

Build your own optical amplifier: design, implementation and physical model of an Erbium Doped-Fiber Amplifier

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I. INTRODUCTION

The optical communication industry has been an emerging sector for the past thirty years. Fiber optical networks are being installed all over the globe to ensure a faster and a cheaper communication. In these optical networks, signals travel large distances without barely any attenuation, however, when the distance become hundreds of kilometers there is a need to amplify the signal in order to ensure an acceptable communication. Doped fiber amplifiers consist on a rare earth doped fiber and their work principle is the stimulating emission of photons by the rare earth ions implanted in the core of an optical fiber. This amplifiers can use doped fiber with different elements such as Ytterbium, Thulium or, as in our case, Erbium. Erbium Doped Fiber Amplifiers (EDFAs) are widely used in fiber optical networks to provide amplification in long distances with fiber loss less than 0.2 dB/km , by providing amplification in the long wavelength window near 1550 nm . Typically Erbium-doped fiber amplifiers with the length of approximately 10 m can achieve amplification of about $> 20\text{...}30\text{ dB}$ [4]. The maximum achievable optical output power of the fiber amplifier is limited by the available pump power, typical Erbium-doped fiber amplifiers permit saturation output powers of $20\text{...}50\text{ mW}$ ($13\text{...}17\text{ dBm}$).

Energy levels of Erbium (Er^{3+}) doped system is shown in the Figure 1 (they are marked with their spectroscopy notation). There are three levels of energy: the ${}^4I_{15/2}$, ${}^4I_{13/2}$ and ${}^4I_{11/2}$, representing respectively the *upper* ($E3$), the *metastable* ($E2$) and the *ground* ($E1$) states. In the absence of any radiation, the electrons are in their ground states $E1$. If a beam of light of appropriate frequency is incident on the system, the electrons will be excited to the higher levels. This radiation, called pump radiation, if chosen at 980 nm , will excite the electrons to the upper level $E3$. The lifetime of the electrons in this upper level is approximately $1\mu\text{s}$. Thus, the electrons readily decay to the metastable level $E2$ by non-radiative transition, i.e. by releasing heat. The time constant at the metastable energy state ${}^4I_{13/2}$ is 10 ms and, therefore, relatively high. This leads to a high population inversion of the electrons even at moderate pump powers. Therefore stimulated amplification is feasible. In order to achieve an optical amplification, generally pump powers

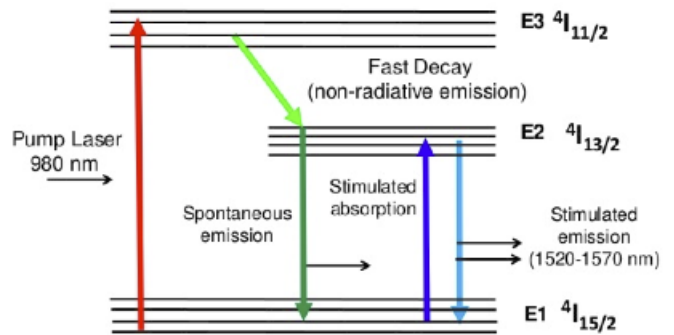


FIG. 1. Energy level diagram of Erbium [2]

of a few 10 mW are sufficient.

Pump can also work directly at 1480 nm to excite the ions directly to the metastable level $E2$. 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. In this case, rapid relaxation would occur to the lowest sub-level within the group of levels $E2$ from which laser action would take place.

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.
- (ii) Stimulated Emission: The stimulated emission takes place in the wavelength window 1520 nm to 1570 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.

Let N_{E3} , N_{E2} and N_{E1} denote the population of the three states (upper, metastable and ground 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 Ei to state Ej , we can write the following rate equations:

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$$\frac{dN_{E1}}{dt} = \frac{N_{E2}}{\tau_{21}} + W_s(N_{E2} - N_{E1}) - W_p(N_{E1} - N_{E3}) \quad (1)$$

$$\frac{dN_{E2}}{dt} = \frac{N_{E3}}{\tau_{32}} - W_s(N_{E2} - N_{E1}) \quad (2)$$

$$\frac{dN_{E3}}{dt} = -\frac{N_{E3}}{\tau_{32}} + W_p(N_{E1} - N_{E3}) \quad (3)$$

