Optical Amplifiers

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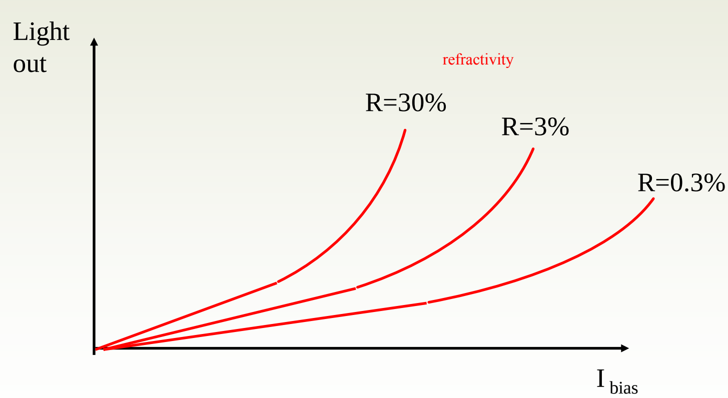
Semiconductor Optical Amplifier, SOA

- Sometimes called Semiconductor Laser Amplifier (SLA), which emphasises the close relationship with a laser diode
- Essentially a laser diode with reflectivities which are the suppressed residual facet reflectivities, which enhances gain but reduces bandwidth and results in a 'cavity resonance' structure to the gain profile with attendant tuning / frequency alignment problems

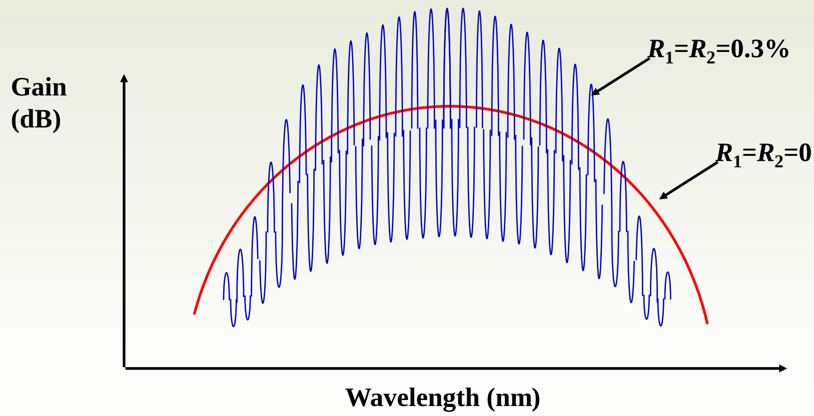
SOA - Continued

- A Travelling Wave SOA with facet reflectivities suppressed given length of device and pumping conditions the signal gain for a TWA is less than for a FP amplifier
- Even a very low level of residual reflectivities can result in significant ‘gain ripple’ associated with the Fabry-Perot mode structure

SOA current -light characteristic



SOA - gain vs wavelength



Some SOA Limitations

- Coupling losses reduce fibre-fibre gain
- Residual facet reflectivities induce gain ripples, particularly problematic for high (internal) gains
- Polarisation sensitive gain due to confinement factor being a function of polarisation since the active area is not symmetrical (greatly improved in more recent designs)
- Gain modulation occurs due to relatively short lifetime

Some SOA advantages

- Available at 1300 nm and 1550 nm by exploiting established semiconductor laser diode technology
- Gain controllable via bias current - allows for relatively rapid gain switching, basis for optical modulation/electronic-controlled optical processing
- Physically small and lends itself to optoelectronic integration (e.g. incorporated with laser transmitter or as an optical pre-amplifier in a receiver

