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# Introduction to Optical Fibers and its Applications

Optical Amplifier.

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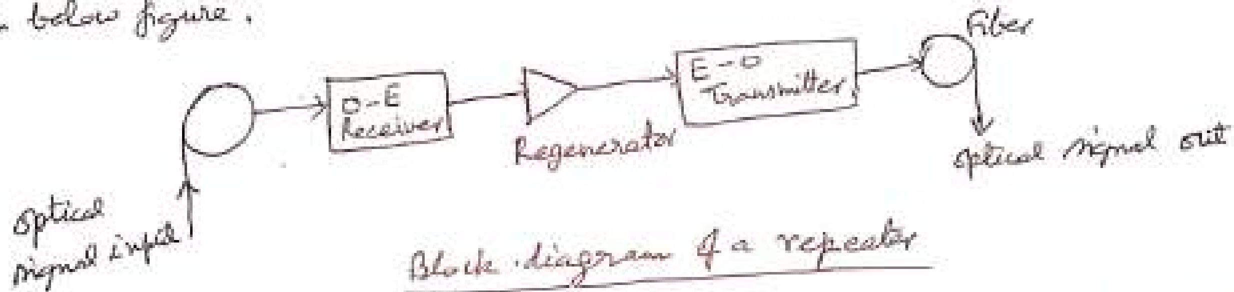
**Optical Amplifiers :-** The electrical-optical and optical-electrical conversion devices are crucial components for the realization of optical fiber communication. These devices are a limiting factor within the implementation of optical fiber systems. The conversion of the information signal from the electrical domain to the optical domain and vice-versa often provides a bottleneck within optical fiber communications which may restrict both the operating bandwidth and the quality of the transmitted signal. Performing operations on signals in the optical domain.

The above considerations have stimulated a growing activity in the area of active devices and components which allow optical signals to be manipulated without returning them back to the electrical regime where such operations have normally been carried out in the past.

✓ In long distance communication systems, the attenuation in fibers and various losses due to optical components, such as multiplexers and couplers, are compensated by inserting regenerative repeaters at equidistant points. Due to the cumulative loss of signal strength the signal becomes too weak to be detected, the signal strength has to be restored before the signal gets buried under background noise. This task is accomplished by a regenerative repeater.

The regenerative repeater converts the optical signal to an electrical signal and restores the signal, that is, it compensates for signal loss and dispersion, and converts the signal back into an optical signal for further transmission. The various functional blocks involved in regenerative repeaters are shown in below figure.




Block diagram of a repeater

× (The job of repeater is different than being only an amplifier) A repeater receives the signal, converts it to an electrical signal, re-clocks and re-shapes it, amplifies it, and converts it back to an optical signal before coupling the signal back in the optical fiber. It is important to mention that this process is code- and timing-sensitive. The repeaters have to be designed to handle the transmission code and the timing scheme. This process works well for moderate-speed, single-wavelength operation. It is complex and expensive for high-speed, multiple-wavelength systems.

Optical amplifiers, as their name implies, operate solely in the optical domain with no interconversion of photons to electrons. Therefore, instead of using regenerative repeaters which require optoelectronic devices for source and detector, together with electronic circuitry, optical amplifiers are placed at intervals along a fiber link to provide linear amplification of the transmitted optical signal.
The optical amplifier provides a much simpler solⁿ in that it is a single component which can be used for any kind of modulation at any transmission rate.

If analog modulation is used, then the situation becomes worse for fiber communications. Regeneration is impossible, because we do not know what the signal is supposed to look like. (In a digital system, we know that the data stream consists of only zeroes and ones. so we have a good chance to reconstruct each bit correctly. In an analog system, the choices of wavelengths are limitless. Conversion of an optical analog signal to electrical form for amplification and retransmission is expensive and noisy. 

Optical amplifiers have many advantages over repeaters, such as:

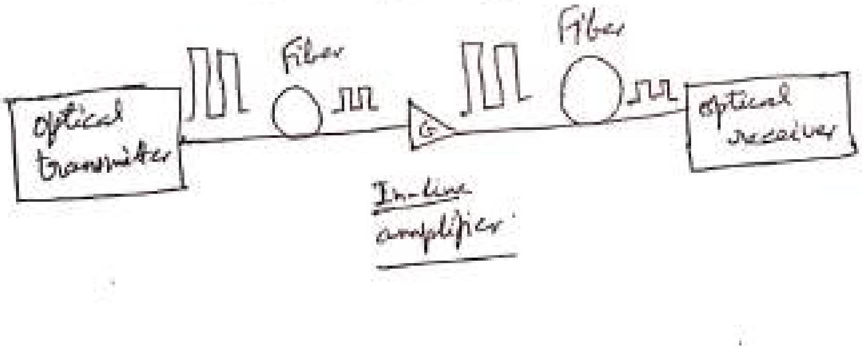
1. Optical amplifiers are insensitive to the bit rate or signal formats. Thus a system using optical amplifiers can be more easily upgraded to a higher bit rate, without replacing the optical amplifiers.
2. Optical amplifiers have fairly large gain bandwidths and as a consequence, a single amplifier can simultaneously amplify several wavelength division multiplexing (WDM) signals, in contrast to a ~~single~~ separate regenerator for each wavelength.

