Optical Amplifiers

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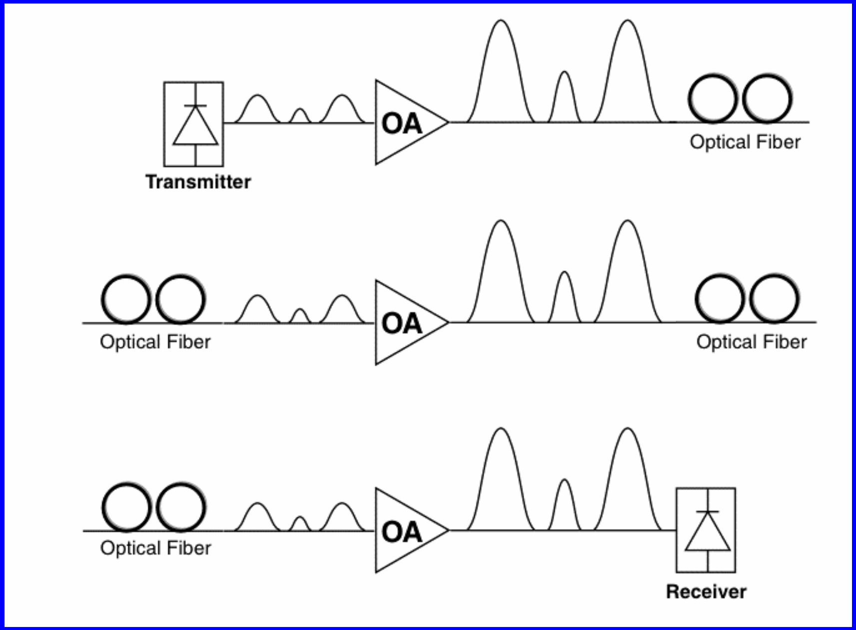
Background - Optical Amplifiers

- **Amplification in optical transmission systems needed to maintain SNR and BER, despite low-loss in fibers.**
- **Early optical regeneration for optic transmission relied on optical to electron transformation.**
- **All-optical amplifiers provide optical gain without any signal conversion to the electron domain.**
- **Higher bandwidth demands further emphasize the need for all-optical amplifiers.**
- **Two types of all-optical amplifiers:**
  - Semiconductor optical amplifiers
  - Fiber-optical amplifiers.

Semiconductor Optical Amplifiers

- **The semiconductor optical amplifier (SOA) provide optical gain without optical-to-electronic conversions.**
- **SOA's are typically used in the following ways:**
  - Used as power boosters following the source (optical PA).
  - Provide optical amplification for long-distance communications (in-line amplification, repeaters).
  - Pre-amplifiers before the photo detector.
  - All-optical signal processing.

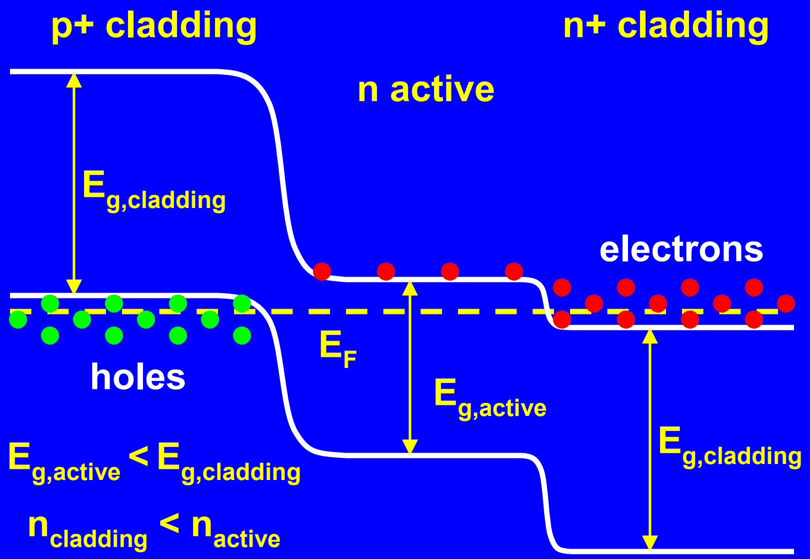


Semiconductor Optical Amplifiers

- **SOA's are based on semiconductor lasers.**
- **Optical feedback of the laser is reduced.**
- **Divided into two sub categories:**
  - Fabry-Perot Amplifiers (FPA)
  - Traveling Wave Amplifiers (TWA)
- **The distinctions depends on the amount of light reflected back into the cavity.**
  - FPA's usually has considerable amount of reflections back to the cavity – reflectivity around 0.3, narrow bandwidth (~0.1 nm with a carrier at 1550 nm).
  - TWA's are designed to get as close to a single pass amplification as possible – reflectivity below 10^{-3}, large bandwidth (>30 nm).

