Optical Amplifiers

Photonics (ELEC-E3240)

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Department of Electronics and Nanoengineering
Aalto University

Lecture Topics

- Course introduction
- Ray optics & optical beams
- Waveguides / optical fibers
- Optical amplifiers
- Fiber optics and applications
- Lab work
- Silicon photonics
- Structural coloration
- Plasmonics
- Poster Presentation & discussion

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Signal Attenuation & Loss of Optical Fibers

Fiber loss: ~4.5% per kilometer

(~90% per kilometer for 0.9mm copper cable)

Distance betw. Otaniemi & Espoo center : ~ 15 kilometers

The total fiber loss (between Otaniemi & Espoo)

$=1-(1-4.5\%)^{15}$

$\cong 50\%$

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How easy with calculation in dB?

Fiber loss: ~4.5% per kilometer
(corresponding to 0.2dB per km)

Distance between Otaniemi & Espoo : ~ 15 kilometers

The total fiber loss (between Otaniemi & Espoo)

=15 km * 0.2dB/km
≅ 3 dB (corresponding to 50%)

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Signal Attenuation & Loss of Optical Fibers

Fiber loss: ~4.5% per kilometer (0.2dB per km)

Distance between Otaniemi & London: ~ 1826 kilometers

The fiber loss (between Helsinki & London)

=1826 km * 0.2 dB/km
= 365 dB

The transmitted signal ≅ $10^{-36.5}$ ≅ 0

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How to compensate the loss?

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One possible strategy: as the signal becomes weak

Optical-to-Electrical-to-Optical (OEO) conversions

- Convert the weak optical signal into electronic form
- Amplifier the converted electronic signal
- Recreate the optical signal with the electronic signal

Problems:
Inefficient, performances limited by slow speed electronics, expensive (>10GHz), complicated.

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Optical Amplifiers: Loss compensation

An *optical amplifier* is a device which amplifies the optical signal directly without ever changing it to electricity. The light itself is amplified (typically every 20-50km).

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Key Characteristics of Optical Amplifiers

There are several performance parameters for optical amplifiers. The importance of each parameter depends on the application. For example, a booster amplifier should have a high saturation output power, whereas low noise is important in preamplifiers. In-line amplifiers need to have broad (and flat) gain bandwidth. The most important characteristics are:

$$G_0 = 10\log\left(\frac{(P_{signal})_{out}}{(P_{signal})_{in}}\right)$$

1) Small signal gain
- Small signal gain describes the amplifier gain, G_0, at very low input power levels (when the output power is much less than the saturation output power).

2) Saturation output power
- Each amplifier has a saturation output power. With increasing input power levels, the gain starts to saturate. The saturation output power is defined as the output power for which the amplifier gain has reduced by a factor of 2 (or 3 dB).

3) Gain bandwidth
- In DWDM systems the amplifiers need to amplify wavelengths within a very broad range, thus the gain bandwidth is very important. The wavelength dependence of gain should also be as flat as possible. Typically gain flattening filters are used to improve the flatness.

4) Noise properties
- All amplifiers decrease the signal-to-noise (S/N) ratio because of spontaneous emission that adds noise to the signal during its amplification. The degradation of S/N is quantified through a parameter called noise figure NF, defined as:

$$NF = (S/N)_{in} / (S/N)_{out}$$

Different Types of Optical Amplifiers

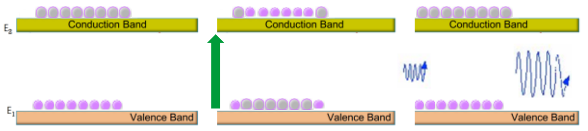
Various techniques have been investigated and are increasingly developed for optical amplifiers for optical communications. At present, the three most important types of amplifiers are following:

1) Semiconductor optical amplifiers (SOAs)

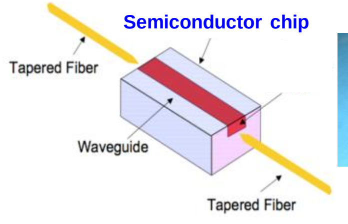
2) Raman amplifiers

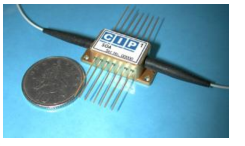
3) Er-doped fiber amplifiers (EDFAs)