Basic Applications of Optical Amplifiers :- Optical amplifiers can be used in both linear and non-linear modes of operation. The common applications are shown below :

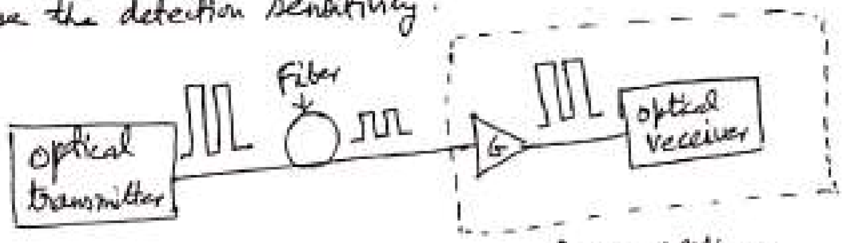
1. In-line optical amplifiers :- optical amplifiers are used as optical linear repeaters in a long-haul communication system.

In optical transmission systems that use single longitudinal mode laser, the effects of fiber despersion may be small, and the main limitation on repeater spacing is the signal attenuation as a result of fiber loss. Such systems do not require a complete regeneration of the signal at each repeater, and linear amplification of the signal is sufficient. Thus, linear optical amplifiers can be used as repeaters. The gain of each amplifier is chosen to compensate exactly for the signal loss incurred in the preceding fiber section of length L :

$$G = \exp(+\alpha L)$$

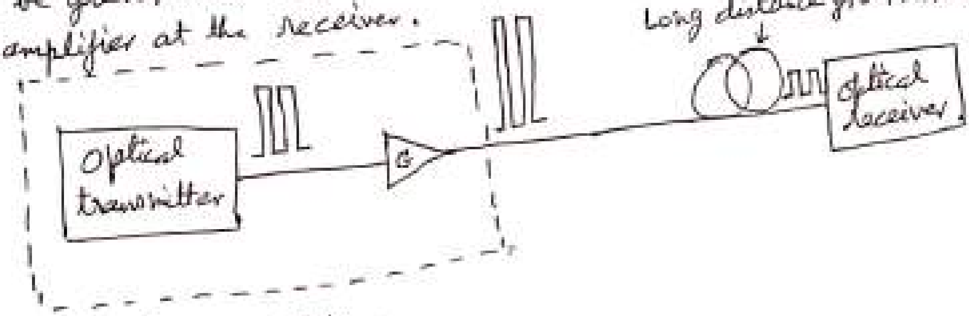


**2. Pre-amplifier :-** optical amplifiers are used as pre-amplifiers to boost weak optical signals before detection. Use of a semiconductor laser amplifier before a photodetector to linearly amplify the optical signal can increase the detection sensitivity.




Pre-amplifier

**(3) Buser or Booster amplifier :-** Power or booster amplifiers are placed immediately after an optical transmitter to boost the transmitted power. The amplifier inputs are generally -2dBm or greater, and the power amplifier gain must be greater than 5dB in order for it to be more advantageous than using a pre-amplifier at the receiver.



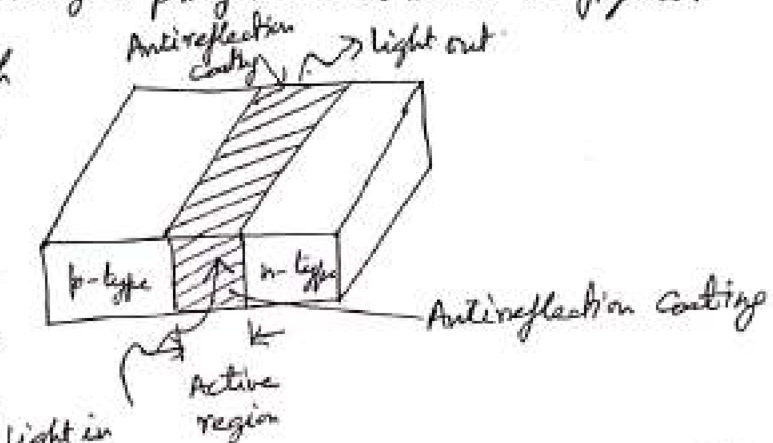

Power amplifier

**Types of optical Amplifiers :-** All optical fiber amplifiers increase the power level of incident light through stimulated emission or an optical power transfer process. Two main categories of optical amplifiers are as follows:

