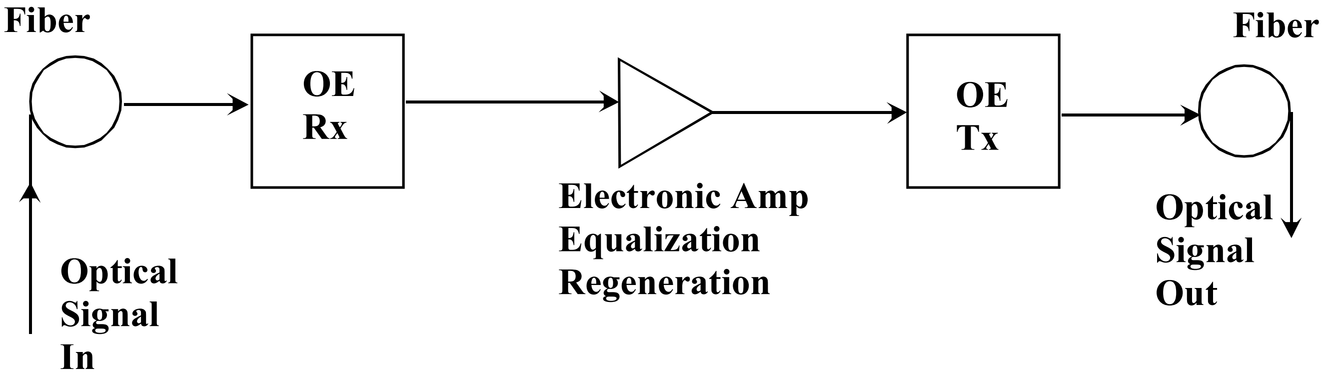
SECTION 5: OPTICAL AMPLIFIERS

OPTICAL AMPLIFIERS

- In order to transmit signals over long distances (>100 km) it is necessary to compensate for *attenuation losses* within the fiber.

- Initially this was accomplished with an optoelectronic module consisting of an optical receiver, a regeneration and equalization system, and an optical transmitter to send the data.

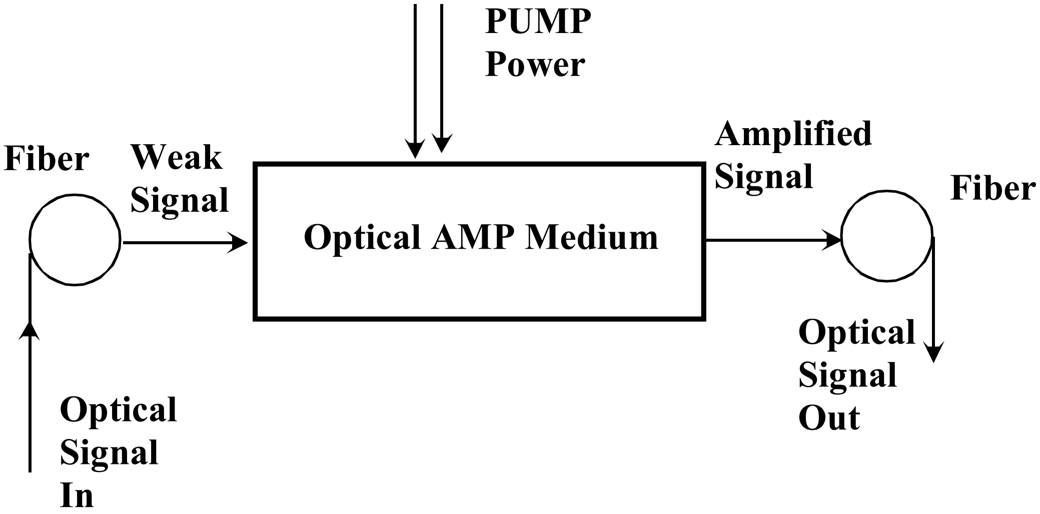
- Although functional this arrangement is limited by the optical to electrical and electrical to optical conversions.



- Several types of *optical amplifiers* have since been demonstrated to replace the OE – electronic regeneration systems.
- These systems eliminate the need for E-O and O-E conversions.
- This is one of the main reasons for the success of today’s optical communications systems.

OPTICAL AMPLIFIERS

The general form of an optical amplifier:



Some types of OAs that have been demonstrated include:

- *Semiconductor optical amplifiers* (SOAs)
- *Fiber Raman and Brillouin* amplifiers
- *Rare earth doped fiber amplifiers* (erbium – EDFA 1500 nm, praseodymium – PDFA 1300 nm)

