

# Module 21 : Raman Amplifier

## Lecture : Raman Amplifier

### Objectives

In this lecture you will learn the following

- Introduction
- **Origin of Raman Scattering**
- Raman Scattering in Optical Fibers
- Fiber Raman Amplifier
- Pumping Schemes for Raman Amplifier
- Impact of Raman Scattering on WDM system

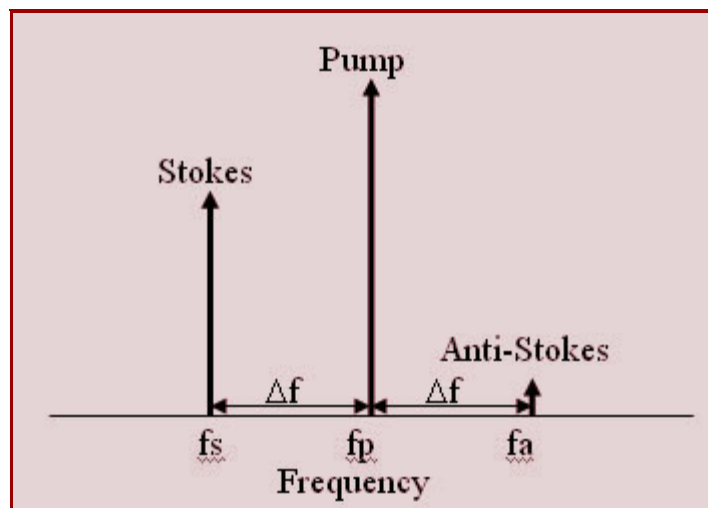
### Introduction

- Raman scattering, especially if it is stimulated, is a very important non-linear effect because it affects the SNR in a WDM system. It can also be used for amplification of the optical signals in a long haul optical communication link.
- The spontaneous Raman scattering was discovered by Sir C. V. Raman.
- In case of spontaneous Raman scattering, a small portion of the incident light is transformed into a new wave with lower or higher frequency. This transformation is because of the interaction of the photon with the vibrational modes of the material.
- The transformation efficiency of spontaneous Raman scattering is very low. Typically photons 1 part per million are transformed to the new wavelength per cm length of the medium.

- Contrary to spontaneous Raman scattering, stimulated Raman scattering can transform a large fraction of the incident light in the new frequency-shifted wave.

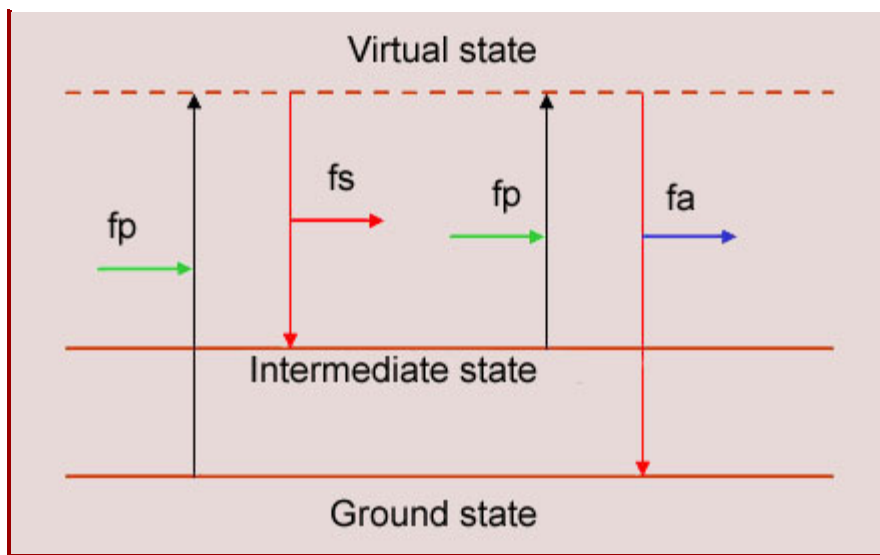
### Origin of Raman Scattering

- In principle, spontaneous Raman scattering can be observed in any material. If a medium is irradiated by an intense monochromatic light and if the scattered light is studied with a spectrometer, the scattered light shows new wavelengths in addition to the original wavelength.
- The wave which irradiates the material is called the Pump wave, the waves with lower frequencies are called the Stokes waves, and the waves with higher frequency are called the Anti-Stokes waves.
- The intensity of the Stokes waves is many orders of magnitude higher than the intensity of the anti-Stokes waves as shown in Fig.



