# ANALYSIS OF ERBIUM DOPED FIBRE AMPLIFIERS

**Murat ARI**
*e-posta: mari@cmyo.ankara.edu.tr*
*Ankara University, Çankırı College of Arts and Technology, Çankırı, Turkey*

**M. Cengiz TAPLAMACIOĞLU**
*e-posta: taplam@gazi.edu.tr*
*Gazi University, Faculty of Engineering, Department of Electrical & Electronics Engineering, Ankara, Turkey*

**Haldun GÖKTAŞ**
*e-posta: goktas@gazi.edu.tr*
*Gazi University, Faculty of Technical Education, Department of Electronics & Computer, Ankara, Turkey*

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ABSTRACT

**In this study, the importance and necessity of EDFA in communication techniques have been analysed. The absorption and stimulated emission theories and also energy levels that are necessary for EDFA have been examined for the further modelling studies. EDFA designers focused on two main approaches either 980 nm or 1480 nm in pumping technique. These methods have been examined and the advantages/ disadvantages of them have been explained by using energy level diagrams.**

## I. INTRODUCTION

Optical amplifiers, as their names imply, amplify light signals solely in the optical domain without the need for optical to electronic conversion. An optical amplifier operates using the same physical mechanisms as a laser. Only difference for optical amplifiers is not having any feedback of the signal as lasers use. (i.e.EDFA is a kind of laser without feedback).

There are two main approaches for optical amplification, one of them is semiconductor laser amplifiers (SLA), the other is rare-earth amplifiers.

The first type amplifier (SLA) uses stimulated emission from injected carrier and is as shown in the Figure 1, the peak of the gain is around 1500 nm (N.B.: special designs let SLA operates around 1300 nm).

The gain of fibre amplifiers is provided by either Raman or Brillouin scattering or by rare-earth doping like Erbium. In Raman and Brillouin scattering, a strong collision occurs in 1400 nm wavelength depends on the theory that the wavelength of the photon is in the same length with the signal wavelength that is a result of scattering of two phonons after the collision. The biggest disadvantage of this scattering is its need to a high power and the narrow spectral width for a strong collision [1].

Erbium fibre amplifiers are of great interest because the gain reaches its maximum at a wavelength in silica fibres and ideally suited for systems operate in the 1550 nm communication window [2].

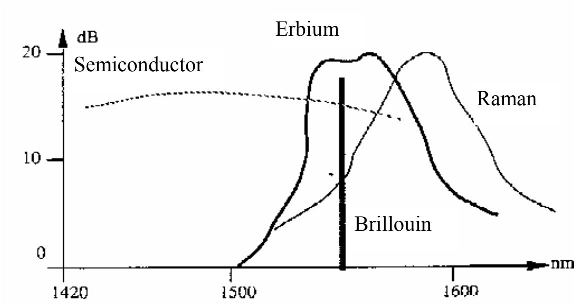


Figure 1. Semiconductor, Erbium, Raman & Brillouin Amplifier Gain Spectra.

Another advantage of Erbium Doped Fibre Amplifiers is the relative flatness of the top of the gain spectrum. Although gain bandwidth of semiconductor laser amplifiers is ideally large, they have several drawbacks like polarisation sensitivity, interchannel cross-talk and large coupling losses. Fibre amplifiers are preferable since the coupling loss due to fusion splice is negligible for them [3]. Fibre amplifiers are also insensitive to polarisation and have negligible noise for interchannel cross-talk, which is one of the main noise source in multichannel transmission or Wavelength Division Multiplexing (WDM).

These reasons and the available high gain properties make the Erbium Doped Fibre Amplifier (EDFA) very suitable for modern optical transmission. They have been extensively studied theoretically and experimentally in literature [4].

Gain coefficients of 4-6 dB/mW of pumping power have been reported and for some experiments by using an EDFA, reached data transmission rates as high as 5 Gbit/s along 9000 km [4]. The difference of lumped EDFAs (Figure 2) is regularly highly amplification of the signal where a discrete amplification is involved.

