Lecture 9: Optical Amplifiers

Fiber Based Optical Amplifiers

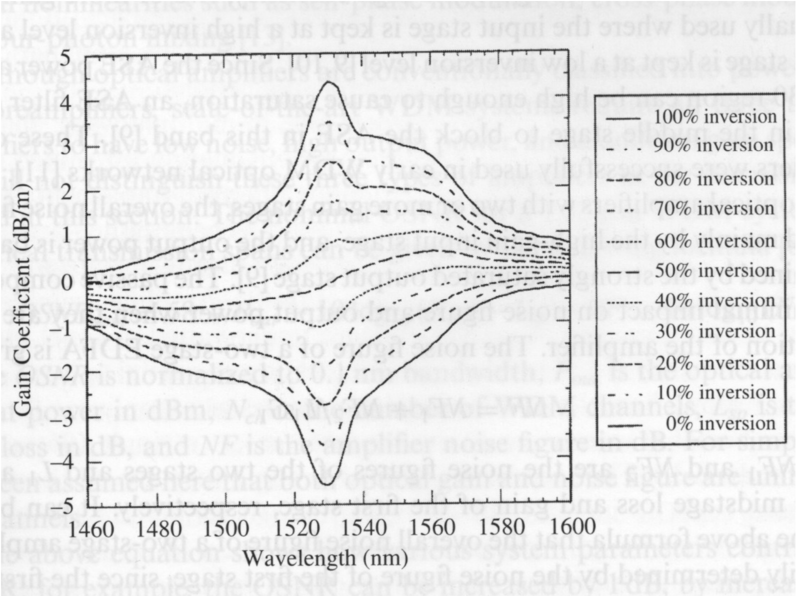
- Last lecture we reviewed the different amplifier technologies and basics of optical amplification. We also look in some detail at the EDFA amplifier.
- In this lecture we are going to look at some more details of the EDFA, specifically pump inversion, amplifier noise, gain flatness, transient behavior.
- We are then going to study a different class of fiber based optical amplifier, the Raman Fiber Amplifier.

EDFA Pump Inversion

- The inversion level at any point (z) in the fiber amplifier is defined as
  - $N_2/(N_1 + N_2)$
- We also define the average inversion level

$$\overline{N_2(t)} = \frac{1}{l}\int_0^l N_2(z,t)dz$$

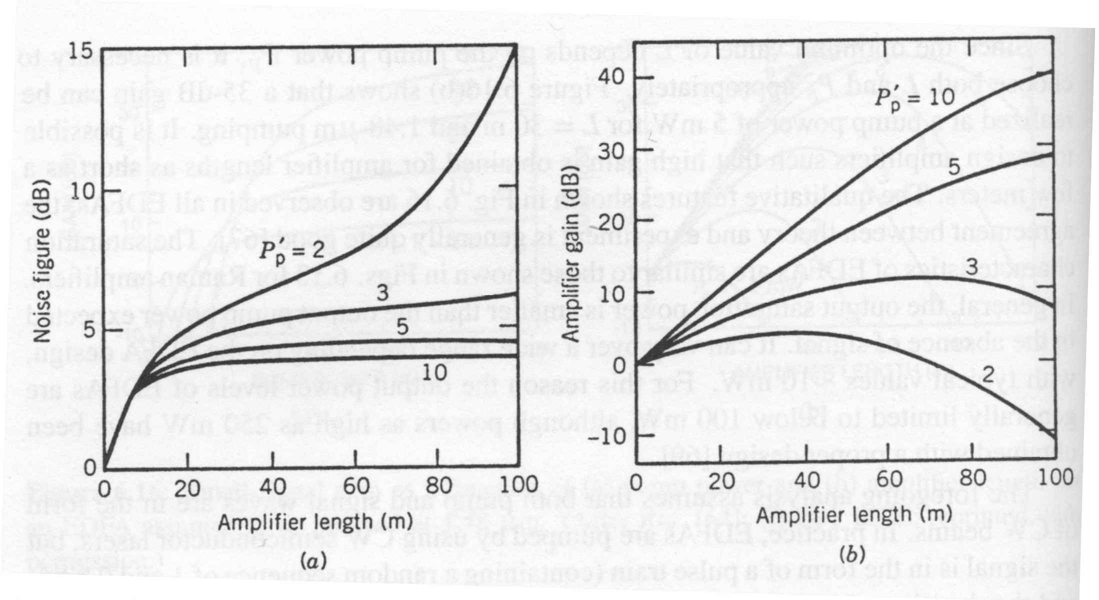
- The figure below shows the EDFA gain coefficient as a function of wavelength for different levels of inversion. If we assume the EDFA gain is homogeneously broadened, the gain of any section of the EDFA (along z) can be assumed to have the characteristics below.
- There are three limits of interest
  - When N_2 is maximum: gain is highest
  - When $P_s \approx P_p$ the EDFA is saturated and level of inversion is reduced
  - In the limit of low pump and low T, the average inversion level goes to zero.



I. Kaminow, Opt. Fiber Telecom. IVA, pp. 177

EDFA Noise Figure

- The spontaneous emission factor is a function of P_p and therefore is a function of (z). We can average n_{sp} over the amplifier length.
- Therefore the noise figure and gain (as seen before) depend on both the amplifier length and pump power.
- Below we see the variation in noise figure as gain and length are varied as a function of $P'_p = P_p / P_p^{sat}$.
- Low noise figure (close to 3dB) can be achieved for high gain and $P_p \gg P_p^{sat.}$



G. Agrawal, Fiber
Opt. Comm Sys.,
pp. 256

EDFA Gain Flatness

- We have looked at wide-band EDFAs by employing multi-stage architectures.
- The gain as a function of wavelength must be kept flat (we call this gain tilt) to better than 1dB if amplifiers are to be cascaded.
- Inserting a filter (e.g. long-period fiber grating filter) in between the two stages is shown at right.

