International Journal of Pure and Applied Physics
ISSN 0973-1776 Volume 3 Number 1 (2007) pp. 83–90
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http://www.ripublication.com/ijpap.htm

Yttria-Alumina-Silicate Erbium Doped Fiber Amplifier Characteristics at 1540 nm

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Abstract

The small signal gain coefficient and the gain of 1540 nm yttria-alumina-silicate erbium doped fiber amplifier have been calculated. The characteristics have been modeled using absorption and emission cross section data, where the later was calculated using McCumber theory. We also show the effect of length of the amplifier on the gain. We found that the gain is high for this new glass fiber amplifier and is saturated as the length of the amplifier increase.

Introduction

In wavelength division multiplexing (WDM) systems, overall transmission capacity depends significantly on the spectral characteristics of the optical amplifiers, such as flatness, bandwidth, and the magnitude of the gain. Erbium-doped fiber amplifiers (EDFAs) have provided an efficient optical gain in the 1.5µm communication windows in conventional single-mode fibers (SMF) [1,2]. When the population is highly inverted, the stimulated emission cross section of erbium ions in silica provides ample gain over the 1520-1560 nm range, called the conventional band or C band. The structure of yttria-alumina-silica (YAS) glasses is somewhat unconventional, as it contains a large number of fivefold and sixfold coordinated aluminum ions which charge compensate the yttrium ions and thus reduce the formation of clusters [3,4]. This structure makes these glasses highly promising as laser gain media for high rare-earth dopant concentrations. Raman measurements [5] show that the maximum vibrational energy in YAS glass is about 950 cm^{-1}, which is less than silica glass. These glasses exhibit high transformation temperatures of about 900^0C, which are virtually independent of composition. Other remarkable properties of these glasses are the high strength and high refractive index, which increases rapidly with the Y_2O_3 content. The glasses are stable and can easily be prepared in large batches. Er : YAS glass shows emission from the level $^4I_{13/2}$ centered at 1534 nm with a width of 46 nm

[6]. The emission lifetime is 7.0 ms, indicating effectively unity quantum efficiency. The fluorescence decay is single exponential in the Er concentration range used.These results make YAS glass an interesting host material for high dopant concentrations, thus enabling short device lengths. Further work on Er: YAS should determine the upper Er concentration limit [6].

Theoretical Model

A- Absorption and Emission Cross Section

A reciprocity relation between absorption and emission cross sections was used in McCumber's theory, this reciprocity relation is temperature dependent and is expressed as [7]:

$$\sigma_e(\nu) = \sigma_a(\nu)\exp\{\frac{(\varepsilon - h\nu)}{KT}\} \tag{1}$$

where ε is the temperature-dependent excitation energy.The physical interpretation of ε is as the net free energy required to excite one Er^{3+} ion from the $^4I_{15/2}$ to the $^4I_{13/2}$ state at temperature T. Since the manifold widths exceed *kT*, the absorption and emission spectra are offset from each other, the absorption to higher frequency and the emission to lower frequency, as illustrated in Fig. (1)**.** The spectra have been plotted as a function of wavelength.

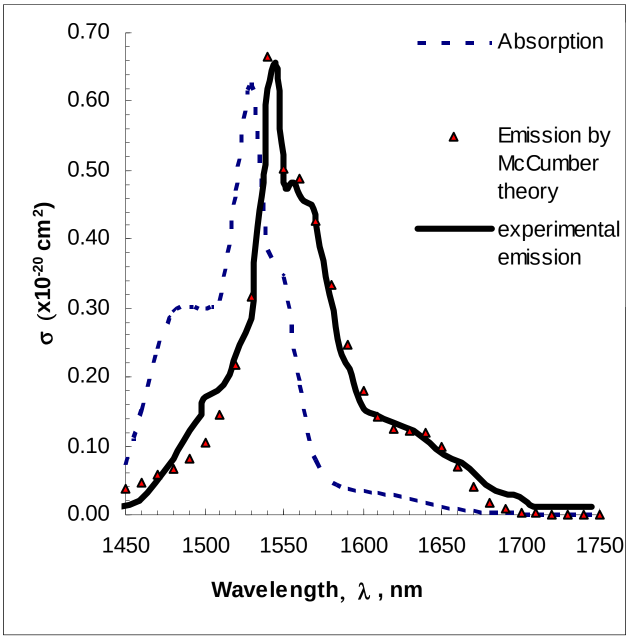

Figure 1: Experimental absorption and emission cross section compared with emission calculated by McCumber theory for Er^{3+}- doped yttria-alumina-silicate glass fiber amplifier