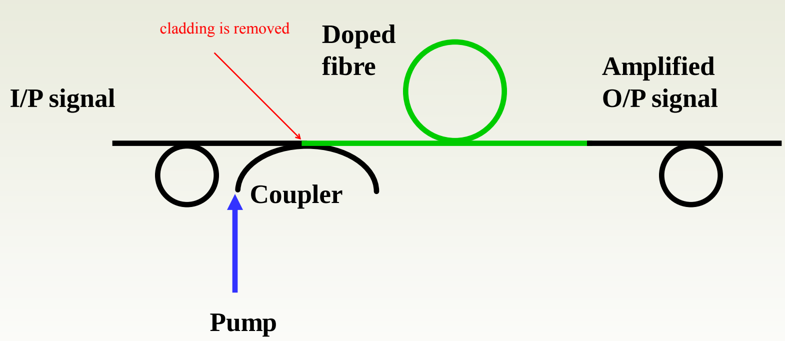
Optical Fibre Amplifiers

- Erbium-doped fibre amplifier (EDFA)
  - Very high performance
    - High output power available
    - Very low noise performance possible
  - Operates in 1550 nm window
  - Fibre-compatible
- Praseodymium doped fibre amplifier
  - Operates in 1300 nm window
  - State of development /performance does not match EDFA
- Alternative fibre amplifiers
  - e.g. Raman fibre amplifier, not so developed / convenient

Rare-earth doped fibre amplifiers

- Erbium, Praseodymium or Ytterbium may be incorporated into silica-based fibre
- Resultant amplifying medium is easily spliced to the system fibre with little loss
- Virtually polarisation insensitive
- We will concentrate on the erbium doped fibre amplifier (EDFA)

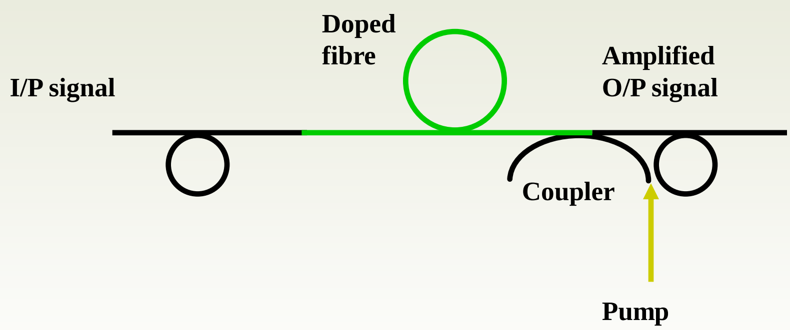
EDFA Schematic - 1



- Forward (co-directional) pumping arrangement

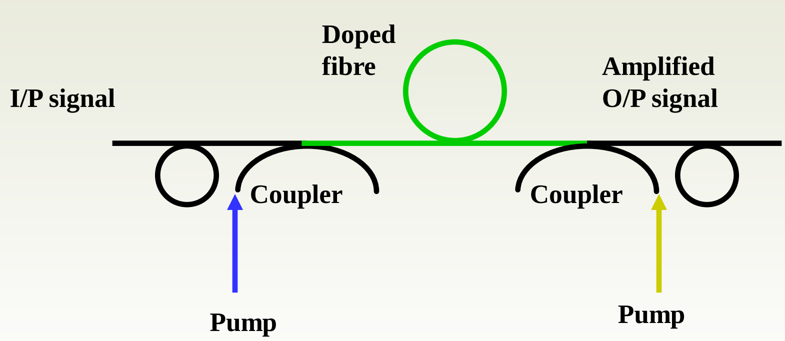
If no signal input, but the pump is working, EDFA will send optical to both direction, which is called ASE, in order to prevent these, we need isolator

EDFA Schematic - 1



- Backward (counter-directional) pumping arrangement

EDFA Schematic - 1



- Bi-directional pumping arrangement

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Pumping arrangements

1.48 um or 980 nm

- Forward pumping: co-directional pumping tends to provide the best noise performance
- Backward and Bi-directional pumping encountered in high output power amplifiers
- Optical isolators commonly incorporated to eliminate problems due to reflections back into the amplifier fibre section which could cause instability given the high gains (~50 dB) which can be supported

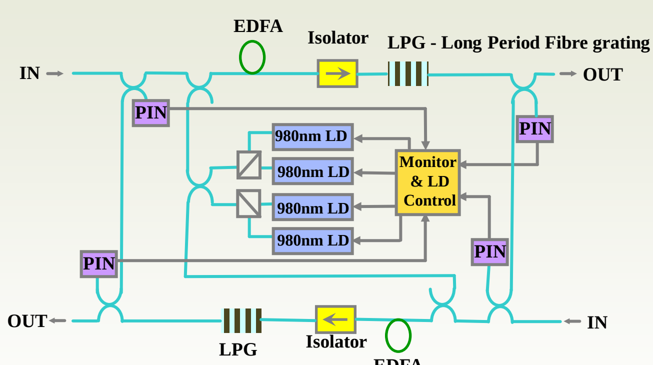
also requires a narrowband filter, to remove noise

