



Optical Amplification



Optical Amplifiers

An **optical amplifier** is a device which amplifies the optical signal directly without ever changing it to electricity. The light itself is amplified.

Reasons to use the optical amplifiers:

- Reliability
- Flexibility
- Wavelength Division Multiplexing (WDM)
- Low Cost

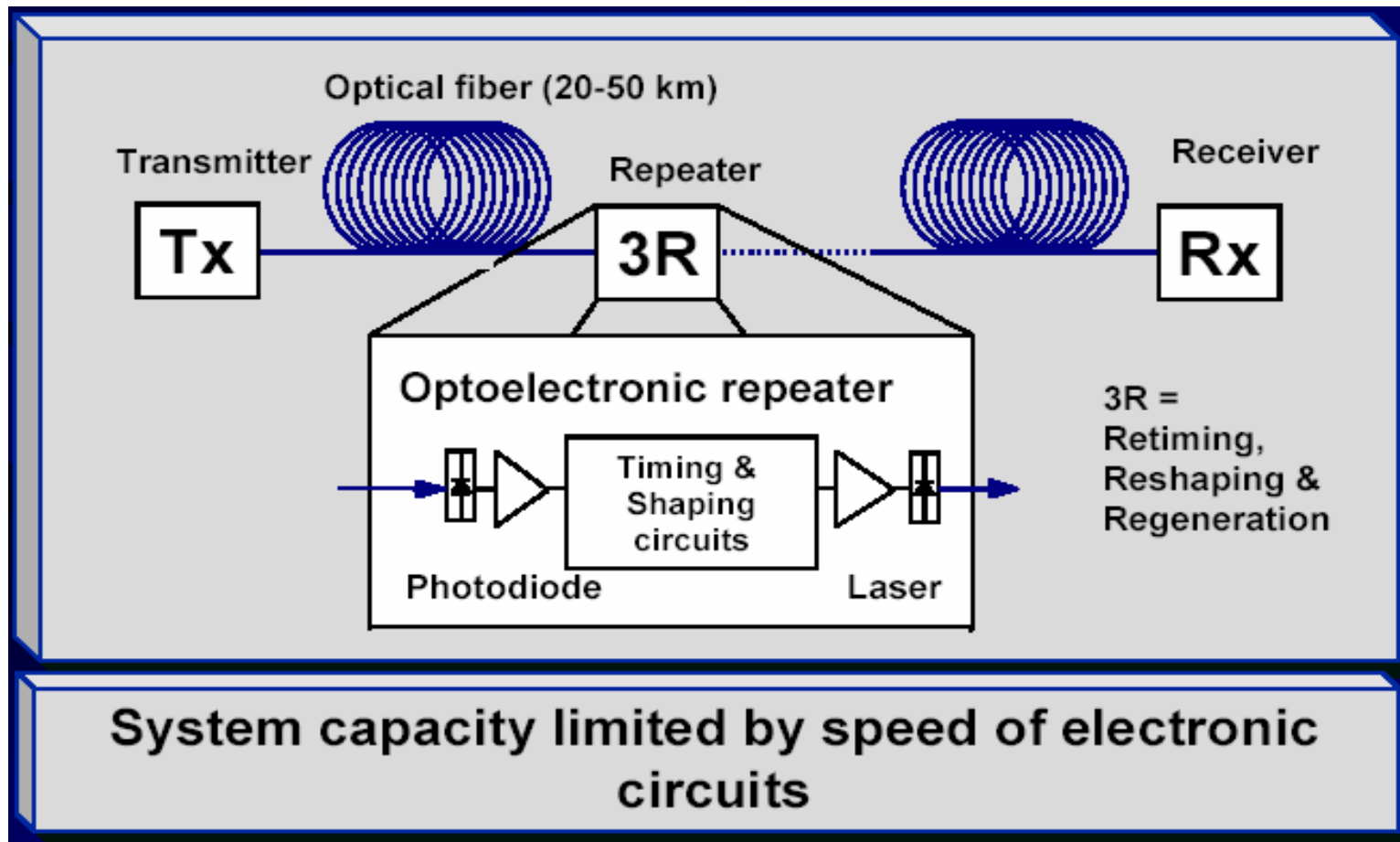
Variety of optical amplifier types exists, including:

- Semiconductor Optical Amplifiers (SOAs)
- Erbium Doped Fibre Amplifiers (EDFAs) (most common)



Traditional Optical Communication System

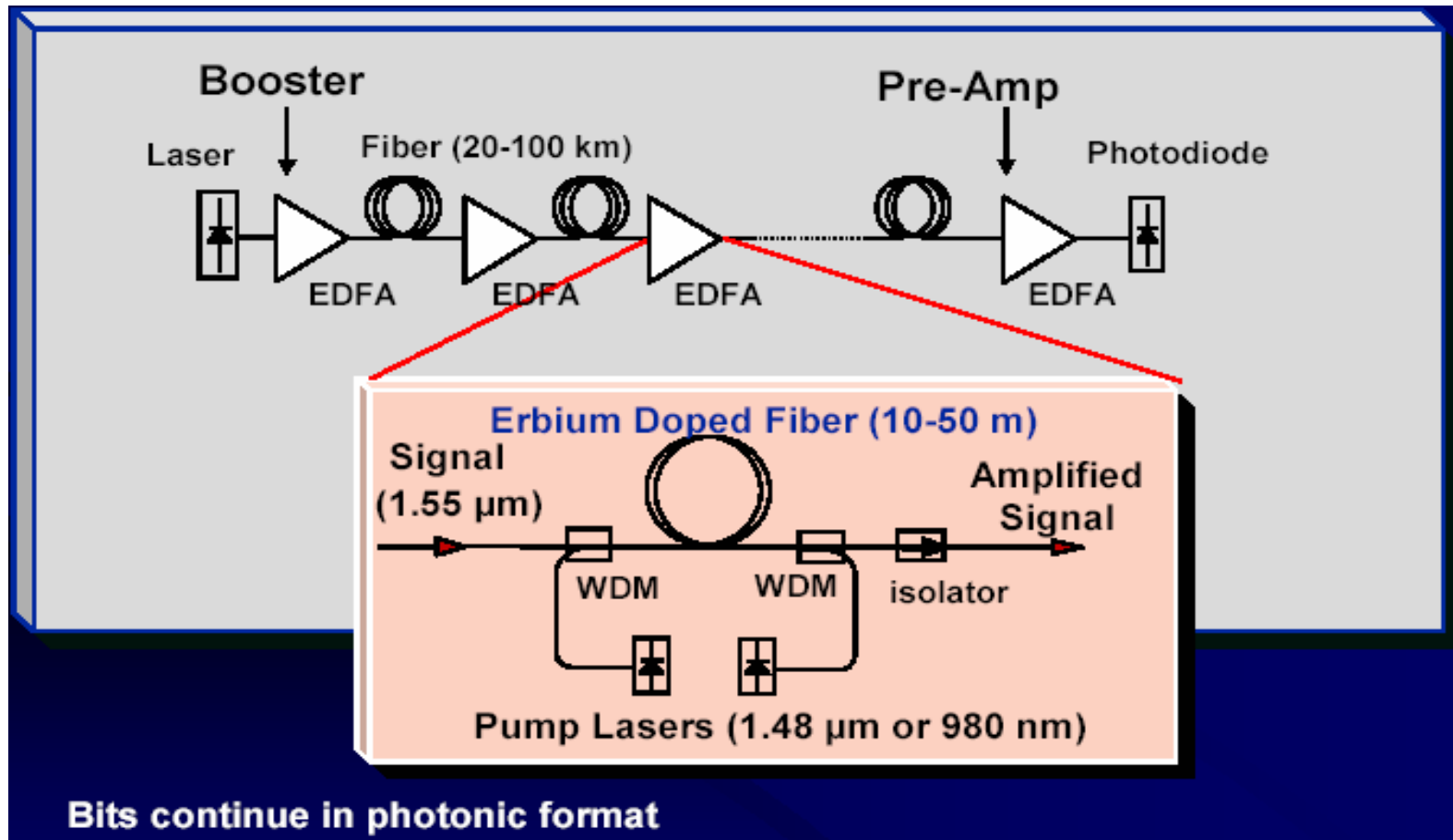
Loss compensation: Repeaters at every 20-50 km





Optically Amplified Systems

EDFA = Erbium Doped Fibre Amplifier





Optical Amplification

- Variety of optical amplifier types exist, including:
 - Semiconductor optical amplifiers
 - Optical fibre amplifiers (Erbium Doped Fibre Amplifiers)
 - Distributed fibre amplifiers (Raman Amplifiers)
- Optical fibre amplifiers are now the most common type
- One of the most successful optical processing functions
- Also used as a building block in DWDM systems



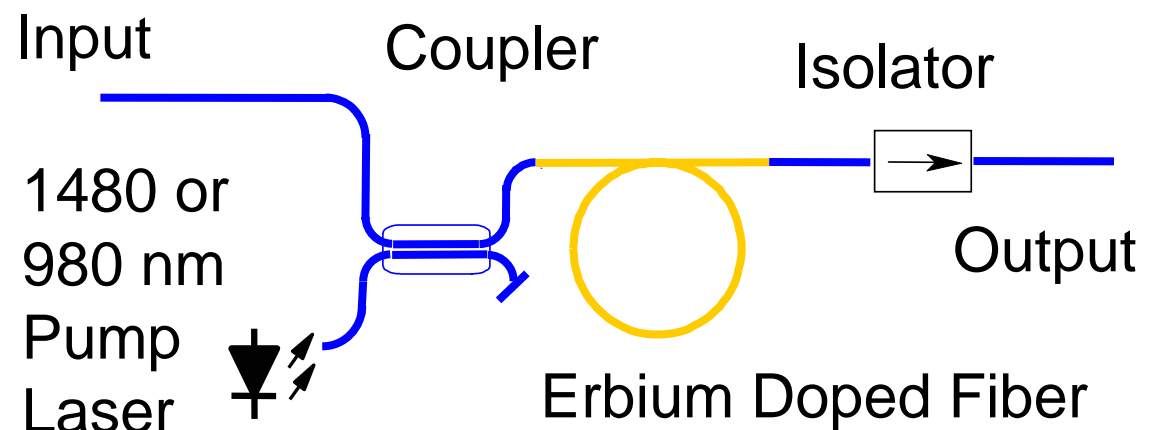
Overview

- **Erbium doped fibre amplifiers**
- **Amplifier applications**
- **Issues: Gain flattening and Noise**
- **Raman amplification**



Basic EDF Amplifier Design

- Erbium-doped fiber amplifier (EDFA) most common
 - Commercially available since the early 1990's
 - Works best in the range 1530 to 1565 nm
 - Gain up to 30 dB (1000 photons out per photon in!)
- Optically transparent
 - “Unlimited” RF bandwidth
 - Wavelength transparent