Principle of SOA

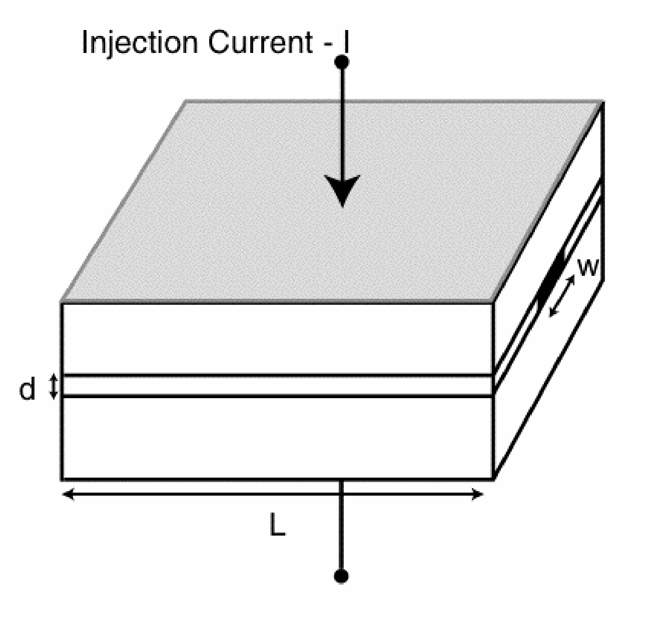
- Efficient semiconductor lasers are usually fabricated as a heterojunction.
- A doped (n/p) active region is sandwiched between two heavily doped regions.
- Large concentration of holes and electron in valence band and conduction band, respectively for the cladding materials.



$E_{g,active} < E_{g,cladding}$

$n_{cladding} < n_{active}$

n-doped region between two degenerated regions (n and p doped) at equilibrium



Example of a SOA (Laser)

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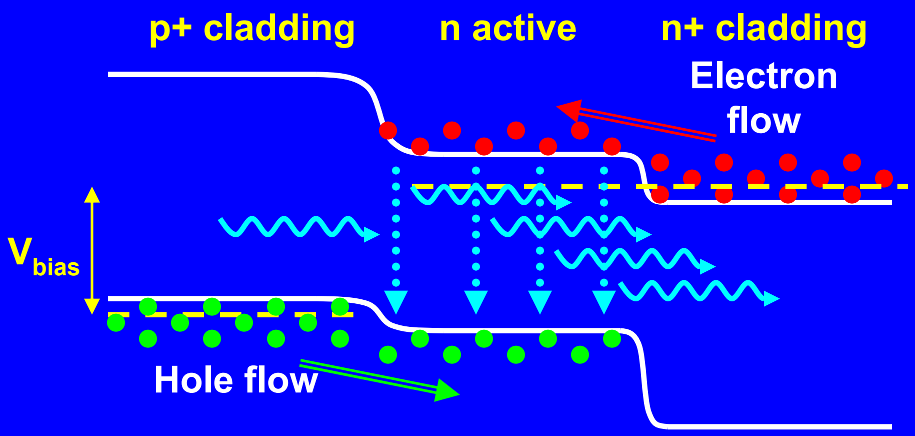
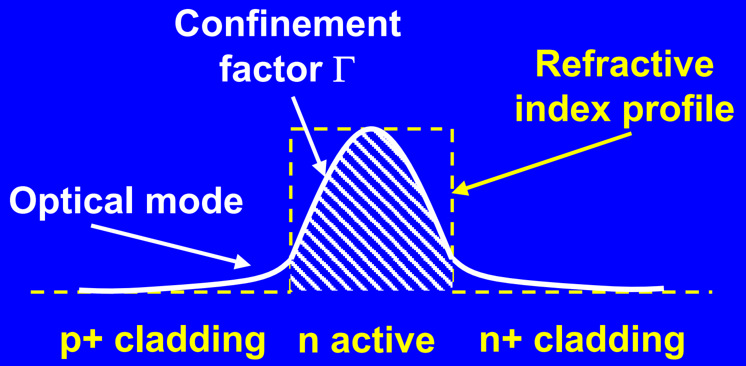
Principle of SOA

- A high forward bias applied to the junction bends the energy bands.
- Holes in the p+ cladding injected in the active region and the larger band gap of the n+ cladding confines the holes in the active region.
- The higher refractive index in the active region acts as a wave guide for the emitted light.
- A laser uses highly reflective facets of the cavity thus applying a positive feedback to the system.
- In an optical amplifier we are only interested of the gain in a single pass thought the amplifier.





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Gain of a SOA

- **Amplification in a SOA - excited electrons in the active region are stimulated to recombine with the holes and releasing the excess energy as identical photons.**

The rate of excited electrons (N) and the number of photons (N_{ph}) is given by:

$$\frac{dN}{dt} = \frac{J}{ed} - R(N) - v_g g(N) N_{ph} \qquad (1)$$

J – injection current density

v_g – group velocity of light traveling in the amplifier

R(N) – recombination rate

G(N) is a material gain coefficient:

$$g(N) = \frac{\Gamma \sigma_g}{V}(N - N_0) \qquad (2)$$

Γ – optical confinements factor

σ_g – differential gain

V=Ldw – volume of active region

N_0 – carrier density needed for transparency.

