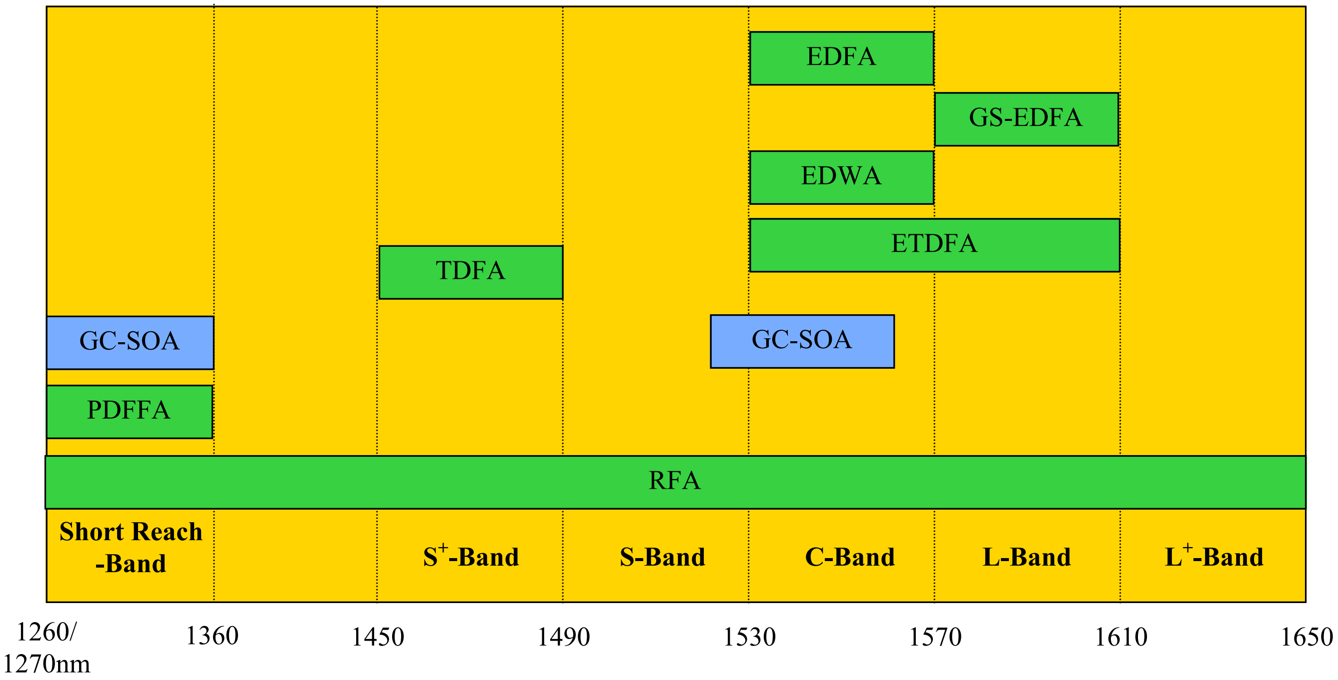
Lecture 8: Intro to Optical Amplifiers

1R Optical Regeneration

- Analog amplification
- Faithfully reproduces input signal with minimal distortion
- Can be used as a linear repeater by periodically boosting optical power
- Can be used in nonlinear region as a level clamping amplifier
- Single amplifier can be used as a multichannel amplifier, ideally with minimal crosstalk and distortion

Waveband Operation



EDFA:	Erbium doped fiber amplifier (1530-1570 nm)
EDWA:	Erbium doped waveguide amplifier
ETDFA:	Telluride based erbium doped fiber amplifier (1532-1608nm)
TDFA:	Thulium doped fluoride based fiber amplifier
PDFFA:	Praseodymium-doped fluoride fiber amplifiers
GS-EDFA:	Gain shifted EDFA
GC-SOA:	Gain clamped semiconductor optical amplifier
RFA:	Raman fiber amplifier

