4.4.1.4 Gain Saturation

The gain saturation occurs when the signal power increases, the amplifier saturates and cannot produce any more output power, therefore the gain reduces. Saturation is also commonly known as gain compression. The gain saturation is occurring in RFA due to the SBS effect, when the input signal exceeds the SBS threshold, a portion of the input signal is reflected in opposite directions with red shift about 0.08 nm in wavelength. While the gain reduces in EDFA due to the following;

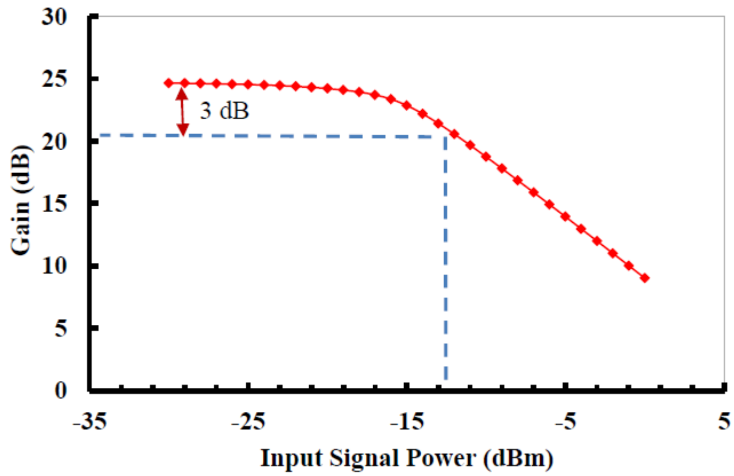

Figure 4.3: Gain saturation.

4.4.2 Power Conversion Efficiency

Power conversion efficiency (PCE) or sometimes known as pump conversion efficiency describes the relation between pump–to–signal power conversion efficiency. PCE is defined as:

$$PCE = \frac{P_s(L) - P_s(0)}{P_0} \times 100$$

Where: Ps(0), Ps(L) and P0 are the input, output signal power and input pump power, respectively.

4.4.3 Noise Figure

The optical noise figure is a parameter used for quantifying the noise penalty added to a signal due to the insertion of an optical amplifier. That is, before the light enters an amplifier the signal to noise ratio is SNR_{in}, after amplification it is SNR_{out}. Thus, the optical noise figure

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can be defined as ratio between SNR_{in} to SNR_{out}. In other words, the noise figure represents the degradation in signal to noise ratio for the optical amplifier.

4.5 Erbium Doped Fiber Amplifier

The EDFA consists of three basic components; erbium doped fiber, the pump laser source, and wavelength selective coupler combine the signal and pump wavelengths, as shown in Figure 4.4. The optimum fiber length used depends upon the pump‟s power, input signal power, amount of erbium doping, and pumping wavelength [49].

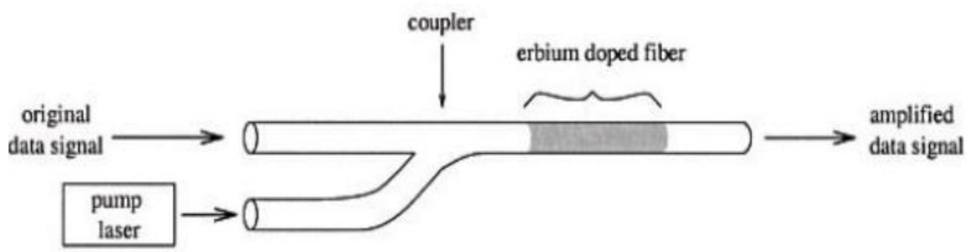

Figure 4.4: Erbium Doped Fiber Amplifier [43].

The EDFAs can be extensively used in optical fiber communication systems due to their compatibility with optical fiber. An EDFA has a comparatively wide wavelength range of amplification, rendering it useful as a transmission amplifier in WDM systems. Theoretically, EDFA is capable of amplifying all the wavelengths, ranging from 1500-1600 nm. However, practically, there are two communication windows; the C and L bands. This allows the data signal to stimulate the excited atoms to release photons.

Most EDFAs are pumped by lasers with a wavelength of either 980 nm or 1480 nm [43]. The 980 nm pump wavelength showed gains efficiencies of around 10 dB/mW, while the 1480 nm pump wavelength results in efficiencies of around 5 dB/mW. Typically, the gains are about 25 dB, while the noise figure lies between 4–5 dB with forward pumping, and equivalent figures for backward pumping are 6–7 dB, assuming 1480 nm pumping light was used.

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4.5.1 Amplification Mechanism

The basic theories on optical amplification based on EDFs are presented in this section. Incident light was amplified using amplifiers via stimulated emission, which is similar to the mechanism utilized by lasers for the same purpose. In EDFs, optical gain is supplied by excited erbium ions (Er3+) when the amplifier is pumped to prompt population inversion. Based on the energy state of the dopant, the pumping schemes can be classified as a 3–level or 4–level scheme, as shown in Figure 4.5.

