Module 15 : ERBIUM DOPED FIBER AMPLIFIERS (EDFA)

Lecture : ERBIUM DOPED FIBER AMPLIFIERS (EDFA)

Objectives

In this lecture you will learn the following

- **Composition of Rare Earth Doped Fiber**
- **Principle of EDFA**
- **Rate Equations**
- **Gain**

ERBIUM DOPED FIBER AMPLIFIERS (EDFA)

1. Introduction :

In optical communication network, signals travel through fibers for very large distances without significant attenuation. However, when distances become hundreds of kilometers, it becomes necessary to amplify the signal during transit. Optical fiber amplifiers provide in-line amplification of optical signals by effecting stimulated emission of photons by rare earth ions implanted in the core of the optical fiber. Erbium is the preferred rare earth for this purpose though amplifiers using Praseodymium are also in use. EDFAs are used to provide amplification in long distance optical communication with fiber loss less than0.2 dB/km by providing amplification in the long wavelength window near 1550 nm.
The principle of rare earth doped fiber amplifier is the same as that of lasers excepting that such amplifiers do not require a cavity whereas a cavity is required for laser oscillation.
Advantages of EDFA are as follows:

- It provides in-line amplification of signal without requiring electronics i.e., the signal does not need to be converted to

  electrical signal before amplification. The amplification is entirely optical.
- It provides high power transfer efficiency from pump to signal power.

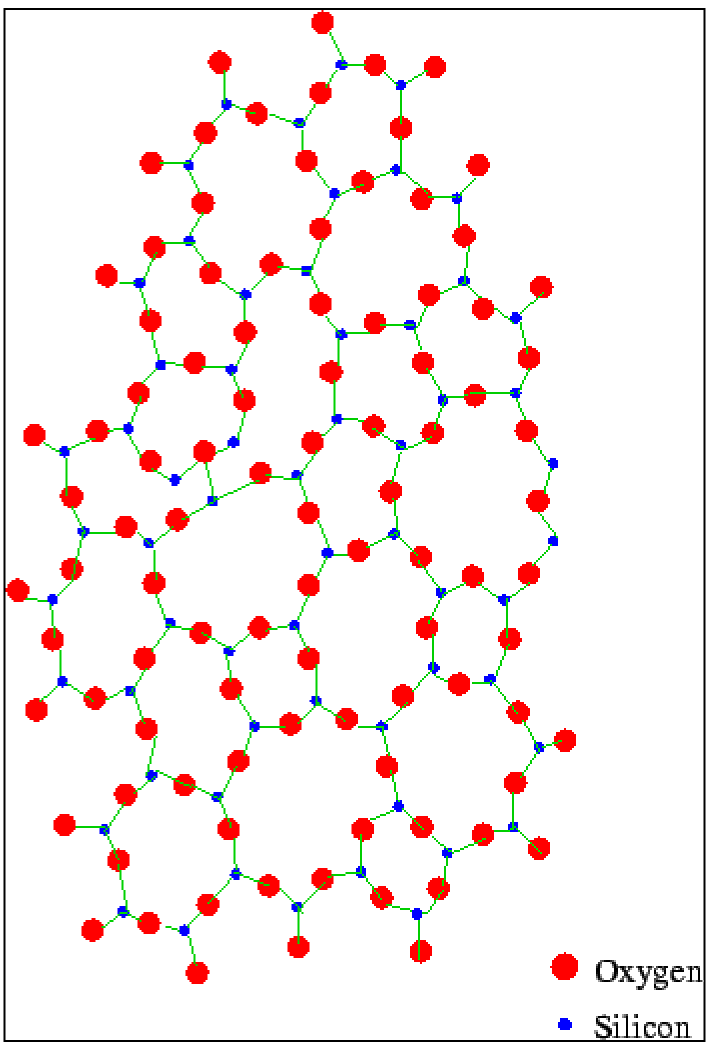
- The amplification is independent of data rate.