🟩 Optically Pumped

🟦 Electrically Pumped

OA Figures of Merit and Design Parameters

Figure of Merit	**Design Parameter**	**Impact**
Unsaturated Gain (G_0)	Pump Power	• Sets the number of photons available for gain, increase in G_0 with increased pump power but reaches an asymptope
	Erbium Doped Fiber Length	• Increased G_0 with increased length for moderate pump power
Gain Flatness	Operation in Saturation	• Higher F_n at shorter wavelengths • Gain sensitivity to channel add/drop
	Erbium Doped Fiber Length	• Optimal length for pump and signal powers
Noise Figure (F_n)	Co-Propagating pump	• Lower F_n than counter-Propagating
	Counter-Propagating Pump	• Higher F_n than co-Propagating
	Erbium Doped Fiber Length	• F_n increases with increase in fiber length
	Pump Power	• F_n decreases with increase in pump power
Maximum amplifier output power ($P_{out,max}$)	Erbium Doped Fiber Length	•
	Pump Power	• $P_{out,max}$ increases with increased pump power

1R Optical Regeneration

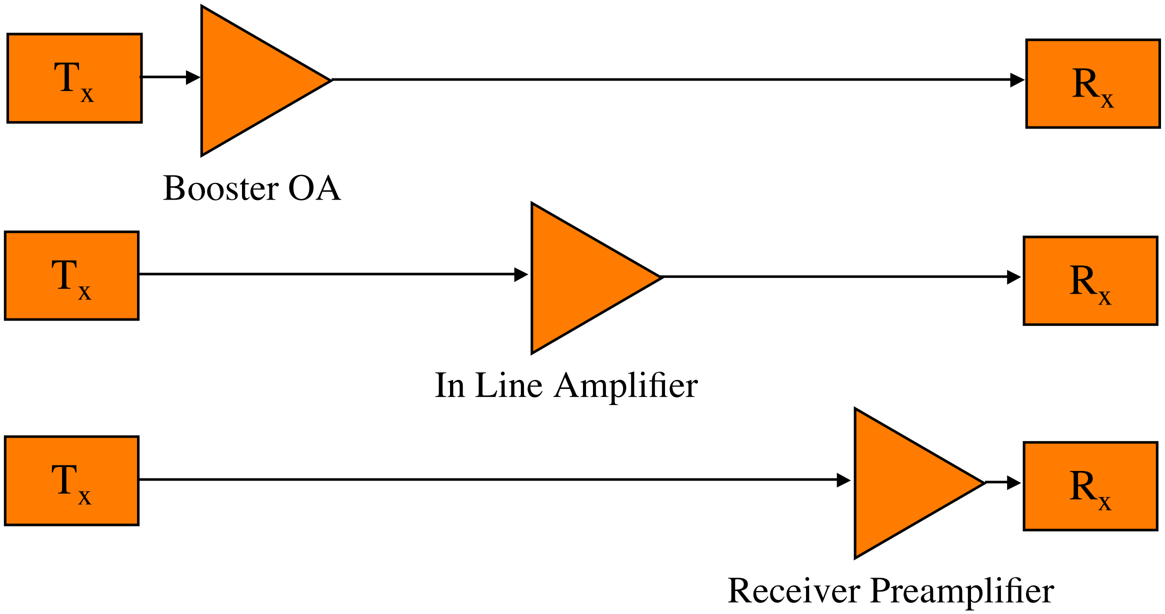
- 1R = Optical Analog amplification, without reshaping or retiming

$$E_{out}(t) = \underset{\text{Amplifier optical Gain}}{\underset{\downarrow}{G}} \cdot E_{in}(t) + \underset{\text{Amplifier emitted optical noise}}{\underset{\downarrow}{n}}(t)$$

  - Faithfully reproduces input signal with minimal distortion
  - Can be used as a linear repeater by periodically boosting optical power
  - Can be used in nonlinear region as a level clamping amplifier
- Available solutions
  - Erbium Doped Fiber Amplifiers (EDFA)
  - Semiconductor Optical Amplifiers (SOA)

