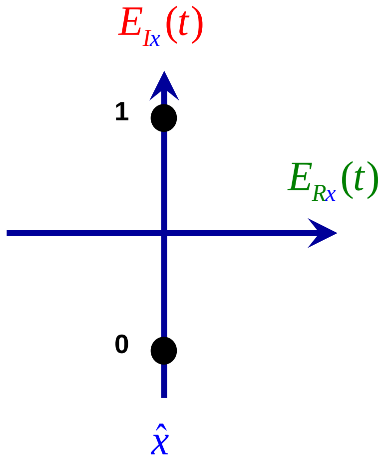
- The laser diode’s bias current is stable
- External modulator operates as a fast shutter to generate a modulated optical signal from the electrical input

Common Modulation Formats

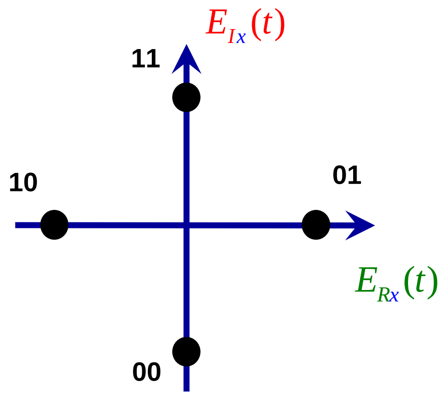
Each modulation format has advantages and disadvantages.

- IM-OOK NRZ: Intensity Modulation – On Off Keying Non Return to Zero
- RZ: return to Zero
- ODB: Optical Duobinary
- (D)PSK: (Differential) Phase Shift Keying
- (D)QPSK: (Differential) Quadrature Phase Shift Keying
- PM-(D)QPSK: Polarization Multiplexing (D)QPSK

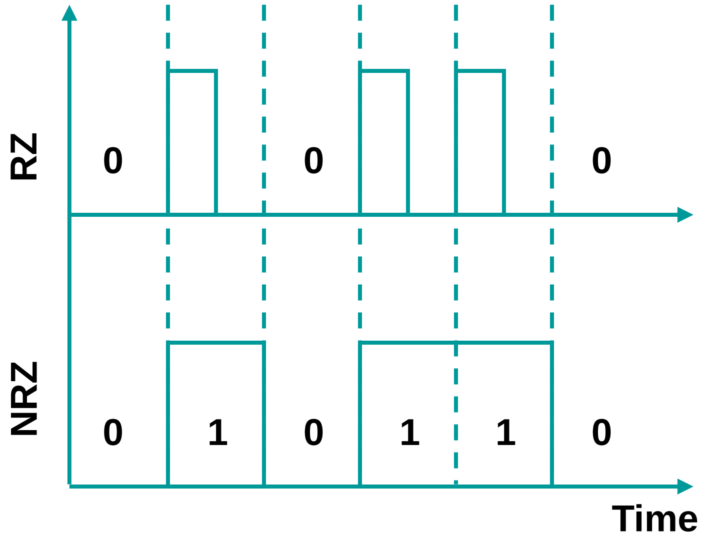
(D)PSK



(D)QPSK



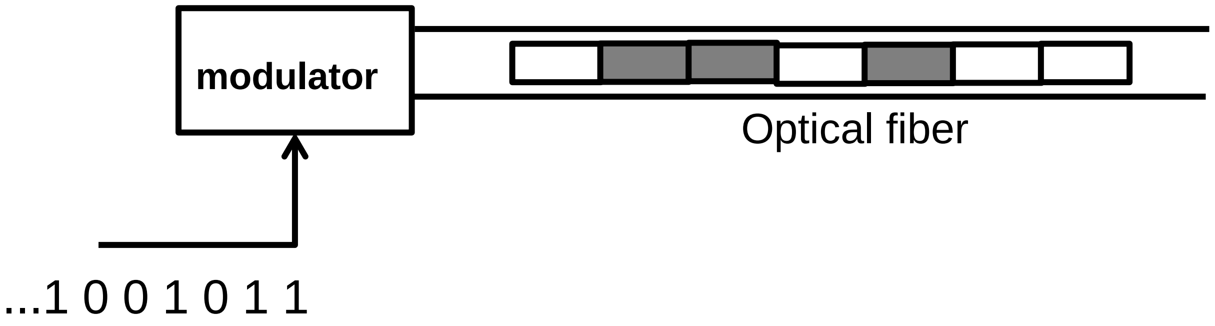
IM-OOK



On-off keying (OOK) modulation

Information is coded as light pulses.
0 = weak pulse ; 1 = strong pulse.

This is a particular scheme of ASK modulation.

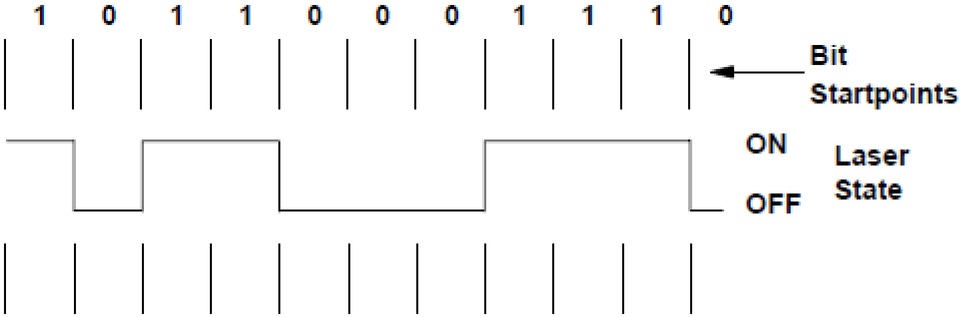


OOK does not assures bit balancing. Assynchronous detection is prone to errors.

NRZ Coding (AMI)

This is the simplest form of OOK used only in low speed systems.

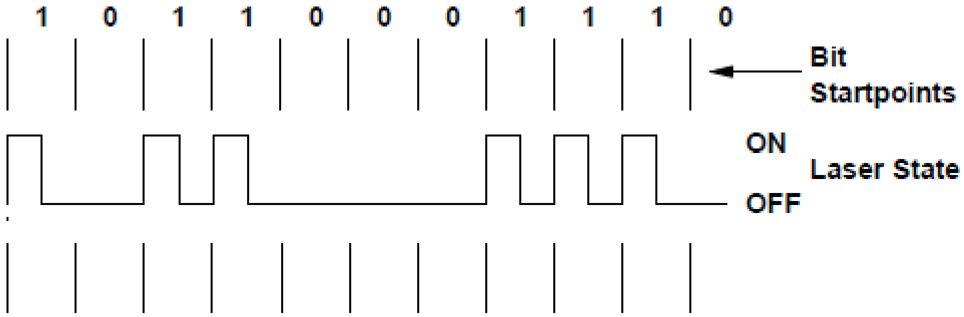
It is used when bit balance is assured by a scrambler. When this happens it is possible to recover source clock.



NRZI is a variation that inverts signal when zero is transmitted

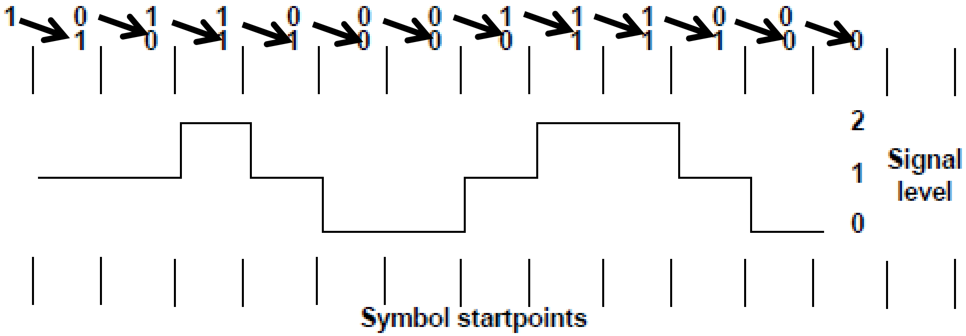
RZ Codification (Manchester)

This system assures a good and fast clock recovery, but baseband signal spectrum is enlarged. This reduces the maximum bit rate.

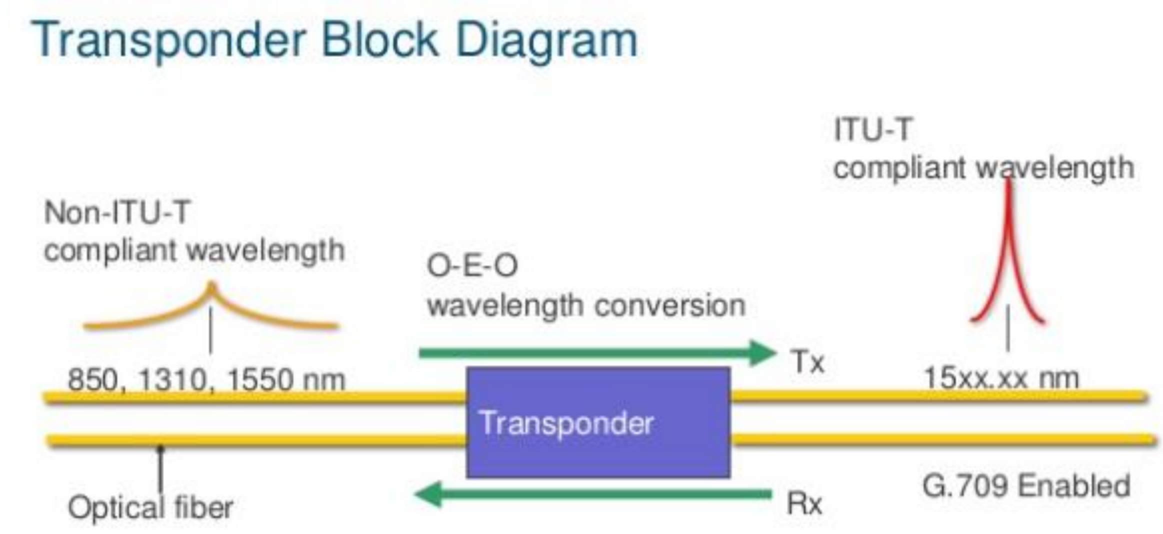


Ternary Codification

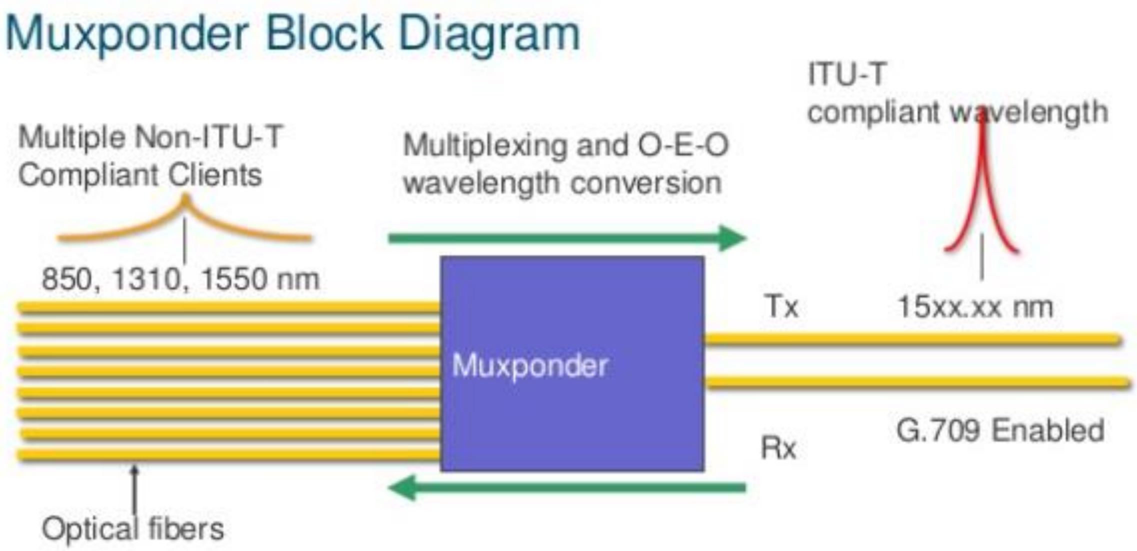
This is a multi-level coding scheme often used in optical systems.
The oldest network with ternary encoding (MLT) is FDDI
It is also called duobinary encoding.



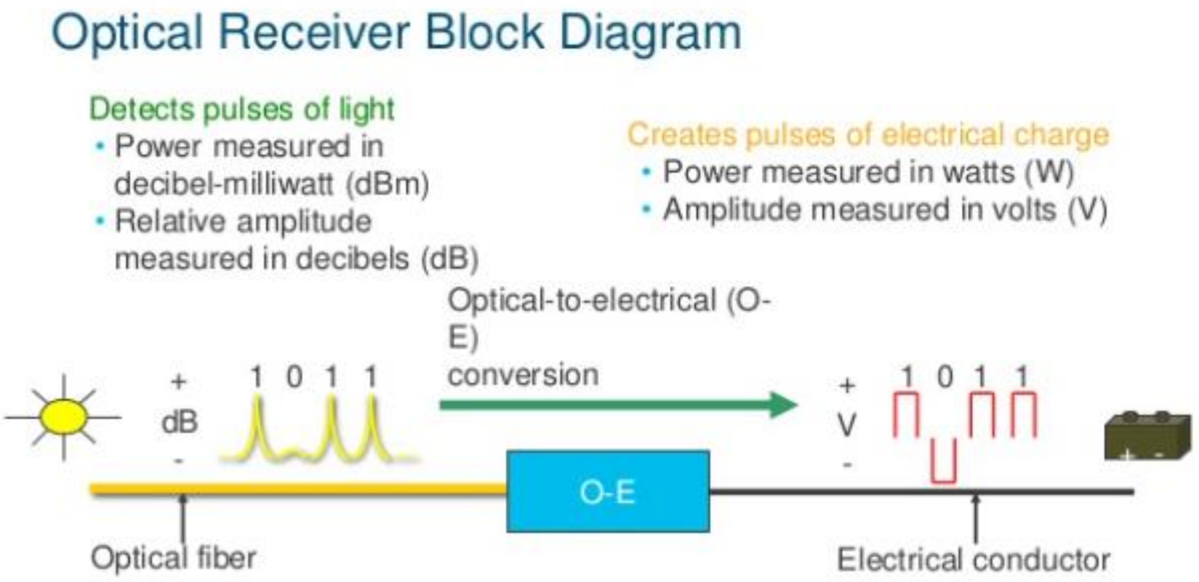
Transponders



Muxponders


Muxponder Block Diagram
ITU-T
compliant wavelength
Multiple Non-ITU-T
Compliant Clients
Multiplexing and O-E-O
wavelength conversion
850, 1310, 1550 nm
Tx
15xx.xx nm
Muxponder
G.709 Enabled
Rx
Optical fibers

Optical Receivers



Optical Receiver Block Diagram

Detects pulses of light
- Power measured in decibel-milliwatt (dBm)
- Relative amplitude measured in decibels (dB)

Creates pulses of electrical charge
- Power measured in watts (W)
- Amplitude measured in volts (V)

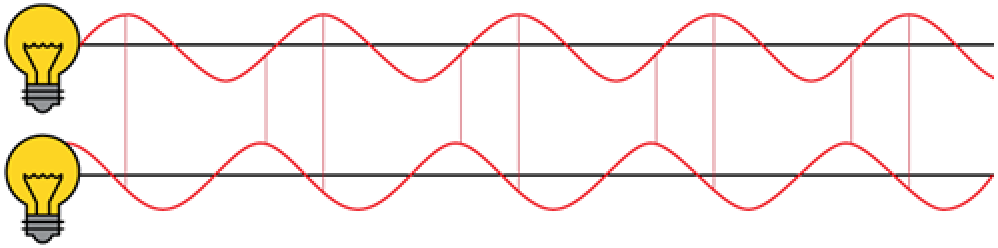
Optical-to-electrical (O-E) conversion

Optical Receivers

The receiver must convert information brought in a ligth beam into a electrical signal

The easiest way of doing this is using a photo-receptor, PIN or APD. This is amplitude detection.