- The gain is relatively flat so that they can be cascaded for long distance use.

  On the debit side, the devices are large, there is gain saturation and there is also presence of amplified spontaneous emission (ASE).

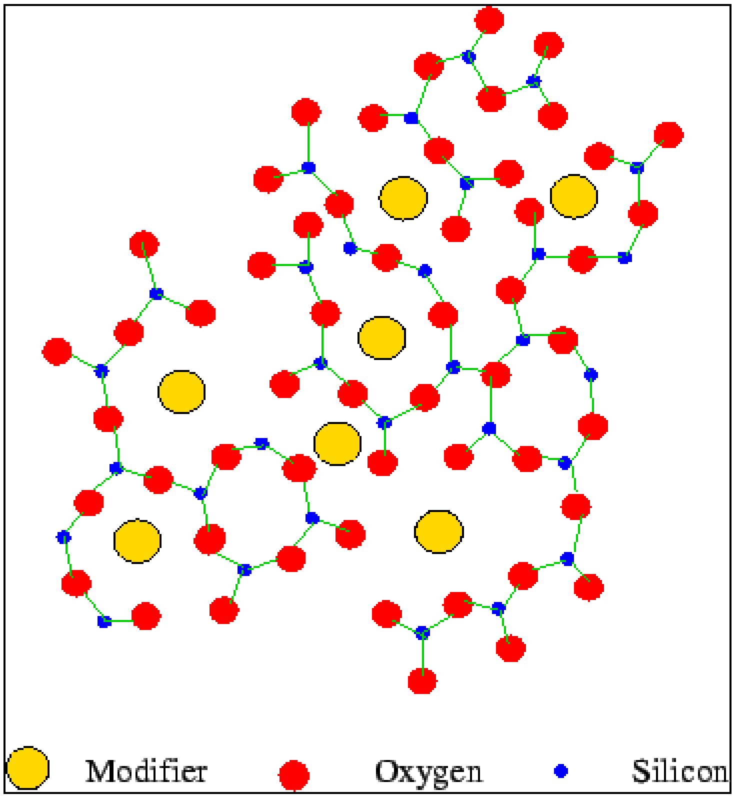
2. Composition of Rare Earth Doped Fiber :

The fiber core consists of glassy material such as SiO_2 and GeO_2. Rare earth ions like Er, Pr are doped into the core. The cladding material is mainly SiO_2.
Glass is, in reality, a liquid with such high viscosity that it mimics a solid, though with disordered arrangement of atoms as in the case of a liquid. As a material for lasr host, glass has several advantages over other solid state material, e.g., transparency, high optical damage threshold, optical quality etc. Oxides, such as SiO_2, GeO_2, Sb_2O_3 etc. which can form glassy structures either by themselves or in combination with other oxides having similar properties are called **glass network formers** .