Optical Amplifiers

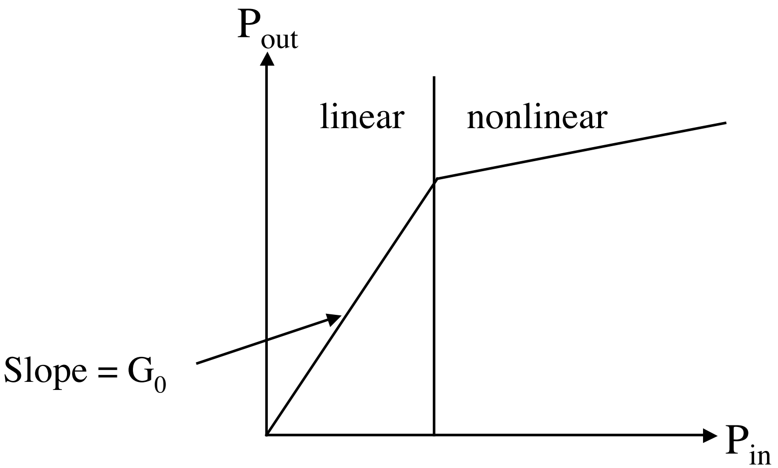
- Three classes
  - Booster (power) amplifiers: Boost power into transmission fiber, low NF, high P_{sat}.
  - In-line amplifiers: Periodically amplify signal due to fiber attenuation, high G, high P_{sat}.
  - Receiver preamplifiers: Boost power into receiver, low NF, high G.

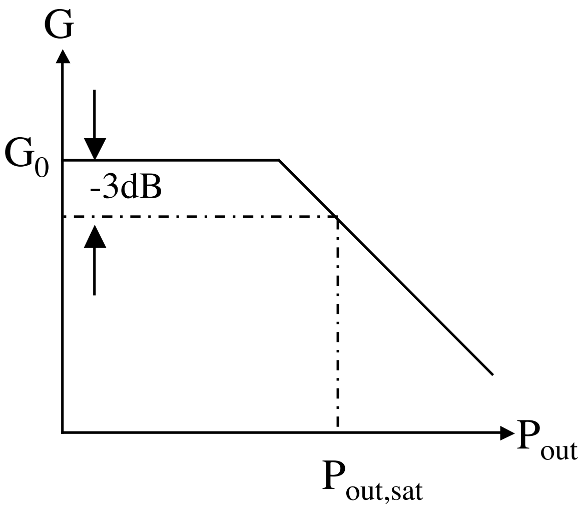


Optical Amplifiers Gain Characteristics

Define: Unsaturated amplifier gain G_0 as the gain achieved at low signal levels and in the linear amplifier regime .

Define: Output saturation power as the output power needed to decrease the amplifier gain by a factor of 2.





Region I: Linear

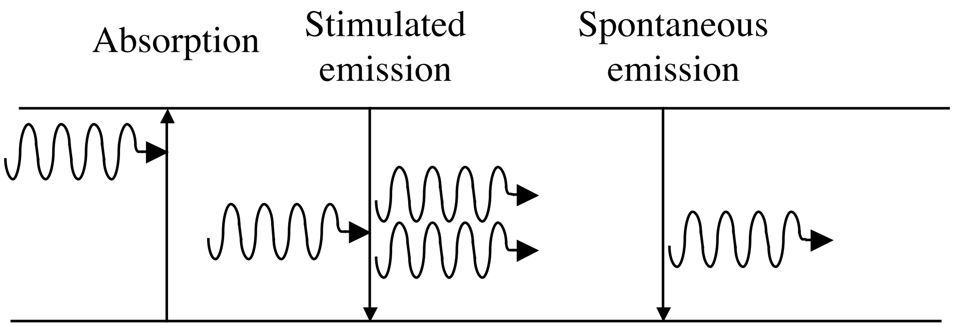
Region II: Nonlinear (Saturated)

$$G_0 = \frac{P_{out}}{P_{in}}$$

$$G = G_0 \exp\left(-\frac{G-1}{G}\frac{P_{out}}{P_S}\right)$$

Optical Amplifier Physics

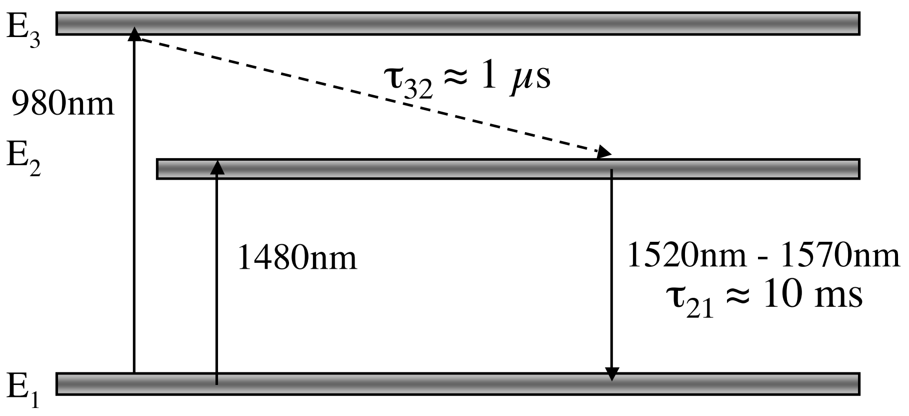
- An atomic system with two energy levels can
  - absorb light
  - amplify light
  - spontaneously emit light



