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Characterization of Optical Fibers Containing Nanoparticles Doped Rare Earth as an Amplifier for Telecommunications

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ABSTRACT

The influence of dielectric nanoparticles in an amplifier is still actively sought in many research laboratories. This paper presents the effect of doped nanoparticle namely magnesium in fiber amplifiers. Phase separation technique at 1700°C was utilized to form dielectric nanoparticles incorporated in silica matrix and encapsulating the luminescent ions with different concentrations. It is observed that there are modifications made to the spectroscopy of Er^{3+} within its spectral bandwidth in some samples. Increasing the concentration of magnesium may result in spectral changes caused by different size of nanoparticles. Length of fibers has been varied successively by using cut-back method in estimating the optimal length for higher amplification. Co-propogative configuration approach was used to analyze the amplifier's gain for variable lengths and pump powers. The fiber length of 2 m is recorded to give the best amplification at all range of wavelengths with pump power of 150 mW.

Keywords: Dielectric nanoparticles, rare earth doped (Er^{+3}), cut-back method, amplifier efficiency.

1. INTRODUCTION

Er^{3+} is one of 15 elements of the lanthanide family in the form of [Xe] $4f^{11}$ with partially filled layer 4f. The Er is the most commonly used ion in telecoms especially in amplification. Nevertheless, a new route was recently proposed to improve the silica-based fiber-rare earth property spectroscopy [1]. Several studies have been done to develop an environment adaptable of the silica. The encapsulating luminescent ions in nanoparticles of magnesium (Mg), strontium (Sr) or calcium (Ca) represents a new source of amplification [2]. These particles are metals alkaline earthy and their nature is earlier crystalline.

Traditional method such as modified chemical vapor deposition (MCVD) with doping in solutions has been used to manufacture nanoparticle doped optical fibers. This method based on two steps where the first step involves preparation of a preform that undergoes different cycles and temperatures while the second step is fiber-drawing. In the first step, the thermal cycles are utilized to trigger a phase separation. The binary phase diagram of SiO2-MO (M = Mg, Ca; Sr) is exploited as a reference where demixing can be observed for temperature above 1700°C. The solution of the prepared nanoparticles is injected into the preform core. It is interesting to note that doping with oxyacid gives a favorable improvement of the luminous properties [3]. The second step which is fiber-drawing requires temperature about 2000°C in which the preform has to be stretched to make the optical fiber. The temperature is carefully

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monitored as its affect size of the nanoparticles. A novel flash vaporization method [4] is introduced for creation of Er^{3+} doped glass-ceramic nanosize core fiber that limits light scattering which is the main problem in dealing with nanoparticles. The manufacture of doped erbium fiber with magnesium allows limited light scattering [5] that depends very strongly on alkaline earth ion.

This work focuses on the Er^{3+} codoped with Mg. Visible modification of spectroscopy of Er^{3+} was consistently performed in the study. Gain and losses measurement are conducted for samples with different nanoparticle sizes.

2. THE ENVIRONMENT OF ER IN NANOPARTICLES

Spectroscopy of Er^{3+} ions is investigated in fiber samples containing Mg of different concentration (low 0.1 mol/L, strong 1 mol/L). The emission spectra and the fluorescence declines are shown in Figure 1 and 2 respectively. A marked modification of the spectroscopic properties is observed by increasing the concentration of Mg [5]. The width at mid-height of the transmission band was increased by 60%. Such widening is sought in the case of amplifying fibers in order to increase the gain spectral band. The lifetime of the fluorescence at 1.55 μm increases from 11.7 ms to 6.7 ms can caused a drop in efficiency.

In low magnesium concentrations, the spectroscopic characteristics are similar to those of the Er^{3+} ions in the silica. As the concentration of magnesium increases, the shape of the emission band and the fluorescence lifetime are similar to those observed in phosphates. It is also interesting to note that the emission spectrum is a band spectrum and no lines as it could be in a crystallized structure. This would indicate that the particles are rather amorphous in nature. It is also essential to note that this enlargement is inhomogeneous, connected with the amorphous nature which subjects it to a different crystalline field, and thus the ions do not all have the same central frequencies.