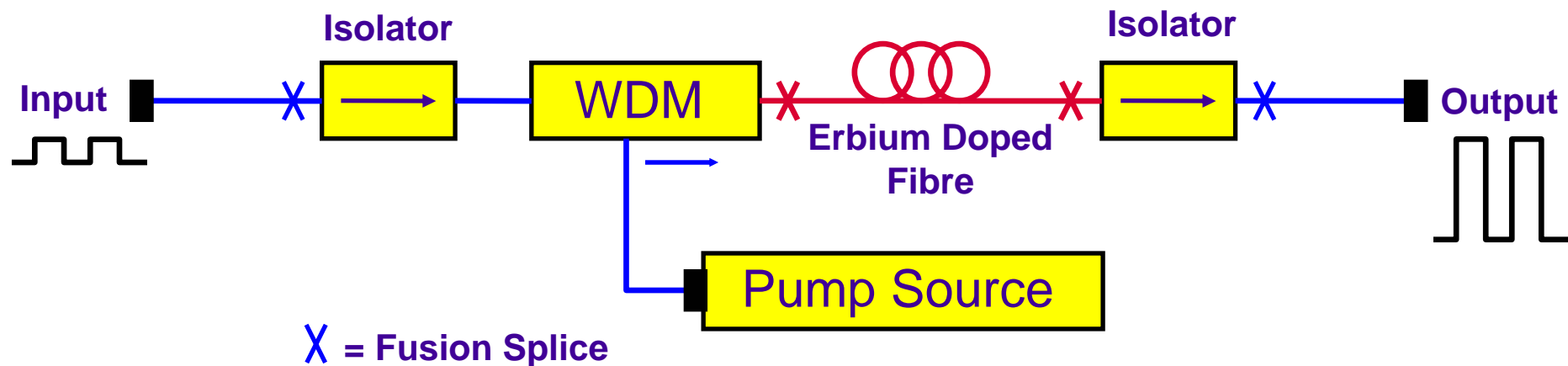




Erbium Doped Fibre Amplifier

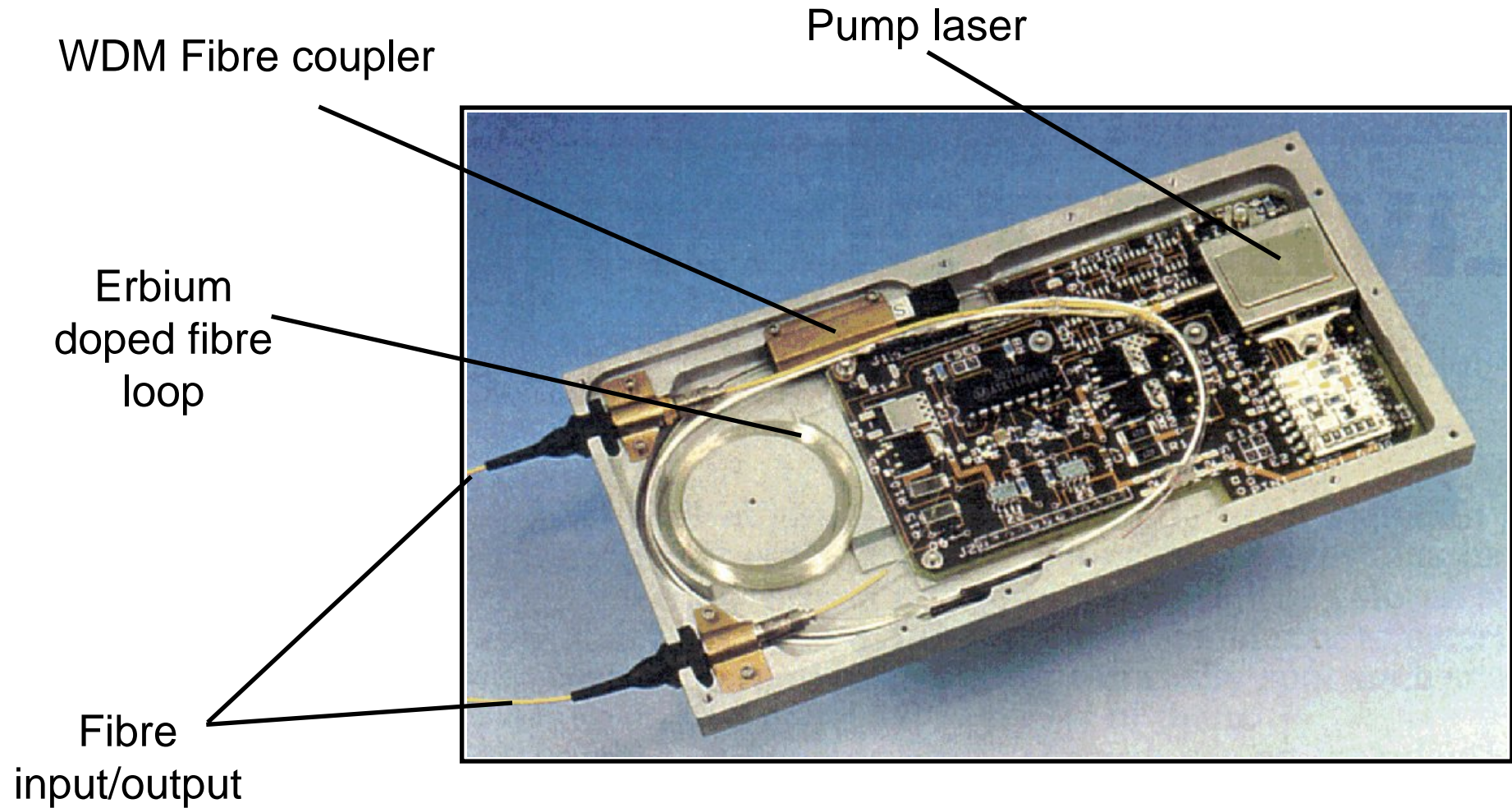
APPLIED OPTOELECTRONICS CENTRE

- A pump optical signal is added to an input signal by a WDM coupler
- Within a length of doped fibre part of the pump energy is transferred to the input signal by stimulated emission
- For operation circa 1550 nm the fibre dopant is Erbium
- Pump wavelength is 980 nm or 1480 nm, pump power circa 50 mW
- Gains of 30-40 dB possible



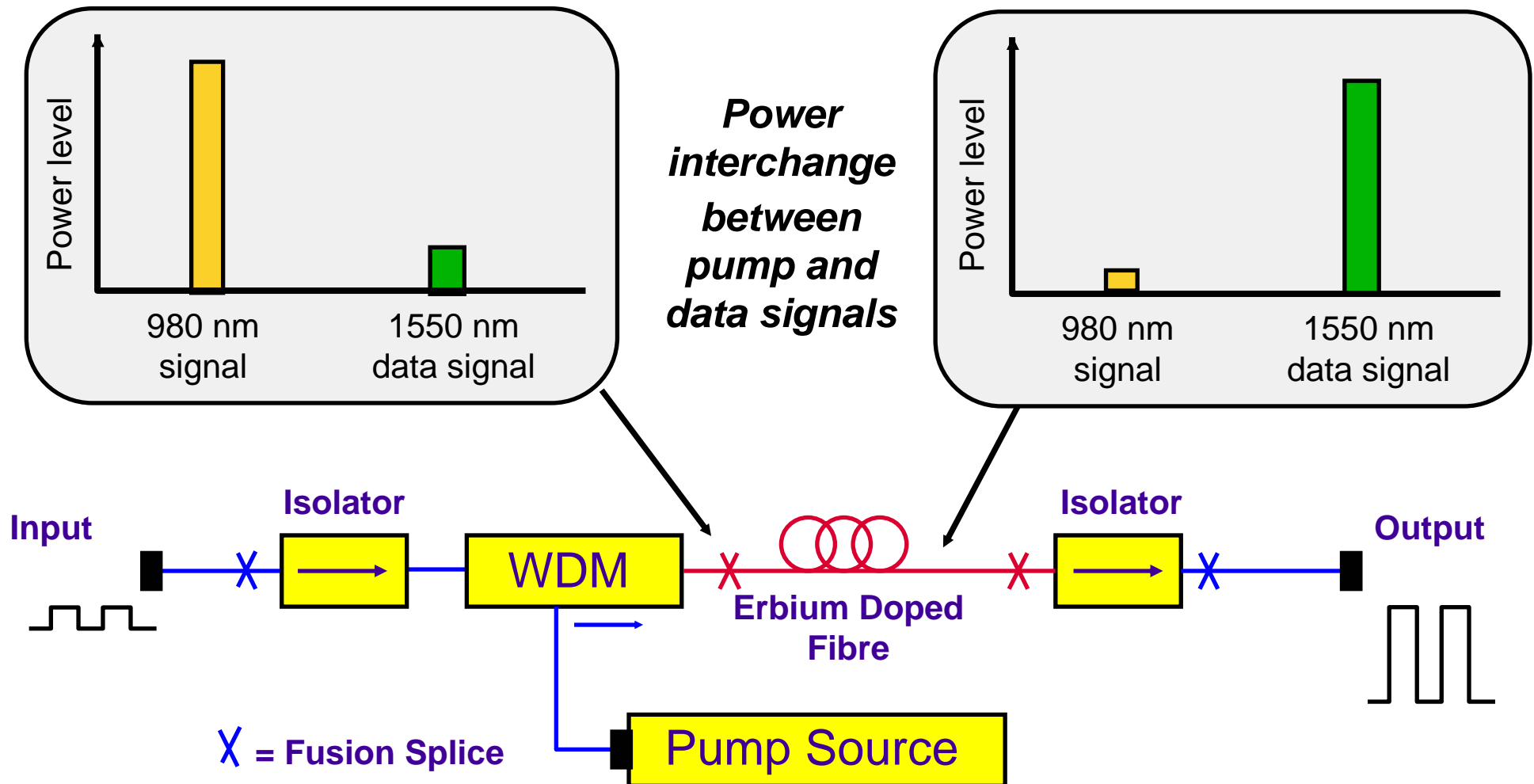


Interior of an Erbium Doped Fibre Amplifier (EDFA)



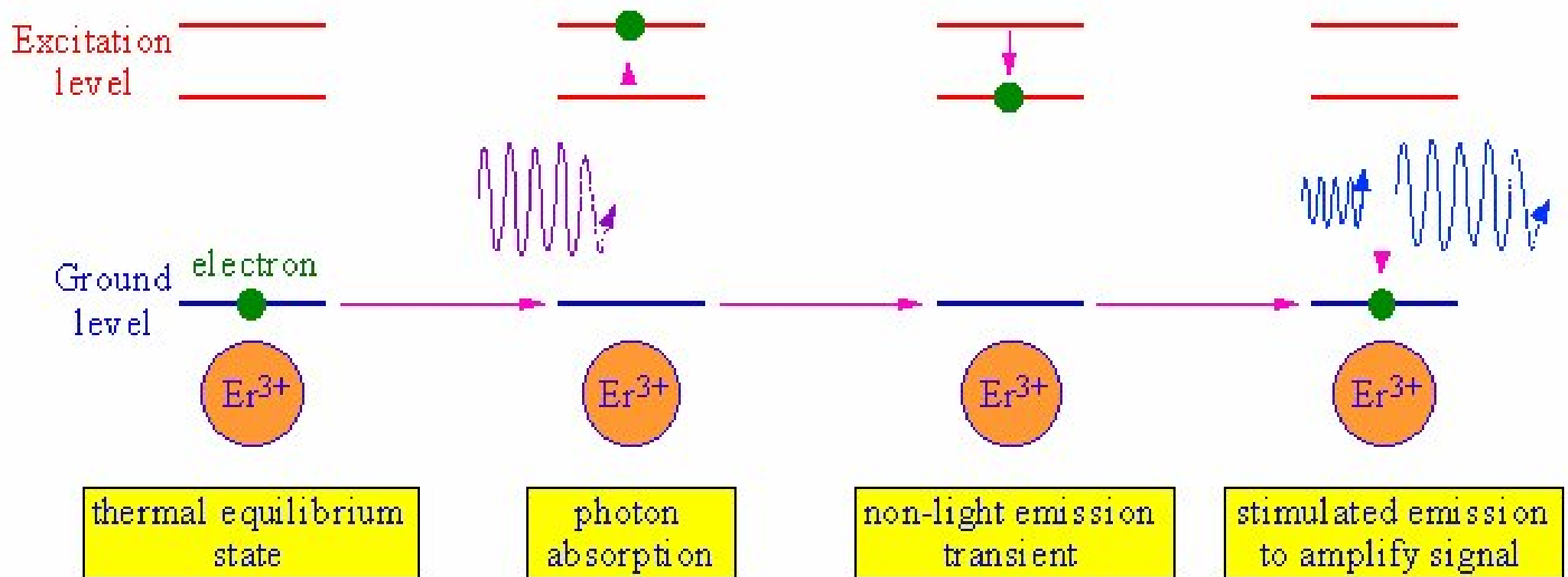


Operation of an EDFA





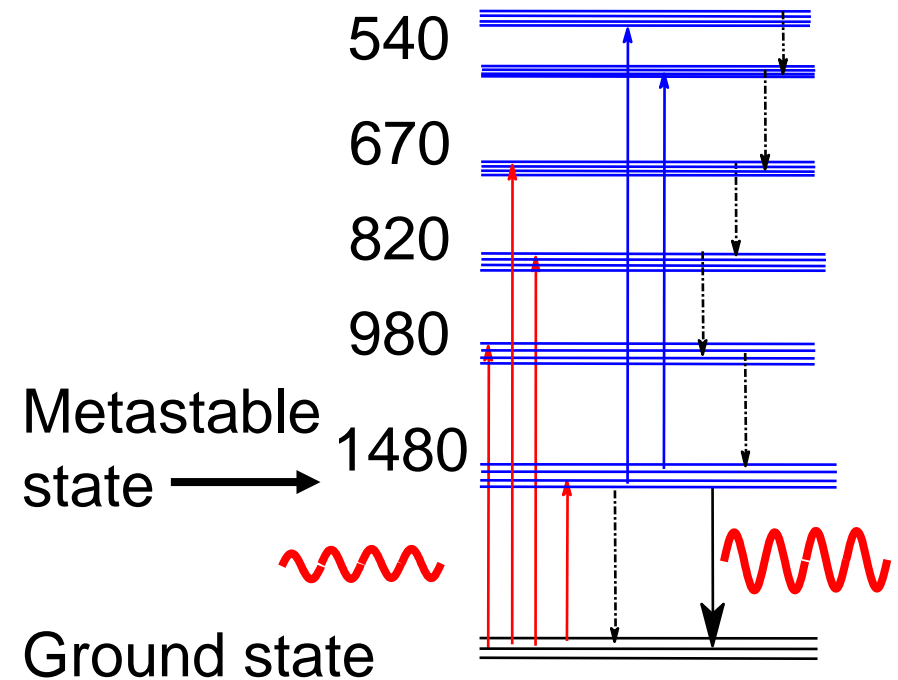
Physics of an EDFA





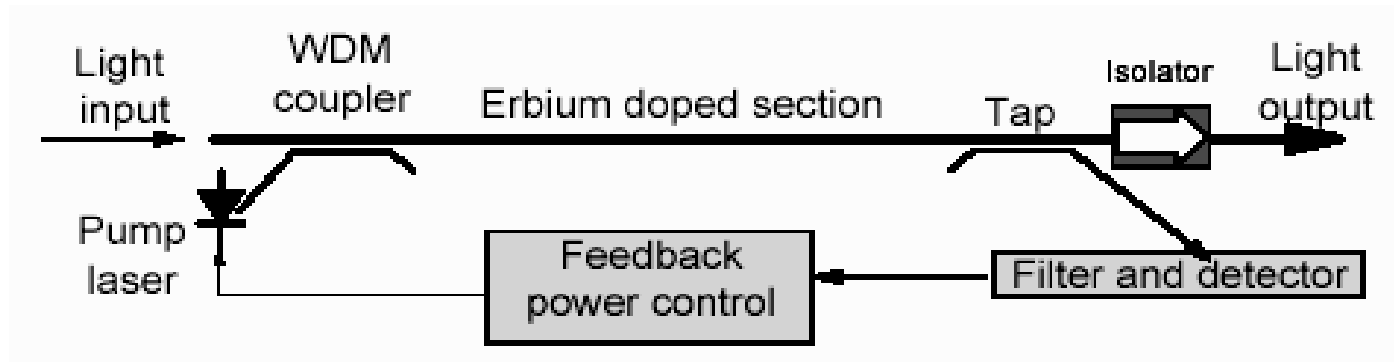
Erbium Properties

- Erbium: rare element with phosphorescent properties
 - Photons at 1480 or 980 nm activate electrons into a metastable state
 - Electrons falling back emit light in the 1550 nm range
- Spontaneous emission
 - Occurs randomly (time constant ~1 ms)
- Stimulated emission
 - By electromagnetic wave
 - Emitted wavelength & phase are identical to incident one





Erbium Doped Fibre Amplifiers



Consists of a short (typically ten metres or so) section of fibre which has a small controlled amount of the rare earth element erbium added to the glass in the form of an ion (Er^{3+}).