Stimulated and spontaneous emission are achieved by pumping the amplifier electrically or optically

Erbium Doped Fiber Amplifier (EDFAs)

Energy levels for Er+ ions in silica glass



Two pumping options:

- 980 nm pump: Complete population inversion -> Low noise figure
- 1480 nm pump: Low population inversion -> high quantum efficiency in converting pump photons to signal photons

EDFA Gain Spectrum

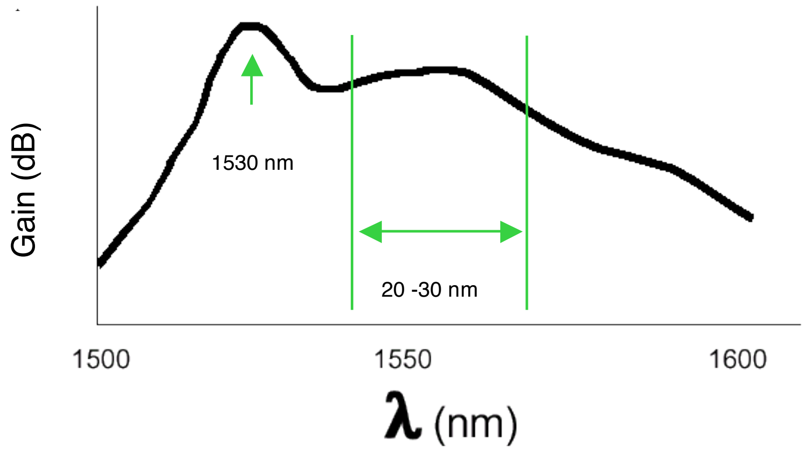
- The gain coefficient for a single atomic transition in the unsaturated regime is given by the peak gain g_0 and the dipole relaxation time T_2 as

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2}$$

- Averaging the gain over the distribution of atomic transition frequencies yields the effective gain

$$g_{eff}(\omega) = \int_{-\infty}^{\infty} g(\omega, \omega_0) f(\omega_0) d\omega_0$$

- An illustration of the effective gain is given below. Note the presence of a gain peak around 1530nm and a semi-flat gain region with optical bandwidth 20-30nm.



EDFA Theory Basics

⇨ Using a simple two-level model for the EDFA assumes that ASE and excited-state absorption are negligible. Also, this model assumes the top excited energy level empties instantly (negligible excited state lifetime).

⇨The population densities of states E_1 and E_2 are given by N_1 and N_2, with the cross section emission and absorption $\sigma_p^a, \sigma_p^e, \sigma_s^a, \sigma_s^e$ for the pump and signal photon flux ϕ_p and ϕ_s. T_1 is about 10ms for EDFAs.

$$\frac{\partial N_2}{\partial t} = \left(\sigma_p^a N_1 - \sigma_p^e N_2\right)\phi_p + \left(\sigma_s^a N_1 - \sigma_s^e N_2\right)\phi_s - \frac{N_2}{T_1}\frac{\delta y}{\delta x}$$

$$\frac{\partial N_1}{\partial t} = \left(\sigma_p^e N_2 - \sigma_p^a N_1\right)\phi_p + \left(\sigma_s^e N_2 - \sigma_s^a N_1\right)\phi_s + \frac{N_2}{T_1}$$

⇨ If we ignore ASE, the evolution of the pump and signal powers along the fiber in direction z can be approximated by taking into account the fiber loss at signal and pump wavelengths (α, α')

$$\frac{\partial P_S}{\partial z} = \Gamma_S\left(\sigma_s^e N_2 - \sigma_s^a N_1\right)P_S - \alpha P_S$$

$$\pm\frac{\partial P_p}{\partial z} = \Gamma_p\left(\sigma_p^e N_2 - \sigma_p^a N_1\right)P_p - \alpha' P_p$$