Using coherent detection, receivers can track the phase of the incoming signal and thereby extract any information conveyed using phase and/or frequency modulation. Thus, coherent detection facilitates much higher capacity without using more bandwidth.

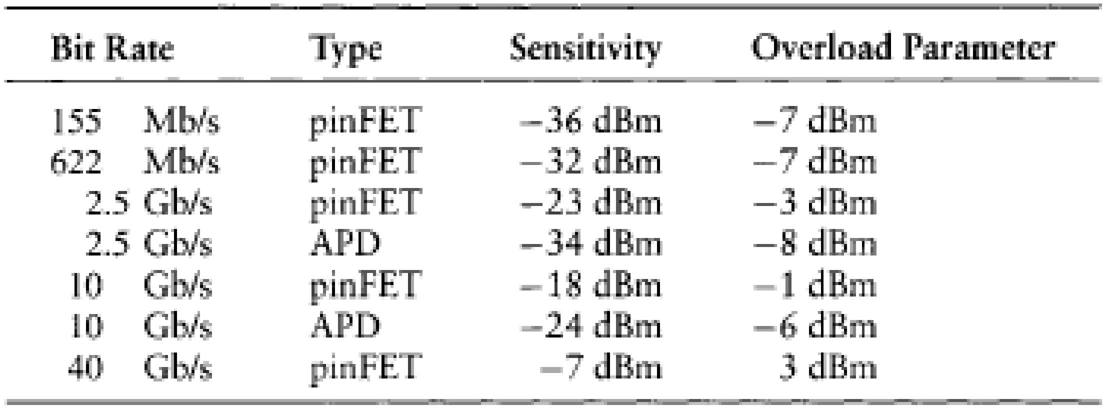


Coherent signals

Receiver

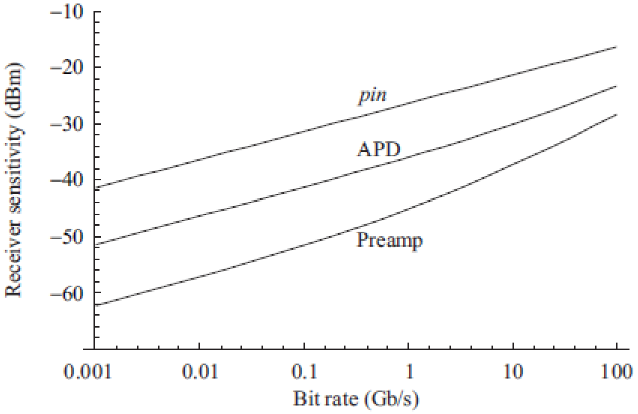
- The key system parameters associated with a receiver are its *sensitivity and overload parameter.*
- The sensitivity is the average optical power required to achieve a certain bit error rate at a particular bit rate.
- It is usually measured at a bit error rate of 10^{-12} using a pseudo-random 2^{23} - 1 bit sequence.
- The overload parameter is the maximum input power that the receiver can accept.
- CTP designs an optical channel for 10^{-15} BER after FEC

Typical sensitivities



Bit Rate	Type	Sensitivity	Overload Parameter
155 Mb/s	pinFET	−36 dBm	−7 dBm
622 Mb/s	pinFET	−32 dBm	−7 dBm
2.5 Gb/s	pinFET	−23 dBm	−3 dBm
2.5 Gb/s	APD	−34 dBm	−8 dBm
10 Gb/s	pinFET	−18 dBm	−1 dBm
10 Gb/s	APD	−24 dBm	−6 dBm
40 Gb/s	pinFET	−7 dBm	3 dBm

Sensibilidade do Receptor PIN e APD



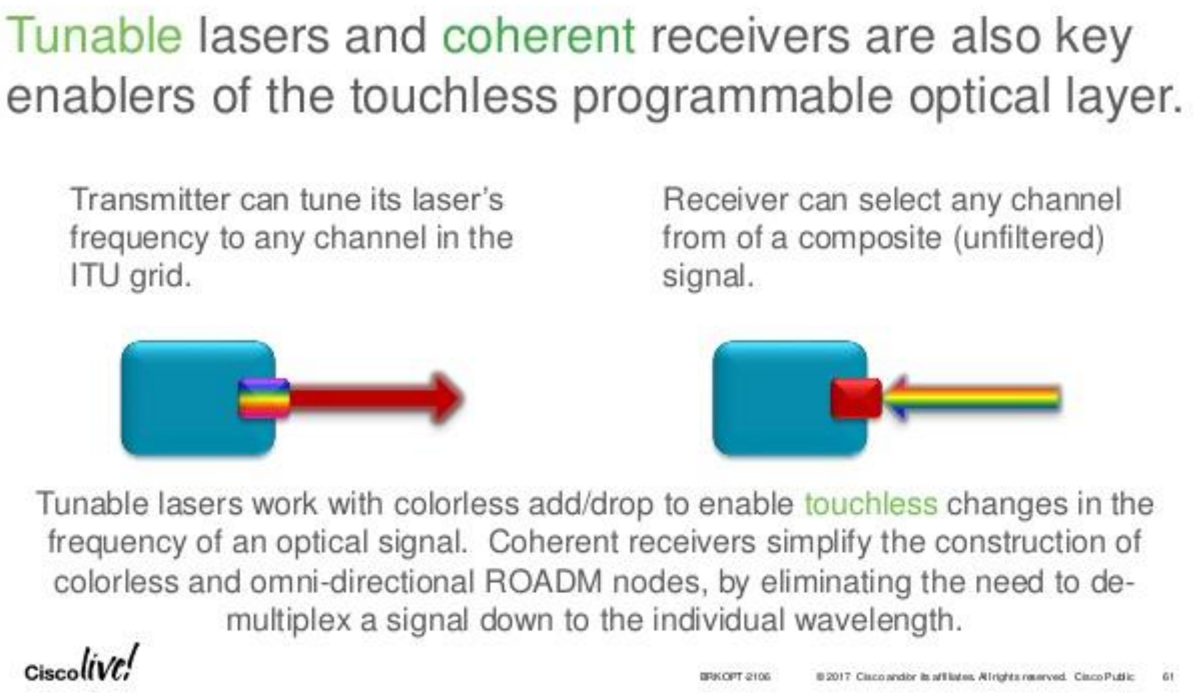
The figure shows the sensivity of photo-receivers PIN calculates with $\eta = 1$ $R = 1{,}25$ A/W and $\gamma = 7$, which correspond to a BER of 10^{-12}.

The same figure shows the sensivity of a diode APD with $k_A = 0{,}7$ and $G_m = 10$. Note the 10 dB advantage of APD.

Sensivity with preamplifier was calculated with noise figure of 6 dB for the optical amplifier and optical bandwidth of 50 GHz, filtering the signal before the amplifier.

Detectors PIN to 10 Gbits/s are commercially available with sensivity of -18 dBm and APD detectors with -24 dBm of sensivity.

Tunable Transmitters and Receivers



Tunable lasers and coherent receivers are also key enablers of the touchless programmable optical layer.

Transmitter can tune its laser's frequency to any channel in the ITU grid.

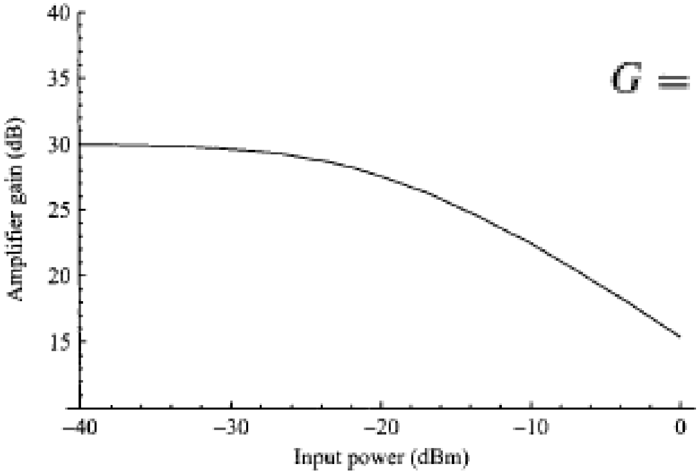
Receiver can select any channel from of a composite (unfiltered) signal.

Tunable lasers work with colorless add/drop to enable touchless changes in the frequency of an optical signal. Coherent receivers simplify the construction of colorless and omni-directional ROADM nodes, by eliminating the need to de-multiplex a signal down to the individual wavelength.

Optical Amplifiers

- Most common types: EDFA and Raman
- Raman amplifiers are used in addition to EDFAs in many ultra-long-haul systems.
- EDFA has a gain bandwidth of about 35 nm in the 1.55 nm wavelength region.
- The great advantage of EDFAs is that they are capable of simultaneously amplifying many WDM channels.
- Amplifiers are used in three different configurations:
  - An optical *preamplifier is used just in front of a receiver to improve its sensitivity.*
  - *A power amplifier is used after a transmitter to increase the output power.*
  - *A line amplifier is used typically in the middle of the link to compensate for link losses.*

Gain Saturation in EDFA

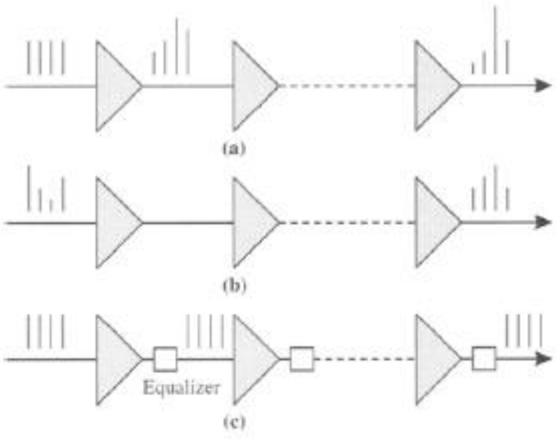


$$G = 1 + \frac{P^{\text{sat}}}{P_{\text{in}}} \ln \frac{G_{\max}}{G}.$$

G_{max} is the unsatured gain
G is satured gain
P_{in} is the input signal power
P^{sat} is the amplifier’s internal saturation power (10 to 20 dBm)

Gain Equalization

- The flatness of the EDFA passband becomes a critical issue in WDM systems with cascaded amplifiers.
- Small variations in gain between channels in a stage can cause large variations in the power difference between channels at the output of the chain.



Cumulative efffects

preemphasis

equalization

Equalization at each stage

- This alternative is more practical to obtain equal gain on 1530 – 1560 region.
- One way is to demultiplex the channels, attenuate each channel differently, and then multiplex them back together.
- This approach involves using a considerable amount of hardware and adds wavelength tolerance penalties due to the added muxes and demuxes.
- Another approach is to use a multichannel filter, such as an acousto-optic tunable filter (AOTF).
- Each channel can be attenuated differently by applying a set of RF signals with different frequencies.
- Each RF signal controls the attenuation of a particular center wavelength
- AOTF requires a large amount of RF drive power (on the order of 1 W)

Fiber Equalization

- The preferred solution today is to add an optical filter within the amplifier with a carefully designed passband to compensate for the gain spectrum of the amplifier so as to obtain a flat spectrum at its output.
- Both dielectric thin-film filters and long-period fiber gratings are good candidates for this purpose.

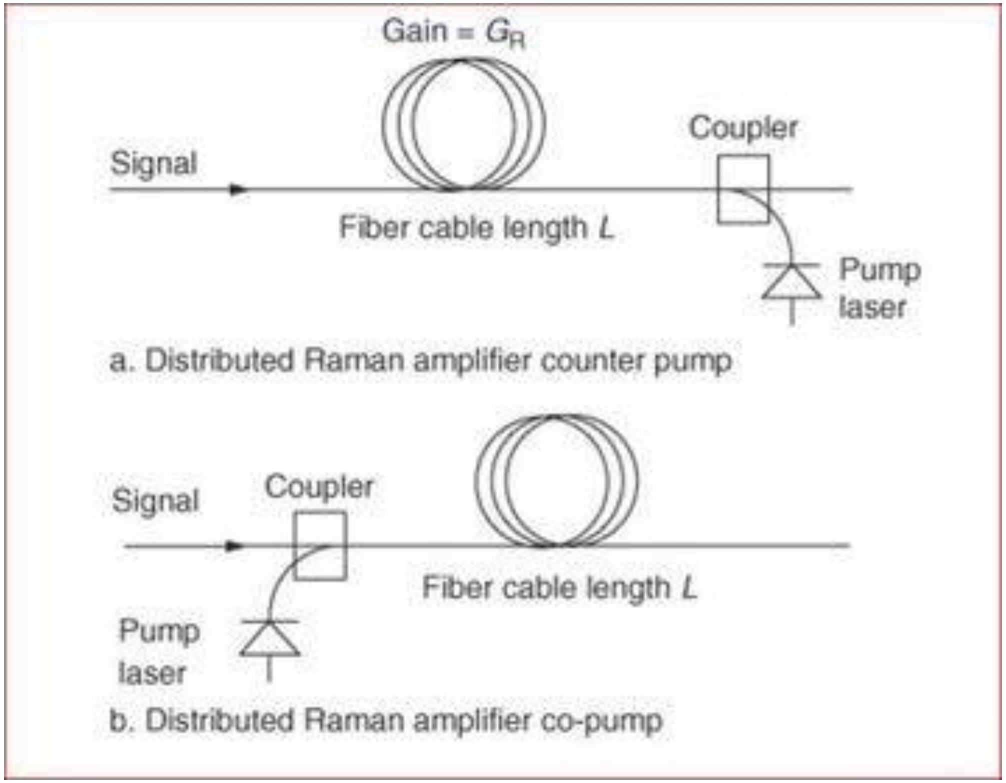
Raman Amplifier

1. The Raman amplifier is typically much more costly and has less gain than an Erbium Doped Fiber Amplifier (EDFA) amplifier. Therefore it is used only for speciality applications.
2. The main advantage that this amplifier has over the EDFA is that it generates very less noise and hence does not degrade span Optical to Signal Noise Ratio (OSNR) as much as the EDFA.
3. Its typical application is in EDFA spans where additional gain is required but the OSNR limit has been reached.
4. Adding a Raman amplifier might not significantly affect OSNR, but can provide up to a 20dB signal gain.
5. Another key attribute is the potential to amplify any fiber band, not just the C band as is the case for the EDFA. This allows for Raman amplifiers to boost signals in O, E, and S bands (for Coarse Wavelength Division Multiplexing (CWDM) amplification application).
6. The amplifier works on the principle of Stimulated Raman Scattering (SRS), which is a nonlinear effect.
7. It consists of a high-power pump laser and fiber coupler (optical circulator).
8. The amplification medium is the span fiber in a Distributed Type Raman Amplifier (DRA).
9. Dstributed Feedback (DFB) laser is a narrow spectral bandwith which is used as a safety mechanism for Raman Card. DFB sends pulse to check any back reflection that exists in the length of fiber. If no High Back Reflection (HBR) is found, Raman starts to transmit.
10. Generally HBR is checked in initial few kilometers of fibers to first 20 Km. If HBR is detected, Raman will not work.