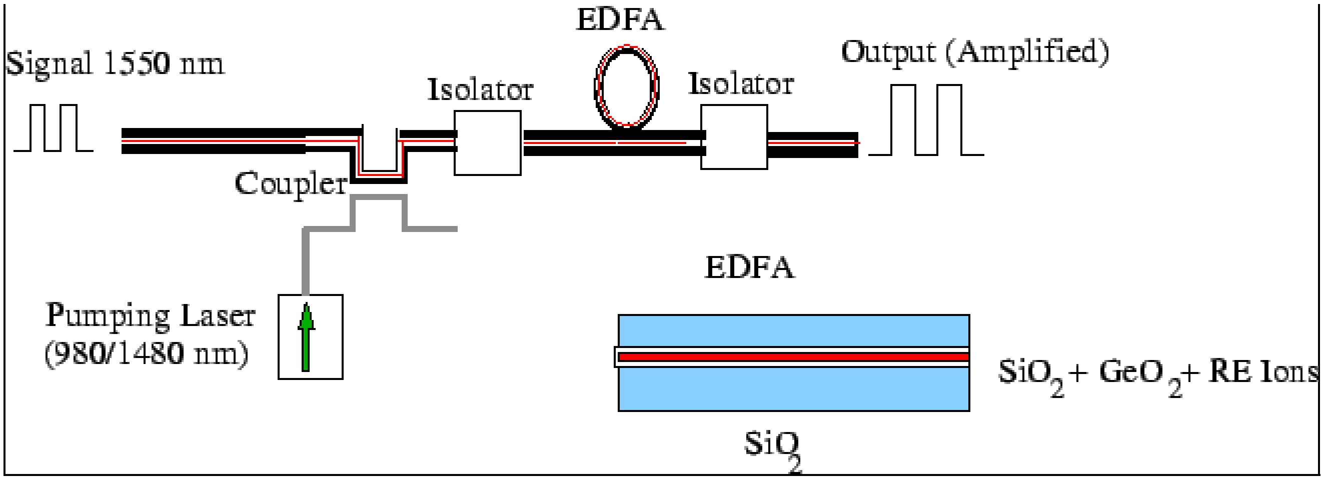


Oxides of alkali metals and those of alkaline earth metals which cannot form glass by themselves but can form glassy structure with network formers mentioned above are known as network modifiers as they modify structure of glass network. Their addition reduces the bond strengths and viscosity of glass. However, their addition assumes importance as pure silica glass can be processed only at very high temperatures whereas addition of modifiers makes it feasible to process them at room temperatures.

Transition metal oxides, such as, TiO_2, Al_2O_3, SnO_2 etc. which are known as intermediates, have strong absorption in visible and in the near infrared. If such oxides are present in the glass network, they will cause losses. Hence such impurities must be removed from the host.



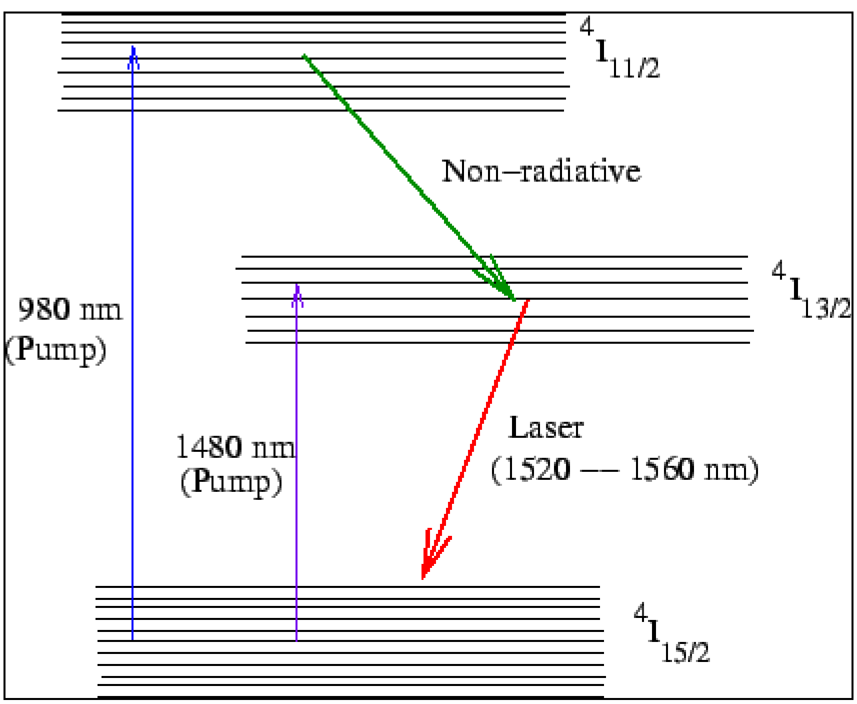
An alternative to using oxide glass is to use fluorozirconate (ZrF_4) glass. commonly known as ZBLAN glass. Though its glassy structure is not fully understood, it provides a good host for rare earth ions. The major glass forming components of ZBLAN glass are Al (which along with Zr, acts as a glass former), La (intermediate), Ba and Na (network modifiers). The La atoms are easily substituted by rare earths such as Er.