Semiconductor Optical Amplifiers: Process



Design of SOA





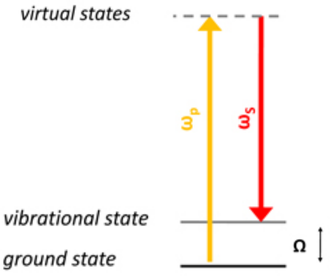
Characteristics of SOAs

- ❑ **Only a small semiconductor chip with electrical and fiber connections (i.e., compact)**
- ❑ **Directly electronically pumping**
- ❑ **The gain bandwidth is smaller, but devices operating in different wavelength regions can be made with bandgap engineering**
- ❑ **The upper-state lifetime and thus the stored energy are much smaller, so the gain reacts to the change in pump power or signal power within nanoseconds**
- ❑ **Changes in gain also cause phase changes, leading to linewidth enhancement factor**
- ❑ **SOAs exhibit much stronger nonlinear distortion (self-phase modulation and four-wave-mixing**
- ❑ **The noise figure is typically higher**
- ❑ **The amplification is normally polarization-sensitive.**

SOA Vs Semiconductor lasers

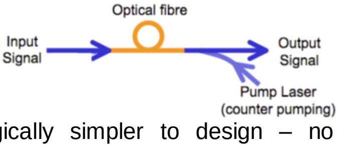
- ❑ Both are very similar in principle and construction
- ❑ Essentially Fabry-perot cavities, with amplification achieved by external pumping
- ❑ The key in SOA is preventing self-oscillations generating laser output
- ❑ This is accomplished by blocking cavity reflections using both an antireflection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

Stimulated Raman Scattering



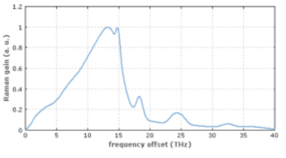
C. V. Raman (1888-1970)

Raman Amplifiers



- ❑ Topologically simpler to design – no special doping is required, as it uses intrinsic optical nonlinearity of fiber (no need of special fiber).
- ❑ High energy pump Raman pumping is usually done backwards, Gain is higher at the end of the fiber.
- ❑ Raman gain depends on the pump power and frequency offset between pump and signal.

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 13.2THz. λ_{pump}=1066nm, $\lambda_{Peak\text{-}signal}$=1116nm; λ_{pump}=1456nm, $\lambda_{Peak\text{-}signal}$=1550nm.
- ❑ The peaks in the Raman spectrum correspond to certain vibration modes of the silica structure.
- ❑ The usable gain bandwidth is ~48nm

Raman Amplifier: Advantages Vs Disadvantages

Advantages:

- ❑ Variable wavelength amplification possible
- ❑ Compatible with installed SM fiber
- ❑ Can result in a lower average power over a span, good for lower crosstalk
- ❑ Very broadband operation may be possible

Disadvantages:

- ❑ High pump power requirement
- ❑ Sophisticated gain control needed
- ❑ Noise is also an issue

Simplified Physics of an Erbium-doped fiber amplifier (EDFA)

Origin of EDFA (Who, When and Where)

No Payne, No Gain!

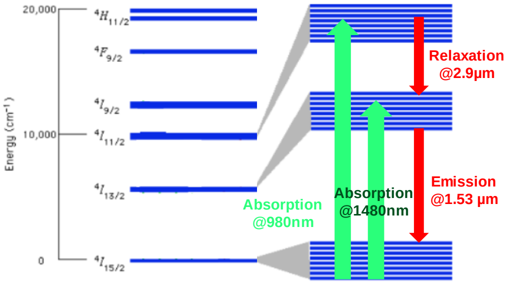
- Prof. David Payne and the team
- Published the research paper in the year 1987
- At the University of Southampton, UK

MILLENNIUM TECHNOLOGY PRIZE

Optical Amplifiers Erbium-doped fiber amplifier (EDFA)

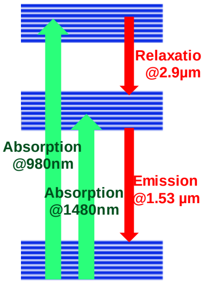
– Commercially available since the early 1990's
– Works best in the range 1530 to 1565 nm
– Gain up to 60 dB (10^6 photons out per photon in!)

Detailed process of an EDFA



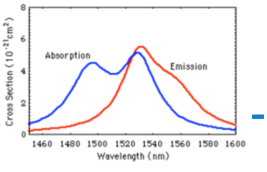
Detailed process of an EDFA

- Erbium-doped fiber is usually pumped by semiconductor lasers at 980nm or 1480nm.
- A three-level model can be used for 980nm pump, while a two-level model usually suffices for 1480nm pump.
- Complete inversion can be achieved with 980-nm pumping but not with 1480-nm pump
- 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.
- A stimulated emission dominates over spontaneous, amplification is more efficient.