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Gain of a SOA

Steady state solution of (1) gives:

$$g(N)=\frac{g_0}{1+\frac{N_{ph}}{N_{ph,sat}}}=\frac{g_0}{1+\frac{I}{I_{sat}}} \qquad (3)$$

Where g_0 is the small-signal gain given by (4) and I_{sat} by (5).

$$g_0=\frac{\Gamma\sigma_g}{V}\left(\frac{J}{ed}\tau_s-N_0\right) \qquad (4)$$

$$I_{sat}=\frac{h\nu Ldw}{\Gamma^2\sigma_g\tau_s} \qquad (5)$$

Net gain per unit length is given by (6).

$$g=\Gamma g(N)-\alpha \qquad (6)$$

α is the total loss coefficient per unit length.

The single-pass gain through the amplifier is given by integrating over the whole length.

Single-pass gain G_s is given by (7).

$$G_s=\exp\left((\Gamma\frac{g_0}{(1+I/I_{sat})}-\alpha)L\right) \qquad (7)$$

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Gain saturation in a SOA

- The gain of a SOA will saturate if the optic input power is too large.
- The high input power will consume many of the EHP’s in the active region.
- The electrons and holes in the cladding regions of the SOA needs some finite time to re-occupy the active region.
- Saturation of the gain is referred to as the output power for which the gain has compressed 3 dB.

Gain saturation in a SOA

Gain compression:

$$P_{3dB} = \frac{h\nu A \eta_o \ln 2}{\tau \Gamma dG/dN} \qquad (8)$$

A - active strip, cross section area

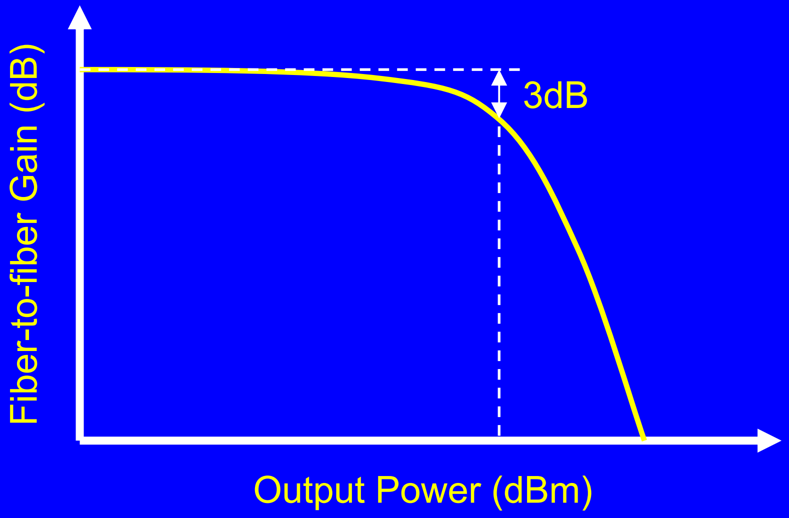
η_o – output coupling efficiency

τ – carrier lifetime

Γ– confinement factor

dG/dN – differential gain

$h\nu$ – photon energy



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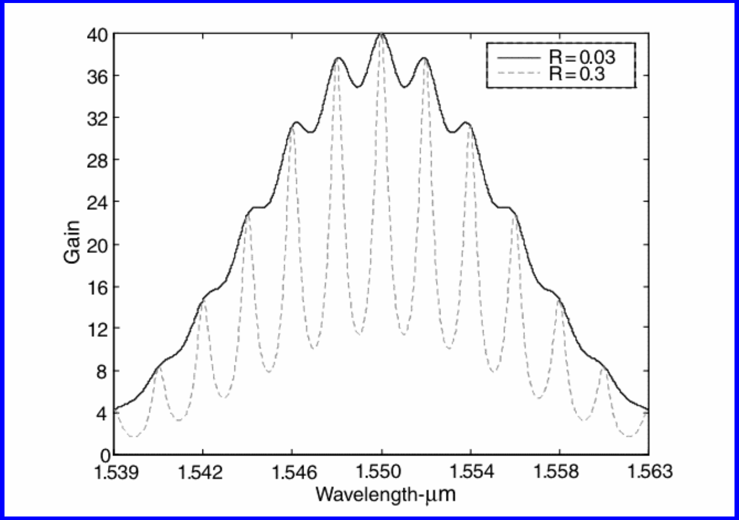
Gain Ripple

- Use a anti-reflective layer on the facets of the laser cavity to reduce the positive feedback .
- Ideal anti-reflective layers hard to obtain.
- Results in ripple in the gain due to the different modes of the laser cavity.
- Amount of ripple depends on gain and reflectivity.