Optical EDFA Repeater

There two types to collect the fiber

1. PC: physical contact, which will cause reflection to fiber, and fluctuation

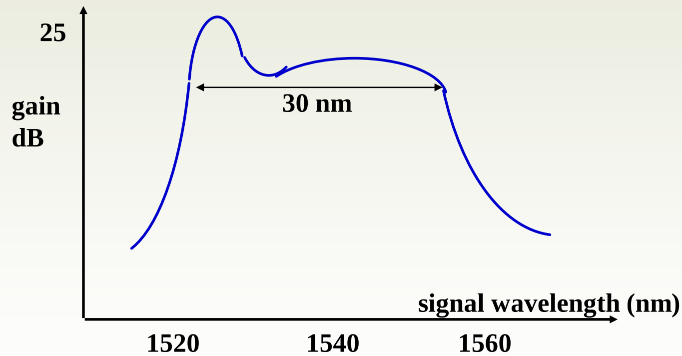
2. APC: Angle physical contact, which will put an angle to prevent reflection



Reasons to choose 980nm LD and forward pump

- 980 nm forward pumped EDFAs are found to have lower noise figures of 4.5 dB as opposed to 6.5 dB for other configurations.

Spectral characteristic



Amplifier Saturation

- EDFA saturation
- Output power at which gain has fallen by 3 dB relative to unsaturated gain is P_{sat} :

$$P_{sat} = \frac{A_s h f_s}{\sigma_{se} T}$$

A_s = cross sectional area of core

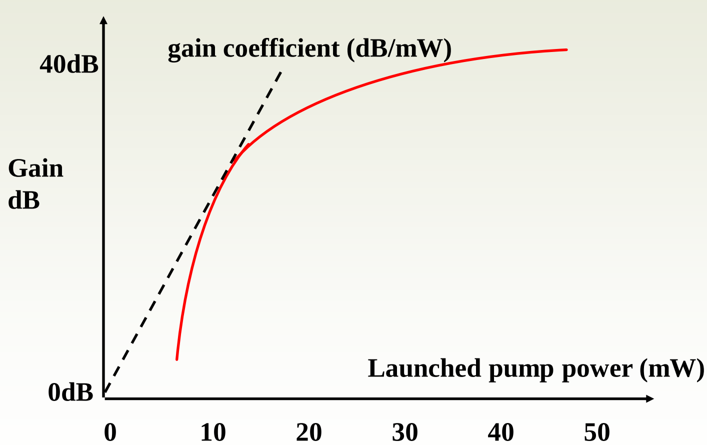
σ_{se} = signal emission cross section at${}_s$

Gain vs Pump Power -1

spontaneous emission: photons goes out randomly
stimulus emission: photons goes all the same way

- Some minimum pumping required to over come losses (achieve transparency)
- Beyond that level, gain increases rapidly with pump power
- Levels out as reach point where all available erbium ions have been inverted throughout the gain region

Gain vs pump power - 2



ASE: amplified spontaneous emission
https://www.fiberoptics4sale.com/blogs/archive-posts/95041542-what-are-ase-amplified-spontaneous-emission-light-sources
https://fibercore.humaneticsgroup.com/services-support/fiberpaedia/a/amplified-spontaneous-emission

POPULATION INVERSION:

