Optical Amplifiers

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Plan

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- Rare-earth doped Fiber Amplifiers
- Raman Amplifiers
- Semiconductor Optical Amplifiers
- General Considerations
- Summary

Amazing Bandwidth of Optical Fibers

- Fiber-grade silica is transparent from $1\mu - 1.6\mu$. The total bandwidth it can carry is

$$\Delta\lambda \approx c/\lambda_1 - c/\lambda_2 = 3.0 \times 10^{14} - 1.1 \times 10^{14} = 11 \text{ THz}$$

- Bandwith of a telephone signal goes from 100 Hz – 3 KHz. By Nyquist Criterion, one conversation requires 2 × 3 KHz = 6 KHz

- So, the number of conversations that can be simultaneously carried over a fiber is approximately,

$$N_f = 1.1 \times 10^{14} / 3 \times 10^{3} = 36 \text{ billion}$$

- So, in principle a single fiber is sufficient to carry ten times all the conversions generated worldwide.

As the signal becomes weak

Amplifier: increases the strength of the optical signal.

It is an analog device, so what you put is what you get; with some noise, of course

Repeater: Converts weak optical signal into electronic form, uses electronic signal to drive a transmitter that recreates the signal

A receiver – transmitter placed back to back

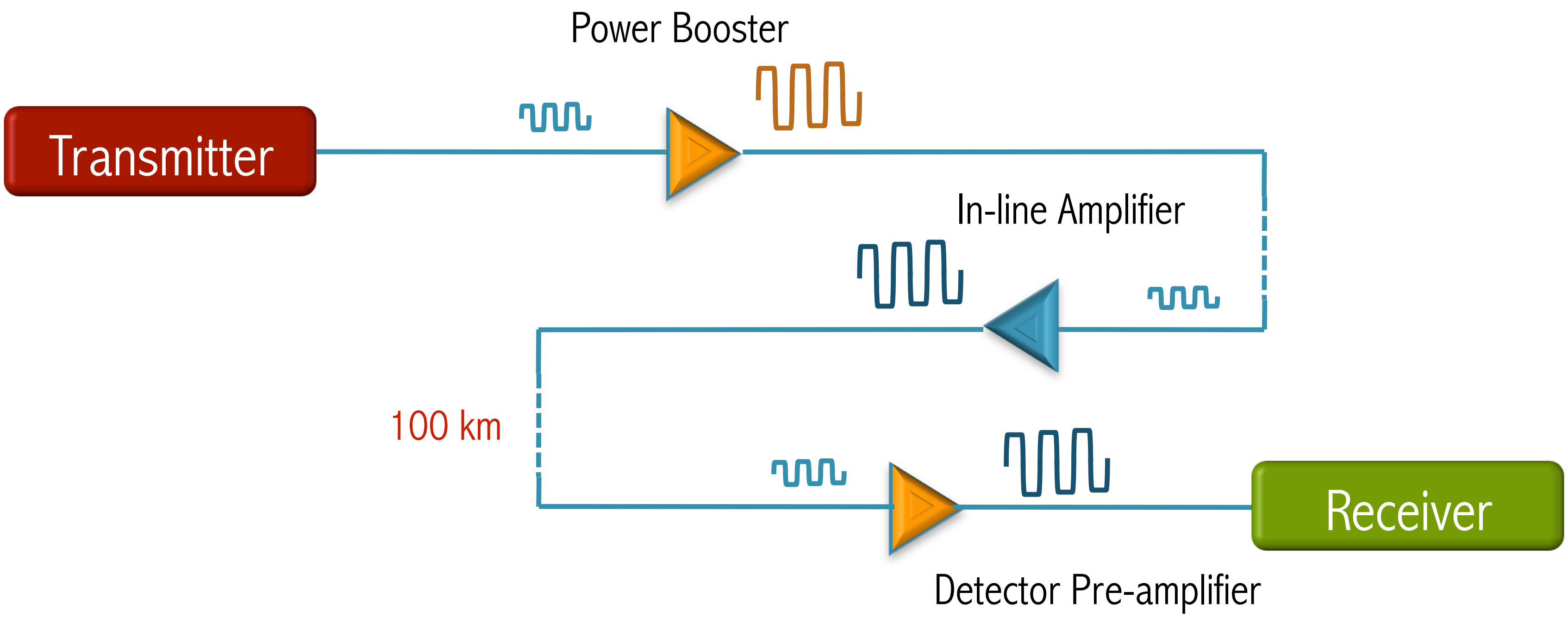
Regenerator: cleans up digital signal by removing noise and distortion and regenerating a fresh signal

They have discrimination circuits that examine the time-varying signal, identifies signal and noise; clean the signal

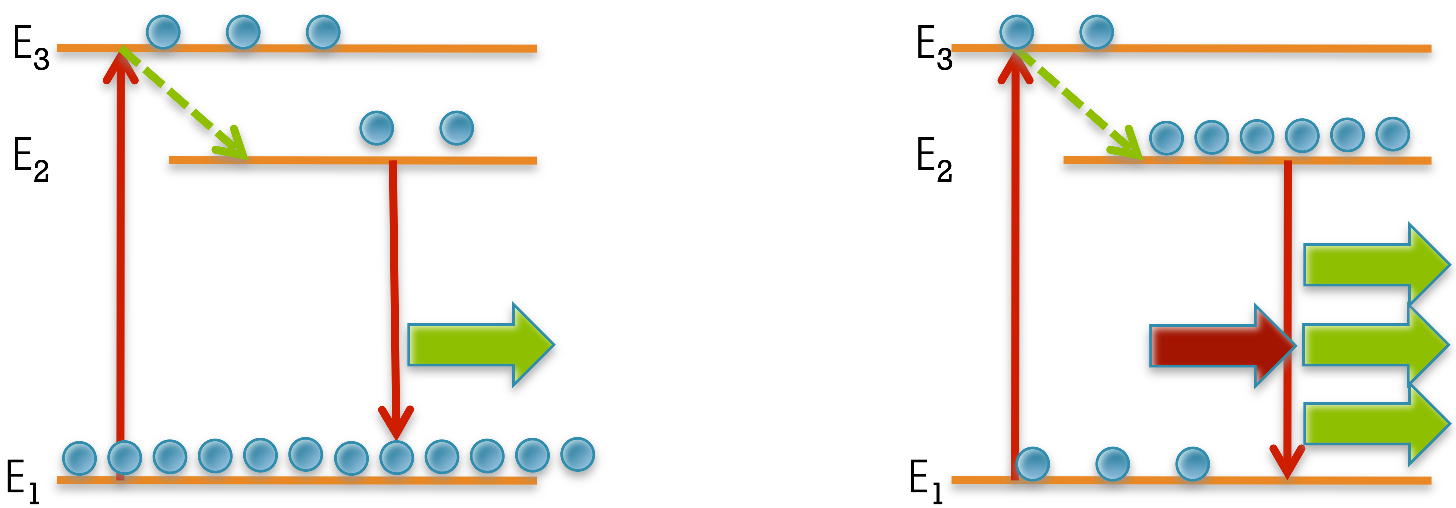
Why do we need Optical Amplifiers?

- Typical fiber loss around 1.5 μm is ~0.2 dB/km.
- After traveling ~100 km, signals are attenuated by ~20 dB,
- They need to be amplified or signal-to-noise ratio (SNR) of detected signals is too low and bit error rate (BER) becomes too high (typically want BER < 10^{-9})
- Can be done by detecting the weakened signals, then modulating a new laser with modulation read off the detected signals
- This {Optical to Electrical to Optical} conversions requires costly high-speed electronics (>10 GHz)
- Best way to amplify is optically, and best optical method is fiber amplifier (lowest loss, most efficient, most stable)

Optical Amplifiers : Functions



Principle of Optical Amplification



- 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

Optical Amplifiers :: Characteristics

An optical amplifier is characterized by:

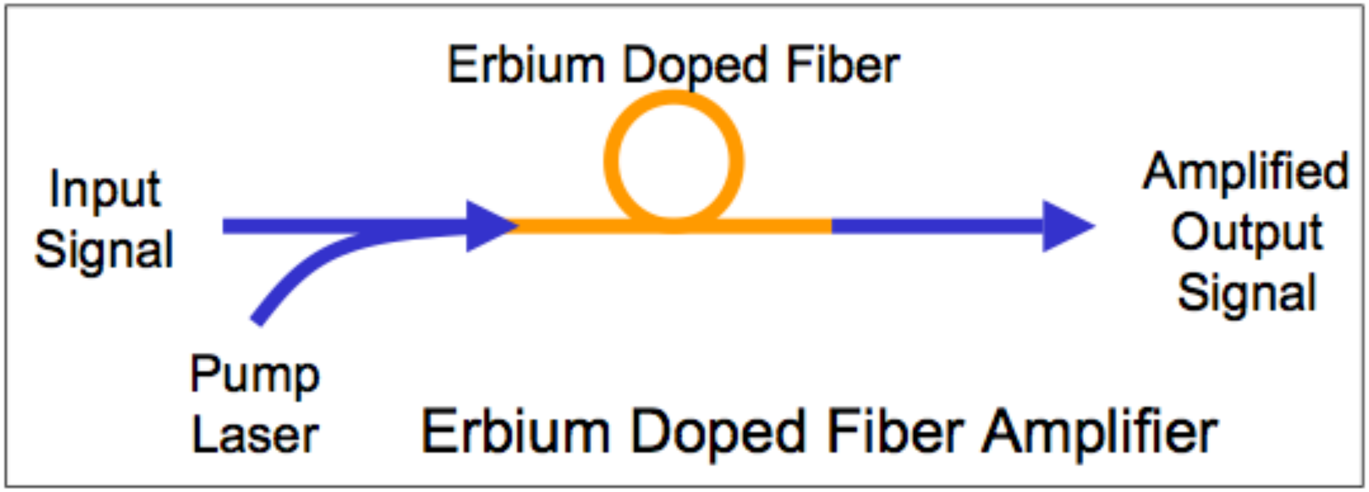
- Gain : ratio of output power to input power (in dB)
- Gain efficiency : gain as a function of input power (dB/mW)
- Gain bandwidth : range of wavelengths over which the amplifier is effective
- Gain saturation : maximum output power, beyond which no amplification is reached
- Noise : undesired signal due to physical processing in amplifier