$$Ripple = \frac{(1+GR)^2}{(1-GR)^2} \qquad (9)$$

G – Gain of amplifier

R – Facet reflectivity



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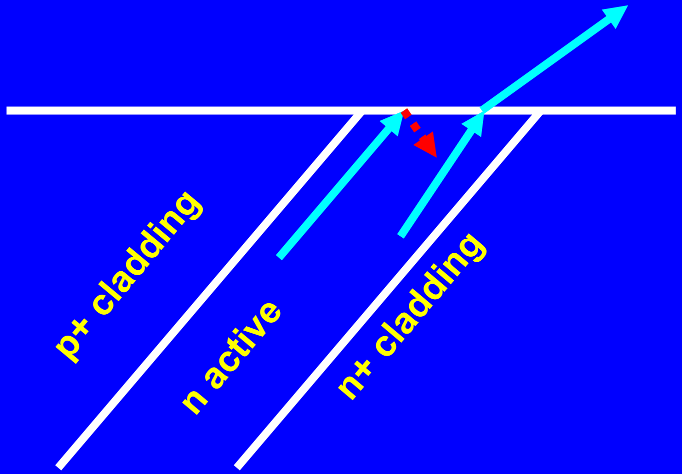
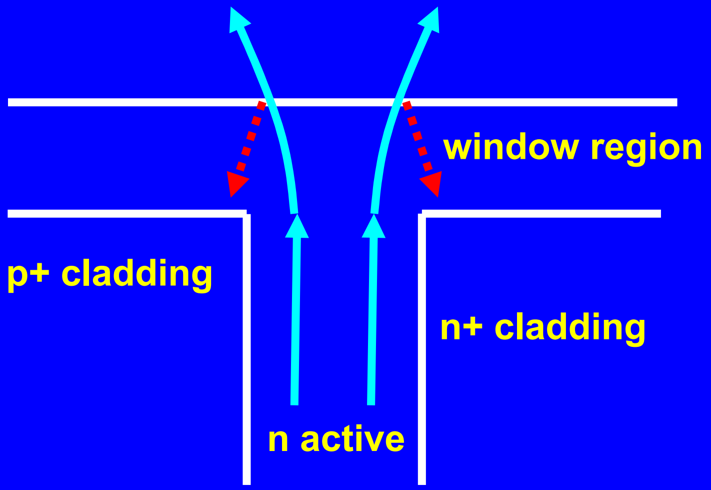
Methods reducing the ripple

- **Place the wave guide at an angle to the facet.**
- **End the wave guide before the facet (window region).**
- **Using a combination of all three methods can result in R < 10^{-5}**

Residual reflections are not directly reflected back to the cavity

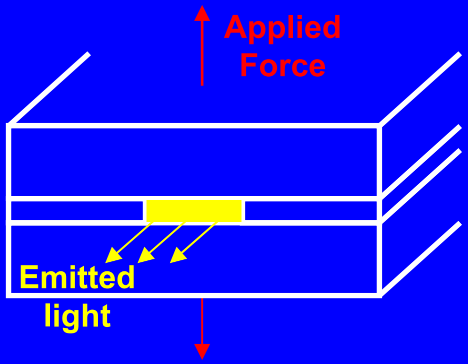


Light starts to diverge in the window region. Reflections are not reflected back to the cavity.



Polarization Dependent Gain

- **Active region without symmetry causes light with different polarization to be amplified differently.**
- **A difference in gain between TE and TM mode of the transmitted light can be as high as tens of dB without countermeasures.**
- **Some tactics to reduce the PDG:**
  - Restore symmetry of the active region.
    - Hard to control in industrial processes because active region needs to be small for single mode.
  - Introduce a tensile strain of a laser cavity that emits TE polarized light.
    - The cavity starts emitting TM polarized light.
    - Strain can be carefully controlled.



Noise in a SOA

- **Stimulated emission is not solely responsible for the light amplification in the SOA.**
- **Spontaneous recombination of EHP's will also be amplified (amplified spontaneous emission).**

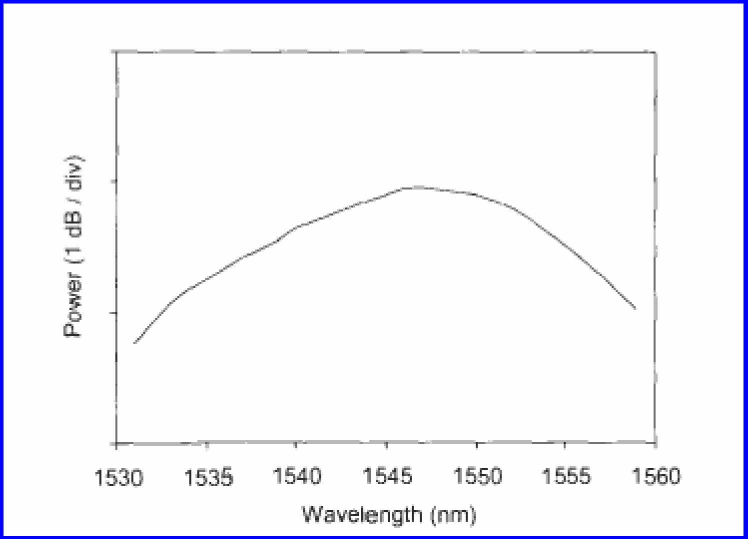
Noise figure of an semiconductor optical amplifier (NF)

$$NF = \frac{2n_{sp}}{\eta_i} \qquad (10)$$

where $$n_{sp} = \frac{N_2}{N_2 - N_1} \qquad (11)$$

N_1 and N_2 is the number of carriers in ground and excited states, respectively.