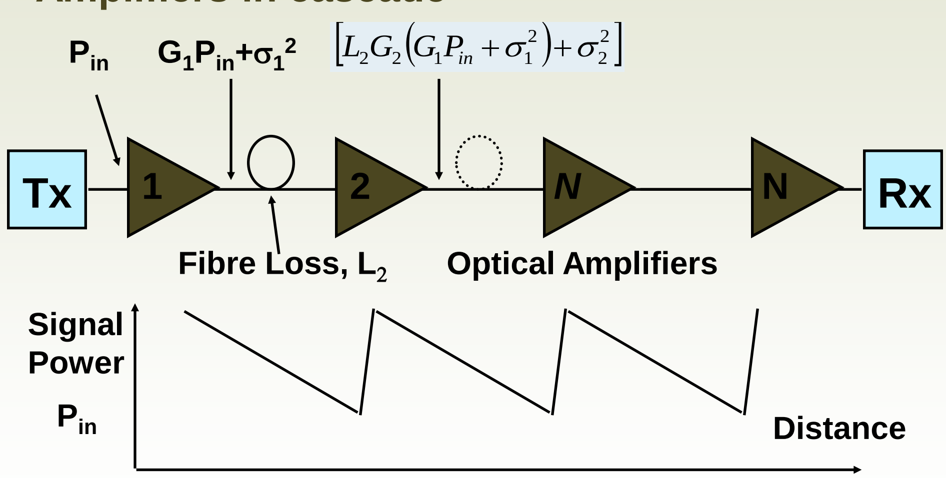
PUMP REFLECTOR

Cascaded Optical Amplifiers

- Consider a cascade of N amplifiers, the fibre is assumed to have a loss of L_i (less than unity) for the i^{th} span.
- It is assumed that an optical isolator has been placed after each of the amplifiers to prevent any backward propagating ASE from accumulating and also to limit non-linear scattering effects.
- In addition a bandpass filter of bandwidth, Δf, is used to limit the ASE propagating from one stage to the next.

isolator, narrowband filter, polarizer should be considered

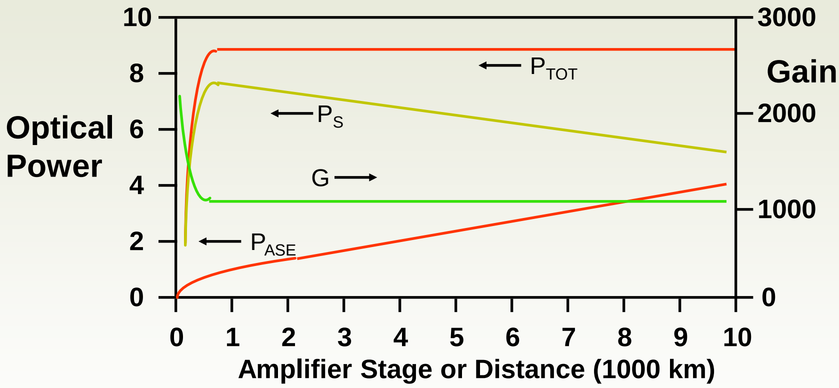
Amplifiers in cascade



at the beginning, signal is weak, large gain is required

total output power is constant, the noise is increasing, the power of signal is decreasing

Signal and ASE along the link



- Gain is slightly saturated at each stage, such that the chain is self-regulating in power

Signal and ASE along the link

- In this example the system is allowed to operate without constraints and is allowed to naturally equilibrate and self-regulate.
- Note that:
  1) the total power stabilises to a constant level
  2) the signal decays slowly
  3) the ASE noise accumulates slowly
  4) the SNR decreases slowly (implied by 2) and 3))

Signal and ASE along the link

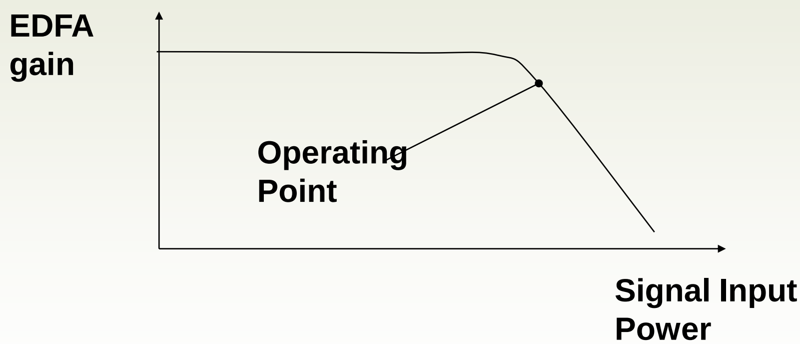
- If the ASE noise increases, as it must, then for the total optical power to remain constant, the signal must decrease as a proportion of the total power.
- At the start of the cascade the signal power is low and the gain self adjusts to a high value.
- As the total power increases the gain drops as the amplifier goes into compression.