Optical Amplifiers :: Types

- Rare-earth doped Fiber Amplifiers
  - Erbium Doped (EDFA) – 1,500 – 1,600 nm band
  - Praseodymium Doped (PDFA) – 1,300 nm band
- Raman (and Brillouin) Amplifiers
- Semiconductor Optical Amplifiers (SOAs) – 400 – 2,000 nm band

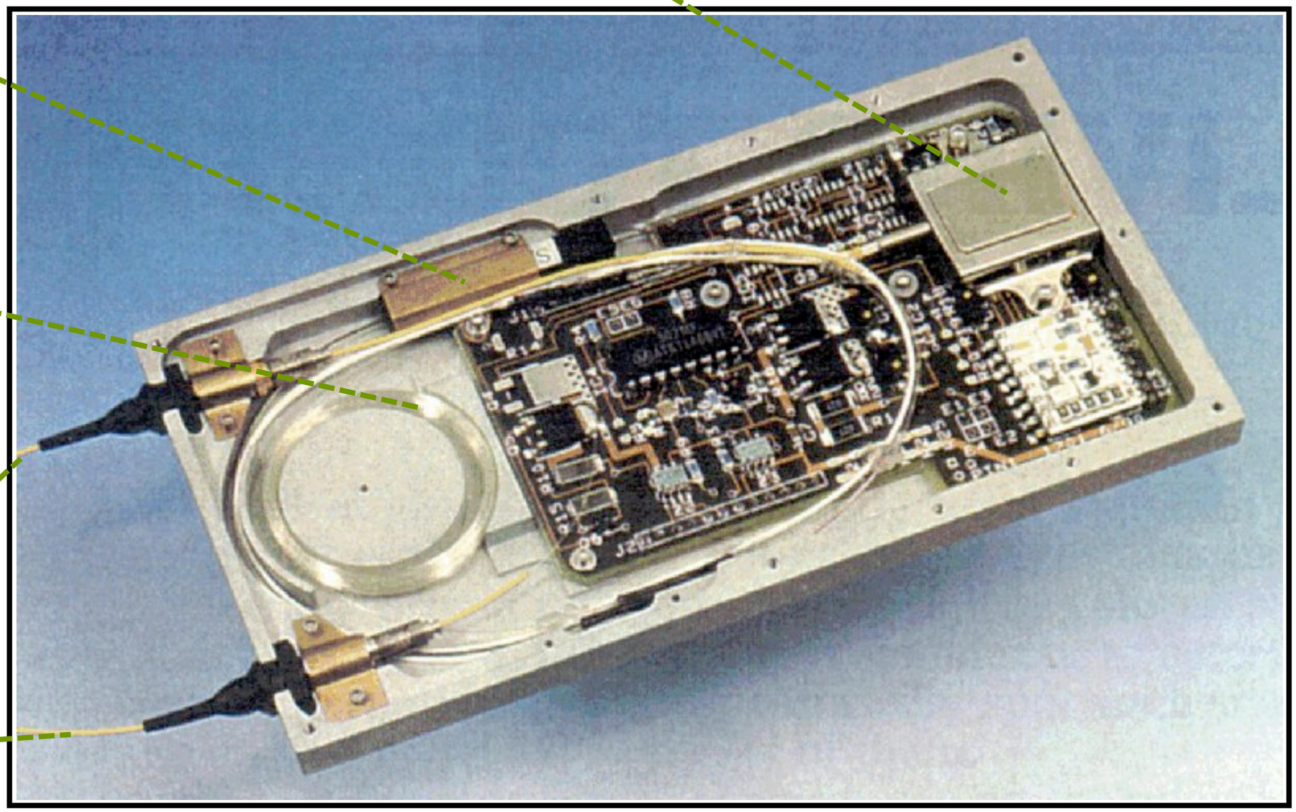
Erbium Doped Fiber Amplifiers

Erbium Doped Fiber Amplifier

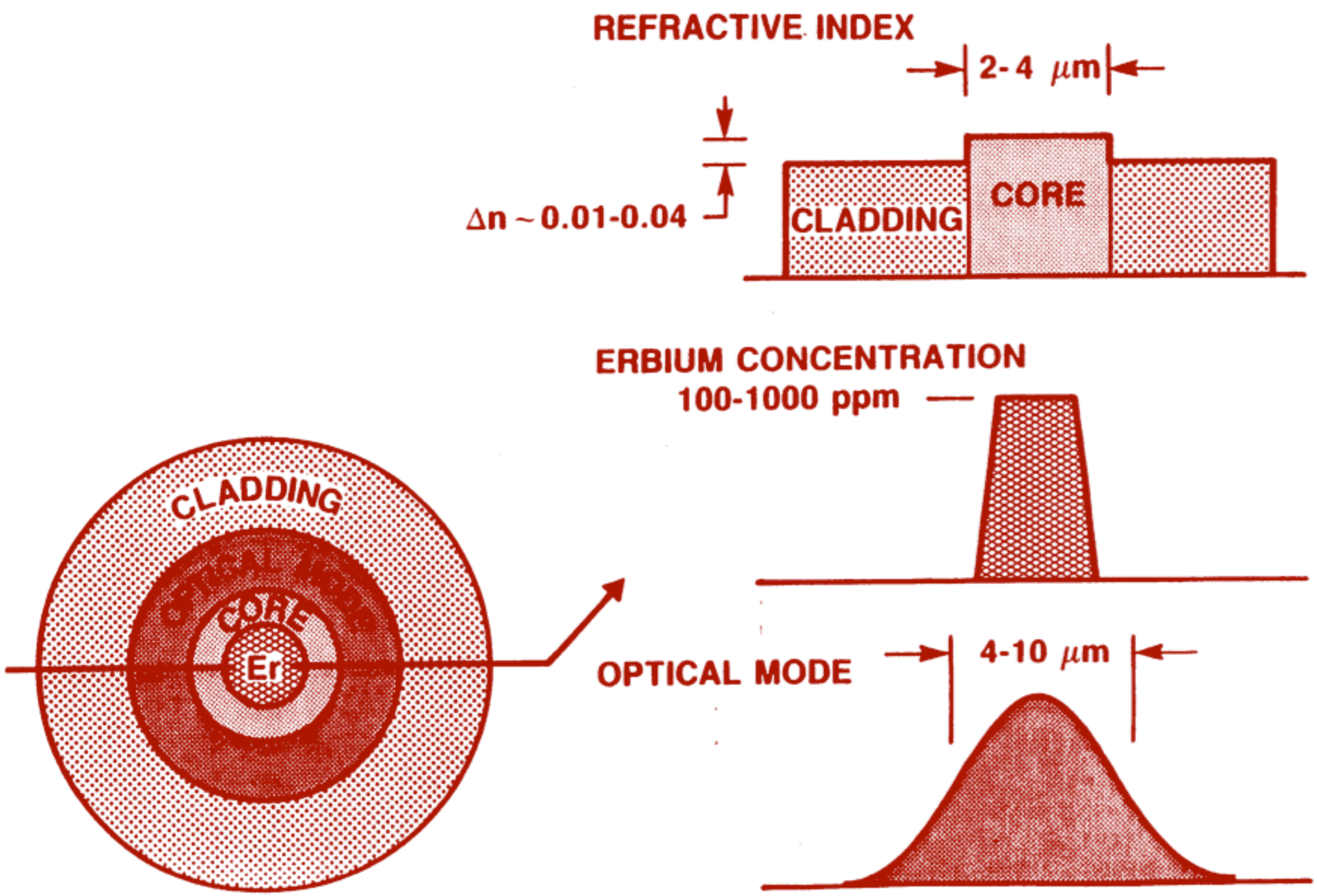


- Commercially available since the early 1990's
- Works best in the range 1530 to 1565 nm
- Gain up to 30 dB (1000 photons out per photon in!

Inside an EDFA



Erbium doped fiber :: Profile

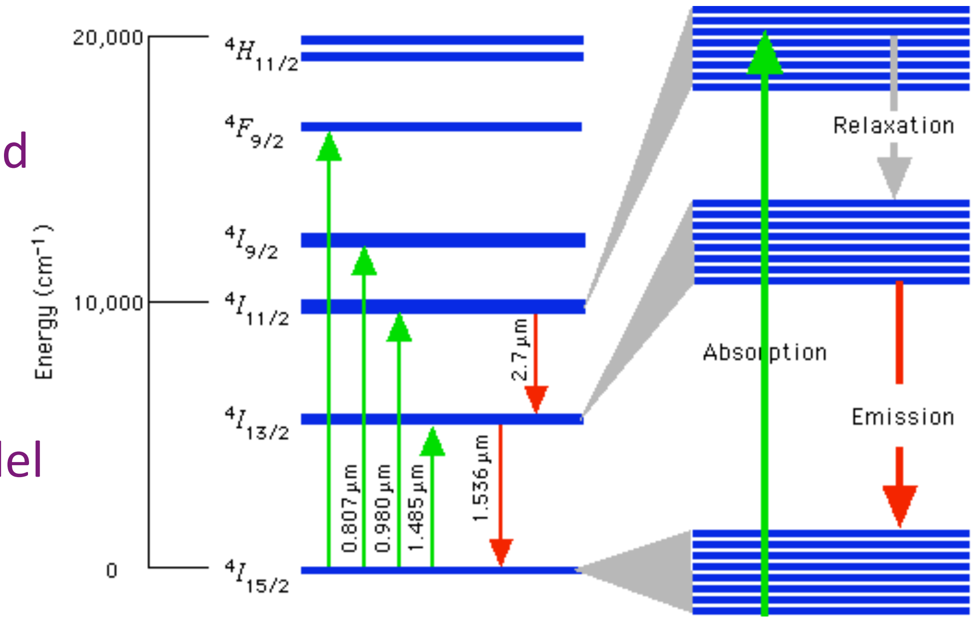


Rare-earth doped fiber characteristics

- Fiber is drawn by same technique as communication fibers
  - fabricate a preform (cm-size silica tube coated with core material)
  - heat and collapse tube
  - pull preform into a fiber
- Rare-earth concentration [RE_2O_3] is typically low
  - a few hundred parts per million (ppm) in silicate hosts
  - a few thousand ppm in fluoride and phosphate hosts
- Network modifiers (Al, P, La) are added to the core glass to increase solubility of RE_2O_3 in silica
- Index modifiers (Ge, Al) are added to the core to raise its refractive index
- At usual concentrations (< 100 ppm), RE_2O_3 has little effect on the index profile

