Optical Amplifiers

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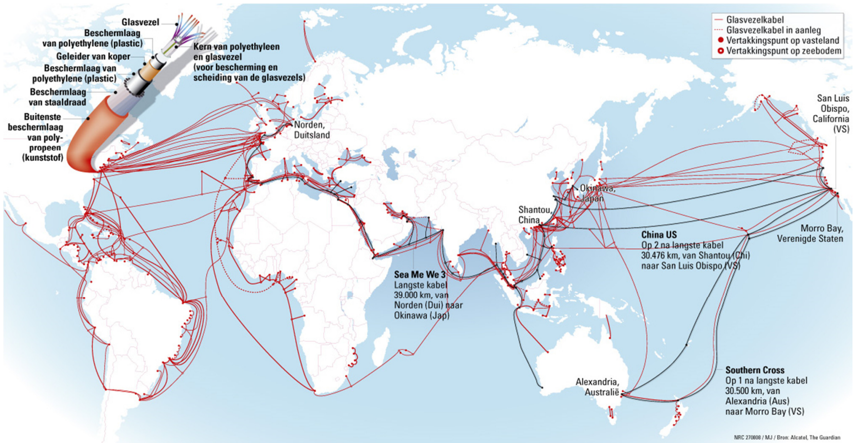
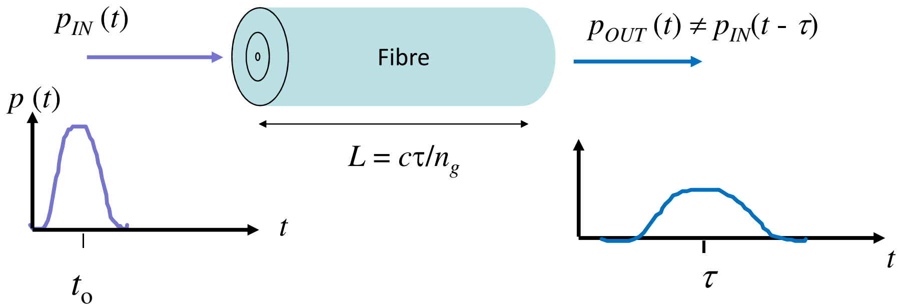
SYSTEM CONSIDERATIONS

Global telecommunications relies on optical fibre:

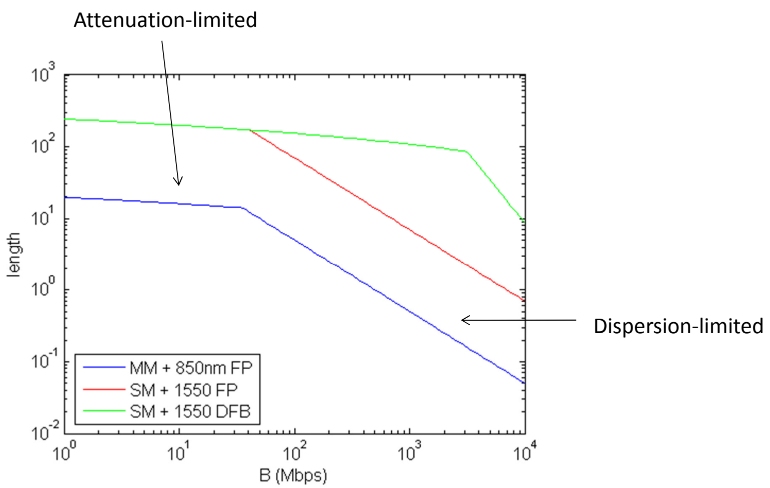


Although optical fibre is an excellent transmission medium (lower loss and larger bandwidth compared to coaxial cable, for example), <u>it is not perfect</u>.



Attenuation & dispersion
- Reduction in pulse energy
- Pulse spreading

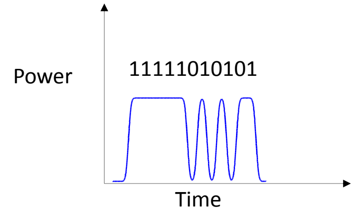
At low bit rates, the maximum transmission distance is limited by attenuation, while at high bit rates the distance is limited by dispersion:

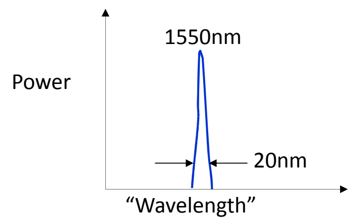


FP = Fabry-Perot laser diode
DFB = distributed feedback laser diode

Chromatic Dispersion

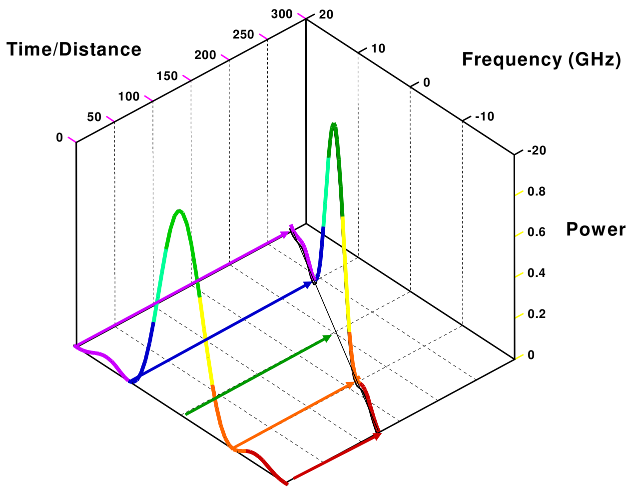
Consider a system transmitting NRZ:





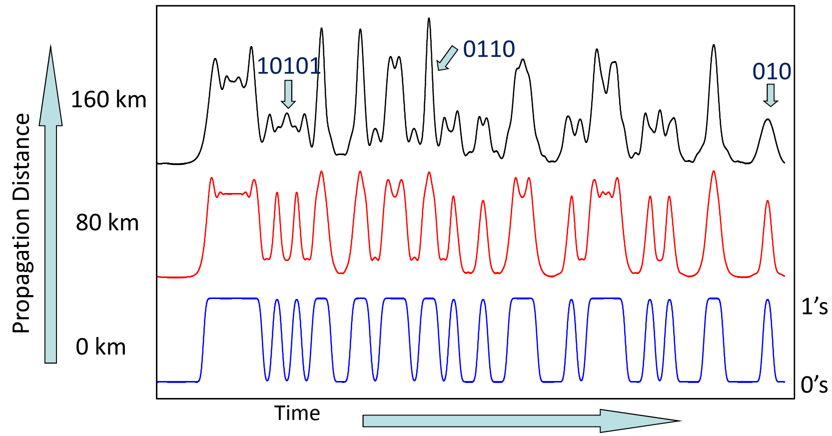
The source is not spectrally pure, it has a finite spectral width, which means that chromatic dispersion from the fibre will lead to pulse spreading.

Chromatic Dispersion



Frequency components of modulated signal travel at different velocities in fibre

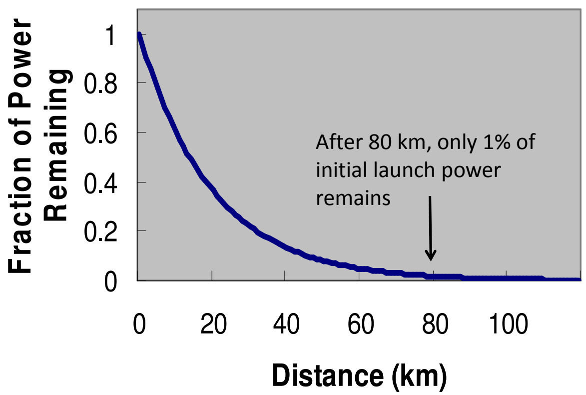
Data distortion from dispersion

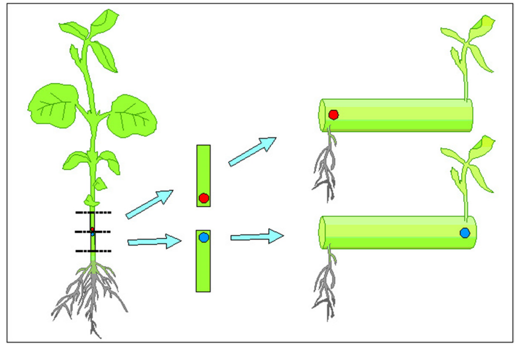


NRZ distortion very pattern dependent!