The principle involved is the principle of a laser.

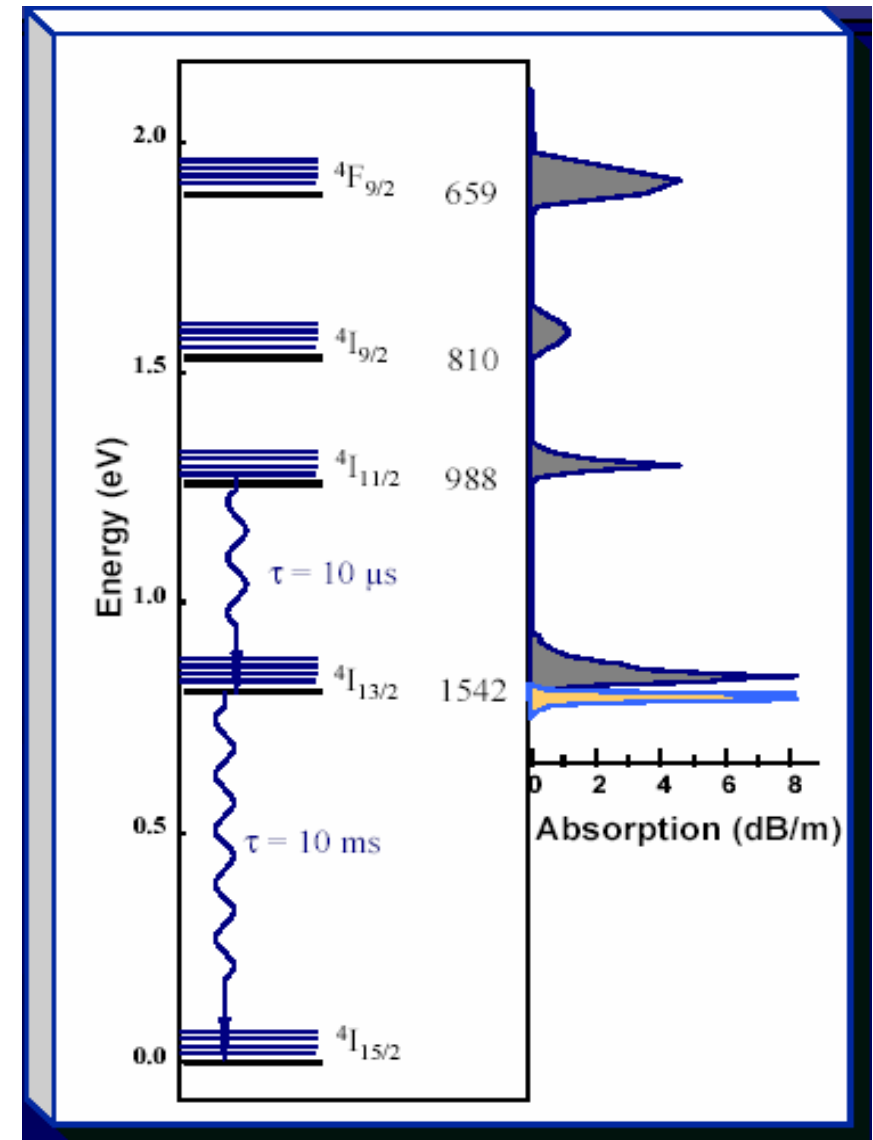
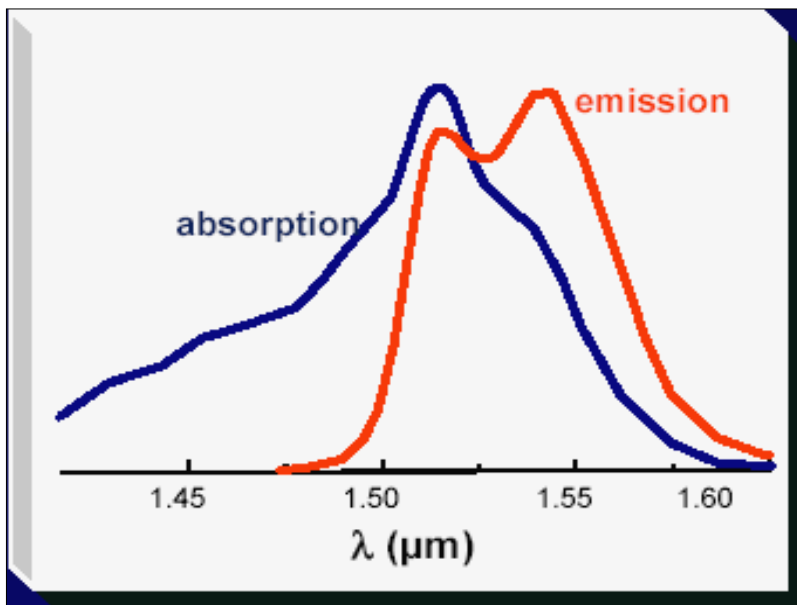
When an erbium ion is in a high-energy state, a photon of light will stimulate it to give up some of its energy (also in the form of light) and return to a lower-energy (more stable) state (“stimulated emission”).

The laser diode in the diagram generates a high-powered (between 10 and 200mW) beam of light at a wavelength such that the erbium ions will absorb it and jump to their excited state. (Light at either 980 or 1,480 nm wavelengths.)



Er³⁺ Energy Levels

- **Pump:**
 - 980 or 1480 nm
 - Pump power >5 mW
- **Emission:**
 - 1.52-1.57 μm
 - Long living upper state (10 ms)
 - Gain \cong 30 dB





EDFA Operation

- 1. A (relatively) high-powered beam of light is mixed with the input signal using a wavelength selective coupler.**
- 2. The mixed light is guided into a section of fibre with erbium ions included in the core.**
- 3. This high-powered light beam excites the erbium ions to their higher-energy state.**
- 4. When the photons belonging to the signal (at a different wavelength from the pump light) meet the excited erbium atoms, the erbium atoms give up some of their energy to the signal and return to their lower-energy state.**
- 5. A significant point is that the erbium gives up its energy in the form of additional photons which are exactly in the same phase and direction as the signal being amplified.**
- 6. There is usually an isolator placed at the output to prevent reflections returning from the attached fibre. Such reflections disrupt amplifier operation and in the extreme case can cause the amplifier to become a laser!**

Technical Characteristics of EDFA

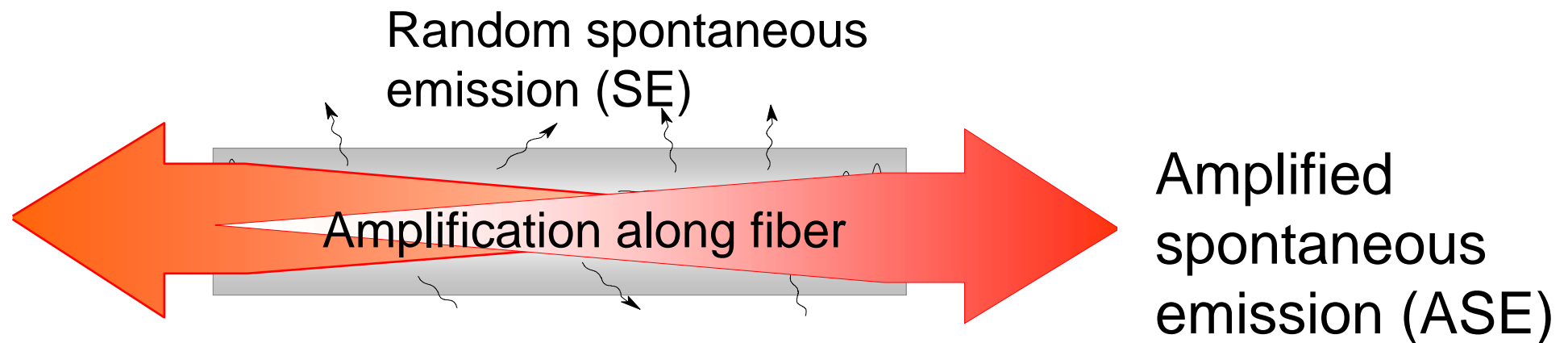
EDFAs have a number of attractive technical characteristics:

- **Efficient pumping**
- **Minimal polarisation sensitivity**
- **Low insertion loss**
- **High output power (this is not gain but raw amount of possible output power)**
- **Low noise**
- **Very high sensitivity**
- **Low distortion and minimal interchannel crosstalk**



Amplified Spontaneous Emission

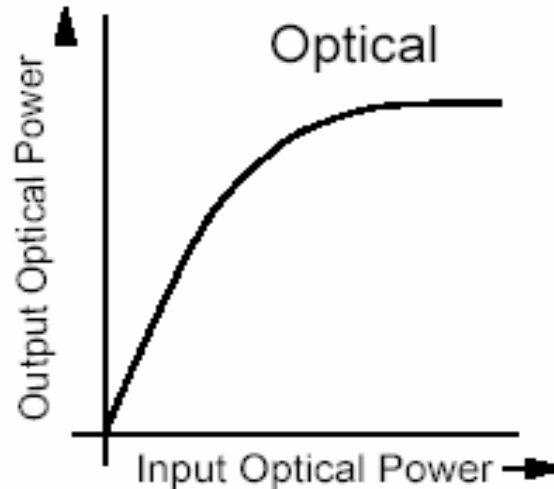
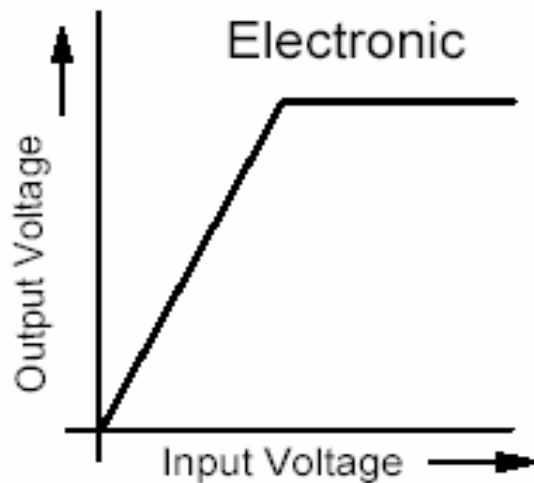
- Erbium randomly emits photons between 1520 and 1570 nm
 - Spontaneous emission (SE) is not polarized or coherent
 - Like any photon, SE stimulates emission of other photons
 - With no input signal, eventually all optical energy is consumed into amplified spontaneous emission
 - Input signal(s) consume metastable electrons → much less ASE





EDFA Behaviour at Gain Saturation

APPLIED OPTOELECTRONICS CENTRE



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 and then it just produces all it can. This means that an electronic amplifier operated near saturation introduces significant distortions into the signal (it just clips the peaks off).

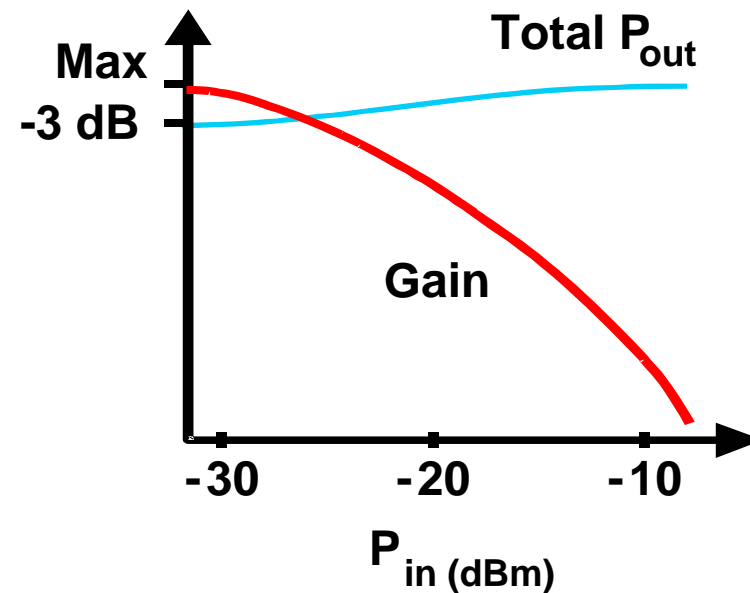
2) An erbium amplifier at saturation simply applies less gain to all of its input regardless of the instantaneous signal level. Thus it does not distort the signal. There is little or no crosstalk between WDM channels even in saturation.



Saturation in EDFAs

Total output power:

Amplified signal + Noise (Amplified Spontaneous Emission ASE)



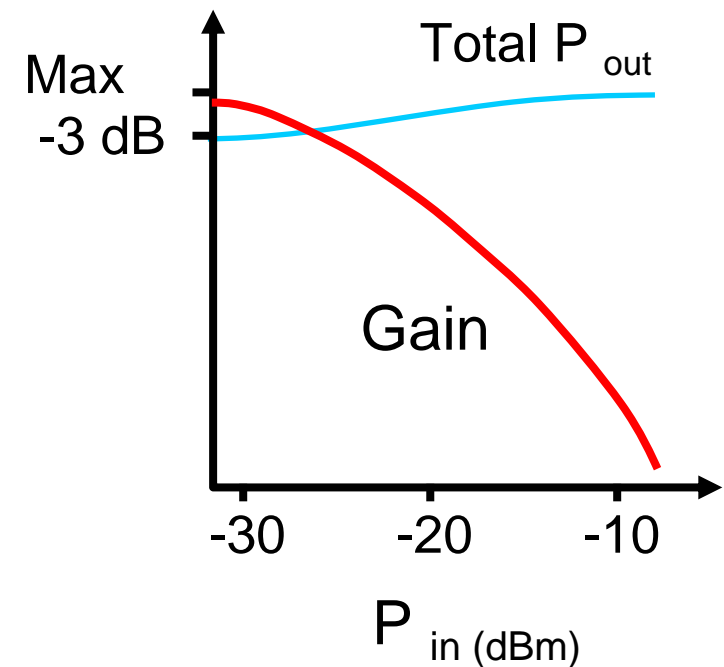
EDFA is in saturation if almost all Erbium ions are consumed for amplification

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





Amplifier Length

- As the signal travels along the length of the amplifier it becomes stronger due to amplification.
- As the pump power travels through the amplifier its level decreases due to absorption.
- Thus, both the signal power level and the pump power level vary along the length of the amplifier. At any point we can have only a finite number of erbium ions and therefore we can only achieve a finite gain (and a finite maximum power) per unit length of the amplifier.
- In an amplifier designed for single wavelength operation the optimal amplifier length is a function of the signal power, the pump power, the erbium concentration and the amount of gain required.
- In an amplifier designed for multiwavelength operation there is another consideration - the flatness of the gain curve over the range of amplified wavelengths. With a careful design and optimisation of the amplifier's length we can produce a nearly flat amplifier gain curve.