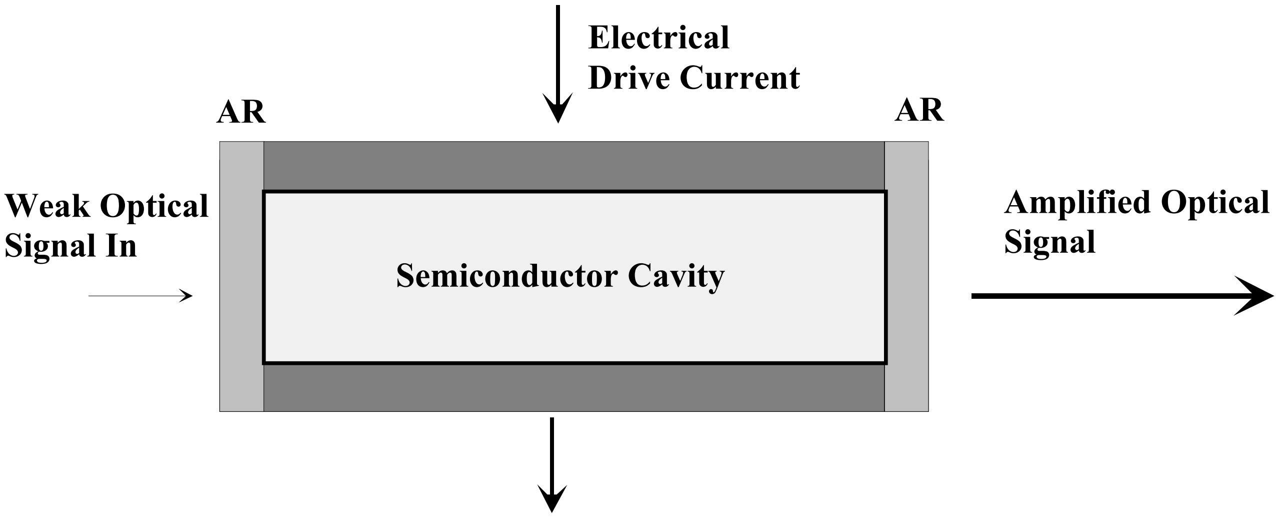
The most practical optical amplifiers to date include the SOA and EDFA types. New pumping methods and materials are also improving the performance of Raman amplifiers.

<u>Characteristics of SOA types:</u>

- Polarization dependent – require polarization maintaining fiber
- Relatively high gain ~20 dB
- Output saturation power 5-10 dBm
- Large BW
- Can operate at 800, 1300, and 1500 nm wavelength regions.
- Compact and easily integrated with other devices
- Can be integrated into arrays
- High *noise figure* and cross-talk levels due to *nonlinear phenomenon* such as 4-wave mixing.

This last feature restricts the use of SOAs.

- *Semiconductor Optical Amplifier* (SOA) – similar to a laser cavity. Used as a discrete amplifiers. They can be integrated into arrays of amplifying switching and gating devices. Finding application in all optical 3R-regeneration systems.



- Limited in operation below 10 Gb/s. (Higher rates are possible with lower gain.)

Rare Earth Doped Fiber Amplifier Characteristics:

Rare earth doped fiber amplifiers are finding increasing importance in optical communications systems. Perhaps the most important version is erbium doped fiber amplifiers (EDFAs) due to their ability to amplify signals at the low loss 1.55 μm wavelength range.

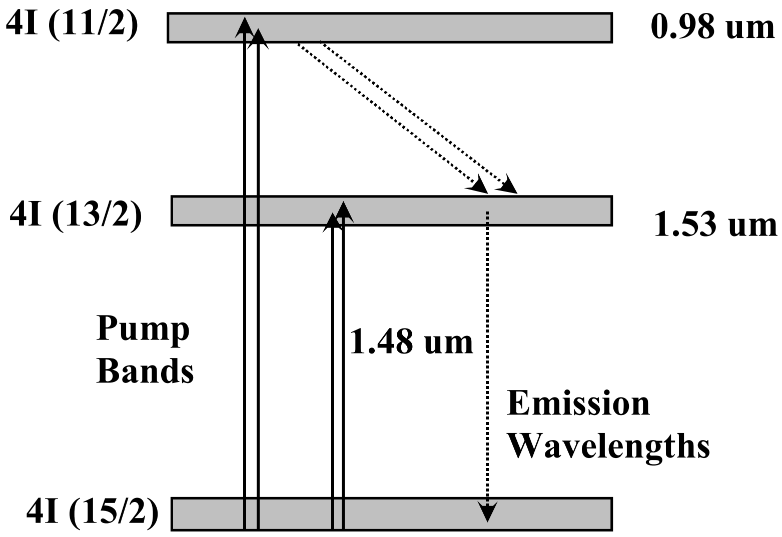
Characteristics of EDFAs (advantages):

- High power transfer efficiency from pump to signal power (> 50%).
- Wide spectral band amplification with relative flat gain (>20 dB) – useful for WDM applications.
- Saturation output > 1 mW (10 to 25 dBm).
- Gain-time constant long (>100 msec) to overcome patterning effects and inter-modulation distortions (low noise).
- Large dynamic range.
- Low noise figure.
- *Polarization independent*.
- Suitable for long-haul applications.

Disadvantages of EDFAs:

- Relatively large devices (km lengths of fiber) – not easily integrated with other devices.
- ASE – *amplified spontaneous emission*. There is always some output even with no signal input due to some excitation of ions in the fiber – *spontaneous noise*.
- Cross-talk effects.
- Gain saturation effects.

- An energy level diagram for Er doped silica is shown below.



- *Pumping* is primarily done *optically* with the primary *pump wavelengths* at 1.48 μm and 0.98 μm. As indicated atoms pumped to the 4I (11/2) 0.98 μm band decays to the primary emission transition band. Pumping with 1.48 μm light is directly to the upper transition levels of the emission band.