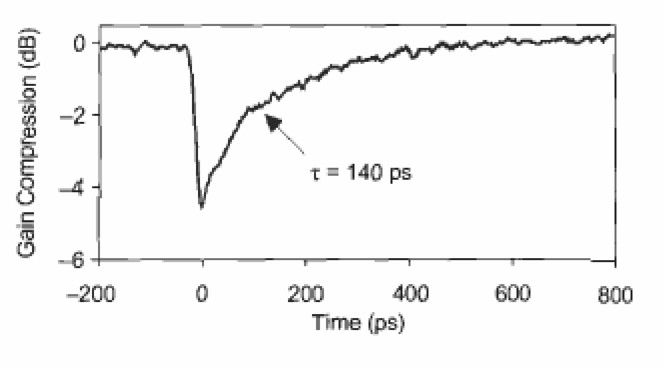
η_i is the input coupling loss.



Typical ASE spectrum of a SOA.

Effects at dynamic operation

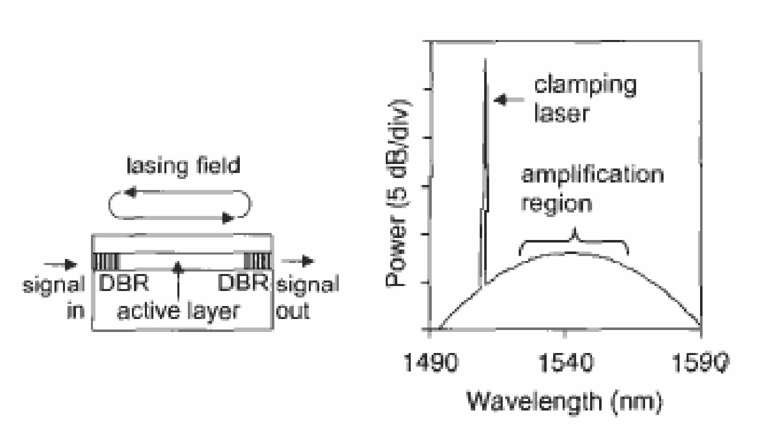
- **Large input signal to amplified in a SOA compress the gain.**
- **For WDM systems the gain compression will cause inter-channel crosstalk.**
  - A large input will compress the gain, limiting the available EHP’s used for amplification of the other channels
- **The gain compression can be used in all-optical signal processing applications.**
  - Wavelength conversion.
  - Cross-gain modulation.
  - Cross-phase modulation.



Fast dynamic response of a SOA.

Gain clamping

- Gain clamping is used to reduce the inter-channel crosstalk for WDM systems.
- Use distributed Bragg reflectors (DBR) on the facets of the cavity of the amplifier.
- Wavelength selective feedback in the cavity.
- Laser mode created at a wavelength outside of the interesting amplification band.



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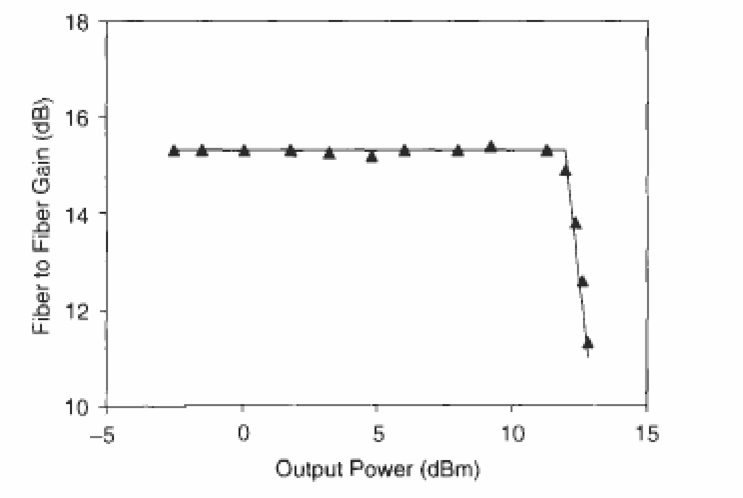
Gain clamping

- A gain clamped SOA has a gain-vs.-output power that is constant over a large power range.
- The laser power is used as a reservoir of optical energy which removes the gain compression.
- When the laser energy is consumed laser action turns off.
- Amplifier saturates very fast.



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Fiber Optical Amplifiers

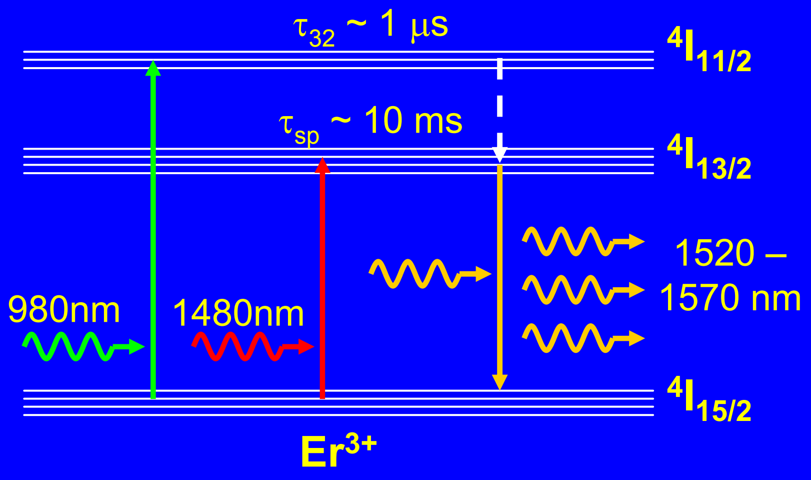
- **Fiber optical amplifiers are based on rare-earth-doped fibers.**
- **Amplification is obtained at different wavelength depending on which rare-earth-ions that is used.**
- **Most commonly used is Erbium (Er) with atomic number 68, placed among a *Lanthanides* in the periodic system.**
- **Silica-fibers doped with Er ions can obtain high gain at a wavelength of 1550 nm.**