ASE increasing, total must be constant, signal decrease

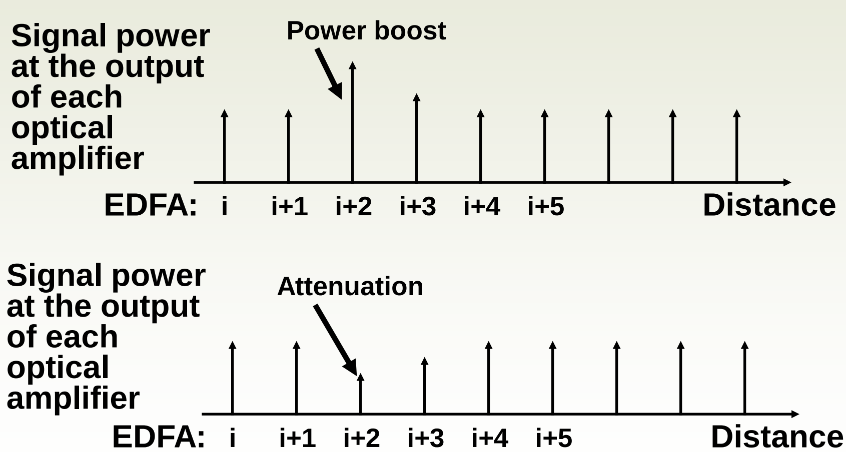
Power Self-Regulation

- The system is designed to operate with each of the amplifiers having a small amount of saturation.
- In this case self-regulation occurs and if the signal experiences a boost or attenuation the chain of amplifiers causes the signal power to return to its original value.
- Assume the system is operating with the gain compressed by 3 dB at each amplifier
- If nothing unexpected happens the signal power will generally be constant from one amplifier to the next.
- However, if a signal undergoes an unexpected boost in power, then this will cause more compression in the following amplifiers and so the signal will return to its original level.

Power Self-Regulation



Power self-regulation



Definition of Q without optical amplifiers

- First consider a system simply consisting of a transmitter, a length of fibre and a receiver for simplicity.
- When the noise is additive and independent of the signal level we can use the method of Gaussian probability distributions on the 1 level and 0 level.
- The Bit error rate (BER) can be found by integration under the Gaussian tail crossing the decision threshold.

$$BER = erfc(Q)$$

where erfc is the complementary error function,

Definition of Q without optical amplifiers

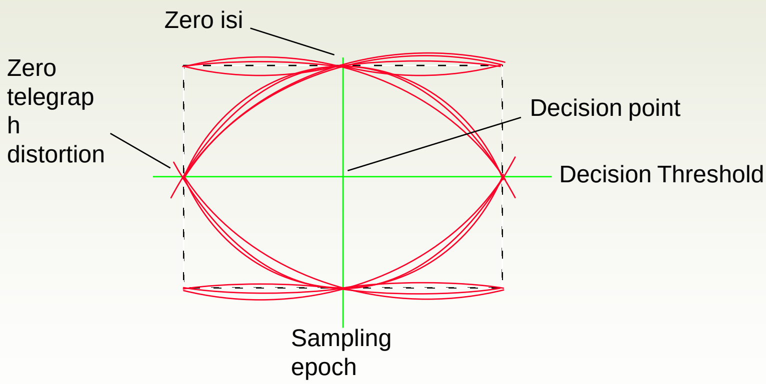
- Q in this case is the ratio of the signal s to rms noise i.e. $Q=s/\sigma$

$$Q(dB) = 20 \log_{10}Q$$

- A BER of 10^{-9} corresponds to Q = 6
- The concept of system operating margin is particularly useful since it represents the extent to which system loss can increase before an error rate of 10^{-9} is obtained.
- The system operating margin may be expressed as an electrical Q margin:

$$M_{elec}(dB)=20\log_{10}(Q/6)$$

Eye Diagram



Signal Dependent Noise

- The noise variance in an optical amplifier is made up of various terms. For simplicity all of the terms are given below in photons squared per Hertz rather than in receiver current.