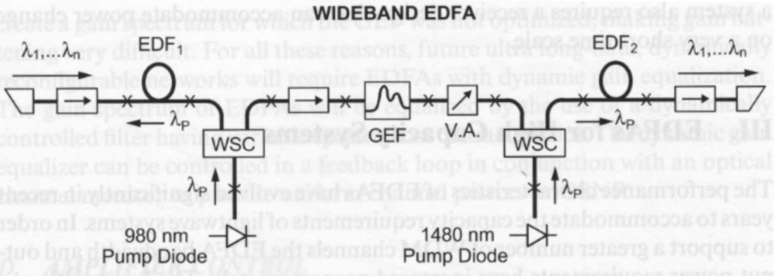


Fig. 4 A two-stage EDFA design with a midstage pumping configuration.

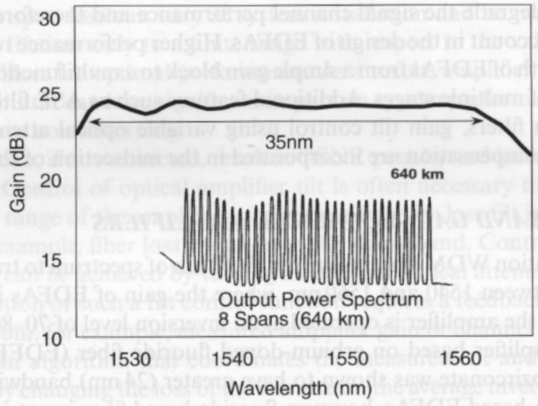


Fig. 5 Gain spectrum from the EDFA of Fig. 3. The gain is flattened with a long-period fiber grating equalization filter. The inset shows the channel power spectrum after transmission through 8 × 80 km spans and 8 EDFAs.

I. Kaminow, Opt. Fiber Telecom. IVA, pp. 184

EDFA Gain Flatness

- The variable attenuator shown in the previous 2-stage configuration is used to adjust the average inversion level of the doped fiber.
- This has the effect of controlling the gain flatness which can change due to variations in
  - Span loss
  - EDFA gain tilt
  - Spectral loss in transmission fiber
  - Dispersion compensation
  - Frequency dependent passive components
  - Nonlinear fiber effects
- To right shows effect of change in span loss
- This can be compensated for using the VA
- Tradeoff is now in noise figure!

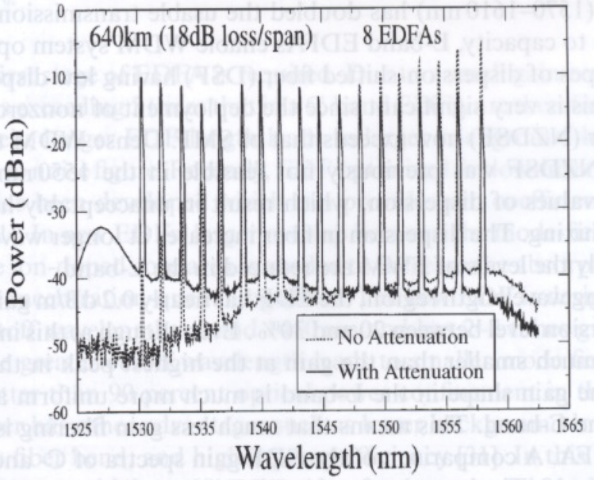


Fig. 8 Spectrum variation as the span loss changes from 24 to 6 dB.

I. Kaminow, Opt. Fiber Telecom. IVA, pp. 187

Spectral Hole Burning in EDFAs

- While the EDFA gain saturation is predominately homogeneously broadened (i.e affects all wavelengths with saturation at any particular wavelength), there is a component of gain saturation that is inhomogeneously broadened (i.e. saturation at one wavelength affects gain for only a limited number of nearby wavelengths).
- A spectral hole of approximately 8nm can be burned at a depth of .027dB per 1dB gain compression. This factor is extremely wavelength dependent (e.g. 4 times larger at 1552nm than at 1551nm).
- Must be considered in long haul transmission systems where gain in neighboring channels within the spectral hole can be affected.
- Systems should be characterized with fully loaded channels at locations within the spectral hole.

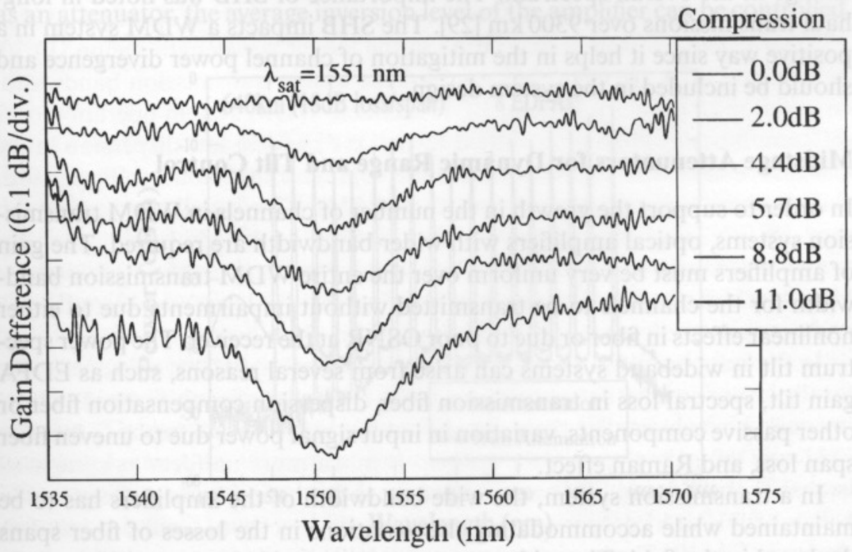
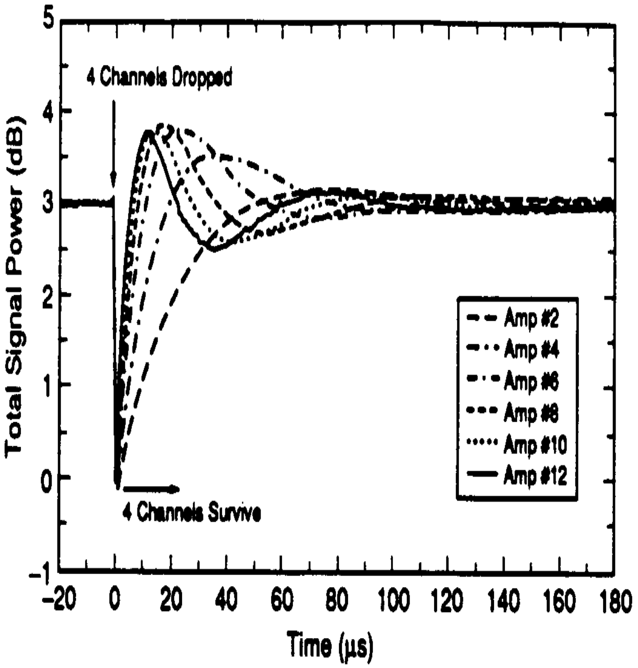


Fig. 6 SHB for different saturation levels [27].