Erbium doped fiber :: Amplification Process

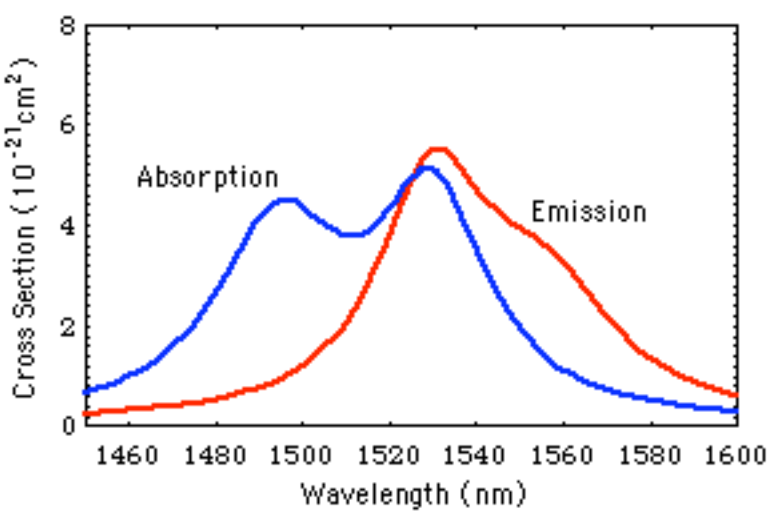
- Erbium-doped fiber is usually pumped by semiconductor lasers at 980 nm or 1480 nm.
- A three-level model can be used for 980-nm pumps, while a two-level model usually suffices for 1480-nm pumps.

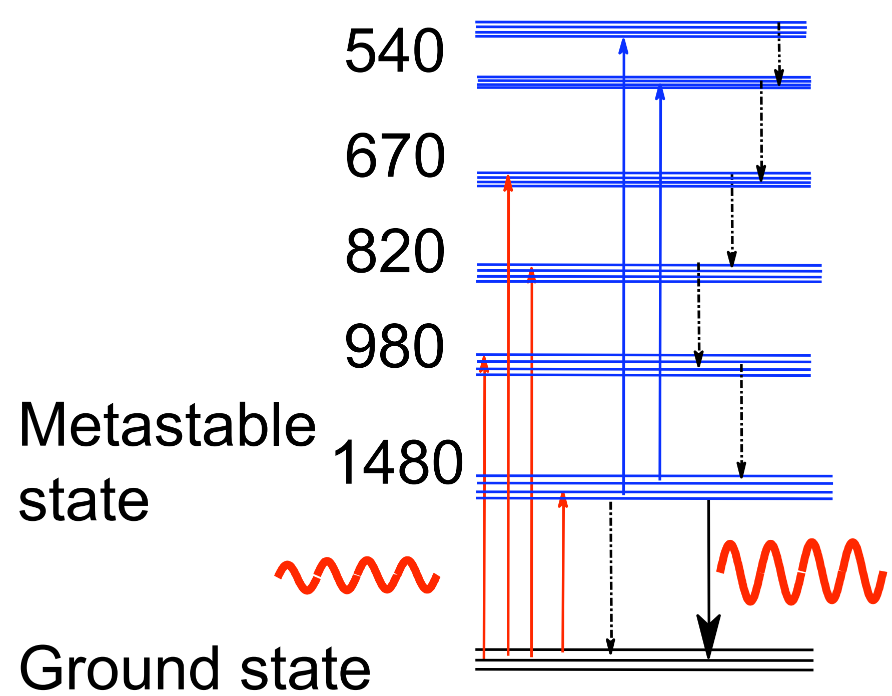


- Complete inversion can be achieved with 980-nm pumping but not with 1480-nm pumping.
- The spontaneous lifetime of the metastable energy level ($^4I_{13/2}$) is about 10 ms, which is much slower than the signal bit rates of practical interest.
- As stimulated emission dominates over spontaneous, amplification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

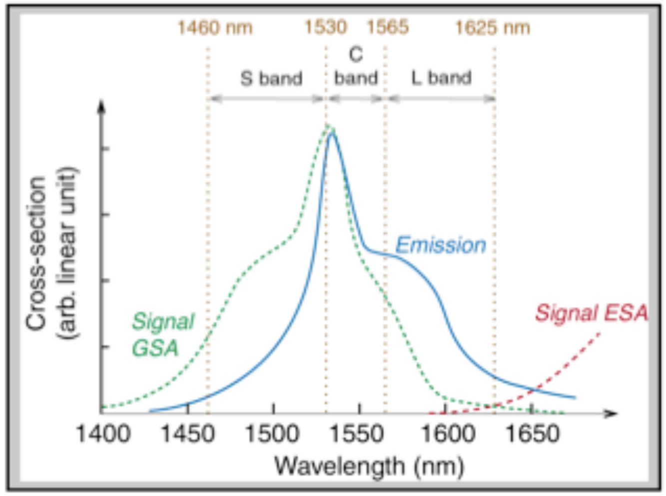
Erbium doped fiber :: Operation

- 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





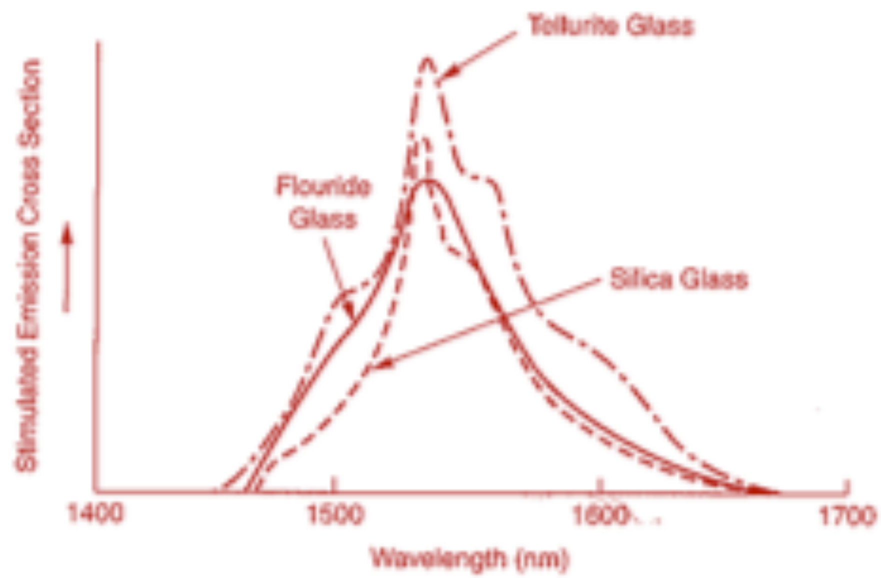
EDFA :: Operating Wavelengths



- So far we have focused on EDFAs operating in the C-band (1530-1565nm).
- Erbium-doped fiber, however, has a relatively long tail to the gain shape extending well beyond this range to about 1605 nm.
- This has stimulated the development of systems in the so-called L-band from 1565 to 1625 nm.
- Gain spectrum of erbium is much flatter intrinsically in the L- band than in the C-band.
- This makes it easier to design gain-flattening filters for the L- band.
- Pump powers required for L-band EDFAs are much higher than their C-band counterparts.

Gain Flatness

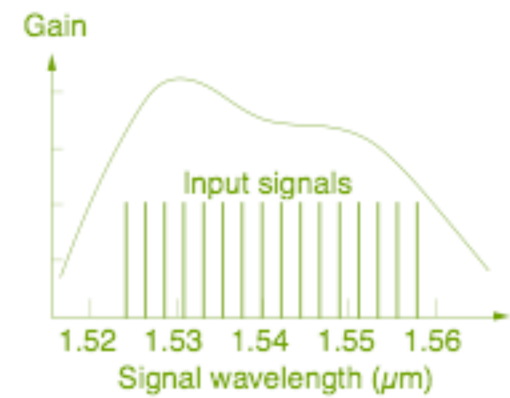
- Population levels at different bands vary
- And hence the gain variation
- Seriously affects WDM systems
- To overcome this
  - Use filter inside amplifier
  - User fluoride glass fiber

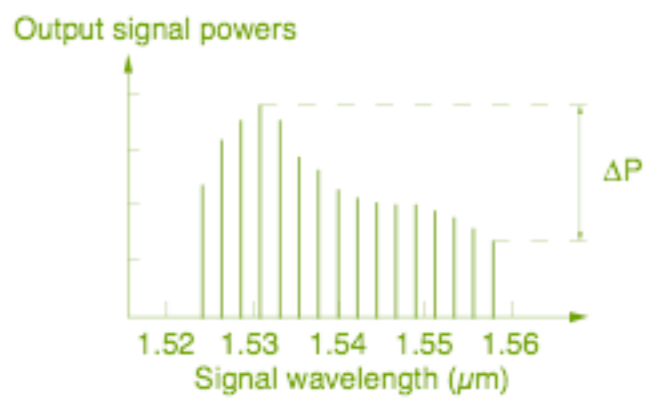


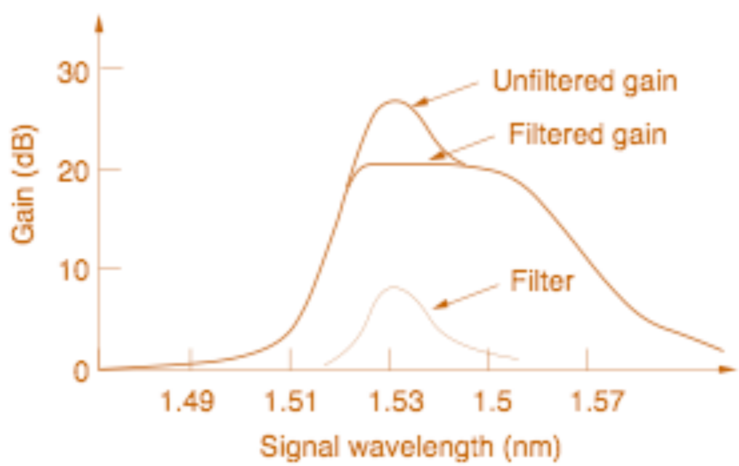
Gain performance of various glass fibers