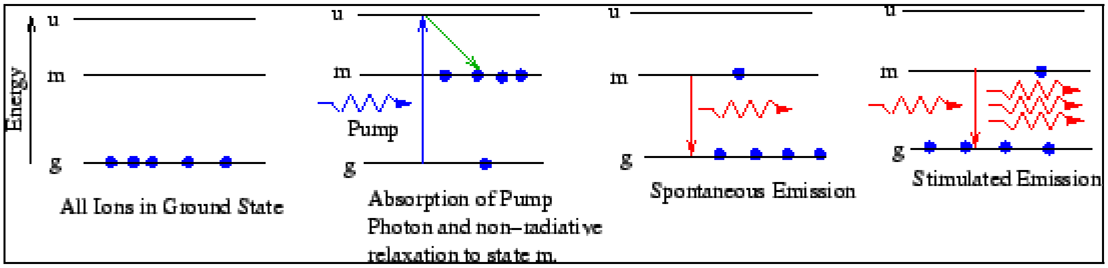
The figure above shows a typical configuration of EDFA based communication system. The optical output is first passed through an optical isolator which prevents reflection, i.e. allows light to move from left to right. The coupler allows the pump input to be fed into the fiber with minimum loss.

3. **Principle of EDFA:**

Energy levels of Er^{3+} doped system is shown in the figure. It may be noted that the energy levels form three groups of energy levels marked with their specroscopic notations. For simplicity, we will model these three groups of energy levels by three sharp levels of energy denoted by u, m and g, representing respectively the upper, the metastable and the ground states.



In the absence of any radiation, the ions are in their ground states g. If a beam of light of appropriate frequency is incident on the system, the ions will be excited to the higher levels. This radiation, called **pump radiation** , if chosen at 980 nm, will excite the ions to the level u. The lifetime of the ions in the level u is approximately $1\mu s$. The ions readily decay to the metastable level m by ***non-radiative*** transition, i.e. by releasing heat.



Pump can also work directly at 1480 nm to excite the ions directly to the metastable level m. In this case, rapid relaxation would occur to the lowest sub-level within the group of levels m from which laser action would take place. Though pumping with 1480 nm is used and has an optical power conversion efficiency which is higher than that for 980 nm pumping, the latter is preferred because of the following advantages it has over 1480 nm pumping.

- It provides a wider separation between the laser wavelength and pump wavelength.
- 980 nm pumping gives less noise.
- Unlike 1480 nm pumping, 980 nm pumping cannot stimulate back transition to the ground state.

The excited ions make transition to the ground state, either by

(i) **Spontaneous Emission :**
Spontaneously emitted photons bear no phase relationship with one another. It can take place in the entire bandwidth of transition and can even travel backwards. These, therefore, contribute to noise. A fraction of the spontaneously emitted photons will be emitted in a direction which is within the numerical aperture of the fiber and will, therefore, be captured and guided. Such photons, in turn, may interact with rare earth ions and be amplified as well. The **Amplified Spontaneous Emission (ASE)** is a major source of noise in the system. For low signal power, ASE is approximately independent of the signal but at high signal power, ASE reduces population inversion faster than the pumping rate.

(ii) **Stimulated Emission :**

The stimulated emission takes place in the wavelength window 1520 to 1560 nm if a data signal with the corresponding wavelength is fed into the fiber. The newly generated photons by stimulated emission are responsible for amplification of signal as it travels along the fiber.

We know that population inversion cannot be achieved in a two level system. However, 1480 nm pumping directly to the metastable level can give rise to population inversion because the levels in case of Er^{3+} are actually sets of closely

spaced levels.