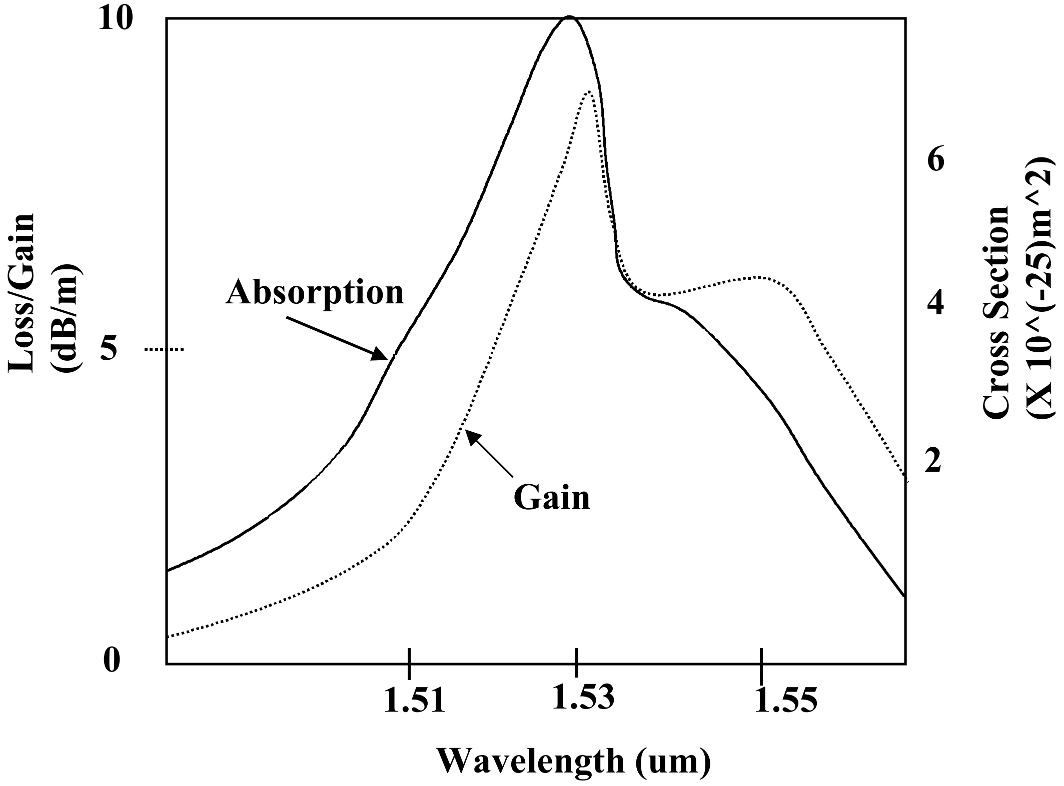
- Semiconductor lasers have been developed for both pump wavelengths.

- 10-20 mW of absorbed pump power at these wavelengths can produce 30-40 dB of amplifier gain.

- *Pump Efficiencies* of 11 dB/mW achieved at 980 nm.

- Pumping can also be performed at 820 and 670 nm with GaAlAs laser diodes. Pump efficiencies are lower but these lasers can be made with high output power.

Typical Absorption/Gain Spectrum for Erbium Doped Fiber:



- Since the gain spectrum of erbium resembles a 3-level atom it is possible to model the gain properties using this approach.

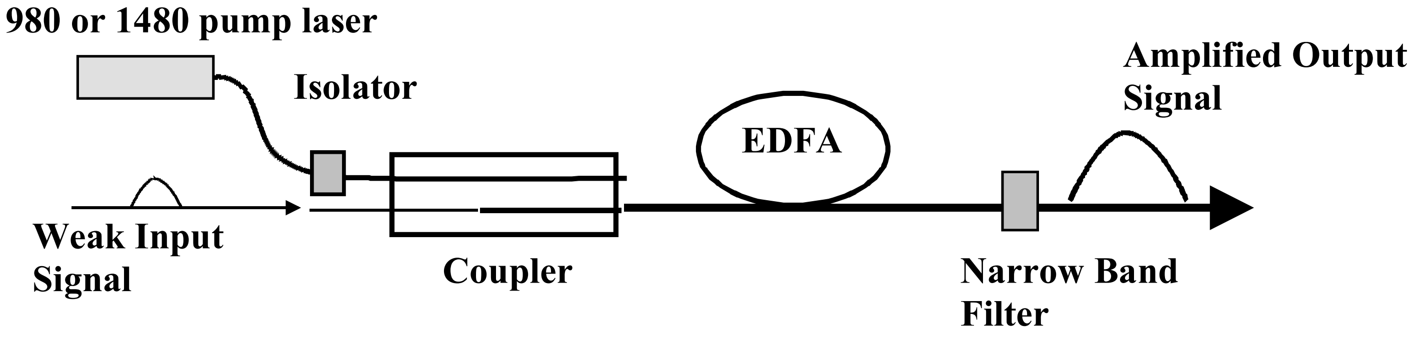
- Several different *wavelength bands* have been designated for wavelength division multiplexing and EDFAs have been designed to operate in these bands.

- The divisions have been designated as[*]:

S-Band 1480-1520 nm
C-Band 1521-1560 nm
L-Band 1561-1620 nm

(* Note some variability in these values is common.)

General EDFA Amplifier Configuration:



Basic Amplifier Characteristics

Optical Gain

- Rare earth doped optical amplifiers work much like a laser.
- The primary difference is that they do not have a resonator.
- Amplification occurs primarily through the *stimulated emission* process.
- The medium is pumped until a *population inversion* state is achieved. Pump powers are typically several 20-250 mW. An isolator is used to reduce reflections at the input to the amplifier. A narrow band optical filter is used to reduce transmission of amplified spontaneous emission frequency components.
- The resultant *optical gain* depends both on the optical frequency and the local beam intensity within the amplifier section.
- For basic discussion consider a *two-level homogeneously broadened* medium.