B- The Small Signal Gain Coefficient

It is useful to consider the dependence of the gain coefficient on wavelength and relative medium inversion. The relative inversion can be defined as [8]: D = $(N_2-N_1)/\rho$ = $(2N_2-\rho)/\rho$, with D= -1 when all laser ions are in the ground state, and D = 1 when they are all in the excited state. The gain coefficient can, therefore, be written as:

$$g = \rho \frac{\{\sigma_e(\lambda_k)(1+D) - \sigma_a(\lambda_k)(1-D)\}}{2}. \qquad (2)$$

C- Amplifier Gain

Introducing the emission and absorption coefficients to the power rate equations, one can get:

$$p_L^+ = p_o^+ \exp[\frac{\alpha_k}{\alpha_p}\{\frac{\eta_p - \eta_k}{1+\eta_p}(q_L^+ - q_o^+) + \log(\frac{q_L^+}{q_o^+})\}] \qquad (3)$$

where p_o^+ and p_L^+ are the normalized input and output signal powers, η_p and η_k are the ratio of the emission to the absorption cross section for the pump and the signal, respectively. The amplifier gain, G, can be obtained as:

$$G = \frac{p_L^+}{p_o^+} = \exp[\frac{\alpha_k}{\alpha_p}\{\frac{\eta_k - \eta_p}{1+\eta_p}(q_L^+ - q_o^+) + \log(\frac{q_L^+}{q_o^+})\}]. \qquad (4)$$

From the definition of the absorption coefficient, α_p, and using an amplifier of length L, one can get the relation between the input and output pump powers, q_o and q_L, as:

$$q_o^+ - q_L^+ = \alpha_p L - \log\left(\frac{q_o^+}{q_L^+}\right) \qquad (5)$$

Equation (4) is now used with Eq.(5) to get:

$$q_L^+ = q_o^+ \exp(-A_G L), \qquad (6)$$

where A_G is the gain-dependant pump absorption coefficient, given by:

$$A_G = \alpha_p \left(\frac{1+\eta_p}{1+\eta_k}\right)\left(\frac{\eta_k - \eta_p}{1+\eta_p} - \frac{\log G_k^+}{\alpha_k L}\right). \qquad (7)$$

The input pump power q_o^+ is then expressed as a function of the amplifier gain G, by eliminating q_L^+ from Eqs.(6) and (7) as:

$$q_o^+ = \alpha_p L \frac{Q_k}{1-\exp(-\alpha_p L(1-Q_k))}, \qquad (8)$$

with

$$Q_k = \frac{1+\eta_p}{1+\eta_k}\left(1+\frac{\log(G)}{\alpha_k L}\right). \tag{9}$$

The output pump power q_L^+ is then rewritten:

$$q_L^+ = q_o^+ \exp(-\alpha_p L(1-Q_k)) \tag{10}$$

For forward pumping case, q_L^+ is always smaller than q_o^+ and hence Q_k must be smaller than one. Equation (9) gives the following condition for the peak gain as:

$$G < \exp\left(\frac{\eta_k - \eta_p}{1+\eta_p}\alpha_k L\right), \tag{11}$$

which sets the upper limit for the gain, G_{max}, through which the amplifier length, L, can be determined.

Results and Discussion

The experimental emission and absorption cross sections of the yttria-alumina-silicate erbium doped fiber glass [6] are fitted to Gaussian curves and the parameters are used in the calculations of the gain

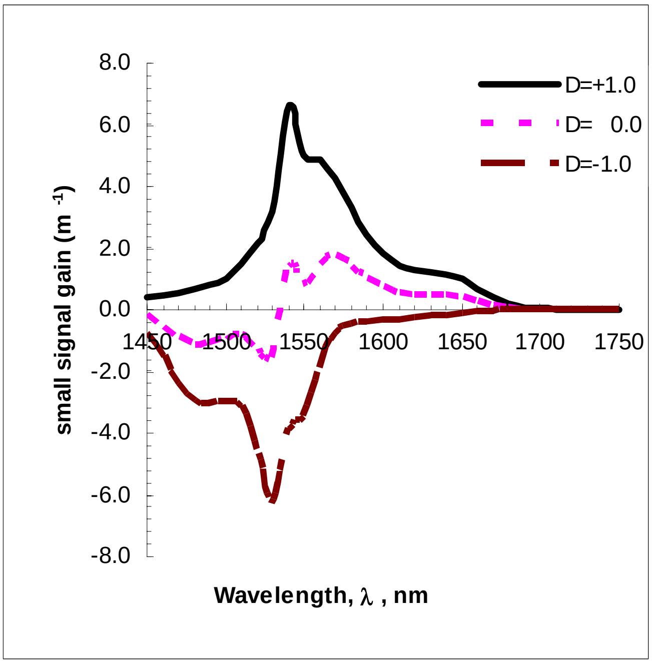

Figure 2: Signal gain coefficient of erbium doped yttria-alumina-silicate glass fiber amplifier.