- The origin of the generation of the new frequencies lies in the energy exchange between the photons and the material molecules. The quantum-mechanical energy diagram for Raman scattering is shown in Fig.





- In the Stokes generation process, the incoming photon of frequency  $f_p$  excites a molecule from the ground state to the virtual state. The molecule returns to the intermediate state releasing a Stokes photon of frequency  $f_s$ . Since the energy difference between the virtual and intermediate levels is smaller than the energy difference between the ground and the virtual states, the frequency of the Stokes photon is lower than the incident photon ( $f_s < f_p$ ).

- In the anti-Stokes generation process, the incoming photon of frequency  $f_p$  excites a molecule from the intermediate state to the virtual state. The molecule returns to the ground state releasing a anti-Stokes photon of frequency  $f_a$ . Since the energy difference between the virtual and intermediate levels is smaller than the energy difference between the ground and the virtual states, the frequency of the anti-Stokes photon is higher than the incident photon ( $f_a > f_p$ ).

- If energy difference between the intermediate level and the ground level is  $\Delta E = h \Delta f$ , where  $h$  is the Planck's constant, then we get

$$f_s = f_p - \Delta f = f_p - \Delta E / h$$

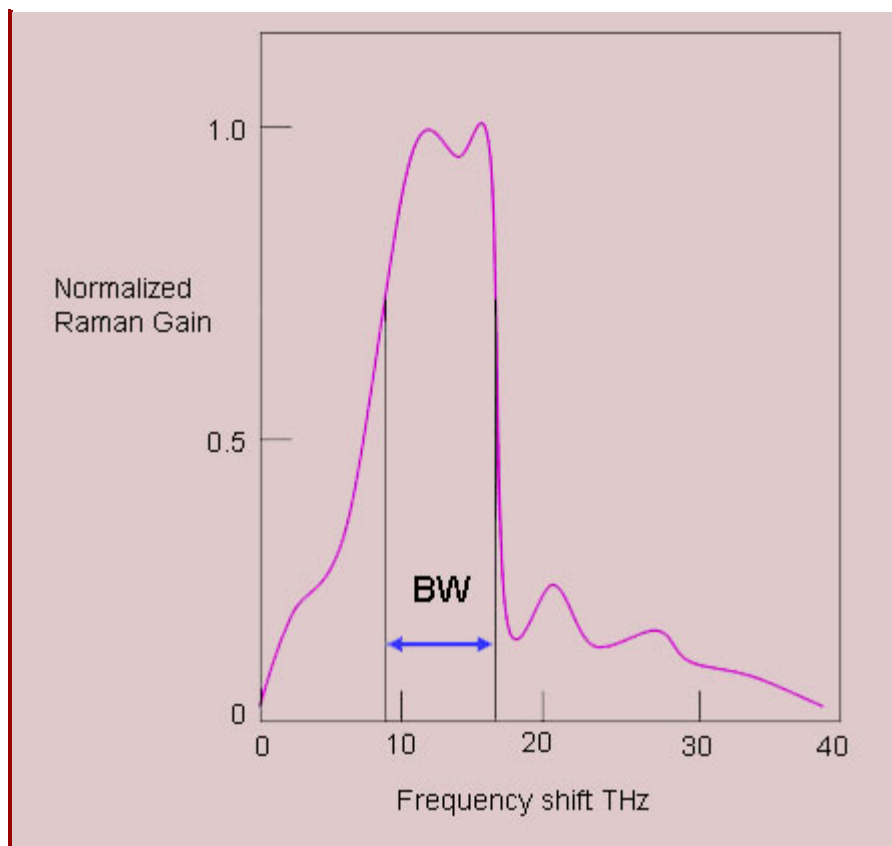
- Energy  $\Delta E$  is the vibrational energy and in the stokes generation process it is delivered to the molecule.
- In anti-Stoke generation process, the molecule supplies vibrational energy to the photon increasing the total energy of the incident photon. In thermal equilibrium, the density of molecules in the intermediate state is much smaller than the density in the ground state, and therefore the number of anti-Stokes photons is much smaller compared to that of the Stokes photons.