- The gain coefficient can be expressed as:

$$g(\omega) = \frac{g_o}{1 + (\omega - \omega_o)^2 T_2^2 + P / P_s},$$

g_o is the peak gain, ω is the optical frequency of the incident signal,

ω_o is the transition frequency, P is the optical power of the incident signal,

T_2 is the *dipole relaxation time*, and P_s is the *saturation power*.

- Typically T_2 is small < 1 ps, and the saturation power P_s depends on *gain medium* parameters such as the *fluorescence time* and the *transition cross section.*

Gain Spectrum and BW:

- When not saturated (i.e. $P/P_s \ll 1$) the *gain coefficient g(ω)* becomes:

$$g(\omega) = \frac{g_o}{1 + (\omega - \omega_o)^2 T_2^2} .$$

- *Gain is maximum* when $\omega = \omega_o$ (i.e. the gain coefficient is at resonance).

- At non-resonant frequencies the gain follows the *homogeneously broadened* characteristics of a *two level atom* (i.e. Lorentzian profile).

- The *gain BW* for this spectrum is typically expressed as the (Full Width at Half Maximum) FWHM

$$\Delta\omega_g = 2/T_2 .$$

$$\Delta\nu_g = \frac{\Delta\omega_g}{2\pi}$$

with $T_2 \simeq 0.1ps$

$$\Delta\nu_g \simeq 3THz$$

- *Large Spectral BW amplifiers* are preferred for fiber optic systems to make them less sensitive to dispersed transmitted signals and useful for WDM systems.

EDFA Gain Spectrum:

- The gain spectrum of erbium ions alone is *homogeneously broadened* and the BW is determined by the *dipole relaxation time* T_2.

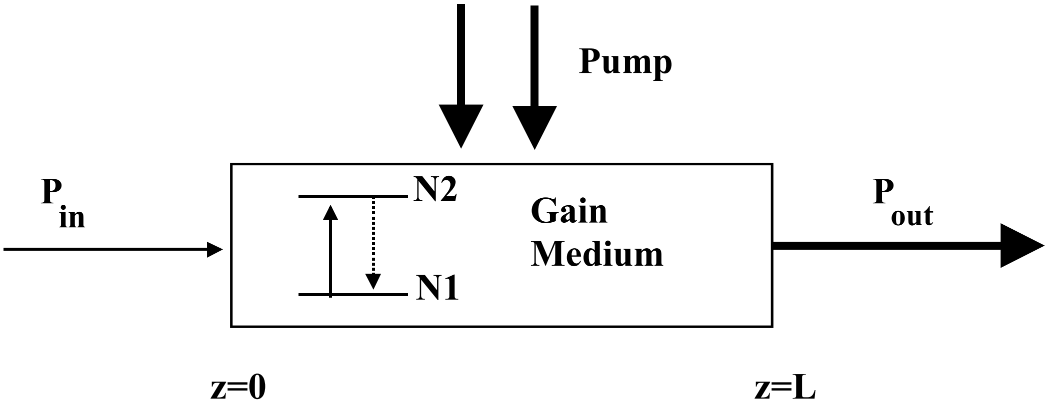
- However when placed in a *glass host* the spectrum is influenced both by the *silica* and any other *dopants*. This can result in *inhomogeneous broadening* contributions.
- The combined *homogeneous and inhomogeneous BW* of EDFAs: ~ 30 nm.

Amplification factor:

- Define as:

$$G = P_{out}/P_{in}$$

P_{out} is the *amplifier output power* and P_{in} the *input power* of a CW input signal.



- From the previous discussion of the laser the gain in optical power per length of gain medium *(z)* with gain *g* is

$$\frac{dP}{dz} = gP\,.$$

- Integrating over a length *z* of amplifier medium gives the resultant optical power

$$P(z) = P(0)\exp(gz)\,.$$

The amplification factor after a length L of OAM (optical amplifier medium) is

$$G(\omega) = \exp[g(\omega)L]$$

Both $g(\omega)$ and $G(\omega)$ are a maximum when the frequency is at resonance $\omega = \omega_o$ and decrease when the frequency is detuned from resonance.

However the *amplifier factor(G)* decreases much faster than the *gain coefficient(g)*.

- The *amplifier BW* $\Delta\nu_A$ is defined as the *FWHM of $G(\omega)$*

$$\Delta\nu_A = \Delta\nu_g \left(\frac{\ln 2}{\ln(G_o / 2)} \right)^{0.5}$$

where $\Delta\nu_g$ is the gain BW, and $G_o = \exp(g_oL)$.

- The *amplifier BW* is smaller than the *gain BW*. The difference depends on the *amplifier gain* characteristics.

If $G_o = 10$, $\Delta\nu_A = 0.656\Delta\nu_g$

Gain Saturation:

- Since $g(\omega)$ depends on the incident optical power when $P \approx P_S$, <u>*G will start to decrease with an increase in optical power P.*</u>

- Assume that the incident frequency is tuned for peak gain ($\omega = \omega_o$)

$$\frac{dP}{dz} = \frac{g_o P}{1 + P/P_s}\,.$$

- With the conditions $P(0) = P_{inc}$ and $P(L) = P_{out} = GP_{inc}$ **the *large signal amplifier gain*** becomes

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

- This expression shows how the amplifier gain decreases when $P_{out} \approx P_s$.