Gain Flattening : A main issue

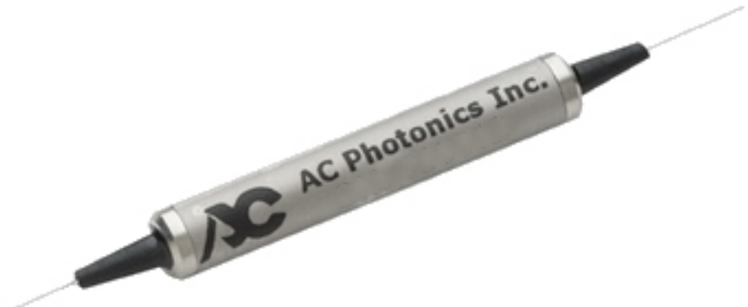
- The gain spectrum of an EDFA (or any other fiber amplifier) is not uniform
- After traveling through a few amplifiers (e.g., 500 km), difference between power of the signals ΔP exceeds 5–10 dB and the bit error rate is too strongly degraded
- Lower-power channels become unusable
- Filters are then introduced to selectively add losses to high gain wavelengths

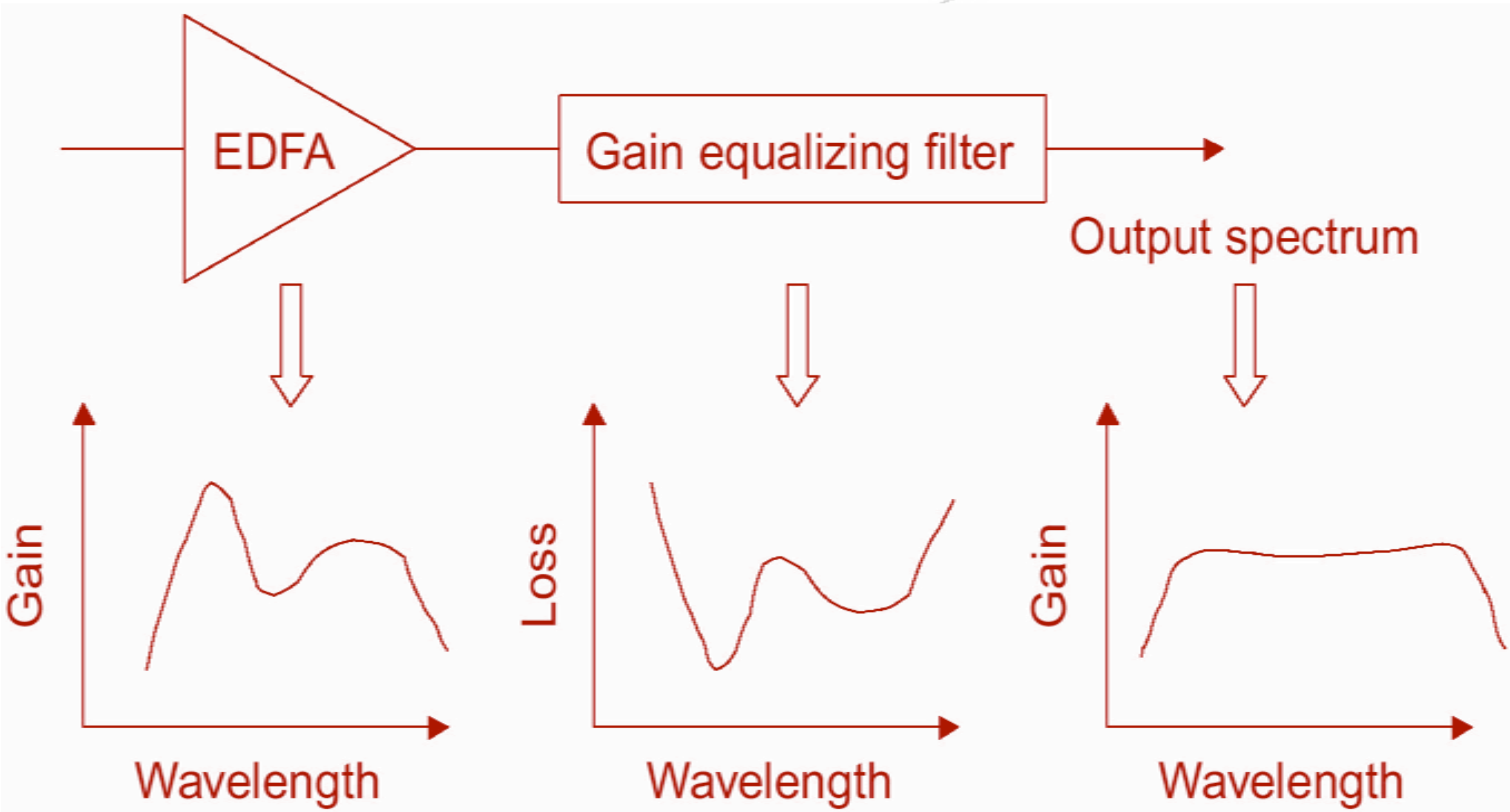






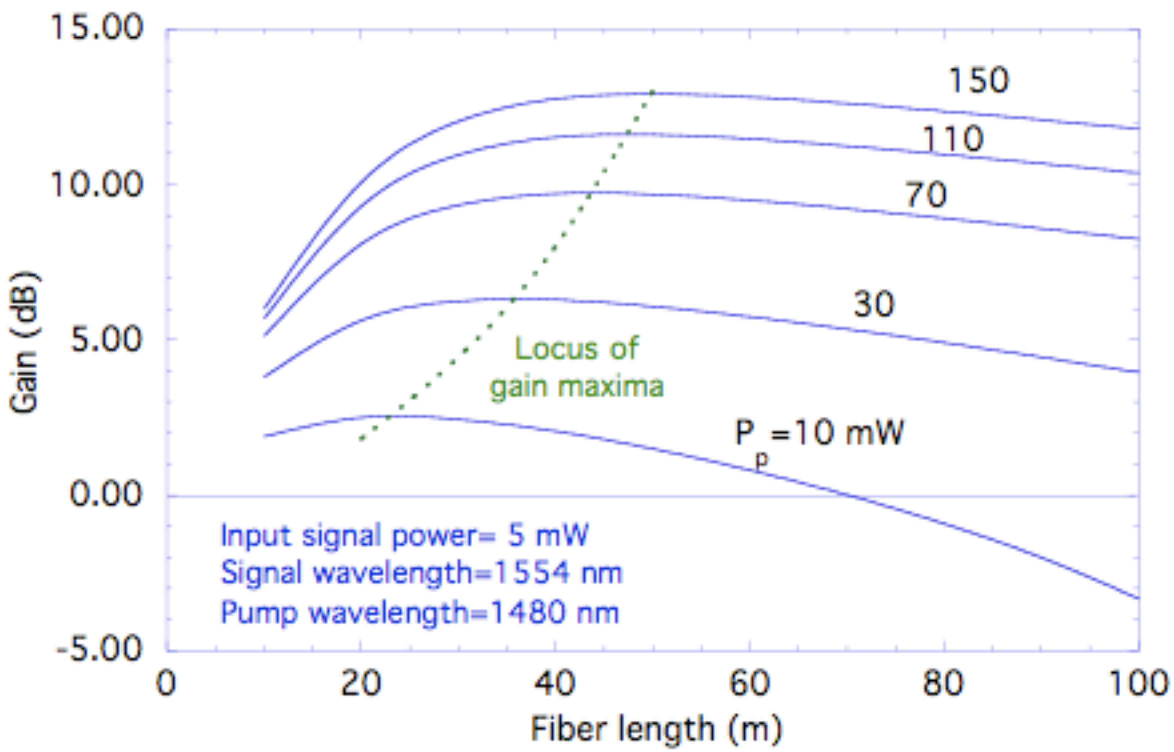
Gain Flattening





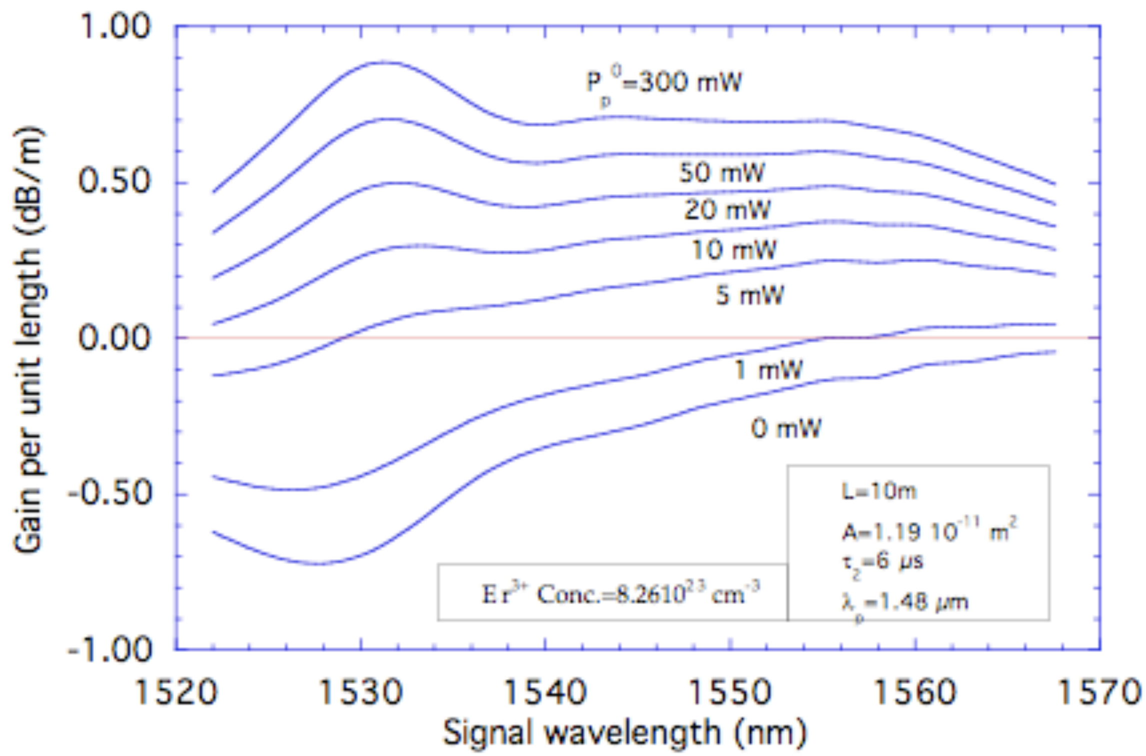
Gain Dependence on fiber length

- Gain is always negative at the end of a long enough fiber
- Length that maximizes gain increases with the pump power