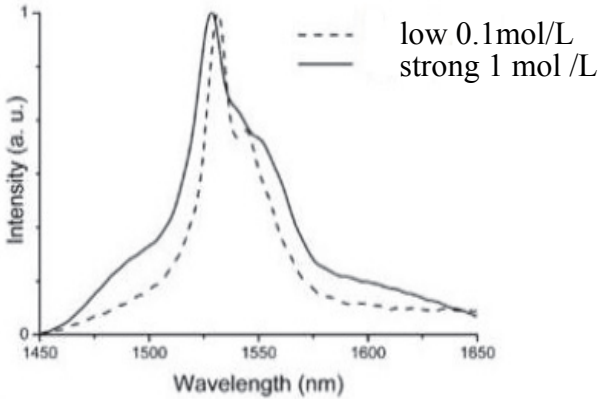


Figure 1. Er-emission spectrum with two concentrations in Mg [9]

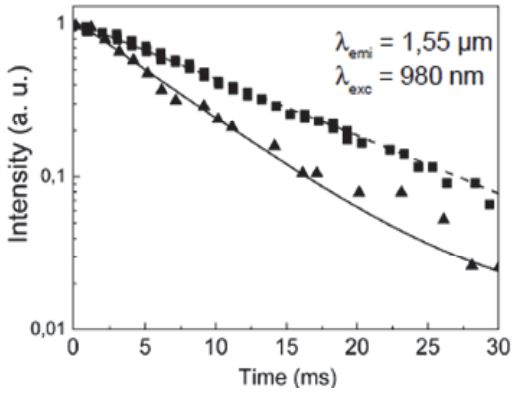


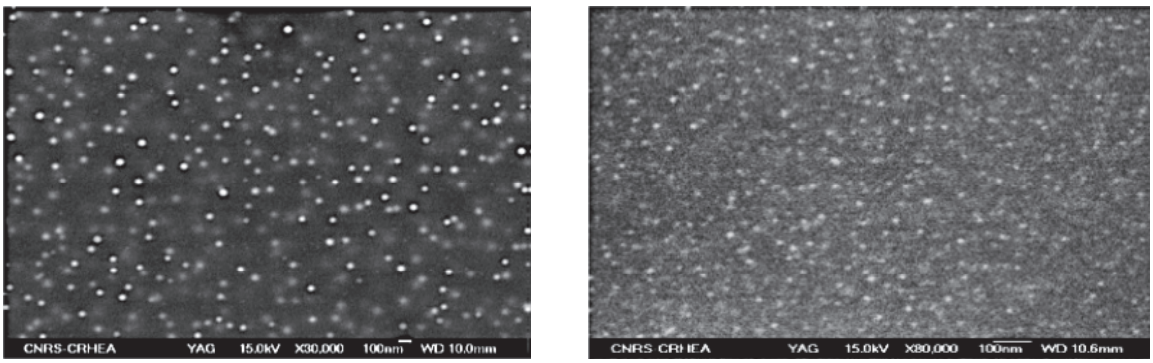
Figure 2. Measured Er fluorescence declines with Mg [9]

3. EXPERIMENTAL WORK

The fibers have been produced in the laboratory of LPMC and characterized by scanning electron microscopy (SEM) as shown in Figure 3. Table 1 presents different concentrations and synthesis with and without nanoparticles of all measured samples. In this part, all identified parameters in EDFA system are characterized and summarized. The effect of occurrence of nanoparticles is discussed in the next section.

Table 1 Sample preparation criteria

Samples	J01	J02	J03	J04	J05	J06
Doped method	Solution	Solution	Solution	Solution	Solution	FVS
Solution (Mg)	1	1	1	0.7	0.1	0.4
Number of Np/m2*	70.10^{10}	19.10^{10}	$1.5.10^{10}$	-	qq.	$1.4.10^{13}$
Average diameter	125 nm	115 nm	-	110 nm	>40 nm	40 nm



(a) (b)

Figure 3. Backscattered electrons SEM images of (a) a polished preform and (b) a cleaved fiber. The white dots correspond to NP on the surface of samples. Scale bars: 100 nm [4]

3.1 Method of measuring the absorption coefficients (α)

The intrinsic loss (α_s, α_p) of fiber can be measured with the spectral attenuation cut-back measurement procedure. The assembly of the cut-back method is illustrated in Figure 4. A white light is used as an input optical source and an optical spectrum analyzer is employed to obtain a spectral information. A standard reference fiber, i.e. SMF-980, is fixed permanently in the center of the setup. The tested fiber has a length of two meters and fused to the SMF-980 which is cleaved to about ten millimeters of the weld. A sheath dump is utilized to eliminate the modes injected into the cladding which can be recoupled in the core of the fiber with the fundamental mode and induces noise. Then several test fibers of different lengths depending on the type of fiber is positioned properly.