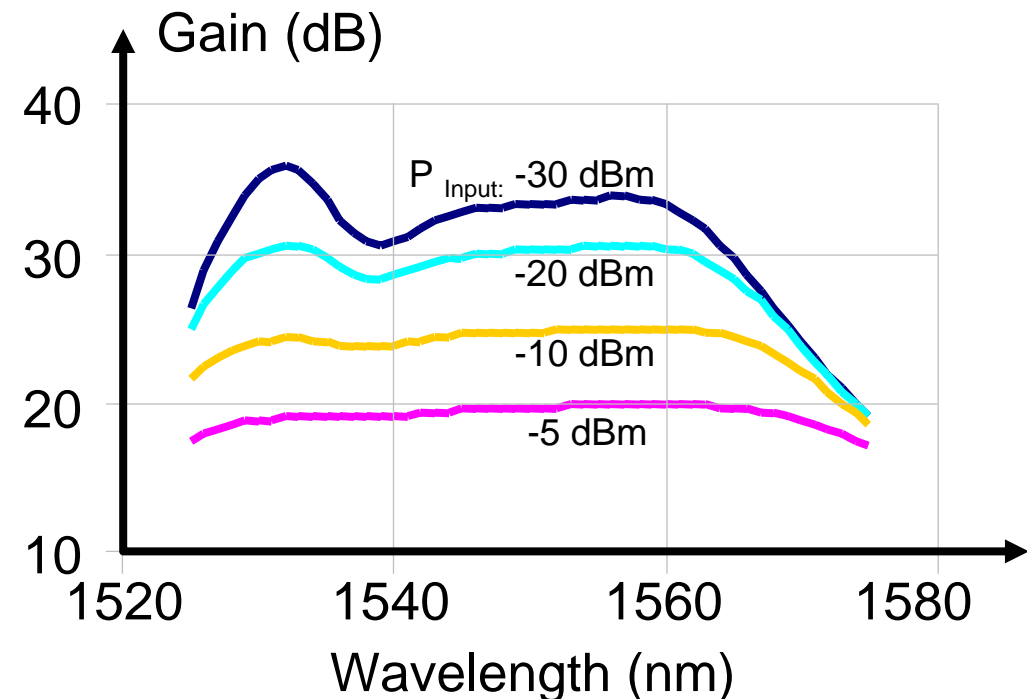
Optical Gain (G)

- $G = S_{\text{Output}} / S_{\text{Input}}$

S_{Output} : output signal (without noise from amplifier)

S_{Input} : input signal

- Input signal dependent
 - Operating point (saturation) of EDFA strongly depends on power and wavelength of incoming signal





EDFA Applications & Selection/Applications



OFAs in the Network

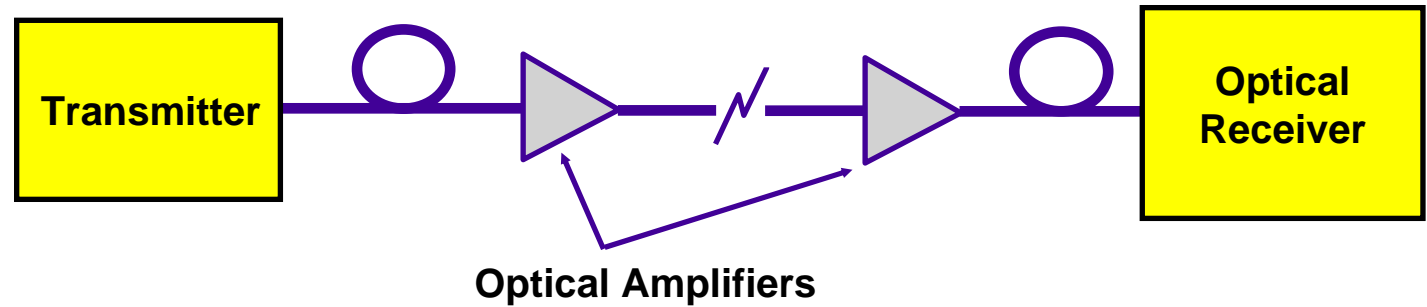
Several attractive features for network use:

- Relatively simple construction
- Reliable, due to the number of passive components
- Allows easy connection to external fibres
- Broadband operation > 20 nm
- Bit rate transparent
- Ideally suited to long span systems
- Integral part of DWDM systems
- Undersea applications for OFAs are now common

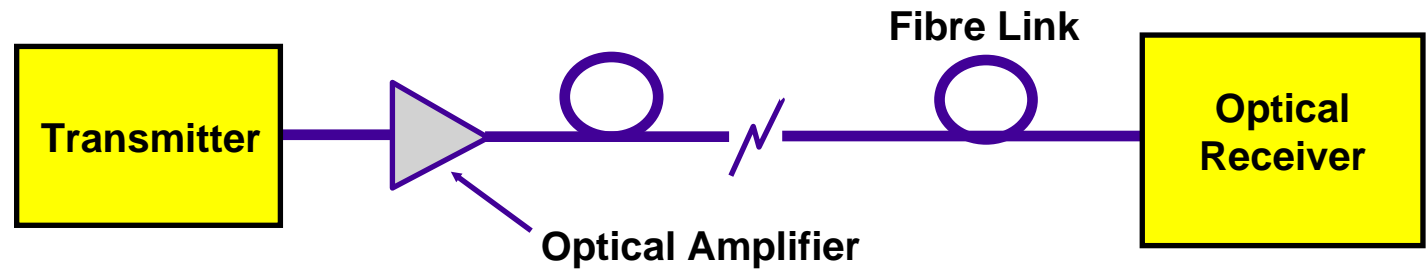


Optical Amplifier Applications

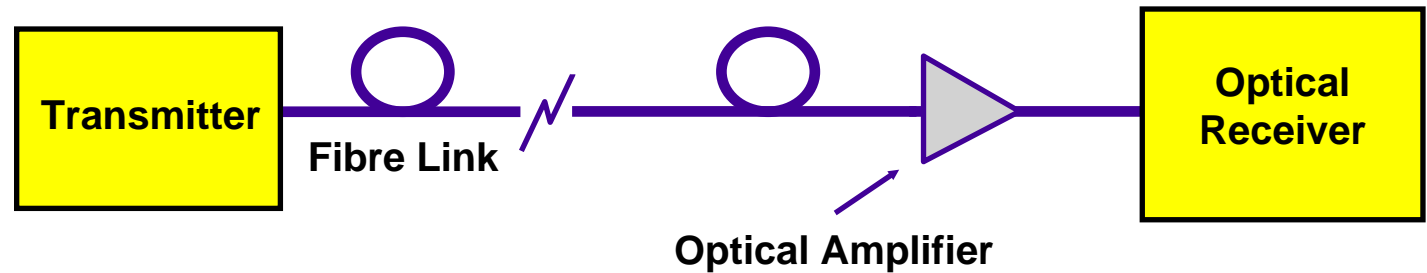
In-line Amplifier



Power Amplifier



Preamplifier





Amplifier Applications

Preamplifiers

An optical preamplifier is placed immediately before a receiver to improve its sensitivity. Since the input signal level is usually very low a low noise characteristic is essential. However, only a moderate gain figure is needed since the signal is being fed directly into a receiver.

Typically a preamplifier will not have feedback control as it can be run well below saturation.

Power amplifiers

Most DFB lasers have an output of only around 2 mW but a fibre can aggregate power levels of up to 100 to 200 mW before nonlinear effects start to occur. A power amplifier may be employed to boost the signal immediately following the transmitter. Typical EDFA power amplifiers have an output of around 100 mW.

Line amplifiers

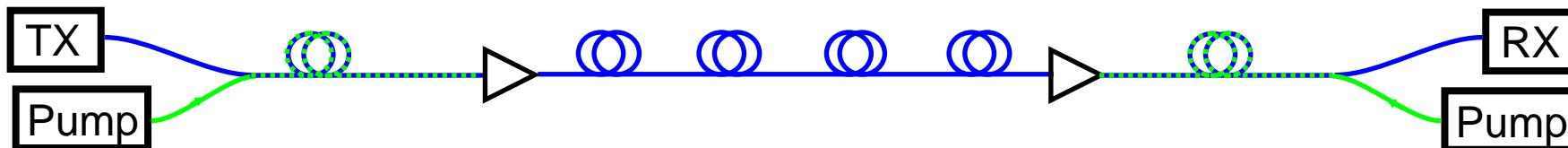
In this application the amplifier replaces a repeater within a long communication line. In many situations there will be multiple amplifiers sited at way-points along a long link.

Both high gain at the input and high power output are needed while maintaining a very low noise figure. This is really a preamplifier cascaded with a power amplifier. Sophisticated line amplifiers today tend to be made just this way - as a multi-section amplifier separated by an isolator.



EDFA Categories

- **In-line amplifiers**
 - Installed every 30 to 70 km along a link
 - Good noise figure, medium output power
- **Power boosters**
 - Up to +17 dBm power, amplifies transmitter output
 - Also used in cable TV systems before a star coupler
- **Pre-amplifiers**
 - Low noise amplifier in front of receiver
- **Remotely pumped**
 - Electronic free extending links up to 200 km and more (often found in submarine applications)





Example: Conventional EDFA

- Best used for single channel systems in the 1550 nm region,
- Systems are designed for use as boosters, in-line amplifiers or preamplifiers.
- Bandwidth is not wide enough for DWDM, special EDFA needed

Erbium Doped Fibre Amplifier		EDFA-14	EDFA-16	EDFA-19
Wavelength Range	nm	1525-1565	1525-1565	1525-1565
Saturation Power	dBm	14	16	19
Maximum Gain in Small Signal	dB	>35	>38	>40
Optimum Gain Flatness (1545-1558nm)	dB	0.6	0.6	0.6
Noise Figure	dB	<6	<6.5	<6
Min. Isolation at Input and Output	dB	30	30	30
Connectors		FC/APC	FC/APC	FC/APC



Gain Flattened EDFA for DWDM

- Gain flatness is now within 1 dB from 1530-1560 nm
- ITU-T DWDM C band is 1530 to 1567 nm

Flat Gain EDFA		EDFA-FG13	EDFA-FG15	EDFA-FG18
Wavelength Range	nm	1530-1560	1530-1560	1532-1560
Saturation Power	dBm	13	15	18
Gain Value	dB	>20	>22	>25
Optimum Gain Flatness (1530-1560nm)	dB	<1	<1	<1
Noise Figure	dB	<6.0	<6.5	<6.0
Min. Isolation at Input and Output	dB	30	30	30
Connectors		FC/APC	FC/APC	FC/APC

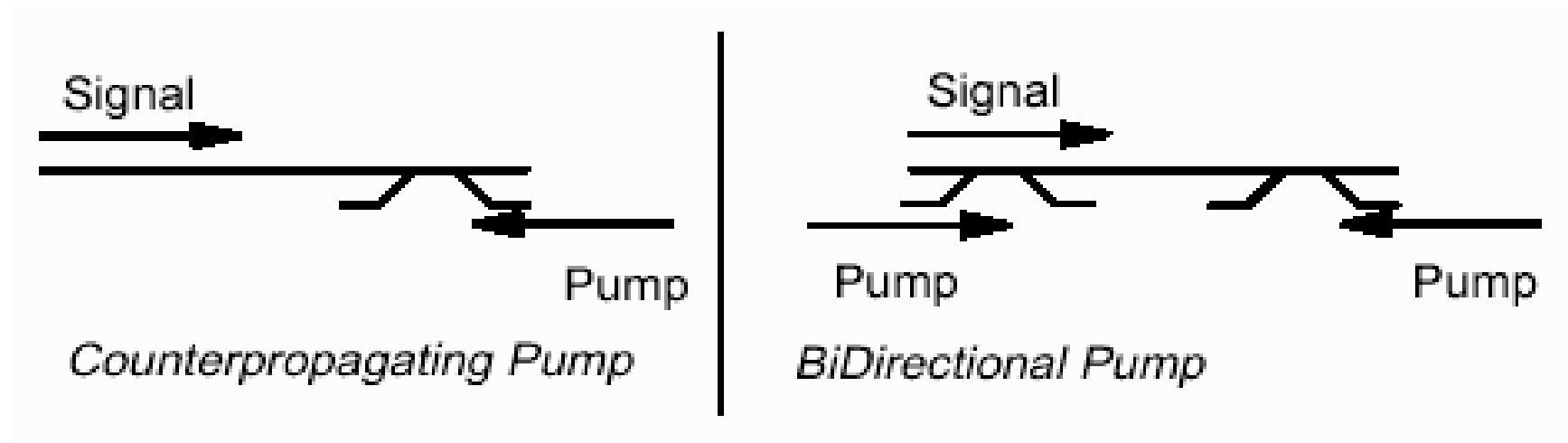


Selecting Amplifiers

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	Low gain	Low output power	Low value < 5 dB essential