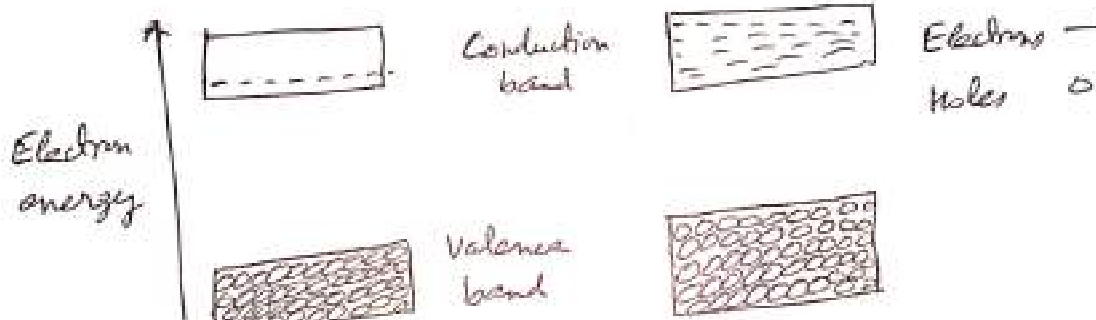
1. Semiconductor optical amplifiers (SOAs) / Cavity amplifier :- Here amplification is done by stimulated emission from injected carriers.
2. Fiber amplifiers (FA) :- Here amplification is provided by stimulated Raman scattering or doping with rare-earth materials, such as erbium (Er) or thulium.

## Semiconductor Optical Amplifier :- The SOA is based on the conventional semiconductor laser structure and is basically a pn junction as shown in figure.

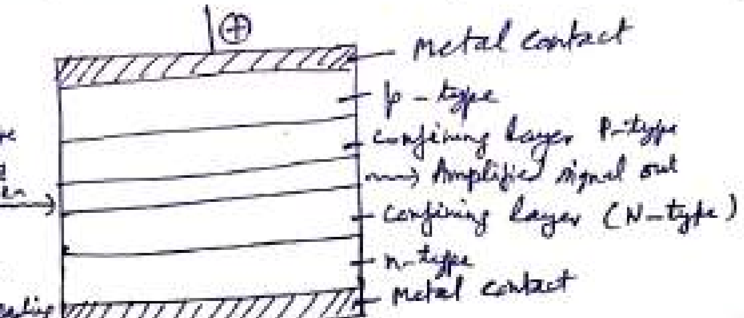
Light is amplified through stimulated emission when it propagates through the active region. The depletion region formed at the junction acts as the active region. The two ends of the active region are given an anti-reflection coating to eliminate ripples in the amplifier gain.




A semiconductor consists of two bands of electron energy levels: valence band and conduction band. These bands are separated by an energy difference called as band gap energy. In a p-type semiconductor material, shown in figure, at thermal equilibrium there is a small concentration of electrons in the conduction band. However, in the population inversion condition, the electron concentration is much higher. Population inversion is achieved by forward-biasing a pn junction.




In a pn junction, the holes diffuse from the p-type semiconductor to the n-type semiconductor, and electron diffuse from the n-type semiconductor to the p-type semiconductor and form a depletion region. When the junction is forward-biased, the width of depletion region reduces and there is a drift of electrons from the n-type region to the p-type region, which increases the electron concentration in the conduction band of the p-type region. This results in population inversion with a sufficiently high forward-bias. In this case, the pn junction acts as an optical amplifier.




Schematic diagram of an SOA.

When a forward bias is applied to the DH, electrons from the n-type semiconductor and holes from the p-type semiconductor travel towards the active layer where they get trapped in a low-band gap potential well. If the biasing current is large enough, large concentration of electrons and holes build up in the active layer, leading to population inversion. Signal photons passing through the active layer can stimulate radiative recombination of $\bar{e}$ and holes, resulting in the amplification of signal power.

## The following are the characteristics of a SOA :-

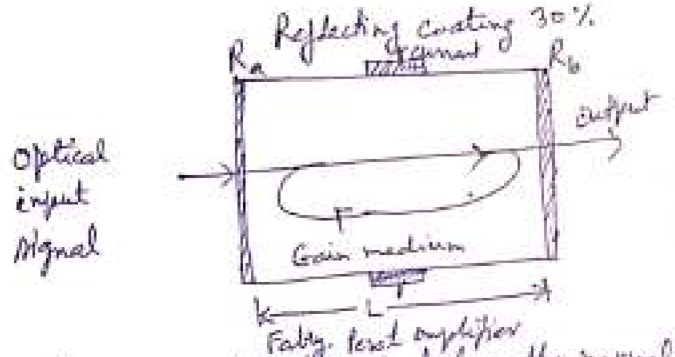
1. Polarization dependent – requires a polarization maintaining fiber.
2. Relatively high gain – 20dB
3. Output saturation power 5-10 dBm.
4. Large bandwidth.
5. Can operate in the 800 nm, 1300nm and 1500 nm wavelength region.
6. Compact and can be easily integrated with other devices.
7. Can be integrated into arrays.
8. High noise figure and crosstalk levels due to non-linear phenomena such as 4-wave mixing.