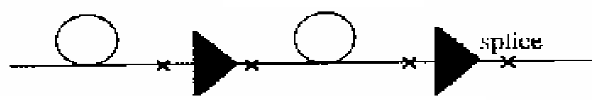

Figure 2 Lumped Amplification

### II. THEORY OF EDFA (ABSORPTION AND STIMULATED EMISSION)

The optical amplification in a rare-earth doped fibre is based on the stimulated emission of a photon. This occurs when a rare-earth ion decays from a higher to a lower energy state (see Figure 3) [6].

This transition is triggered by an incident photon from an input signal which is to be amplified. The emitted photon will have the same wavelength and phase as the incident photon, i.e. they are synchronous and coherent to each other. This is the basis of the laser effect.

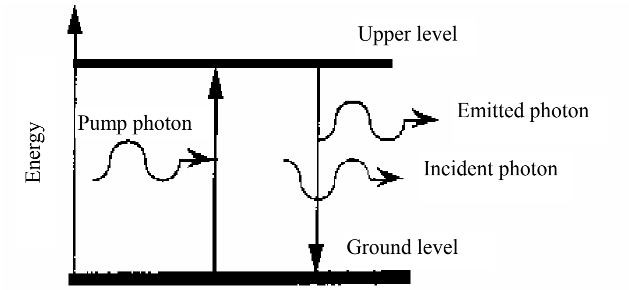

Figure 3. Light Emission and Absorption

The emitted light is reflected into an amplifying medium itself to excite the ions, this is the feedback mechanism, which leads to self sustained oscillations.

In optical amplifiers, there is no feedback and all the energy required to invert the ion population is supplied by a powerful source. In the case of fibre amplifiers this source is optical (a laser) source and called as the pump.

The larger population of excited ions is caused to reach to maximum gain. If all the ions are excited, the ground level population is totally inverted.

The signal and pump wavelengths depend on the emission and absorption aptitude of the doping ion. The probability of a photon at wavelength $\lambda$ to be absorbed is figured by a value called absorption cross-section. The emission cross-section denotes the likelihood for an incident photon to stimulate the emission of a photon.

At pump wavelength, the absorption should be predominant. However, to achieve some amplification, the emission must be much larger than the absorption at signal wavelength.

Figure 4. shows the Erbium emission and absorption cross-section spectra [5].

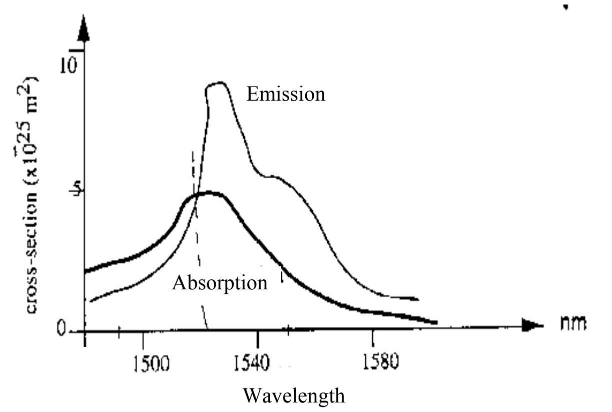

Figure 4. Emission and Absorption Cross – Sections Spectra

As seen in Figure 4. the emission cross-section at 1550 nm is larger than the absorption, thus the signal will be amplified.

On the other hand, at pump wavelength (around 1480 nm) the erbium is only absorbed and therefore the pumping will be efficient.

In fact, the erbium ions have more than two energy levels, as shown in Figure 5.

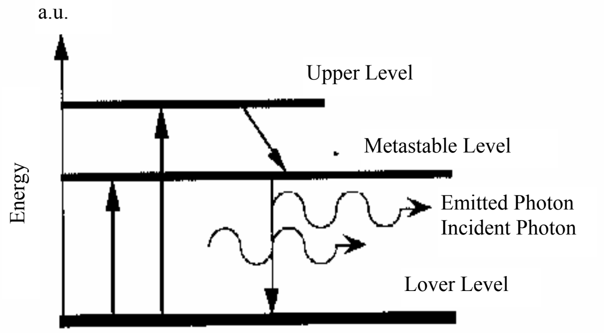

Figure 5. Energy Level Diagram

The ground level is the lowest energy level.