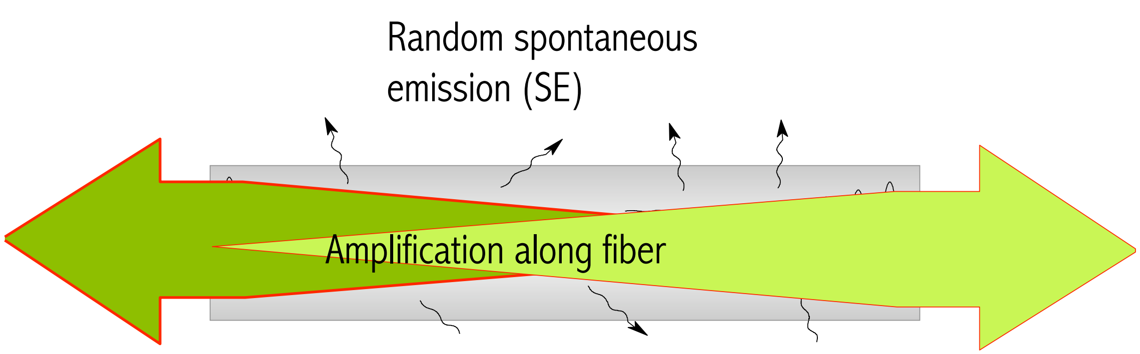
Spectral gain dependence on pump power

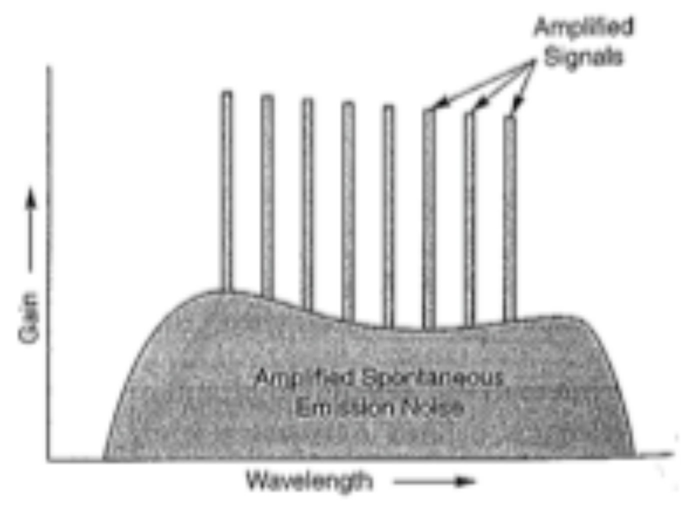
- As the pump power increases gain shifts towards 1530 nm from L band
- At a right pump power gain is flat over a wide wavelength range (Gain Flattening Technique)



Noise : Amplified Spontaneous Emission

- The light that starts stimulated emission originates spontaneously
- When excited state releases its energy without stimulation, spontaneous emission occurs
- As this travels through the amplifying medium, this spontaneous emission also gets amplified
- This creates a background noise called Amplified Spontaneous Emission
- This broadband noise is very similar to static in AM Radio



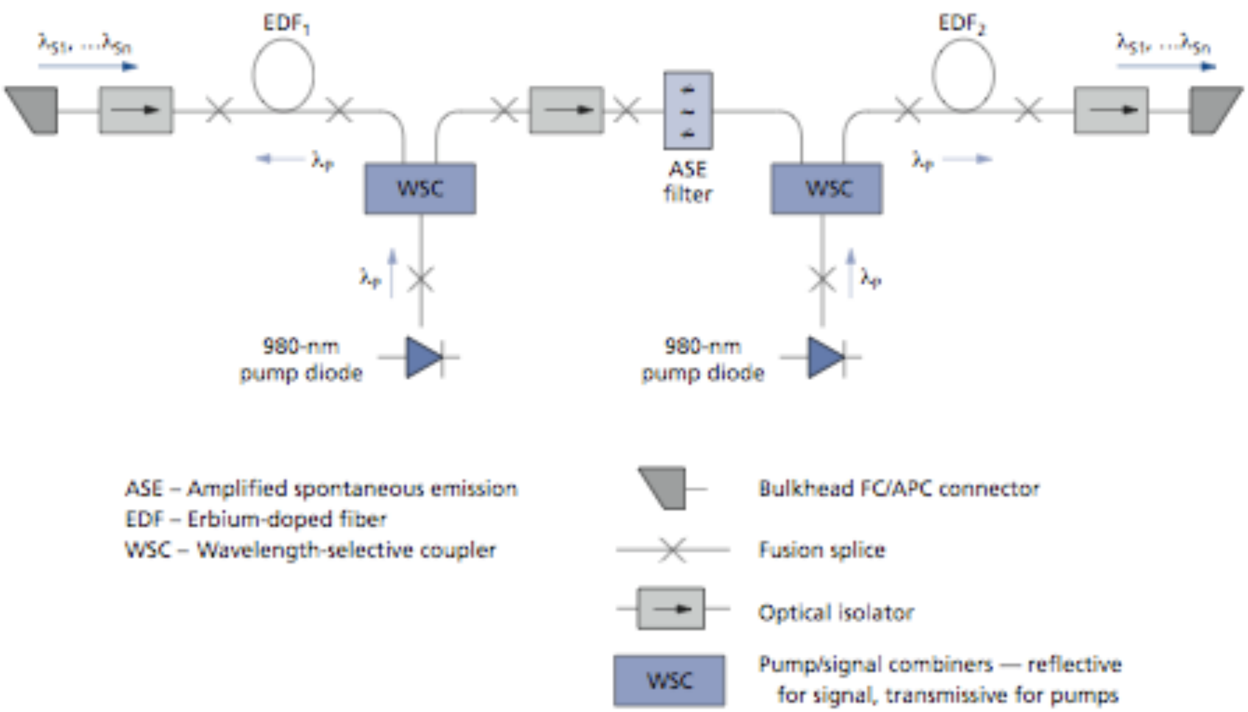


EDFA : Parameters

- Wide bandwidth -40 nm (5000 GHz)
- High amplification - 30 do 40 dB
- High output power -do +20dBm (100 mW)
- Low noise -4 dB (Noise factor F)
- Pump wavelength - 980 or 1480 nm
- No dispersion compensation

EDFA : Schematic

Schematic diagram of a two-stage erbium-doped fiber amplifier for low noise figure and high output power operation



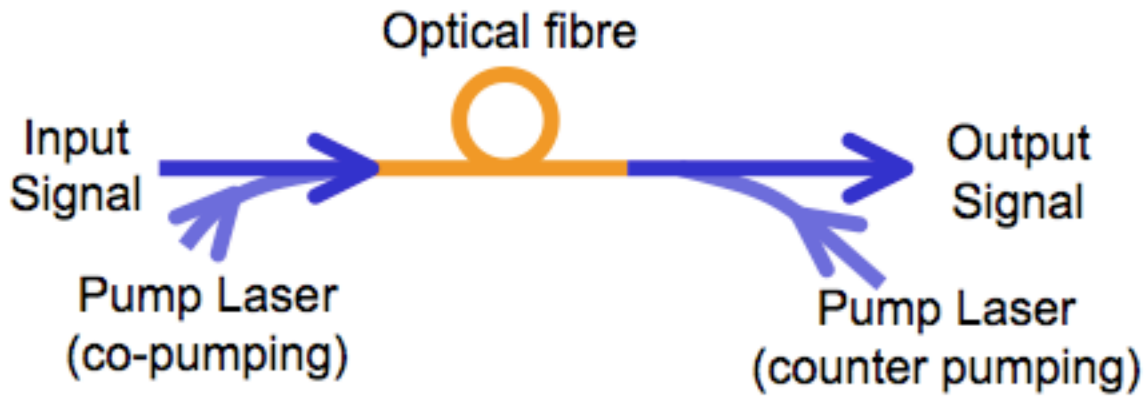
EDFA : Advantages and Disadvantages

- EDFAs have high pump power utilization (>50%)
- Directly and simultaneously amplify a wide wavelength band (> 80 nm) in the 1550 nm region, with a relatively flat gain.
- Flatness can be improved by gain-flattening optical filters
- Gain in excess of 50 dB
- Low noise figure Suitable for long haul applications

- EDFAs are not small
- Cannot be integrated with other semiconductor devices

Raman Amplifiers

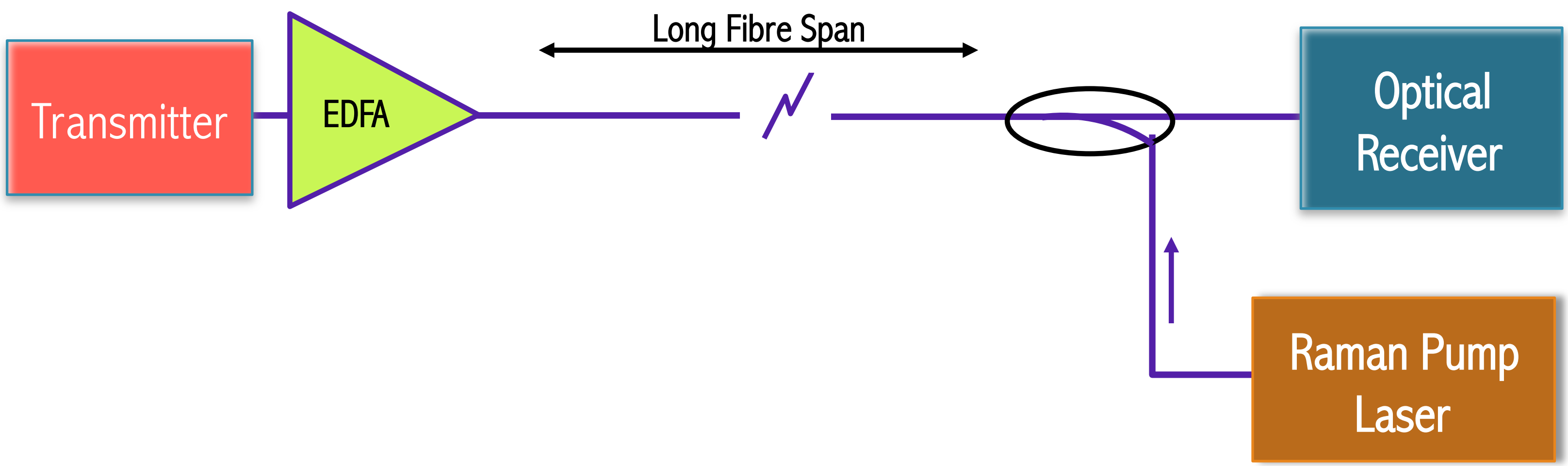
Raman Amplifier



- Topologically simpler to design – no special doping is required
- Uses intrinsic optical nonlinearity of fiber
- Amplification takes place throughout the length of transmission fiber
- Hence also known as Distributed Amplifier