- The vibrational energy depends upon the molecular resonances.
- The Raman scattering depends upon particular material resonances. In crystalline material these resonances show a very narrow bandwidth. Therefore the frequencies of the Stokes and the anti-Stokes waves reflect material property. This fact made the Raman scattering a useful tool in the field of spectroscopy.

### **Raman Scattering in Optical Fibers**

- The basic material used in optical fibers is glass which is not crystalline but is amorphous in nature.
- The molecular resonance frequencies of the vibrational modes in glass are overlapped with each other to give a rather broad frequency band. The optical fibers therefore show Raman scattering over a large frequency range.
- The energy conversion process between the pump and the Stokes is characterized by a parameter called the Raman Gain ,  $g_R$ .
- The Raman gain depends mainly on the material composition of the fiber core and contained dopants.
- A typical Raman gain spectrum of silica glass fiber is shown in Fig.



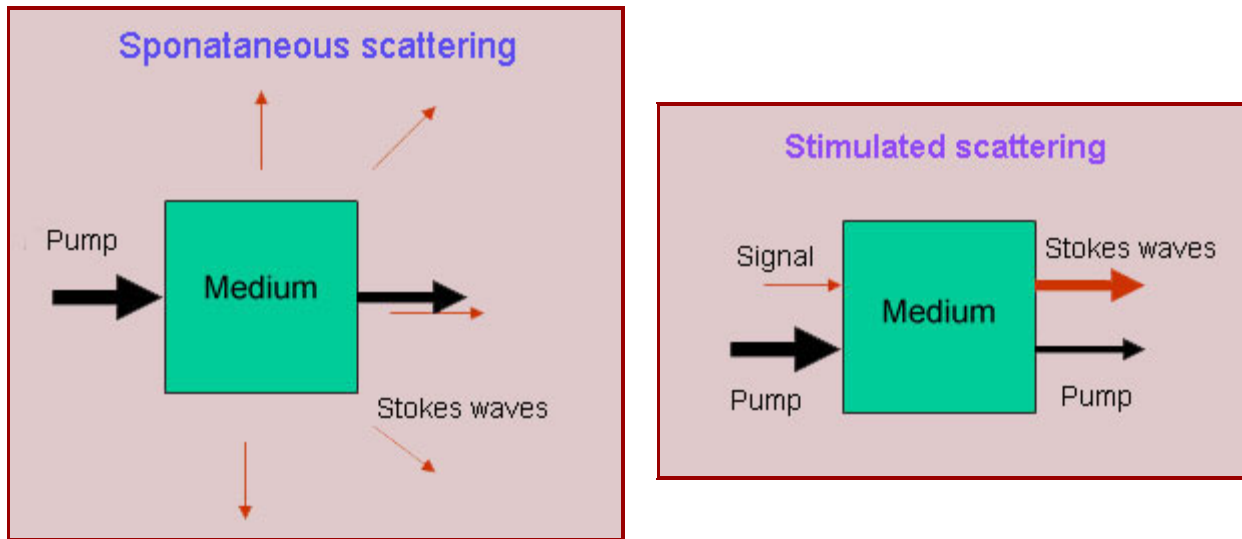


- The Raman gain for silica glass has one main and many small side maxima.
- If minor peaks in the spectrum are included, the Raman gain has a wide bandwidth of about 40 THz.
- The maximum gain is practically constant over a bandwidth from 9THz to 16THz. The mean of the high gain region is around **13THz** ( which at 1550nm wavelength corresponds to  $\Delta\lambda = 112 \text{ nm}$  ) . The maximum Raman gain in pure glass is  $g_{R\text{max}} = 1.9 \times 10^{-13} \text{ m/W}$  .
- Raman gain is inversely proportional to the wavelength of the pump and depends on the polarization of the wave. The Raman gain is much higher for parallel polarization (when the pump and the Stokes waves have same polarization) compared to that for the perpendicular polarization (i.e. when the pump and the Stokes waves have orthogonal polarization).
- In optical fiber however, due to birefringence, the polarization states of the pump and the Stokes wave change continuously and if the fiber is long enough, the effective Raman gain is the mean of the parallel and perpendicular gains. So in a fiber we may say that the Raman gain is polarization independent.

- Raman scattering can be seen in the forward as well as backward direction. In optical communication the forward Raman scattering is of importance since it causes cross talk in a multi channel WDM system. Backward scattering can be exploited for signal amplification in Fiber Raman Amplifier.