Impact of attenuation

Consider a fibre with an attenuation factor of 0.25 dB/km:

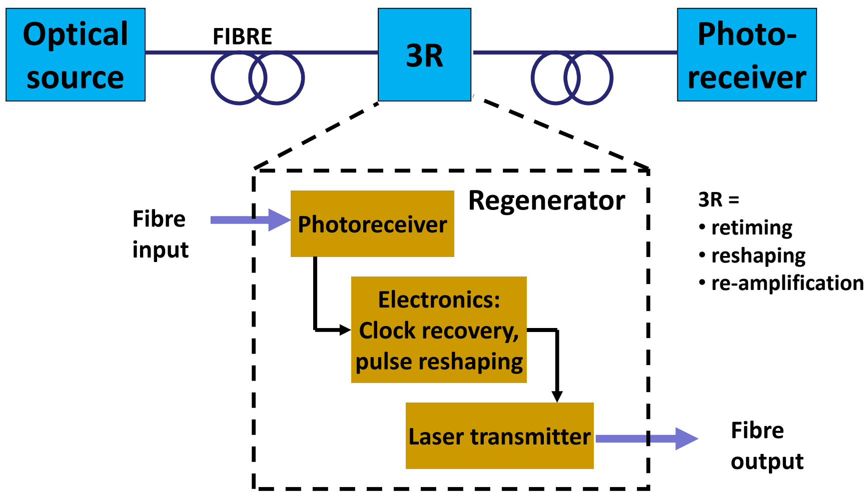




REGENERATION

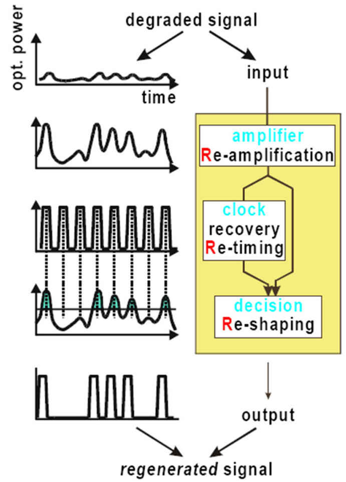
Optical Signal Regeneration

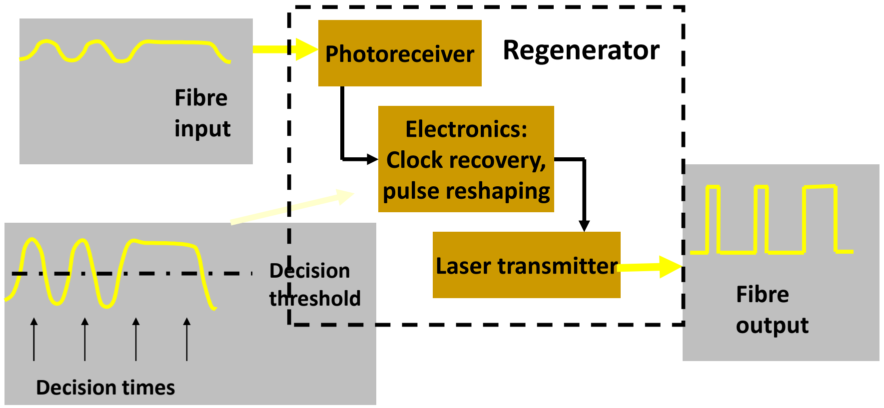
- It is necessary to re-amplify and reshape the pulses at regular intervals using regeneration:



Optical regenerators are classified into three categories by the 3-R's scheme.

1R : re-amplification of the data pulse alone is carried out.
2R : in addition to re-amplification, pulse reshaping is carried out.
3R : in addition to re-amplification and reshaping, retiming of data pulse is done.

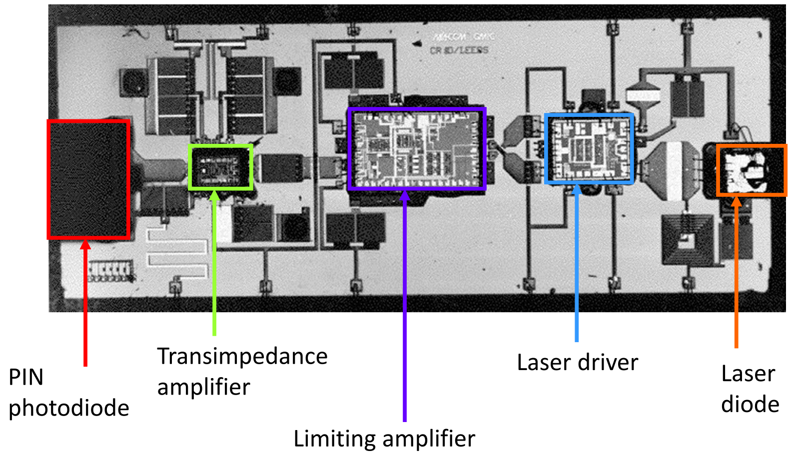




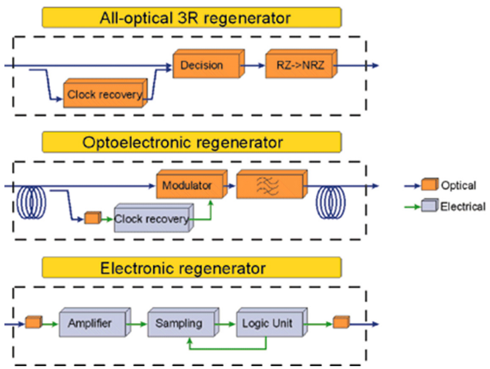
- Advantages:
  - Clock recovery
  - Pulse reshaping

- Disadvantages:
  - O/E & E/O conversion needed
  - Bit rate is “locked in” – no upgrades
  - Single wavelength only

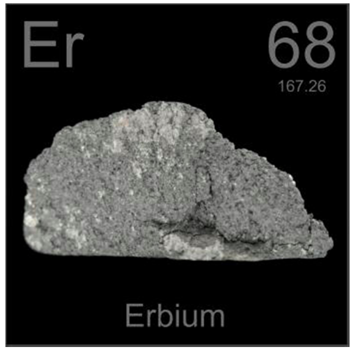
Example of a fibre-optic regenerator (622 Mb/s)



Electronic regenerators make use of mature technology, but the ideal goal is to go towards all-optical regeneration:



All-optical 3R regeneration is an active research topic.

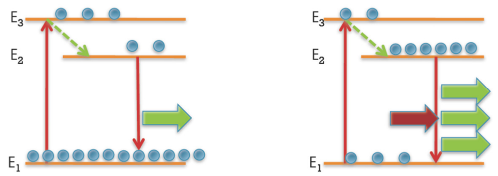


OPTICAL AMPLIFICATION

Optical Amplifiers

- <u>All-optical</u> components (i.e. optical input/output). Fibre-based amplifiers also contain lasers, but this is to create a population inversion in the gain medium.
- Have replaced electronics-based regenerators, in which optical signals had to be photodetected, amplified electronically and then applied to optical source.
- Have revolutionised optical communications
  - used in wavelength division multiplexed (WDM) systems
  - allow the use of soliton transmission at ultra high bit rates (1000s of Gb/s) over thousands of km
  - Have removed the speed and wavelength bottleneck associated with all-electronic regeneration.

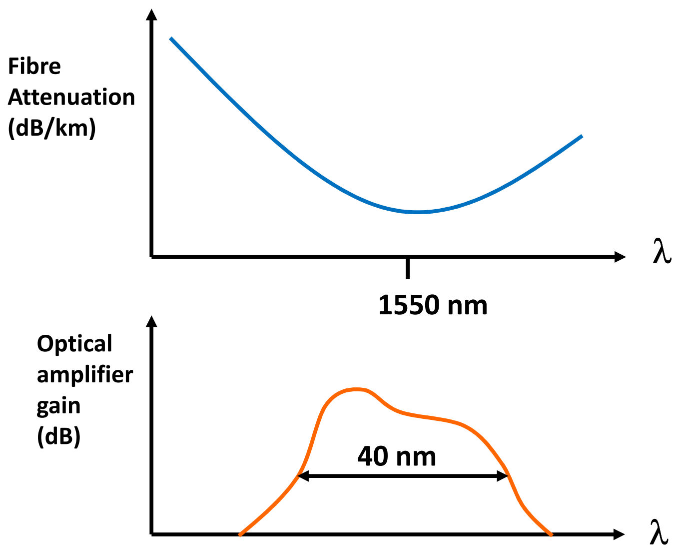
Physical Principle of Optical Amplifiers



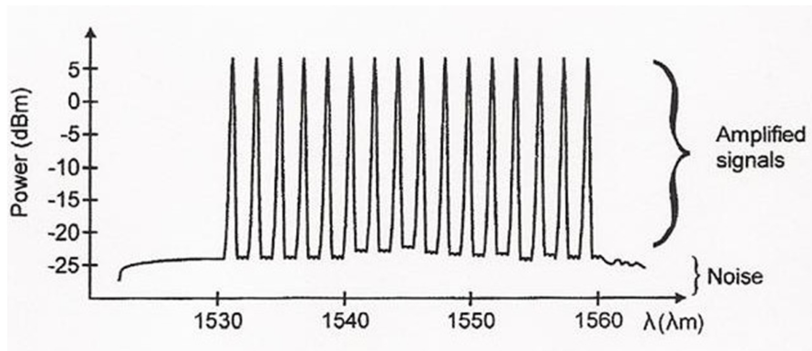
- Spontaneous Emission versus Stimulated Emission
- In general, light is absorbed as it propagates
- If the population at the higher energy state is higher than a lower state, light gets amplified as it travels through the medium
- Amplified light bears the characteristics of the signal photon

Note: This model does not apply to Raman amplifiers

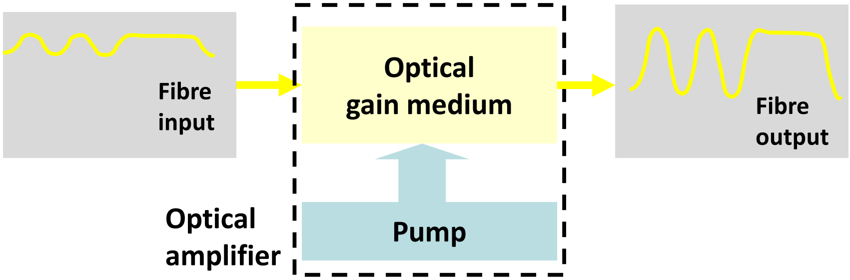
- An optical amplifier provides gain over a useful spectral range, as shown here for an erbium-doped fibre amplifier:



- This broad spectral range enables a number of wavelengths to be multiplexed onto a fibre, thus increasing the bit rate that can be transmitted.

