Erbium-Doped Fiber Amplifier Review

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***Abstract*- This paper is describing and investigating four crucial areas of Erbium Doped Fiber Amplifier (EDFA). First is the atomic part, where it is meaningful to give deep and details information of erbium spectra structure and its energy level. The atomic spectrum is one crucial part in defining and understanding amplification phenomena. The second part based on understanding, investigating and analyzing of the theoretical background of EDFA where spontaneous and stimulated emissionsare the main targets of this portion. The third part is the EDFA design, where variety of investigationsillustrated viadifferent design of configurations from the single pass to the quadruple pass. Thepurpose of EDFA designsis to prove experimentally the high-gain and low-noise-figure utilizing novel methods and techniques. The fourth is the critical-review part, where many research papers reviewed to figure out their strengthsand weaknesses at different interpretation. The critical review is to describe and specifythe limitationsof the classical understanding of EDFA and to depict and conceive the next generation characteristics of the fiber laser and fiber amplifier.**

***Index Terms*-- Erbium, erbium doped fiber amplifier, energy level, optical amplifier.**

1. INTRODUCTION

As it found in the massive literature of photonics, laser and amplifier take an important part in the current scientific age due to paradigm shift of transmission and communications towards Tbps[1]. The importance of optical amplifier [2] is owing to its ability to amplify the signal and revive it through the length of millions of Kilometers.Vast numbers of books and papers published since the early discover of laser in 1960 by Theodore Maiman and amplification by Snitzer[3]. Amplification and lasing phenomena are worthy to be analyzed carefully. The scientists illustrate and investigate the beneath behavior of laser at specific conditions and parameters of the design.

The laser and amplification discovered thenfollowed by focused research of different models and theories to harmonize the results with the experiment. The base of amplification is the quantum theory of Planck and Einstein formulas. To understand and elaborate the construction of laser and amplification phenomena, it is of great consequence to combine theory and experiment in one thinking head.

The elucidation of laser and amplifierrelated to what we call the energy level or the atomic structure that emits the photon from their sublevels. The question is how this photon born? How it constructed within the sublevel of the atomic orbits? Or what is the physical meaning of the electron jumping to generate photons? How the amplification phenomena can explained at the formula-experimentbase? All these questions need very clear answer to understand the laser and amplifier conception. Amplifier, with the stimulated and spontaneous emission phenomena is considered to be the pass-key to future revolution of communication. Light is paradox phenomena, by understanding its mechanism clearlyit leads to great revolution that can affect deeply; high speed, quantum and teleportation.

EDFA theorylinked to laser and its phenomena of light-matter dual interaction, where the spontaneous and stimulation emission occurred at specific conditions. Based on lasers studies, numerous formula given in different books and articles to find the exact model for lasing and amplification and to find suitable, precise and clear formula. Owing to the vast factor affecting both laser and amplifier output it is complex problematic to find the precise formula for output laser, gain, and NF by giving consideration to all parameters. In general, the basic formalism used for modeling light amplification in EDFA is based on [3, 5]:

- Electromagnetics
- Quantum Optics
- Laser Physics

The fundamental laser and amplification parameters are:

- Optical mode distributions
- Dopant-ion type and concentration
- Decay time
- Emission and absorption cross section
- Fiber parameter

The rate equation is to combine the following:

- Signal
- Pump
- ASE

A remarkable effect of configurations observed [6], designs are affecting clearly the output. In general, the simple EDFA configuration is made by splicing the wavelength division multiplexing (WDM) with the active medium EDF and pump power fiber;then the amplification of input signal will occur due to stimulated emission along with the generation of amplified spontaneous emission noise. The gain gap between the single stage single pass configurations typesdoes not show big difference and saturation will occur at low pump power. The study presented shows the effect of different configurations on the gainefficiency of EDFA.

In addition, a tremendous progress have achieved for the development of broadband EDFA, which form the backbone of high capacity light wave communication systems. The amplifier provides high output power and low NF to support the ever-increasing capacity demand on light wave systems. Spectral gain ripples and non-uniformities of Silica-based erbium-doped fiber amplifiers represent a bottleneck in broadband all-optical light wave systems.

2. ATOMIC LEVEL

Ions and atoms are critical for the amplification phenomena. The erbium ion is a crucial factor for the generation of the stimulated and spontaneous emission. Studying the erbium characteristics is an important step to understand the amplification phenomena.