EDFA Theory Basics

⇨ For short amplifiers (10-20m), optical loss can be ignored ($\alpha = \alpha' = 0$). Let $N_1+N_2=N_{total}$, and a_d be the cross-sectional area of the doped portion of the fiber core. The steady state solution for the rate equations reduces to

$$N_2(z) = -\frac{T_1}{a_d h\nu_s}\frac{\delta P_s}{\delta z} \pm \frac{T_1}{a_d h\nu_p}\frac{\delta P_p}{\delta z}$$

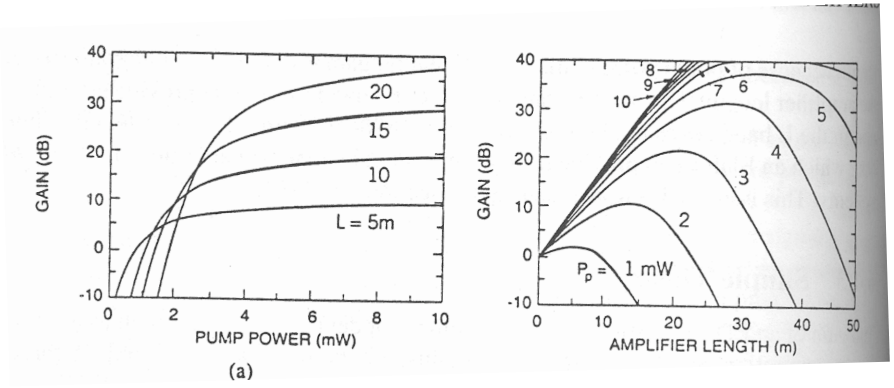
$$a_d = \Gamma_s a_s = \Gamma_p a_p$$

⇨ Substituting this equation into the power evolution equations and integrating over the length of fiber, the gain can be computed by taking the ratio of output to input power

$$G = \Gamma_S \exp\left[\int_0^L \sigma_s^e N_2 - \sigma_s^a N_1 dz\right]$$

EDFA Basics

- From the figure below we observe that
  - For a given amplifier length the gain initially increases with pump power then saturates
  - For a given pump power, the amplifier gain becomes maximum at optimum L, then rolls off sharply as the pump photons have all been absorbed.
  - Both L and P_p must be optimized for a particular amplifier design.



(a)

EDFA pumps

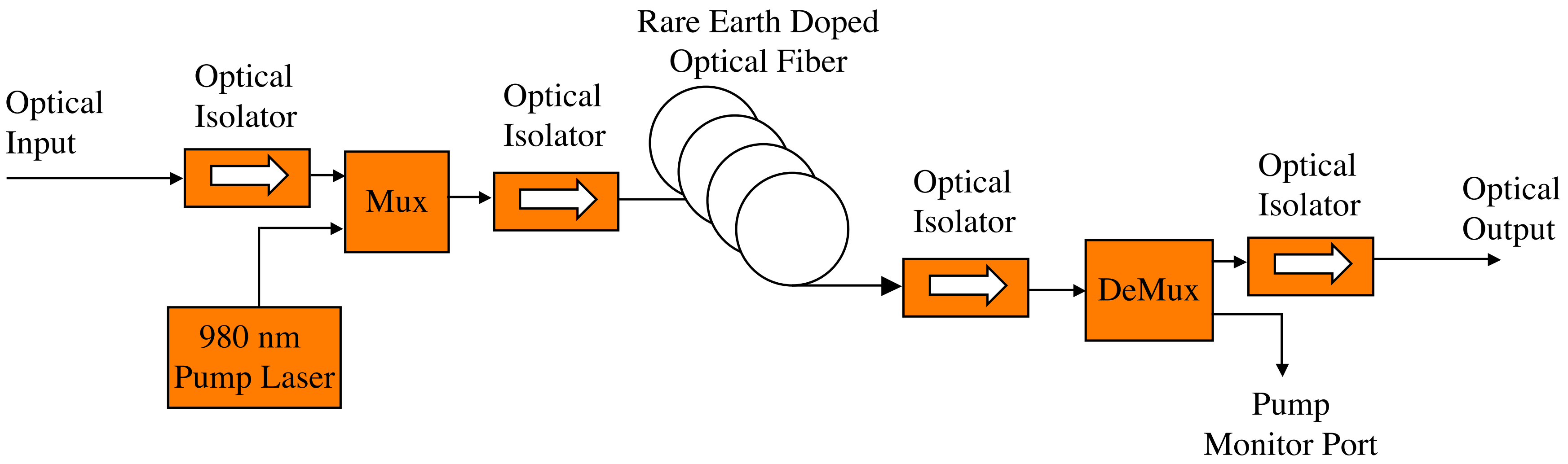
- 1480 nm pumping: it was the choice for most of the first commercial solutions
  - Mainly due to the fact that 1480 nm laser were more resilient and commercially available at high output power (which is usually in the order of 200-400 mW)
  - Generally less expensive
  - From a pure transmission point of view, they have low performance in terms of noise figure (see later)
- 980 nm pumping:
  - Today laser technology has reach a high reliability even at 980 nm
  - Most current commercial EDFAs use this solution, sometimes together with 1480 nm