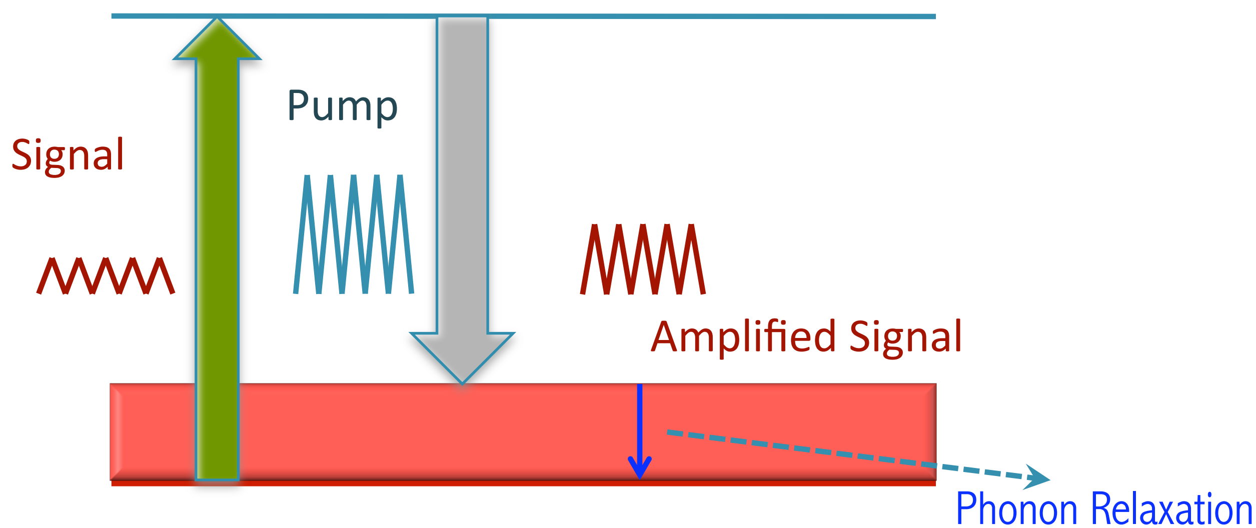
Distributed Amplification

- Raman pumping is usually done backwards
- Gain is higher at the receiver end of the fiber than at the transmitter end
- This is very useful in compensating for the losses

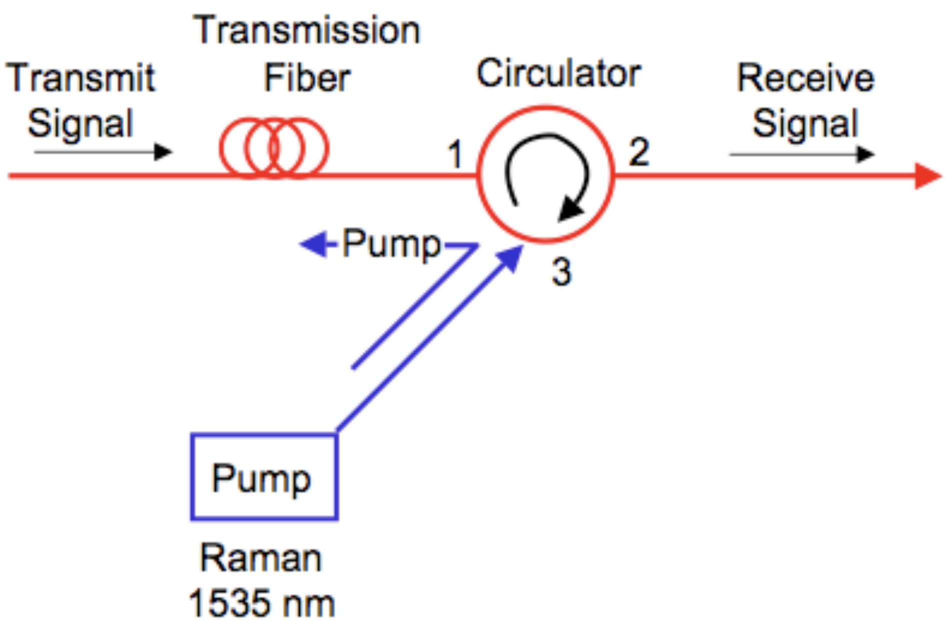


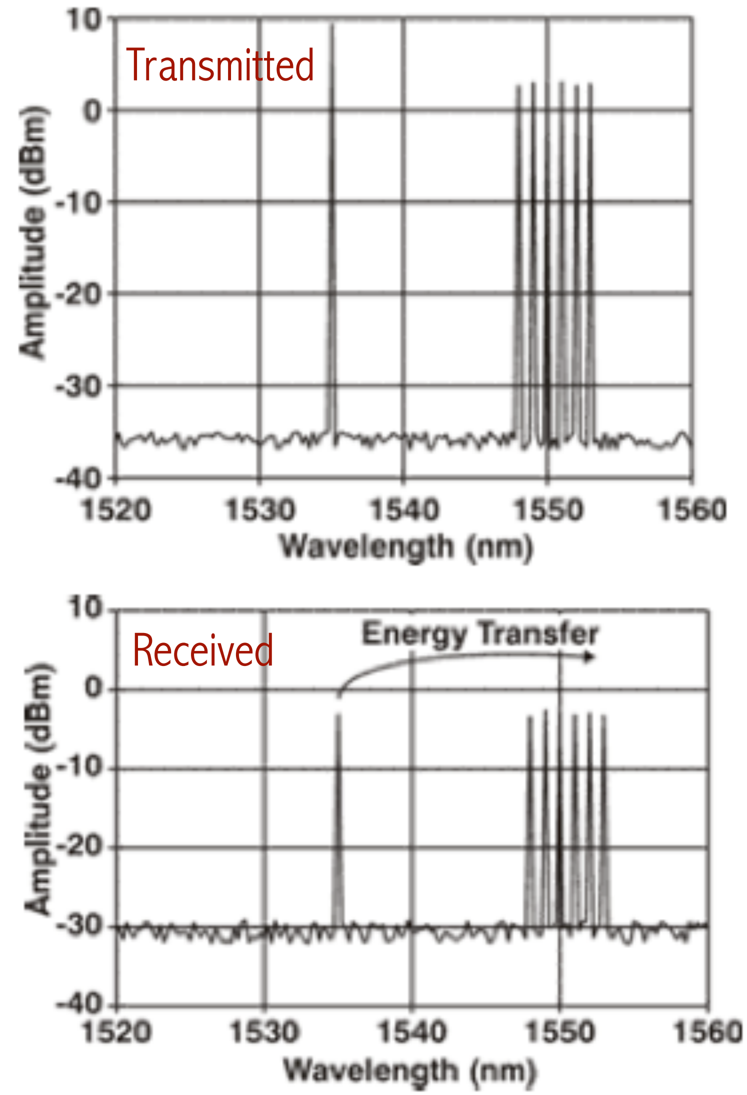
Raman Amplifier

- Uses intrinsic property of Silica fiber → Medium of transmission itself combats signal loss
- The physics behind is called Stimulated Raman Scattering
- High energy pump wave is co-launched into the fiber
- Raman gain depends on the pump power and frequency offset between pump and signal
- Pump photon gives up energy to create a signal photon
- Residual vibrational energy is absorbed as phonons



Typical configuration

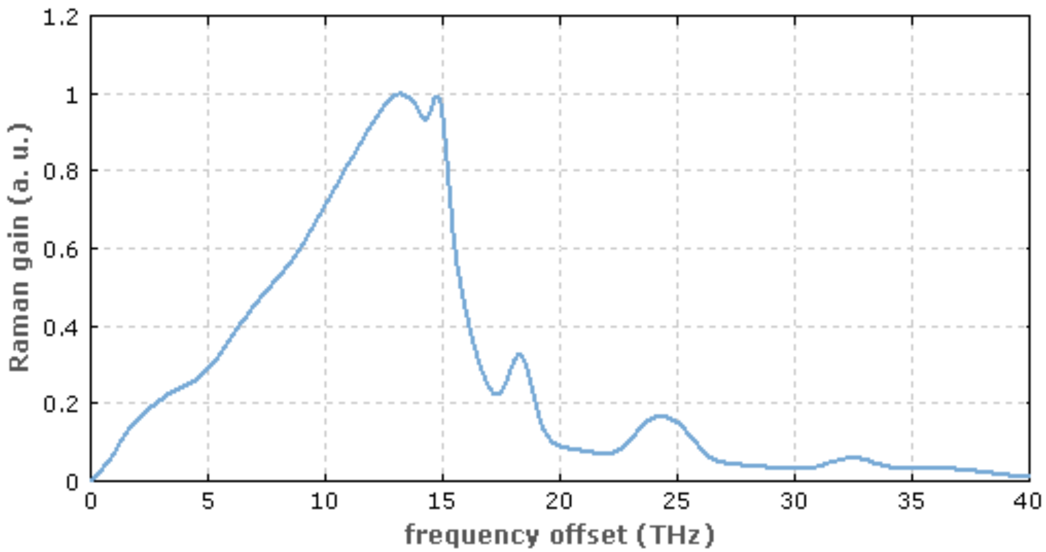




Advantages of backward pumping

- Backward pumping in Raman amplifier has several advantages
- Raman is an almost instantaneous process
- Pump noise strongly affects WDM signals to be amplified if forward pumping is applied
- If pump has a slight fluctuation in time, individual bits are amplified differently
- This leads to amplitude fluctuations or jitter
- In backward pumping, power fluctuations are averaged out