- **Fiber optic amplifiers can be used as:**
  - Power amplifiers
  - Repeaters, in-line amplifiers
  - Pre-amplifiers

Erbium Doped Fiber Amplifier

- **An Erbium-ion doped fiber pumped with light of certain wavelengths.**
- **Erbium ions are excited to any of their excited states.**
- **Most common pump wavelengths used are 980 nm and 1480 nm.**
- **Excites the Erbium-ions to the second and first excited energy level, respectively.**

- Electrons in the $^4I_{11/2}$ energy level leaves that energy level for $^4I_{13/2}$ with a spontaneous life time of τ_{32}.
- The transition between $^4I_{11/2}$ and $^4I_{13/2}$ are a non-radiative transition that emits a quantum vibration to the crystal lattice (*phonon*).
- Light with wavelength between 1520 nm and 1570 nm induce stimulated emission in the Er-ions.



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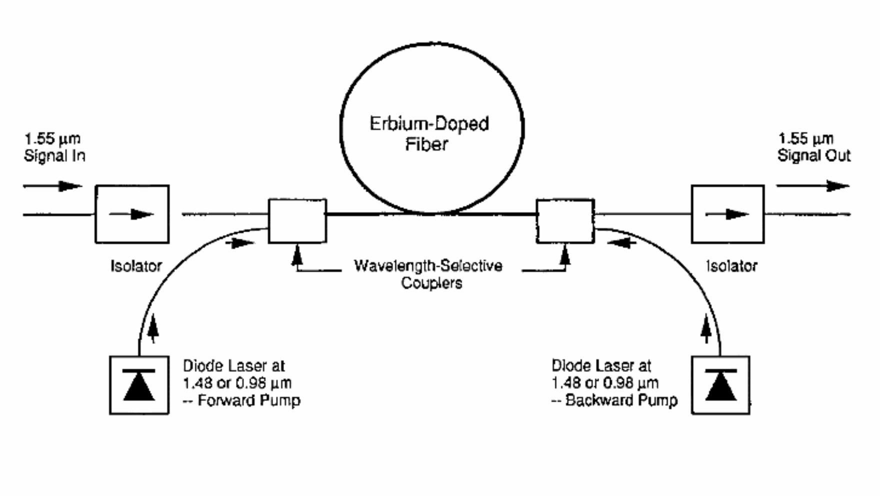
Erbium Doped Fiber Amplifier

- A basic EDFA setup includes optical isolators, wavelength selective couplers, pump lasers, and the fiber itself.
- Fiber can be pumped with light that either co- or counter-propagates with the amplified light, or both.
- The optical isolators are used to limit the ASE and any lasing modes in the fiber.



General Erbium-doped fiber configuration

Gain in EDFA’s

- **The amplification in a EDFA is supplied when incoming light stimulates the Er-ions to return to the ground state and emitting the excessive energy as coherent light.**

Gain in the EDFA is defined as (12) where g(λ,z) is the gain coefficient over the length of the ED fiber according to (13).

The emission coefficient and absorption coefficient are given by (14) and (15) respectively.

Γ_s is the confinement factor of the fiber, n_{Er} is the concentration of Er-ions in the core, σ_e and σ_a are the signal emission and absorption cross sections as functions of wavelength.

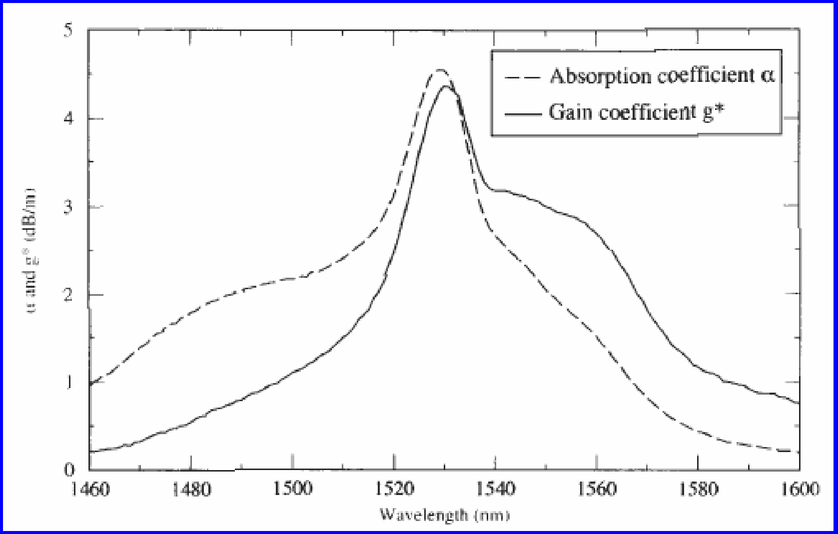
$$G(\lambda) = \frac{P_{out}}{P_{in}} = \int_0^L g(\lambda, z) \cdot dz \qquad (12)$$