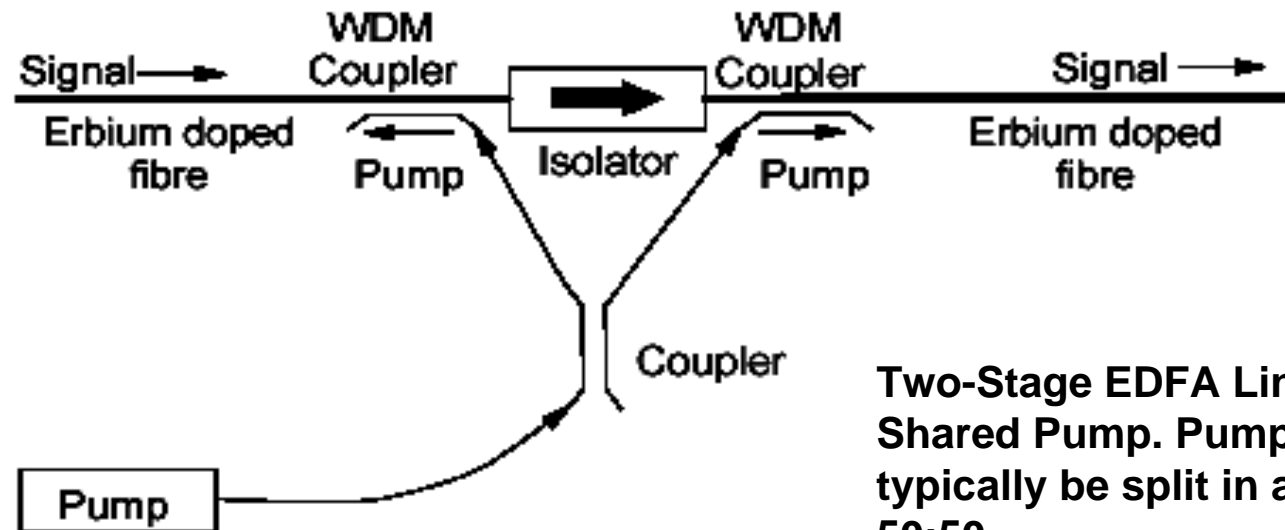
Pumping Directions



Additional pumping options



Multistage EDFAs



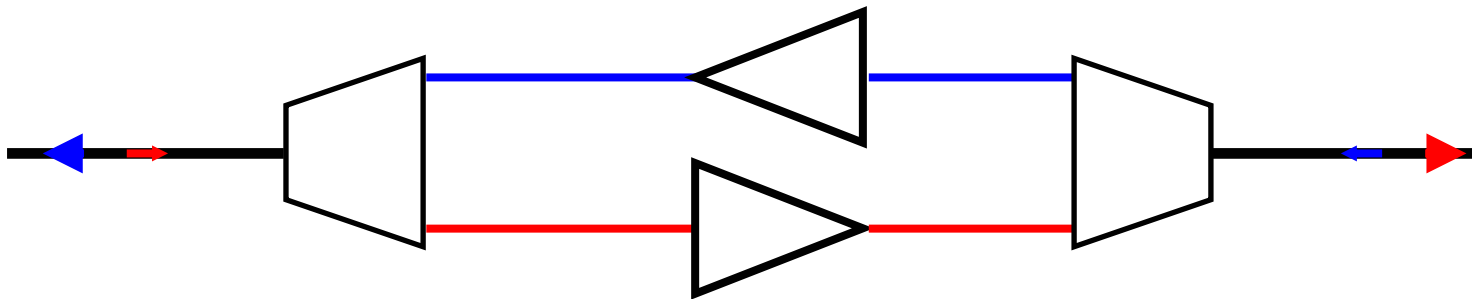
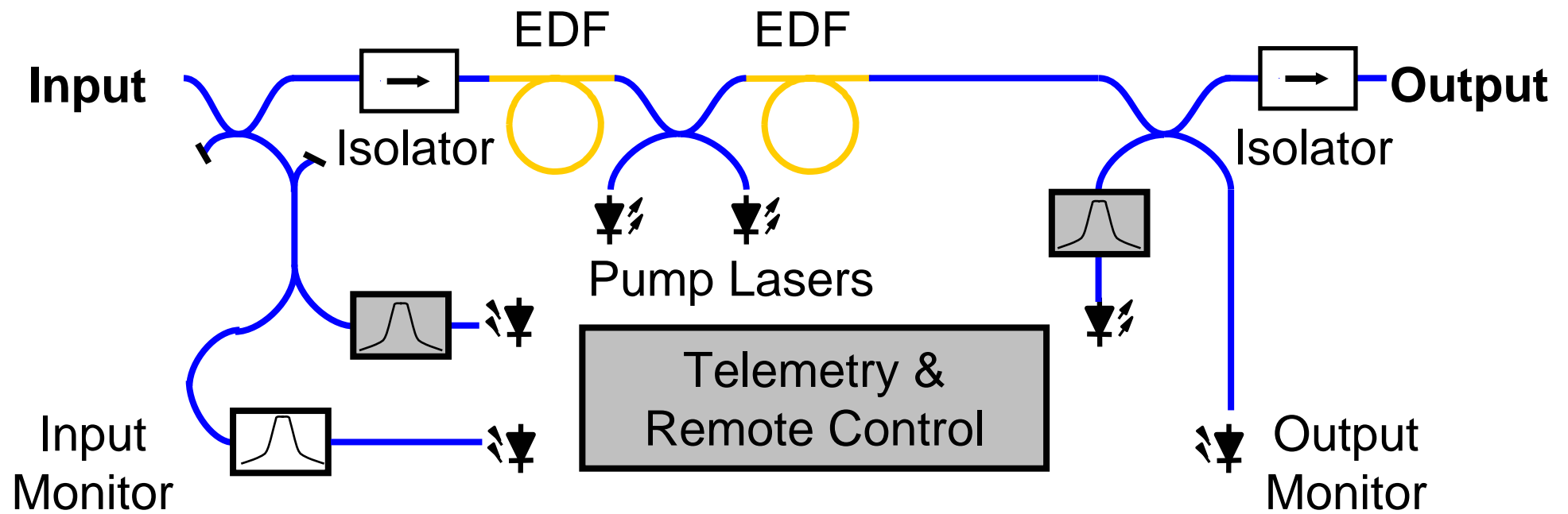
Two-Stage EDFA Line Amplifier with Shared Pump. Pump power would typically be split in a ratio different from 50:50.

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



Commercial Designs



Security/Safety Features

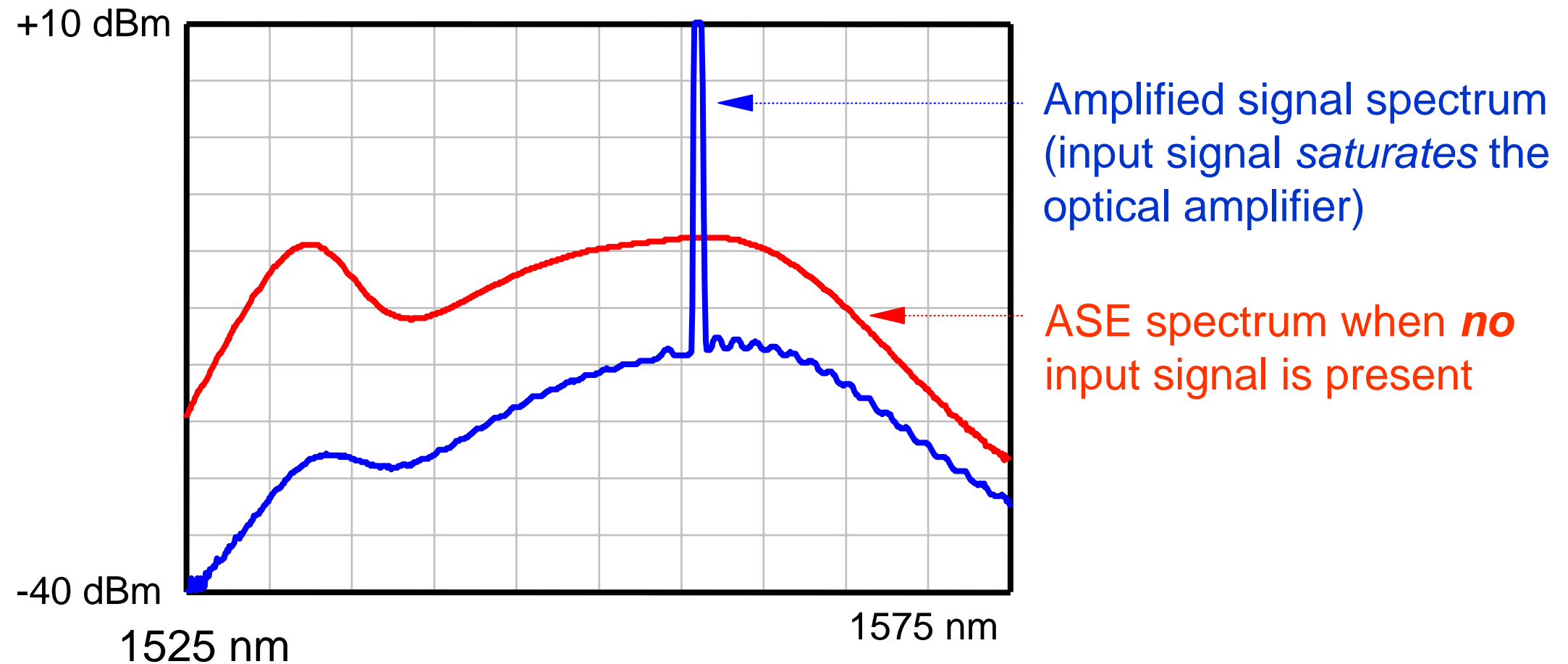
- **Input power monitor**
 - Turning on the input signal can cause high output power spikes that can damage the amplifier or following systems
 - Control electronics turn the pump laser(s) down if the input signal stays below a given threshold for more than about 2 to 20 μ s
- **Backreflection monitor**
 - Open connector at the output can be a laser safety hazard
 - Straight connectors typically reflect 4% of the light back
 - Backreflection monitor shuts the amplifier down if backreflected light exceeds certain limits



Spectral Response of EDFAs & Gain Flattening



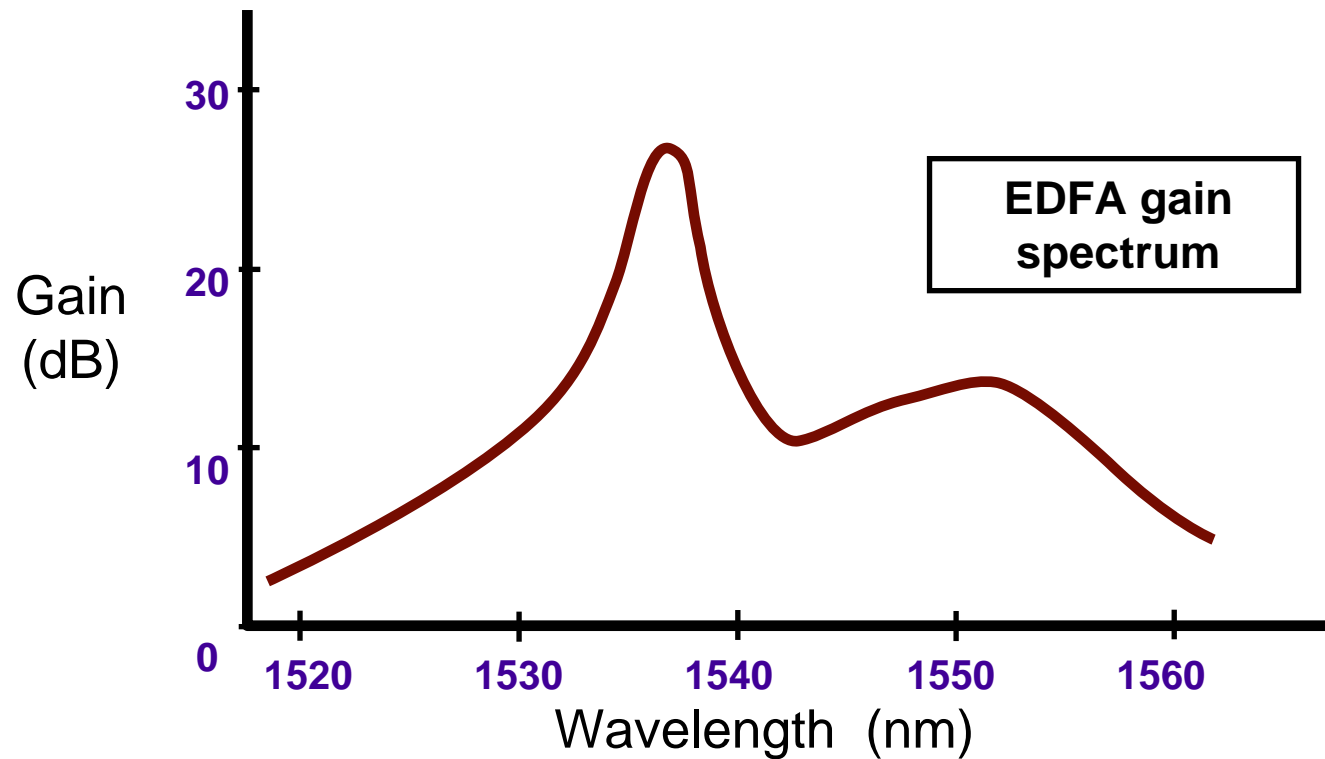
Output Spectra





EDFA Gain Spectrum

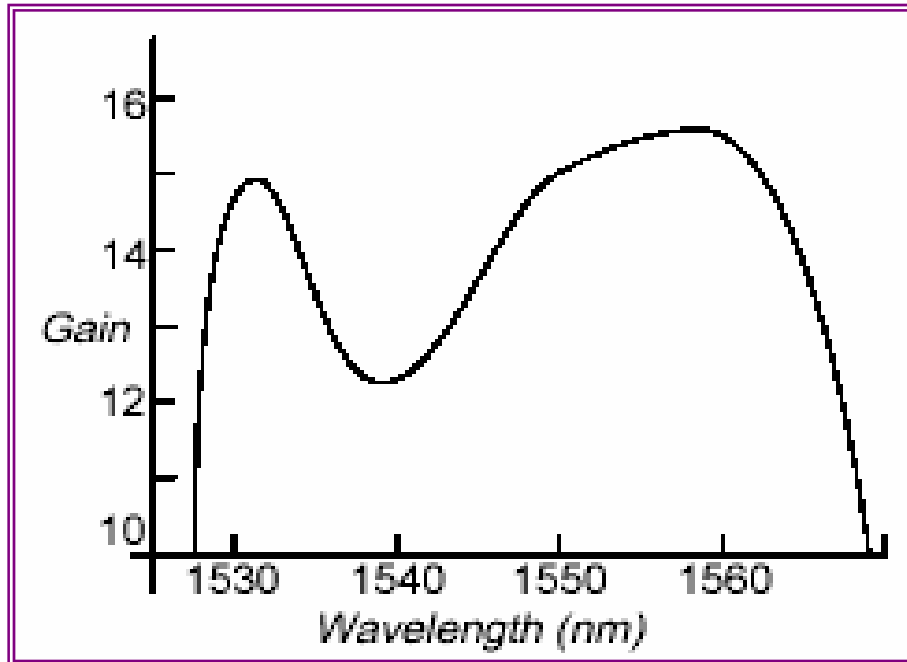
- Erbium can provide about 40-50 nm of bandwidth, from 1520 to 1570 nm
- Gain spectrum depends on the glass used, eg. silica or zblan glass
- Gain spectrum is not flat, significant gain variations