I. Kaminow, Opt. Fiber Telecom. IVA, pp. 187

Gain Dynamics in Optically Amplified WDM Networks



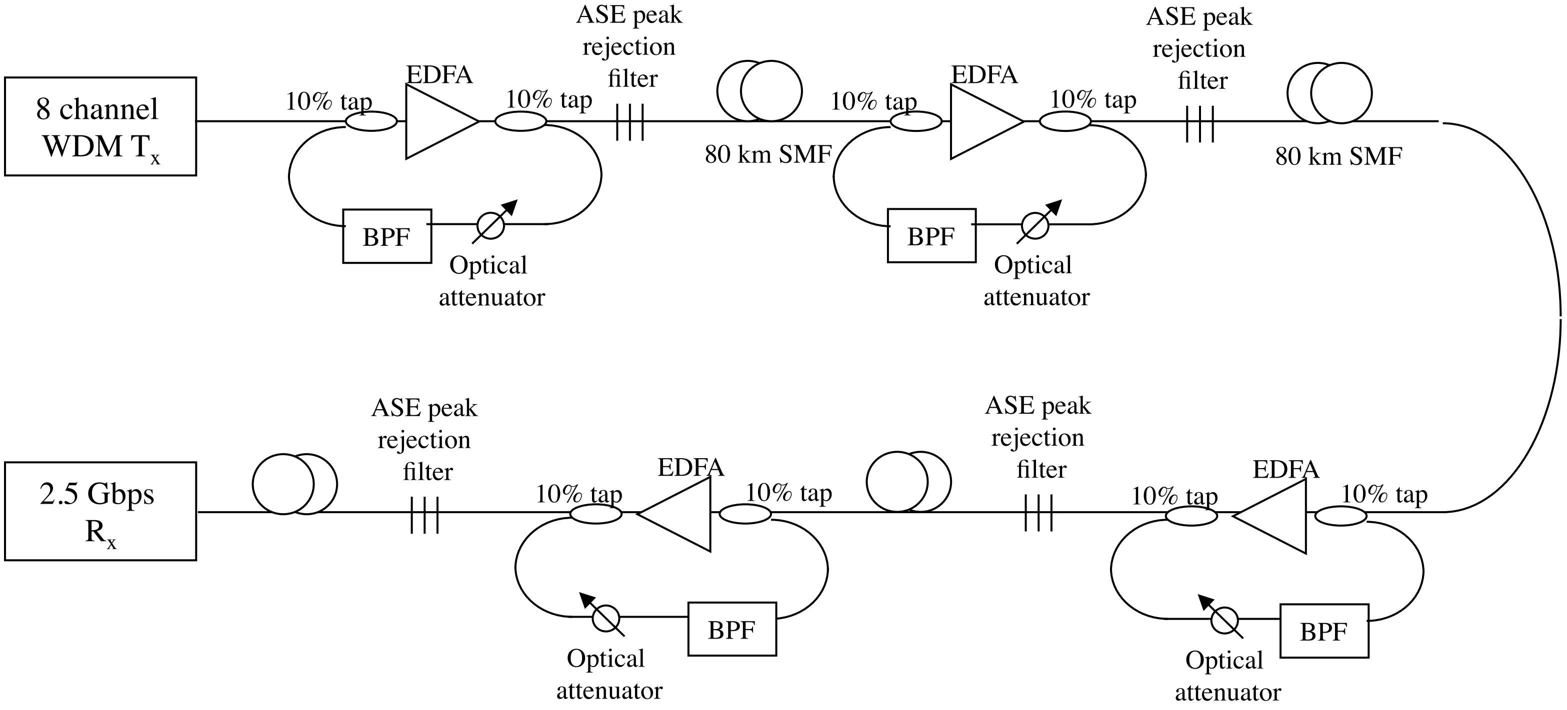
Measured output power as a function of time after 2, 4, 6, 8, 10, and 12 EDFA's. At time t = 0 one laser is blocked, corresponding to loss of 4 of 8 signal channels.

J. L. Zyskind et.al., OFC' 96, PD31-2

- Adding or dropping channels in a WDM Network which contains N Erbium Doped Fiber Amplifiers, either in nodes or regenerators, would cause a power fluctuation in the surviving channels, sometimes even doubling the power in EDFAs farther down the chain.
- Typical time scales for gain changes in EDFAs are of the order of tens of microseconds.
- To limit performance penalties, power fluctuations should be limited to 1dB.
- Response times of the EDFAs should be 100 - 200 ns.
- Solution: Dynamic gain control or gain clamping

Stabilization with Gain Clamped EDFAs

'Address problem of channel add/drop rates on order of EDFA gain relaxation oscillation frequency and gain clamped amplifier loop time constant. This is our first look at gain clamped amplifiers. Will discuss more in next lecture.