s: signal strength

ones always contain more noise than zeros

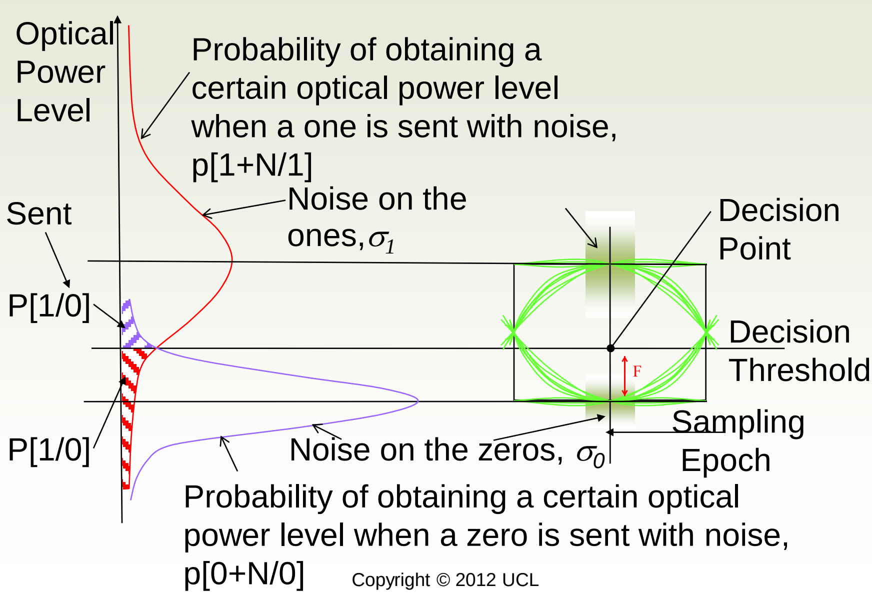
  - Signal shot noise: 2*s* (present only on data ones)
  - Spontaneous shot noise: *n'* (present on ones and zeros)
  - Signal-spontaneous beat noise: $2sn'/\Delta f$ (only on data ones)
  - Spontaneous-spontaneous beat noise: $n'^2/(2\Delta f)$ (on both ones and zeros)
- *s* is the mean signal in photons per second.
- *n'* is the mean spontaneous noise in photons per second in a specific optical bandwidth of Δf

Signal Dependent Noise

- The signal-spontaneous noise is signal dependent.
- Hence EDFA cascades and optical pre-amplifier based receivers exhibit substantial variation in noise level between 1s (light present) and 0s (light absent), which we then indicate as σ_1 and σ_0.
- In this case it is, therefore, best to position the decision threshold somewhat ***below*** half way in the eye in order to minimise the total error rate, corresponding to errors occurring approximately equally for 1s and 0s: P[0/1]=P[1/0].

two area of gaussian noise are both 1, so they are the same

Signal Dependent Noise



Signal Dependent Noise

- The decision threshold is (nominally) set such that P[1/0] = P[0/1].
- With perfect extinction for 0s and normalised decision threshold of F this corresponds to equal 'margins' for 0s and 1s of F and (1-F) relative to the respective RMS noise values σ_1, σ_2, such that:

$$\frac{F}{\sigma_0} = \frac{1-F}{\sigma_1}$$

$$F = \frac{\sigma_0}{\sigma_0 + \sigma_1}$$

Signal Dependent Noise

- Note that the total probability must always be one so the area under the two probability distributions below must be the same.
- The probability of a bit error can be found by integrating under the Gaussian tails where they cross the decision threshold.
- The actual integration is to infinity but only part of the integrated region is shown shaded in the figure below.
- Note that $\sigma_1 > \sigma_0$ so that the decision threshold is ***below*** the half way point of the eye.

Signal Dependent Noise Q definition

- Signal dependent noise requires a definition of Q which accommodates an optimum threshold level of less than 0.5.
- 2s, the peak signal level, is the number of photons per second for a "1" bit for a mean level of s photons per second.
- The threshold is optimally placed at $\sigma_0/(\sigma_0+\sigma_1)$

$$Q = \frac{2s}{\sigma_0 + \sigma_1}$$

- which is the signal to average noise ratio.