## Types of Semiconductor Optical Amplifier :-

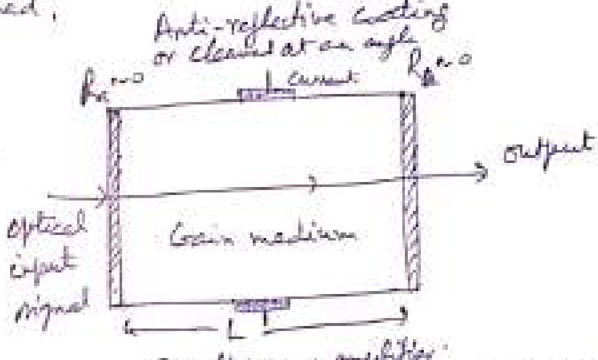
These are classified into two main groups.

1. Fabry – Perot amplifiers. (FPAs)
2. Traveling wave amplifiers (TWAs)

The main difference between the two types of amplifiers is the facet reflectivity. In Fabry-Perot amplifiers, the facet reflectivities are of the order of 0.01 to 0.3 and a highly resonant amplifier is formed.



Fabry Perot amplifier



Traveling wave amplifier

FPAs are normally biased below the normal lasing threshold current and light entering one facet appears amplified at the other facet, together with inherent noise. These devices are very sensitive to fluctuations in bias current, temperature, and signal polarization.

In traveling wave SOAs, to eliminate or reduce the end reflectivities, a thin layer of $TiO_2$, silicon oxide or silicon nitride is applied on the end facets. The reflectivities are reduced to $1\times10^{-3}$ or less, this operates the traveling wave amplifier in the single-pass amplification mode. The transmission characteristics less dependent upon fluctuations in bias current, temperature and input signal polarization. Hence, TWAs are superior to FPAs, particularly for linear applications.

When compared to an FPA, a TWA requires significantly higher bias currents for operation.

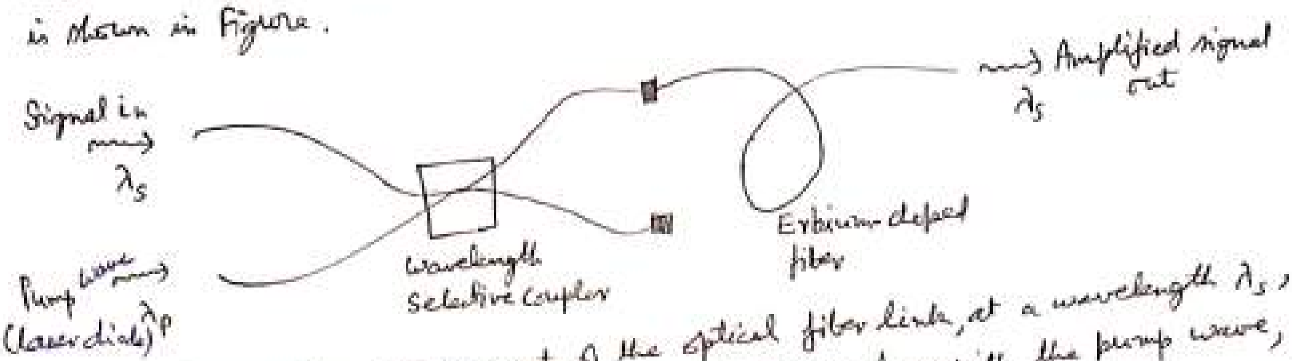
Figure shows the output light versus current characteristics for SOA with different facet reflectivity. The lasing current threshold increases with decrease in facet reflectivity.

**Erbium Doped Fiber Amplifier (EDFA) :—** EDFA is a inline optical amplifier. If the signal through the link is sent and the signal is weak then an optical amplifier can be used between the fiber.