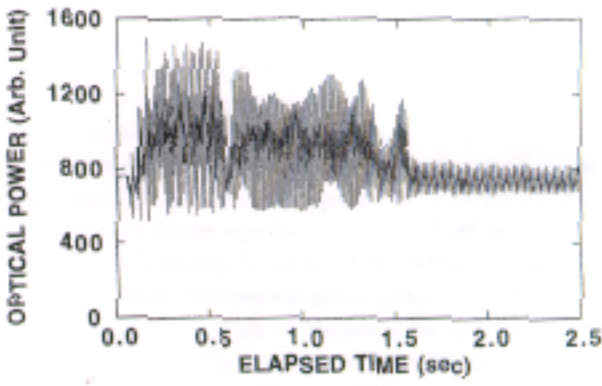


S. Y. Kim et. al., Electron. Letts., Aug. 1997

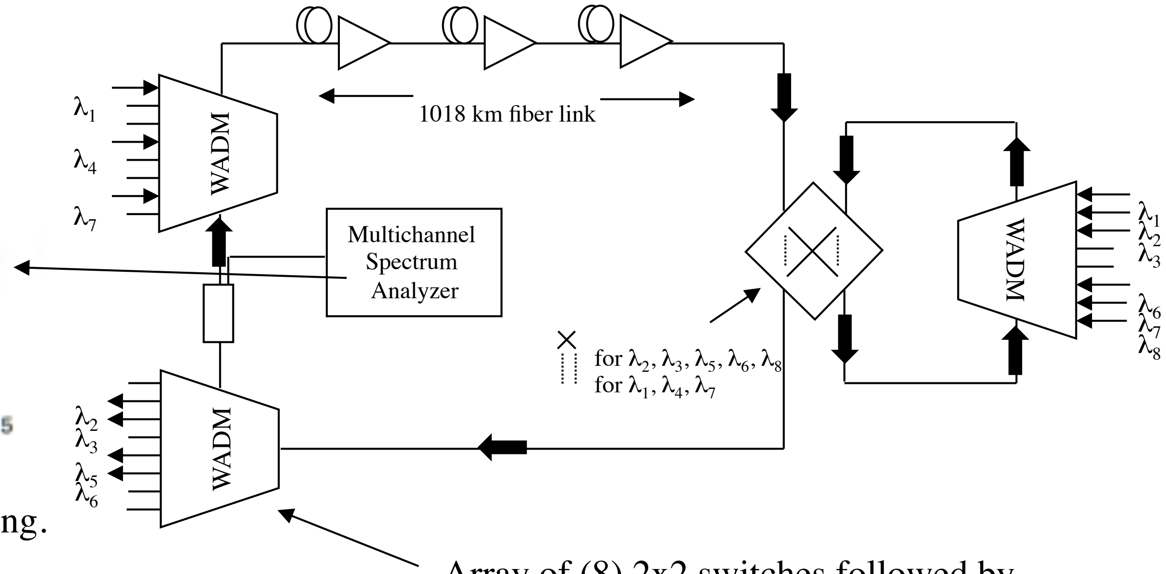
Power Fluctuations in Cascaded Channel Power Equalizers

State 1: 1,4,and 7 only through EDFA link

State 2: Add 2,3,5 and 6 to EDFA link



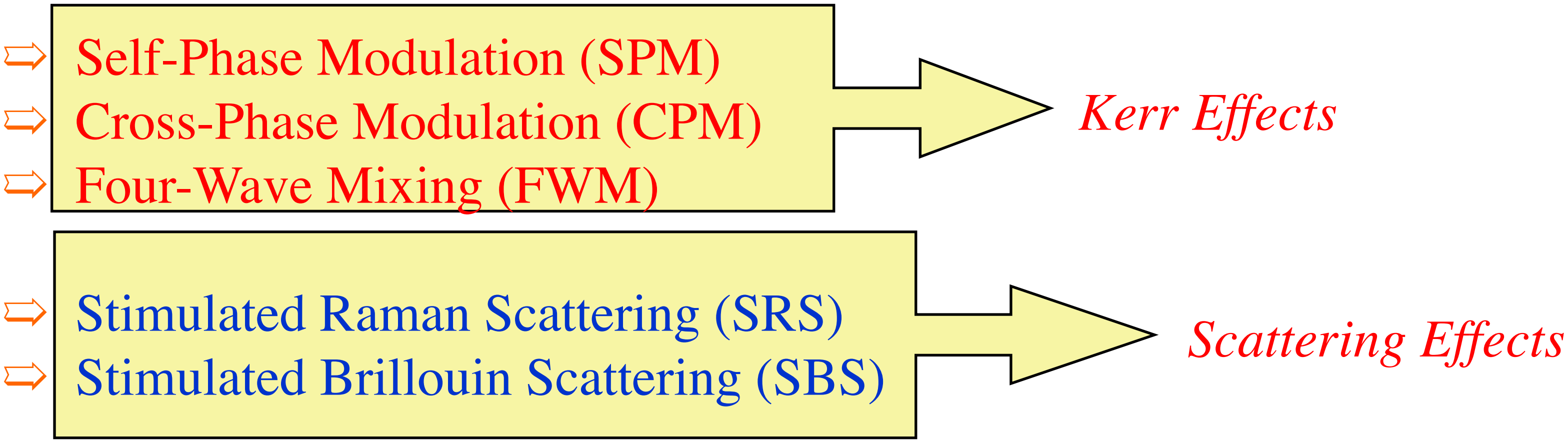
Channel 7 without EDFA gain clamping.
Gain clamping greatly reduces effect.



Array of (8) 2x2 switches followed by array of (8) automatic channel power equalizers

Fiber Non-linearities

- There are several conditions where the optical power in the fiber can actually cause signal distortion or crosstalk with other optical wavelengths and transfer energy between optical frequencies



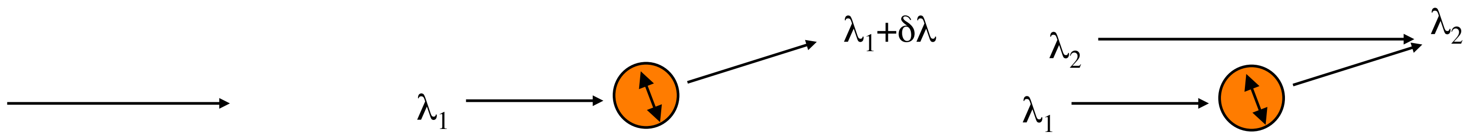
- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (CPM)
- Four-Wave Mixing (FWM)

Kerr Effects

- Stimulated Raman Scattering (SRS)
- Stimulated Brillouin Scattering (SBS)

Scattering Effects

Stimulated Raman Scattering (SRS)



Optical signal at λ_1
propagates in fiber (glass)

Optical signals scatter off molecular vibrations (Optical Phonons) in the fiber. This results in a frequency shift to a longer wavelength

Energy couples between two different wavelengths with the shorter λ acting as an optical pump for the longer λ

New wavelengths can be generated up to 100 nm away from the original signal !