Gain Characteristics of EDFA

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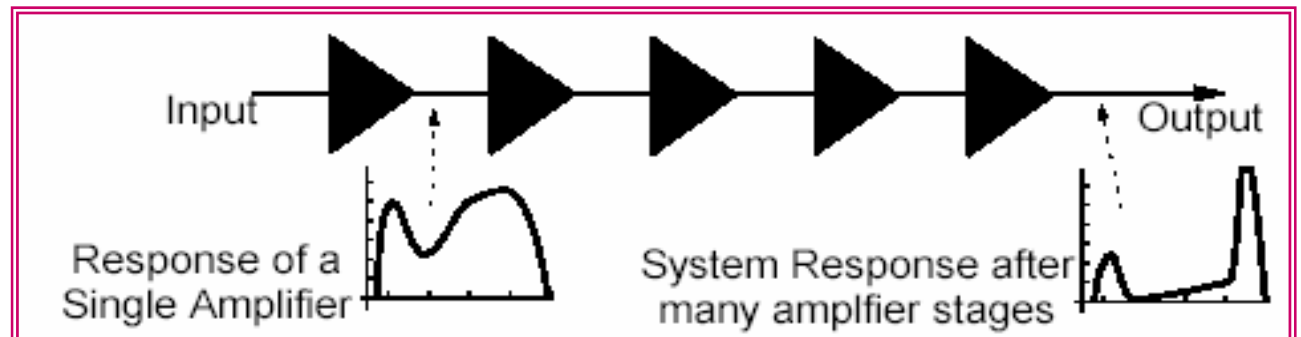


Gain (amplifier) - is the ratio in decibels of input power to output power.

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.





Flattening of the Gain Curve Techniques

APPLIED OPTOELECTRONICS CENTRE

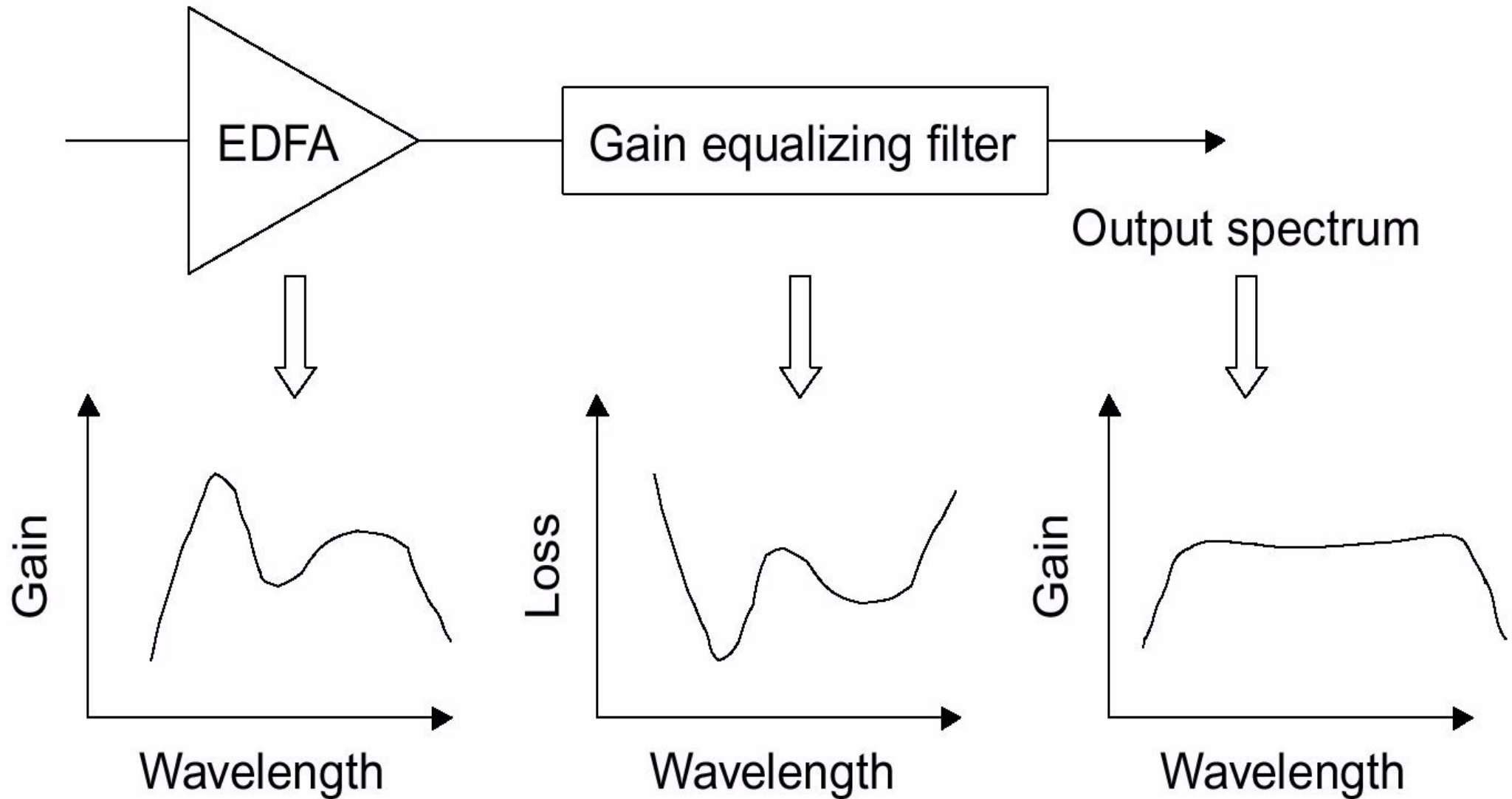
1. **Operating the device at 77° K. This produces a much better (flatter) gain curve but it's not all that practical.**
2. **Introducing other dopant materials (such as aluminium or ytterbium) along with the erbium into the fibre core.**
3. **Amplifier length is another factor influencing the flatness of the gain curve.**
4. **Controlling the pump power (through a feedback loop) is routine to reduce amplified spontaneous emission.**
5. **Adding an extra WDM channel locally at the amplifier (“gain clamping”).**
6. **Manipulating the shape of the fibre waveguide within the amplifier.**

At the systems level there are other things that can be done to compensate:

1. **Using “blazed” fibre Bragg gratings as filters to reduce the peaks in the response curve.**
2. **To transmit different WDM channels at different power levels to compensate for later amplifier gain characteristics.**



Gain Flattening Concept





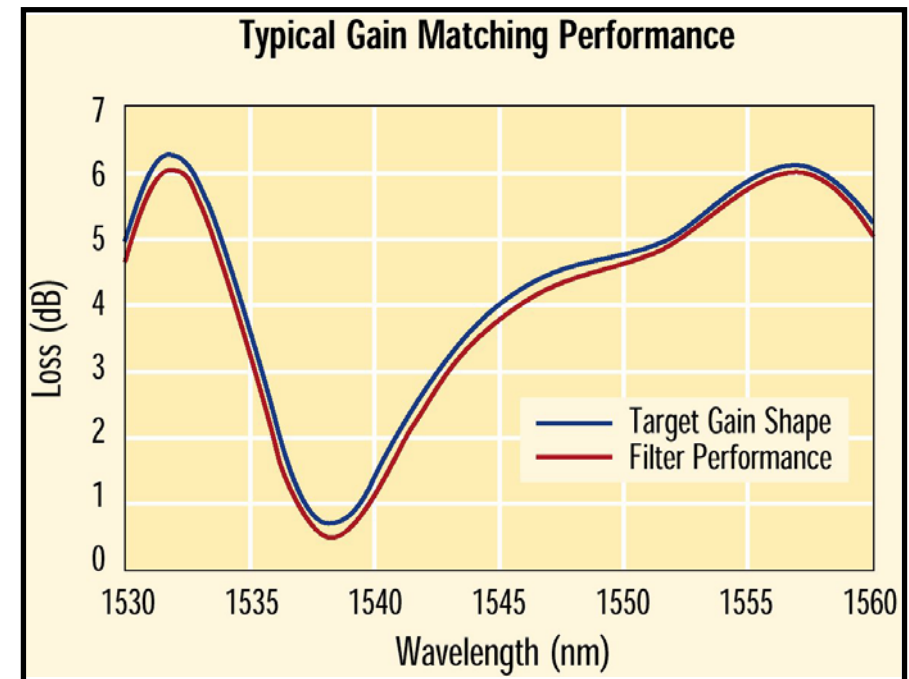
Gain Flattening Filters (Equalizers)

- Used to reduce variation in amplifier gain with wavelength, used in DWDM systems
- The gain equalisation is realised by inserting tapered long period gratings within the erbium doped fibre.
- Designed to have approximately the opposite spectral response to that of an EDFA

Inline Dicon gain flattening filter spectral response



Inline Dicon gain flattening filter





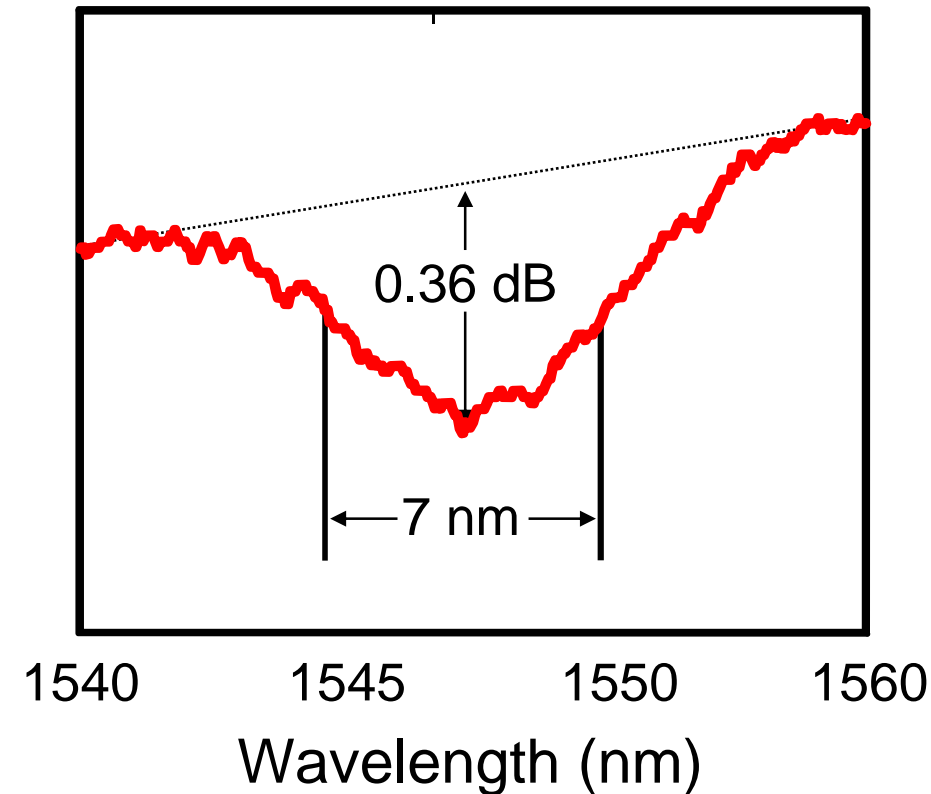
Spectral Hole Burning (SHB)

- Gain depression around saturating signal

- Strong signals reduce average ion population
- Hole width 3 to 10 nm
- Hole depth 0.1 to 0.4 dB
- 1530 nm region more sensitive to SHB than 1550 nm region

- Implications

- Usually not an issue in transmission systems (single λ or DWDM)
- Can affect accuracy of some lightwave measurements



Polarization Hole Burning (PHB)

- Polarization Dependent Gain (PDG)
 - Gain of small signal polarized orthogonal to saturating signal 0.05 to 0.3 dB greater than the large signal gain
 - Effect independent of the state of polarization of the large signal
 - PDG recovery time constant relatively slow
- ASE power accumulation
 - ASE power is minimally polarized
 - ASE perpendicular to signal experiences higher gain
 - PHB effects can be reduced effectively by quickly scrambling the state of polarization (SOP) of the input signal