1000ppm (1000 parts per million weight)

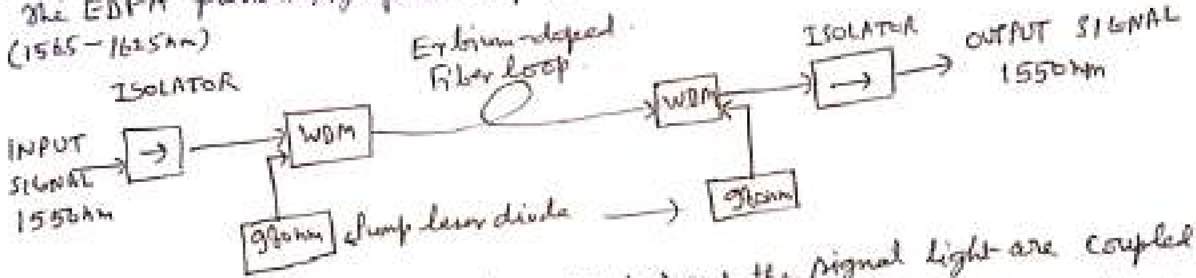
An optical fiber of suitable length (about 10–30m) that has been doped with a rare-earth element such as erbium (Er), holmium (Ho), neodymium (Nd), Samarium (Sm), ytterbium (Yb), thulium (Tm) can also serve as an amplifier.

A popular material for such an optical fiber is silica-rich glass doped with erbium ions ($Er^{3+}$). Therefore, these devices are called erbium-doped fiber amplifiers (EDFA). The reason for their popularity is that they operate in the low-attenuation window around 1.55 μm*. The basic configuration of an EDFA is shown in Figure.




The signal wave from one segment of the optical fiber link, at a wavelength $\lambda_s$, is coupled to a short length of an erbium-doped fiber along with the pump wave, usually from a diode laser, at a wavelength $\lambda_p$. Pump photons excite $Er^{3+}$ ions and produce population inversion. The passage of the signal wave through the EDF trigger stimulated emission around $\lambda_s$ and in this process gets amplified. The amplified signal is then coupled into the next segment of the communication link.

The EDFA provides significant amplification in the C-Band (1530–1565nm) and L-Band (1565–1625nm)




The pump light (from 980nm laser diodes) and the signal light are coupled to the doped fiber by a combining WDM. This device is a wavelength-dependent directional coupler of the sort used for WDM systems. The optical isolators prevent the amplified signal from reflecting back into the device, where it could increase the amplifier noise and decrease its efficiency.

* Fluorozirconate glass doped with Pr (Praseodymium) or Nd (Neodymium) are used for operation in the 1300nm window.

Early experiments used the visible radiation emitted from argon-ion, Nd:YAG, or dye lasers even though such pumping schemes are relatively inefficient. From a practical standpoint the use of semiconductor laser is preferred.

* Pumping at 980nm is preferred, since it produces less noise and achieves larger population inversion than pumping at 1480nm.

* Fibers with higher doping concentration will have a larger absorption coefficient for the pump laser so a shorter length of fiber is needed to give equivalent gain.

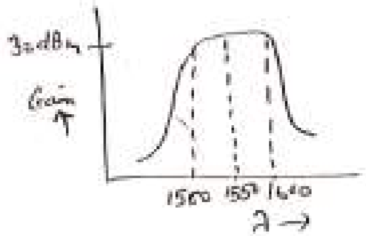
- It is a very important device which is used in Dense-wavelength division multiplexing (DWDM) around wavelength 1550nm. This EDFA is a type of fiber laser.

Weak incoming signal and pump wavelength are coupled to the $Er^{+}$ doped fiber length by a WDM multiplexer. The pumping wavelength photons are absorbed by $Er^{+}$ atoms raising them to excited state and causing population inversion. The excited photons are stimulated to emit larger $\lambda$ photons at $\lambda = 1.55\mu m$ and so amplifying the signal at $\lambda = 1.55\mu m$.

The weak signal photon and pumping beam travel down the fiber (EDFA) and then signal strength increases and pump photons strength decreases or pump power is absorbed and so depleted. Gain of incoming photons on the length of EDFA.

At the end of amplifier, Demux, removes any pump photons left which are not absorbed by $Er^{+}$ ions and amplified signal photons are output through and hence after amplification link length increases. Pump photons are DMUX so that they do not interfear at the receiver when signal is detected.

The gain of EDFA amplifier is perfect match with wavelength 1.55 μm which is the wavelength of lowest fiber loss.




The Gain is also uniform and about +30dBm.

If operating wavelength $\Delta\lambda$ of 5nm is chooson then 20 channels can be multiplexed i.e. simultaneously amplified and transmitted.

EDFA can be easily coupled because it is also a fiber.

⇒ Noise figure $(N_F) = \dfrac{(S/N)_{in}}{(S/N)_{out}}$, is a measure of noise characteristic of an amplifier.

$N_F > 1$ means amplifier degrade signal quality. But noise figure degration is ignored comparing to the gain of EDFA.