$$g(\lambda, z) = \frac{1}{P(\lambda, z)} \frac{dP(\lambda, z)}{dz} =$$

$$= g^*(\lambda) N_2(z) - \alpha(\lambda) N_1(z) \qquad (13)$$

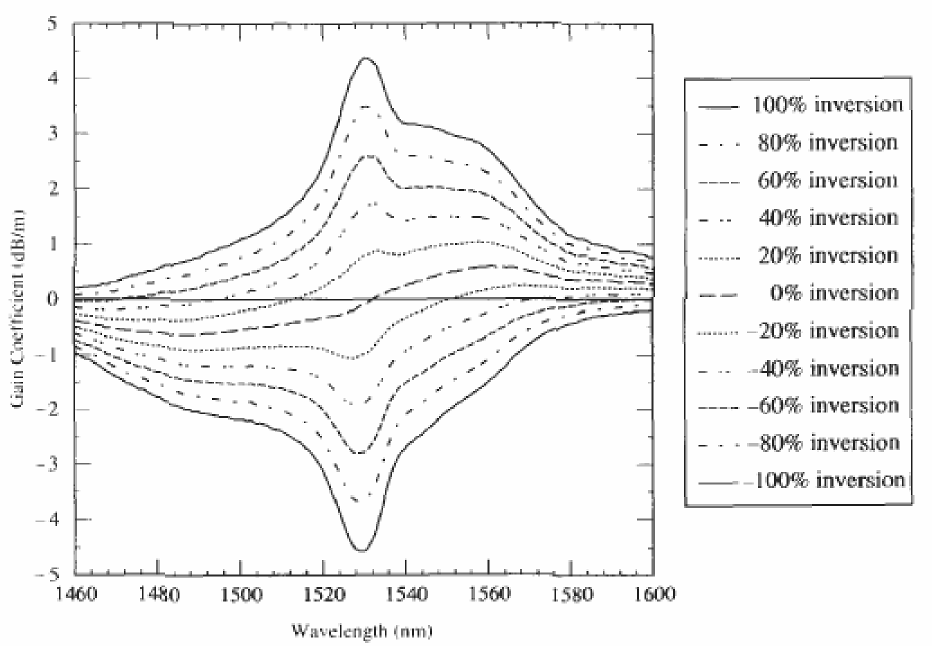
$$g^*(\lambda) = \Gamma_s n_{Er} \sigma_e(\lambda) \qquad (14)$$

$$\alpha(\lambda) = \Gamma_s n_{Er} \sigma_a(\lambda) \qquad (15)$$



Gain in EDFA's

- **The gain spectrum of a EDFA is not flat over a wide wavelength range.**
- **Gain coefficient depends highly on the inversion of the fiber.**



- 100 % inversion – all ions excited to first excited energy state or higher.
- -100 % inversion – non of the ions excited and incoming light is absorbed.

Gain saturation

- **Gain saturation occurs when the stimulated emission is balanced by the absorption of pump energy.**
- **The higher the pump power the more excited Er-ions and the higher saturation power.**
- **P_{sat} defined as the power where the gain coefficient is reduced by half.**

$$P_{sat} = \frac{h\nu_s A_c}{(\sigma_{es} + \sigma_{as})\Gamma_s \tau_{sp}} \left(1 + \frac{\sigma_{as} P_p}{\sigma_{es} P_p^{th}}\right) \qquad (16)$$

Where σ_{es} and σ_{as} are the emission and absorption cross sections, respectively, at the signal wavelength

A_c is the core are area, τ_{sp} is the spontaneous lifetime of the first excited state of the Er-ions, and P_p is the pump power.

The pump threshold for transparency is given by (17).

Below the pump threshold the gain coefficient is negative, because there are several non-excited ions in the fiber that absorbs the incoming signal.

$$P_p^{th} = \frac{\sigma_{as}}{\sigma_{es}} \frac{h\nu_s A_c}{\Gamma_p \tau_{sp} \sigma_{ap}} \qquad (17)$$

Where $h\nu_p$ is the pump photon energy, Γ_p is the confinement factor of the pump mode and σ_{ap} is the pump absorption cross section.