Output saturation power ≡ *the optical power at which G is reduced to $G_o/2$ (3 dB)*

$$P_{sat}^{out} = \frac{G_o \ln 2}{G_o - 2} P_s\,.$$

- Typically $G_o = 1000$ (30 dB),

$$\therefore\ P_{out}^{s} \approx (\ln 2) P_s \approx 0.69 P_s\,.$$

Amplifier Noise:

- *Spontaneous emission* in the amplifier will *degrade the SNR* by adding to the noise during the amplification process.

- SNR degradation is quantified through the *amplifier noise figure F_n*

$$F_n = \frac{(SNR)_{in}}{(SNR)_{out}}$$

where the SNR is based on the electrical power after converting the optical signal to an electrical current. Therefore F_n is referenced to the detection process and depends on parameters such as detector bandwidth (B_e) and thermal and shot noise.

- Consider a simple case with an ideal detector with performance limited by *shot noise.*

- The amplifier has an *amplification factor G* ($P_{out} = G\,P_{in}$).

- SNR of the input signal:

$$SNR_{in} = \frac{\langle I\rangle^2}{\sigma_s^2} = \frac{(RP_{in})^2}{2q(RP_{in})B_e} = \frac{P_{in}}{2h\nu B_e},$$

$$\sigma_s^2 = 2q(RP_{in})B_e\,.$$

- The spontaneous emission contribution is amplified along with the signal. The *Spectral density* of the *spontaneous emission induced noise* is nearly constant (white noise) and can be expressed as:

$$S_{sp}(\nu) = (G-1)n_{sp}h\nu$$

- *Spontaneous emission population inversion factor n_{sp} is given by:*

$$n_{sp} = \frac{N_2}{N_2 - N_1}\,.$$

N_2 and N_1 are the population densities for the excited and ground states of the amplifying medium.

- Alternatively can express the *spontaneous emission power* within the receiver bandwidth B_e as:

$$P_{sp} = 2S_{sp}B_e$$

- *Spontaneous emission* adds *fluctuations to the amplified power* and is converted to *current fluctuations* at the *detector output*.

- Major contribution to receiver noise results from coherent interference (beating) between the spontaneous emission with the signal. This results in a noise current given by

$$\Delta I = 2R(GP_{in}P_{sp})^{1/2}\cos\theta$$

- The variance in the photocurrent after the signal is passed through the amplifier is

$$\sigma^2 \approx 4(RGP_{in})\cdot\left(RS_{sp}\right)B_e$$

where $\cos^2\theta$ is replaced with its average value of ½. (Note that this relation assumes several idealizations on the detection process i.e. other noise sources are negligible.)

- The SNR of the amplified signal becomes

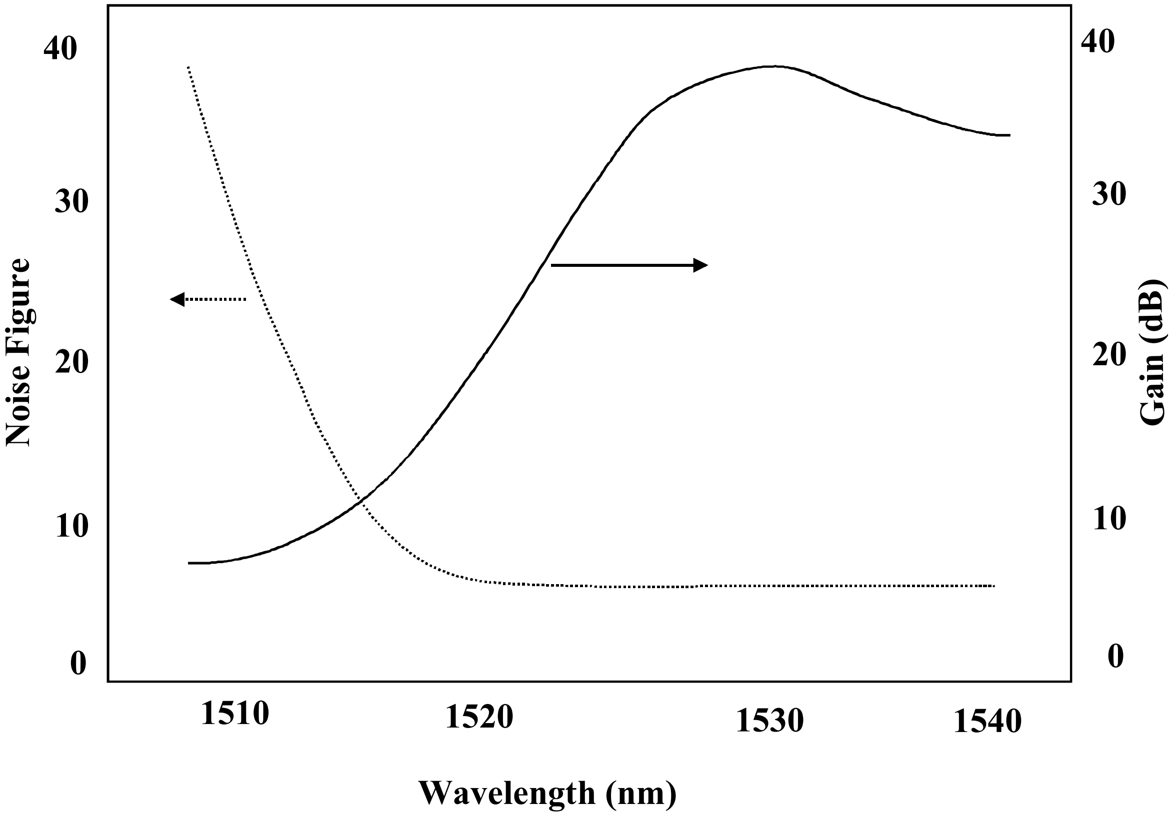
$$SNR_{out} = \frac{\left(RGP_{in}\right)^2}{\sigma^2} \approx \frac{GP_{in}}{4S_{sp}B_e}$$