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Consider an amplifier with the gain G such that the output power and input powers are related by $P_{out} = G P_{in}$

The parameter $n_{sp}$ is called the spontaneous-emission factor (or the population-inversion factor) and is given by

$$n_{sp} = N_2/(N_2 - N_1)$$

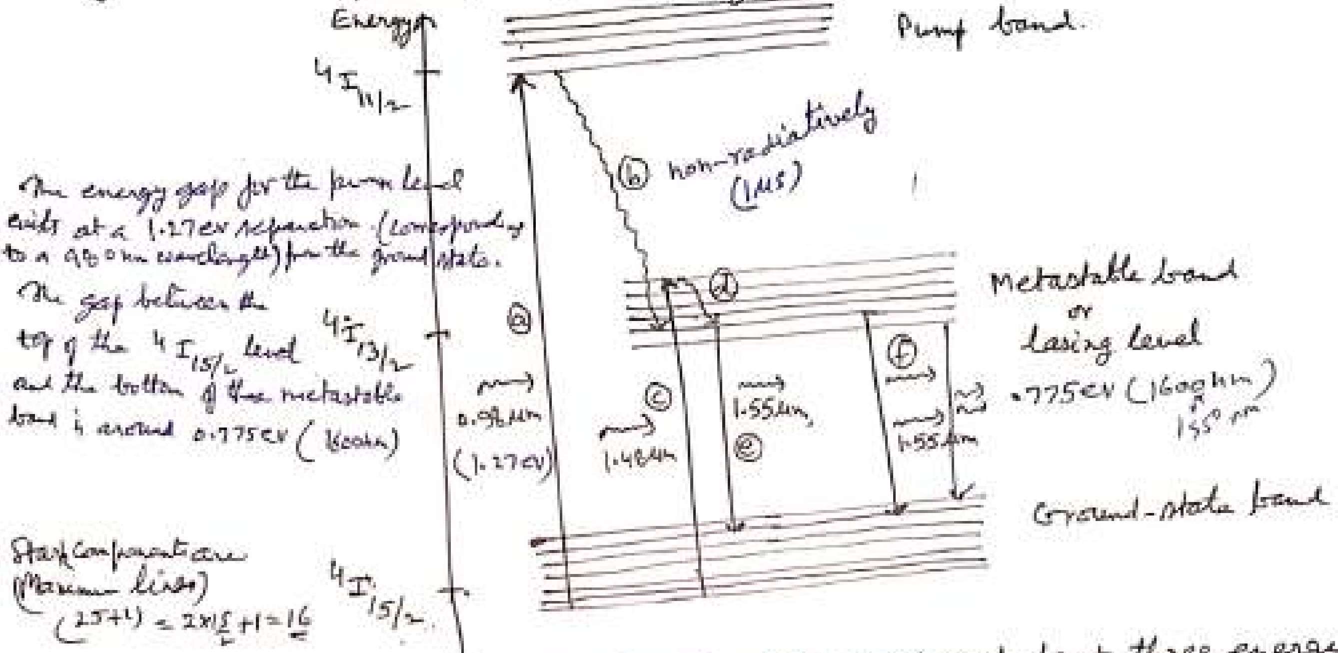
where $N_1$ and $N_2$ are the atomic population for the ground and excited states, respectively.

SNR refers to the electric power generated when the optical signal is converted into an electric current.

$$N_F: \quad N_F = 2n_{sp}(G-1)/G \approx 2n_{sp}$$

This eqn shows that the SNR of the amplified signal is degraded by 3dB even for an ideal amplifier for which $n_{sp} = 1$. For most practical amplifiers, $N_F$ exceeds 3dB and can be as large as 6-8dB. For its application in optical communication systems, an optical amplifier should have $N_F$ as low as possible.

**Operating Principle of EDFA :-** The energy-level diagram of an erbium ion ($Er^{3+}$) in silica glass is shown in figure. Each level is labelled with the corresponding Russel-Saunders coupling term ($^{2S+1}L_J$), where S, L and J denote the total spin, total orbital angular momentum, and total angular momentum, respectively. The quantum number L is denoted by the letters S, P, D, F, ... for L = 0, 1, 2, 3, ... respectively. When an $Er^{3+}$ ion is embedded in an amorphous host material such as silica, these individual energy levels are split into a number of sublevels and also get broadened to form energy bands. Only those bands that are important from the point of view of communication applications are shown in figure.




An EDFA uses the process of optical pumping. This requires at least three energy levels (the ground, metastable and pump levels). The energy of the pumping photon, which corresponds to the difference between the ground and pump levels, is absorbed and the system is raised to the higher excited state (pump level). After reaching there, the electron rapidly loses part of its energy non-radiatively and falls to the metastable level (also known as the lasing level). If the pump power is high, the population in the lasing level may exceed that in the ground level. This is called population inversion. Under such a condition if a signal photon (corresponding to the wavelength of light being transmitted through the optical fiber link, which is 1.55μm in the present case) passes through this medium, it can trigger a stimulated emission from the lasing level to the ground level, thus producing a new photon that is identical to the signal photon. Therefore, this process requires the energy of the pumping photon to be greater than that of the signal photon. In other words, the pump wavelength should be shorter than the signal wavelength.