Fig. (2) plots the gain coefficient around the 1.5 μm for a typical Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier for three values of the relative inversion D, (D= +1.0, D= 0.0, D= -1.0). It is clear that for D = -1, all ions are in the ground state and the medium is absorbing at all signal wavelengths, as the gain coefficient is negative. As the value of D becomes zero, there is a range of wavelength, ($\lambda < 1530$) at which the medium is absorbing and at ($\lambda > 1530$) the medium is completely is amplifying, however, a spectral region near the long wavelength side of the transition is characterized by a positive gain coefficient.

The gain spectrum of this new glass fiber amplifier is plotted against the wavelength for three values of the input power= 51.9, 10.9 and 6.9 mW for defined values of the length of the amplifier. In Fig.(3) the gain spectrum is plotted at length L=20 m, Fig.(4) the gain spectrum is plotted at L=27m. Also Figs.(5, 6 and 7) show the gain spectrum at length L=34, 41 and 48 m for three values of input power against the wavelength as mentioned before.

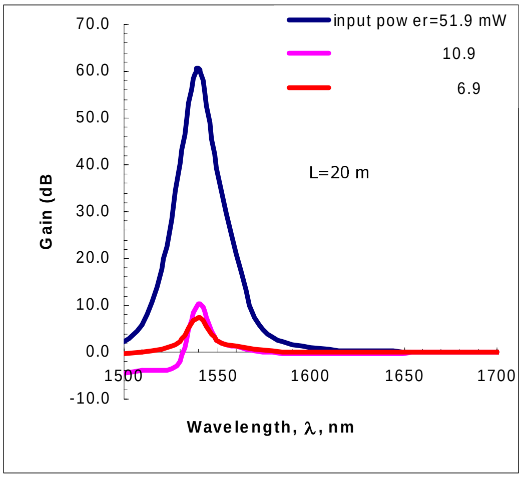

Figure 3: The gain spectrum at three values of the input power which 51.9, 10.9 and 6.9 mW at length of amplifier L=20m for Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier.

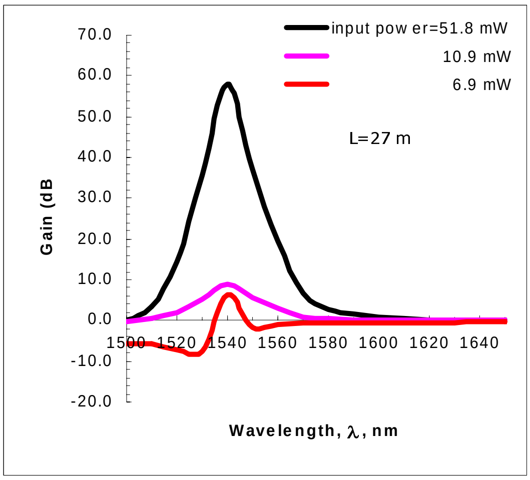

Figure 4: The gain spectrum at three values of the input powerwhich 51.9, 10.9 and 6.9 mW at length of amplifier L=27m for Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier.

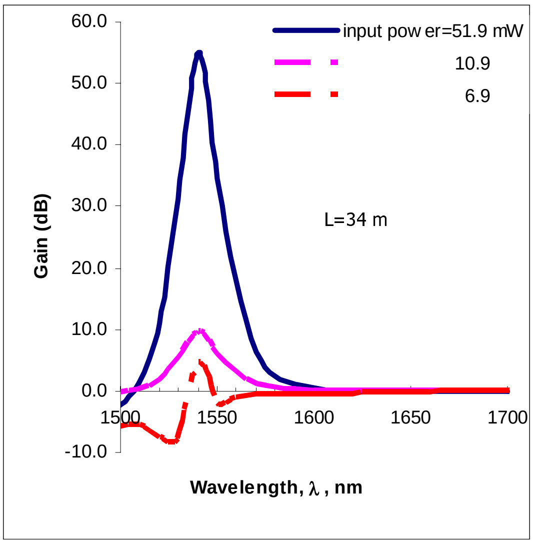

Figure 5: The gain spectrum at three values of the input power which 51.9, 10.9 and 6.9 mW at length of amplifier L=34m for Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier.