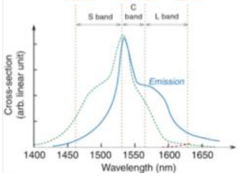
Pump wavelength of EDFA

- 980nm pump is preferred for low noise amplification.
- More powerful 1480nm diodes are available
- At 1480nm, silica fibers have low loss, therefore residual pump can co-propagate with the signal.
- 1480nm pump may even be placed remotely.



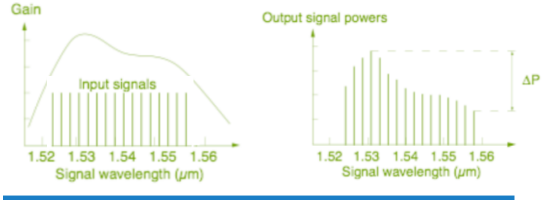
Operation Wavelength of EDFA

- Typically operating in the C-band (1530-1565nm).
- EDF, has a relatively long tail to the gain shape extending well beyond this range to ~1605nm (i.e., L-band from 1565-1625nm)

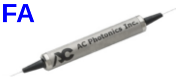


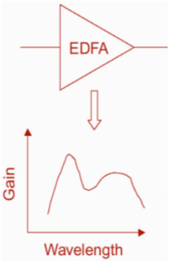
Gain Flatness of EDFA

- Population levels vary at different bands, leading to the gain variation
- Serious affects WDM systems

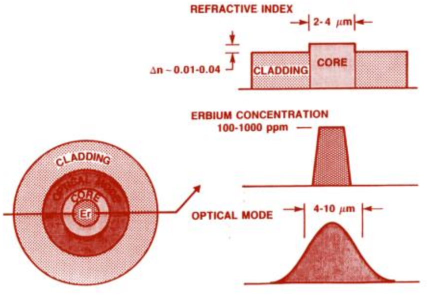


Gain Flatting in EDFA

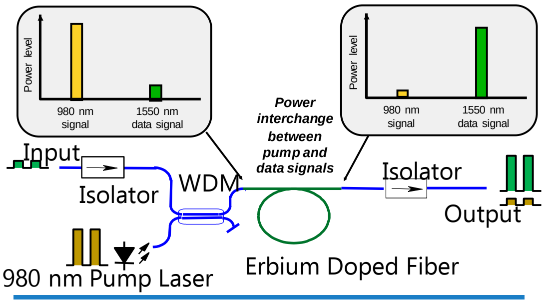




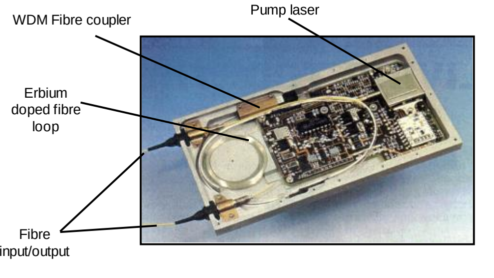
Erbium Doped Fiber: Profile



Operation Setup of an EDFA



Interior of an Erbium Doped Fiber Amplifier (EDFA)



EDFA: Advantages Vs Disadvantages

Advantages:

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

Disadvantages:

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

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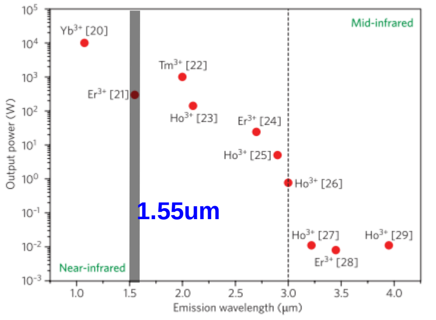
Other doped fiber amplifiers



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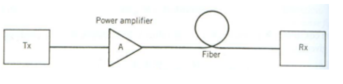
S. D. Jackson, Nat. Photonics **6**, 423 (2012).