The second level (the metastable level) is quite stable and the average lifetime of an erbium ion at this level is about 10 ms.

The third and upper energy level is just the opposite: an erbium ion pumped into this level will transit very quickly to the metastable level, without emitting any photon. This is a non-radioactive decay.

The transition of an erbium ion from the metastable to the lowest level yields a photon in the signal band between 1520-1570 nm wavelength.

There are two approaches to pump an Erbium ion into the metastable energy level:

- either the $Er3^+$ ion is directly pumped into the metastable level, using a pump wavelength in the 1460 – 1500 nm bandwidth. This is called a resonant pumping;
- or using a 980 nm pump, the ion is excited in the upper level, filling the metastable level taking advantage of the non- radioactive decay from the third energy level.

### III. PUMPING AT 980 nm BANDWİDTH

This pumping scheme was extensively studied since the absorption skill of Erbium at 980 nm is much higher than around 1500nm, consequently the pump efficiency is greater [6, 7]. However, 980 nm pumping suffers a high loss in the silica fibre [1, 9]. The pump power is then quickly depleted along the fibre, leading to a low even negative gain in the amplifier.

Therefore, this type of pumping is not suitable for long fibre amplifiers as distributed EDFA (DEDFA).

The high energy of the pumped photons allows the erbium ions of the metastable state to be excited into another upper energy level, as shown in the Figure 6.

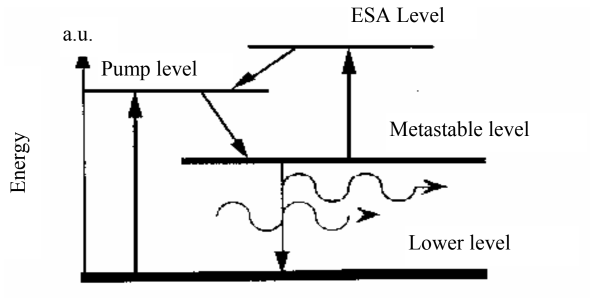


Figure 6. ESA in a 4 level model

The ions decay to the pump level without emitting any photon, and then to the metastable level [3, 8].

This effect is called Excited State Absorption (ESA) and leads to a lower metastable population, subsequently to a lower gain.

Those two problems (the loss at the pump wavelength and the ESA) make the 980 nm pumping scheme unsuitable for DEDFA.

### IV. PUMPING AT 1460-1500 nm BANDWIDTH

If the resonant pumping is considered, the anamorpheous nature of the silica will be helpful and each energy level is split into a small energy band. This allows us to use the metastable manifold for both pumping and emission. Taking into account of the emission and absorption spectra of the Erbium ion (Figure 4), the pumping band is 1480 – 1500 nm and the signal band is 1520 – 1570 nm.

In this case, ESA cannot occur since the erbium ion is pumped into the metastable manifold and also cannot reach any higher energy level [8].

A rapid heating of Erbium ion in the metastable manifold yields to a quick decay from the pump level to the signal energy level without emitting any photon. This allows us to simplify this model to a 2-level model (see Figure 7).

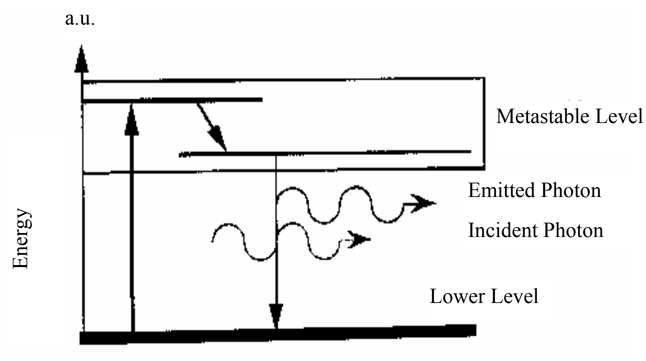


Figure 7. Two Levels Model

The transition between the two manifold levels is quick and non-radioactive.

Using the advantage of the absence of excited state absorption and from the low loss at the pump wavelength, the 1460 – 1500 nm pumping band is the most appropriate bandwidth. Owing to a peak of absorption at this wavelength, the pump usually operates at 1480 nm. This allows us to consider a 2 levels model corresponds to the resonant pumping.