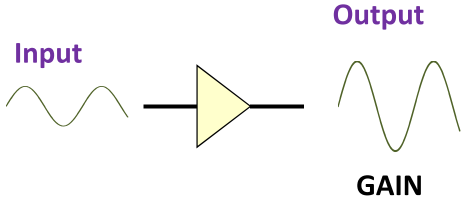


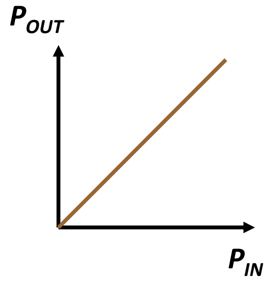
Spectrum of 16 amplified WDM channels (using EDFA)

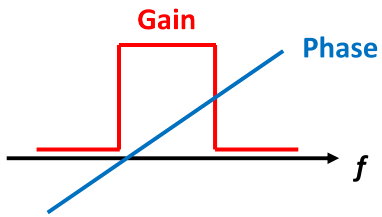


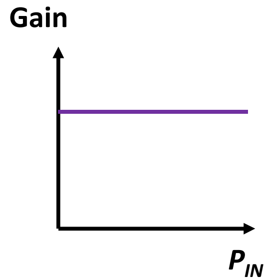
- Advantages:
  - Optical input & output
  - Photons in – more photons out
  - Transparent to both bit rate & modulation format
  - Supports many wavelengths
    - WDM: Wavelength division multiplexing
- Disadvantages:
  - No pulse reshaping
  - ∴ Needs dispersion compensation
  - Adds noise to output signal

Ideal amplifier:



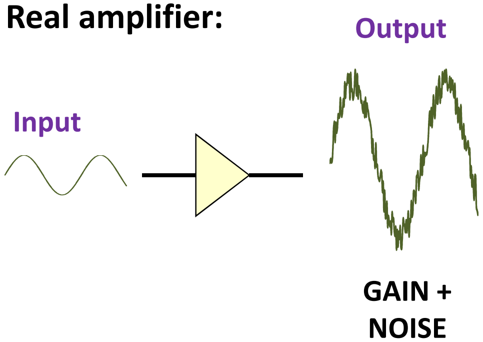


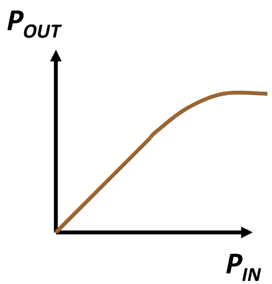


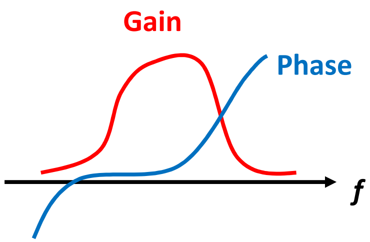


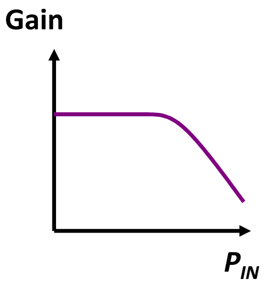
- **Flat gain response**
- **Linear phase response**

Real amplifier:

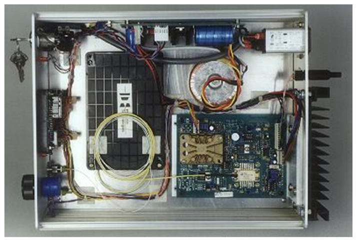








- **Gain saturation**
- **Nonlinearity**



TYPES OF OPTICAL AMPLIFIER

Types of optical amplifier

- Semiconductor laser amplifiers (SLAs)
  1. Fabry-Perot amplifiers: essentially laser diodes that are biased below lasing (oscillation) threshold.
  2. Travelling-wave amplifiers: here, the facet reflectivities are virtually eliminated by using anti-reflection coatings or angled facets.
- Fibre amplifiers
  1. Making use of nonlinear effects, such as stimulated Raman or Brillouin scattering (these are also known as distributed fibre amplifiers).
  2. Rare earth doped fibres: most common type is ***erbium-doped*** (1.55μm central wavelength), but praseodymium-doped also available (1.3μm).

Important parameters for optical amplifiers include:

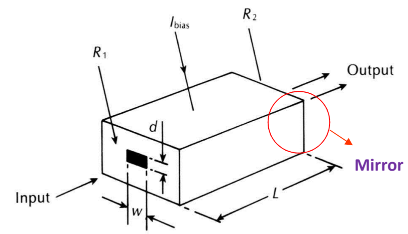
i. Gain
ii. Noise figure
iii. Saturation output power

Semiconductor Optical Amplifiers

Gain medium – semiconductor

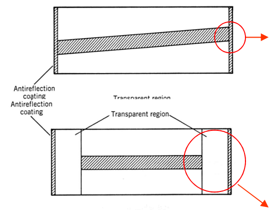
Pump – injection current

Basic structure is similar to a laser diode



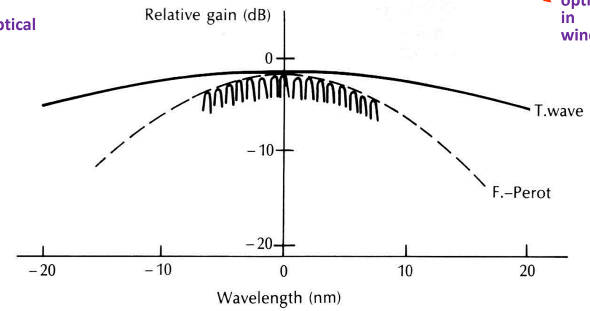
Fabry-Perot Semiconductor Optical Amplifier (SOA)

Travelling Wave Semiconductor Optical Amplifier (SOA)

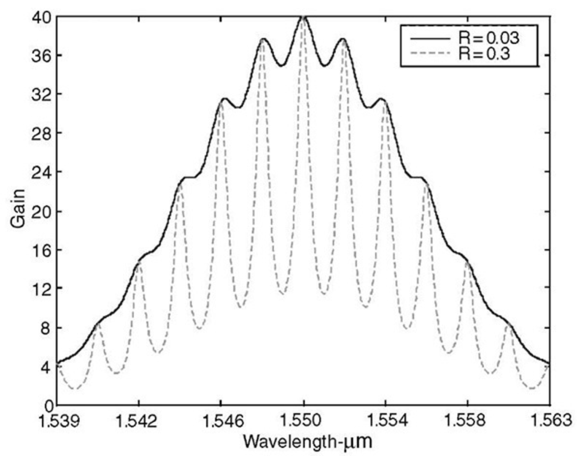


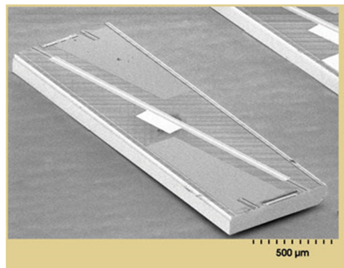
Angled-facet or tilted-stripe – the reflected beam at the facet is physically separated from the forward beam

Buried-facet or window facet – the optical beam spreads in the transparent window

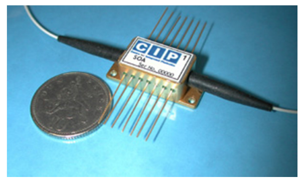


Too much facet reflectivity in a Fabry-Perot SOA is not good....