The relationship between the principal quantum numbers organized as shown in Fig. 1. It is very clear that all the quantum numbers ordered in such way that gives the specific structure of the atom. This structure, will affect strongly the characteristics of the atom and its interaction with light absorption or emission.

The Russel-Saunder theory is labeling the energy level with the following label: $^{2S+1}L_J$, where L is the total orbital angular momentum, 'S' is the total spin of electrons, and 'J' is the total angular momentum. From Fig. 1 the value of 'S'can be calculated as S = (1/2)+(1/2)+(1/2) = 3/2. 'L' also extracted from Table 1, as the energy state for a system of electrons. These states or term letters are represented as follows: From Fig. 1 and Table 1, L = 6 and 6 is coincided with I.

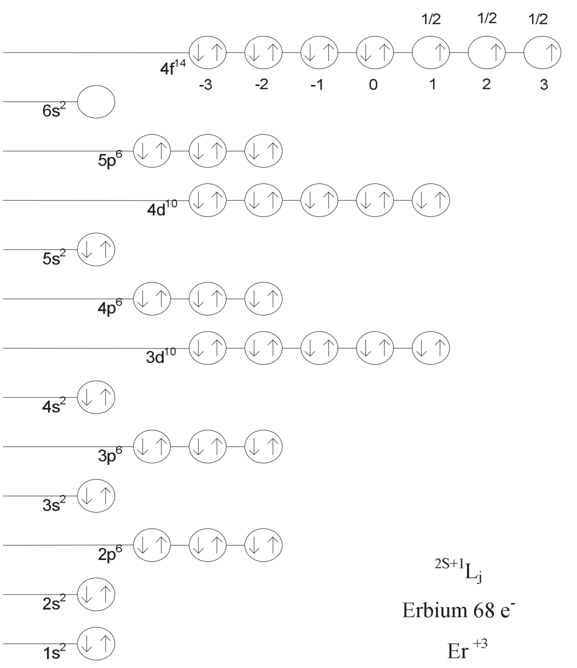

Fig. 1: Energy level following the electrons distribution in Erbium ion.

TABLE 1

Total orbital Momentum

S	P	D	F	G	H	I	J	K
0	1	2	3	4	5	6	7	8

The $^{2S+1}L_J$ calculated by the following methods:

$$2S + 1 = 2\left(\frac{3}{2}\right) + 1 = 4, L = I$$

And $J = L + S, L + S - 1, L + S - 2, \dots \dots \dots \dots \dots \dots L - S$

The $^{2S+1}L_J$ becomes $^4I_{J=L+S,L+S-1,L+S-2,\dots\dots\dots\dots L-S}$

J calculated as the following:

$$J = 6 + \frac{3}{2} = \frac{15}{2}$$

$$J = 6 - 1 + \frac{3}{2} = \frac{13}{2}$$

$$J = 6 - 2 + \frac{3}{2} = \frac{11}{2}$$

$$J = 6 - 3 + \frac{3}{2} = 3 + \frac{3}{2} = 6 - \frac{3}{2} = L - S = \frac{9}{2}$$

At the end the $^{2S+1}L_J$ can be given as shown in Fig. 2 as the following: $^4I_{(15/2)}$, $^4I_{(13/2)}$ $^4I_{(11/2)}$ and $^4I_{(9/2)}$.

The number of fine manifold measured based on the following formula:

$$g = \frac{(2J + 1)}{2}$$

$$g_1\left(J = \frac{15}{2}\right) = 8, \quad g_2\left(J = \frac{13}{2}\right) = 7, \quad g_3\left(J = \frac{11}{2}\right) = 6, \quad g_4\left(J = \frac{9}{2}\right) = 5.$$

The energy levels distribution of the Erbium ion shown in Fig. 2 and the energy levels shown in the figure as proved.

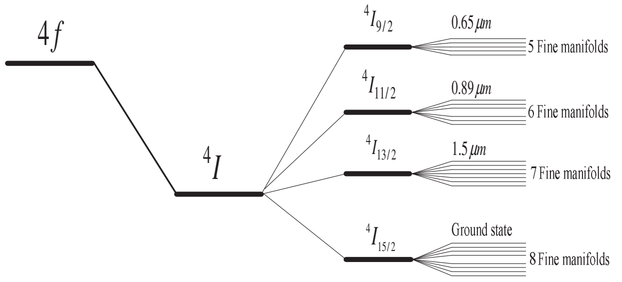

Fig. 2: The energy levels distribution of the erbium atoms

3. THEORETICAL LEVEL

The analysis and interpretation of EDFA based on the theory of the energy level. Fig.3(a) and (b) portray a conceived drawing on the activities taking place at the sublevel of atomic amplification. Water tanks equipped with water pump used to depict nearly similar to what is happening at the sublevel of atomic structure and how the conversion rate of the population simplified.