$$\mathrm{BER}_{\mathrm{opt}} = erfc(Q)$$

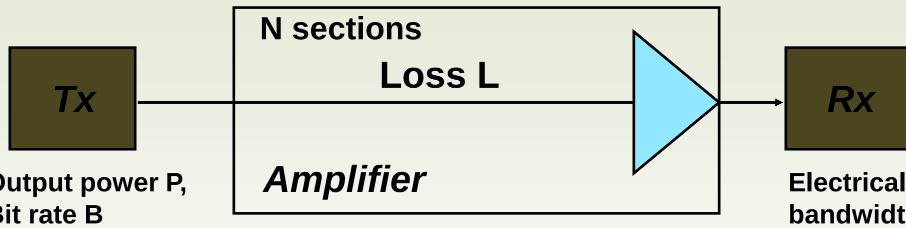
Signal Dependent Noise Q Definition

- It is convenient to define a signal to noise ratio in terms of the mean number of signal photons per second, s, and the mean spontaneous noise, n, in photons per second at any point in a system:

$$\mathrm{SNR(dB)}=10\log_{10}(s/n).$$

- Note that optical dB calls for a factor of 10 multiplier while electrical Q uses a factor of 20

Optically amplified system



Output power P,
Bit rate B

Output power P(dbm)
Gain G (dB)
Noise Figure NF (dB)
Optical Bandwidth Δf (Hz)

Electrical bandwidth B, Optical filter bandwidth Δf

- General schematic of optically amplified system, treating chain of amplifiers and fibre as a ‘black box’

Definition of optical amplifier Q

- In systems having an amplifier close to the receiver or many cascaded amplifiers the ***beat noise*** tends to dominate the receiver noise. In this beat noise limit the SNR and Q are related by:

$$Q = \frac{2SNR}{1+\sqrt{1+4SNR}}\sqrt{\frac{\Delta f}{B}}$$

$$SNR = Q\left(1+Q\sqrt{\frac{B}{\Delta f}}\right)\sqrt{\frac{B}{\Delta f}}$$

- where *B* is the electrical receiver bandwidth and Δf is the optical filter bandwidth

Unrepeatered Submarine Systems

- Unrepeatered systems are links less than 400 km long without submerged repeaters.
- Without the need for submerged electronic repeaters, unrepeatered systems offer a cost effective approach.
- Long spans may be achieved using single wavelength at 2.5 Gbit/s with 24 fibre pairs giving 2.5 x 24 = 60 Gbit/s
- High bit rates but shorter spans can be achieved using 40 wavelength channels (DWDM) at 10 GBit/s with 24 fibre pairs gives an aggregate bit rate of 40 x 10 x 24 = 9.6 Tbit/s

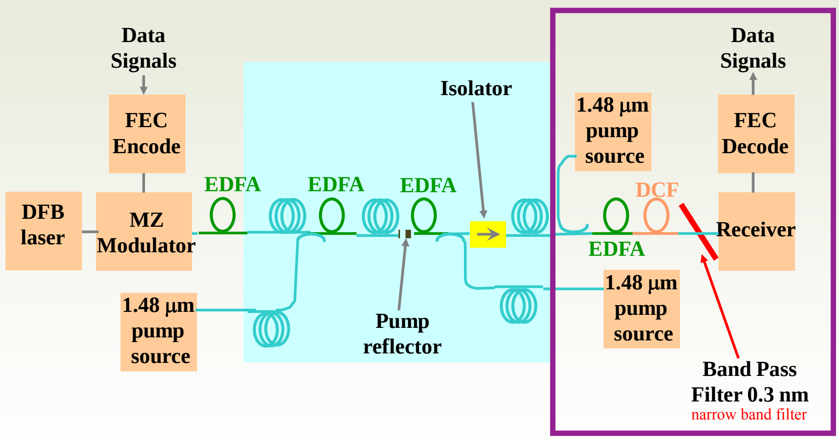
Unrepeatered Submarine Systems

- Used for mainland-mainland or mainland-island or island-island. Island hopping occurs in the CJFS system using remotely pumped optical amplifiers.
- Costal “Festoons” can be created along coastlines e.g. 1300 km system with 10 unrepeatered links off coast of Thailand; 6 fibre pairs at 565 Mb/s
- Often tested across lakes and rivers.

without repeater

529 km Unrepeatered System

Receiver



529 km Unrepeatered System

- 2.5 Gbit/s over 529 km having a loss of 93.8 dB.
- Remotely pumped pre - and post- amplifiers.
- High power 1W, Raman laser pump sources.
- Separate low loss fibres for transporting the pump to the EDFA.
- DCF - Dispersion Compensating Fibre with -8000 ps/km/nm
- FEC using (255,239) Reed - Solomon code.