and the amplifier noise figure is

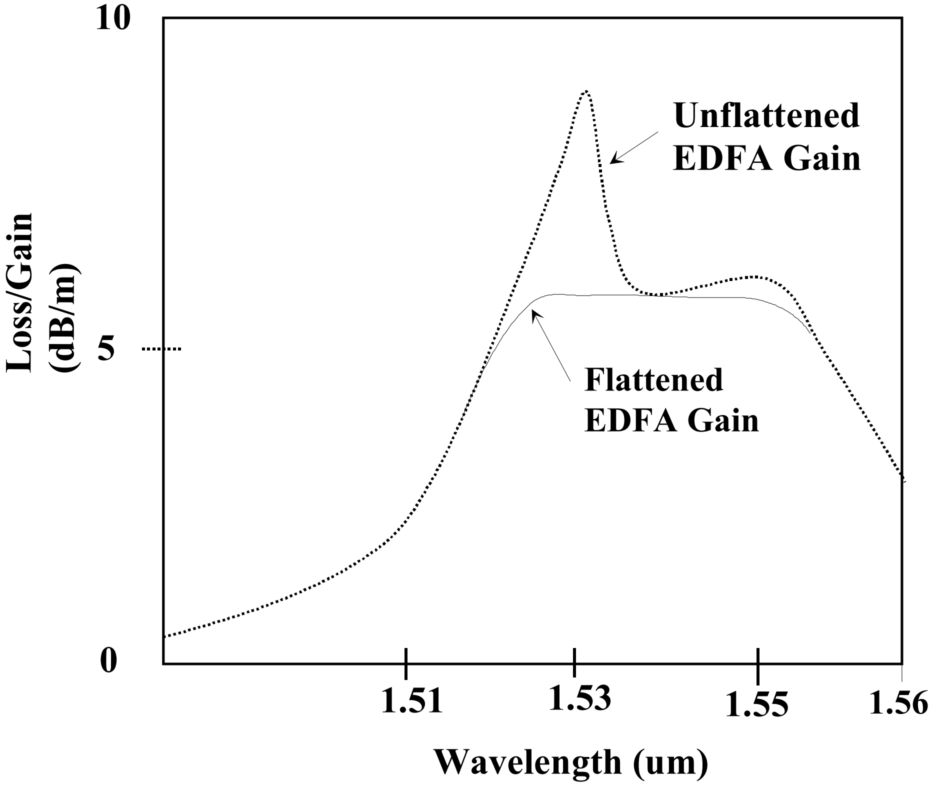
$$F_n = 2n_{sp}\left(G-1\right)/G \approx 2n_{sp}\,.$$

- For most amplifiers $F_n > 3$ dB and can be 6-8 dB.

- Characteristic plot of gain and noise figure for an erbium doped fiber amplifier pumped ~30 mW at 980 nm.



EDFA Gain Equalization



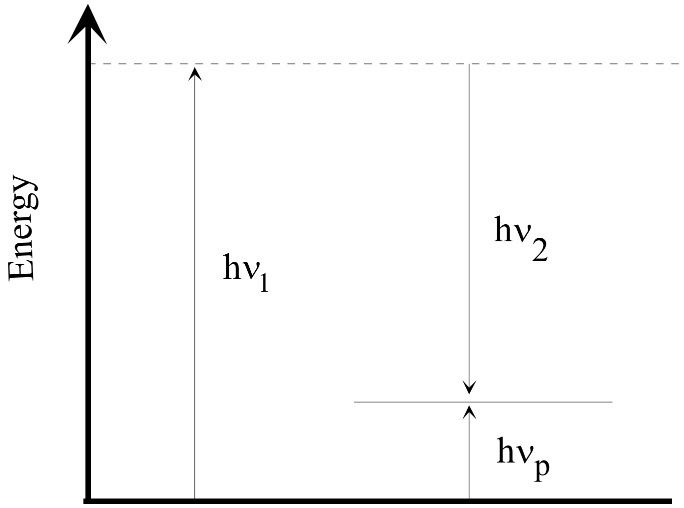
- Gain equalization can be accomplished in several ways:
    a. Thin film filters
    b. Long period fiber gratings
    c. Chirped fiber Bragg gratings

Raman Scattering, Stimulated Raman Scattering, and Raman Amplifiers:

- Raman scattering is an *elastic scattering mechanism*. Does not require a population inversion.

- A photon with energy $h\nu_1$ traveling through a material can excite a *vibrational transition* of the material forming an *optical phonon* with energy $h\nu_p$ and a photon with slightly reduced energy $h\nu_2$ given by

$$\nu_2 = \nu_1 - \nu_p$$



- Molecule is raised to a new *vibrational state* and the energy of the photon is reduced.

- There is a large difference between the photon and phonon energies.

- Raman scattering is *weak effect*. It occurs through a slight modulation of the refractive index through molecular vibrations of the material.

- Can derive the effect through a discussion of polarizability of a material.