Raman Gain in Fiber



- Depends mainly on the optical frequencies; but also on the pump frequency and polarization
- There is a maximum Raman gain for a frequency offset of 13.2 THz. For example, a pump wave at 1064 nm leads to the largest Raman gain at a signal wavelength of 1116 nm.
- The peaks in the Raman spectrum correspond to certain vibration modes of the silica structure.
- The usable gain bandwidth is about 48 nm

Advantages and Disadvantages

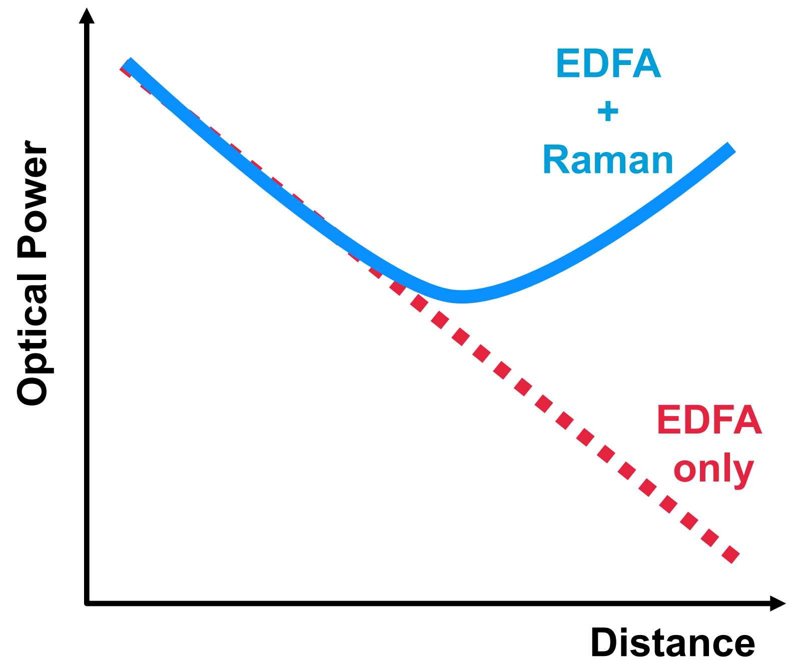
- Advantages
  - Variable wavelength amplification possible
  - Compatible with installed SM fibre
  - Can be used to "extend" EDFAs
  - Can result in a lower average power over a span, good for lower crosstalk
  - Very broadband operation may be possible
- Disadvantages
  - High pump power requirements,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

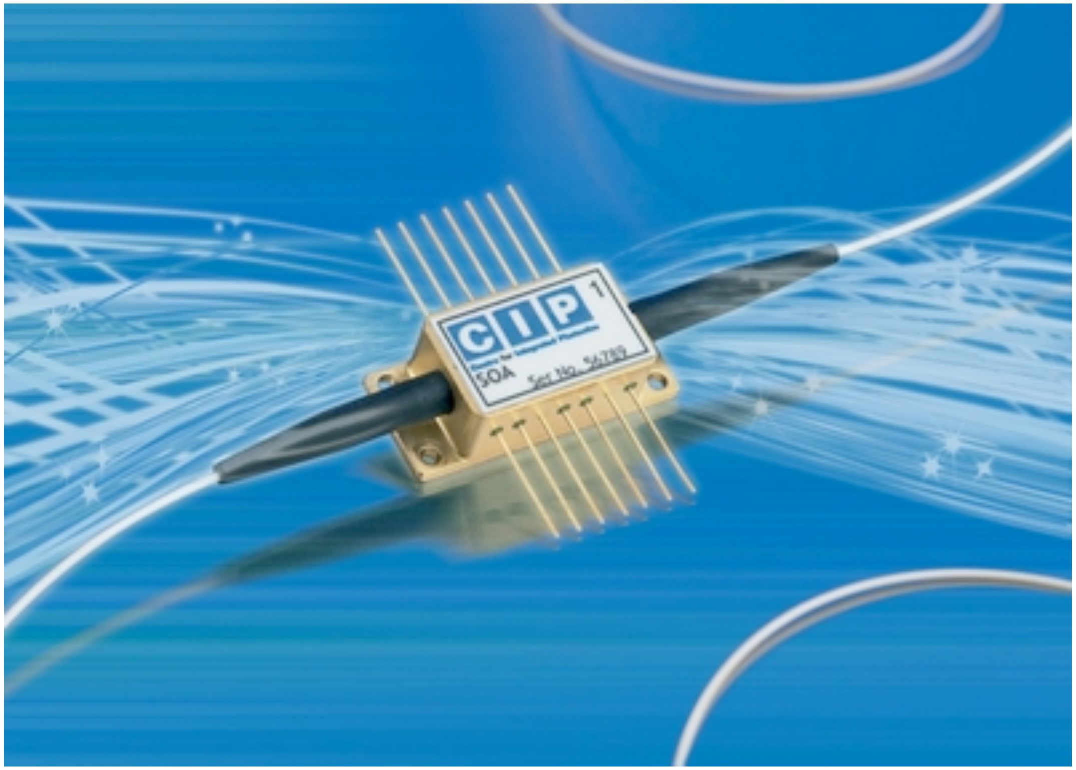
EDFA – Raman Amplifiers : Comparison

Characteristic	EDFA	Raman
Amplification band	Dopant dependant	Depends on pump wavelengths
Bandwidth	20 nm, More for multiple dopants	48 nm, more for multiple pumps
Gain	20 dB or more; depends on ion concentration, fiber length and pump config	4-11 dB, proportional to pump intensity and eff. fiber length
Saturation Power	Depends on gain and material constants	Equals about power of pump
Wavelength	980 nm or 1480 nm for EDFA	100 nm lower than signal at peak gain

Combined EDFA and Raman Amplifications

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





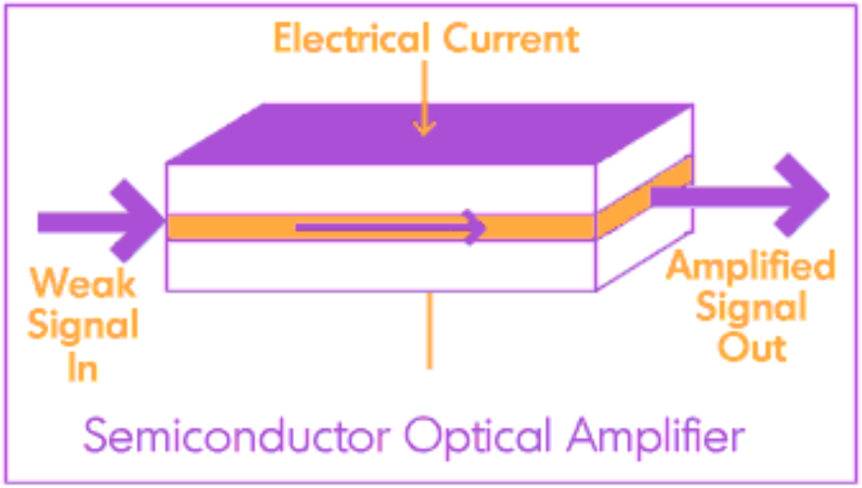
Semiconductor Optical Amplifiers

Semiconductor Optical Amplifier

- An electrical current is passed through the device that excites electrons in the active region.
- When photons (light) travel through the active region it can cause these electrons to lose some of their extra energy in the form of more photons that match the wavelength of the initial ones.
- Therefore, an optical signal passing through the active region is amplified and is said to have experienced "gain."

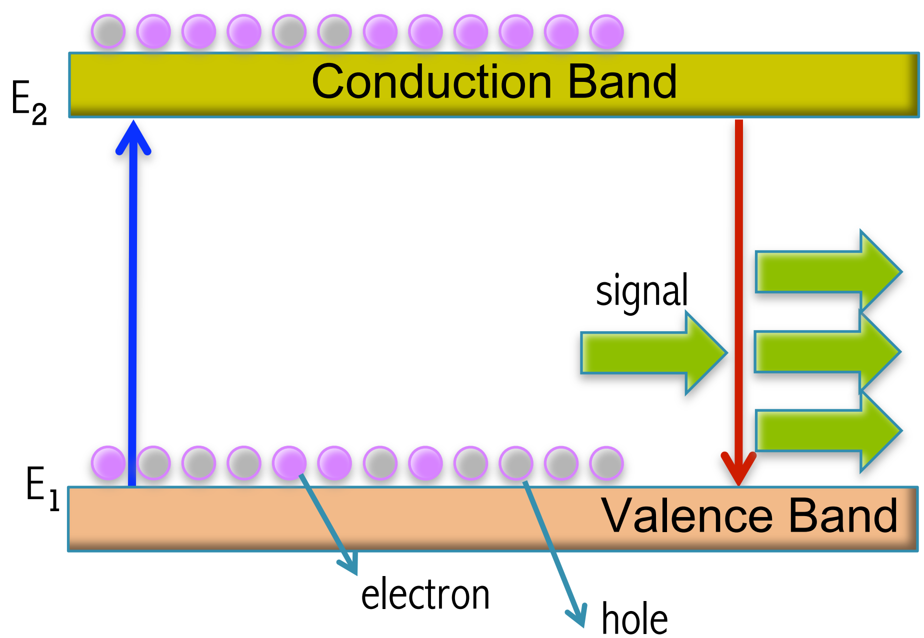
•Both edges (or "facets") of the SOA are designed to have very low reflectivity so that there are no unwanted reflections of the signal within the semiconductor itself.

•This is the main difference from regular lasers that have reflective facets in order to build up the intensity of light within the semiconductor material.