The optimum signal wavelength for DEDFA has been found to be 1554 nm when a 1480 nm pump wavelength is used [10].

### V. EDFA ENERGY LEVELS AND LIGHT AMPLIFICATION

A few meter length erbium doped fibre is used in amplification process in EDFA. The core of this fibre is doped with homogenous erbium ion ($Er^{3+}$) whose density is parts per million. To modify the spectral characteristics in amplification process, semi-doped elements, Germanium and/or Aluminium are used that will increase the refraction index when added to host fibre. The incident light is amplified by stimulated emission as the working process of lasers. Optical gain is received by pumping the erbium-doped fibre optically to reach the population inversion.

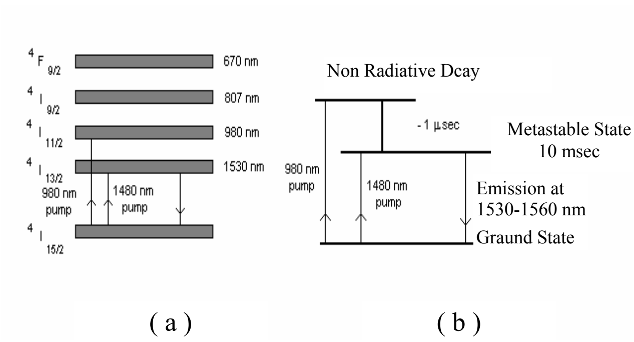


Figure 8. The energy level diagrams of Erbium ions in Silica fibre

(a) The main pumping bands

(b) The schematic demonstration of the mostly used pumping methods

Figure 8.a. shows a simplified diagram of $Er^{3+}$ energy levels in silica glass. The energy transition responsible for 1.55 µm emission is from metastable state ($^4I_{13/2}$) to ground state ($^4I_{15/2}$). The Stark splitting of these two levels makes 1.55 mm emission band as broad as 40 nm, extending from 1520 nm to 1560 nm. To achieve the population inversion, it is necessary to pump optically the amplifying fibre at a wavelength region corresponding to the energy level transitions as shown in the diagram. However, the significant unwanted absorption of pump energy may occur at some pumping bands, since erbium ions can be further excited from metastable state ($^4I_{13/2}$) to higher energy states if a transition of appropriate energy exists. This effect is known as pump excited state absorption (ESA) and is detrimental in EDFAs since it depletes the metastable state and reduces the pumping efficiency. The efficient pump wavelengths for $Er^{3+}$ are 980 nm and 1480 nm where ESA is negligible. The pumping efficiency may further be increased by confining erbium ions to the centre of the fibre core by reducing the core diameter or the use through of a high-NA core.

Figure 8.b. shows the most commonly used the transition dynamic of 980 nm and 1480 nm pumping bandwidth. If the active fibre is pumped in 1480 nm, a pump photon is absorbed in 1480 nm and this stimulates an electron from ground state to metastable state. In this situation with a randomly occurred spontaneous emission or an another stimulation of a signal coming from the entrance. A transition from metastable state to ground state realises and thus a photon in 1550 nm is propagated. The absorption of pump photons in this way causes the production of new signal photons (in another words the amplification of signal optically). Absorption of a pump photon in 980 nm provides stimulation of an electron to a higher energy level. However, electron rapidly decreases to metastable state. The transition from metastable state to ground state results in photon emissions in 1550 nm wavelength.

## VI. CONCLUSION

The technique of EDFA has been used commonly since 1987. EDFA was used in TAT-12-13 cables which was set up in 1996 and linked England to USA. A 5 Gbite/s conduction has been achieved. In these amplifiers, the gain was 30-50 dB and the noise factors were about 4-5 dB. The optic amplifiers are used everywhere especially place where attenuation is a problem, that is long distance links (submarine or continental) in fibre optic cable TV distribution network or experimental aimed laboratories. EDFAs are operated in 1500nm wavelength in which silicon fibre attenuation is minimum. The polarization sensitivity speaking inter-channels and other losses, seen in semiconductor laser amplifiers are insignificant in EDFAs. That is why the importance of EDFAs are getting more and more everyday.

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