Amplification Window :

EDFA can be used to amplify signal in two bands of wavelengths in the third transmission window. The wavelength range 1525 nm to 1565 nm is known as the C-band or the conventional band and trhe second band from 1568 nm to 1610 nm is known as the L-band or the long band. The name long band is given because the doped section used for this band is longer.

4. Rate Equations :

Let N_u, N_m and N_g denote the population of the three states. If W_p is the pumping rate, W_s is the rate of absorption of photons from the signal and τ_{ij} is the lifetime of spontaneous emission from the state i to the state j, we can write the following rate equations :

$$\frac{dN_g}{dt} = \frac{N_m}{\tau_{mg}} + W_s(N_m - N_g) - W_p(N_g - N_u) \quad (1)$$

$$\frac{dN_m}{dt} = \frac{N_u}{\tau_{um}} - W_s(N_m - N_g) \quad (2)$$

$$\frac{dN_u}{dt} = -\frac{N_u}{\tau_{um}} + W_p(N_g - N_u) \quad (3)$$

Population inversion implies that $N_m > N_g$. For steady state conditions, the time derivatives vanish. Since the lifetime of the state u is much smaller than the lifetime of the state m, the population of the excited state is essentially given by the Boltzmann distribution

$$N_u = N_m e^{-(E_u - E_m)/kT} \equiv \beta N_m \quad (4)$$

where $\beta = e^{-(E_u - E_m)/kT}$. From Eqn. (1), we have, for steady state conditions

$$\frac{N_m}{\tau_{mg}} + W_s(N_m - N_g) - W_p(N_g - N_u) = 0$$

which can be simplified using Eqn. (4) to give the **inversion level** as

$$n = \frac{N_m}{N_m - N_g} = \frac{(W_p + W_s)\tau}{W_p\tau(1-\beta) - 1}$$

The inversion level is thus related to both the pump and signal powers and also to the pump wavelength through the Boltzmann factor.
The factor β explains why 980 nm pumping is more effective in achieving population inversion than 1480 nm pumping. It was seen that because of small lifetime of the level u, the ions thermalize to the level m. The energy difference between these two levels is substantial (~ 0.4 eV) as a result of which $\beta \simeq 0$. In case of 1480 nm pumping the thermalization occurs to the lowest energy sub-level within the group m. The value of β for this case is about 0.4.

For strong pumpimg ($W_p\tau \gg 1$) and small signal power ($W_s \approx 0$), the inversion factor almos becomes 1 in case of 980 nm pumping whereas for 1480 nm pumping the best one gets is about 1.6.

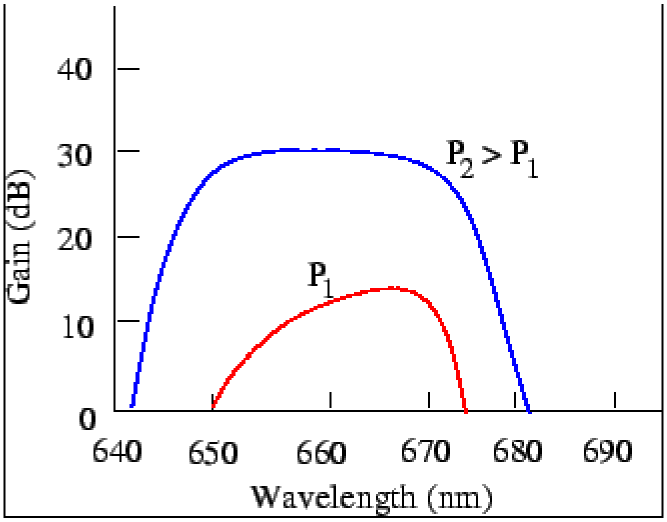
5. **Gain :**

The ratio of the output signal power to input signal power is the gain of an amplifier. It is conventional to specify gain in the logarithmic dB unit