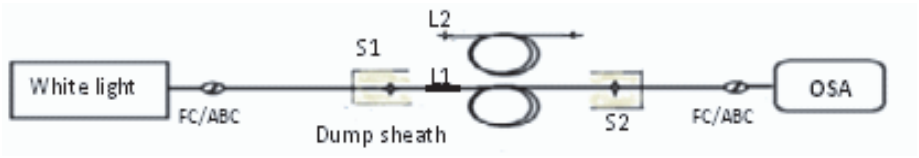


Figure 4. Cut back method where S1 and S2 represent welder losses

The spectrum is recorded to obtain the first reference measurement (L1). Later, the fiber is cut to a shorter length (L2) and the spectrum is observed again. This technique is often called "cut-back". A power uncertainty of 0.1 dB arises from the need to redo a fusion between the fibers. In this process, misaligned fiber center can increase scattering loss. Thus, to limit the uncertainties, only one cut is done at a time. The process is repeated from a single cut-back to so called multi cut-back. Mathematically, the spectral attenuation in S1 and S2 is given by [8]:

$$A(\lambda)dB/m = \frac{10}{L_{ref}-L}\log_{10}\left[p_{ref}(\lambda) / P(\lambda)\right] \quad (1)$$

where $P(\lambda)$ and $P_{ref}(\lambda)$ are the spectral power distributions measured with the long and short fibers represented the fiber lengths of L and L_{ref} respectively. Knowing the absorption coefficient of fibers makes it possible to control the manufacturing parameters of the preforms (average concentration of dopant ions, purity of the synthesized materials, manufacturing quality, etc.) and also the losses induced by the EDFA.

3.1.1 Reference fiber (J0)

Fiber used as a reference in this work does not contain a nanoparticle. The Er^{3+} is doped in the core with germanium and aluminum (to increase the index of refraction). The core diameter is 8.2 μm and singlemode at signal pump of 1550 nm. The absorption coefficients are portrayed in Figure 5. It is observed that the losses are 6.9, 8.09 and 0.1 dB/m at wavelength (λ) of 980, 1531 and 1200 nm respectively. The loss at 1200 nm expresses the diffusion losses which are the main problem for the doped fibers with the presence of nanoparticles. Note that this value is very small thus negligible. This is because the fiber does not contain a nanoparticle. Moreover, Er^{3+} does not absorb at 1200 nm.

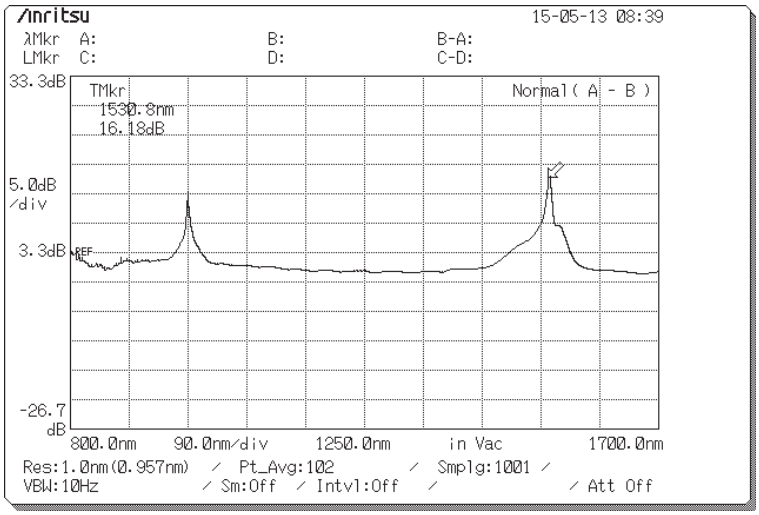


Figure 5. J0 absorption coefficient spectrum

3.1.2 Fiber with nanoparticle

The same technique is performed as in the previous section for samples with the presence of nanoparticles. Table 2 highlights the absorption coefficient of all samples.