Typical Pump Source Characteristics

Performance parameter/wavelength	980 nm	1480 nm
Minimum noise figure	<4 dB	5.5 dB
Optical conversion power efficiency	35%	50%
Diode laser quantum efficiency	0.92 W/A @ 240 mW	0.36 W/A @ 200 mW
Module wall-plug efficiency	39% W/W	13% W/W
1999 rated module power	200 mW	180 mW
State-of-the-art module reliability	110 FIT	65 FIT
Mean time to failure	$>2\times10^6$ hours @ 150 mW	$>5\times10^6$ hours @ 120 mW
-3dB Er absorption band in silica	976 to 984 nm	> ~1450 nm

Rare Earth Fiber Amplifiers

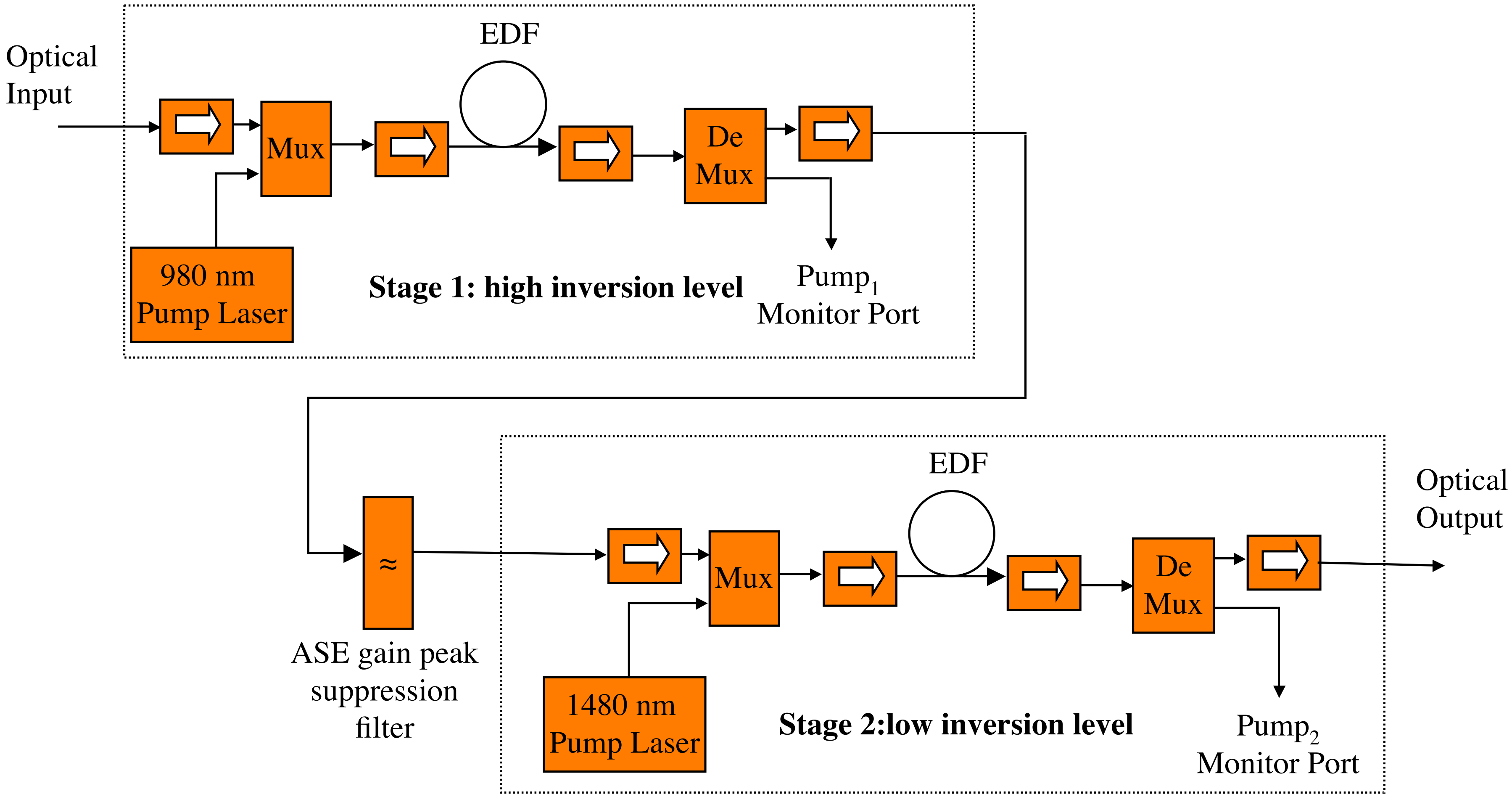
Rare Earth Doped Fiber Amplifier: Single pump, single stage geometry