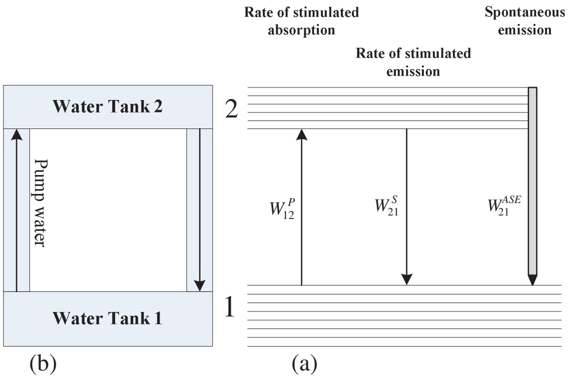

Fig. 3 Energy level and water tank

$$\frac{\partial N_1}{\partial t} = W_{21}^{S} N_2 - W_{12}^{P} N_1 + W_{21}^{ASE} N_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\frac{\partial N_2}{\partial t} = W_{12}^{P} N_1 - W_{21}^{S} N_2 - W_{21}^{ASE} N_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (2)$$

The negative sign means the reduction rate of the populations and vice versa. The notation N is the population per volume at the two levels. The W is the rate at which the populations are jumped from one level to another. When the pumping power is interacting with erbium ions the result will be aspontaneous emission but adding the targeted signal for amplification the interaction will create stimulated emission with specific condition. The interacting powers inside the doped fiber are: Pump power P^P, Signal power P^S and amplified spontaneousemission power P^{ASE}, these powers are described based on the number of photons per unit of time as the following:

The number of photons in pump beam per unit time is$\left(\frac{P^p}{hv}\right)$, where hv is the energy of one pump photon. In order to determine the number of photons in a particular cross sectional area of the core, where the erbium ions distributed uniformly, divide again by A_{Er}. The value $\left(\frac{P^p}{A_{Er}}\right)$is the pump intensity. Since the two fibers are spliced,the confinement factor Γ is multiplied, which is the ratio of the core area of the EDF and the core area of the spliced fiber of the pump. Number of photons in the core per unit time$\left(\frac{P^p}{A_{Er}.hv}\right)$

The probability of an ion in the core to absorb pump photon defined as the absorption cross section area. Each wavelength has a specific absorption cross section $\sigma^a$and specific emission cross section σ^e therefore; this value is a function of frequency.

Probability of a single ion being excited into the upper state $= \frac{P^p.\Gamma}{A_{Er}.hv}$

Based on this formula we can write the emission and absorption rate as the following

$W_{21}^{S} = \frac{\sigma_{21}^{e} P^S\, \Gamma}{A\, h\nu_S}$, Stimulated emission rate

$W_{12}^{P} = \frac{\sigma_{12}^{a} P^P\, \Gamma}{A\, h\nu_P}$, Pump emission rate

$W_{21}^{ASE} = \frac{\sigma_{21}^{e} P^{ASE}\, \Gamma}{A\, h\nu_{ASE}}$, ASE emission rate

In laser physics, transition cross sections used to quantify the likelihood of optically induced transition events. Transition cross sections depend on the optical frequency. When signal light beam, with power P^S at λ^S, traverses a slice of fiber medium of thickness dz and atomic population density N_{Er}, the amplification produce the difference between input and output power. This difference in power depends on various factors like erbium ions doped inside the core of the fiber, the pumping power, the input signal power, the fiber length the absorption and emission cross section.

Absorption and emission cross sections are two most important parameters of EDFs. They quantify the ability of an erbium ion in the EDF to absorb and emit light. To be more accurate, the cross sections represent the probabilities of transitions to occur between ground and excited states.

