Introduction to Raman Amplifiers
Most of the modern applications of optical communications operate at 1550nm window. The optical amplifier used in this window is the Erbium Doped Fiber Amplifier (EDFA) which has a bandwidth of about 30-40nm around 1550nm. But lately, an inevitable need has been felt for an amplifier that has a large bandwidth of operation.

The most important need for a successful Solitonic propagation inside an optical fiber is that, the non-linearity level is maintained appropriately throughout the length of the fiber so that the frequency chirps due to dispersion and non-linearity cancel each other and we obtain a stable undistorted optical pulse. But if we take the loss in the optical fiber into consideration, maintaining a constant power level needs a distributed amplification mechanism as already discussed earlier.

The above two scenarios serve as the foremost motivations for the search of a new optical amplifier that not only provides a distributed amplification but also has a large bandwidth which is way larger than an EDFA. The search for such an amplifier resulted in the Raman amplifier. In the subsequent discussion, we shall study the Raman amplifier in more detail.

**RAMAN SCATTERING**

The basic principle behind the Raman amplifier is the phenomenon of Raman Scattering which is also one of the non-linear effects in an optical fiber. For convenience of explanation of Raman Scattering, let us consider a material having an energy level diagram as shown below:

![Figure 37.1: Energy Level Diagram](image)

The two fixed states- ground state and the intermediate state have fixed energy difference of \( \Delta \) between them. The intermediate state is also known as the vibrational state. When the above material is excited from the ground state to the virtual state, some of the electrons release their energy to come down to the vibrational states. The energy of this transition corresponds to frequency \( f_s \) which is less than the excitation pumping frequency \( f_p \) by a frequency \( \Delta f \). Some of the electrons in the vibrational state get excited by \( f_p \) and migrate to the virtual states and they decay to the ground state, releasing energy...
corresponding to frequency $f_a$ which is more than the pumping frequency $f_p$ by the frequency $\Delta f$. That is:

$$f_s = f_p - \Delta f$$  \hspace{1cm} (37.1)$$

$$f_a = f_p + \Delta f$$  \hspace{1cm} (37.2)$$

The two equations suggest that there is fixed change in the frequency of the released energy compared to the excitation frequency. The frequency with which the material is excited is called the pump and the frequency corresponding to released energy from virtual to vibrational states is called as Stokes (denoted by $f_s$). Only about $10^{-6}$ of the entire optical energy impinging onto the material gets converted into the stokes frequency. If the transition from vibrational state to the virtual and then back to the ground state is made possible, the frequency corresponding to energy released during the transition to ground state is called the anti-stokes frequency (denoted by $f_a$). This is the basic idea of Raman scattering. That is when a material is illuminated with a beam of light the frequency of a small portion of the incident beam gets down-shifted to the stokes frequency and an even smaller portion gets up-shifted to the anti-stokes frequency. If we look into the spectral domain, the situation is as follows:

![Figure 37.2: Spectral Domain Representation](image)

The change in frequency `$\Delta f$' is a property of the material as it depends on the energy difference between the vibrational and the ground states. Different materials exhibit different values of $\Delta f$. The realization of the generation of anti-stokes frequency requires special systems. Hence, we shall limit our discussion to stokes frequency only in which a material exposed to a pump frequency $f_p$ generates a stokes frequency which is down-shifted from the pump frequency by a fixed amount. In practice, no material has such discrete levels of energy as shown in figure 37.1. The different states are, actually, bands of energy levels which are closely packed. Therefore, the spectral domain representation consists of finite bands of frequencies around the stokes frequency when the material is exposed to a pump frequency. Because of this band nature, we can bring in the concept of relative frequency wherein the pump frequency is taken as the reference and the gain is plotted w.r.t. the shift in frequency from the pump frequency. The Raman gain profile is, thus, shown below:
The above gain profile shows the Raman gain \( g_R \) for glass with respect to the shift in frequency from the pump frequency which is taken as the reference. For the above plot, the pump wavelength is \( 1\mu m \) (frequency=300THz). Clearly, the Raman gain attains a maximum at a shift of about 13THz (≈20µm) from the pump frequency i.e. at 313THz. One must note the fact that the above plot is not absolute i.e. if the pump signal is shifted in frequency, the maximum also shifts by the same amount in frequency. In speech, we say that the signal is 13THz down-shifted compared to the pump frequency. The Raman Scattering, thus, creates a band of frequencies around the stokes frequency over which the gain is considerable.

![Figure 37.3: Raman Gain Profile](image)

This observation has been made use in the designing of a wide-band optical amplifier. If we look carefully, the Raman gain has large values for about 10-15THz frequency range which, in terms of wavelength, is a very wide range.

The figure below shows the pictorial representation of the spontaneous and stimulated Raman Scattering phenomenon.