EDFA Characteristics

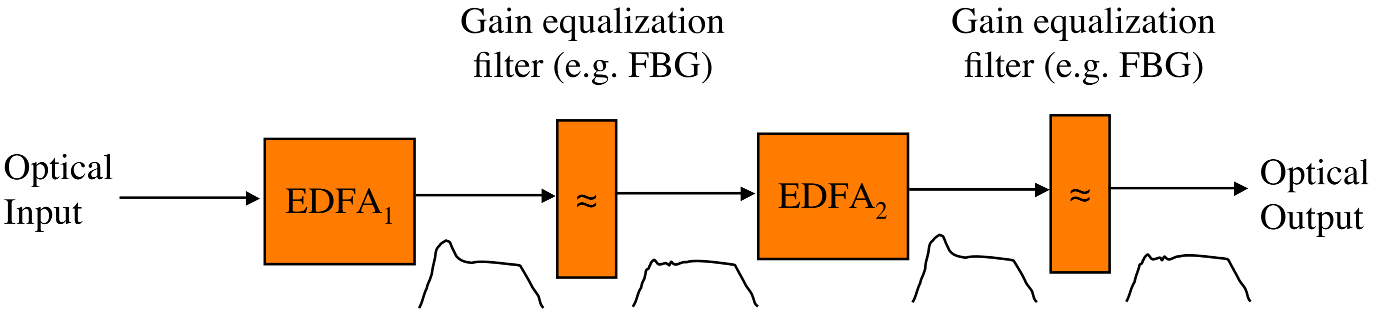
- Gain:
  - Higher gain requires high
- High Output Power:
  - Requires high $P_{out,sat}$ which requires high optical pump power and high inversion
- Gain Flatness
  - Is a function of inversion level.
  - Typically 40%-60% inversion leads to broadest gain with lowest ripple
- Gain Bandwidth:
  - Can be enhanced using optical filtering and composite gain media
- Noise Figure:
  - High population inversion level
- Transient Behavior:
  - Can be suppressed using optical gain clamping or dynamic gain control feedback

Two-Stage EDFA Optical Amplifier



Wideband EDFAs

Gain Equalization



Gain equalization filter (e.g. FBG)

Gain equalization filter (e.g. FBG)