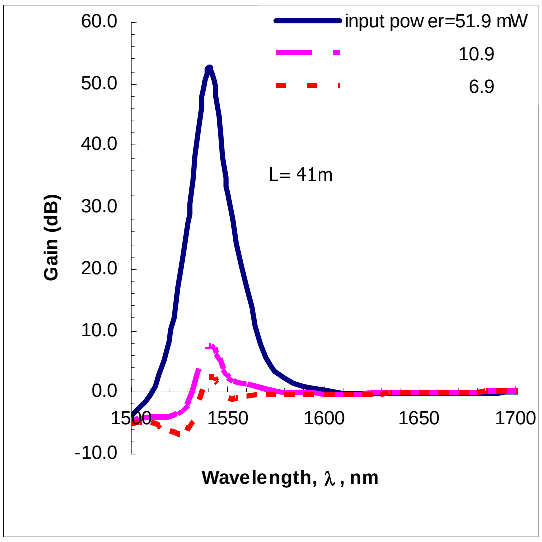

Figure 6: The gain spectrum at three values of the input power which 51.9, 10.9 and 6.9 mW at length of amplifier L=41mfor Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier.

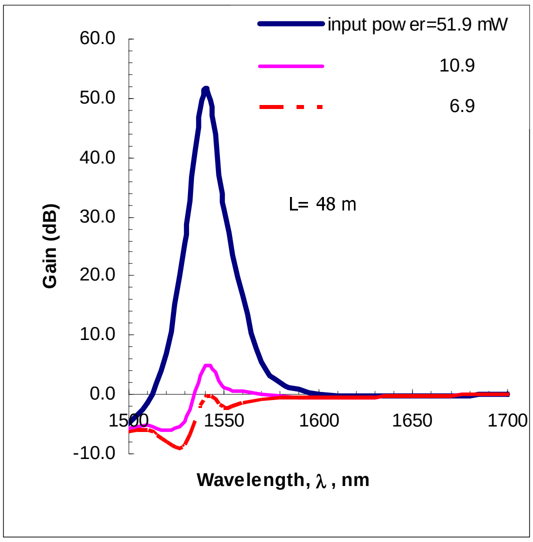

Figure 7: The gain spectrum at three values of the input power which 51.9, 10.9 and 6.9 mW at length of amplifier L=48m for Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier.

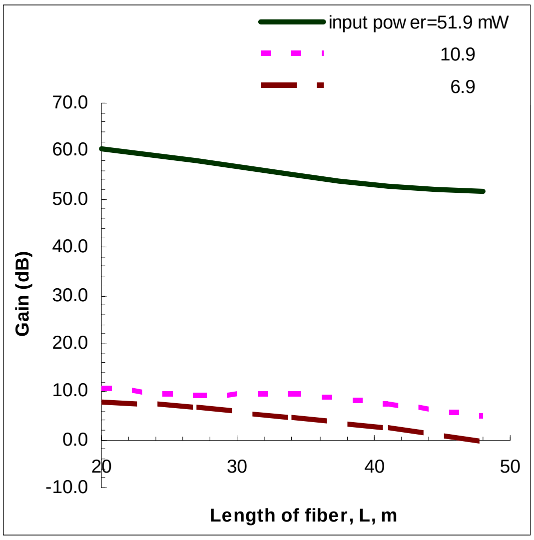

Figure 8: The gain spectrum at three values of the input power which 51.9, 10.9 and 6.9 mW is plotted against length of amplifier for Er^{3+}-doped yttria-alumina-silicate glass fiber amplifier.

It is found that this new glass fiber amplifier gives large gain compared with other glasses. And the gain decrease slightly as fiber length increase tell to becomes saturated at large lengths of the amplifier as this shown in Fig.(8), where the gain is plotted against the fiber length.

Table (1) summarizes the data of the gain obtained for series of different glasses. It could be noticed that the highest gain was obtained for yttria-alumina-silicate which gives a value of 60 dB compared with the value 33.37 dB for Al_2O_3 fiber glass.

Table 1: The gain of different doped fiber glasses

Host	λ_o (nm)	G_{max} (dB) (L=20m)
yttria-alumina-silicate	1540	60
Bismuth	1550	23
$LiNbO_3$	1553	25.3
Tellurite	1530	20
Sodium niobium phosphate	1540	12.9
Oxyfluoride silicate	1540	39
Al_2O_3	1530	33.37
Fluoride phosphate	1530	29

Conclusions

A numerical investigation of the signal gain and the gain spectrum at different values of input power at different values of the length of the fiber glass amplifier of yttria-alumina-silicate erbium doped fiber amplifier have been done. One can find that this new glass fiber amplifier gives large gain compared with other glasses like bismuth glass, $LiNbO_3$ glass, tellurite, sodium niobium phosphate glass, oxyfluoride silicate, Al_2O_3 and fluoride phosphate glass fiber amplifier and the gain decrease slightly as fiber length increase tell to becomes saturated at large lengths of the amplifier. The characteristics have been modeled using absorption and emission cross section data, where the later is calculated using McCumber theory. A good agreement between experimental and calculated emission cross section by McCumber theory could be found. The gain at length L=20 m is higher than other lengths of the amplifier (at L=20m, the gain=60 dB at input power=51.9 mw at 1540 nm).

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