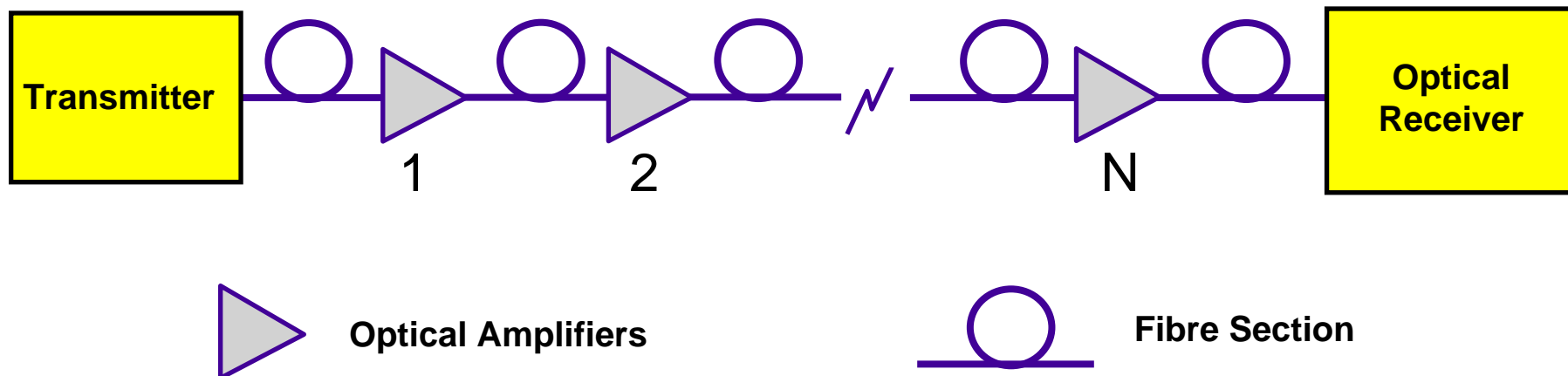


Noise in EDFAs



Optical Amplifier Chains

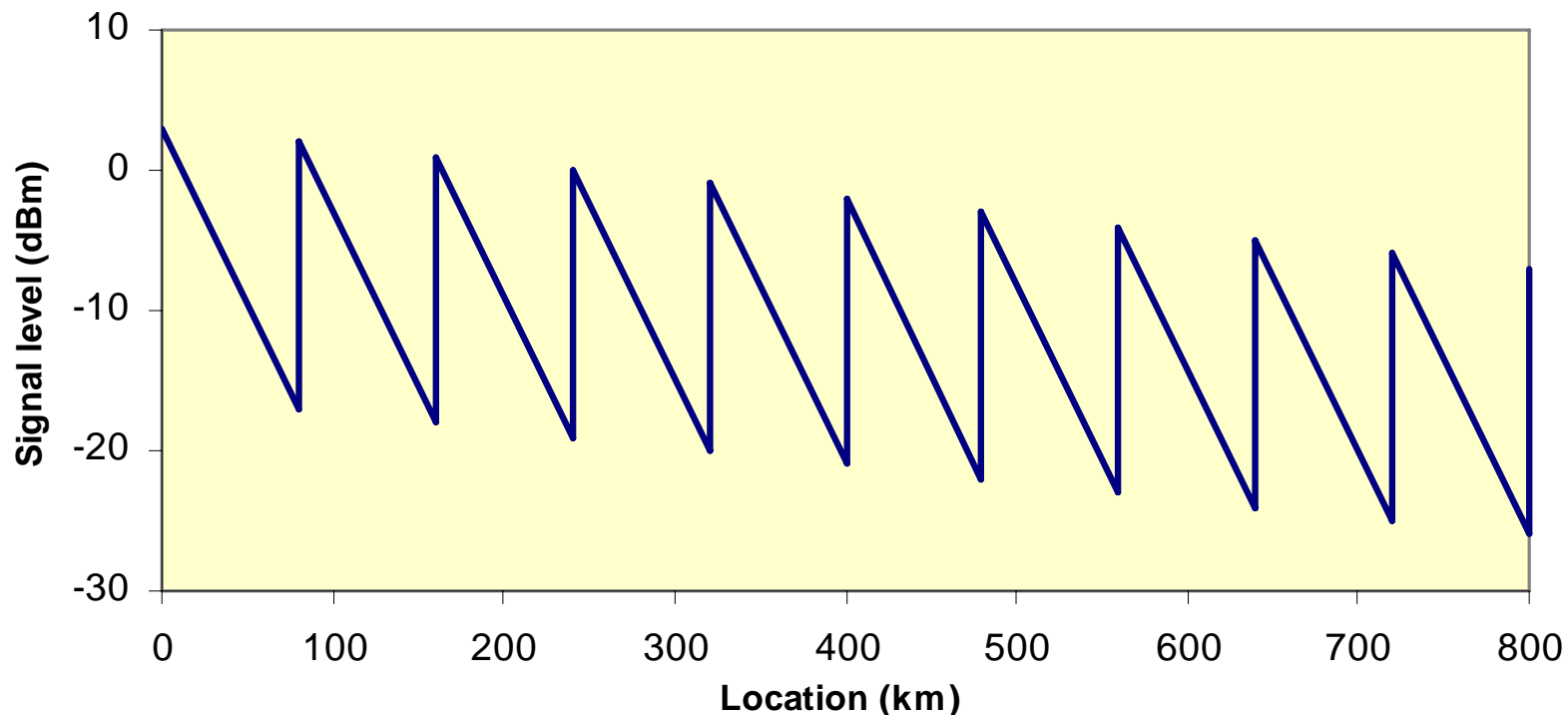
- Optical amplifiers allow one to extend link distance between a transmitter and receiver
- Amplifier can compensate for attenuation
- Cannot compensate for dispersion (and crosstalk in DWDM systems)
- Amplifiers also introduce noise, as each amplifier reduces the Optical SNR by a small amount (noise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





Amplifiers Chains and Signal Level

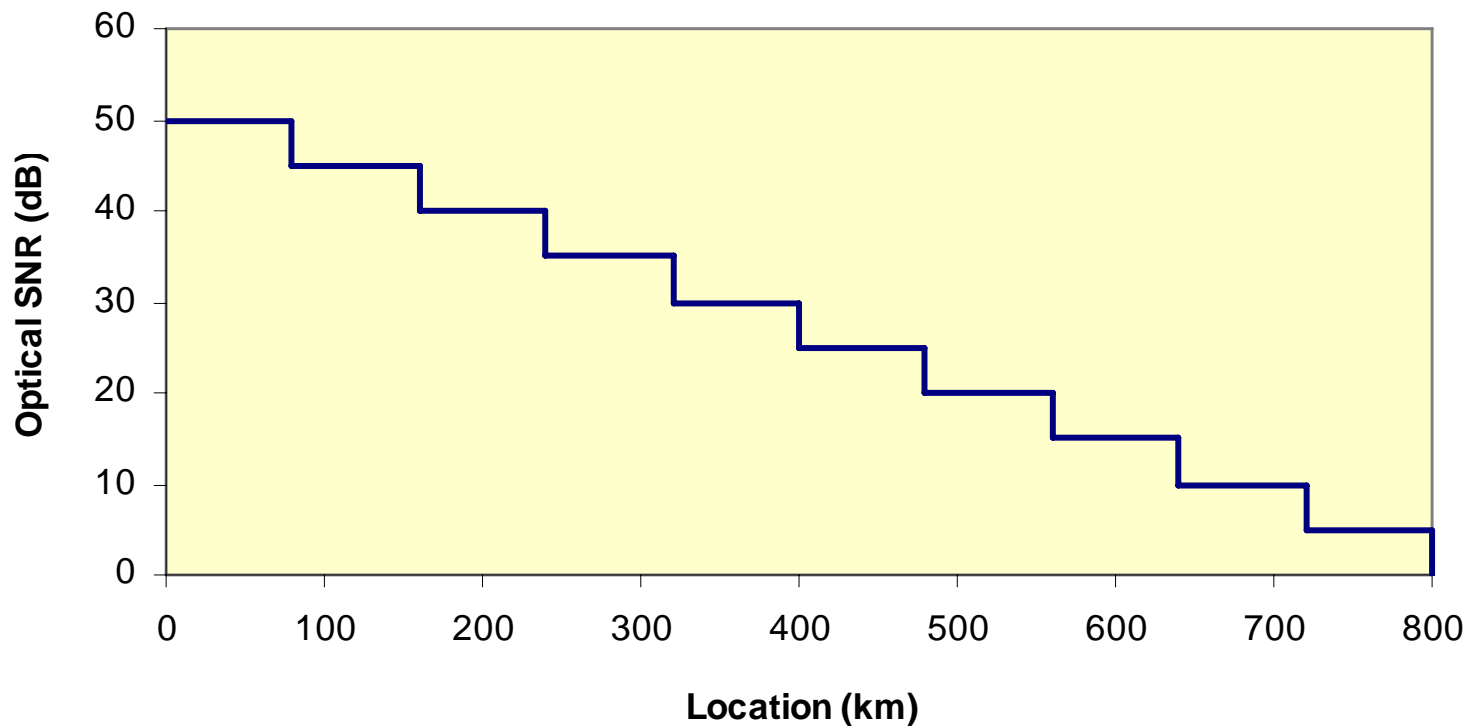
- Sample system uses 0.25 atten fibre, 80 km fibre sections, 19 dB amplifiers with a noise figure of 5 dB



- 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 +

Amplifiers Chains and Optical SNR

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

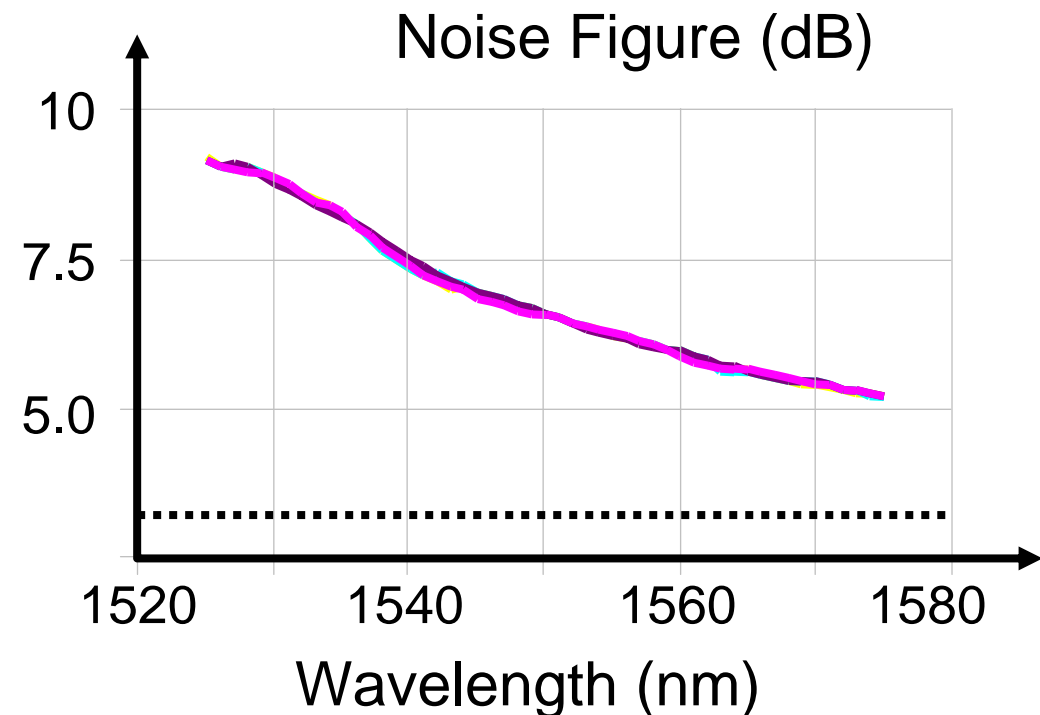


- Optical SNR drops with distance, so that if we take 30 dB as a reasonable limit, the max distance between T/X and R/X is only 300 km



Noise Figure (NF)

- **$NF = P_{ASE} / (h \cdot \nu \cdot G \cdot B_{OSA})$**
 - P_{ASE} : ASE power measured by OSA
 - h : Planck's constant
 - ν : Optical frequency
 - G : Gain of EDFA
 - B_{OSA} : Optical bandwidth [Hz] of OSA
- Input signal dependent
 - In a saturated EDFA, the NF depends mostly on the wavelength of the signal
 - Physical limit: 3.0 dB





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's 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.