Optical Input

EDFA$_1$

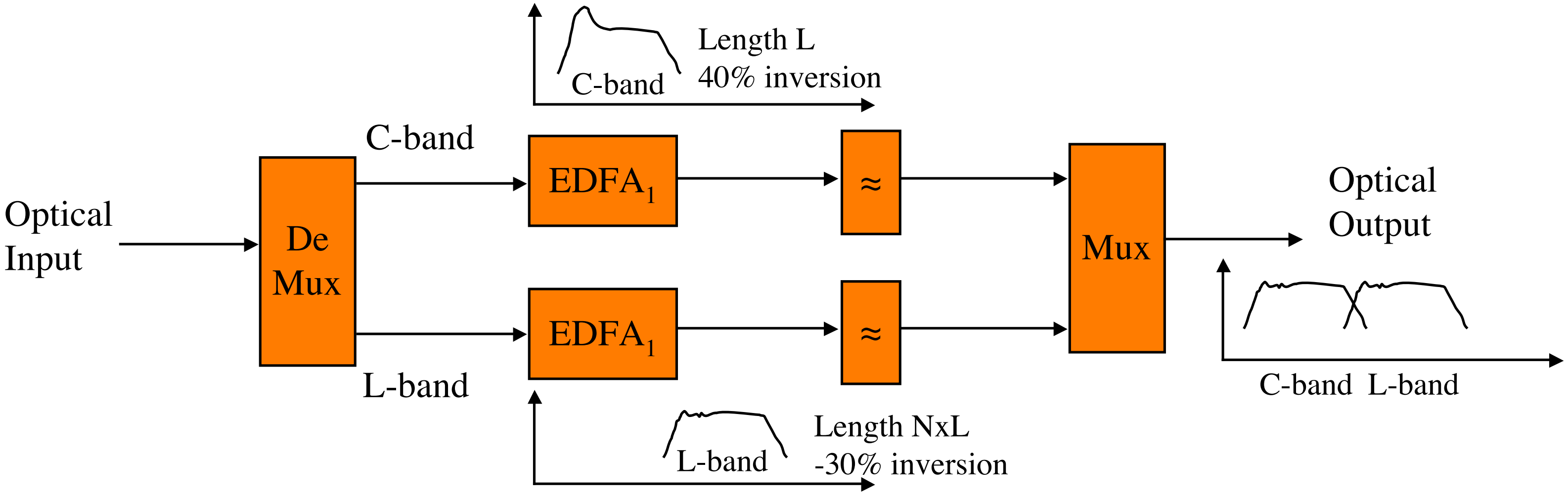
≈

EDFA$_2$

≈

Optical Output

Split-Band Amplification



C-band

Length L
40% inversion

Optical Input

De Mux

C-band

EDFA$_1$

≈

L-band

EDFA$_1$

≈

Mux

Optical Output

C-band L-band

L-band

Length NxL
-30% inversion

ASE noise in EDFA

- The output ASE noise is:

$$P_{ASE}^{out} \cong 2n_{sp}h\nu(G-1)\Delta B$$

- where:
  - n_{sp} = $(N_2 - N_1)/N_2$ is the spontaneous emission factor, mainly dependent on the degree of inversion
  - h is the Plank constant
  - ν is the central optical frequency
  - G is the EDFA gain
  - ΔB is the bandwidth over which the noise is measured

- The noise figure of the EDFA is defined as: $F = 2n_{sp}$
- The optimal value for an EDFA is F=3 dB
  - Typical values are from 4 to 5 dB

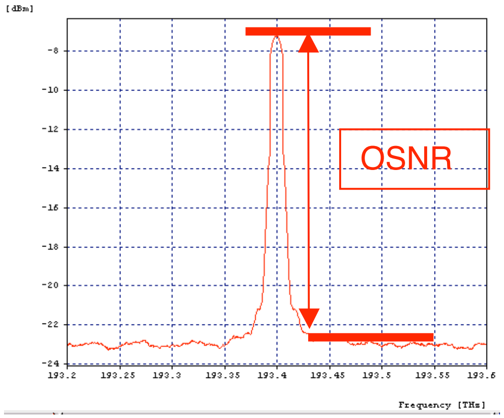
ASE noise in EDFA -II

- The output ASE noise on a 0.1 nm bandwidth is approx. given by:

$$\boxed{P_{ASE}^{out} \cong -58dBm + F_{EDFA} + G_{EDFA}}$$

- The ASE noise is one of the factor that sets the ultimate limits of optically amplified systems
  - The optical signal-to-noise ratio (OSNR) cannot go below a given level to have acceptable BER at the receiver
  - Given an input signal power P_{in}

$$\boxed{OSNR\big|_{dB} \cong P_{signal}^{in} + 58dBm - F_{EDFA}}$$



EDFA features

- In a WDM environment, the crosstalk among channels generated by EDFA is very low
  - This is one of the main reason for the EDFA success
  - Physically, this is related to the (slow, ms) time constant of the saturation process in EDFA
    - A comb of tens of channels can be amplified by a single EDFA with negligible crosstalk
- Still, in some important situation, transient effects in EDFA may be relevant
  - Add/drop of channels
  - Bursty/packetized traffic