Unrepeatered Submarine Systems

- Various system configurations are possible
  - Simple fibre with FEC and terminal amplifiers 261 km
  - + Raman pre-amplification after the submerged fibre but before the receiver, 300 km.
  - + Remote optical pre-amplification using a submerged doped fibre with a pump through the same fibre from the transmitter 338 km.
  - + Remote optical pre-amplification using a submerged doped fibre with the pump being fed along a second parallel low loss fibre to the submerged doped fibre, 349 km.
  - Optical post-amplification giving +25 dBm can be used after the transmitter in addition.

Optical Amplifiers

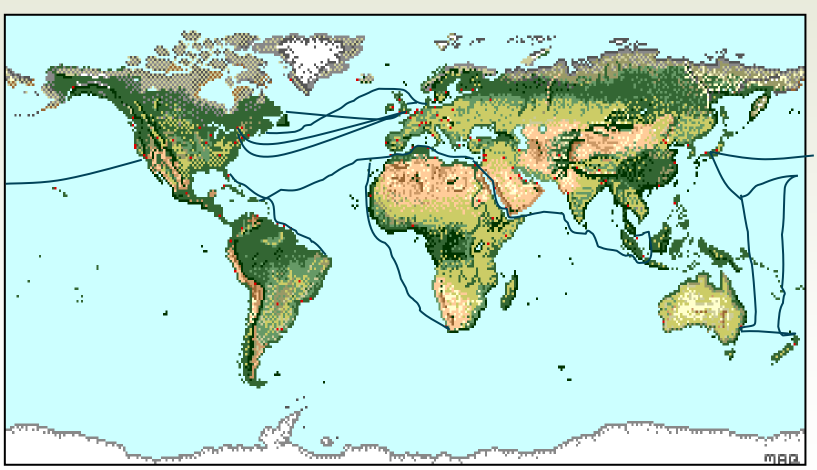
- Raman Pre-amplification requires a large > 1 W pump to be sent back down the fibre from the receiver.
  - This gives a broad gain with the maximum 100nm above the pump wavelength. So a 1450 nm pump can be used to amplify 1550 nm signals.

combine above all to the system to build the best performance

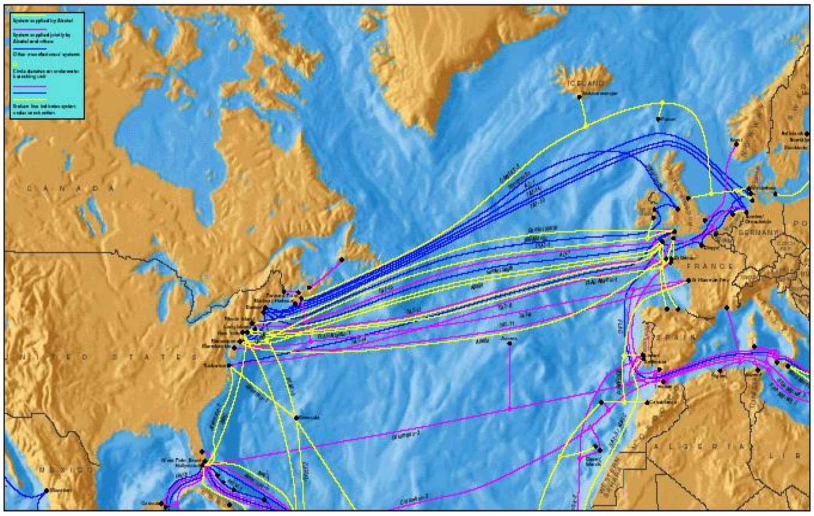
Optical Amplifiers

- Remote optical amplifiers (ROPA), 30 - 60 km from terminal
  - A 1480 nm pump is sent from the terminal down to the 20 - 200 m of doped fibre which has been spliced in.
  - A pre-ROPA at the receiver it gives a larger increase in possible system length than that achieved using Raman pre-amplification.
  - A post-ROPA at the transmitter gives less non-linearities than a large power post-amplifier.
- Powerful 1 W pump beams of either 1450 nm or 1480 nm can be provided by a Raman pump source (RPS) which uses a Raman resonator.

Undersea Cables



North Atlantic Fibre Systems



Aggregate Transmission Rates