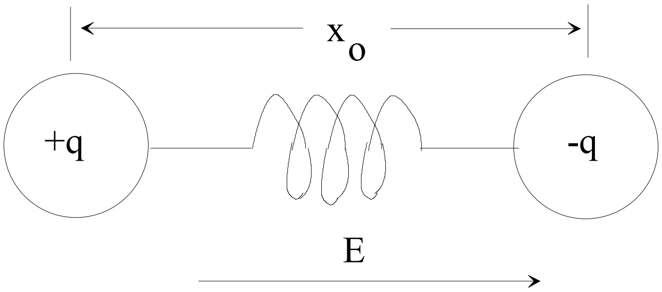
- The electric field induces a *dipole moment of the molecule*

$$p = qx$$

or

$$p = \alpha E$$

where α is the complex polarizability of the molecule.



- The *bulk polarizability* of a material is expressed as

$$P = \varepsilon_o \chi^{(1)} E$$

with $\chi^{(1)}$ the linear susceptibility of the material.

- Response of α to an incident *harmonic electric field*:

$$\alpha(x) = \alpha_o + \left.\frac{\partial \alpha}{\partial x}\right|_{x_o} \delta x$$

δx is the displacement from the *equilibrium molecular length* x_o

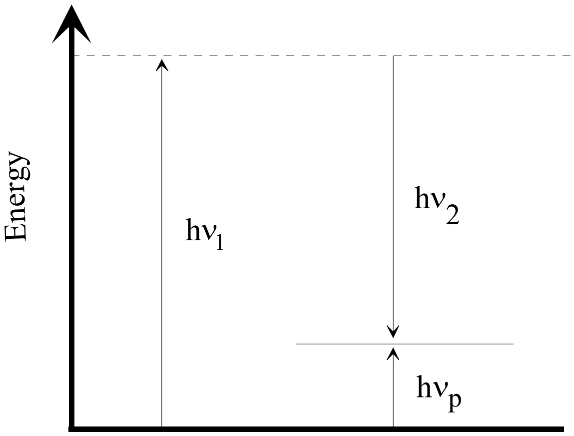
$$\delta x(t) = \delta x_o e^{\pm j\omega_p t}$$

$$
\begin{aligned}
p(t) &= \alpha(t)E(t) \\
\therefore \qquad &= \left(\alpha_o + \left.\frac{\partial \alpha}{\partial x}\right|_{x_o} \delta x_o e^{\pm j\omega_p t} \right) E_o e^{j\omega_1 t} \\
&= \alpha_o E_o e^{j\omega_1 t} + \left.\frac{\partial \alpha}{\partial x}\right|_{x_o} \delta x_o E_o e^{j(\omega_1 \pm \omega_p)t}
\end{aligned}
$$

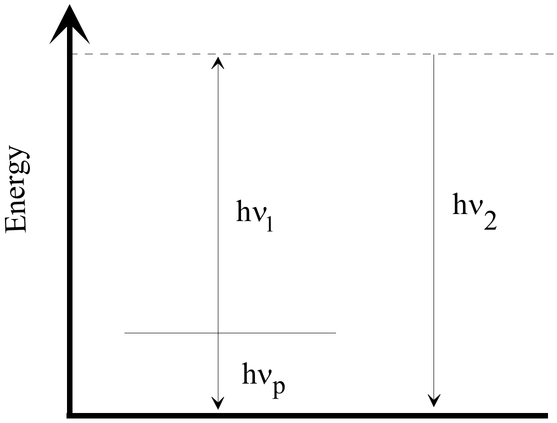
- There are two frequency components: a) ω_1 ; b) $\omega_1 \pm \omega_p$

- The second component is *nonlinear* → the output frequency is different from the input frequency.

Stokes



Anti-Stokes



- Scattered light with lower energy ($\nu_2 < \nu_1$) → *Stokes Scattering*.

- Scattered light with higher energy ($\nu_2 > \nu_1$) → *Anti-Stokes Scattering*.

- Stokes scattering typically dominates due to greater population of the ground state relative to the vibrational state when the system is in thermal equilibrium.

- At *low illumination levels* the Raman process results in low scattering levels.

- The molecules contributing to the process are vibrating independently and the scattered light is non-directional. *Spontaneous Raman Scattering.*

- At *higher intensity levels* the generated photons begin to act *in phase* or *coherently* – i.e. the molecules oscillate as an array of vibrating oscillators. This gives rise to *Stimulated Raman Scattering (SRS).*

- *SRS* can be can be a problem but it can also be used as a signal amplification process.

- On the negative side it contributes to *dispersion* and places an *operational limit on the amount of power* that can be transmitted through a fiber.