Population inversion implies that $N_{E3} > N_{E1}$. For steady state conditions, the time derivatives vanish, and, since the lifetime of the state $E3$ is much smaller than the lifetime of the state $E2$, the population of the excited state is essentially given by the Boltzmann distribution:

$$N_{E3} = N_{E2} e^{-(E_{E3} - E_{E2})/kT} = \beta \cdot N_{E2} \quad (4)$$

where $\beta = e^{-(E_{E3} - E_{E2})/kT}$ is the Boltzmann factor. From 1, we have, for steady state conditions:

$$\frac{N_{E2}}{\tau_{21}} + W_s(N_{E2} - N_{E1}) - W_p(N_{E1} - N_{E3}) = 0$$

which can be simplified, using 4, to give the inversion level as:

$$n = \frac{N_{E2}}{N_{E2} - N_{E1}} = \frac{(W_p + W_s)\tau}{W_p\tau(1 - \beta) - 1}$$

The inversion level is, thus, related to both the pump and signal powers and also to the pump wavelength through the Boltzmann factor, β . This 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 $E3$, the ions thermalize to the level $E2$. The energy difference between these two levels is substantial ($\sim 0,4 eV$) 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 $E2$. The value of β for this case is about 0,4.

For strong pumping ($W_p\tau \gg 1$) and small signal power ($W_s \simeq 0$), the inversion factor almost becomes $n = 1$ in case of 980 nm pumping, whereas for 1480 nm pumping the best one is about $n = 1,6$.

II. EDFA SET-UP

In its most basic form, the EDFA consists of a length of EDF (typically 10m – 30m), a pump laser, and a component for combining the signal and pump wavelengths (often referred to as a WDM, Wavelength Division Multiplexer) so that they can propagate simultaneously through the EDF.

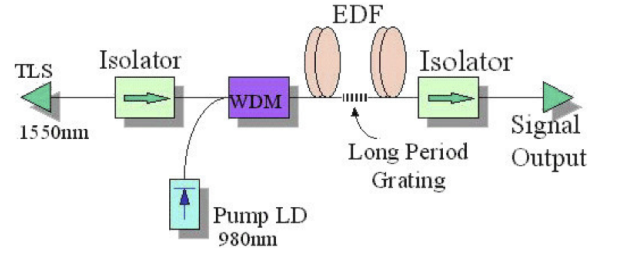


FIG. 2. Experimental setup

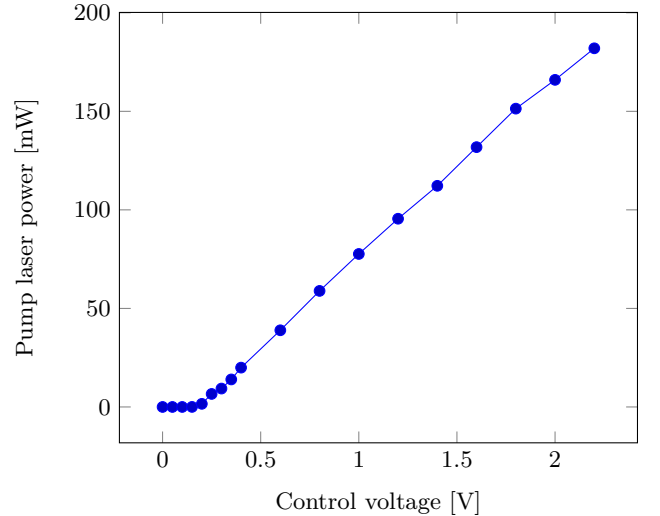


FIG. 3. Voltage control of pump laser power

In principle, EDFA's can be designed such that pump energy propagates in the same direction as the signal (forward pumping), the opposite direction to the signal (backward pumping), or both directions together.

The pump energy may either be 980 nm pump energy (laser diode InGaAs), 1480 nm pump energy (laser diode InGaAsP), or a combination of both. Practically, the most common EDFA configuration is the forward pumping configuration using 980 nm pump energy, because this configuration makes the most efficient use of cost-effective, reliable and low power consumption.

In our experimental setup we used a forward configuration and the pumping source was implemented using an InGaAs diode laser which is powered by a controllable input current (Figure 2). The control of the input current was carried out using an Arduino Due connected with a voltage-current converter; as such, one can manually specify the desired output current in a user interface designed with *MATLAB Simulink* and the current will be fed to the laser diode.

The operating characteristic of the pumping source has been obtained by recording the output power as a function of the input voltage (Figure 3).