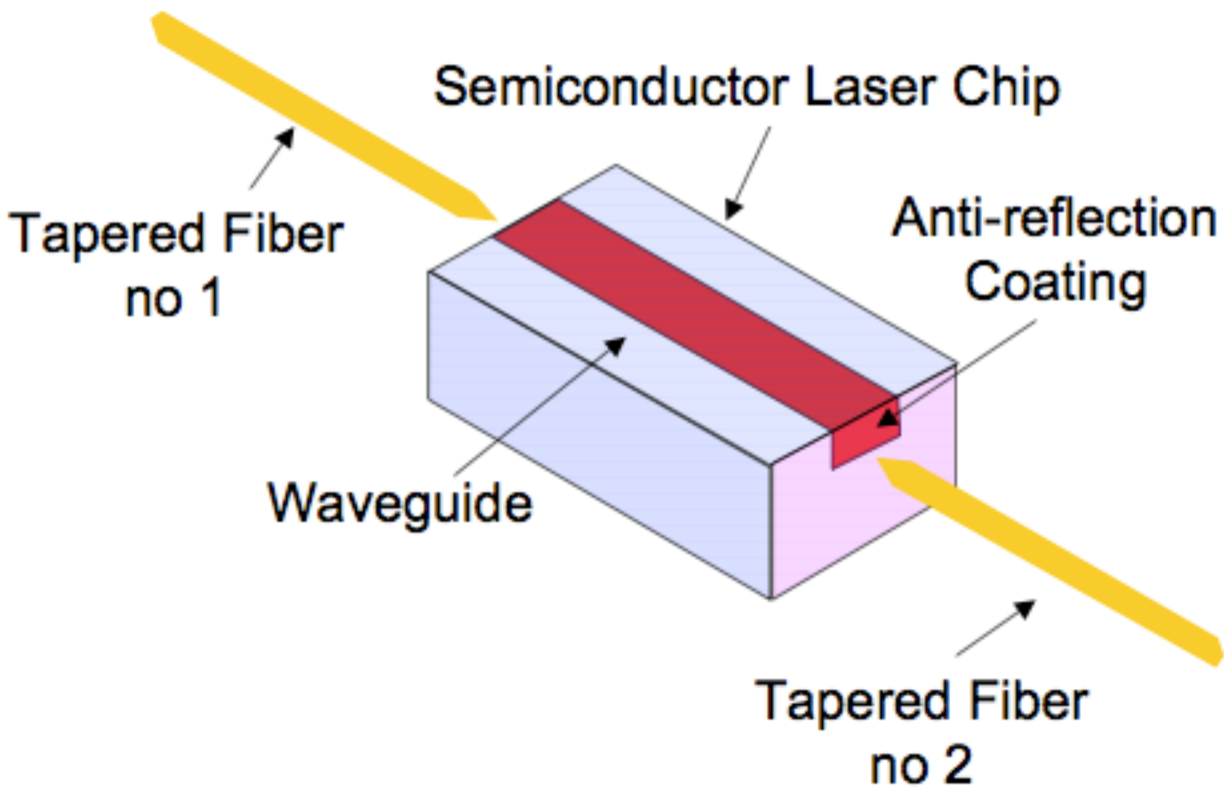


SOA :: Amplification Process

- Semiconductors have Valence and Conduction bands
- At thermal equilibrium valence band has higher population
- Under population inversion condition conduction band will have higher population
- Population inversion is achieved by forward biasing the p-n junction



SOA :: Design


Semiconductor Laser Chip
Tapered Fiber
no 1
Anti-reflection
Coating
Waveguide
Tapered Fiber
no 2

SOA vs Semiconductor Laser

- Both are very similar in principle and construction
- Essentially Fabry-Perot cavities, with amplification achieved by external pumping
- The key in SOA is preventing self-oscillations generating laser output
- This is accomplished by blocking cavity reflections using both an antireflection (AR) coating and the technique of angle cleaving the chip facets.
- SOAs are electrically pumped by injected current

SOA :: Characteristics

- Compact > only a small semiconductor chip with electrical and fiber connections.
- The output powers are significantly smaller.
- The gain bandwidth is smaller, but devices operating in different wavelength regions can be made.
- The upper-state lifetime and thus the stored energy are much smaller, so that the gain reacts to changes in pump power or signal power within nanoseconds (instead of milliseconds).
- Changes in gain also cause phase changes leading to linewidth enhancement factor.
- SOAs exhibit much stronger nonlinear distortions {self-phase modulation and four-wave mixing}.
- The noise figure is typically higher.
- The amplification is normally polarization-sensitive.

SOA :: Gain vs Signal Power

- In SOAs the gain dynamics are determined by the carrier recombination lifetime (few hundred picoseconds).
- The amplifier gain will react relatively quickly to changes in the input signal power.
- This dynamic gain can cause signal distortion, which becomes more severe as the modulated signal bandwidth increases.
- These effects are even more important in multichannel systems where the dynamic gain leads to interchannel crosstalk.
- This is in contrast to EDFAs, which have recombination lifetimes of the order of milliseconds leading to negligible signal distortion.
- SOAs also exhibit nonlinear behaviour => problems such as frequency chirping and generation of intermodulation products.
- Nonlinearities can also be of use in SOAs as functional devices such as wavelength converters.

SOA :: Applications

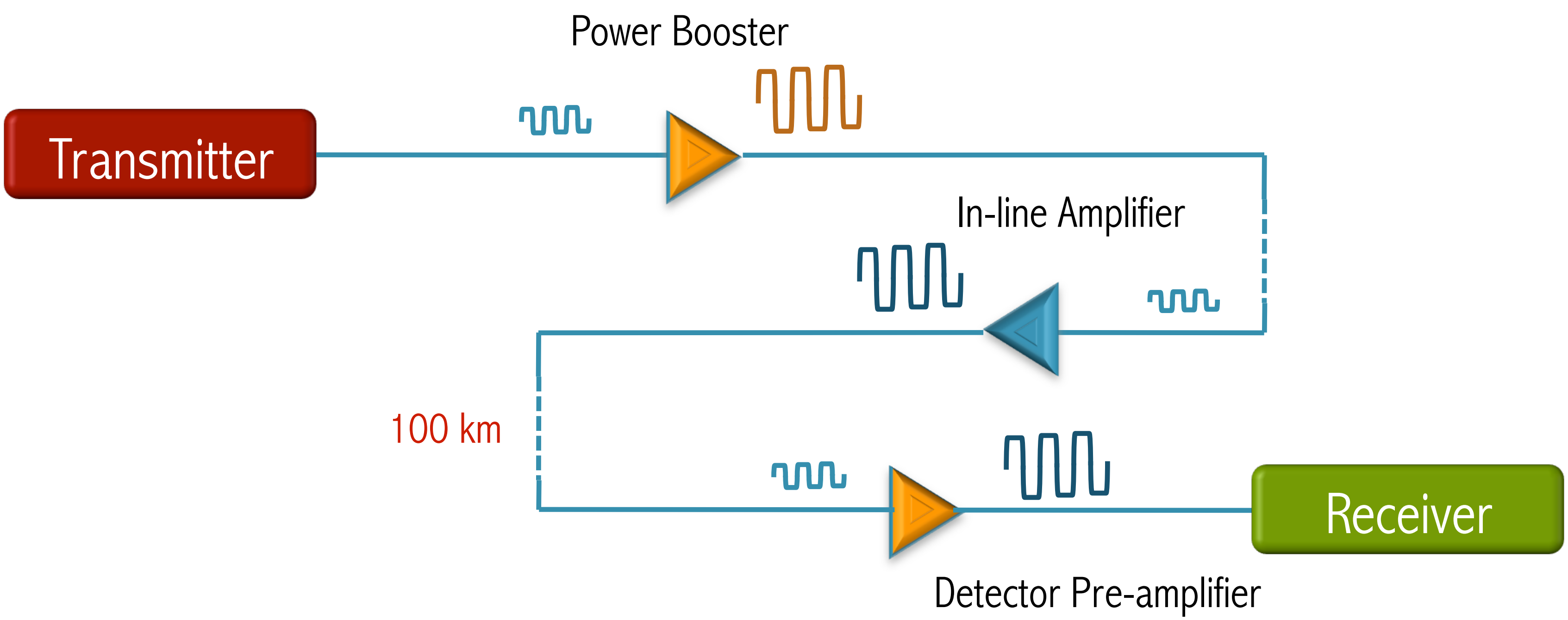
- Power booster – Immediately after Laser Diode
- In-line amplifier
- Detector preamplifier
- Optical switching element
- Wavelength converter

Optical Amplifiers : Comparison

Property	EDFA	Raman	SOA
Gain (dB)	> 40	> 25	>30
Wavelength (nm)	1530-1560	1280-1650	1280-1650
Bandwidth (3dB)	30-60	Pump dependent	60
Max. Saturation (dBm)	22	0.75 × pump	18
Polarization Sensitivity	No	No	Yes
Noise Figure (dB)	5	5	8
Pump Power	25 dBm	>30 dBm	< 400 mA
Time Constant	10^{-2} s	10^{-15} s	2 x 10^{-9}
Size	Rack mounted	Bulk module	Compact
Switchable	No	No	Yes
Cost Factor	Medium	High	Low

Considerations

- Power booster : Placed immediately after transmitter. Help increase the power of the signal, noise may not be the major issue
  - SOA
- In-line amplifier : Compensate for the signal attenuation as it propagates. Needed in long-haul networks. Noise plays a considerable role as the signal weakens
  - Combination of EDFA, Filters and Raman Amplifiers
- Preamplifier : A weak optical signal is usually amplified before it enters the receiver. Noise is a crucial factor



Other doped fiber amplifiers

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

References

- Erbium-Doped Fiber Amplifiers by Philippe C. Becker, N. Anders Olsson, and Jay R. Simpson
- Rare-Earth-Doped Fiber Lasers and Amplifiers, Revised and Expanded by Michel J.F. Digonnet
- Raman Amplification in Fiber Optical Communication Systems (by Clifford Headley and Govind Agrawal
- Raman Amplifiers for Telecommunications 1: Physical Principles by Mohammad N. Islam
- Raman amplification design in WDM systems, Web Proforum Tutorials, http://www.iec.org

and various internet resources

Questions?

Thank you