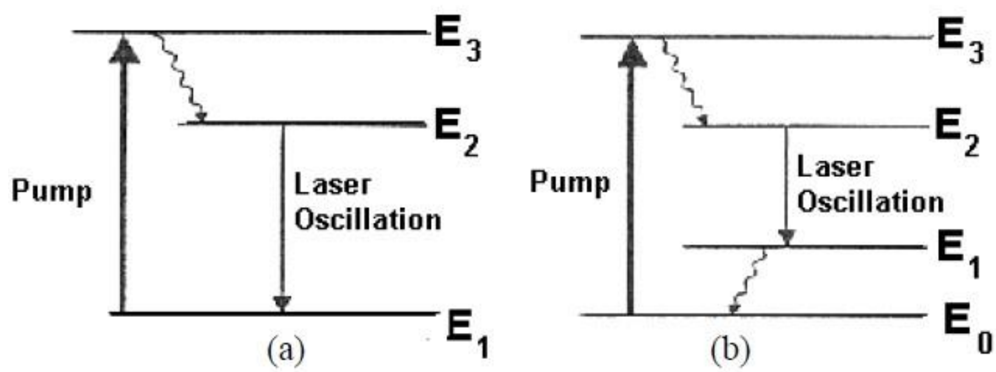


Figure 4.5: Schematic illustration of (a) Three level pumping scheme (b) Four level pumping scheme [52].

In the context of both cases, the dopants were excited to a higher energy state by absorbing the pump photons, followed by rapid relaxation to a lower excited state (state 2). This energy amplified a signal beam via stimulated emission; the energy is sent from the pump to the signal. 3–level and 4–level pumping schemes differ based on the energy state occupied by the dopant post-stimulated emission. For the three level scheme, the lower level is the ground state, while in the four level scheme, the ground state is the excited state that comes with a fast relaxation time. This difference makes stronger pumping for the 3–level scheme necessary to realize population inversion [53].

4.5.2 Gain Saturation

The gain is achieved in EDFA due to population inversion of the dopant ions. The inversion level of the EDFA is set, primarily, by the power of the pump wavelength and the power at the amplified wavelengths. As the signal power increases, the inversion level will reduce and thereby the gain of the amplifier will be reduced. This effect is known as gain saturation – as the signal level increases, the amplifier saturates and cannot produce any more output power, and therefore the gain reduces. Saturation is also commonly known as gain compression. To achieve optimum noise performance DFAs are operated under a significant amount of gain compression (10 dB typical), since that reduces the rate of spontaneous emission, thereby reducing ASE. Another advantage of operating the DFA in the gain saturation region is that small fluctuations in the input signal power are reduced in the output amplified signal: smaller input signal powers experience larger (less saturated) gain, while larger input powers see less gain. The leading edge of the pulse is amplified, until the saturation energy of the gain medium is reached. In some condition, the width (FWHM) of the pulse is reduced.

4.6 Raman Fiber Amplifier

The transformation of a small fraction power from the incident light to the scattered light is called the spontaneous Raman scattering. This phenomenon was discovered by C. V. Raman in 1928 [57]. Generally, the frequency of the scattered light differs from those of the incident light by an amount defined by the vibrational levels of the medium. The spontaneous Raman scattering is regarded as a weak process. For example, if the light is propagated through a medium with a volume of 1 cm3, only one part of the millions of the incident light will be scattered into the Stokes frequency.

However, if an intense laser source is incident on a molecular medium, there might be an occurrence of high scattering component, and more than 10% of the incident power is transferred to the scattering components [58]. This type of nonlinear scattering was discovered in 1962, called the stimulated Raman scattering (SRS) phenomenon [59].

Biswanath Mukherjee described in [43] the fundamental advantages of a Raman amplifier. First, Raman gain exists in every fiber, which provides a cost–effective means of upgrading the terminal ends. Second, the gain is non-resonant, which is available over the entire transparent region of the fiber. The third advantage of Raman amplifiers is that the gain spectrum can be tailored by adjusting the pump‟s wavelengths. For instance, multiple pump lines can be used to increase the optical bandwidth, and the pump distribution determines the gain‟s flatness. Another advantage is that it is a relatively broadband amplifier, with a bandwidth of > 5 THz, and the gain is reasonably flat over a wide wavelength range.

4.6.1 Amplification Mechanism

The SRS process is governed by the following set of two coupled ordinary differential equations [14]:

$$\frac{dP_S}{dz} = g_R P_P P_S - \alpha_S P_S \qquad \textbf{(Equation 4.1)}$$

$$\frac{dP_P}{dz} = -g_R P_P P_S - \alpha_P P_P \qquad \textbf{(Equation 4.2)}$$

Where g_R is the Raman gain coefficient of the fiber normalized with respect to the effective area of the fiber A_{eff}, α_S and α_P are the attenuation coefficient at the Stokes and pumps wavelength respectively, P_S and P_P are Stokes and pump intensity.

(**Equation 4.1**) and (**Equation 4.2**) show that the signal receives gain proportional to the pump power with a constant proportion given by the Raman gain efficiency and loss due to the attenuation of optical fiber, while the pump power receives loss due to the energy transfer to the Stokes and the attenuation of optical fiber.