As we can verify this output characteristic has the typical profile of a laser, since from a certain voltage of threshold (around 0.23V) the output power follows a lin-

ear relationship with the input current and, consequently, with the input voltage.

Following Figure 2, our experimental setup contain a WDM (Wavelength division multiplex) that allow us to multiplex the 1550 nm signal and the 980 nm pump signal. After the WDM we added 14,9m of Erbium Doped-Fiber that we characterized checking that it has the losses specified by the company. We performed measurements without pumping laser to determine a loss of $2dB/m$, which is an important parameter for the simulations and it is linear to the Erbium concentration. After the EDF we have added a demultiplex that separate the 1550 nm already amplified signal form the 980 nm pump signal. Normally EDFAs incorporate isolators to avoid it from lasing, in our case we have not incorporate them.

The WDMs have been characterized adding losses of $0.6dB$ each and all components are linked using connectors that also add losses. The total losses of the circuit without the Erbium fiber are $1.3dB$.

III. EDFA SIMULATION

We used a fiber laser and amplifier design toolbox, which is written in Matlab and whose source code is freely available on the Matlab community website [1]. The available fiber amplifier functions are the following [3]: (a) Small signal gain is calculated as a function of wavelength, and also as a function of pump power for a fixed input wavelength (these calculations use the small signal gain model and are valid only for small input signals); (b) The distribution of the pump power, the amplifier signal and the upper state population can be visualized along the length of the amplifier's doped fiber using the numerical gain stage simulator; (c) The power distribution throughout the fiber can be calculated for multiple wavelengths using the numerical simulator; and (d) The amplifier output power can be calculated as a function of doped fiber length, pump power and input signal power using the numerical simulator (it also can be calculated as a function of both input signal power and doped fiber length for a fixed pump power).

The parameters that we will use for the simulation, so that it resembles the experimental assembly as much as possible, will be the following:

Parameter	Value
Pump wavelength (nm)	980
Signal wavelength (nm)	1550
Pump power (mW)	180
Signal power (mW)	0,11
Doped fiber length (m)	14,9
Doped fiber core diameter (μm)	5,5
Core E-field overlap with dopant (%)	75
Doping concentration ($\times 10^{24}/m^3$)	0,77
(OR) Fiber absorption (dB/m at 1530nm)	2

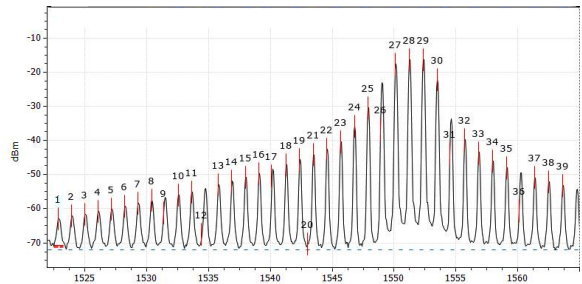


FIG. 4. Input signal

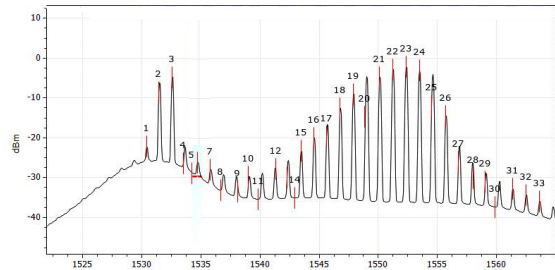


FIG. 5. Output signal with pump

Pump direction	forward
Pumping approach	core

In our experimental setup, the parameter that can be adjusted continuously is the pumping power. We also can reduce the signal power, for example, connecting 50 km of optical fiber between the signal source and the EDFA's input (wich means losses of 5, 7 dB). The fiber absorption has been found experimentally, resulting the same value given by the fiber provider.

IV. RESULTS

With the optical spectrum analyzer we study the spectrum of the input and output signal. The results obtained for the maximum pump and signal power are shown in the Figures 4 and 5.

Our first consideration is that neither the output signal nor the input are perfectly monochromatic. In fact, the lack of a good isolator at the output and the cavities created between not welded fibers lead to new peaks around 1532nm. Hence, to compare with the simulations (which only treat the 1550nm wavelength) we can not a simple power-meter, as it would give the overall power.