At the steady state the rate of N_1 equal the rate of N_2:

$$N_1 W_{21}^{ASE} = N_2 (W_{21}^{S} + W_{12}^{P})$$

$$N_{Er} = N_1 + N_2 \Longrightarrow N_2 = N_{Er} - N_1$$

$$N_1 = \frac{N_{Er}(W_{21}^{S} + W_{21}^{ASE})}{(W_{21}^{S} + W_{12}^{P} + W_{21}^{ASE})}$$

$$N_2 = \frac{N_{Er} W_{12}^{P}}{(W_{21}^{S} + W_{12}^{P} + W_{21}^{ASE})}$$

4. DESIGN LEVEL

An efficient amplification occurs at the signal wavelength of 1550 nm when it travels along the fiber doped with Erbium ions at the core and pumped with specific value of wavelength. The highest gain, lowest noise figure, and broad-flat output power is a perfect amplifier [6,7]. A higher power and wider spectrum of ASE observed for the double pass compared with single pass. A comparative investigation presented and analyzed for various configurations.

Design and implementation of single stage optical amplifier made by splicing EDF with WDM and optical isolator. This type of amplifier considered as a basic amplifier. Six configurations are shown in Fig. 4 (a) SPSS: single pass single stage, (b) DPSS: double pass single stage, (c) DPSSF: double pass single stage with filter, (d) TPDS: triple pass double stage, (d) TPDSF: triple pass double stage with filter, and QPDSF: quadruple pass double stage with filter. The difference between these configurations is owing to the additions of TBF and the second stage can be single pass or double pass. The circulators used as loop back where port 1 and 3 spliced and the TBF is incorporated between these ports to suppress and eliminate the unwanted ASE.

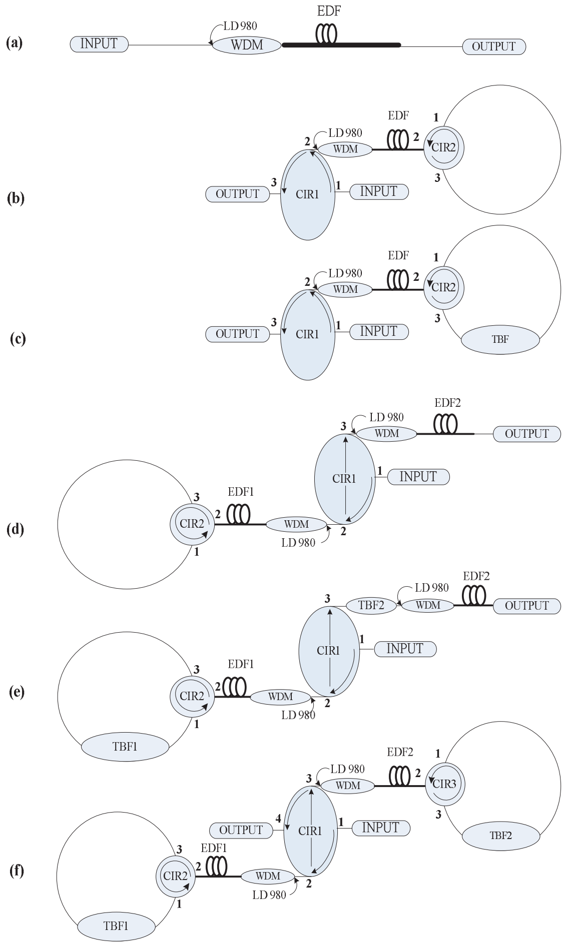

Fig. 4: Experimental configurations of EDFA: (a) single pass single stage (SPSS), (b) double pass single stage (DPSS), (c) double pass single stage with filter (DPSSF), (d) triple passes double stage (TPDS), (e) triple passes double stages with filter (TPDSF) and (f) quadruple passes double stages with filter (QPDSF). TBF: tunable bandpass filter, CIR: circulator, EDF: erbium-doped Fiber, LD: laser diode, and WDM: wavelength division multiplexing, INPUT: tunable laser source, and OUTPUT: optical spectrum analyzer.

The Key role of Tunable Bandpass Filter (TBF) in the continuous increase of gain is impressive and crucial where the TBF can stop the build-up of both the forward and backward ASE powers outside the signal bandwidth, and therefore increase optical gain and pump efficiency by the increase of stimulated emission.