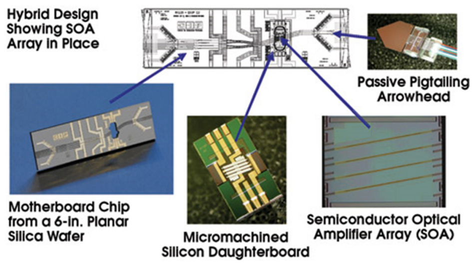


Travelling-wave SOA with angled facets



Packaged SOA

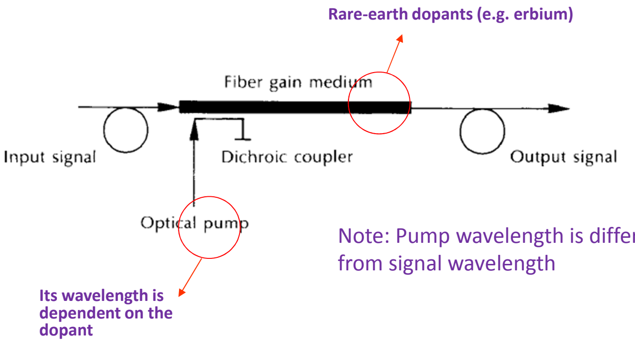
Advantage of SOAs is that they are small and can be integrated with other devices



Doped Fibre Amplifiers

Gain medium – fibre

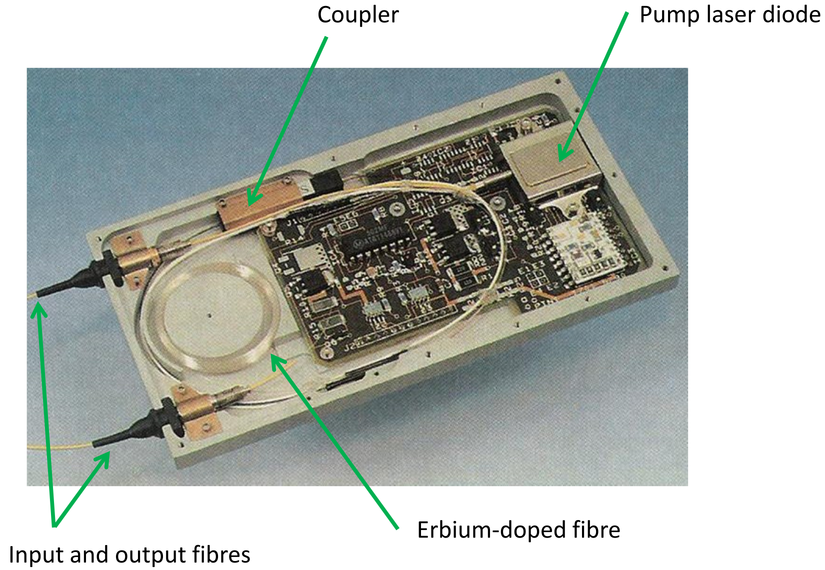
Pump – laser



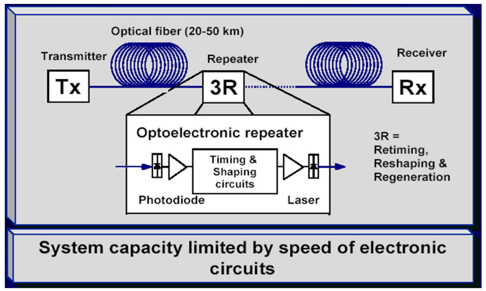
Note: Pump wavelength is different from signal wavelength

Raman and Brillouin optical amplifiers have a similar structure, but instead of doped fibre, they use highly nonlinear fibre.

Packaged erbium-doped fibre amplifier (EDFA)

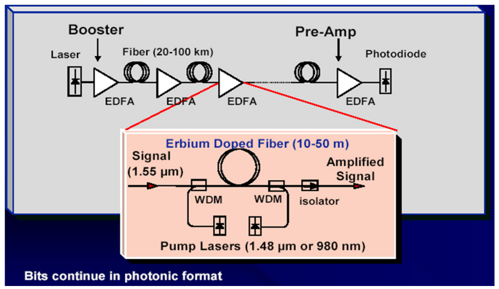


The most commonly used amplifiers are EDFAs



EDFAs have replaced the approach taken with early generation links that used all-electronic 3R regenerators.

EDFAs are used in all modern long-distance optical links, but usually the regeneration is 1R.

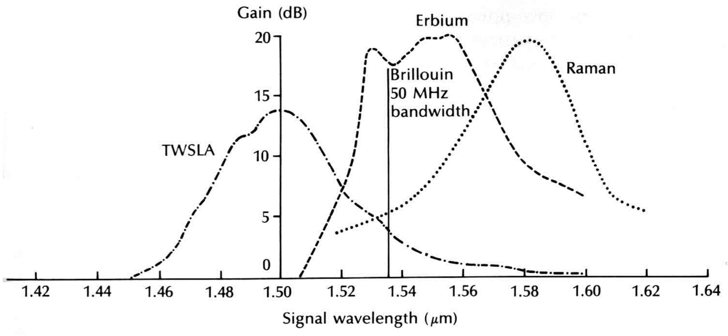


Other doped fibre amplifiers

Band name	Meaning	Wavelength (nm)	Technology
O	Original	1260-1360	Praseodymium
E	Extended	1360-1460	
S	Short	1460-1530	Thulium
C	Conventional	1530-1565	Erbium
L	Long	1565-1625	Erbium
U	Ultra-long	1625-1675	

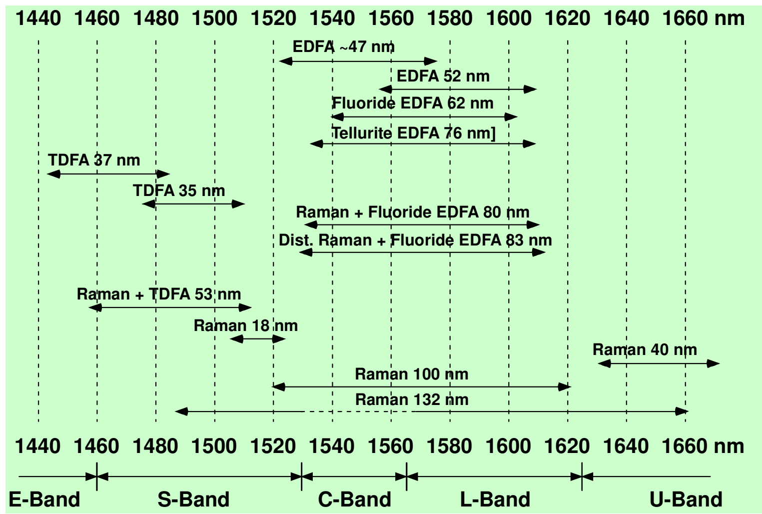
Optical Amplifier Gain Characteristics

- Travelling wave semiconductor optical amplifier (TWSOA), erbium doped fibre and Raman fibre amplifiers provide wide spectral bandwidth suitable for WDM applications.
- Brillouin fiber amplifier has a very narrow spectral bandwidth ~50MHz and it can be used for channel selection within a WDM system

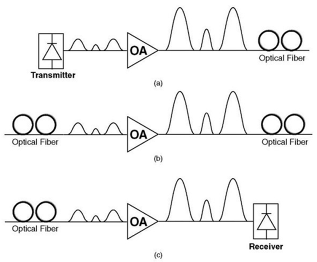


Note: TWSLA = travelling wave semiconductor laser amplifier – just another name for TWSOA

Bandwidth of various fibre amplifiers (doped and Raman)

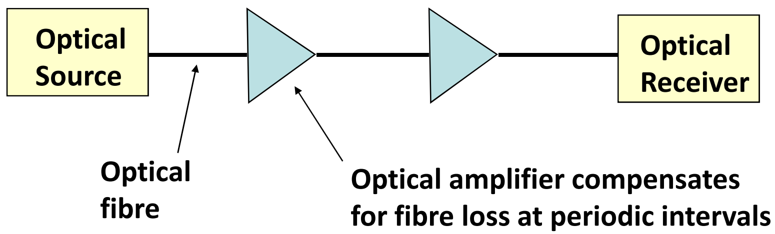


TDFA = thullium-doped fibre amplifier, EDFA = erbium-doped fibre amplifier

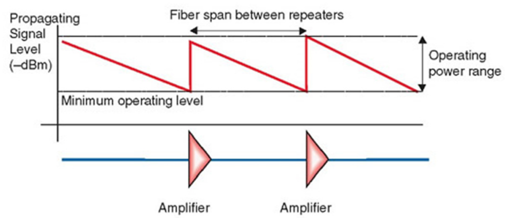


APPLICATIONS OF OPTICAL AMPLIFIERS

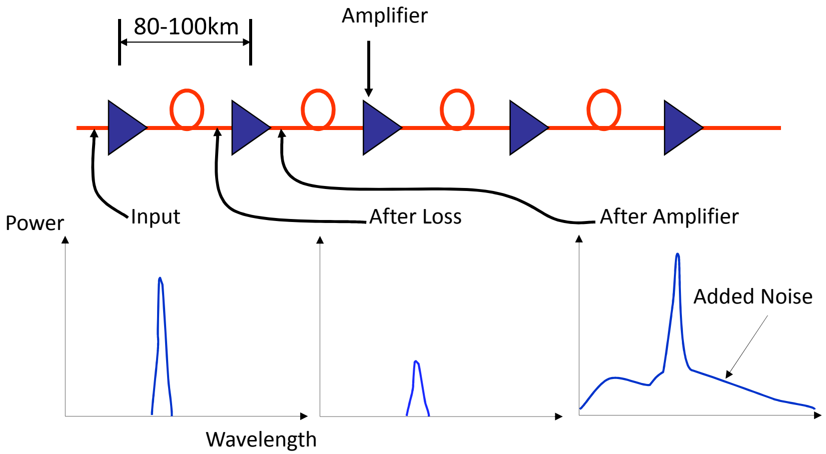
• Application 1: As in-line amplifiers in long-haul links to compensate for attenuation in the 1550 nm window. Mostly EDFAs and Raman.