### Fiber Raman Amplifier

- For optical amplification we need stimulated Raman scattering. The basic difference between spontaneous and stimulated Raman scattering is shown in Fig.



- If the intensity of the incident field is below a threshold, spontaneous scattering occurs
- The important thing to note is, the stimulated process can be used for light amplification. If a small signal at Stokes frequency is present along with the pump, the signal gets amplified keeping all the characteristics of the input signal.
- The differential equations governing the intensities of the pump and the Stokes waves are

$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s \quad (A)$$

$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p \quad (B)$$

where  $I_p, I_s$  are the intensities of the pump and the signal respectively.  $\omega_p, \omega_s$  are the frequencies and  $\alpha_p, \alpha_s$  are the attenuation constants of the pump and the Stokes waves.

- The equations show that the Stokes grows exponentially with distance whereas the pump decays exponentially with distance.
- In first approximation it is generally assumed that the pump depletion due Raman scattering is small. The first term on the RHS in equation (B) can be neglected. The pump then decays along the fiber due to fiber attenuation and its intensity is given by

$$I_p = I_p(0) e^{-\alpha_p z} \quad (C)$$

- Introducing  $I_p$  in (A) we get intensity of the Stokes wave as

$$I_s = I_s(0) \exp(g_R I_p(0) L_{eff} - \alpha_s z)$$

where  $L_{eff}$  is the effective interaction length of the pump and is given as

$$L_{eff} = \frac{1 - \exp(-\alpha_p z)}{\alpha_p}$$

- For long fibers  $\alpha_p z \gg 1$ , and  $L_{eff} = \frac{1}{\alpha_p}$
- The threshold for stimulated scattering is defined as input intensity  $I_{pth}$  value of the pump for which Stoke wave shows gain in the fiber. The Raman gain process then must exceed the fiber loss to give

$$g_R I_{pth} L_{eff} \gg \alpha_s z$$

- Assuming that the length of the fiber is approximately  $L_{eff}$ , we can get threshold intensity for Stimulated Raman Scattering (SRS) as

$$I_{pth} \gg \alpha_s / g_R$$

- For a SM fiber typically the core effective area is  $80 \mu m^2$ , and  $\alpha \approx 0.2 \text{ dB/Km}$ , Raman gain is  $7 \times 10^{-14} \text{ m/W}$ , the Raman threshold power  $P_{th} = I_{pth} A_{eff} \gg 53 \text{ mW}$ .