Table 2 Peak of absorption of Er^{3+} at 980,1532 nm, and at 1200 nm (plague), * the measurement is exceeding the limit of noise

Sample	J0	J01	J02	J03	J04	J05	J06
α_{aps}(980nm)dB/m	6.9	*	5.95	5.6	60	5.8	5.23
α_{aps}(1532nm)dB/m	8.09	75.4	20.7	10.7	25.3	12.1	7.77
α_{aps}(1200nm)dB/m	0.1	17.3	2.15	0.6	21.6	0.7	1.26

The absorption coefficient for sample J01 is not observed at 980 nm because it exceed the noise limit of -90 dBm. Hence, it is impossible to amplify the signal because it has losses due to diffusion related to the size of nanoparticles i.e. greater than 50 nm. Similarly, in sample J04 with particle size of 110 nm there is no Mg presence. Therefore, this confirms the influence of Mg which reduces the size of nanoparticles as depicted in Figure 6. In addition, the absorption coefficients predict the possibility of gains at 1480 nm. Measurement of overlap parameter (Γ) can improve the characterization if the power is increased beyond 150 mW as this is our limitation. In sample J02, the absorption of optical pumping is small compare to the absorption of 1532 nm (emission signal), no amplification of the signal. Small losses of diffusion but high loss of absorption (emission signal) is recorded in sample J03 and J05. Thus, no amplification is possible. Sample J06 demonstrated the acceptable values of absorption pumping and scattering related to the size of nanoparticles 40 nm. However, the distribution of Er (clustering) diminished the luminous ion, hence no amplification is observed.

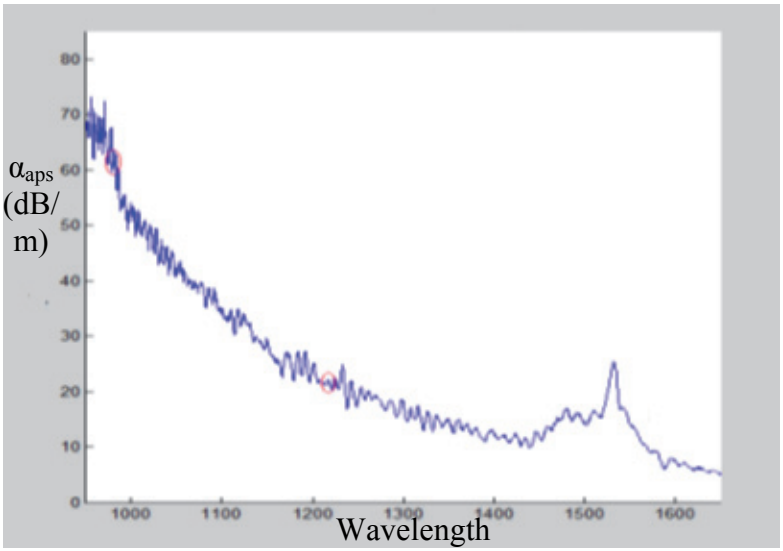


Figure 6. Evaluation of absorption coefficient of J05

All the losses of diffusion have been associated to the size of nanoparticles which are greater than 50 nm. This optical energy loss is due mainly to the diffusion of Rayleigh, where Rayleigh scattering is produced by inhomogeneities of the material over distances under the exposure of light [10,12]. In other published work, lanthanides as Eu^{3+}/Tb^{3+} codoped LaF3 nanoparticles were reported to avoid the Rayleigh scattering [4,7].

3.2 Gain measurement method

Gain is the essential parameter of the EDFA, as it determines the amount of amplification that can be granted by the system. The gain can be defined by the following equations:

$$G_{dB} = 10 \times \log_{10}\left(\frac{p_s}{p_e}\right) \quad (2)$$

$$G_{dB} = [p_s(\lambda)\, dBm - p_e(\lambda)\, dBm] \quad (3)$$

The signal gain of the optical amplifier reflects the signal increment in the fiber. The gain depends on the cross-section of absorption and emission, and also of the concentration of Er in the fiber [7]. The influence of nanoparticles permits the energy exchange between the Er^{3+} and the nanoparticles. This exchanged of energy leads to increase in the gain if the exchanged is radiative, otherwise there is no gain and decrement of signal (clustering) is observed [5]. A method known as co-propogative configuration as illustrated in Figure 7 is adopted in analyzing amplifier's gain.