Theory of SRS Amplification

⇨ The Raman gain can be characterized by the gain coefficient g_R such that

$$g(z) = g_R I_P(z)$$

$$g(\omega) = g_R(\omega)\frac{P_P}{a_P}$$

⇨ where $I_p(z)$ is the pump intensity at position z in the fiber, P_p is the pump power, and a_p is the cross-sectional area of the pump beam inside the fiber. Since a_p varies with each fiber design, we use the ratio g_R/a_p as the measure of Raman gain efficiency.

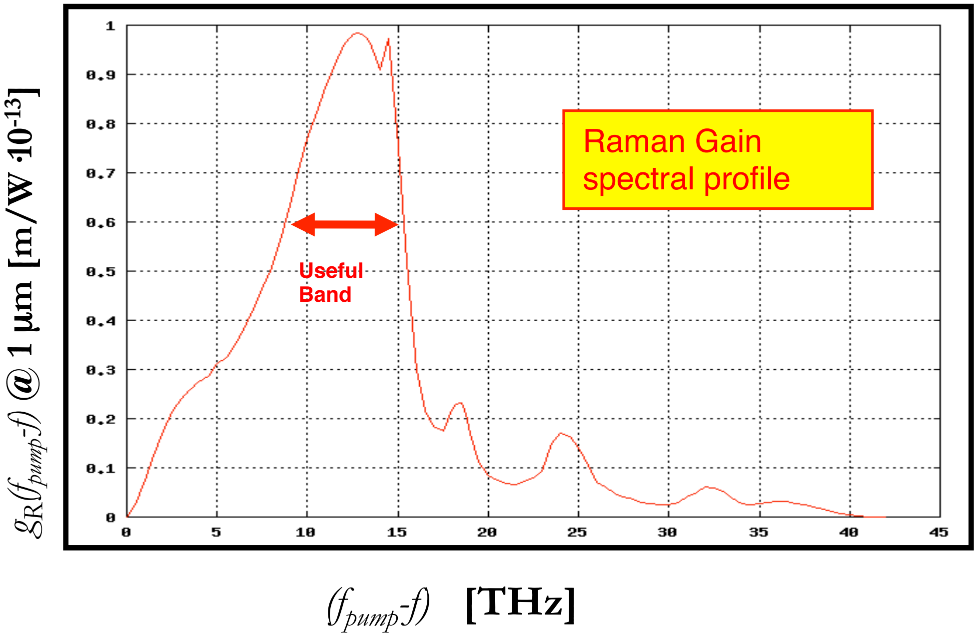
⇨ Raman amplifiers can be forward or reverse pumped. For forward pumped, the coupled power equations can be written for the pump and signal power (P_s, P_P)

$$\frac{dP_S}{dz} = -\alpha_S P_S + \left(\frac{g_R}{a_P}\right) P_P P_S$$

$$\frac{dP_P}{dz} = -\alpha_P P_P - \left(\frac{\omega_P}{\omega_S}\right)\left(\frac{g_R}{a_P}\right) P_S P_P$$

RAMAN Fiber Gain

- The gain coefficient $g_r(\omega)$ has a dependence on the detuning between the pump and observation (or probe) frequency as shown below. The gain bandwidth is indicated below, and can change depending on the fiber type (e.g. dispersion compensating fiber, dispersion shifted fiber, normal single mode fiber).
- A typical gain bandwidth defined at the FWHM of the main peak is 6THz!



Theory of SRS Amplification

- If we neglect depletion of the pump power at all points z in the fiber (i.e. an unlimited power supply) we can approximate amplification of the signal power assuming the following evolution of the pump (and ignoring the last term in the coupled equations)

$$P_P(z) = P_P(0)\exp\left(-\alpha_P z\right)$$

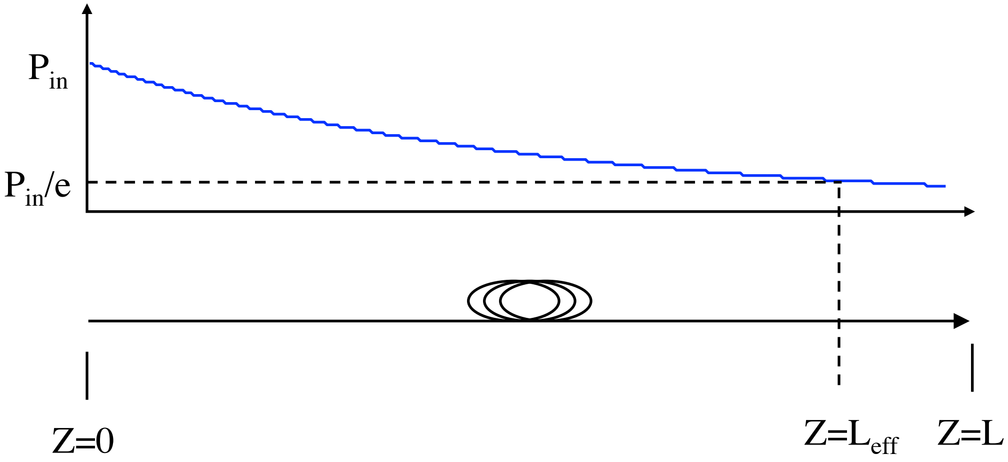
$$P_S(L) = P_S(0)\exp\left({g_R P_0 L_{eff}}\big/{a_P} - \alpha_S L\right)$$

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

- Where the concept of effective length (L_{eff}) has been introduced and is described in more detail on the next slide.