There are several ways to optically pump an erbium-doped optical fiber and achieve gain. An intense source of pumping, e.g., a laser emitting 0.98 μm can be used to excite $Er^{3+}$ ions from the ground band $^4I_{15/2}$ to the pump band $^4I_{11/2}$ as shown in ⓐ. The excited ions decay non-radiatively in about 1μs from the pump band to the metastable band as shown by transition ⓑ. Within this band, the electrons of the excited ions tend to populate the lower end of the band. The lifetime of spontaneous emission from this band to the ground-state band is very long (about 10ms).

Similarly, $^4I_{15/2}$ to $^4I_{13/2}$ transition can be achieved using photons of wavelength 1.48 μm. The absorption of this pump photon excites an electron from the bottom of the ground band to the lightly populated top of the metastable band as shown by transition ⓒ. These electrons then relax to the more populated lower end of the metastable band as transition ⓓ. Some of these ions in the metastable state may get de-excited in the absence of any external photons and fall back randomly to ground state with the emission of photons of 1.55 μm. This is called spontaneous emission as shown by ⓔ.

However, if a flux of signal photons of energies corresponding to the energy gap between the ground-state band and the metastable band passes through this medium (erbium-doped fiber), stimulated emission may occur, that is, the signal photon may trigger an excited ion to drop back to the ground state, thereby emitting a new photon with identical energy, wave vector, and polarization as the signal photon as transition ⓕ; but this transition is possible when population inversion has occurred. Normally, stimulated emission occurs in the wavelength range 1.53–1.56 μm.

In practice, most EDFA employ 0.98 μm pump lasers, as they are commercially available and can provide more than 100 mW of pump power. Sources of 1.48 μm are also available, but require larger fibers and higher pump powers.

# EDFA (Erbium Doped Fiber Amplifier) Tutorial

**Introduction**

Erbium-doped fiber amplifiers are the by far most important fiber amplifiers in the context of long-range optical fiber communications; they can efficiently amplify light in the 1.5-µm wavelength region, where telecom fibers have their loss minimum.

**Setup and Operation Principle**

A typical setup of a simple erbium-doped fiber amplifier (EDFA) is shown in Figure 1. Its core is the erbium-doped optical fiber, which is typically a single-mode fiber. In the shown case, the *active fiber* is "pumped" with light from two laser diodes (bidirectional pumping), although unidirectional pumping in the forward or backward direction (co-directional and counter-directional pumping) is also very common. The pump light, which most often has a wavelength around 980 nm and sometimes around 1450 nm, excites the erbium ions ($Er^{3+}$) into the 4I13/2 state (in the case of 980-nm pumping via 4I11/2), from where they can amplify light in the 1.5-µm wavelength region via stimulated emission back to the ground-state manifold 4I15/2. (See also Figure 1 in the article on erbium-doped gain media.)

Figure 1:


The setup shown also contains two "pig-tailed" (fiber-coupled) optical isolators. The isolator at the input prevents light originating from amplified spontaneous emission from disturbing any previous stages, whereas that at the output suppresses lasing (or possibly even destruction) if output light is reflected back to the amplifier. Without isolators, fiber amplifiers can be sensitive to back-reflections.

Apart from optical isolators, various other components can be contained in a commercial fiber amplifier. For example, there can be fiber couplers and photo detectors for monitoring optical power levels, pump laser diodes with control electronics and gain-flattening filters. For particularly compact packages, various passive optical components can be combined into a photonic integrated circuit (*planar light wave circuit*).

2011, 2009

(11) EDFA Optical Fiber Amplifier (Erbium ion doped fiber Amplifier) (11)

In fiber optic communication links in line fiber Optical Amplifiers can be inserted. EDFA is one such amplifier. It is a length of Silica fiber that amplifies the incoming light beam. The rare earth element erbium is a active material. It has gain near wavelength 1.55 μm when pumped in around by wavelength 980 nm or 1480 nm. Wavelength 1.55 μm is very important wavelength window range in optical communication links because attenuation is minimum at this wavelength. EDFA gain is +30 dbm for approx 10 meter length of the fiber and gain is uniform for certain wavelength range as shown in fig ①

