Optical Amps-Raman and Erbium Doped Fiber Amplifiers EDFAs pp. 244-260

- Equations for Raman gain characteristics
- EDFA equations and descriptions
Raman amplifier gain equations

\[ g(\omega) = g_R(\omega)(P_p / a_p) \]

\( g_R \) is called the Raman gain coefficient (units of m/W). 
\( P_p \) is the pump power. \( g(\omega) \) is the gain coefficient (units of cm\(^{-1}\)). \( a_p \) is the cross-sectional area of the pump beam in the fiber.

Here are some typical numbers for the Raman amp:
\( g_R = 6 \times 10^{-14} \) m/W at the gain peak of 1.55 micron.
For \( G = 30 \) dB, we must have \( gL \) of about 6.9
If we have a 1 km fiber (yes, this is long!) and \( a_p = 50 \) µm\(^2\), then the pump power is 5.75 W. For longer than 1 km, we might have to take into account fiber losses.

\[ \frac{dP_s}{dz} = -\alpha_s P_s + \left( \frac{g_R}{a_p} \right) P_p P_s \]

\[ \frac{dP_p}{dz} = -\alpha_p P_p - \left( \frac{\omega_p}{\omega_s} \right) \left( \frac{g_R}{a_p} \right) P_s P_p \]
Raman amplifier characteristics

For now, ignore depletion of the pump beam down the fiber, but do include fiber losses, i.e., \( P_p(z) = P_p(0)\exp(-\alpha_p z) \) in (6.3.2) one obtains:

\[
P_S(L) = P_S(0)\exp\left(\frac{g_R P_0 L_{eff}}{a_p} - \alpha_s L\right)
\]

\[
L_{eff} = \left[1 - \exp(-\alpha_p L)\right]/\alpha_p
\]

An effective length over which the fiber losses operate

\[
G_A = \frac{P_S(L)}{P_S(0)\exp(-\alpha_s L)} = \exp(g_0 L)
\]

The denominator is the signal out in the absence of Raman gain

\[
g_0 = g_R \left(\frac{P_0}{a_p}\right)\left(\frac{L_{eff}}{L}\right) \approx \frac{g_R P_0}{a_p \alpha_p L}
\]

This equation is valid for when \( \alpha_p L >> 1 \). In which case \( L_{eff} = 1/\alpha_p \)
A simplified schematic illustration of an EDFA (optical amplifier). The erbium-ion doped fiber is pumped by feeding the light from a laser pump diode, through a coupler, into the erbium ion doped fiber.

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The gain coefficient will depend on inhomogeneous and homogeneous broadening. The point to get across is that the gain spectrum is considerably broadened (inhomogeneously) by the host silica material which is amorphous. Only short range order in the material structure.

Note the double peak in the gain spectrum. 980 nm is the more efficient pumping scheme, although 1480 nm is also used. Each energy level is not discrete, but broadened into bands.

\[ g_{\text{eff}}(\omega) = \int g(\omega, \omega_0)f(\omega_0)d\omega_0 \]
EDFA quick facts

- The Er$^{3+}$ ion is implanted in the host glass material at a level of about 500 ppm.
- The host fiber core is usually based on silica-germania. The silica core is also sometimes doped with alumina.
- The $4I_{11/2}$ levels decay very rapidly and the $4I_{13/2}$ levels are long-lived, on the order of 10 ms.
- The gain is not flat across the 1525-1565 nm spectrum.
- The gain efficiency is typically 8-10 dB/mW at 980 nm pumping.
- Typical length of an EDFA is 10-20 meters.
Amplifier gain equation in EDFAs

\[ G = \Gamma_s \exp \left[ \int_0^L \left( \sigma_s^e N_2 - \sigma_s^a N_1 \right) dz \right] \]

\[ N_1 = N_t - N_2 \]

\( N_t \) is the total ion density. \( N_1 + N_2 = N_t \)

\( \Gamma_s \) is the optical confinement factor in that the doped core region is the only place where the gain is although the optical mode of the signal wavelength covers a much bigger cross-section. The sigma’s are the emission and absorption cross sections.
Optimizing pump power and amplifier length in EDFAs
Optimizing noise figure and gain with amplifier length in EDFAs
Gain flattening in EDFAs

What is the long period grating filter for? How is it designed? Why is the second stage pumped with 1480 nm?
More gain flattening in EDFAs

Why is the second stage pumped at 1480 nm?
## Current Optical Amplifier Technologies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Raman</th>
<th>EDFA</th>
<th>SOA Quantum Well</th>
<th>SOA Linear Quantum Well</th>
<th>SOA Quantum Dot</th>
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<tr>
<td>Size comparison xSOA</td>
<td>200x</td>
<td>100x</td>
<td>1x</td>
<td>1x</td>
<td>1x</td>
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<tr>
<td>Crosstalk Free single channel up to 10 Gb/s + (pattern effect)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes (if linearized)</td>
</tr>
<tr>
<td>Crosstalk free inter channel</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes (if linearized)</td>
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<tr>
<td>Broad spectrum</td>
<td>Yes</td>
<td>No (30 nm)</td>
<td>Yes 50 nm</td>
<td>Yes 50 nm</td>
<td>Yes Potential for 100 nm +</td>
</tr>
<tr>
<td>Integratable on a single chip?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Temperature insensitivity?</td>
<td>No (cooled pumps)</td>
<td>No (cooled pumps)</td>
<td>No (TEC required)</td>
<td>No (TEC required)</td>
<td>Yes (Potential for un-cooled operation)</td>
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<tr>
<td>Low Noise Figure</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes – Potential to match EDFA</td>
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<td>Polarization Independence</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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Courtesy of Tom Tumillo, Zia Laser, Inc.