Optical amplifiers boost the signal at regular intervals (e.g. between 30 km to 80 km) to make sure power level in link does not drop below the required receiver sensitivity

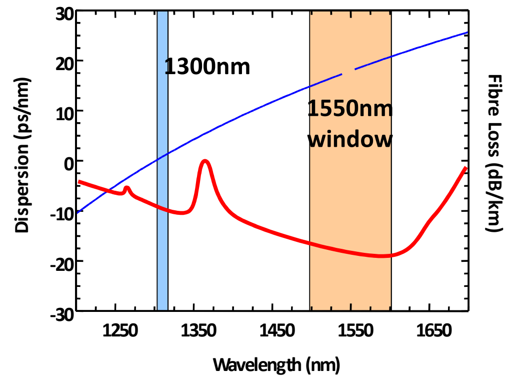


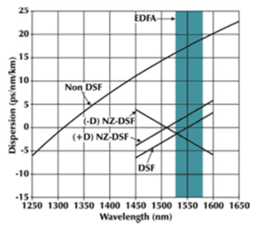
Optical amplifiers compensate for loss, but they also introduce noise:



Hence a low noise figure is important, as well as saturation power (being able to handle medium power levels)

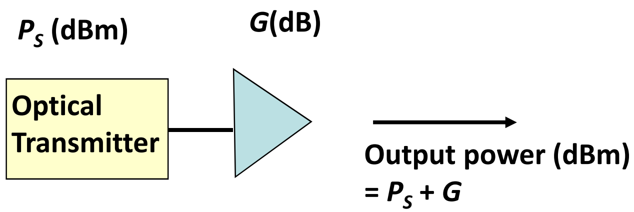
The other problem is that for standard single-mode fibre, the 1550 nm window offers low loss, but minimal chromatic dispersion is at 1310 nm.





Hence some kind of "dispersion management" or dispersion compensation is required, e.g. by using dispersion-shifted fibre (DSF)

- Application 2: As power amplifiers to increase source power (post-amplifiers):



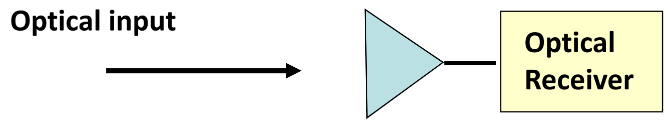
- Most laser diodes used in optical transmitters have powers of a few mW, but fibre can handle of the order of 100 mW before optical nonlinear effects occur. So a power amplifier can be used to boost signal immediately after the source.

- SOAs are useful because they can be integrated with lasers, but EDFA power amplifiers are also available with output powers around 100 mW.

- Amplifier adds noise, but this is attenuated by the fibre

- Important that the amplifier is not saturated by the transmitter

- Application 3: As pre-amplifiers to improve receiver sensitivity:



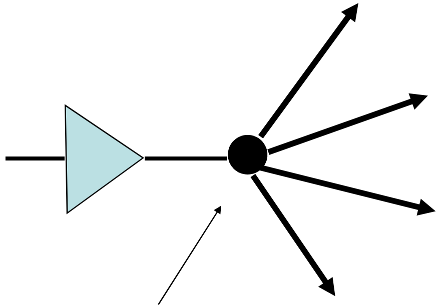
- Optical amplifier is placed immediately before the optical receiver in order to improve sensitivity.

- At this point the signal is weak, so good gain is required, but even more important is the fact that the amplifier must not add a lot of noise, so a low noise figure is required (typically less than 5 dB).

Selecting Amplifiers for Applications 1,2,3

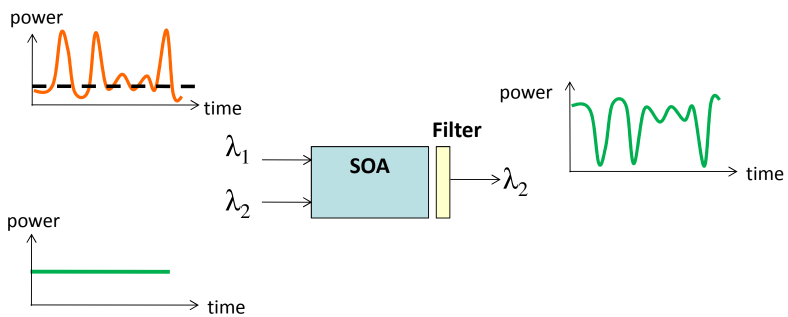
Type	Gain	Maximum Output power	Noise figure
Power Amplifier	High gain	High output power	Not very important
In-line	Medium gain	Medium output power	Good noise figure
Preamplifier	High gain	Low output power	Low value < 5 dB essential

• Application 4: As booster amplifiers in distribution networks (e.g. local access) to compensate for losses in a fibre splitter:

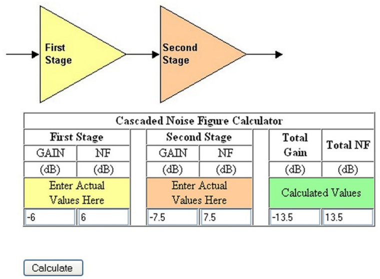


Star coupler: splits into *N* fibres; has insertion and splitting loss

• Other applications: It also possible to take advantage of nonlinearities in semiconductor optical amplifiers to perform operations such as wavelength conversion:



• Input wavelength 1 drives the SOA into compression, and so modifies the gain that wavelength 2 sees. After filtering, the output appears on wavelength 2 as an inverted version of the input on wavelength 1.



FIGURES OF MERIT FOR OPTICAL AMPLIFIERS

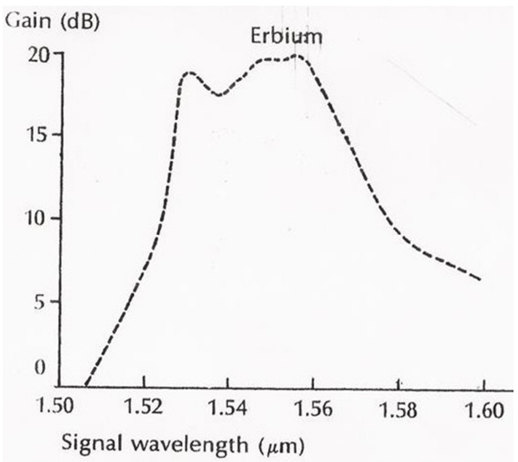
Important figures of merit & considerations for an amplifier

- Include:
  - Gain
  - Bandwidth
  - Gain saturation
  - Noise

Properties of Ideal Optical Amplifiers

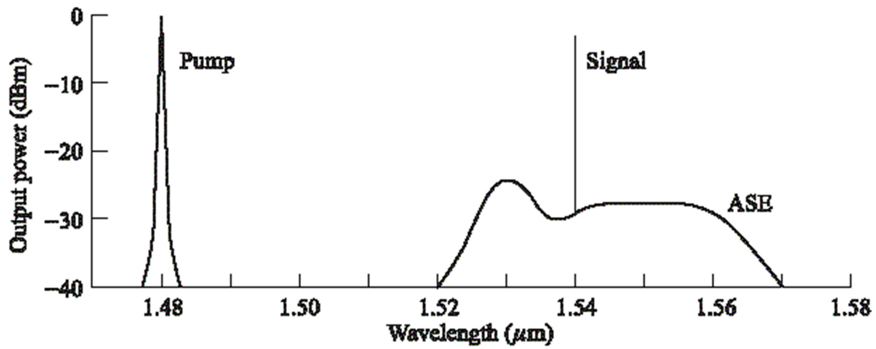
- Provide high gain
  - (30 dB or more)
- Have a wide spectral bandwidth
  - to allow several wavelengths to be transmitted
- Provide uniform (i.e. flat) gain vs. λ
  - to maintain relative strength of spectral components
- Allow bi-directional operation
  - i.e. gain in both directions
- Have low insertion loss
  - to maximise benefits of amplifier gain
- Have no crosstalk
  - i.e. no interference between different spectral components
- Have wide dynamic range
  - gain should not saturate with high input powers
- Have a good conversion efficiency
  - pump power converted to amplifier gain