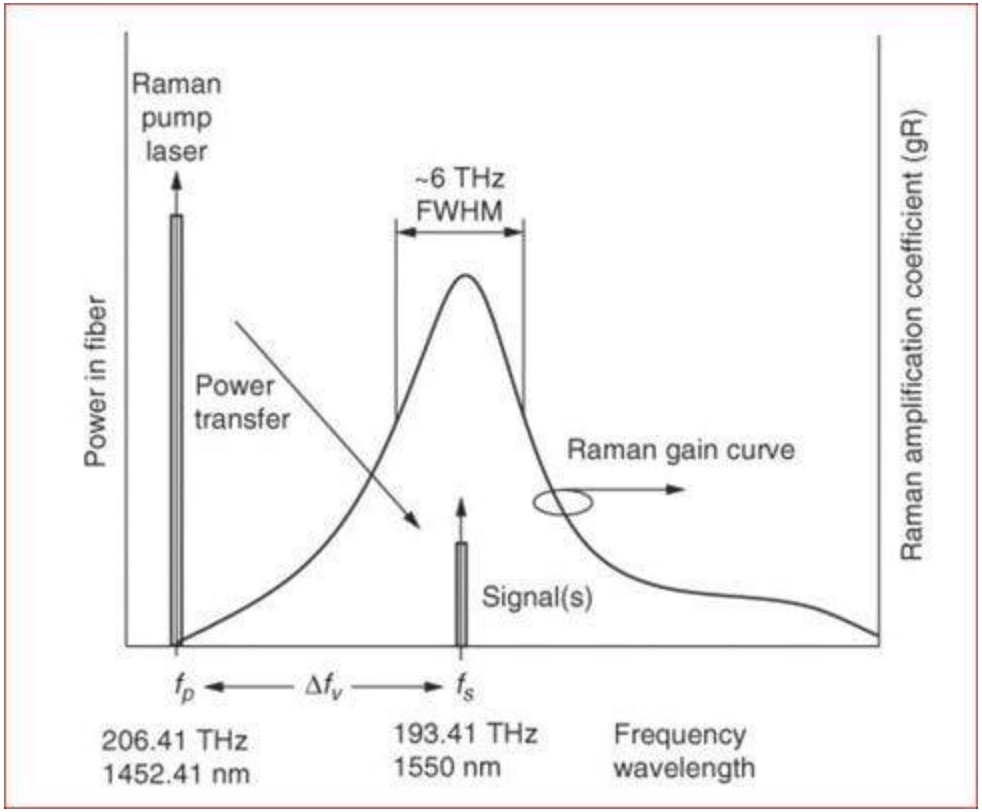
Stimulated Raman Scattering

- If two or more signals at different wavelengths are injected into a fiber, SRS causes power to be transferred from the shorter-wavelength channels to the longer-wavelength channels.
- Channels up to 150 THz (125 nm) apart are coupled due to SRS, with the peak coupling occurring at a separation of about 13 THz.
- Coupling occurs for both copropagating and counter-propagating waves.
- Coupling occurs between two channels only if both channels are sending 1 bits (that is, power is present in both channels).
- Thus the SRS penalty is reduced when chromatic dispersion is present because the signals in the different channels travel at different velocities, reducing the probability of overlap between pulses at different wavelengths at any point in the fiber.
- Typically, chromatic dispersion reduces the SRS effect by a factor of 2.

Types of Raman Amplifiers

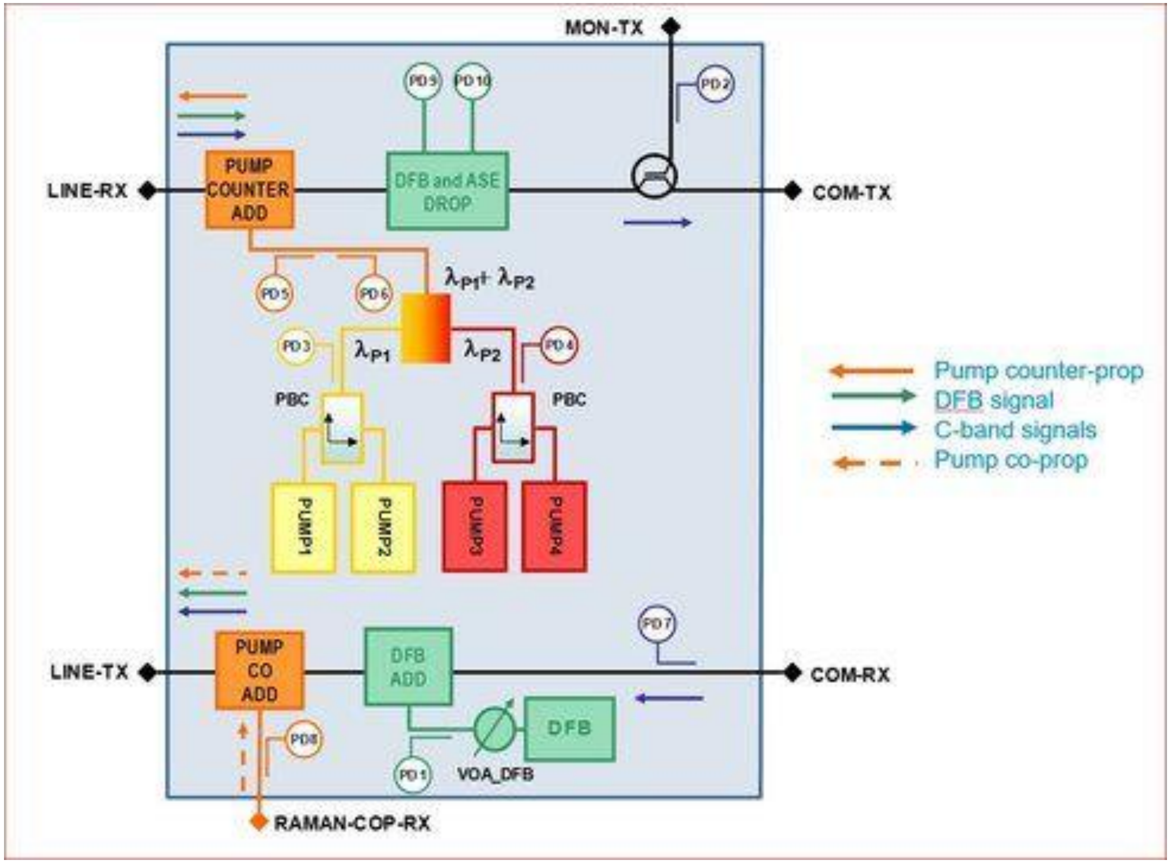


Raman Amplification Frequency



Δf_v=13,2 THz

Typical Raman Card



Dispersion Compensation

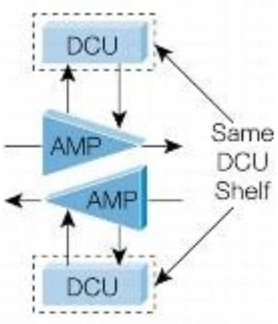
- Dispersion management is a very important part of designing WDM transmission systems, since dispersion affects the penalties due to various types of fiber nonlinearities.
- We can use several techniques to reduce the impact of chromatic dispersion:
  - (1) using external modulation in conjunction with DFB lasers
  - (2) using fiber with small chromatic dispersion
  - (3) by chromatic dispersion compensation.

Dispersion Compensation Units

As metropolitan (metro) transport networks grow from 2.5-generation (2.5G) services to 10G and eventually 40G, the underlying optical systems need to compensate for the lower chromatic dispersion tolerances on the 10G and 40G interfaces. In optical networks, the dispersion compensation unit (DCU) compensates for accumulated chromatic dispersion effect in fiber. It provides a flexible solution for accumulated chromatic dispersion without dropping and regenerating the wavelengths on the link, a process that would otherwise be necessary when accumulated chromatic dispersion exceeds the maximum allowed dispersion tolerance. To provide effective compensation, the DCU is designed to operate over the entire band from 1525 to1565 nm.

DCU shelf 15216

DCU Unit 15216



Dispersion Compensating Fibers

- Special chromatic dispersion compensating fibers (DCFs) have been developed that provide negative chromatic dispersion in the 1550 nm wavelength range.
- For example, DCFs that can provide total chromatic dispersion of between -340 and -1360 ps/nm are commercially available.
- An 80 km length of standard single-mode fiber has an accumulated or total chromatic dispersion, at 17 ps/nm-km, of 17 x 80 = 1360 ps/nm.
- Between amplifier spans is standard single-mode fiber, but at each amplifier location, dispersion compensating fiber having a negative chromatic dispersion is introduced.

Multiplexers and Demultiplexers

Because DWDM systems send signals from several sources over a single fiber, they must include some means to combine the incoming signals.

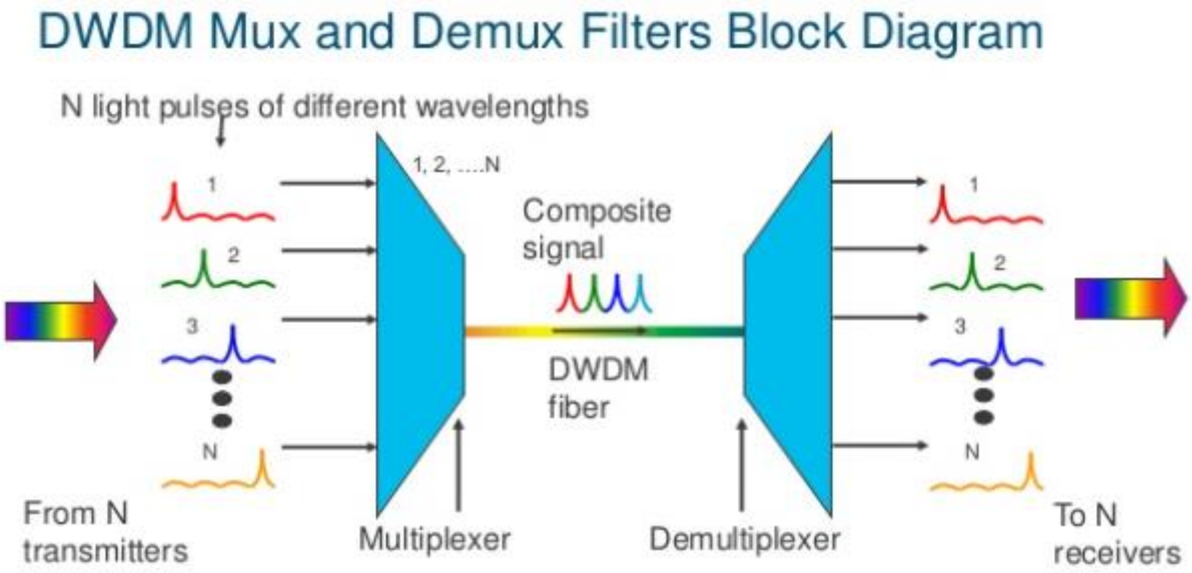
This is done with a multiplexer, which takes optical wavelengths from multiple fibers and converges them into one beam.

At the receiving end the system must be able to separate out the components of the light so that they can be discreetly detected.

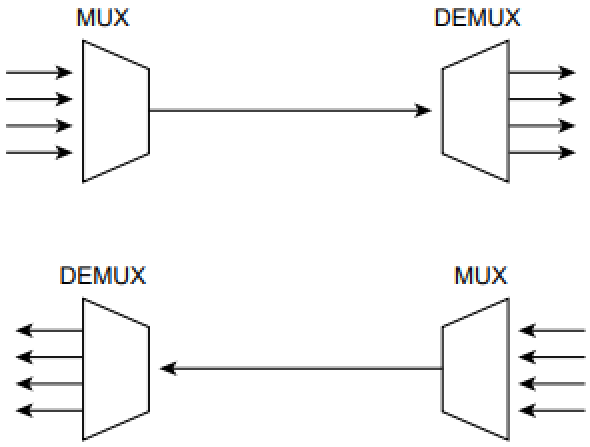
Demultiplexers perform this function by separating the received beam into its wavelength components and coupling them to individual fibers.

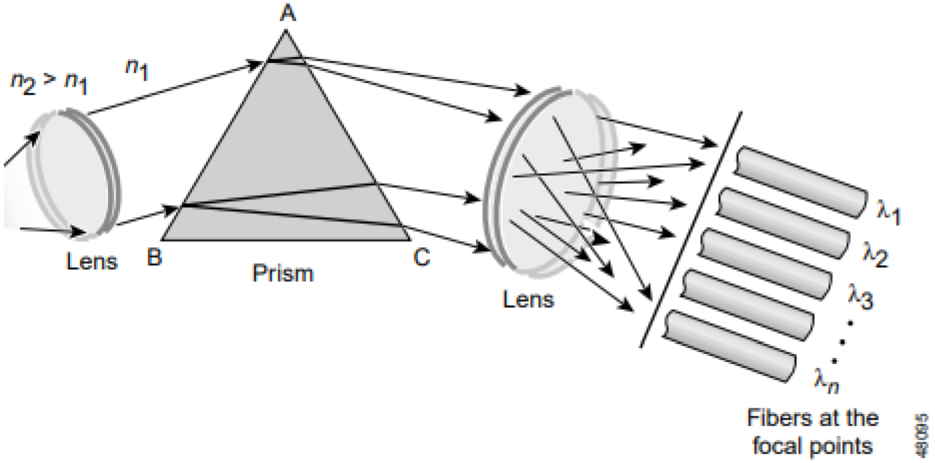
Demultiplexing must be done before the light is detected, because photodetectors are inherently broadband devices that cannot selectively detect a single wavelength.

MUX and DEMUX Operation

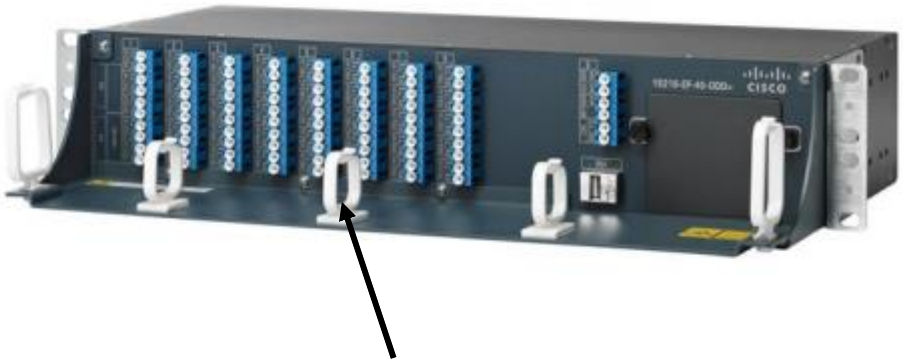


Mux-Demux Operation





Passive multiplexers Cisco ONS 15216



40 ports

Figure 2. 40-Channel Standalone Configuration

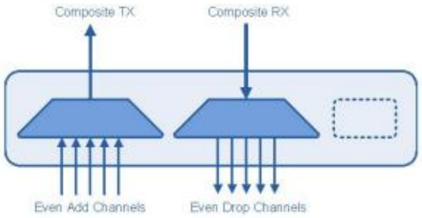


Figure 3. 40-Channel In-Service Upgrade to 80 Channel Standalone Configuration

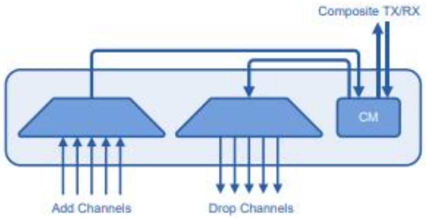
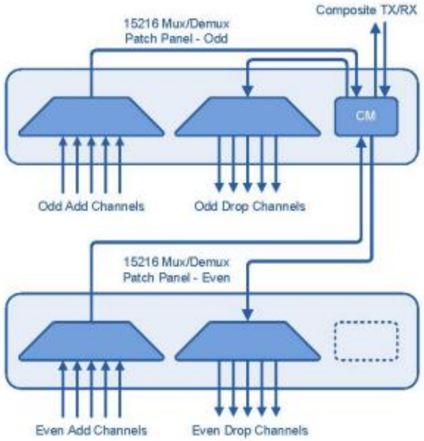
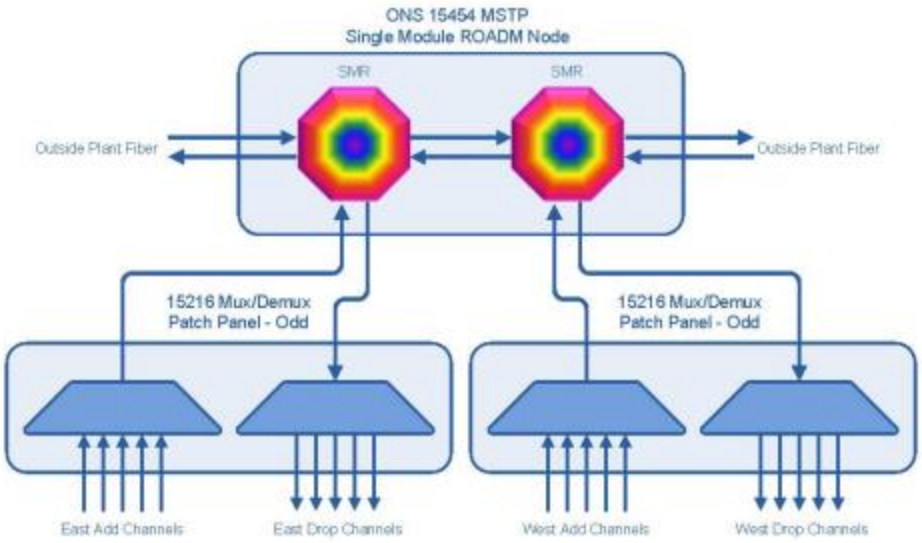