Fig. 5 shows very high gap between two types of configuration at the same pumping power. By including the filter within the circulators ports at specific position, the gain will increase sharply. At higher pumping power, the gain shifted from 21.04 to 62.56 dB. All these results are at 1550 nm input signal power and -50 dBm. This result shows clearly the impact of the varied construction of configurations, the filter and the double pass technique on the gain value. So, with the change of configuration from SPSS to QPDSF, the gain difference reach 40dB as you can see in Fig. 5.

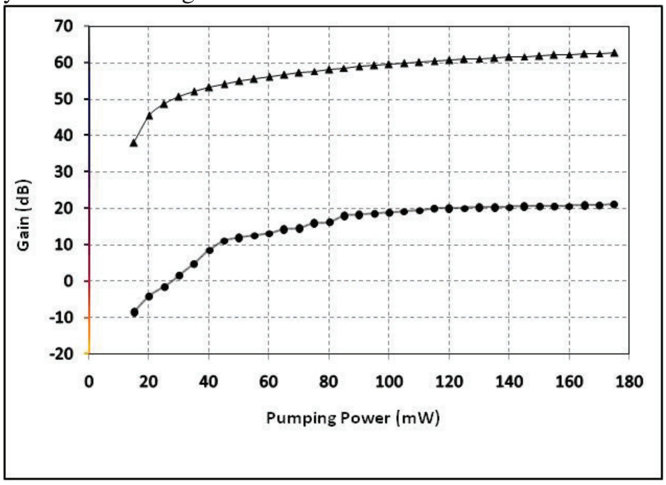

Fig. 5: Experimental results of gain (dB) versus pumping power (mW) for (•) single pass configuration and (▲) double pass dual stage configuration.

The main and principal focus was to find an idea where the gain and noise figure improved better more than the existed one. The hope becomes a truth when the tunable band pass filter positioned between the port 1 and port 3 of the circulator. This new position of the TBF increases the gain. With the same EDF lengths and the same pumping power and the same wavelength the gain is jumped from 20dB single pass to 40 dB double pass with filter and this was a big achievement. Adding another stage double pass to the first stage the configuration becomes dual stage double pass with filter, see Fig. 5, the gain reach 62.56 dB. The huge gap between the single pass configuration and the double passes dual stage gain shows how efficient the configuration design can affect the gain and output power values.

In Fig. 5, the results are showing the difference between dual stage double pass and single pass. By increasing the pumping power for both configurations, the gap between the two configurations gain is a constant.

5. CRITICAL LEVEL

- Most of the published papers and books on EDFA are focusing on the experimental process and results with less concentration on theory and modeling. This owes to the complexity and difficulties faced during the analysis and explanations of spontaneous and stimulated emission. Dealing with the fiber amplifier endless of factors are affecting the amplifier output such as, EDF length, erbium concentration, material host, type of optical component, type of configuration, pump wavelength, overlap factor, signal wavelength and the filter. All these factors and parameters have their direct impact on the output power, flattening, gain, and NF.
- Based on the amplifier factors complexity, it is required to find a combination between theory and experiment to understand the real phenomena and this is what not fully

analyzed in the published papers and books. To harmonize the theory and experiment it is difficult and complex task for researchers.

- Most of the implemented experiments are just descriptions of graphs and their trends and not physical explanation phenomena based on the formula. The vast factors and parameters controlling the laser and amplifier cause misunderstanding of theory analysis. Amplifier in communications system still in its early stage and this needsother steps for the next generation. It is important and necessary to find new and simple formula for laser and amplifier to understand clearly what happened within the atomic subshells.
- There is a need for comprehensive and simple formula to explain amplifier and laser.
- There are less published papers, studying the comparison between both lasers and amplifiers at different configurations.
- Since decade the EDFA gain value is not increased, and the noise complexity generated from the amplifier is not solved.
- EDFA gain ripple still a major problem for broadband amplifier and laser since the discovery of laser and amplifier.
- Nano-EDFA laser and amplifier still at its early stage.
- Less interest given to amplifier and laser for the undergraduate study level.

6.CONCLUSION

A detailed investigation of EDFA is givenat four principal levels; first is the atomic structure where Erbium ion was investigated and interpreted. The energy levels of Erbium atom described and calculated. The second level is the theoretical analysis, where it is worth to understand the physical meaning behind the amplification phenomena and linkittoeasy, simple and basic formula. The third level is the presentation of various configurations and their performance parameters related to different structures. The last one is the critics inside EDFA topic, where many published papers and books show superficial and insignificant investigation concern the experiment and theory of EDFA.

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