Gain profile of erbium-doped silica fibre



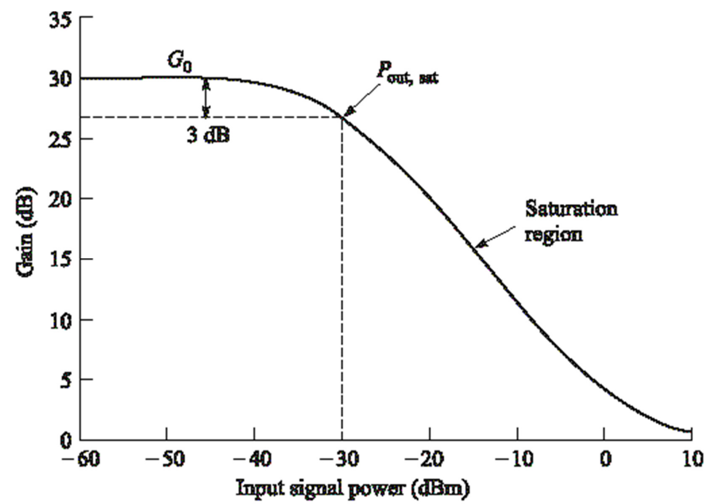
High gain over a wide spectral bandwidth, but the gain profile is not flat.

Spectrum of EDFA with1480 nm pump

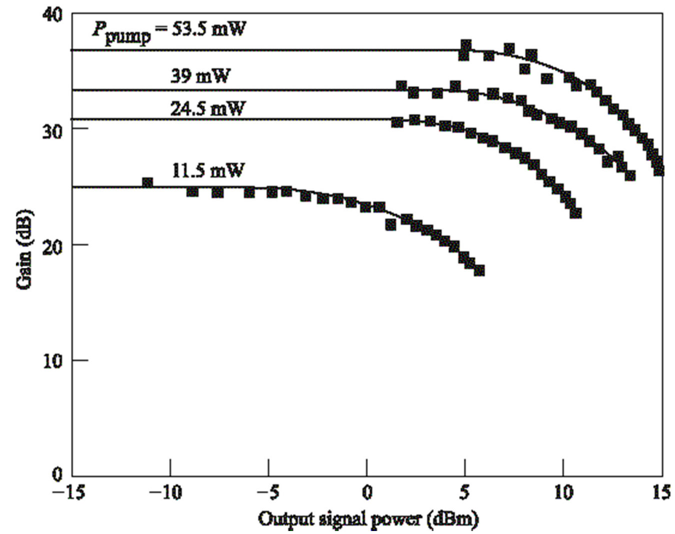


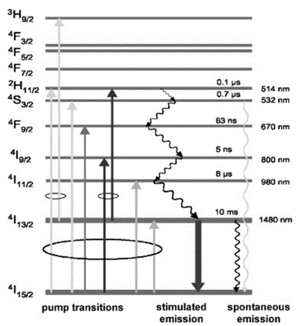
ASE: Amplified spontaneous emission noise

Typical gain versus power profile for optical amplifier:



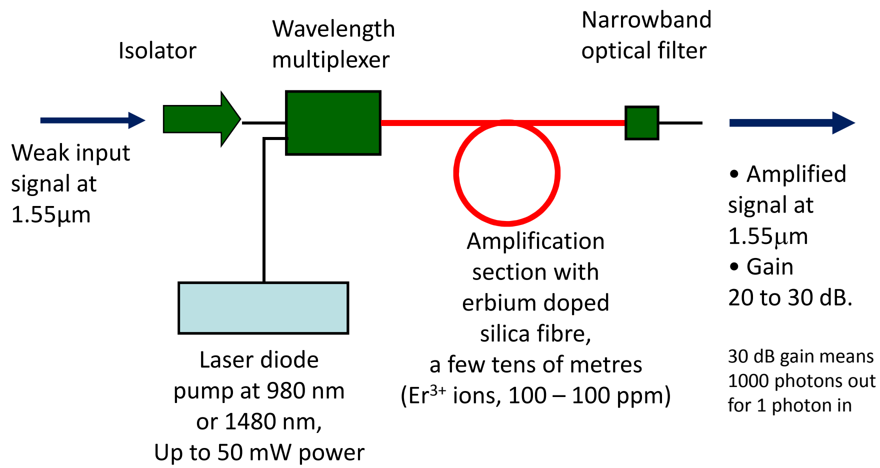
EDFA gain versus pump level



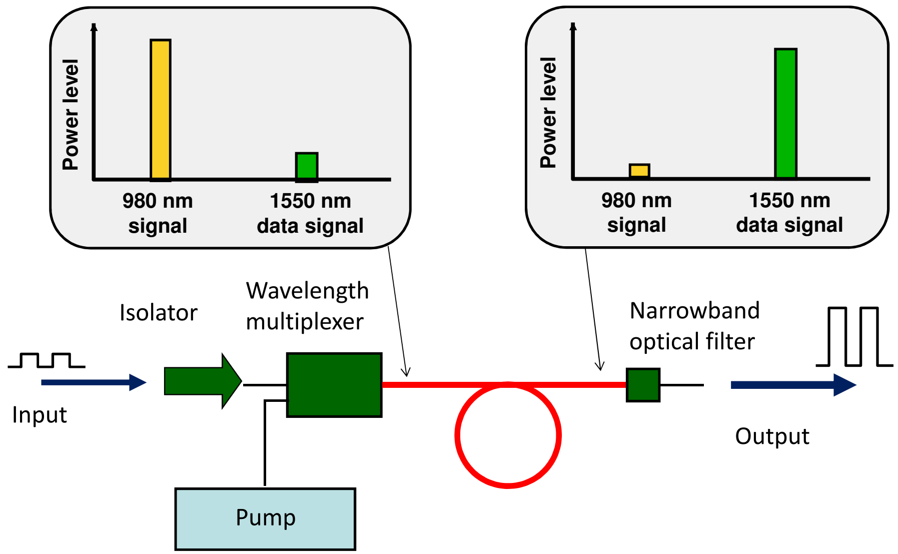


ERBIUM-DOPED FIBRE AMPLIFIERS – BASIC PHYSICS

EDFA Basic Structure

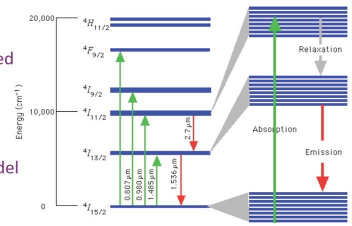


Power exchange



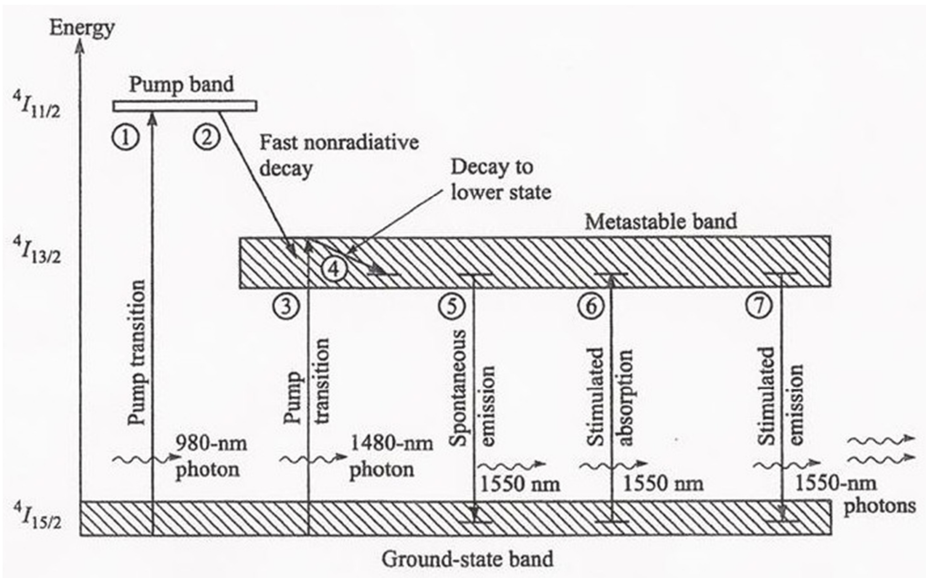
Erbium doped fiber :: Amplification Process

- Erbium-doped fiber is usually pumped by semiconductor lasers at 980 nm or 1480 nm.
- A three-level model can be used for 980-nm pumps, while a two-level model usually suffices for 1480-nm pumps.