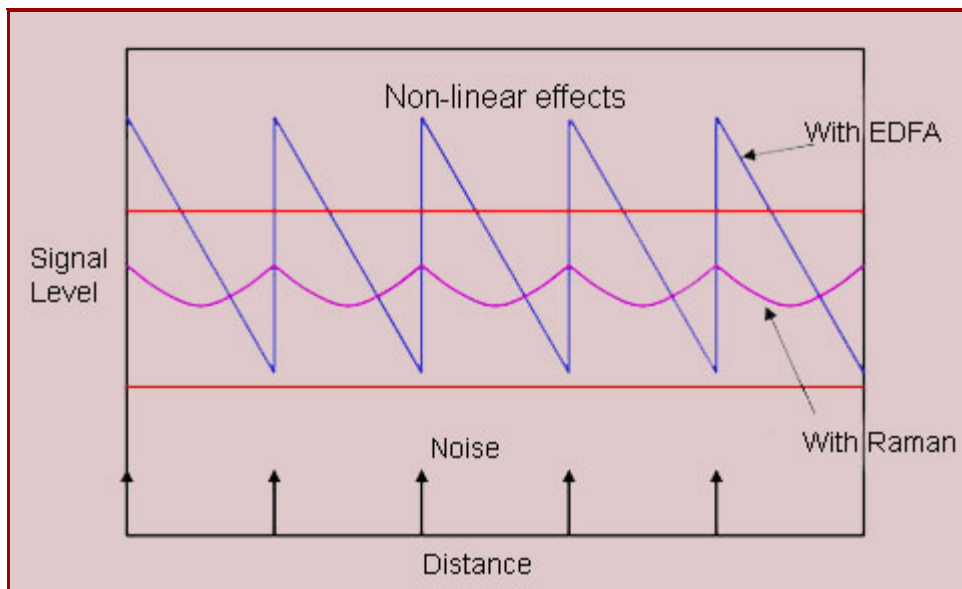
### Note:

- The threshold given above just tells that above this pump power there will be gain for any signal above the noise. However still the Stokes power is orders of magnitude smaller than the Pump.

- If we define the threshold as the input power for which the output powers of pump and Stokes are equal, then its value is approximately

$$I_{th} = \frac{16}{g_R L_{eff}}$$

- Typical power to achieve this threshold intensity in a SM fiber is about 1 W.
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- Raman amplification has renewed interest in recent years due to several reasons:
    - 1) Laser diodes which deliver the required power at several wavelengths are commercially available.
    - 2) Using Raman amplification the whole transmission bandwidth of the optical fiber can be exploited. (The EDFA makes use of a very small fraction of the transmission window).
    - 3) In an optical fiber multiple Raman processes can go on simultaneously. That means using multiple pumps, ultra wideband amplifiers can be realized.
    - 4) **Most Important:** It is a distributed amplifier as compared to the EDFA or the semiconductor optical amplifier (SOA).
  - The signals levels on a long haul optical link with EDFA and with Raman amplification are shown in Fig. The arrows indicate the location of EDFAs or pumps for Raman amplification.



- It can be seen from the Fig. that the signal level for Raman amplification remains more or less constant at a level much higher than the noise floor in the system.