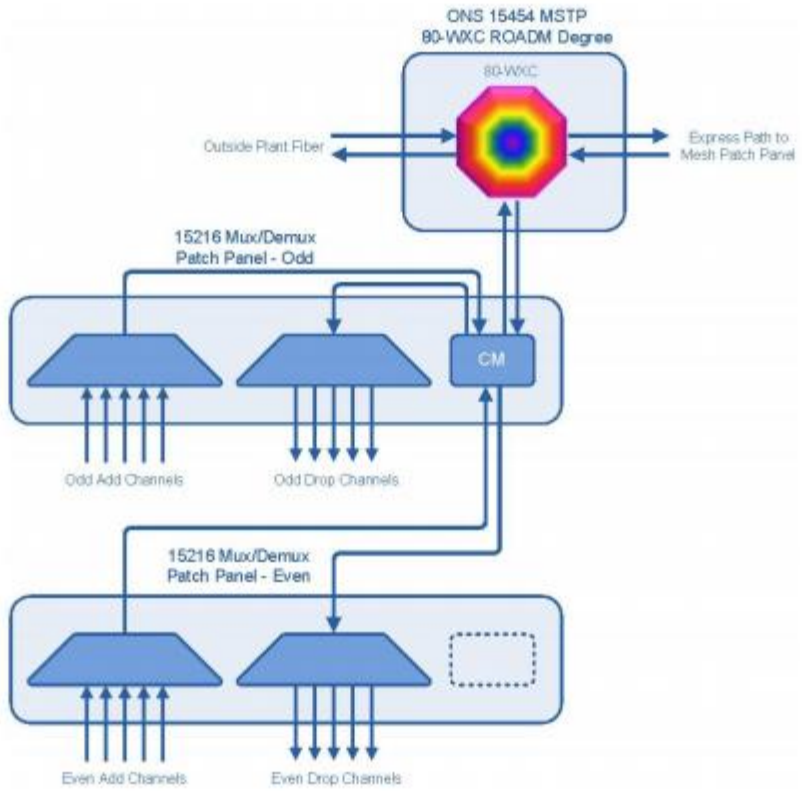
Figure 4. 80 Channel Standalone Configuration



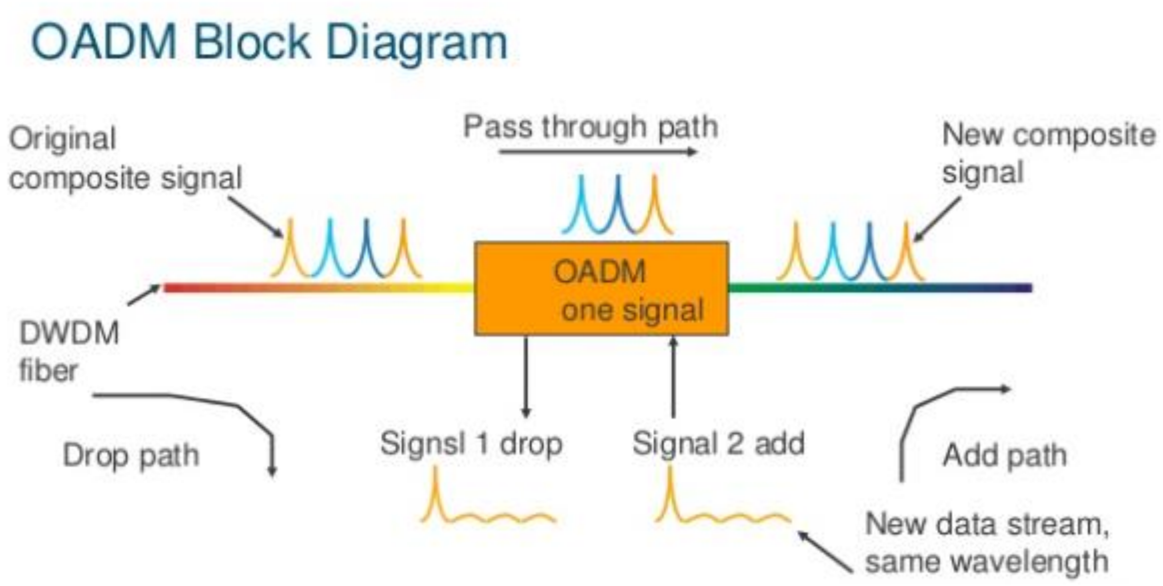
40 channel dual side scheme



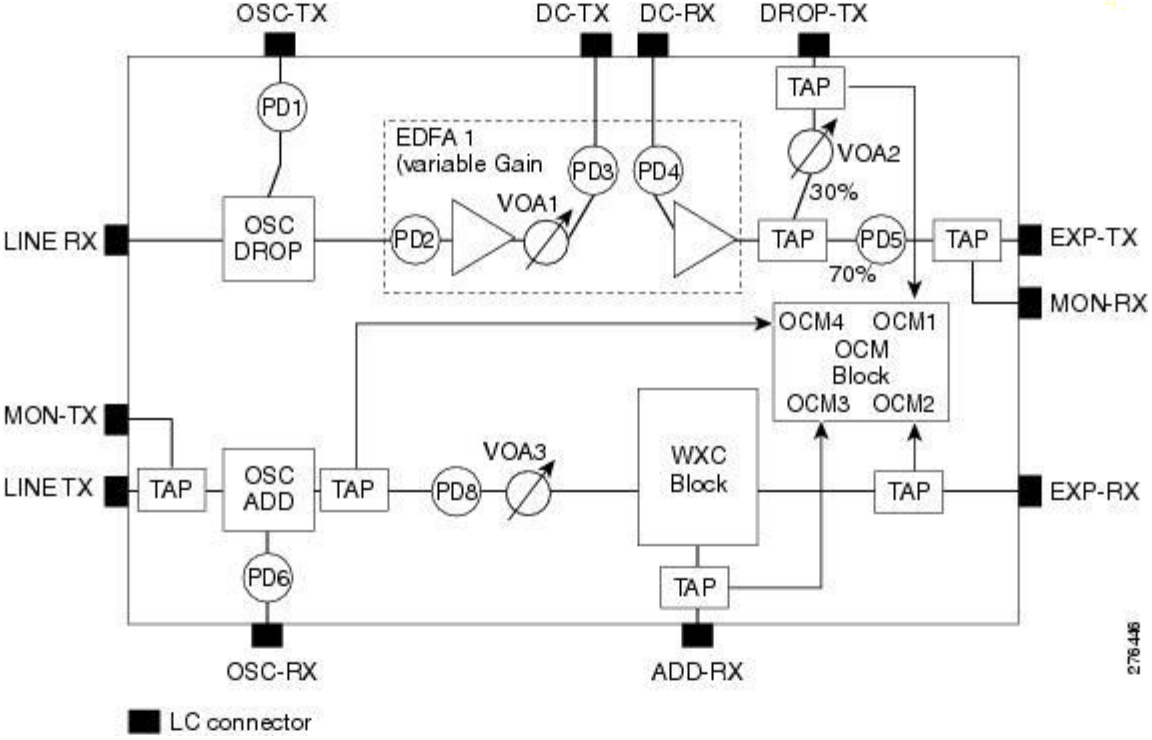
80-channel multidegree



OADM Functionality

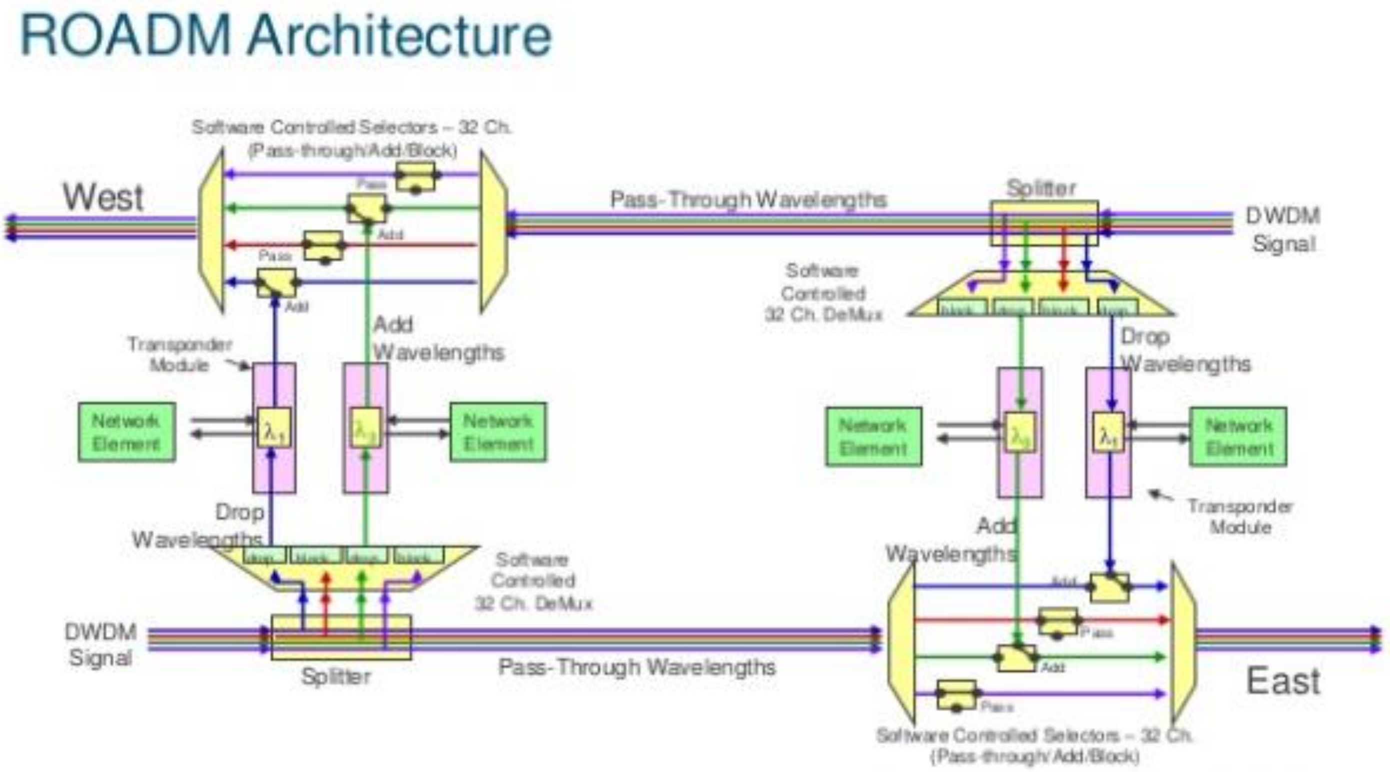


ROADM Model



1. 1. The “LINE-RX” is where the light coming
2. in from the previous site enters the card.
3. For now, ignore the “LINE-TX”, but
4. yes – that’s where light going to that site exits.

ROADM ARCHITECTURE



Optical Sides

From a topological point of view, all DWDM units equipped in an MSTP node belongs to a side.

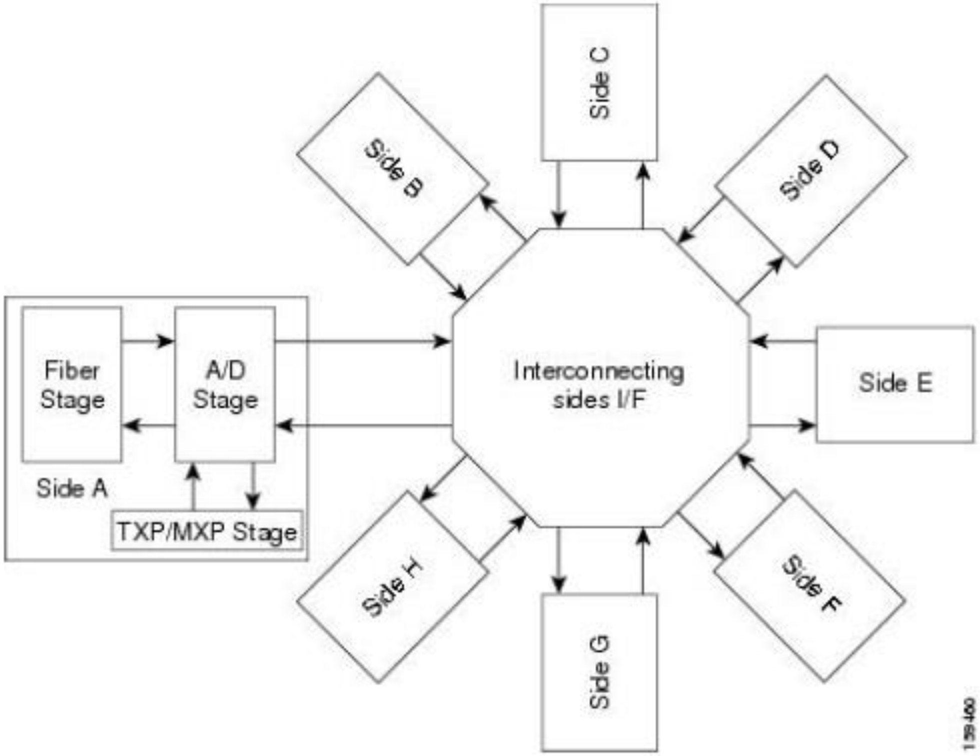
A side can be identified by a letter (A, B, C, D, E, F, G, or H), or by the ports (called as side line ports, that are physically connected to the spans.

An MSTP node can be connected to a maximum of 8 different spans.