- The Stokes wave is amplified as it propagates through the medium

$$\frac{dI_2}{dz} = G_r I_2 I_1$$

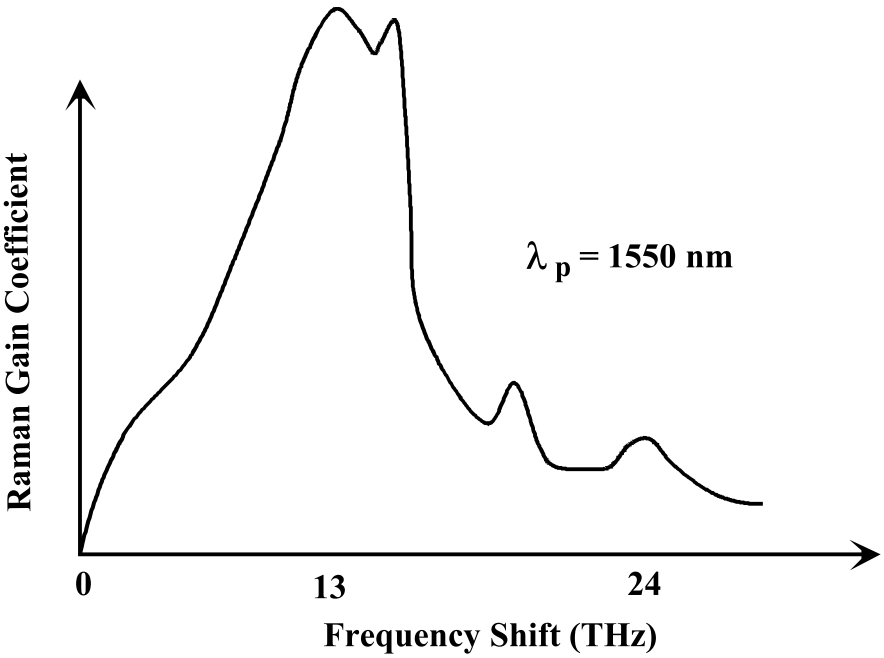
I_2 is the intensity of the *Stokes shifted light* $(\omega_s = \omega_1 - \omega_{vib})$; I_1 is the intensity of the *pump beam* (ω_1); and G_r is the *Raman gain* term that includes material factors such as $\partial\alpha/\partial x$ and varies as $1/\lambda^2$.

  - For $I_2 << I_1$ and cases where the pump beam is not significantly depleted:

$$I_2(z) = I_2(0)e^{G_r \cdot I_1 \cdot z}$$

<u>Properties of Raman Amplifiers:</u>

- The peak resonance in silica fibers occurs about 13 THz from the pump wavelength. At 1550 nm this corresponds to a shift of about 100 nm.



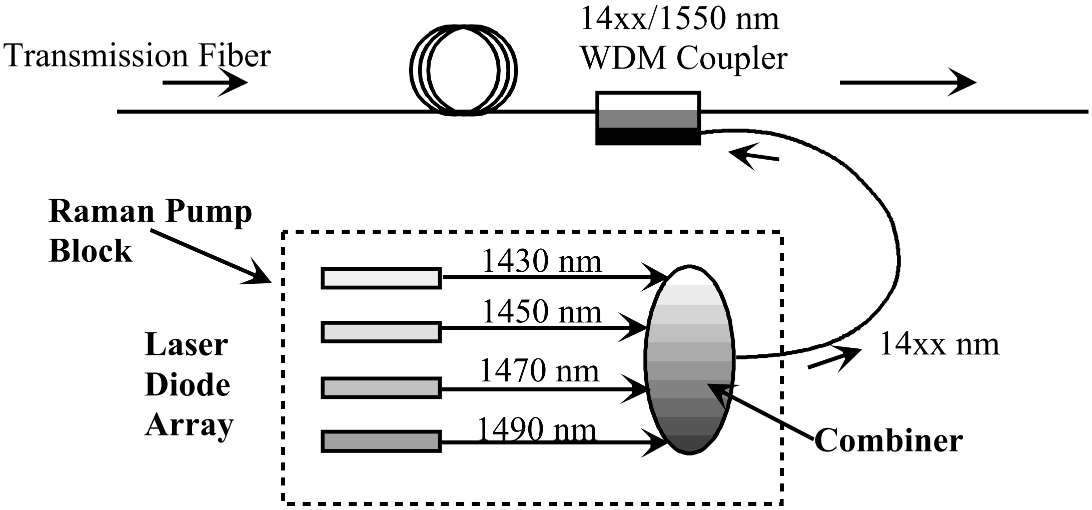
- As indicated power is transferred from shorter wavelengths to longer wavelengths.

- Coupling with the pump wavelength can be accomplished either in the forward or counter propagating direction.

- Power is coupled from the pump only if the signal channel is sending a 1 bit.

Pump Arrangement to Extend the Range for Stimulated Raman Amplification:

- An array of laser diodes can be used to provide the Raman pump. The beams are combined and then coupled to the transmission fiber. The pump beams can counter propagate to the direction of the signal beams.



Difficulties with Raman Amplifiers:

- The Pump and amplified signals are at *different wavelengths*. Therefore the signal and the pump pulses will separate due to dispersion *(waveguide dispersion)* after a certain propagation distance. The difference in *propagation time* is given by:

$$\delta\tau = \left(L/c\right)\lambda^2 d^2 n / d\lambda^2 \left(\delta\nu/\nu\right)$$

L is the fiber length.

- A 1 psec pump pulse at 600 nm separates from a 1 psec Stokes pulse in ~ 30 cm.
- A *second problem* is that the *pump power decreases* along the fiber length due to linear absorption and scattering – Raman gain is greater at the input end.
- A final problem results from *amplifying spontaneous Raman photons*. This occurs when the pump power is increased to offset attenuation losses and spontaneous Raman photons are coupled into the guided mode all along the length of the fiber. This increases noise.
- Upper limit on the power into a communications signal from SRS amplification can be defined as the *point at which the Stokes power P_r equals the signal power P_{sig}.*

$$P = \frac{16\pi w_o^2}{G_r L_{eff}}$$

$$\underline{L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}}$$

Example:

$$\lambda_p = 1.55\mu m$$

$$w_o \approx 5\mu m \rightarrow A_{\mathrm{mode}} \approx 80\mu m^2$$

$$\alpha_{linear} \approx 0.2dB/km \rightarrow L_{eff} \approx 20km \rightarrow \underline{\textbf{700 mW}}$$

$$G_r = 9\times10^{-12} m/W$$

QUITE LARGE compared to normal optical signal powers (~1 mW).