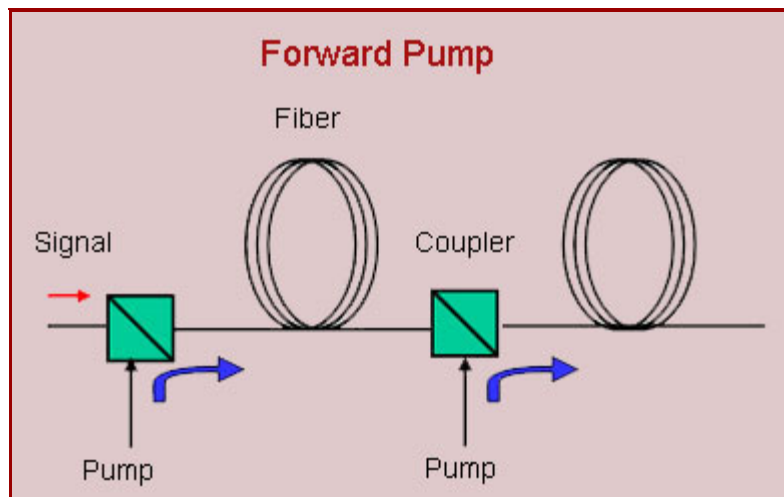


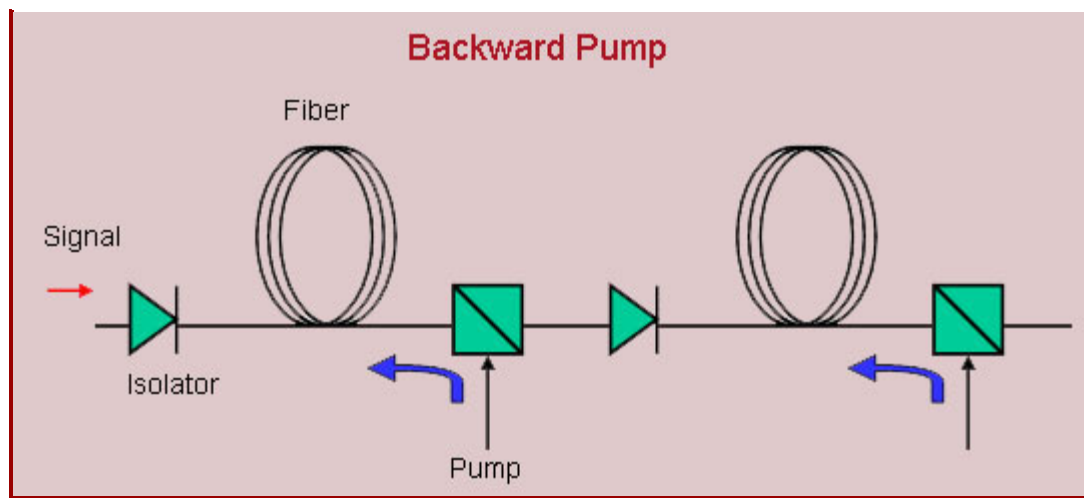
- In case of EDFA the signal level reaches close to the noise floor just before the amplifier, and just after the amplifier it increases to such a high value that the non-linear effects like SPM, XPM, FWM become effective. In presence of non-linear effects the signal gets distorted. The lumped amplification system like the EDFA has worse noise as well as distortion performance.

### Pumping Schemes for Raman Amplifier

- The Raman amplifier can be pumped with forward as well as backward pump since Raman gain is independent of the pump direction. The two schemes are shown in Fig.
- The forward pump scheme has two main drawbacks (1) The pump level is higher where signal is stronger giving increase of signal power at the beginning of the section (2) the residual co-propagating pump is to be filtered.

- The maximum length or gain beyond which the Raman amplifiers no longer improve the system performance is determined by the so called double Rayleigh back scattering (DRBS) multi-path interference (MPI) noise. This can be explained as follows.
- Suppose a signal is amplified by a co-propagating pump. Due to Rayleigh scattering a part of the signal is scattered back. The SRS being direction independent amplifies the backward scattered signal. The scattered light becomes strong enough to generate double back scattered signal which travels with the pump. Superposition between the signal and the time delayed double back-scattered light leads to time dependent noise.