Noise in EDFA’s

- **EDFA also experience amplified spontaneous emission (ASE).**
- **Light emitted by spontaneous decay of excited erbium ions captured by the waveguide and amplified.**
- **ASE acts as background noise to the amplified signal.**

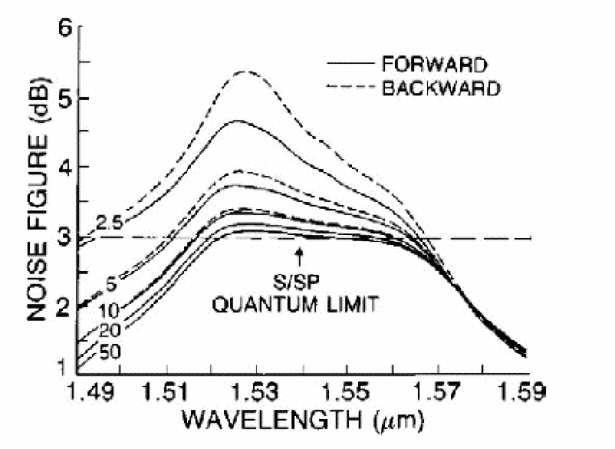
$$NF \approx 2n_{sp} \qquad (18)$$

n_{sp} is the spontaneous emission factor.

$$n_{sp} = \frac{\sigma_{es}N_2}{\sigma_{es}N_2 - \sigma_{as}N_1} \qquad (19)$$

The closer n_{sp} is to 1 the lower the noise.

EDFA’s can be efficiently inverted and NF can therefore be close to 3 dB which is the fundamental quantum limit of optical amplifiers.



Coupling Loss

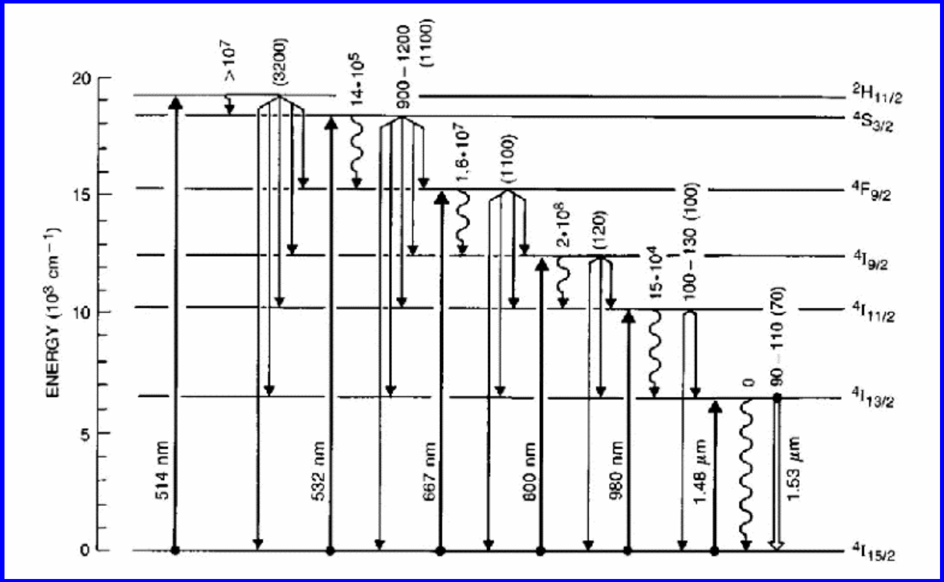
- **Mismatch between the Er-doped fiber modes and transmission fiber modes.**
- **Er-doped fibers usually 2-4 μm in diameter – ordinary transmission fiber have a diameter of 8-10 μm.**
- **Direct Butt-coupling would have coupling loss of several dB.**
- **Fusion splice is used to couple the fibers.**
- **Doping in splice region can be controlled so that a optimized low-loss tapered region is formed.**
- **Total input and output coupling noise of a EDFA fiber using spliced fusion regions is usually less than 1.5 dB.**

Polarization

- Because of the symmetric core of the Er-doped fiber, the gain is virtually independent of polarization.
- One of the main advantages of EDFA’s compared to SOA’s.
- Small polarization dependence by different polarization of ions in fiber.

More on pumping

- Why is the two pump wavelengths of 980 nm and 1480 nm chosen?
- The Er^{3+} ions next four excited energy levels corresponds to pumping wavelengths of 514 nm, 532 nm, 667 nm, and 800 nm.
- Why not use any of these wavelengths?



More on pumping

- Pump light of any of the six specific wavelength will excite the Er-ions to the corresponding energy level.
- The ions decays nonradiatively down to the first excited state.
- Laser diodes developed for 665 nm and 800 nm - could be used for pumping Er-doped fibers.
- Pump efficiency for shorter wavelengths is lowered due to excited state absorption (ESA)
- ESA - pump light excites Er-ions at the first excited state to higher states
- Absorbs the pump light and thus reduces amplification.
- Efficient pumping is achieved at the wavelengths for 980 nm and 1480 nm, which is way they are chosen.

Summary

- Optical amplifiers provide amplification in fiber optic transmission without opto-electron conversions.
- Two types of optical amplifiers – semiconductor optical amplifiers and fiber optical amplifiers.
- SOA's based on lasers – can be either wide or narrow band
- Main application besides amplification – all optical signal processing.
- EDFA's provide gain in a fiber by pumping it with laser light – Optimal for signal wavelength close to 1.55 μm.
- Vertically no polarization dependence on the gain.