![Figure 37.4: Process Representation of basic Raman Scattering](image)

![Figure 37.5: Spontaneous and Stimulated Raman Scattering](image)
When there is no seed signal input to the material along with the pump, a very small portion of the input pump signal gets down-shifted to stokes waves as discussed earlier. This is due to the spontaneous decay of electrons from the virtual state and so, it is known as the spontaneous Raman scattering. However, if we provide an input signal along with the pump signal to the material and if the frequency of the input signal coincides with the peak frequency of the Raman gain profile, then the Raman scattering can be transformed into a stimulated coherent scattering process. This stimulated emission is put to use to amplify the input signal. Thus, we arrive at a Raman Amplifier whose bandwidth position on the frequency axis gets decided by the position of the pump wavelength as discussed earlier. Proper choice of the pump wavelength provides us with an amplifier with the proper (desired) bandwidth of operation. With this principle a basic Fiber Raman amplifier can be constructed and with proper feedback mechanism, the Raman amplifier may also be converted into a Fiber Raman LASER.

Let us now carry out a simple analysis of the Fiber Raman Amplifier. For the convenience of the analysis, let us assume a pump signal of intensity $I_p$ and frequency $\omega_p$ and an optical signal of intensity $I_s$ and frequency $\omega_s$ travel together through the optical fiber (along z-direction) which has attenuation constants $\alpha_p$ and $\alpha_s$ respectively corresponding to the pump and the signal wavelengths as they travel through the optical Fiber Raman Amplifier. As the device is an amplifier, the power from the pump transferred to the signal which causes reduction in the pump power and also, due to the loss on the optical fiber, both the powers decay with distance along the optical fiber. The differential equations describing the above situation can be written as:

For Signal:  
$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s$$  \hspace{1cm} (37.3)

For Pump:  
$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p$$  \hspace{1cm} (37.4)

The quantity $g_R$ is the gain coefficient of the Raman amplifier as discussed earlier and the ratio of the two frequencies occurs from the principle of conservation of photons in the process of scattering. From the principle of conservation photons, the rate of change of total number of input photons with distance must be zero. That is:

$$\frac{d}{dz} \left( \frac{I_p}{\omega_p} + \frac{I_s}{\omega_s} \right) = 0$$  \hspace{1cm} (37.5)

In order to analyse the system of equation (37.3) and (37.4), we may assume that the signal power to be so smaller than the pump power that the decrease in the pump power due to the amplification in the signal power is negligibly small. Under this assumption, the first term on the RHS of equation (37.4) vanishes and the solution to the resulting equation can be written as:

$$I_p(z) = I_p(z=0) e^{-\alpha_p z}$$  \hspace{1cm} (37.6)

Substituting this into equation (37.3), we may the solve equation (37.3) as:
The term $L_{\text{eff}}$ is known as the effective length of the optical fiber which is the physical length of the optical fiber over which the optical power is substantially large. The effective length is defined as:

$$L_{\text{eff}} = \frac{1-e^{-\alpha_p z}}{\alpha_p}$$ (37.8)

In the absence of external input signal, the thermal excitation of electrons generates stokes waves as seen in case of spontaneous scattering. These spontaneously generated photons in the stokes waves serve as input and get amplified. If we assume that each frequency bin generates one photon, the total power generated in stokes waves can be determined by integrating equation (37.7) over the entire frequency axis. That is, the total stokes power is given by:

$$P_s(z) = \int_{-\infty}^{+\infty} h\omega \left\{ g_R(\Omega)I_p(z=0)L_{\text{eff}} - \alpha_s z \right\} d\omega$$ (37.9)

The quantity $\Omega$ is the relative frequency and is defined as:

$$\Omega = \omega_p - \omega$$ (37.10)

Let us now define an effective bandwidth for the Raman gain profile of figure 37.3 as shown below:

$$B_{\text{eff}} = \frac{2\pi}{\left| \frac{\partial^2 g_R}{\partial \omega^2} \right|_{\omega=\omega_0}}$$ (37.11)

In the above expression, $\omega_0$ is the frequency shift corresponding to the peak of the maximum of the Raman gain profile. For glass, the peak is about 13THz away from the pump frequency. For the spontaneous scattering process, the total input power is given as:

$$P_{s0} = h\omega_s B_{\text{eff}}$$ (37.12)

Hence, the total output power is given as (integrating equation (37.9)):

$$P_s(z) = P_{s(z=0)} \exp\left\{ g_R(\Omega)I_p(z=0)L_{\text{eff}} - \alpha_s z \right\}$$ (37.13)