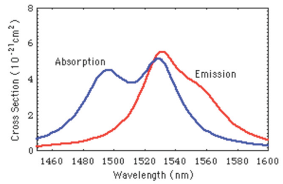
- Complete inversion can be achieved with 980-nm pumping but not with 1480-nm pumping.
- The spontaneous lifetime of the metastable energy level ($^4I_{13/2}$) is about 10 ms, which is much slower than the signal bit rates of practical interest.
- As stimulated emission dominates over spontaneous, amplification is efficient

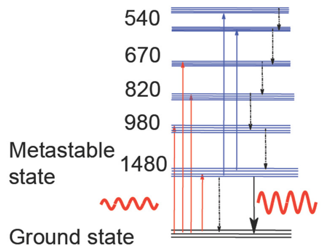
Energy Transitions in Er^{3+} - Doped Silica Fibre



Erbium doped fiber :: Operation

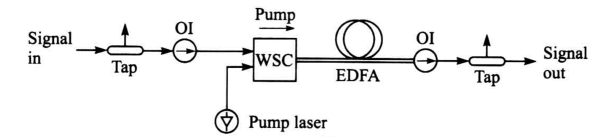
- Higher the population inversion lower the amplifier noise
- 980 nm pump is preferred for low noise amplification
- However more powerful 1480 nm sources are available
- At 1480 nm, silica fibers have low loss; hence pump can co propagate with the signal
- Pump may even be placed remotely



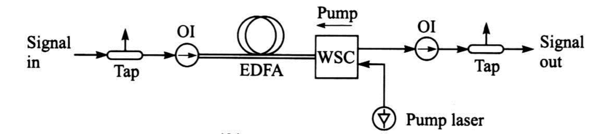


Pumping Configurations

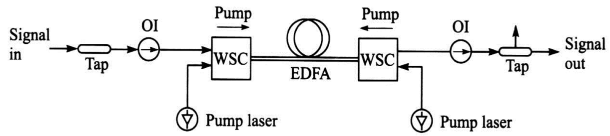
Forward-pumping
(same direction as signal)



Backward-pumping
(opposite direction to signal)



Bidirectional-pumping
(both directions)



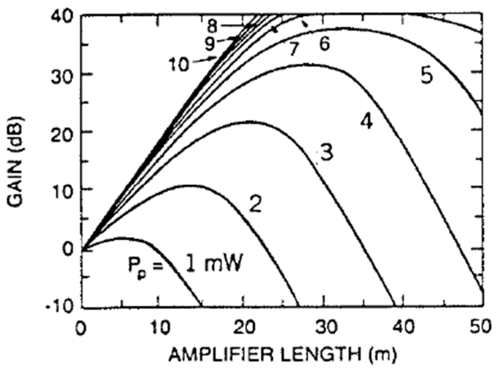
Pumping Configurations

forward pumping → gives less noise

backward pumping → gives higher gain

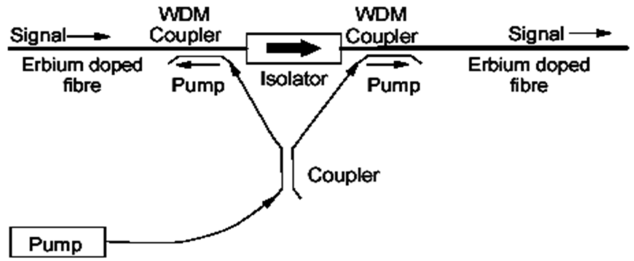
bidirectional pumping → population inversion relatively uniform along amplifier length

Gain as a function of length of erbium-doped fibre



If the fibre is too long, there will be more absorption than gain, but if the fibre is too short we will not have as much gain as we could. Optimum length depends on the pump power.

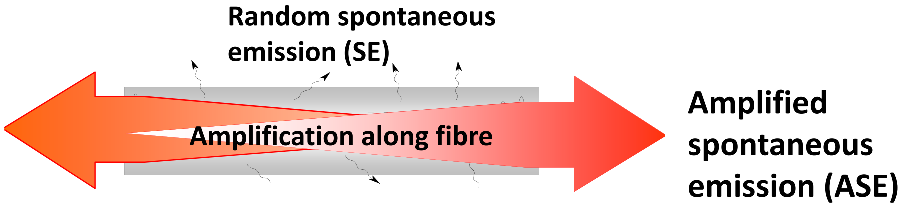
Two-stage EDFA



Some new EDFA designs concatenate two or even three amplifier stages. An amplifier "stage" is considered to consist of any unbroken section of erbium doped fibre. Multistage amplifiers are built for a number of reasons:

1. To increase the power output whilst retaining low noise
2. To flatten the total amplifier gain response
3. To reduce amplified stimulated emission noise

NOISE & GAIN COMPRESSION IN ERBIUM-DOPED FIBRE AMPLIFIERS

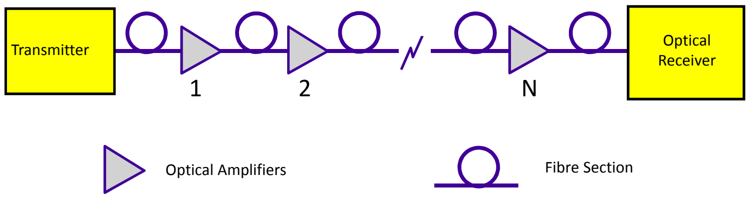


Erbium randomly emits photons between 1520 and 1570 nm

- Spontaneous emission (SE) is not polarized or coherent
- Like any photon, SE stimulates emission of other photons
- With no input signal, eventually all optical energy is consumed into amplified spontaneous emission

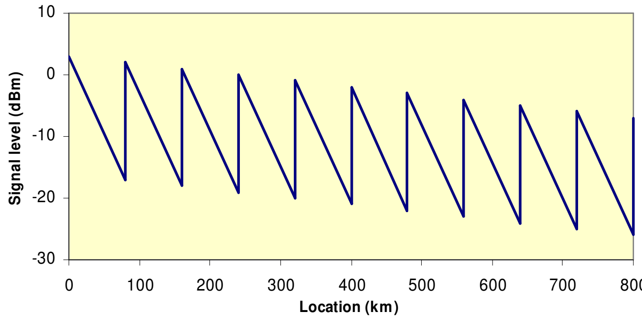
Optical Amplifier Chains

- Optical amplifiers allow one to extend link distance between a transmitter and receiver
- Amplifier can compensate for attenuation
- Cannot compensate for dispersion (and crosstalk in DWDM systems)
- Amplifiers also introduce noise, as each amplifier reduces the Optical SNR by a small amount (noise figure)



Amplifier Chains and Signal Level

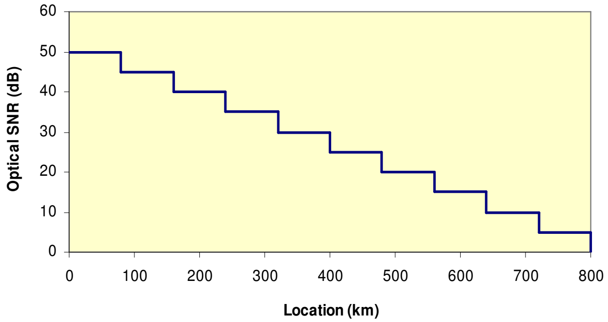
- Example: system uses fibre with 0.25 dB/km attenuation, 80 km fibre sections, amplifiers with 19 dB gain a noise figure of 5 dB



- Each amplifier restores the signal level to a value almost equivalent to the level at the start of the section - in principle reach is extended to 700 km +

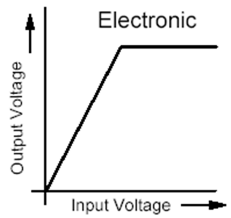
Amplifier Chains and Optical SNR

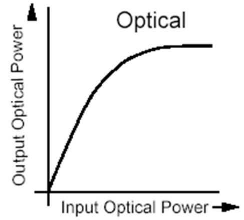
- Same system: Transmitter SNR is 50 dB, amplifier noise figure of 5 dB,



- Optical SNR drops with distance, so that if we take 30 dB as a reasonable limit, the max distance between T/X and R/X is only 300 km

EDFA Behaviour at Gain Saturation





There are two main differences between the behaviour of electronic amplifiers and of EDFAs in gain saturation:

1) As input power is increased on the EDFA the total gain of the amplifier increases slowly.

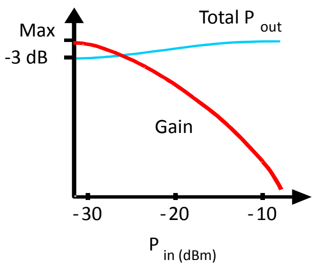
An electronic amplifier operates relatively linearly until its gain saturates. This means that an electronic amplifier operated near saturation introduces significant distortion into the signal (it just clips the peaks off).

2) An erbium amplifier at saturation simply applies less gain to all of its input regardless of the instantaneous signal level. Thus it does not distort the signal. There is little or no crosstalk between WDM channels even in saturation.