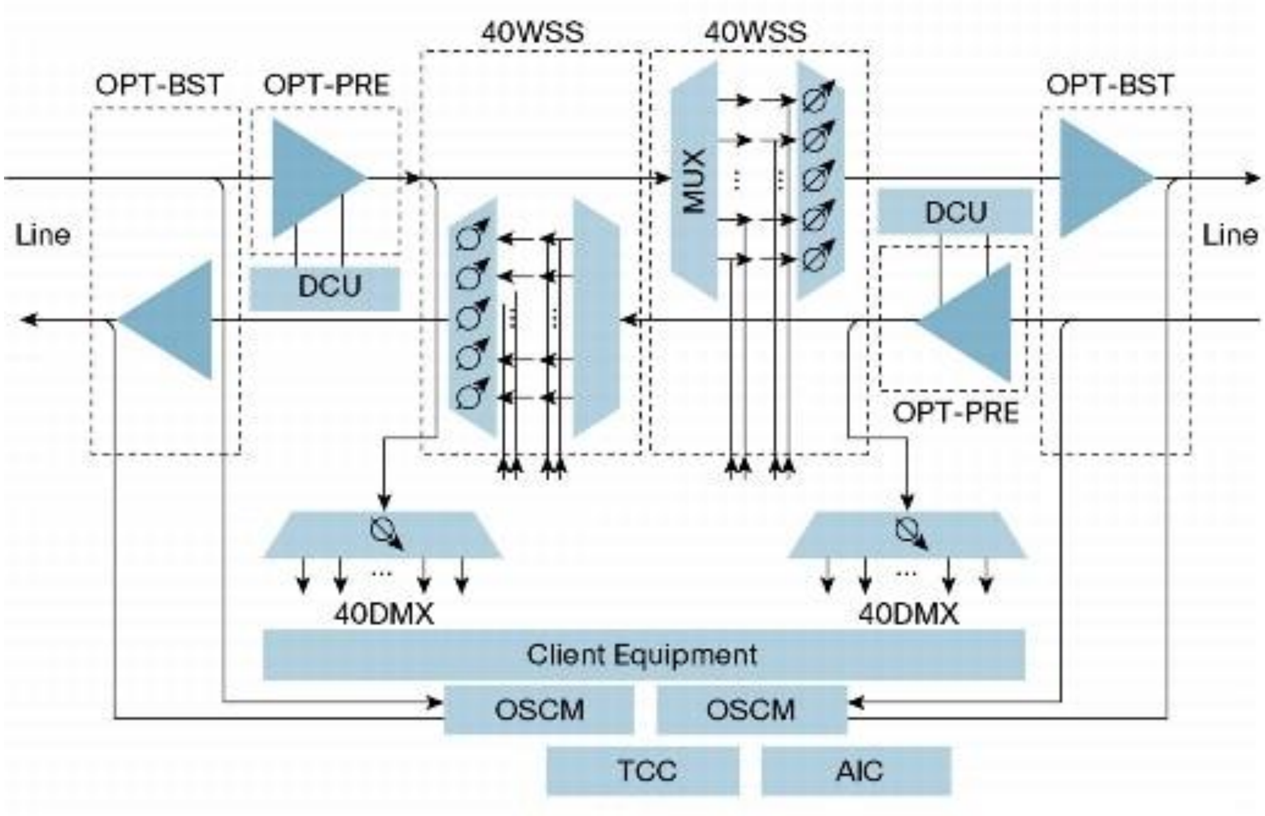
Each side identifies one of the spans the MSTP node is connected to.

Side A and Side B replace “west” and “east” when referring to the two sides of the ONS 15454 shelf. Side A refers to Slots 1 through 6 (formerly “west”), and Side B refers to Slots 12 through 17 (formerly “east”).

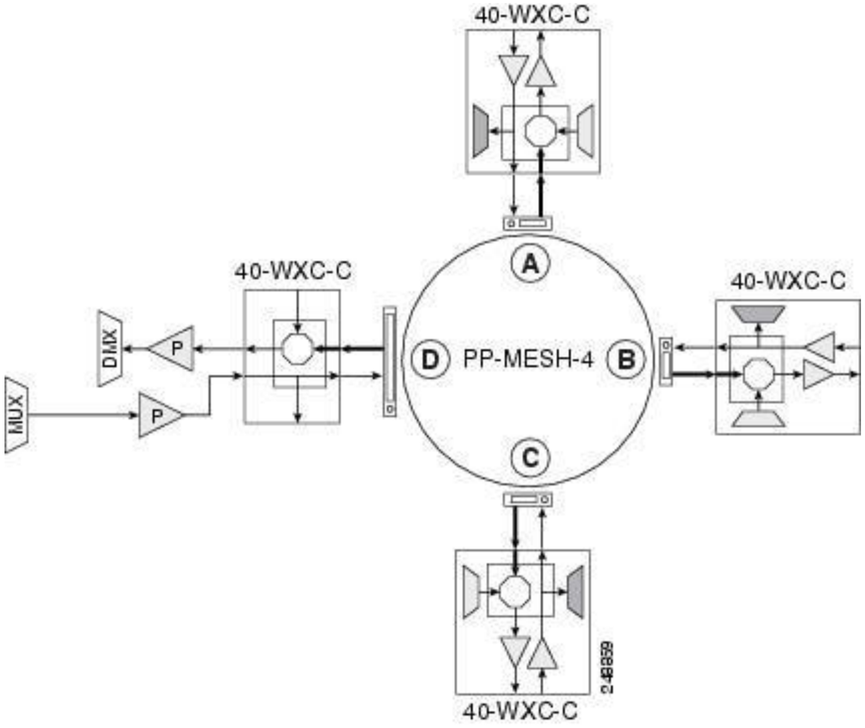
Site Model


Side C
Side B
Side D
Fiber Stage
A/D Stage
Side A
TXP/MXP Stage
Interconnecting sides I/F
Side E
Side H
Side G
Side F
159460

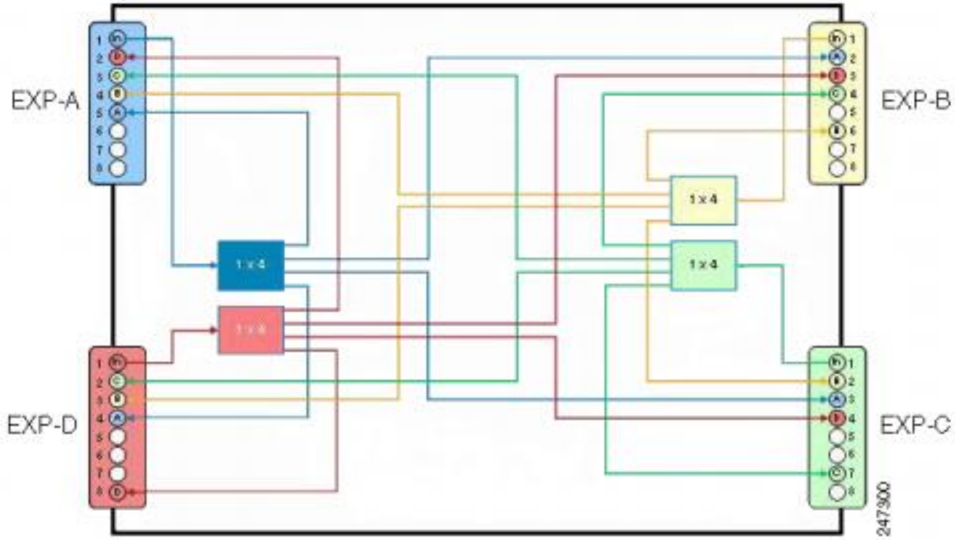
2-Side Add Drop Architecture



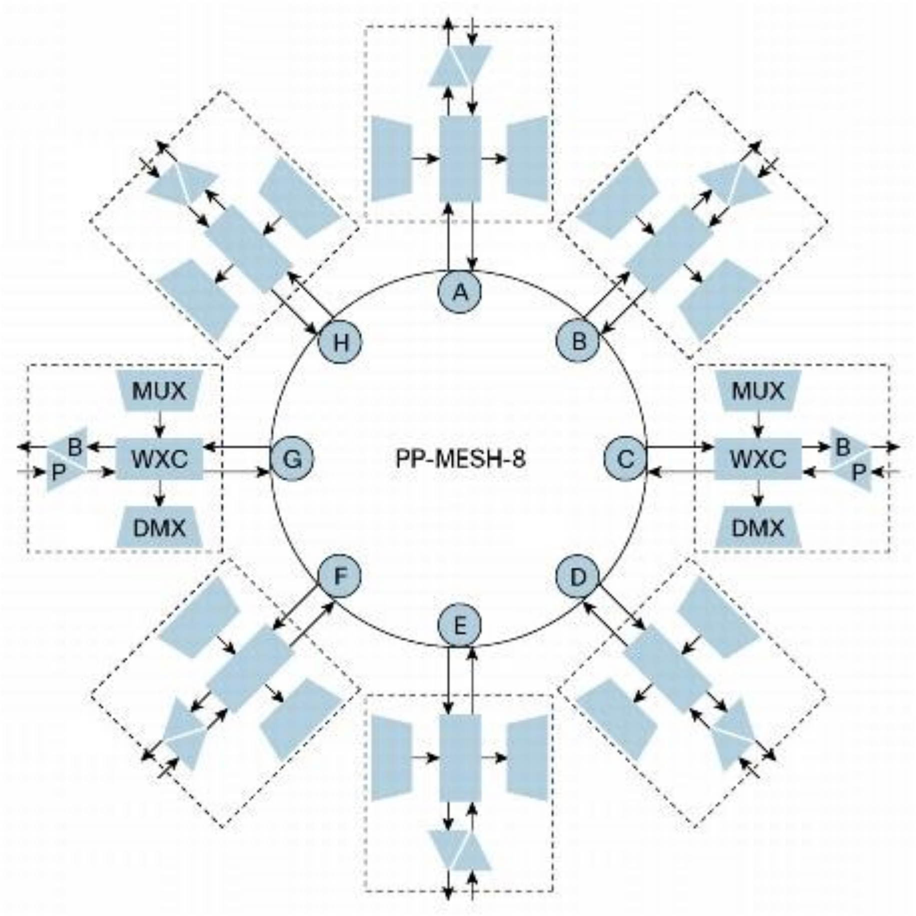
4 - Degree Site 40 channels



PP-MESH-4



8 Degree Site



Single Module ROADM

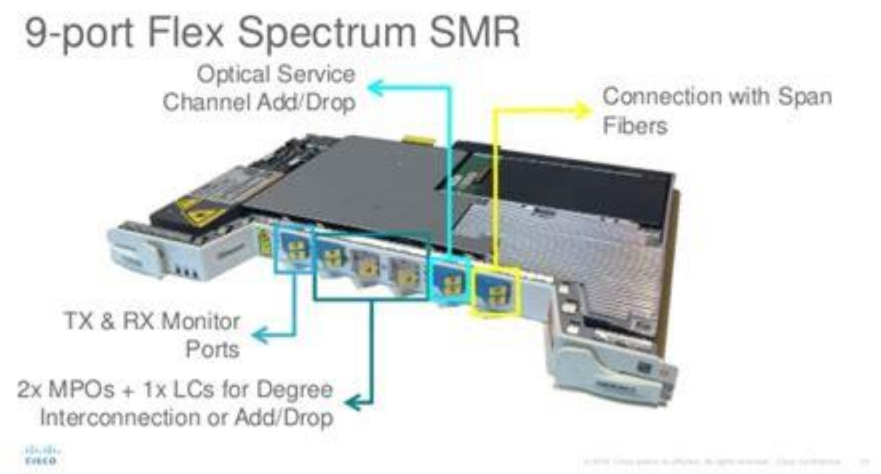
SMR-1

SMR-9

40-channel single-module ROADM with integrated optical pre-amplifier (part number 40-SMR1-C) combines the OSC add/drop filter, a pre-amplifier, and a 2x1 wavelength selective switch (WSS)-based ROADM core into a single-slot unit. This unit is optimized for Degree-2 reconfigurable nodes.

40-channel single-module ROADM with integrated optical pre-amplifier and boost amplifier (part number 40-SMR2-C) includes the OSC add/drop filter, pre- and boost amplifiers, and a 4x1 WSS-based ROADM core. This unit provides an effective way to support multi-degree nodes up to Degree-4, allowing in-service upgrade from Degree-2 up to Degree-4 at a very competitive price point.

9-SMR Ports



9-port Flex Spectrum SMR

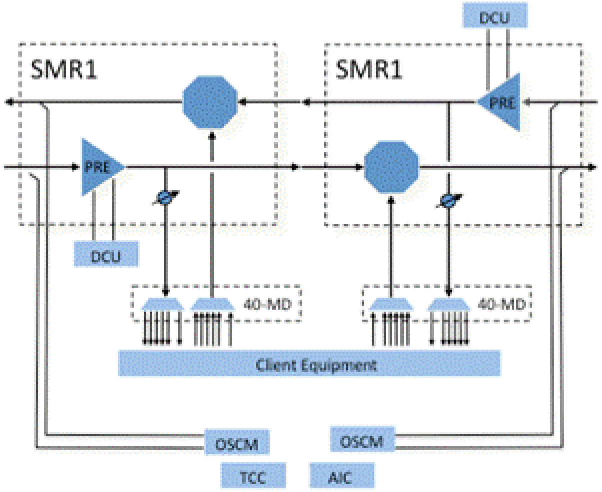
Optical Service Channel Add/Drop

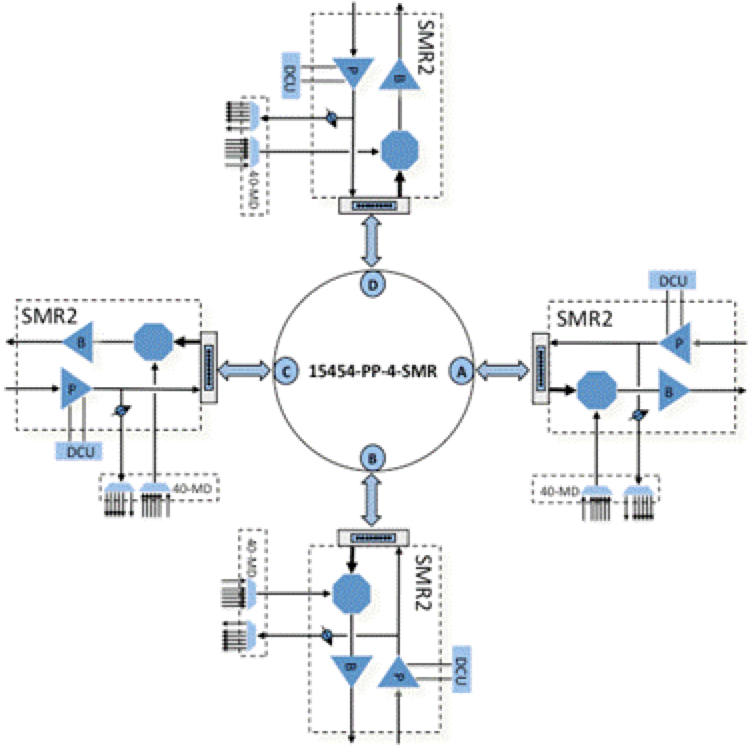
Connection with Span Fibers

TX & RX Monitor Ports

2x MPOs + 1x LCs for Degree Interconnection or Add/Drop

Logical Diagrams for SMR



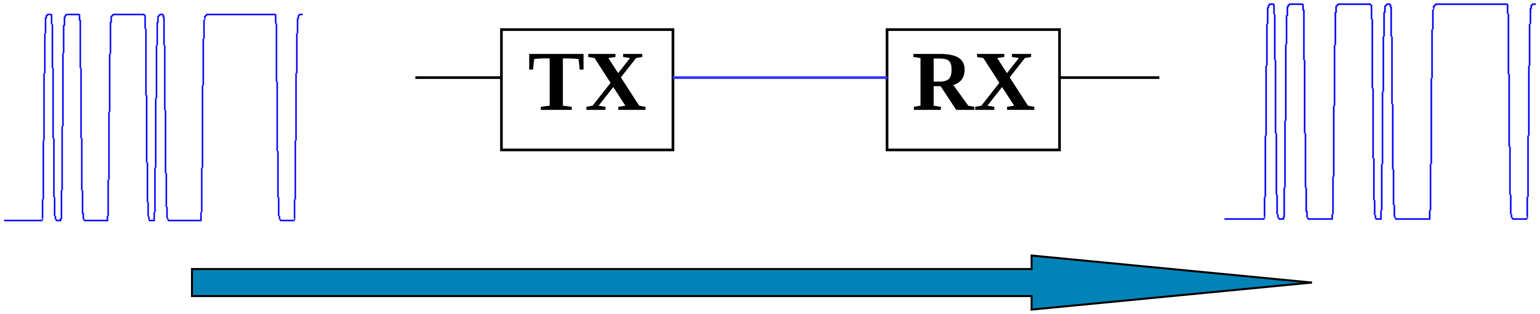


Bit Error Rate (BER)