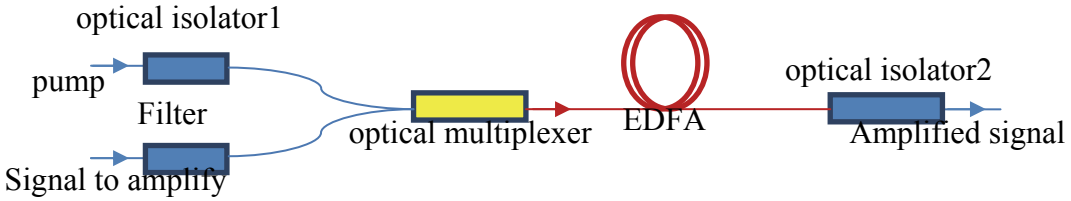


Figure 7. The diagram of an amplifier

The signal source to be amplified is supplied by the super-luminescent diode (SLD) of power range between 0.10 to 20.80 mW that covers the entire band C as depicted in Figure 8. It is connected to an optical filter [7] where the selection of wavelengths is conducted. Laser diode at 980 nm is employed as the pump source.

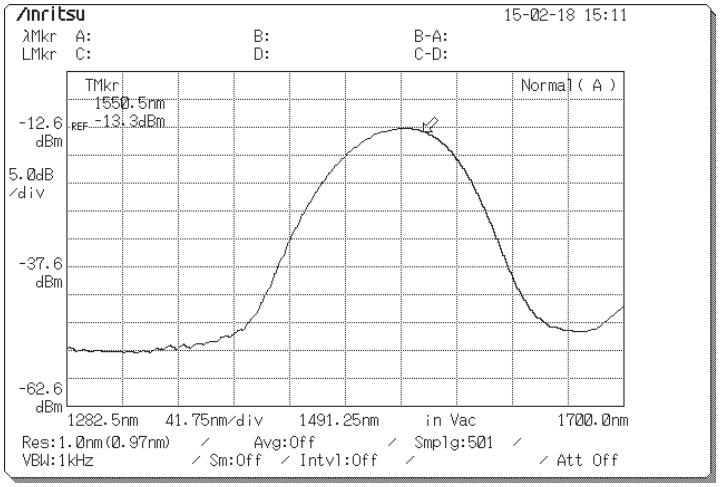


Figure 8. Transmission spectrum of (SLD)

Gain measurements (reference J0) are carried out by measuring the input signal as depicted in Figure 9.

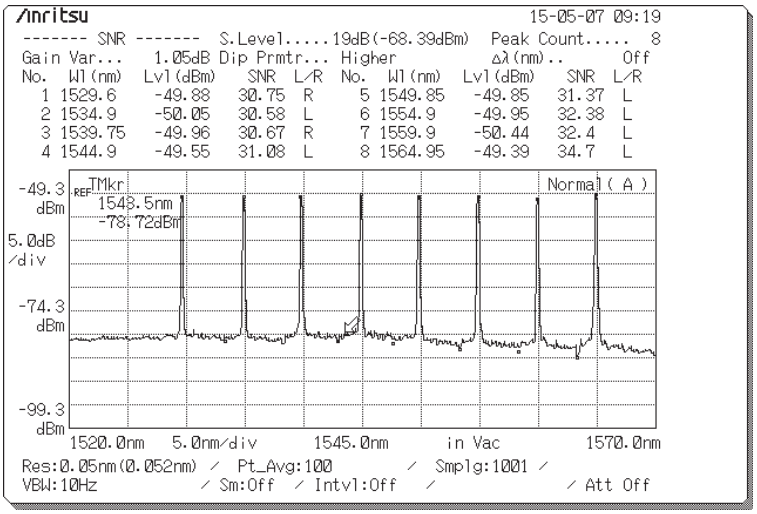


Figure 9. Input signal spectrum

Then, the pump is used with the signal source in order to produce an amplified signal as shown in Figure 10.

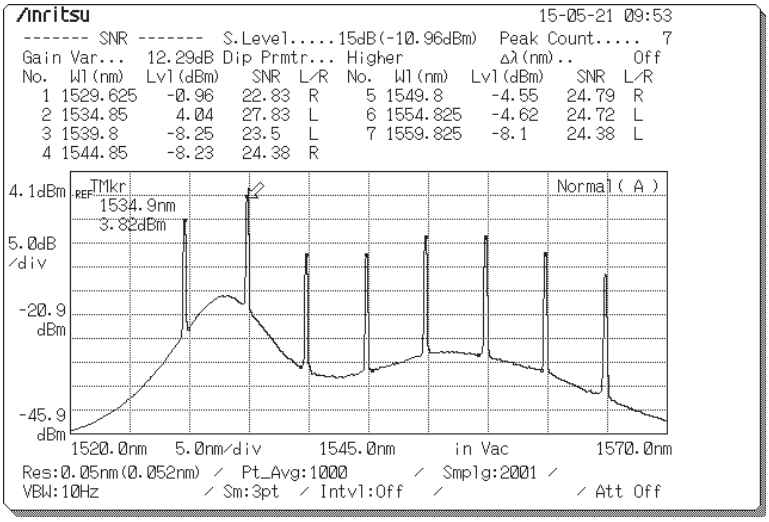


Figure 10. Signal spectrum amplified by J0 (150mw, L = 11m)