$$\text{Gain (in dB)} = 10\log_{10}\frac{P_{out}}{P_{in}}$$

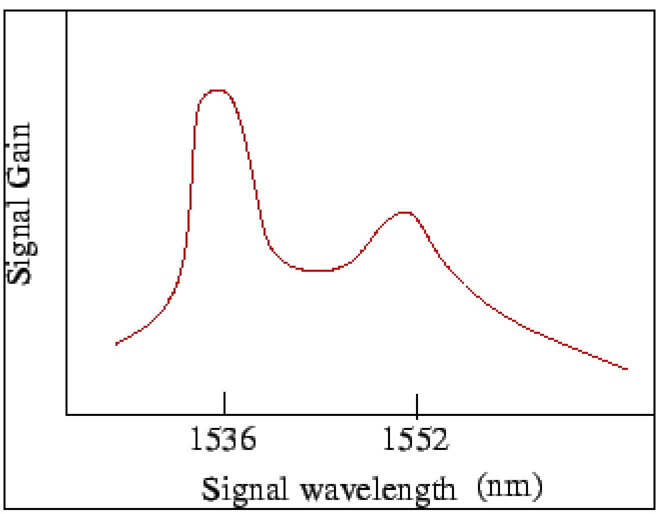
Gain of EDFA depends on the pump power as well as on the pump wavelength.

The figure alongside shows typical gain characteristics as a function of wavelength for two different levels of pump power. It may be seen that for small pumping power, the gain spectrum has a maximum at about $\lambda = 665$nm. However, as pump power increases, the gain becomes roughly independent of pump wavelength. The gain can be increased by reducing the temperature. at liquid nitrogen temperatures, the gain for a pumpingb power of 100 mW is approximately 30 dB.

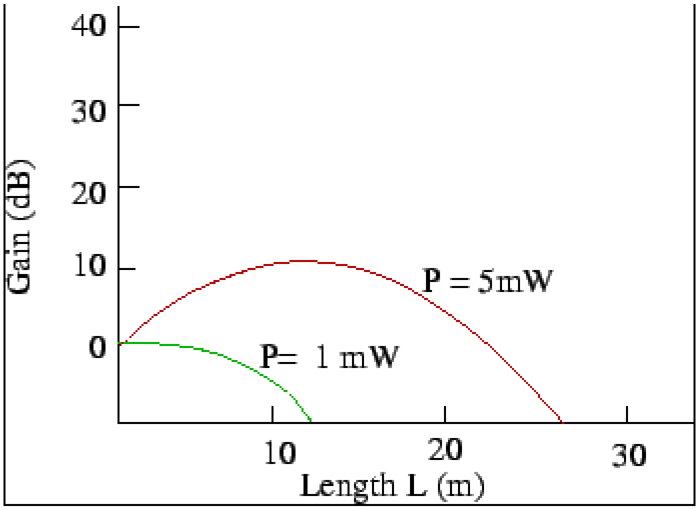


For a given pump power, the gain depends both on signal wavelength and the length of the EDFA section in the fibr. Typical gain spectrum against signal wavelength is shown in the figure below.

For a Ge/Er doped fiber, the gain spectrum has two peaks in the C-band, one at 1536 nm and the other at 1552 nm. ASE noise superposes the entire bandwidth. If the fiber host material is changed from silica to ZrF_4, flattening of the gain spectrum takes place. **Gain flattening** is required if EDFAs are to be cascaded. Relative flat gain greater than 20 dB is useful for WDM applications.



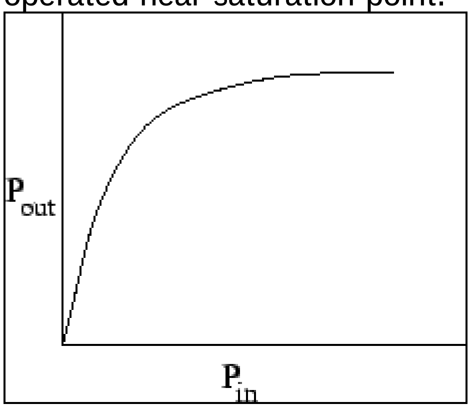
For a given pump power, the gain becomes maximum for an optimal value of the length L and it decreases again with further increase in length. Thus to maximize gain, one needs to optimize both pumping power and the length of the fiber.