- BER is a key objective of Optical System Design

  BER is the number of erroneous bits received divided by the total number of bits transmitted over a stipulated period

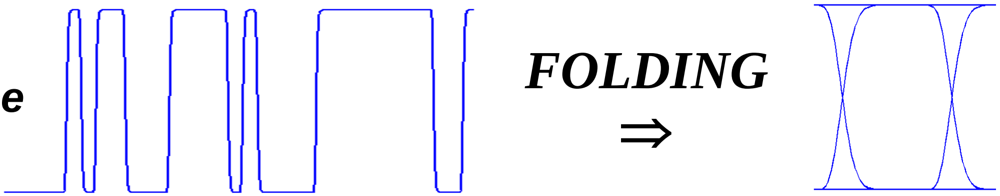
- Goal is to get from the Tx to Rx with a BER less than the BER threshold of the Rx
- Typical minimum acceptable system BER is 10^{-12} (10^{-15} with Forward Error Correction)



- With no noise
- With no Inter Symbol Interference

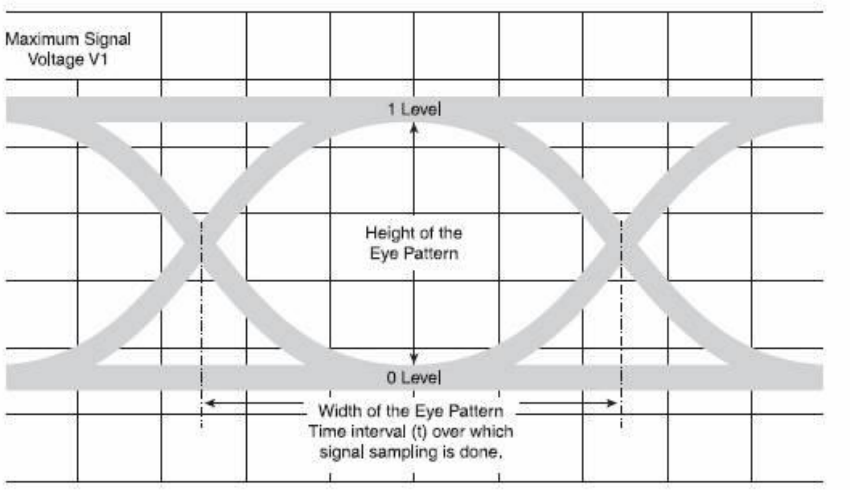
⇒ BER=0 independent of power

Eye Diagram



Tx bit sequence

FOLDING
⇒



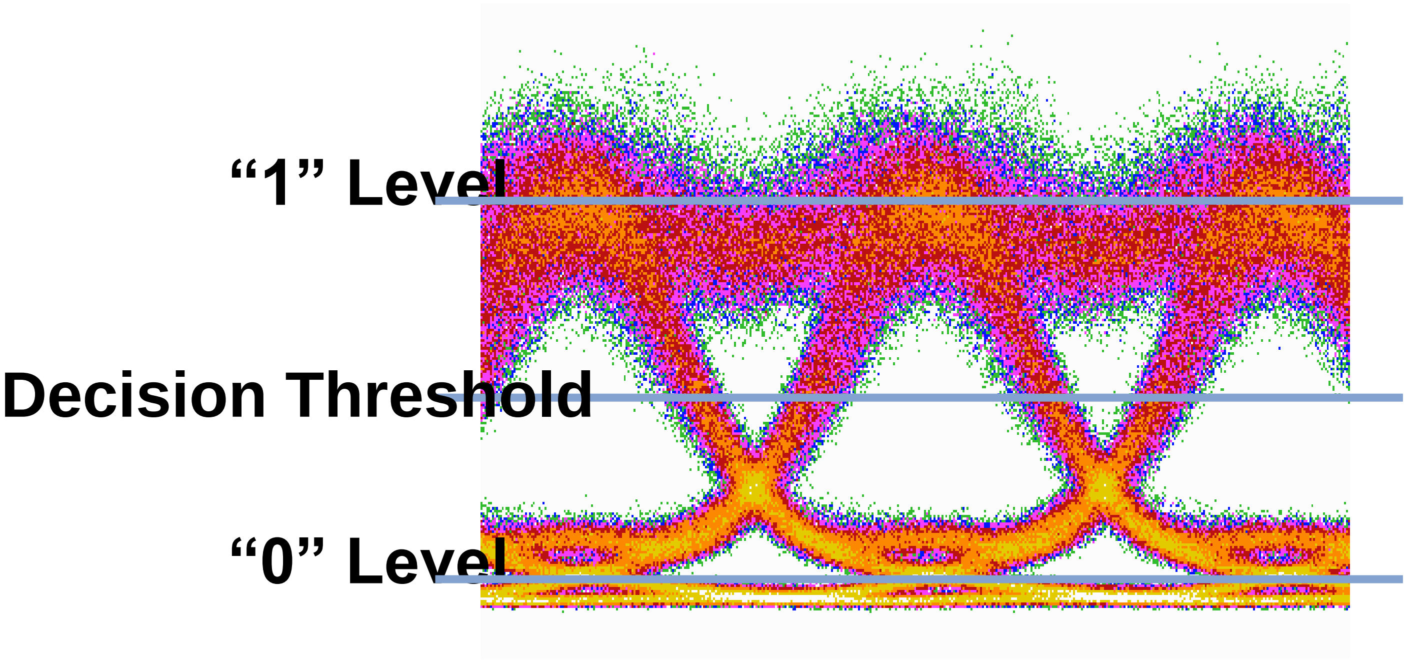
- **The vertical eye opening shows the ability to distinguish between a 1 and a 0 bit**
- **The horizontal opening gives the time period over which the signal can be sampled**

Bit Errors in Signal Transmission

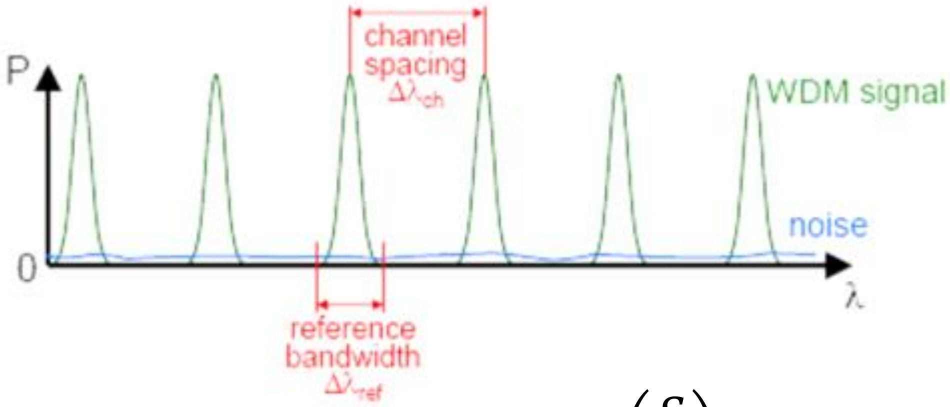
What causes bit errors:

- Noise introduced through receivers and amplifiers
- Pulse shape distortion introduced through dispersion and non-linear effects

These contribute to errors in bit detection when determining if a bit is a “1” or a “0”



OSNR Definition



$$OSNR_{dB} = 10log\left(\frac{S}{N}\right)$$

Optical Signal to Noise Ratio (OSNR) [dB] is the measure of the ratio of signal power to noise power in an optical channel.

OSNR is Complex

Optical signal suffers more than only attenuation. In amplitude, spectrally, temporally signal interaction with light-matter, light- light, light-matter-light leads to other signal disturbances such as :

- Power reduction
- Dispersion
- Polarization
- Unbalanced amplification

Thus leading to random noise, which causes misalignments, jitter and other disturbances resulting in erroneous bits, the rate of which is known as ***bit-error-rate***

OSNR and BER

Because of all possible influences outlined bits transmitted by source and bits arriving at the receiver may not have the same value. In actuality a threshold value is set at the receiver, above the threshold refers to a logic “one” and below threshold refers to a logic “zero”.

$$\text{BER} = \frac{\text{no. of incorrect received bits}}{\text{no. of transmitted bits}}$$

In order to measure BER in photonic regime, the optical signal is converted to electrical signal.

Given the OSNR, the empirical formula to calculate BER for single fiber is

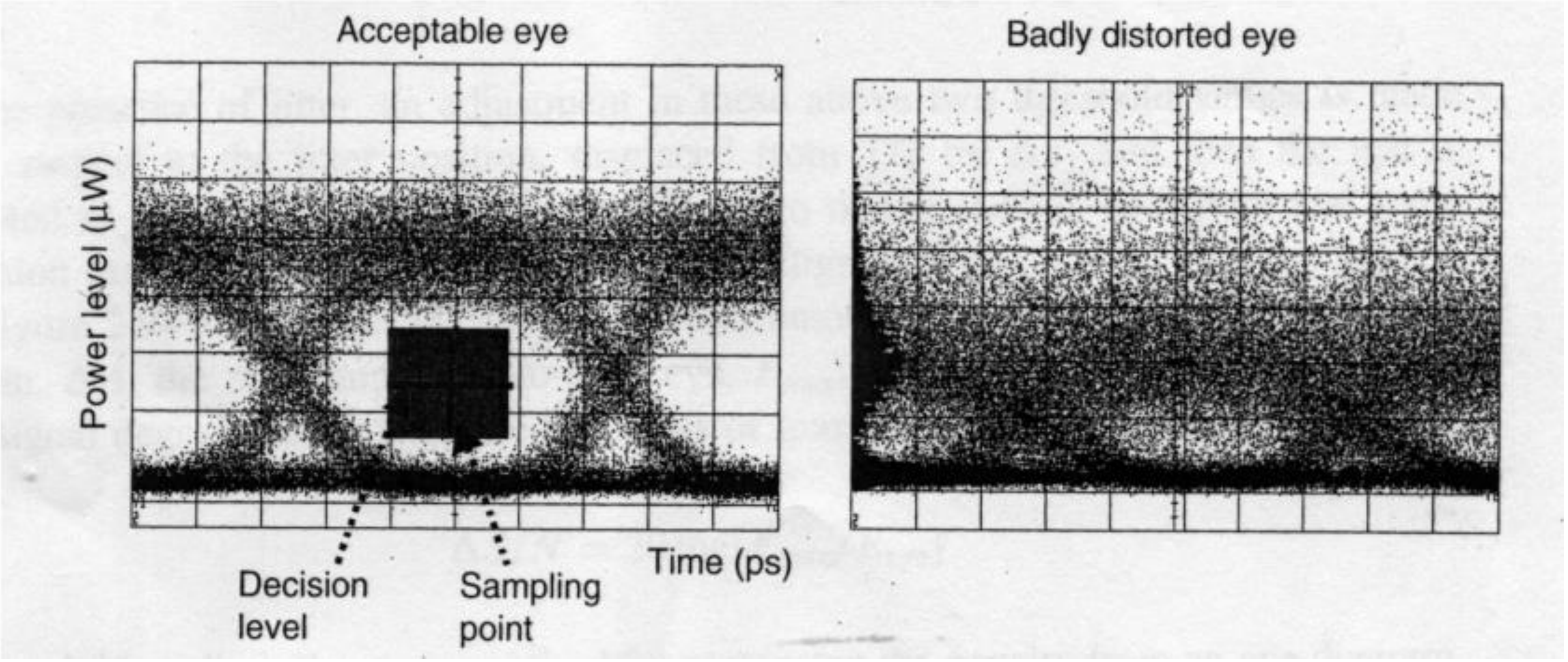
$$\log(BER) = 10{,}7 \ - 1{,}45(OSNR_{dB})$$

Example:

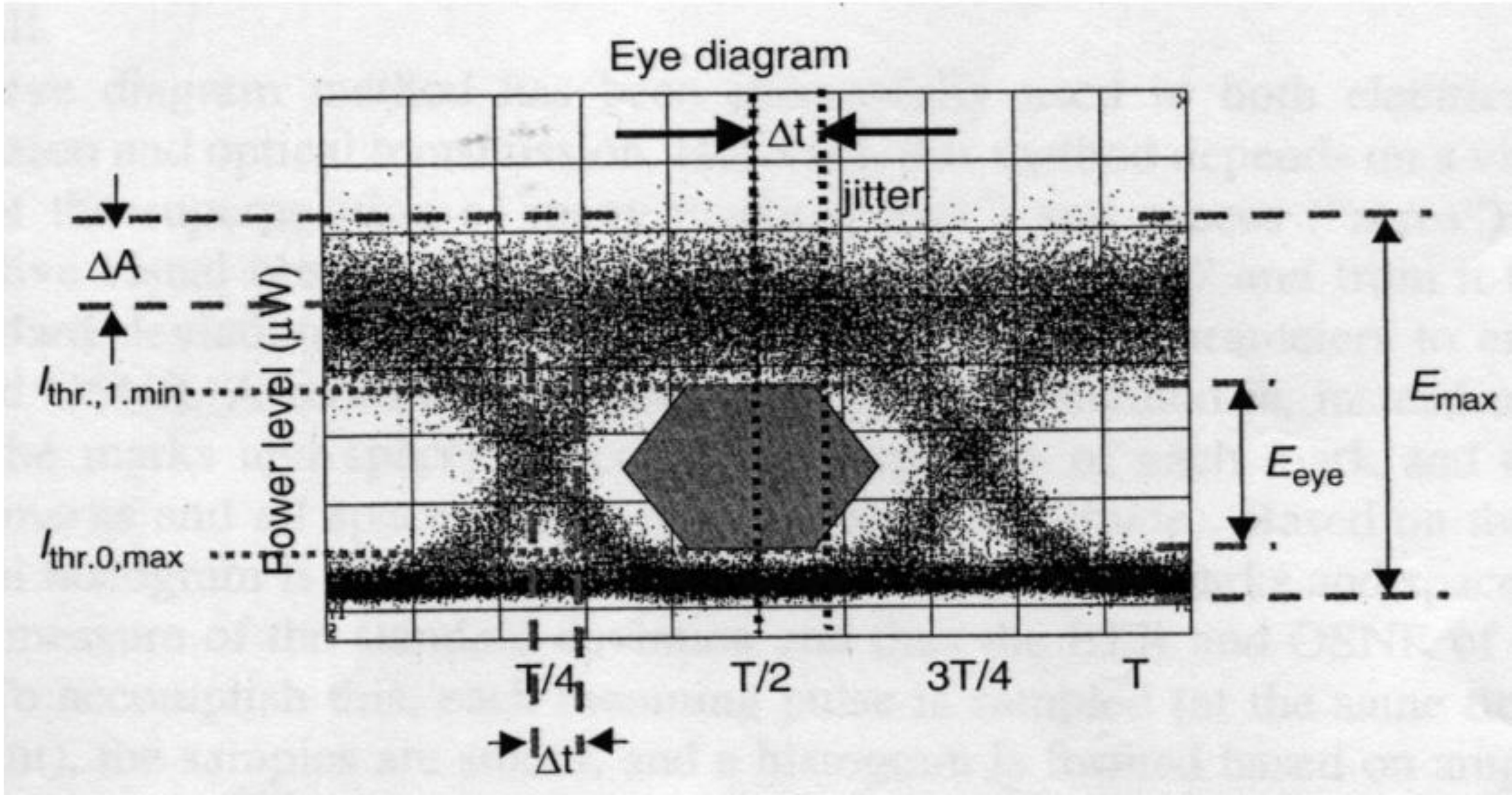
Assume that OSNR = 14.5 dB
ThenLog10 (BER) = 10.7-1.45 (14.5) = -10.30

Therefore BER = $10^{(-10.30)}$
BER is approx 10^{-10}

Eye Diagram


Acceptable eye
Badly distorted eye
Power level (μW)
Time (ps)
Decision level
Sampling point

Measuring Eye Diagram



Quality Factor (Q)

If the standard deviation for logical bit “1” is σ_1 and the standard deviation for logical bit “0” is σ_0 , then:

$$Q = \frac{E_{eye}}{\sqrt{|\sigma_1^2 - \sigma_0^2|}}$$

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$

OSNR DEFINITION

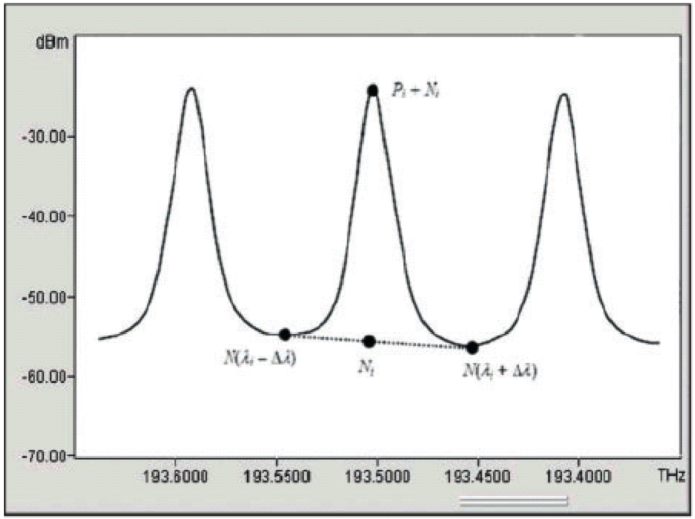
Measures the degree of impairment when the optical signal is carried by an optical transmission system that includes optical amplifiers.