Effective Fiber Length

Any nonlinear effect depends strongly on the optical intensity within the fiber.
Therefore, fiber loss plays a role in how far along the fiber the nonlinearities occur



This result can also be interpreted as follows:
Fiber non-linear effects take place mostly in the first 25 km

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

$$L_{eff} \approx \frac{1}{\alpha}\ , \text{ For large L}$$

$$L_{eff} \approx 25\ km \text{ for } L > 50\ km$$

Where L is the fiber length and α is the fiber attenuation factor.

Raman Amplifier Theory

- The overall amplifier gain can be defined as the signal level with Raman gain compared to the signal level in the same length of fiber without Raman gain ($P_s(L) = P_s(0)\exp(-\alpha_s L)$), and by defining the small signal gain g_0

$$G_A = \frac{P_S(L)}{P_S(0)\exp(-\alpha_S L)} = \exp(g_0 L)$$

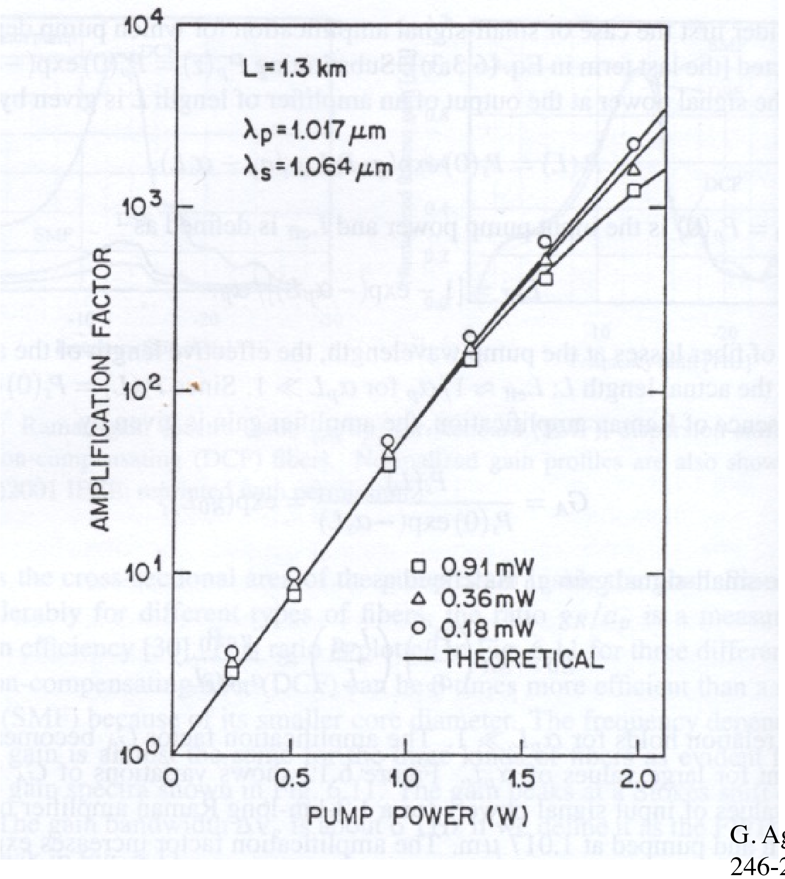
$$g_0 = g_R\left(\frac{P_0}{a_P}\right)\left(\frac{L_{eff}}{L}\right) \approx \frac{g_R P_0}{a_P \alpha_P L}$$

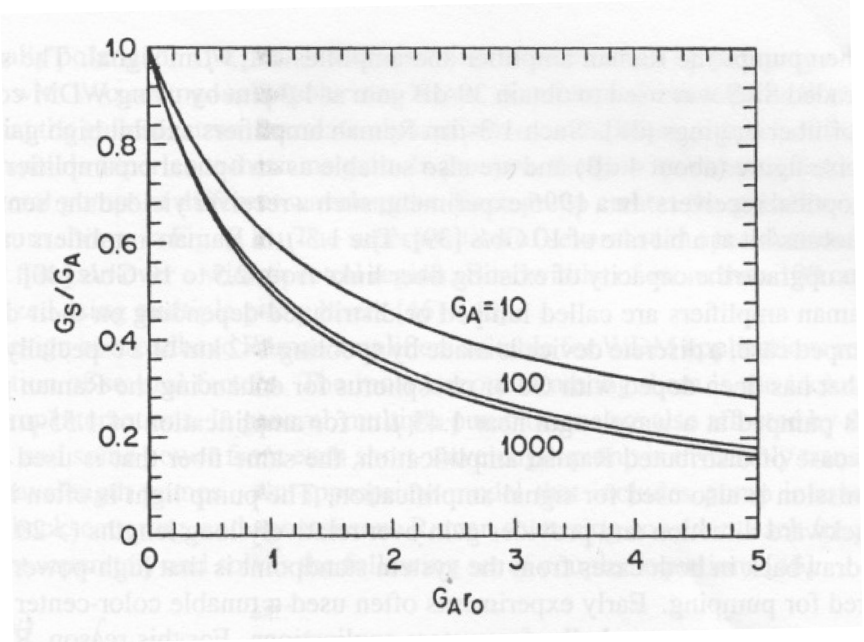
- If we take into account gain saturation, where the pump power is depleted, we can approximate the saturated gain by taking $\alpha_S = \alpha_P$