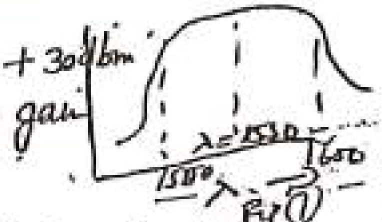
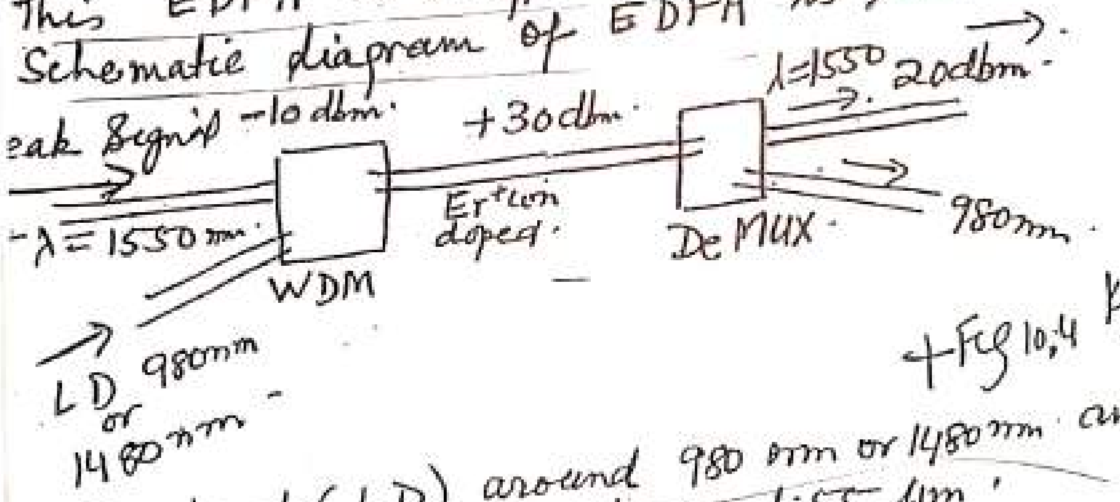


Fig ①

so it is a very important device which is used in DWDM (Dense WDM) around wavelength 1550 nm.

This EDFA is a type of fiber Laser.

Schematic diagram of EDFA is shown below.




+ Fig 10.4 Khare Book page 256.

The pump (LD) around 980 nm or 1480 nm and output signal is at λ = 1.55 μm.

Weak incomming signal and pump wavelength are coupled to the Er+ doped fiber length by a WDM Multiplexer. The pumping wavelength photons are absorbed by the Er+ atoms raising them to

ED

(12)

excited state and causing population inversion

3. The excited photons are stimulated to emit 'longer λ photons' at $\lambda = 1.55$ and so amplifying the signal at $\lambda = 1.55\ \mu m$.

4. The weak signal (photons) and the pumping beam travel together down the fiber (EDFA) and then signal strength increases and pump photon strength decreases or pump power is and so depleted. Gain of incoming photons depend on the length of the "EDFA" through which light travels.

5. At the end of the Amplifier a (DMUX) removes any pump photons left which are not absorbed by $Er^+$ ions and amplified signal photons are out put through and hence after amplif. link length can be increased.

Pumped ($\lambda = 980$) photons are DeMux so that they do not interfere at the receiver when signal is detected.

6. The gain of EDFA is $Er^+$ ion ~~doped amplifier is~~ in perfect match with wavelength 1.55 which is the wavelength of 'lowest fiber loss'.

7. The gain is also uniform and about +30db. for approx 10m length of fiber and is uniform for around 100 nm range.

8. If operating wave length ($\Delta\lambda$) of 5 (nm) is chosen then approx 20 channels can be (DWDM) can be multiplexed i.e simultaneously amplified and transmitted.

9. EDFA can be easily coupled because it is also a fiber.

10. Noise Figure $= \dfrac{(S/N)_{in}}{(S/N)_{out}}$ is a measure of Noise characteristic of an amplifier

NF > 1 means amplifier degrades ...

| WDM | OFDM |
| --- | --- |
| 1. Use Seperate Optic Sources | 1. Use same but temperature tuned source for different channels. |
| 2. Can be detected by Direct Detection | 2. Require Heterodyne detection scheme. More complex. |
| 3. Sort out or Seperate the channels in optic domain before photodetection | 3. It seperate out channels in electronic domain after optic detection |
| 4. Wide frequency gap in different channels | 4. Much more selective (close in frequency) are the adjacent channels. |
| 5. less channels can be accomodated by this technique of WDM. | 5. More channels can be accomodated. |
| 6. Optic seperation is difficult | 6. Electrical seperation or demodulation technique in frequency region is easy |
| 7. Limited window regions are available for transmission. (850 nm) (1300 nm) (1550 nm) etc | 7. FDM is achieved at one wavelength window region. (1300) or (1550) where losses are minimise or less. |
| | 8. Optic filter = 2 nm is equivalent to a pass band of 240 GHz. Electrical filter of 2 GHz provides a much higher frequency selectivity. |

$$\Delta\nu = \frac{c\Delta\lambda}{\lambda^2}$$

$\lambda = 1300\ nm$

$\Delta\lambda = 3\ nm$

$\Delta\nu = ?$

$$= \frac{3\times10^{8}\times3\times10^{-9}}{(1300)\times10^{-9}\times1300\times10^{-9}}$$