Optical Signal to Noise Ratio, expressed in dB, is given by the following:

- $OSNR=10 \times \log(P_{sig}/N) + \log(B_m/ B_r)$

where:

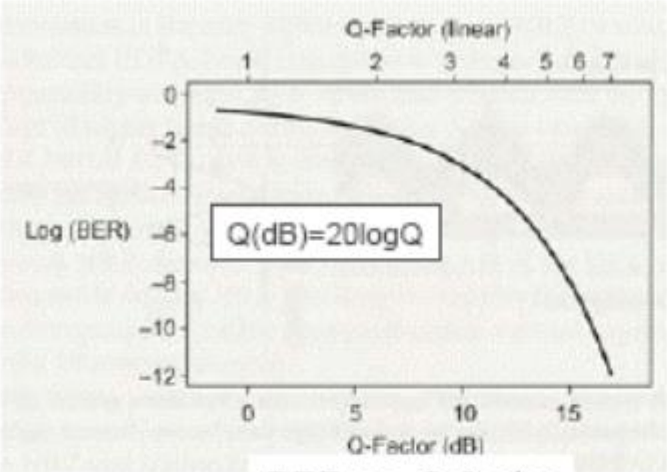
- P_{sig} is the optical signal power (mW)
- B_m is the resolution bandwidth (nm)
- Nis the noise power measured in B_m (mW)
- B_r is the reference optical bandwidth, typically chosen to be 0.1 nm



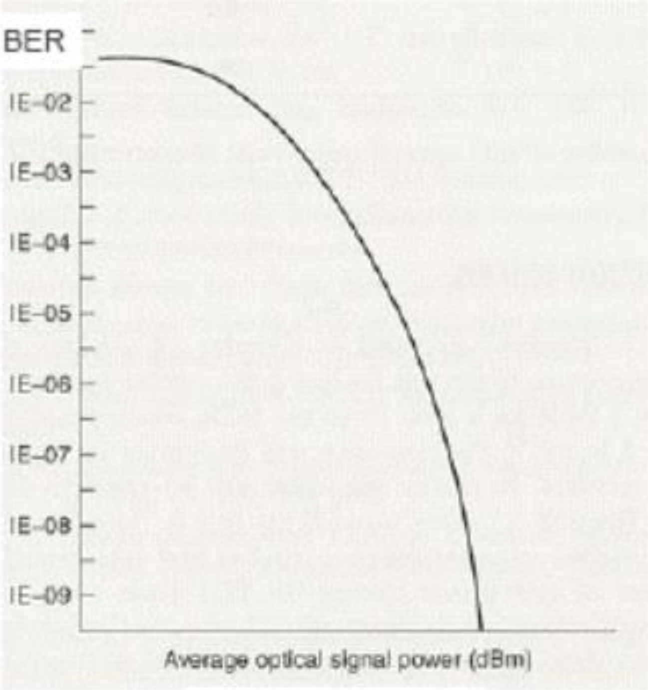
Typical OSNR value in 0.5 nm resolution bandwidth is >10 dB

$$logBER = 10{,}7 - 1{,}45(OSNR)$$

Q Factor and BER



BER vs. Q-factor



BER vs. $P_{received}$

Receptor Ideal

- Um receptor ideal pode ser visto como um contador de fótons.
- Obviamente há outras limitações para o desempenho de um receptor que serão vistas posteriormente
- O receptor examina a presença ou ausência de luz durante o intervalo de um bit. Se não há luz, infere-se que um bit zero foi transmitido, se alguma luz é vista infere-se que foi transmitido um bit 1.
- Esta operação é chamada *detecção direta.*
- Mesmo na ausência de outros problemas isso não implica em um detetor livre de erros porque o processo de chegada e contagem de fótons no receptor é aleatório.
- Um sinal de luz chegando com potência P, pode ser pensado como um feixe de fótons com taxa média P/hf_c (fótons/segundo). Este feixe pode ser analisado como um processo de Poisson.

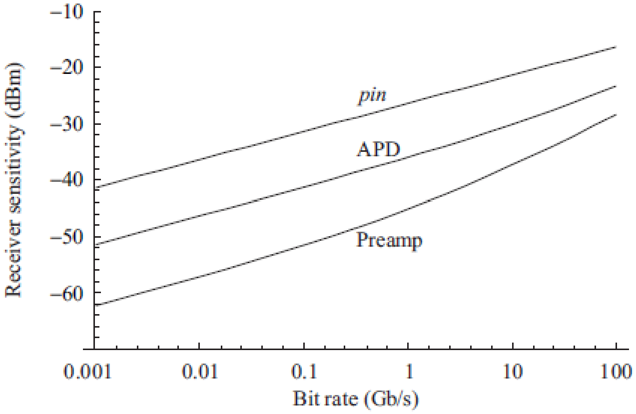
Critério de Detecção e taxa de erros

- O detetor ideal não comete erros quando um bit 0 é transmitido.
- Contudo, quando um bit 1 é enviado, o detetor pode decidir que foi enviado um bit 0, se nenhum fóton é detetado durante o período do bit.
- Se a taxa de bits é B (bits/s), então a probabilidade de n fótons serem recebidos durante um intervalo de bit, 1/B, é:

$$P(n\ fotons \mid 1\ bit) = e^{-(P/hf_cB)} \frac{\left(\frac{P}{hf_cB}\right)^n}{n!}$$

- Desta forma basta fazer n = 0 para ter a probabilidade de zero fótons.
- Assumindo que 0s e 1s são equiprováveis, tem-se: $BER = \frac{1}{2} e^{-\frac{P}{hf_cB}}$
- Chamando M o expoente acima, vem: BER = ½ e^{-M}, o que implica em 27 fótons para uma taxa de erros de 10^{-12}

Sensibilidade do Receptor PIN e APD



A figura mostra a sensibilidade dos foto-receptores PIN calculados com $\eta = 1$ $R = 1{,}25$ A/W e $\gamma = 7$, o que corresponde a um BER de 10^{-12}.

Na mesma figura é apresentada a sensibidade de um diodo APD com $k_A = 0{,}7$ e $G_m = 10$. Note a vantagem de 10 dB do APD.

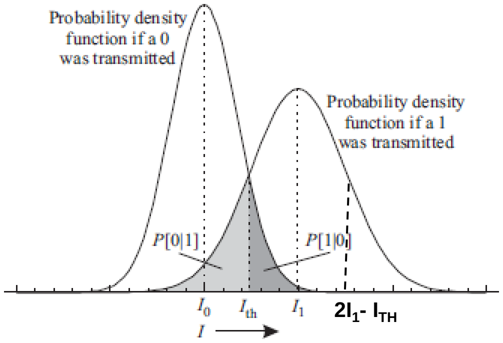
A sensibilidade com pré-amplificador foi calculada como discutido a seguir, com figura de ruído de 6 dB para o amplificador óptico e banda passante óptica de 50 GHz, sendo o sinal filtrado antes do amplificador.

São comercialmente disponíveis detectores PIN para 10 Gbits/s com sensibilidade de -18 dBm e detectores APD com sensibilidade de -24 dBm.

Probabilidade de erro

$$I_{th} = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1}$$

$$P[0/1] = \frac{1}{\sqrt{2\pi}\sigma_1}\int_{2I_1-I_{TH}}^{\infty} e^{-\frac{(x-I_1)^2}{2\sigma_1^2}}\,dx$$



Fazendo: $y = \frac{x - I_1}{\sigma_1}$

$$P[0/1] = \frac{1}{\sqrt{2\pi}}\int_{\frac{I_1-I_{TH}}{\sigma_1}}^{\infty} e^{-\frac{y^2}{2}}\,dy = Q\left(\frac{I_1 - I_{TH}}{\sigma_1}\right)$$

Analogamente: $P[1/0] = Q\left(\frac{I_{TH}-I_0}{\sigma_0}\right)$

A partir desses resultados é fácil mostrar:

BER = ½ P[0/1] + ½ P[1/0] = $Q\left(\frac{I_1-I_0}{\sigma_0+\sigma_1}\right)$

Assim, conhecendo as fotocorrentes médias e as variâncias de ruído o BER pode ser calculado

Observações

A função Q é calculada numericamente e tabelada. Seja $\gamma = Q^{-1}(BER)$, para BER = 10^{-12} deve-se ter $\gamma \approx 7$ e para BER = 10^{-9} deve-se ter $\gamma \approx 6$

O método aqui utilizado para cálculo do BER só é viável na prática se o transponder permitir ajuste do nível de detecção. Muitos produtos comerciais usam um nível fixo em $(I_1 + I_0)$ o que resulta em um BER maior.

No caso acima, o BER é calculado como: $BER = \frac{1}{2}\left[Q\left(\frac{I_1 - I_0}{2\sigma_1}\right) + Q\left(\frac{I_1 - I_0}{2\sigma_0}\right)\right]$

Frequentemente, ao invés de calcular o BER deseja-se saber a potência necessária para atingir um BER especificado. A sensibilidade do receptor é definida como a mínima potência média para conseguir um BER especificado (geralmente 10^{-12}). Um receptor mais sensível consegue o mesmo BER com menos potência óptica.

A sensibilidade é dada por: $\bar{P}_{sens} = \frac{P_0 + P_1}{2}$ e com $P_0 = 0$, resulta $P_1 = 2P_{sens}$.

A sensibilidade também pode ser expressa como o número de bits necessário para detecção de um bit 1 com a BER dada: $M = \frac{2\bar{P}_{sens}}{hf_cB}$

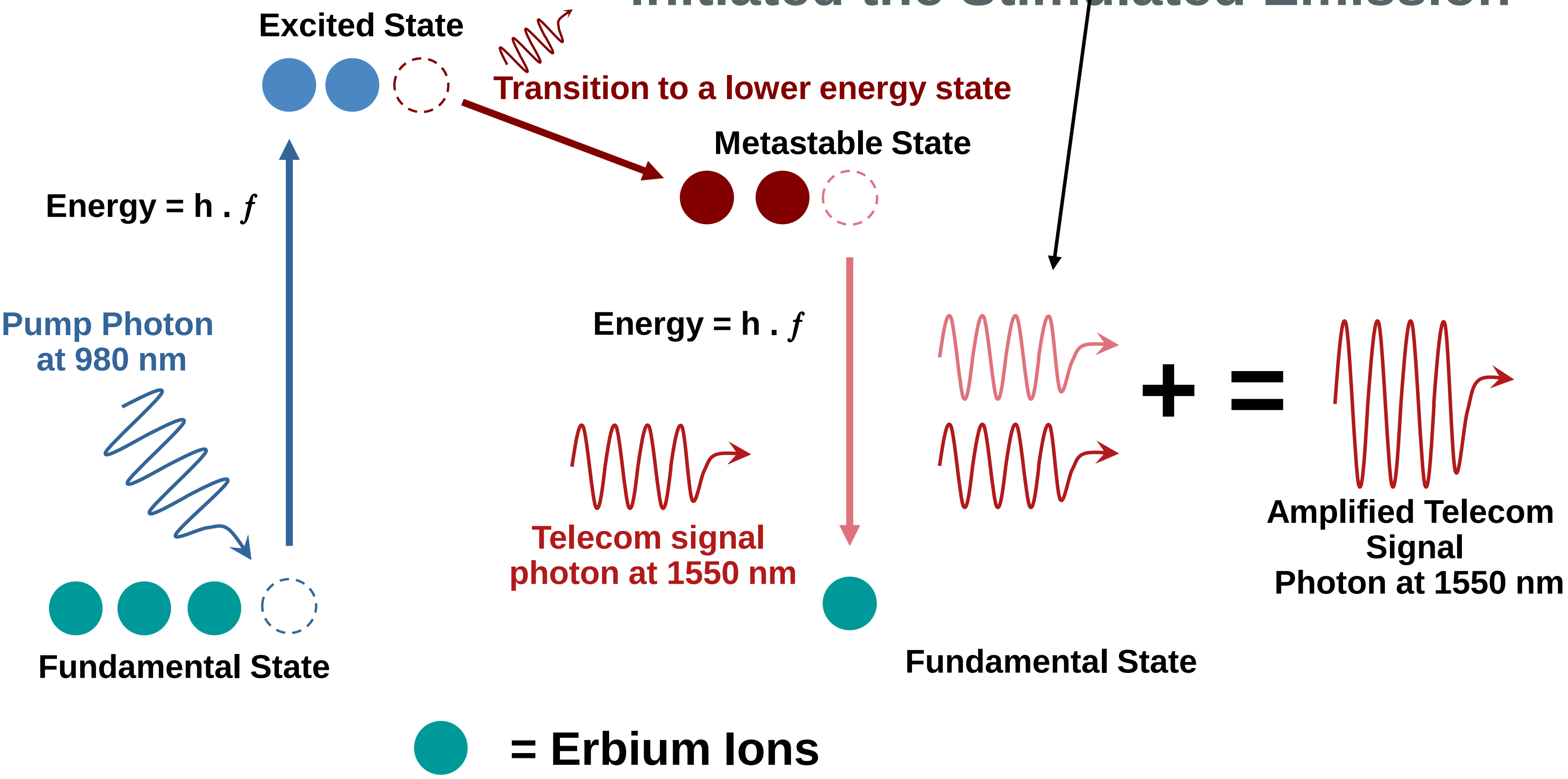
Optical Amplifiers

Erbium Doped Fiber Amplifier (EDFA)

- Erbium Doped Fiber Amplifiers (EDFA)
  - Operating range: C-band: 1530 to 1565 nm
    L-band: 1605 to 1625nm
  - Gain up to 30 dB, 1000x amplification for small signals
  - High output saturation power up to +27 dBm, 500 mW
- Low signal distortion and cross-talk
- Optically Transparent
  - Signal format and Bit rate independent

EDFA Gain Mechanism

- The photon generated by the decay of the Erbuim ion back to Its fundamental state is in phase with the signal photon that initiated the Stimulated Emission