$$G_S = \frac{1 + r_0}{r_0 + G_A^{-(1+r_0)}}$$

$$r_0 = \frac{\omega_P}{\omega_S}\frac{P_S(0)}{P_P(0)}$$

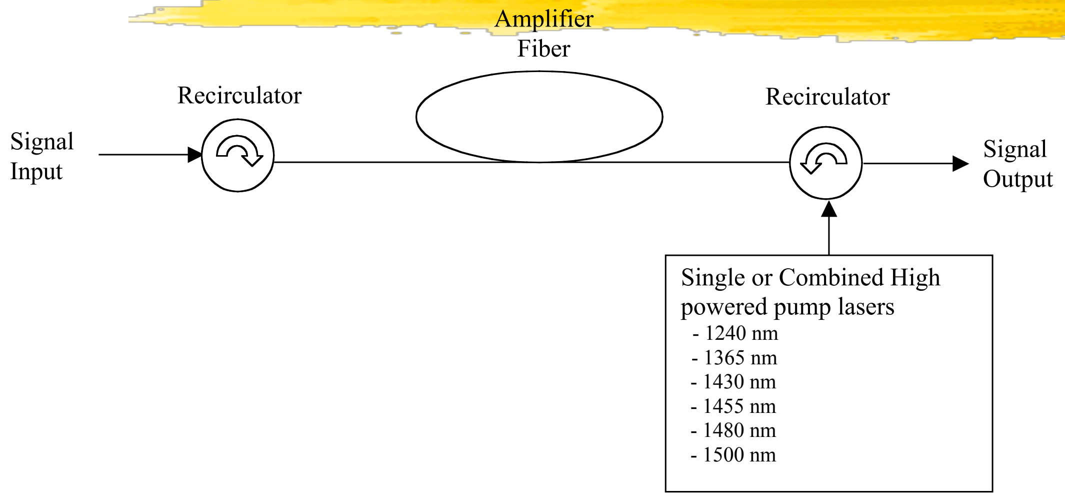
Raman Amplifier Characteristics





G. Agrawal, Fiber Opt. Comm Sys., pp. 246-247

Raman Fiber Amplifiers (RFAs)



Single or Combined High powered pump lasers
- 1240 nm
- 1365 nm
- 1430 nm
- 1455 nm
- 1480 nm
- 1500 nm

(a)

$$G_A = \exp\left(\frac{g_R P_{pump} L_{eff}}{A_{eff}}\right)$$

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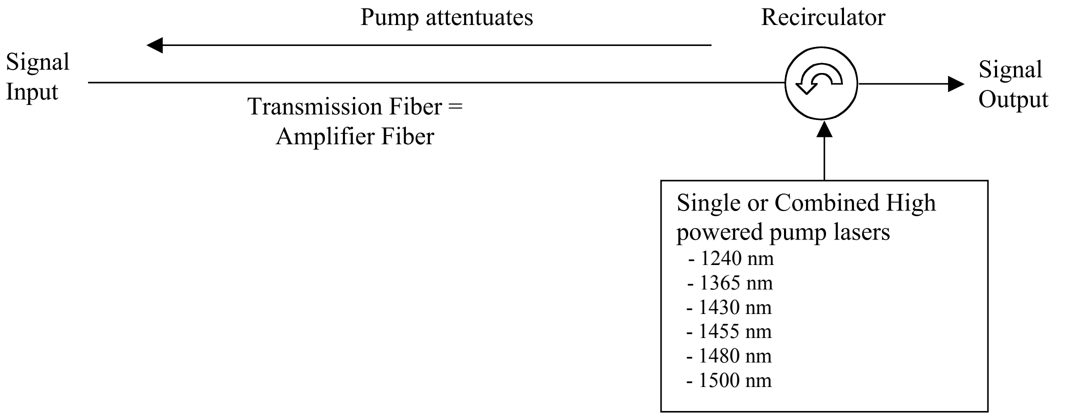


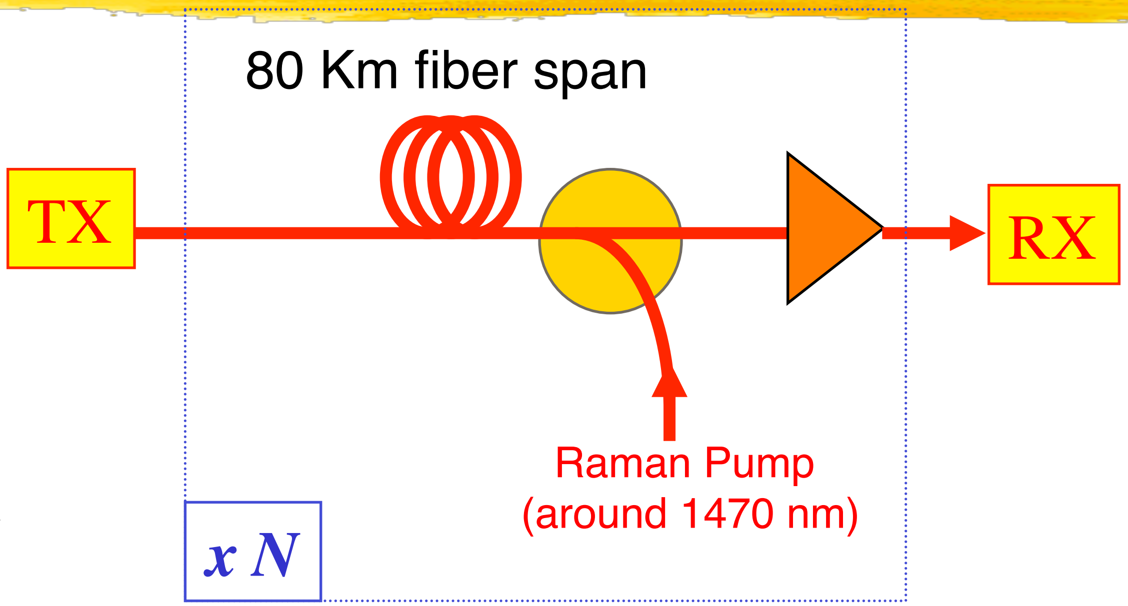
Single or Combined High powered pump lasers
- 1240 nm
- 1365 nm
- 1430 nm
- 1455 nm
- 1480 nm
- 1500 nm