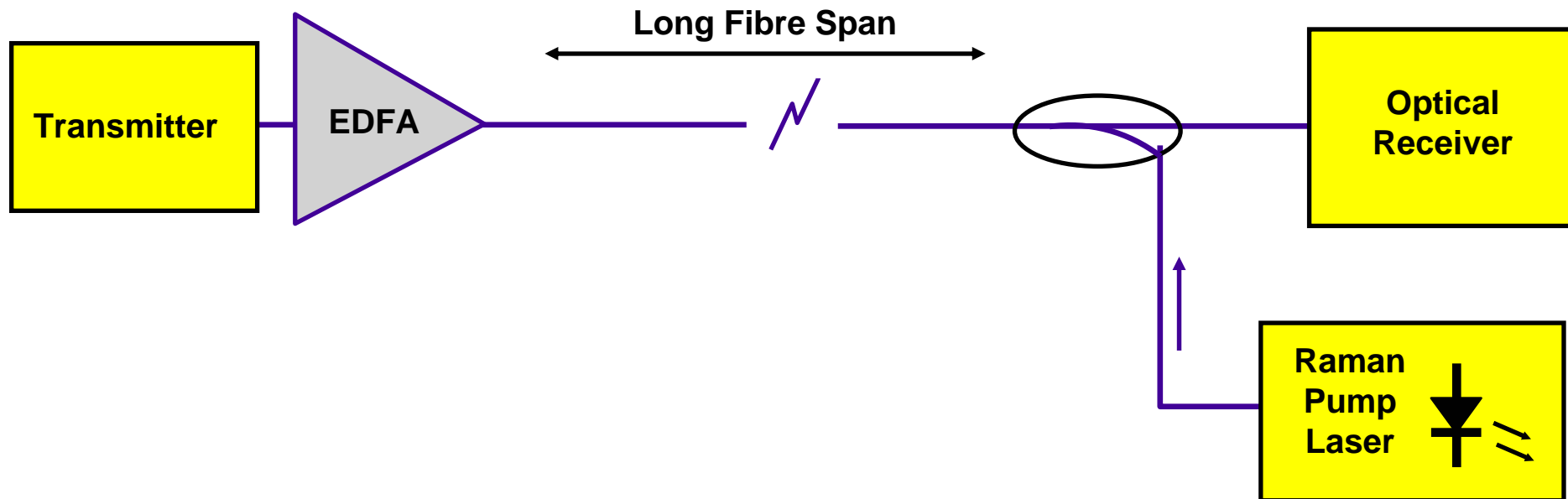
It is easy to build a Raman amplifier, but there is a big problem:

we just can't 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)

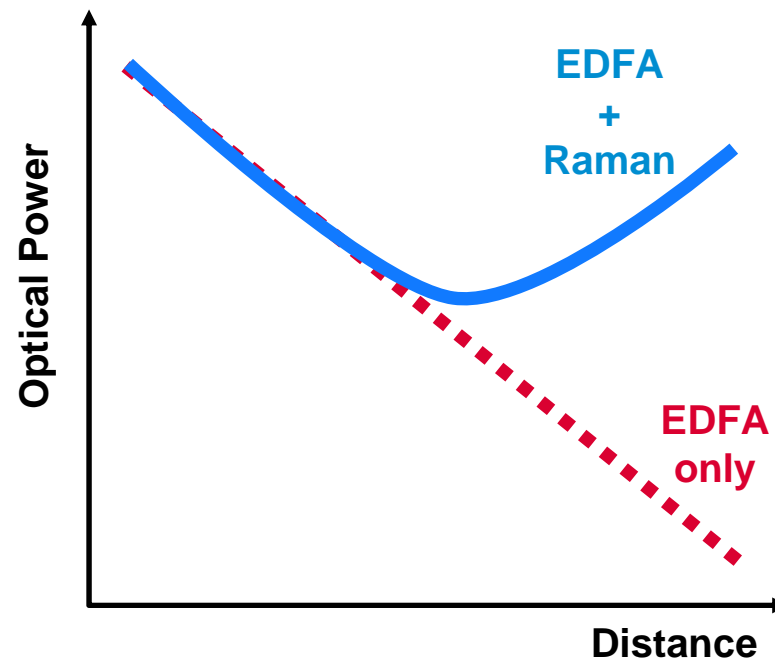
- Raman pumping takes place backwards over the fibre
- Gain is a maximum close to the receiver and decreases in the transmitter direction





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

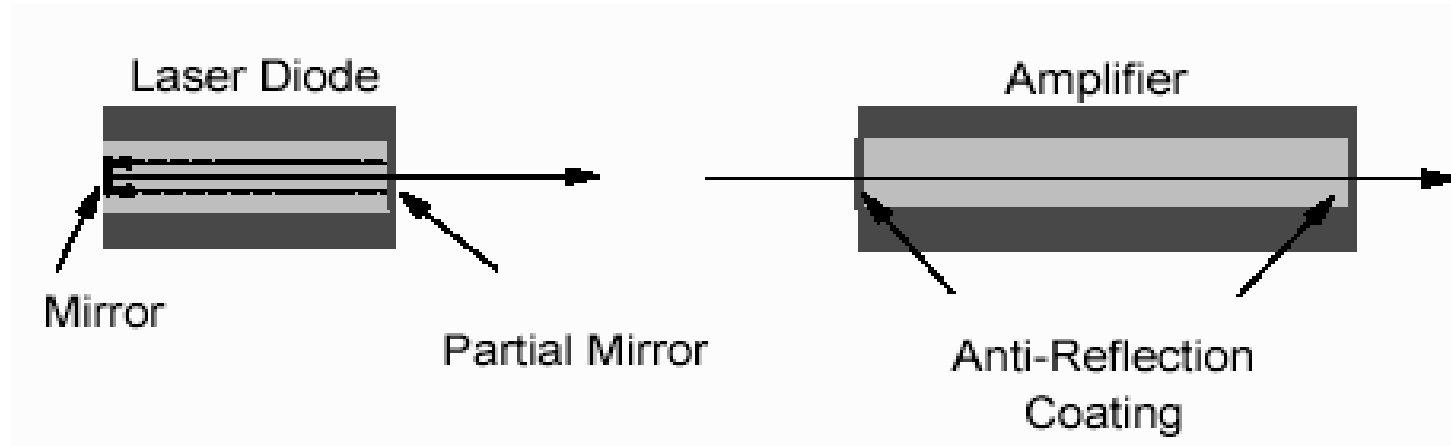
- Variable wavelength amplification possible
- Compatible with installed SM fibre
- Can be used to "extend" EDFAs
- Can result in a lower average power over a span, good for lower crosstalk
- Very broadband operation may be possible

- Disadvantages

- High pump power requirements, high pump power lasers have only recently arrived
- Sophisticated gain control needed
- Noise is also an issue



Semiconductor Optical/Laser Amplifiers (SOAs/SLAs)



There are two varieties:

Simple SOA

are almost the same as regular index-guided FP lasers. The back facet is pigtailed to allow the input of signal light.

The main problem is that it has been difficult to make SOAs longer than about $450\text{ }\mu\text{m}$. In this short distance there is not sufficient gain available on a single pass through the device for useful amplification to be obtained.

One solution to this is to retain the reflective facets (mirrors) characteristic of laser operation. Typical SOAs have a mirror reflectivity of around 30%. Thus the signal has a chance to reflect a few times within the cavity and obtain useful amplification.

Travelling wave SLA (TWSLA)

Travelling Wave SLAs (TWSLAs)

The TWSLA is different from the SOA in a number of ways:

1. The cavity is lengthened (doubled or tripled) to allow enough room for sufficient gain (since the amplifier uses a single pass through the device and doesn't resonate like a laser). Devices with cavities as long as 2 mm are available.
2. The back facet is anti-reflection coated and pigtailed to provide entry for the input light.
3. The exit facet of the amplifier is just the same as for a laser except that it is also anti-reflection coated.
4. Because of the absence of feedback the TWSLA can be operated above the lasing threshold giving higher gain per unit of length than the simple SOA (Gains of up to 25 dB over a bandwidth range of 40 nm).

Limitations/Advantages/Applications

SOAs have severe limitations:

- **Insufficient power (only a few mW). This is usually sufficient for single channel operation but in a WDM system you usually want up to a few mW per channel.**
- **Coupling the input fibre into the chip tends to be very lossy. The amplifier must have additional gain to overcome the loss on the input facet.**
- **SOAs tend to be noisy.**
- **They are highly polarisation sensitive.**
- **They can produce severe crosstalk when multiple optical channels are amplified.**

This latter characteristic makes them unusable as amplifiers in WDM systems but gives them the ability to act as wavelength changers and as simple logic gates in optical network systems.

A major advantage of SOAs is that they can be integrated with other components on a single planar substrate. For example, a WDM transmitter device may be constructed including perhaps 10 lasers and a coupler all on the same substrate. In this case an SOA could be integrated into the output to overcome some of the coupling losses.



Other Amplifier Types

- **Semiconductor Optical Amplifier (SOA)**
 - Basically a laser chip without any mirrors
 - Metastable state has nanoseconds lifetime
(-> nonlinearity and crosstalk problems)
 - Potential for switches and wavelength converters
- **Praseodymium-doped Fiber Amplifier (PDFA)**
 - Similar to EDFAs but 1310 nm optical window
 - Deployed in CATV (limited situations)
 - Not cost efficient for 1310 telecomm applications
 - Fluoride based fiber needed (water soluble)
 - Much less efficient (1 W pump @ 1017 nm for 50 mW output)

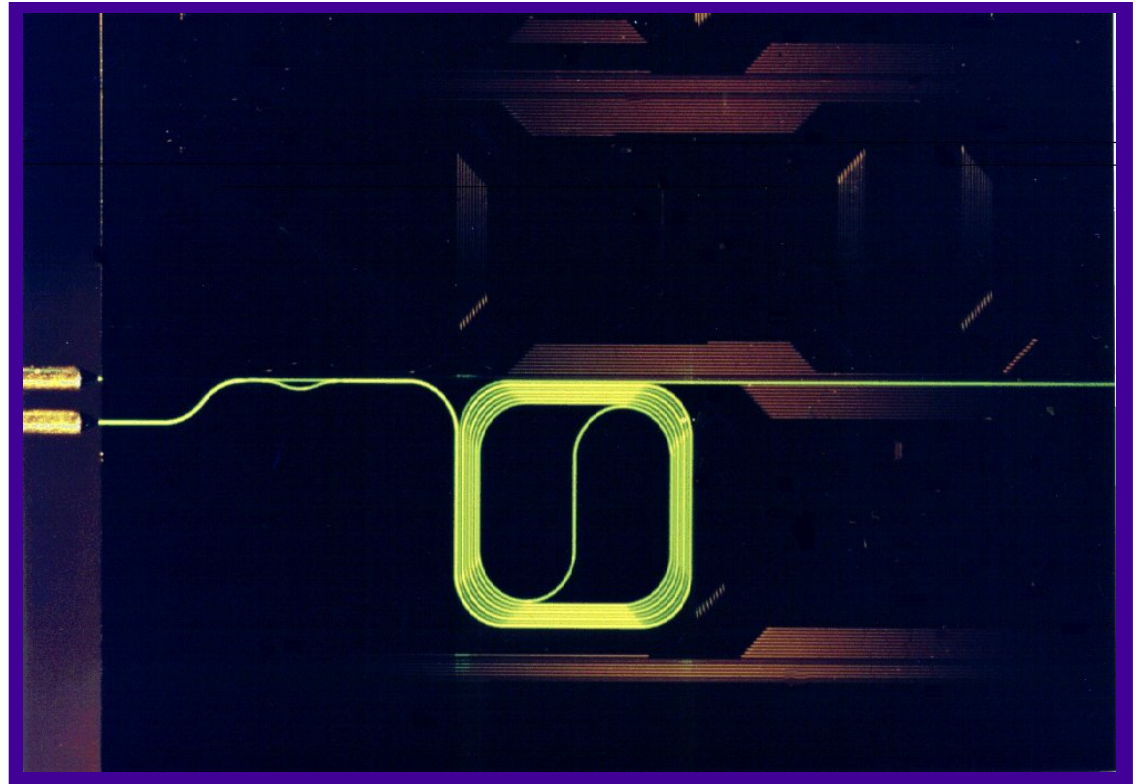


Small Footprint Amplifiers and 1300 nm Amplifiers



Miniature Optical Fibre Amp

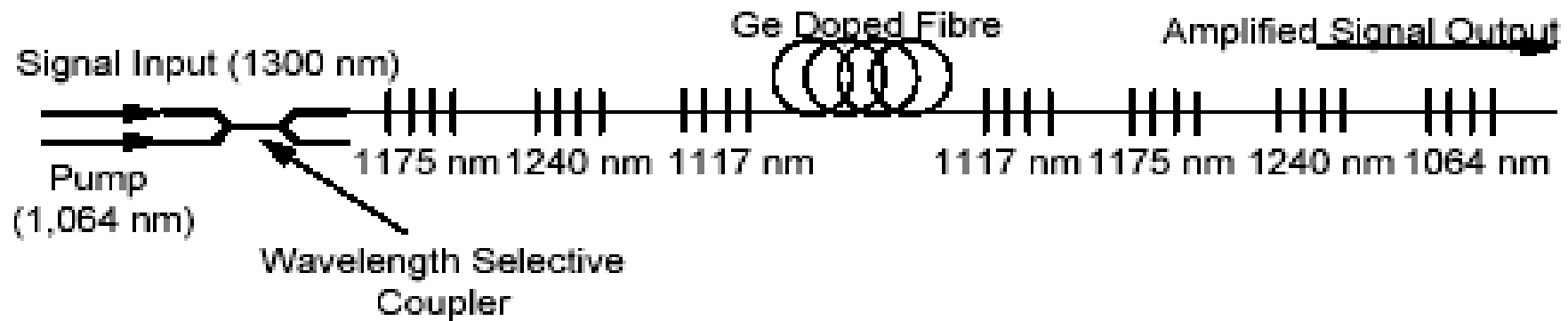
- Erbium doped aluminium oxide spiral waveguide
- 1 mm square waveguide
- Pumped at 1480 nm
- Low pump power of 10 mW
- Gain only 2.3 dB at present
- 20 dB gain possible



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A 1310 nm Band Raman Amplifier



Operation is as follows:

- 1. Signal light and pump light enter the device together through a wavelength selective coupler.**
- 2. The pump light at 1064 nm is shifted to 1117 nm and then in stages to 1240 nm.**
- 3. The 1240 nm light then pumps the 1310 band signal by the SRS and amplification is obtained.**

To gain efficiency a narrow core size is used to increase the intensity of the light.

Also, a high level of Ge dopant is used (around 20%) to increase the SRS effect.

This is a very effective, low noise process with good gain at small signal levels.



Future Developments

- Broadened gain spectrum
 - 2 EDFs with different co-dopants (phosphor, aluminum)
 - Can cover 1525 to 1610 nm
- Gain flattening
 - Erbium Fluoride designs (flatter gain profile)
 - Incorporation of Fiber Bragg Gratings (passive compensation)
- Increased complexity
 - Active add/drop, monitoring and other functions