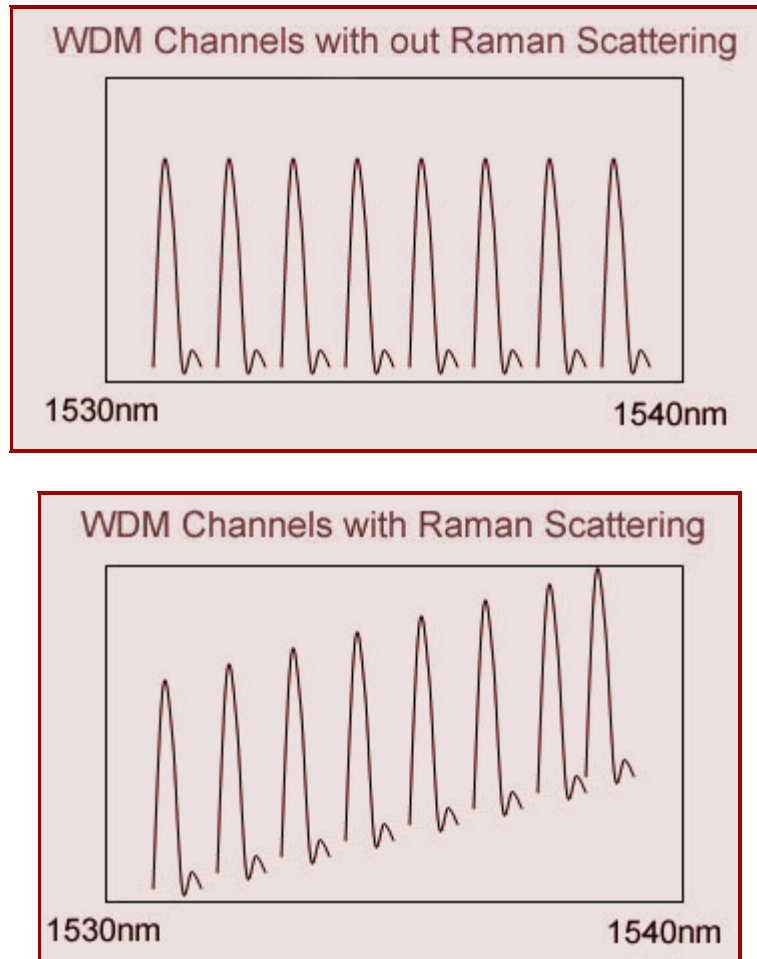
### Broad Banding of Raman Amplifier

- The Raman amplifier with single pump gives a bandwidth of about 7 THz which is approximately 60nm. The transmission window of the fiber is about 400nm (1200nm to 1600nm). A broad band amplifier therefore is very desirable.
- Using multiple pumps, wide band amplifiers with a very small gain ripple can be designed. It should be kept in mind however, that in a multiple pump scheme, there is exchange of power between the pump themselves due to Raman process.

### Impact of Raman Scattering on WDM system

- If only one channel propagates on an optical fiber, the Raman effect is observable only if the input power of the channel is of the order of the threshold for the forward Raman scattering. Since the threshold is very high the SRS can be neglected in a single channel system.
- A completely different behavior can be seen in WDM systems. Here the initial Stokes wave is not generated by the spontaneous process because the waves of right frequency shifts are already present in the system. Further the input power of the Stokes wave is more or less same as the input power of the pump (the channels of shorter wavelengths act as pump for the channels of the longer wavelengths).
- Since the Raman gain peaks around 13THz frequency shift, channels separated by about 100nm influence each other maximally. In other words, channels from different bands like L, C influence each other more. Nevertheless, channels within a band also influence each other though to a lesser extent.

- For DWDM system the Raman interaction is very complicated. Every wavelength acts as a pump for wavelengths longer than it, and as Stokes wave for a wavelength shorter than it. Hence Due to Raman scattering every channel receives power and every channel loses power. There is systematic flow of power from higher frequency channels to the lower frequency channels. So to start with if all channels had equal power, at the end the spectrum will be as shown in Fig.



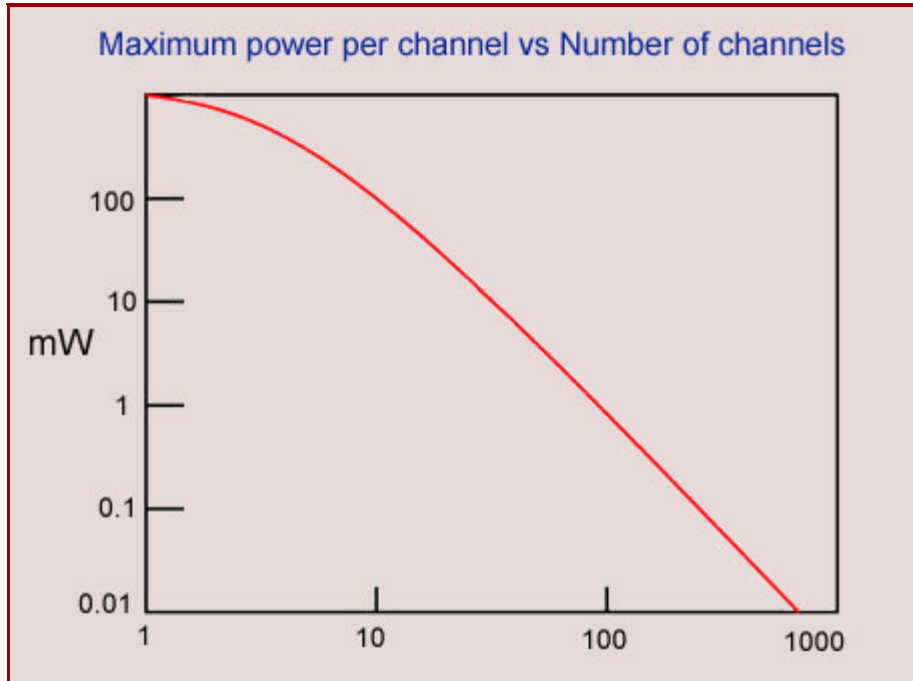
- Decrease in channel power is a problem in WDM system as it reduces SNR and increase the BER.
- The decrease in power of a channel can be estimated analytically assuming a triangular Raman gain profile from 0 to 15 THz. If the acceptable reduction in the channel power is 1dB, the power-bandwidth product