The distortion of amplified signal in Figure10 is subjected to amplified spontaneous emission (ASE). It can be induced even at much lower pump power due to a very long gain medium and a spatially confined laser beam in the core of the fiber. Several lengths of fibers (L = 2, 6, 11, 15, 20 m) are studied in terms of its gain measurement relation with variable wavelength as depicted in Figure 11 and Figure 12. In the case of a maximum pump power at 150 mW, the maximum gain 55 dB is observed at 1535 nm with length of 6 m. It is noted that the gain is negative for a low pump power suggesting that the population inversion is not realized. Also one notices that there is a point where all the gains are almost crossed and constant by what they have more or less the same gains (called Flat Gain).

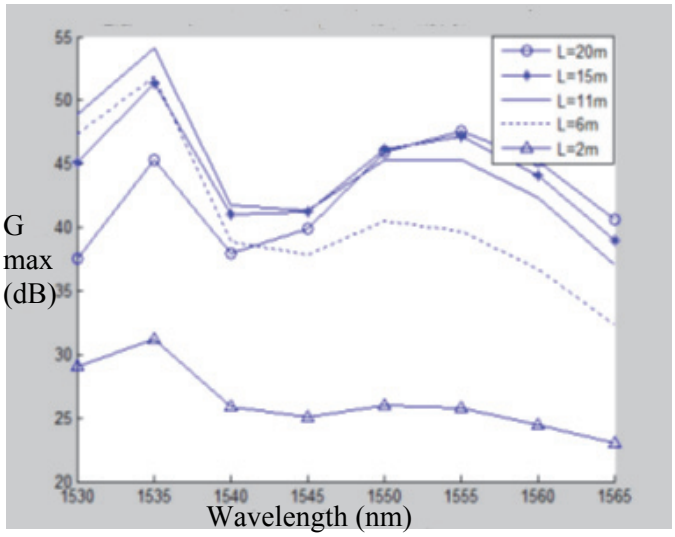


Figure 11. Maximum gain of fibers

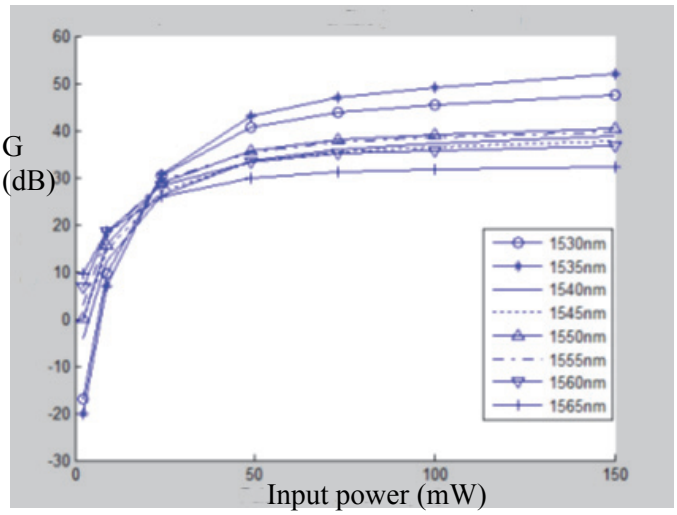


Figure 12. Maximum gain for different wavelengths (Ref J0, L=6m)

Table 3 Gains for NP-doped fibers

Reference	L (m)	G.max(dB)	λ (nm)
J06	0.04	-2	1535
J05	0.5	17	1535
	1	18	1535
	2	19	1535
J03	2.5	27	1535
	6	35	1535
	8	33	1535
J02	4	24	1556
	3	28	1555
	2	31	1535
J04	-	-	-
J01	-	-	-

The observed results are summarized in Table 3. It is noticed that the gains are important for samples J03 and J02, where the gains reached more than 33 dB (J03 = 6m, J02 = 2m) with injected pump power of 150 mW. Thus, J02 has a higher concentration of active ions than the fiber J03. A larger gain can be observed if it is pumped with more than 150 mW. In contrast to sample J06, no gain is indicated. This means that the sample has suffered very large absorption losses because it is connected to the high concentration of Er^{3+} in the encapsulated nanoparticles. Huge number of nanoparticles is measured about 1.4×10^{13} per m^2. This amount produces the effect of clusters, which greatly limits the gains by the exchange of non-radiative energy. Samples J04 and J01 are tested due to the losses of diffusion. Finally, sample J05 shows a small signal gain but less significant in comparison to J03 and J02.