From the obtained optical spectra we can estimate the gain at the central frequency, 1550nm, and we obtain a value of $12.8dB$. Taking an account that the general losses in the circuit, measured component by component, are $1.3dB$, we obtain a fiber gain of $14.1dB$ which we can compare with the result proposed by the simulation software (Figure 6). We verify that there is a good

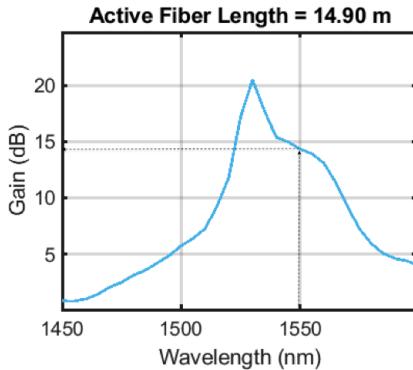


FIG. 6. Gain at 1550nm obtained by simulation

agreement between the value contributed by the simulation (14.3dB) and the value registered experimentally (14.1dB).

However, if we analyze the gain at a different wavelength, the experimental result is not the predicted one. That is because the main wavelength (1550nm) is interfering the amplification, as it is also amplifying other wavelengths. Therefore, the output power is greater than the predicted, specially for the wavelengths with lower input signal. To obtain an adequate record of the gain in each frequency, we should use a tunable laser that would allow us to scan it for all wavelengths.

To analyze the operation of the EDFA in our experimental assembly, we have also registered the gain obtained by modifying the pump power (with values from 0 to 180mW), obtaining the results shown in the Figure 7. These results compare satisfactorily with those obtained by the EDFA simulation software, as shown in the same Figure 7. They both reach a limit of pump power where the gain saturates. The only notable discrepancy that can be observed is that in the simulation the saturation is reached much earlier than in the experiment. Also, the experimental gain at 0dBm is $-30dB$, as it should be in a fiber with linear losses of $2dB/m$.

To understand better the concordance between the experiment and simulations, Figure 8 presents the experimental and the simulation gain with different pump and signal inputs. We can see that the simulation do not gives different results for different signals, but theres a substantial variation in the experimental gain.

Both *high signal / high pump* and *low signal / low pump* match perfectly, and we can justify the other cases. *High signal / low pump* experimental gain is lower because that real losses are higher and the pump is not high enough to take the fiber to the saturation. *Low signal / high pump* experimental value, instead, is higher because the dominance of spontaneous emission and the interference of other wavelengths, which is not contemplated in the simulation.

Finally, we have checked the output power of spontaneous emission versus the pump power, setting the signal

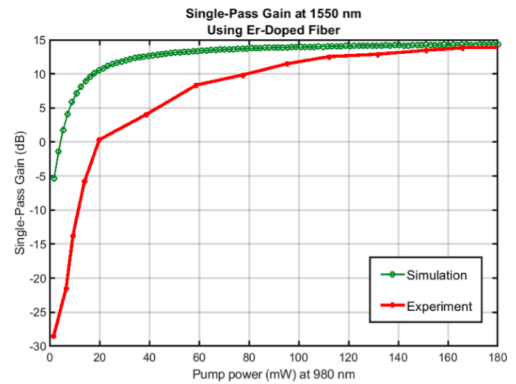


FIG. 7. Gain as a function of pumping power (Experiment and Simulation)

Pump \ Signal	0.03mW	0.1mW
	20 mW	11.0
180 mW	10.7	6.5
	14.3	14.3
	15.8	14.1

FIG. 8. Fiber gain shown as: Experimental value \ Simulation value (in dB)

out and measuring the integrated signal with the powermeter. The curve obtained has the same form of a normal output curve with signal, with a value of saturation of $2dBm$ (integrated signal in the 1550nm bandwidth). As we said at the start of this section, the output signal have various non desired peaks, so it is understandable to have a relatively high value of noise.

V. CONCLUSIONS

The fiber amplifier is a key enabling technology for high speed optical communication. In this project, an EDFA has been built and its characteristics have been analyzed in an experimental setup in order to compare it with the physical model implemented on the Matlab simulations.

Our results conclude that an EDFA montage like what we have performed is described correctly with the equations implemented on the simulation, and the saturation gain is predicted with accuracy.

However, although the qualitative curve is described correctly, the model struggles with giving the correct gain value in cases where the spontaneous emission is strong or the pump power is not high enough to saturate.

Finally, we have also seen in the experimental setup that the lack of an isolator at the output leads to the formation of powerful peaks near the central wavelength, and there is some interference between wavelengths that are not considered in the monochromatic model..

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