In many practical situations, pump power is so large compared with the signal power that pump depletion can be neglected for the purpose of estimating the Raman gain. The (**Equation 4.2**) is easily solved if the first term on its right side is neglected and the result is:

$$P_P(z) = P_P(0)e^{-\alpha z}$$ (**Equation 4.3**)

Where $P_P(0)$ is the input pump power at z = 0. (**Equation 4.3**) is substituted into (**Equation 4.1**) and the result is [15]:

$$\frac{dP_S}{dz} = g_R P_P(0)\exp(-\alpha_P z)P_S - \alpha_S P_S$$ (**Equation 4.4**)

(**Equation 4.4**) is easily solved by integrating it over the fiber length L, and the Stokes intensity will be as:

$$P_S(L) = P_S(0)\exp(\frac{g_R}{A_{eff}} P_o L_{eff} - \alpha_S L)$$ (Equation 4.5)

The effective fiber length is reduced from L -to- L_{eff}, due to fiber losses, and it is given by:

$$L_{eff} = [1 - \exp(-\alpha L)]/\alpha$$ (Equation 4.6)

The unsaturated gain is defined as the ratio of the output signal to the input signal:

$$G(L) = \frac{P_S(L)}{P_S(0)} = \exp(\frac{g_R}{A_{eff}} P_o L_{eff} - \alpha_S L)$$ (Equation 4.7)

The quantity G (L) represents the net signal gain and can be even<1 (net loss) if the Raman gain is not sufficient to overcome fiber losses. It is useful to introduce the concept of the on–off Raman gain using the definition:

$$G_A = \frac{P_s\ (L)\ \text{with pump on}}{P_s\ (L)\ \text{with pump off}} = \exp\left(g_R P_0 L_{\text{eff}}\right)$$ (Equation 4.8)

4.7 Examples

Example:1 Amplifier gain = 37 dB

Power in = 0.003 mW

What is the power out ?

P_{dBm} = -25.2 dBm

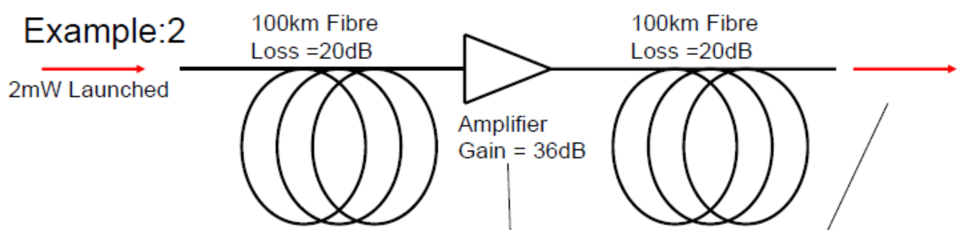
P_{out} = P_{in} + G_{amp}

= -25.2 + 37

= 11.8 dBm

= 15 mW

Example:2

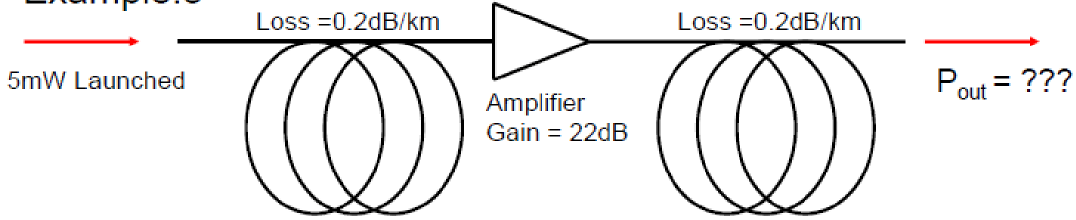


What is P_{out} ?

P_{in}= 2mW = 3dBm

P_{out} = 3 – 20 + 36 –20 dBm = -1 dBm = 0.1mW

Example:3



Coupled power = 7dBm

First fibre loss = 140 x –0.2 = -28dB (-21dBm)

Amplifier Gain = +22dB (1dBm)

Second fibre loss = 100 x –0.2 = -20dB (-19dBm)

Output power = -19dBm = 0.012mW

4.8 PROBLEMS

Q1: Why the Need for Optical Amplification?

Answer:

Semiconductor devices can convert an optical signal into an electrical signal, amplify it and convert the signal back to an optical signal. However, this procedure has several disadvantages:

1. Costly
2. A large number is required over long distances
3. Noise is introduced after each conversion in analog signals
4. Restriction on bandwidth, wavelengths and type of optical signals being used, due to the electronics

By amplifying signal in the optical domain many of these disadvantages would disappear.

Q2:

A Raman amplifier is pumped in the backward direction using 1 W of power. Find the output power when a 1 μW signal is injected into the 5 km-long amplifier. Assume losses of 0.2 and 0.25 dB/km at the signal and pump wavelengths, respectively, Aeff = 50 μm^2, and $g_R = 6\times10^{-14}$ m/W. Neglect gain saturation.

Answer:2.7 μW

Q3- using the coupled equations to prove that the Raman on-off gain is:

$$G_A = \frac{P_s(L)\text{ with pump on}}{P_s(L)\text{ with pump off}} = \exp(g_R P_0 L_{\text{eff}})$$