Optical Amplifier Comparison

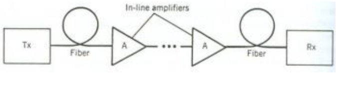
Property	EDFA	Raman	SOA
Gain (dB)	> 40	> 25	>30
Wavelength (nm)	1530-1560	1280-1650	1280-1650
Bandwidth (3dB)	30-60	Pump dependent	60
Max. Saturation (dBm)	22	0.75 × pump	18
Pump Power	25 dBm	>30 dBm	< 400 mA
Time Constant	10^{-2} s	10^{-15} s	2 x 10^{-9}
Cost Factor	Medium	High	Low

Types of Optical Amplifiers

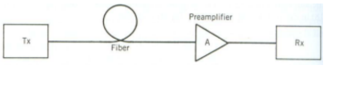
a) A booster (or power) amplifier
- just after the transmitter to increase the output power from the laser diode.



b) An in-line amplifier
-to eliminate the need for Optical-to-Electrical-to-Optical (OEO) conversions along the transmission link (the most important application).

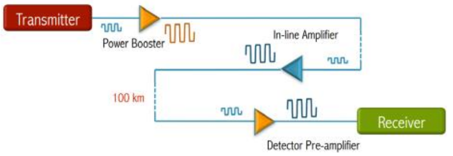


c) A preamplifier
- to improve the receiver's sensitivity.



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
- Pre-amplifier: A weak optical signal is usually amplified before it enters the receiver. Noise is a crucial factor



Hands-on Practice in Making EDFA

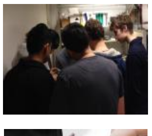
A Check list of components

1. Isolators (two) 
2. Laser Diode (one) 
3. WDM (one) 
4. Erbium doped fiber (0.3 meter) 
5. Coupler
6. Manuals of the components

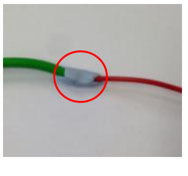
Hands-on Practice in Making EDFA

“Fiber splicing”

Lab practice



Good!

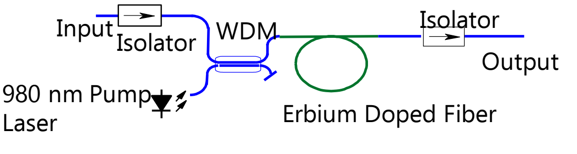


Bad!

Hands-on Practice in Making EDFA

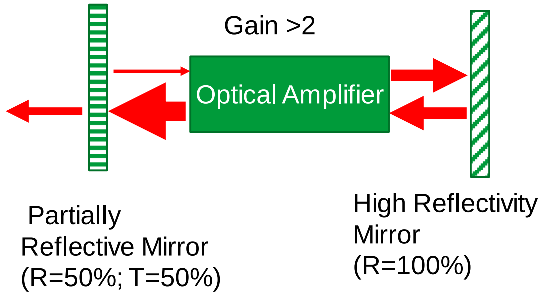
EDFA Setup: List of components needed

1. Isolators (two)
2. Pump laser diode (one)
3. WDM (one)
4. Erbium doped fiber (0.3 meter)
5. Manuals of the components



How to build a fiber laser?

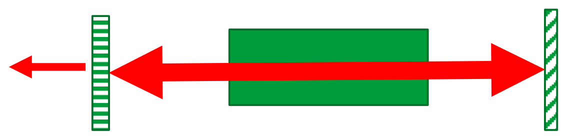
Amplifier VS Laser (Light amplification by stimulated emission of radiation)



Let us make a EDF baser Laser (EDFL)!

EDFL Setup: List of components needed

1. Isolators (two)
2. Pump laser diode (one)
3. WDM (one)
4. Erbium doped fiber (0.3 meter)
5. Coupler



Lecture Topics

- **Course introduction**
- **Ray optics & optical beams**
- **Waveguides / optical fibers**
- **Optical amplifiers**
- **Fiber optics and applications**

Lab work

- **Silicon photonics**
- **Structural coloration**
- **Plasmonics**
- **Poster Presentation & discussion**

Summary about the next week work

2. Home exercise:
   - Prepare the home assignment (3 questions) and announce it on the mycourses website before 10AM 30th, April.
   - Collect all answers from your peers before 10AM 7th, May
   - Evaluate the home assignments of your peers and announce it on the mycourses website before 10AM 9th, May, and send me the results (the evaluation + answer sheets).
   - Exercise lecture on 9th, May 12:30-14:00.
3. Finish the exercises prepared by group 2 (DL: 10AM 7th, May) & group 3 (DL: 10AM 7th, May)
4. Submit your poster PPT to your group leaders (DL: 14th, May)