The Raman threshold is defined as the power level at which the power in the stokes waves equals the pump power. In the case of spontaneous scattering where the material is excited only with the pump and no external signal is applied to the material, the spontaneously generated photons get amplified as they travel through the material. The power of the spontaneous photons comes from the pump input. If the pump input power is increased, the power in the stokes also increases and the input power at which both the powers become equal is known as the Raman Threshold. One must note the fact that...
Raman threshold does not signify the onset of stokes waves in the material. It is merely the input power level for a given length of an optical fiber, at which the power in the stokes waves equals the input pump power. Stokes waves are generated even when the input pump power is below the Raman threshold. The Raman threshold can, thus, be defined as:

$$P_s(z) = P_p(z) = P_{p(z=0)}e^{-\alpha_p z}$$  

(37.14)

The quantity $P_{p(z=0)}$ is the input power to the fiber at $z=0$ and is given by the product of the pump intensity $I_{p(z=0)}$ and the effective fiber area $A_{eff}$. We may also assume that for wavelengths near 1550nm, the attenuation constants of the optical fiber for the pump signal and the input signal are almost equal, i.e. $\alpha_p = \alpha_s$. We can, hence, use this assumption in equation (37.14) and obtain:

$$P_{s(z=0)} \exp \left\{ g_R(\Omega)P_{p(z=0)} \frac{L_{eff}}{A_{eff}} \right\} \approx P_{p(z=0)}$$  

(37.15)

Using the above equation for the assumed parameters, we obtain:

$$g_R(\Omega)P_{p(z=0)} \frac{L_{eff}}{A_{eff}} \approx 16$$  

(37.16)

For an optical fiber with an attenuation coefficient of 0.2dB/Km, the effective length, which is approximately equal to the reciprocal of the attenuation constant, is about 20Km. The Raman gain coefficient is about $10^{-13}$ at wavelength of 1µm and the effective area of a typical optical fiber is about 50µm². Substituting these parameters in equation (37.16), we obtain the value of the threshold power as:

$$P_{p(z=0)} \approx 600mW$$  

(37.17)

For a single mode optical fiber carrying only a single channel, the above threshold power level is rarely reached as the input power to the single mode fiber is generally about a few milliwatts. However, in case of WDM systems, where the optical powers are larger in magnitude, the above threshold may be reached and considerable amount of input power may be converted into stokes waves. One must note the fact that generation of stokes waves is a natural phenomenon occurring in glass whenever light propagates inside glass. A small portion of the input optical power is down-shifted to generate stokes waves. Thus, generation of stokes waves takes place on any fiber because it is an intrinsic property of glass. This observation eases out the construction of an optical amplifier without requiring any special modifications to be made to the basic optical fiber. The only requirement is to provide for the pump input to the optical fiber. The power from this pump input then gets gradually transferred to the signal and the signal, thus, gets amplified inside the fiber. Also, since there is no special lumped device as in case of EDFA, the above amplification takes place throughout the length of the optical fiber as long as the pump signal exists to supply power to the input signal. This observation realizes the distributed amplifier that was the initial motivation behind the discussion. Also, there exists no restriction to the relative direction of the pump and the input signals. Therefore, like the EDFA, one may have co-directional or counter-directional amplification schemes and the signal amplification would take place through the Raman Scattering mechanism.
One may now wonder about the practical implications of the Raman Scattering in an optical communication system. Since the Raman Scattering is an one sided phenomenon, whenever there is a frequency on an optical fiber, we also have down-shifted frequency. This means, in WDM systems, each frequency component acts as a pump because a small portion of each frequency component generates its own down-shifted frequency which is 13THz lower than itself. And each frequency component is also a signal because it receives power from a corresponding frequency which is 13THz higher (in case of the peak). But in principle, since the Raman spectrum is a distributed spectrum, in a WDM system, every frequency receives power from its higher frequency and every frequency loses power to its lower frequency. However, the above process of loss of power to lower frequencies is a systematic phenomenon. That is, the highest frequency would transfer power to all the lower frequencies; the second highest frequency would lose power to frequencies lower than itself and so on. In other words, due to the above exchange of power between different frequencies, there occurs some sort of cross-talk between the different channels in WDM systems due to Raman Scattering. Cross-talk is a highly undesirable phenomenon in data communications.

Before going into the details of cross-talk in WDM systems, let us have a comparative understanding of the Raman amplification mechanism with that of an EDFA. The following figure shows the manner in which a Raman amplifier and an EDFA amplify the optical signal:

![Figure 37.6: Signal Amplification by an EDFA and a Raman Amplifier](image)

The section of the optical fiber represents a long haul optical communication link in which the loss on the optical fiber causes the signal to attenuate with distance. However, the periodically placed EDFAs (represented by arrows) amplify the signal at appropriate points and as a result we obtain a saw-tooth type of signal amplification profile with large variations in signal level. But with a Raman amplifier which provides a distributed amplification, the signal level almost remains steady in comparison to that in case of an EDFA and the variation in the signal levels is small as shown in the above figure.
Secondly, in case of WDM systems we have already stated that higher frequencies lose power to lower frequencies in a systematic manner. Therefore, the power in the lower frequencies (higher wavelengths) shows a gradual increase as compared to that in case of absence of Raman scattering. This leads to cross-talk in a WDM system which is shown in the following figure:

![Figure 37.7: Cross-talk in Raman amplification](image)

The query that comes to the mind is that what is the power penalty to be paid in case of Raman Scattering in WDM systems so that the performance of the system even in the presence of cross-talk remains unaltered? To answer this question, let us have a simple analysis as discussed below:

Let us consider a DWDM system with $N$ equally spaced channels with a wavelength separation of $\Delta \lambda = 0.8\text{nm}$ between two consecutive channels. Let us assume the bandwidth of the Raman amplifier gain to be $\Delta \lambda_R \sim 125\text{nm}$ and the value of the Raman gain coefficient $g_R$ to be $6 \times 10^{-14}\text{m/W}$. Now, because of Raman scattering, power from the lower wavelengths would get coupled to all the higher wavelengths. Therefore, power coupled from the $0^{th}$ channel to the $i^{th}$ channel is given as:

$$P_0(i) = g_R \frac{\Delta \lambda}{\Delta \lambda_R} \cdot \frac{P_{I_{\text{eff}}}}{2A_{\text{eff}}}$$  \hspace{1cm} (37.18)

Due to the above loss in power to the lower channels, the power in the $0^{th}$ channel would decrease. The total loss in power in the $0^{th}$ channel as a result of power coupling to the lower channels can be determined by addition of all the coupled powers to the channels. That is:
\[ P_0 = \sum_{i=1}^{N-1} P_0(i) = gR \frac{\Delta \lambda}{\Delta \lambda_R} \cdot \frac{P_{L_{\text{eff}}}}{2A_{\text{eff}}} \cdot \frac{N(N-1)}{2} \]  

(37.19)

Thus the power penalty \( \delta \) that needs to be supplied to the 0th channel to maintain the required SNR on the channel is given by:

\[ \delta = -10 \log(1 - P_0) \]  

(37.20)

It is always desirable to have a lower value of the power penalty in WDM systems. For \( \delta < 0.5 \text{dB}; P_0 < 0.1 \), i.e. \( NP(N-1)\Delta \lambda L_{\text{eff}} < 40000 \text{mW} - \text{nm} - \text{Km} \) (with chromatic dispersion present, it can be relaxed to \( 80000 \text{mW} - \text{nm-Km} \)), the maximum power required per channel to avoid coupling between different channels due to Raman effect can be plotted as a function of link length as shown below:

\[ \text{For } \delta < 0.5 \text{dB}; P_0 < 0.1 \quad \text{i.e.,} \]

\[ NP(N-1)\Delta \lambda L_{\text{eff}} < 40000 \text{mW-nm-km} \]

With chromatic dispersion present, it can be relaxed to \( 80000 \text{mW-nm-km} \)

\textbf{Figure 37.8:} Power per channel required for desired performance

Clearly, we can see that, as the link length increases, the power per channel decreases which suggests that power cannot exceed the given limit at any point of time in order to ensure satisfactory performance of the system. The above plot can also be plotted with different axes of reference as shown below:

\textbf{Figure 37.9:} Power Vs Number of Channels

It can be seen that as the number of channels increases, the power required per channel decreases. Also, as the power per channel decreases, the link length decreases because there is a minimum power required by the detector for the successful detection of the optical signal as we had discussed in case of optical detectors.
Thus Raman scattering provides us with a distributed amplification mechanism which was the basic requirement for Solitonic propagation. However, the same scattering phenomenon also introduces cross-talk between different channels in a WDM system. To avoid cross-talk, the power level in any channel cannot be allowed to exceed certain limits so that the total power inside the optical fiber at any point of time does not exceed the pre-determined limit to ensure desired performance of the system. These limits, in turn, limit the inter-repeater distance on a long-haul optical communication link which are installed to maintain the required SNR on the channels.

One may, now, wonder- what would be the spectral distribution of the output of an optical fiber to which a high power pump signal is provided as input? To answer this question let us first have the spectral distribution of the output:

![Figure 37.10: Output spectrum of a High power pump input to an Optical fiber](image)

The pump signal gives rise to a stokes frequency due to Raman scattering which is shown as the 1\textsuperscript{st} stokes. As the power level of the 1\textsuperscript{st} stokes is large enough, it gives rise to a stokes frequency of its own which is denoted as the 2\textsuperscript{nd} stokes. Again, the power in the 2\textsuperscript{nd} stokes being considerably large, a 3\textsuperscript{rd} stokes frequency gets generated and this process continues till the power level in the subsequent stokes reduce to such low values that no further significant stokes get generated.