3.3 Method of Measuring Optimum Length

Figure13 depicts the influence of optimum length on the maximum gain. It is noted that the optimum length for the wavelengths of 1530, 1535, 1540 and 1545 nm is 11 m because there is re-absorption beyond this point. In other signals, re-absorption of powers by the atoms of Er is dominated. The output power of the signal varies as a function of fiber length in all cases. Gain decrement is observed due to signal re-absorption.

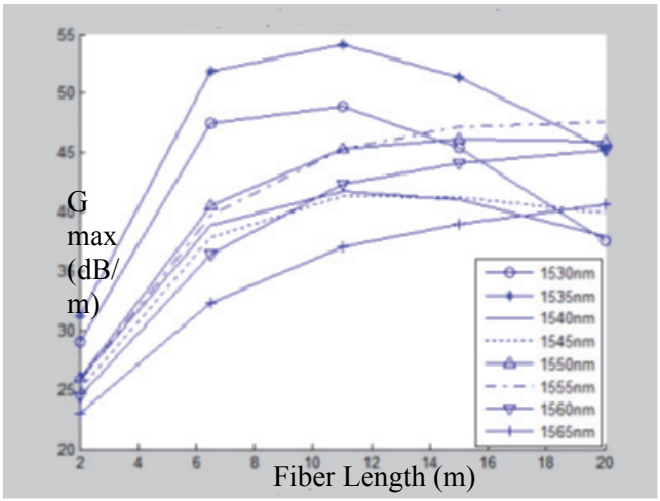


Figure 13. Optimum Length for fiber (J0) with pump power, Pp (150 mW), (9150mw) H04, P=150mW

3.4 Noise figure

Noise figure reflects the signal degradation which is defined as in Eq. (4) where SNR_i is signal to noise ratio who present the level of a desired input signal to the level of background noise and SNR_o is signal to noise ratio who present the level of a desired output signal to the level of background noise.

$$NF=SNR_i/SNR_o \quad (4)$$

This work observed the NF as plotted in Figure14. The minimum noise is recorded for the fiber length of 6.5 m with its value 4.5 dB at 1545 nm and maximum power 150 mW. This value is closed to the 3 dB limit. The greatest noise is measured in fiber length of 11 m, because a very large gain is observed. This means that it amplifies the noise corresponding to ASE [11].