Excited State

Transition to a lower energy state

Metastable State

Energy = h . *f*

Pump Photon at 980 nm

Energy = h . *f*

+ =

Telecom signal photon at 1550 nm

Amplified Telecom Signal Photon at 1550 nm

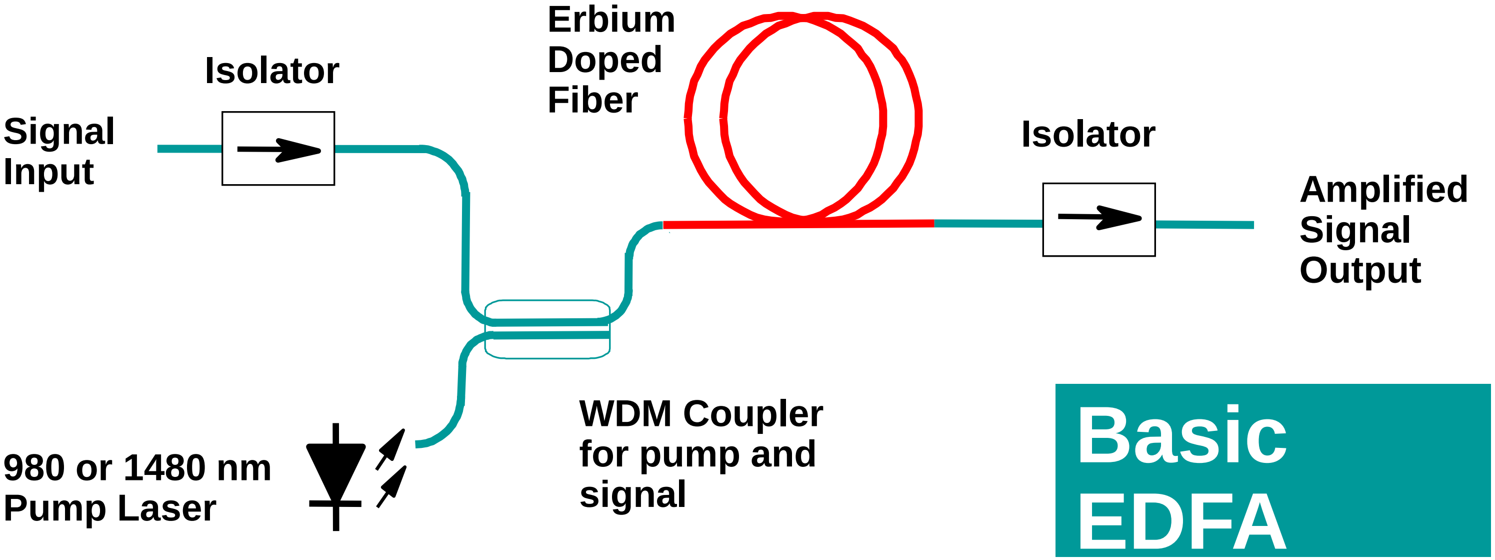
Fundamental State

Fundamental State

● = Erbium Ions

EDFA Components

- Gain though high power pump laser(s) at either 980nm or 1480nm pumping into the absorption bands of the erbium ions
- Input and output isolators stop the EDFA “lasing” due to reflected power passing back through EDFA
- WDM coupler efficiently combines pump and signal wavelengths



Signal Input

Isolator

Erbium Doped Fiber

Isolator

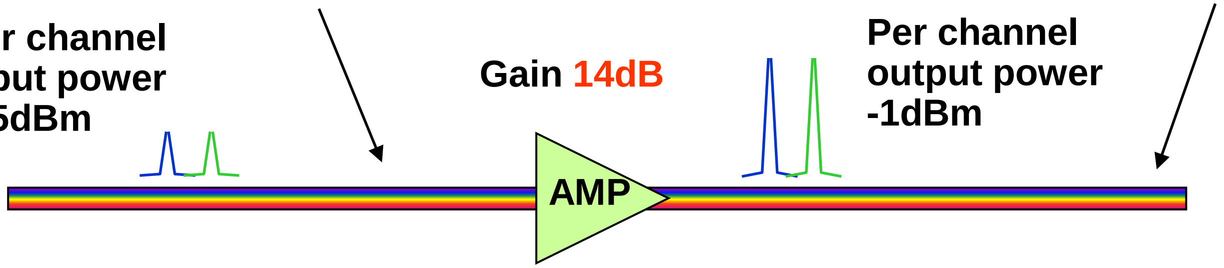
Amplified Signal Output

980 or 1480 nm Pump Laser

WDM Coupler for pump and signal

Basic EDFA

EDFA Modes of Operation



Total Input Power : -12dBm

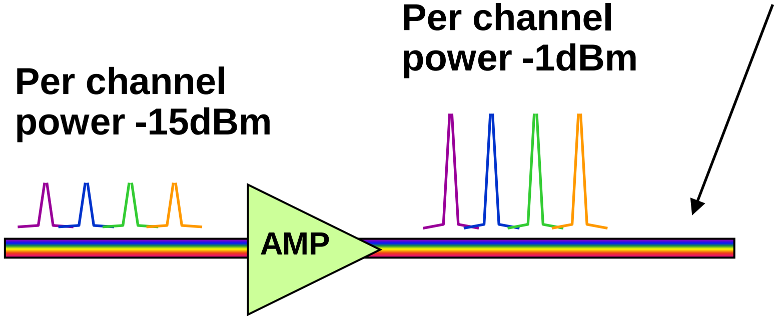
Total Output Power : +2dBm

Per channel input power -15dBm

Gain 14dB

Per channel output power -1dBm

Constant Gain Mode



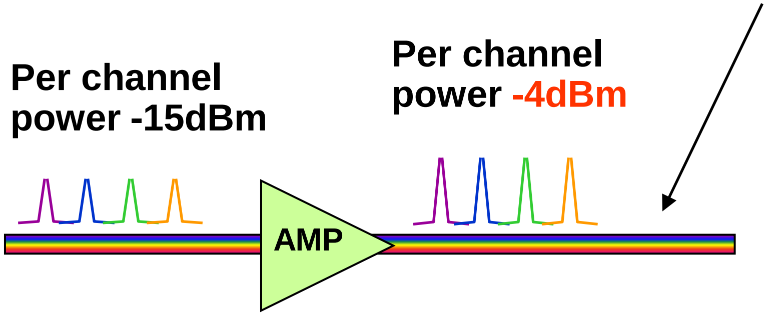
Total Output Power +5dBm

Per channel power -1dBm

Per channel power -15dBm

Gain Stays Constant : Gain 14dB

Constant Power Mode



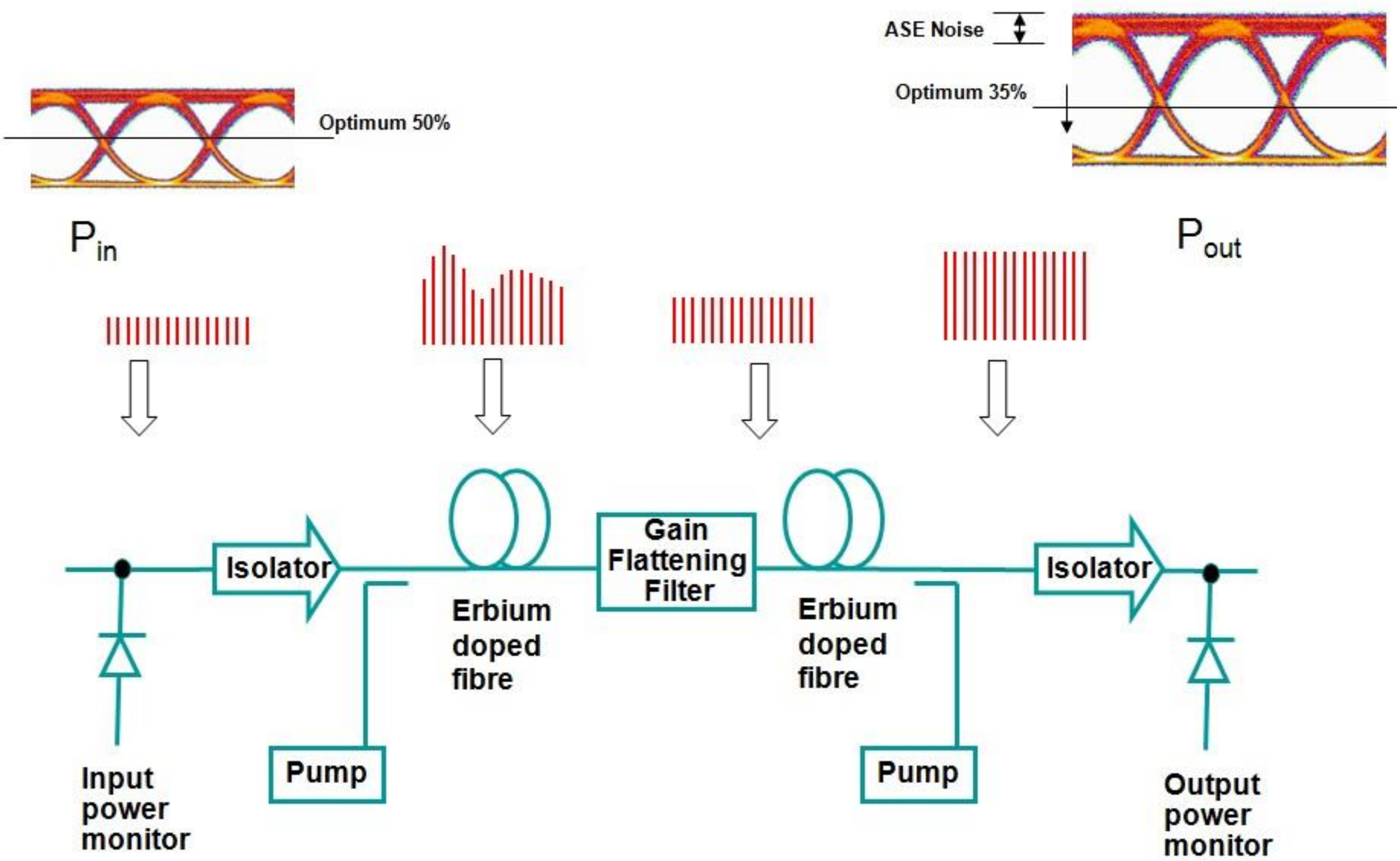
Total Output Power +2dBm

Per channel power -4dBm

Per channel power -15dBm

Total Output Power Constant : +2dBm

Channel Power Evolution Through EDFA



ASE Noise

Optimum 35%

Optimum 50%

P_{in}

P_{out}

Isolator

Erbium doped fibre

Gain Flattening Filter

Erbium doped fibre

Isolator

Input power monitor

Pump

Pump

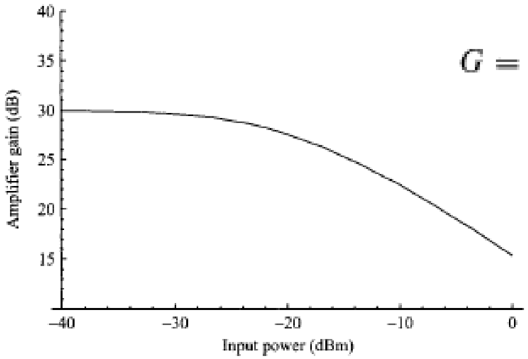
Output power monitor

EDFA OSNR Degradation

- EDFAs are the source of noise, Amplified Spontaneous Emission noise (ASE) in a system
- The difference between the optical power of a channel and the noise power is called the Optical Signal to Noise Ratio, OSNR
- Between EDFAs, the OSNR stays constant
- The lower the input power to the EDFA the lower the OSNR at the output
- The only way to recover OSNR is via an OEO Regeneration.
- OSNR is tracked on a per channel basis, each channel will have a different OSNR

Every optical interface (line card, Transponder etc) has a minimum OSNR

Gain Saturation in EDFA



$$G = 1 + \frac{P^{\mathrm{sat}}}{P_{\mathrm{in}}} \ln \frac{G_{\max}}{G}.$$

G_{max} is the unsatured gain
G is satured gain
P_{in} is the input signal power
P^{sat} is the amplifier’s internal saturation power (10 to 20 dBm)

Amplifier Cascades

Consider a system of total length L with amplifiers spaced l km apart.

The loss between two stages is $e^{-\alpha l}$ where α is the fiber attenuation.

Each amplifier adds some spontaneous emission noise, so optical signal-to-noise ratio, OSNR, gradually degrades along the chain.

Suppose the unsaturated amplifier gain to be larger than the loss between stages.

For the first few stages, the total input power (signal plus noise from the previous stages) to a stage increases with the number of stages.

Consequently, the amplifiers begin to saturate and their gains drop.

Farther along the chain, a spatial steady-state condition is reached where the amplifier output power and gain remains the same from stage to stage.

Amplifier Cascades: steady-state

The steady-state behavior can be found, solving:

$$\underbrace{(\overline{P}_{\text{out}}e^{-\alpha l})}_{\text{Total input power}}\overline{G} + \underbrace{2P_n B_o(\overline{G} - 1)}_{\text{Local Emission noise}} = \overline{P}_{\text{out}}.$$

$P_n = n_{sp}hf_c$
n_{sp} = fator de emissão espontânea
h = Planck constant = $6.63 \cdot 10^{-34}$ J/Hz
f_c = carrier frequency
B_o = optical bandwidth

$$\overline{G} = 1 + \frac{P^{\text{sat}}}{\overline{P}_{\text{out}}e^{-\alpha l}} \ln \frac{G_{\max}}{\overline{G}}.$$

Approximate Analysis

The previous equation shows that $\overline{G}e^{-\alpha l} < 1$

The difference is the noise power introduced at each stage

As an aproximattion we can take $\overline{G}e^{-\alpha l} = 1 \Rightarrow \overline{G} = e^{\alpha l}$

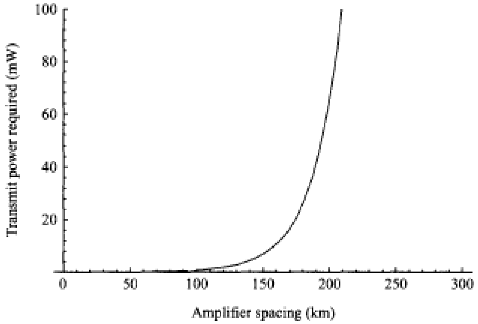
Considering L/l amplifiers and that we wish a given OSNR, we can conclude :

$$P_{noise}^{tot} = 2P_n B_0 \left(\overline{G} - 1\right)\frac{L}{l} = 2P_n B_0 \left(e^{\alpha l} - 1\right)\frac{L}{l}$$

$$P \geq (OSNR).P_{noise}^{tot}$$

The following graph shows how to choose l without non-linearities

Transmit Power versus Amplifier Space



OSNR = 50
n_{sp} = 2
B_0 = 20 GHz
A = 0.22 dB/Km
L = 1000 Km

Amplifier Spacing Penalty

In an amplifier cascade the gain of each amplifier must approximately compensate for the span loss (the loss between two amplifier stages in the cascade).

For a given span length, say, 80 km, this determines the gain of the amplifiers in the cascade.

For example, for a span length of l = 80 km and a fiber loss of $\alpha(dB) = 0.25$ *dB/km,* we get an amplifier gain $G = 20$ *dB.*

We will study the effect of the span length, or, equivalently, the amplifier gain G, on the noise at the output of an amplifier cascade.

This will enable us to then discuss quantitatively the penalty reduction we can obtain by the use of distributed amplifiers, in particular, distributed Raman amplifiers.

Amplifier Spacing Penalty (cont)

- The ideal situation is to have an amplifier totally distributed, this imply $G = 1$, with $N \to \infty$, but with $G^N = e^{\alpha L}$
- Remember that $\lim_{G \to 1} \frac{G-1}{\ln G} = 1$
- The total noise (ASE) can be written as: ($G = e^{\alpha l}$)

$$P_{\text{noise}}^{\text{tot}} = 2L P_n B_o \alpha (G - 1)/\ln G.$$

- Soon, the power penalty correspond to the factor:

$$PP_{\text{lumped}} = \frac{G-1}{\ln G},$$

- For G = 20 dB, PP_{lumped} = 13.3 dB, while for G = 10 dB, PP_{lumped} = 5.9 dB.
- Thus, assuming a = 0.25 dB/km, the total ASE noise in an amplifier cascade can be reduced by more than 7 dB by reducing the amplifier spacing to 40 km from 80 km.