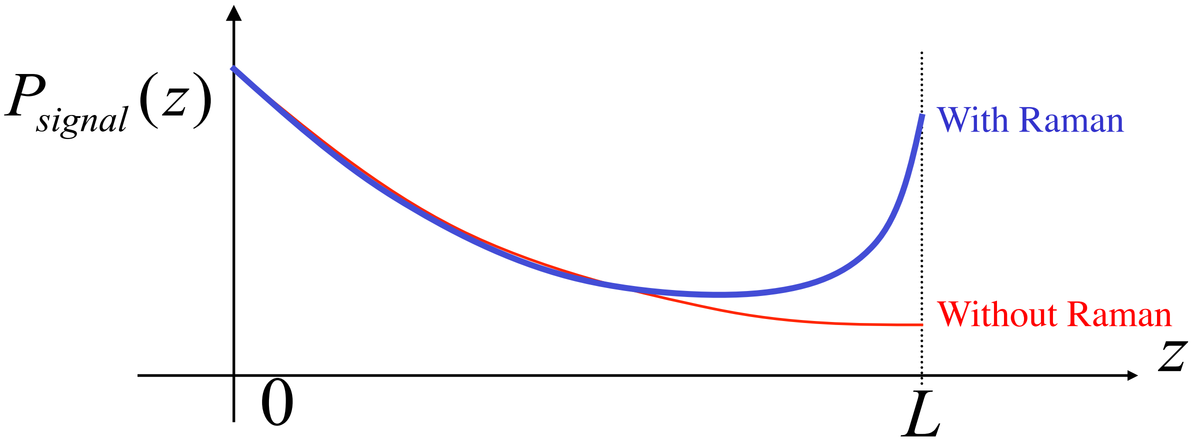
(b)

$$L_{eff} = \left(\left. 1-\exp(-\alpha L) \right/ \alpha \right)$$

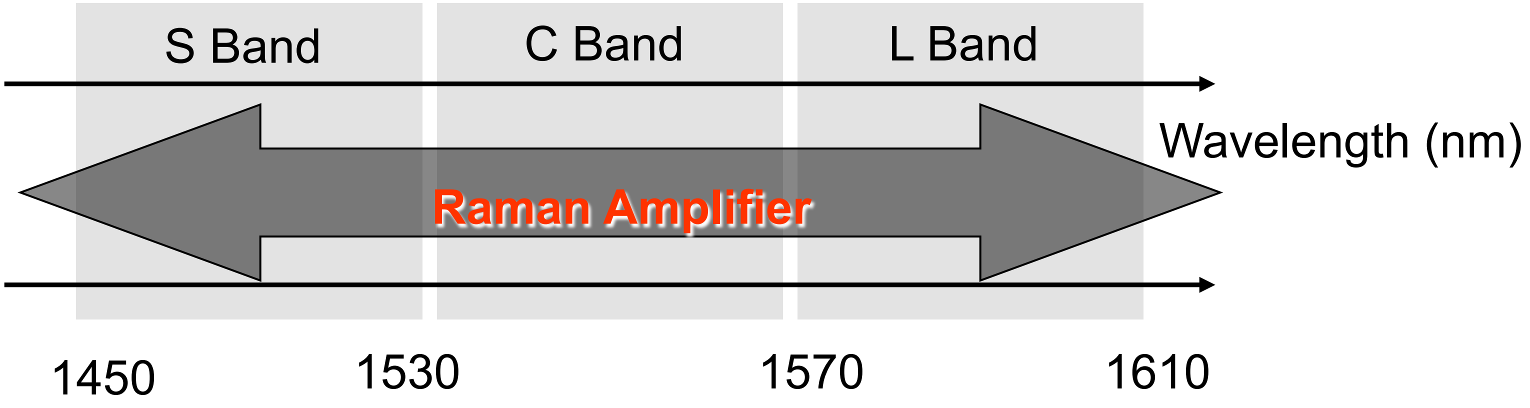
Typical application

- The typical configuration for ultra long system is based on
  - Hybrid Raman-EDFA configuration
  - Counter-propagating Raman pumping





Multi-Pump Raman Configurations


S Band

C Band

L Band

Wavelength (nm)

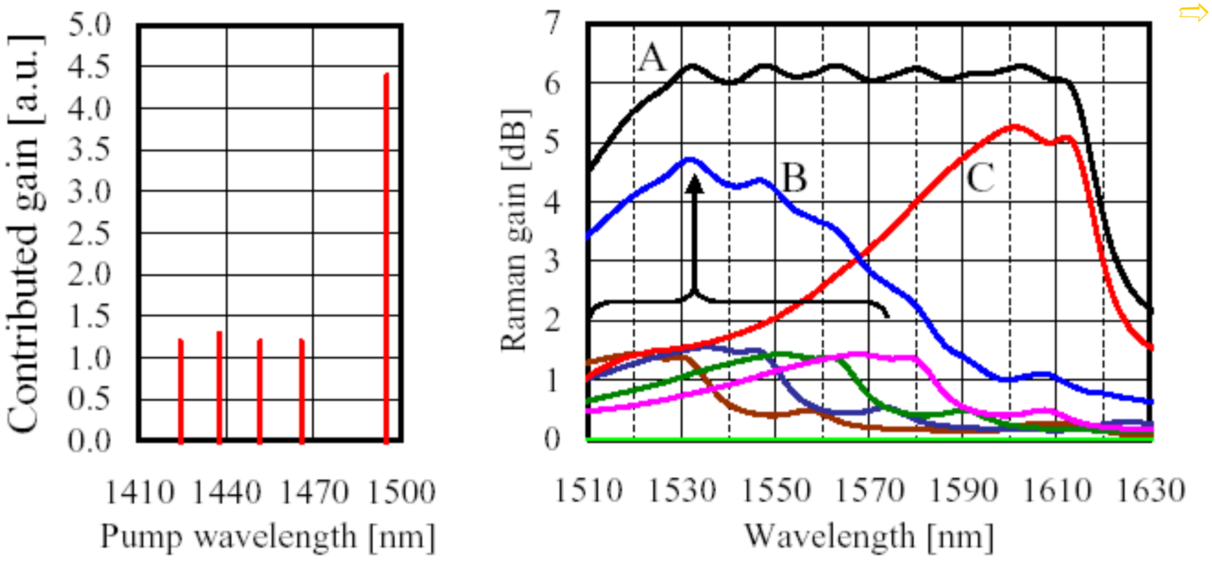
Raman Amplifier

1450

1530

1570

1610



Ref. Y. Emori et al., ECOC2001, Tu A. 2.2

- ⇨ RA bandwidth
  - ⇨ Gain available at any λ
  - ⇨ Selection of pump wavelength
  - ⇨ Number of pumps used
  - ⇨ Power levels
  - ⇨ Versatile
  - ⇨ Wavelength transparency