Gain saturation :

Gain in EDFA is achieved due to population inversion of dopant ions. As there are limited number of dopant ions, increasing pumping power to a level at which all the dopant are excited will not increase the population of the excited level any further and the gain saturation will take place. Further as the input signal power increases, inversion level reduces and there will be no further amplification. The maximum output power beyond which no amplification occurs is called **gain saturation.**

The behaviour is different from that of electronic amplifiers where the gain curve is linear till saturation abruptly occurs. This results in signal distortion for an electronic amplifier that is operated near saturation point.



Noise Figure :

Noise figure is a measure of the quality of amplification. It is defined as the quotient of the signal to noise ratio (SNR) of the input signal to that of the output signal.

$$\text{N.F.} = \frac{(\text{SNR})_{input}}{(\text{SNR})_{output}}$$

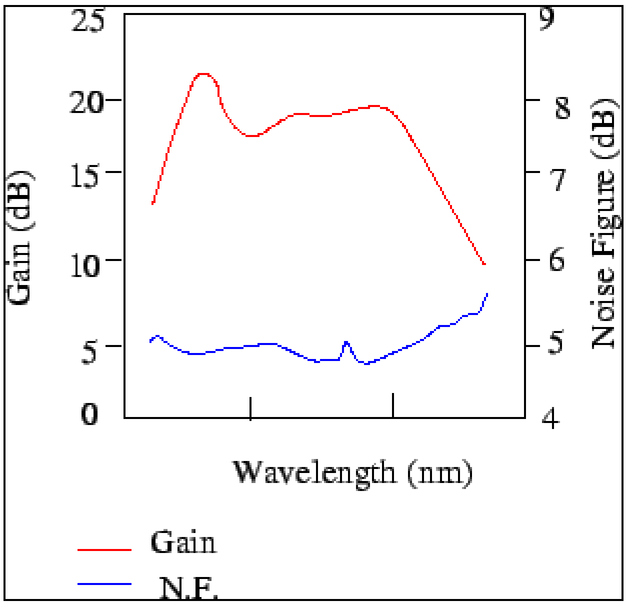
Due to ASE, the output SNR is smaller than that of the input and hence N.F. > 1, i.e. an optical amplifier cannot improve the optical signal SNR. Like gain, N.F. is also measured in logarithmic scale

$$\text{N.F.(dB)} = 10\log_{10}\text{N.F.}$$

The value of N.F. depends on the pump frequency. For large SNR values, an approximate expression for N.F. is given by

$$\text{N.F.} = \frac{1}{G}\left[1 + \frac{2P_{ASE}}{h\nu\Delta}\right]$$

where P_{ASE} is the noise power of ASE, ν is the pump frequency and Δ the bandwidth of EDFA. The noise figure thus depends both on the pump power and EDFA length.



Quantum mechanics puts a lower limit of 3 B to the optical noise figure at high optical gain. 980 nm pimping provides a value of 3.1 dB, close to the quantum limit whereas 1.48 μm pumping gives a value of 4.2 dB. 980 nm pumping also gives ahigher signal gain, the maximum gain coefficient being 11 dB/mW against 6.3 dB/mW for the 1.48 μm pumping. The reason for better performance of 980 nm pumping over the 1.48 μm pumping is related to the fact that the former has a narrower absorption spectrum.

References :

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Shoichi Sudo (eds.), Optical Fiber Amplifiers : Material, devices and applications, artech House Inc. (1997)
C. R. Pollock, Fundamentals of optoelectronics, Irwin (1995)

Recap

In this lecture you have learnt the following

- Composition of Rare Earth Doped Fiber
- Principle of EDFA
- Rate Equations
- Gain

Congratulations, you have finished Module 15. To view the next lecture select it from the left hand side menu of the page