Saturation in EDFAs

Total output power:

Amplified signal + Noise (Amplified Spontaneous Emission ASE)

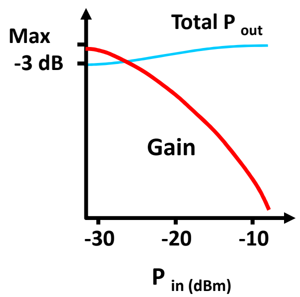


EDFA is in saturation if almost all Erbium ions are consumed for amplification

Total output power remains almost constant, regardless of input power changes

Gain Compression

- Total output power: Amplified signal + ASE
  - EDFA is in saturation if almost all Erbium ions are consumed for amplification
  - Total output power remains almost constant
  - Lowest noise figure
- Preferred operating point
  - Power levels in link stabilize automatically



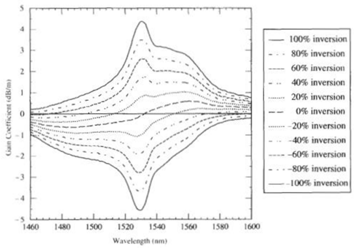
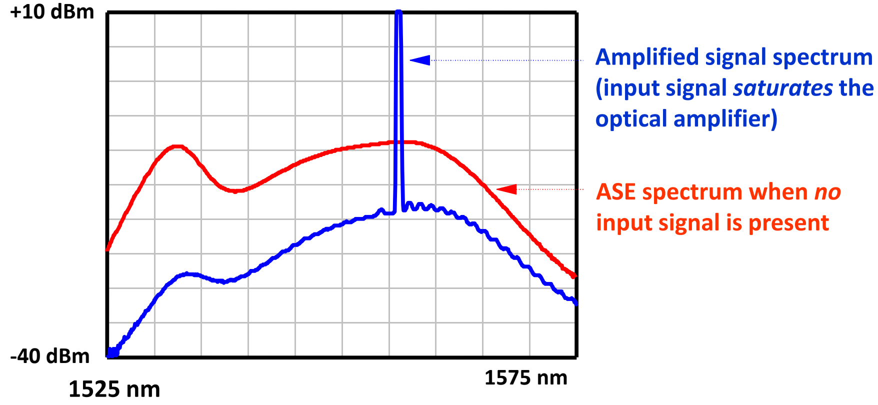


Fig. 2.5 Gain coefficient spectra for different values of inversion for an erbium-doped fiber with Al and Ge co-doping.

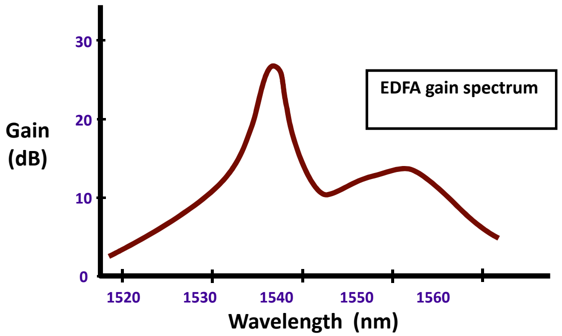
GAIN PROFILE OF ERBIUM-DOPED FIBRE AMPLIFIERS

EDFA Output Spectra

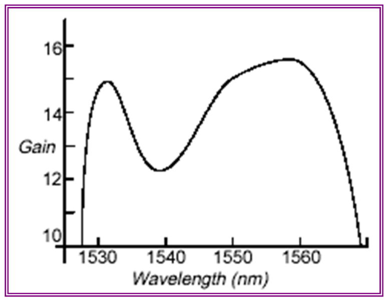


EDFA Gain Spectrum

- Erbium can provide about 40-50 nm of bandwidth, from 1520 to 1570 nm
- Gain spectrum depends on the glass used, eg. silica or zblan glass
- Gain spectrum is not flat, significant gain variations (basically because of different population levels in different bands).

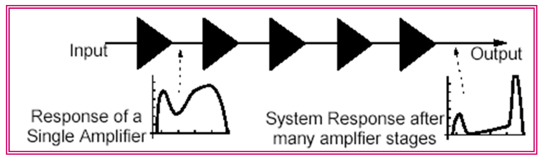


Gain Characteristics of EDFA

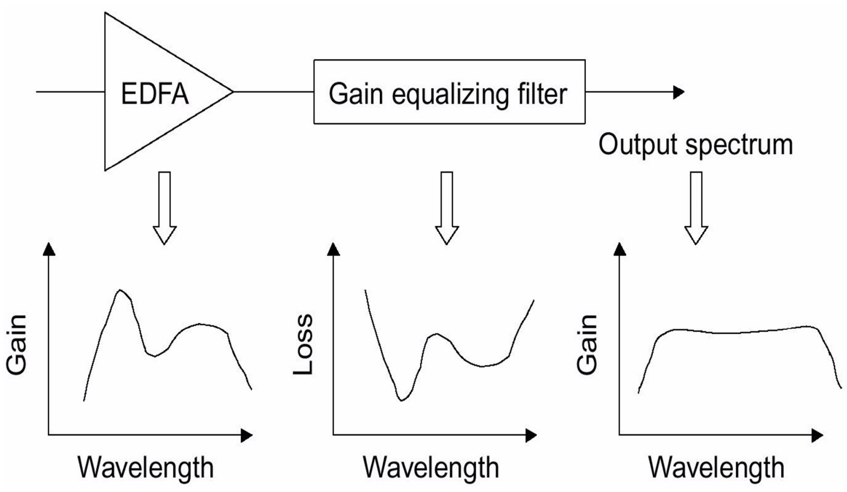


Gain (amplifier) - is the ratio in decibels of input power to output power.
Gain at 1560 nm is some 3 dB higher than gain at 1540 nm (this is twice as much).
In most applications (if there is only a single channel or if there are only a few amplifiers in the circuit) this is not too much of a limitation.

WDM systems use many wavelengths within the amplified band. If we have a very long WDM link with many amplifiers the difference in response in various channels adds up.



Gain Flattening Concept



RAMAN AMPLIFICATION

Raman Amplifiers

- Raman Fibre Amplifiers (RFAs) rely on an intrinsic non-linearity in silica fibre
- Variable wavelength amplification:
  - Depends on pump wavelength
  - For example pumping at 1500 nm produces gain at about 1560-1570 nm
- RFAs can be used as a standalone amplifier or as a distributed amplifier in conjunction with an EDFA

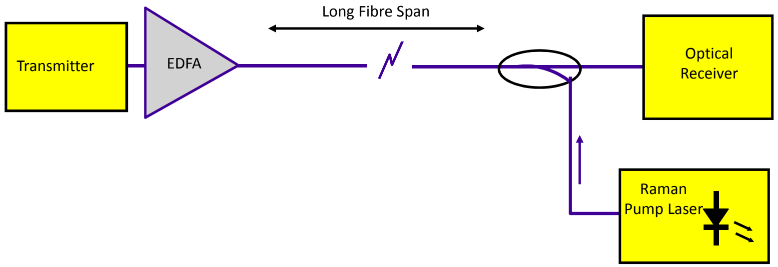
Raman Effect Amplifiers

- *Stimulated Raman Scattering (SRS)* causes a new signal (a Stokes wave) to be generated in the same direction as the pump wave down-shifted in frequency by 13.2 THz (due to molecular vibrations) provided that the pump signal is of sufficient strength.
- In addition SRS causes the amplification of a signal if it is lower in frequency than the pump. Optimal amplification occurs when the difference in wavelengths is around 13.2 THz.
- The signal to be amplified must be lower in frequency (longer in wavelength) than the pump.
- It is easy to build a Raman amplifier, but there is a big problem:

  we cannot build very high power (around half a watt or more) pump lasers at any wavelength we desire! Laser wavelengths are very specific and high power lasers are quite hard to build.

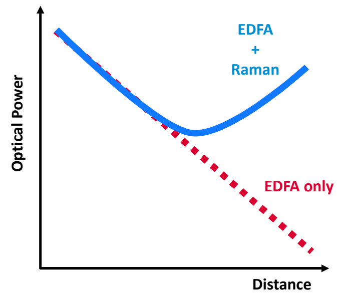
Distributed Raman Amplification (I)

- Raman pumping takes place backwards over the fibre
- Gain is a maximum close to the receiver and decreases in the transmitter direction



Distributed Raman Amplification (II)

- With only an EDFA at the transmit end the optical power level decreases over the fibre length
- With an EDFA and Raman the minimum optical power level occurs toward the middle, not the end, of the fibre.



Broadband Amplification using Raman Amplifiers

- Raman amplification can provides very broadband amplification
- Multiple high-power "pump" lasers are used to produce very high gain over a range of wavelengths.
- 93 nm bandwidth has been demonstrated with just two pumps sources
- 400 nm bandwidth possible?

Advantages and Disadvantages of Raman Amplification

- Advantages
  - Variable wavelength amplification possible
  - Compatible with installed SM fibre
  - Can be used to "extend" EDFAs
  - Can result in a lower average power over a span, good for lower crosstalk
  - Very broadband operation may be possible
- Disadvantages
  - High pump power requirements, high pump power lasers have only recently arrived
  - Sophisticated gain control needed
  - Noise is also an issue