$$[nP][(n-1)\Delta f] < 500 \text{ W-GHz}$$

Where  $n$  is the number of DWDM channels,  $P$  is the power per channel, and  $\Delta f$  is the channel separation.

## Impact of Raman Scattering on WDM system(contd)

- If number of channels is small, the maximum power per channel decreases as  $1/n$ , but if the number of channel is large, the power decreases as  $1/n^2$ . A plot of maximum power per channel as a function of number of channel is shown in Fig.



- In a long haul system with periodic amplification, SNR performance in presence of Raman scattering has been estimated. If the acceptable decrease in SNR in the channel with smallest wavelength is 0.5dB, the number of transmittable channels N can be calculated using

$$n(n-1) = \frac{8.7 \times 10^{15}}{P \Delta f L_{eff}}$$

where  $L_{eff}$  is the effective interaction length of the system with amplifiers.

- The noise power in the system due to the amplifiers is

$$N = 2m h\nu n_{sp} B_0 (G-1)$$

where  $m$  is number of amplifiers ( $m = L/L_A$ ,  $L$  is the link length and  $L_A$  is the amplifier spacing),  $h\nu$  is the photon energy,  $n_{sp}$  is excess noise factor of the amplifier,  $B_0$  is the optical bandwidth of the receiver, and  $G$  is the gain of each amplifier.

- If the required SNR is  $R$ , the average input power in each channel is

$$P = 2(L / L_A) h\nu n_{sp} B_0 (G - 1) R$$

- For large number of channels, the channel capacity can be obtained as

$$C < \sqrt{\frac{1.8 \times 10^{14}}{2(L / L_A) h\nu n_{sp} L_{eff} (G - 1) R}}$$

Here is assumed that channel spacing is 6 times the data rate and receiver filter bandwidth is 4 times the data rate.

- **For a link of few thousand Km length, the capacity is < 100Gbps even for a DWDM system.**
- The expression given above neither includes the dispersion effects nor arbitrary distribution of the bits in different channels. In some sense the results given above are the worst case results.
- The Raman gain is most effective when the pulses of different channels align with each other in time. In a WDM system, since different channels are completely asynchronous, and the data bits are randomly distributed between 0 and 1 levels, it is unlikely that the 1's in all the channels will be aligned in time. On average half the 1's in any channel will align with the 1's of the other channel. The Raman interaction therefore is reduced.
- Additionally, since the fiber is a dispersive medium, there is a difference in group velocities of the different channels. The data pulses of different channels therefore slide with respect to each other giving pulse walk off. This reduces the Raman interaction and the Raman induced cross talk.

## Recap

In this lecture you have learnt the following

- Introduction
- **Origin of Raman Scattering**

- Raman Scattering in Optical Fibers
- Fiber Raman Amplifier
- Pumping Schemes for Raman Amplifier
- Impact of Raman Scattering on WDM system

Congratulations, you have finished Module 21. To view the next lecture select it from the left hand side menu of the page