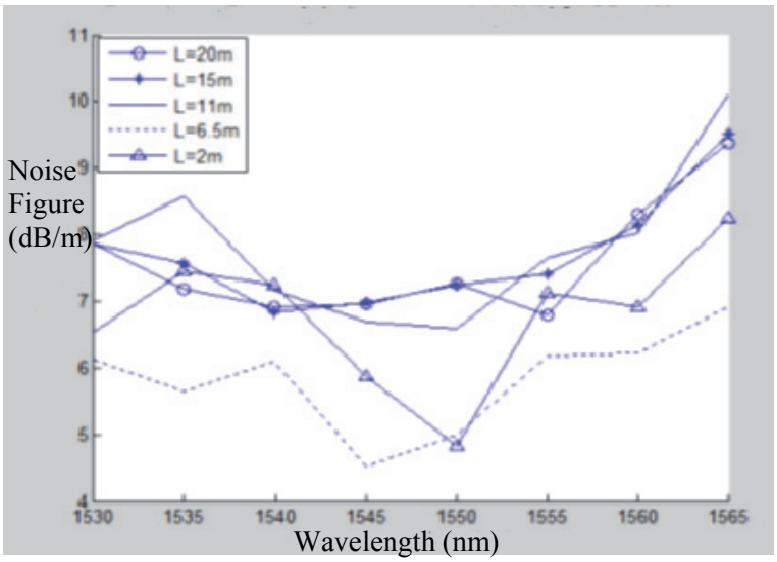


Figure 14. Noise figure for fiber J0 at *P*=150 mW

3.5 Amplifier efficiency

The efficiency of amplifiers is obtained from efficiency slope in Figure 15. This parameter has been used to evaluate the performance of the amplifier. The slope is represented by the value of gain divided by the pump power. It is inaccurate to measure the efficiency this way but it estimates effectiveness. The reference J0 has acceptable efficiency of 4.6 dB/mW as shown in Figure 16. However, this value is smaller compared to the optimum value of 11dB/mW [8]. Sample J02 shows 5.56 dB/mW, thus it is better than J0. Table 4 simplifies EDFA characterization data. There is a big gain observed in sample J02 with 2 m length. Thus, it could realize the compact system of EDFA with high efficiency.

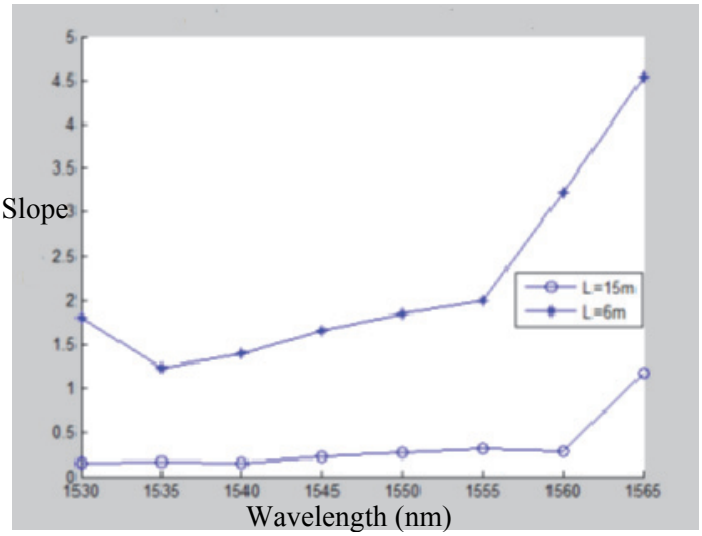


Figure 15. Efficiency slope for fiber J0

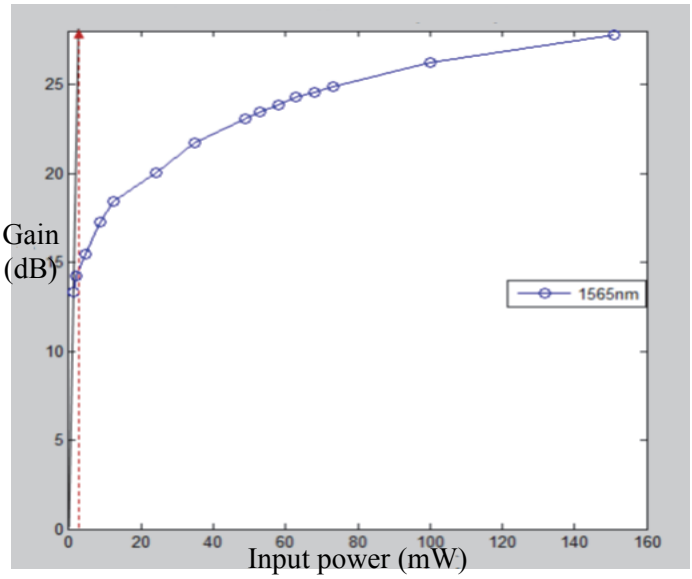


Figure 16. Efficiency of J02 with L = 2 m and P_p = 150 mW

Table 4 EDFA characterization parameters

Reference	$L_{optimal}$ (m)	G.max (dB) (λ=1535nm)	Efficacy (db/mw) (λ=1565nm)	NF(db) (λ=1535nm)
J05	2(for all λ)	19	3.4	7.5
J03	6 (*λ)	35	0.46	7.5
J02	2(for all λ)	31	5.56 (**λ)	9

L_{op} λ*=1530, 1535, 1540, 1545nm. Eff. λ**=1535

4. CONCLUSION

This work has demonstrated the influence of nanoparticle encapsulated in Er^{3+} ions. Samples with different density of nanoparticles are analyzed in terms of its losses and efficiencies. Distribution of nanoparticles in the samples may affect homogeneousity and its absorption properties. Length of the fibers also plays and important role in building a good EDFA. In the future, higher pump power may be employed to realize a good result.

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