Study the Effect of Temperature on the Optimum Length of Er\textsuperscript{3+} Doped Almino-germanosilicate, Aluminum-Oxide and Yattria-Silicate Glass

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Abstract: In this study the effect of temperature on the optimum fiber length for maximum gain of Erbium doped almino-germanosilicate, aluminum oxide and yattria-silicate glass, with fixed pump power. The optimum length depends strongly on the temperature and increases as the temperature increases. The maximum gain also depends on the wavelength and power of the signal which validate our findings through distributed gain measurements and so optimum length too.

Key word: EDFA, optical amplifiers, optimum length, temperature effect

INTRODUCTION

In order to increase the transmission capacity of Wavelength Division Multiplexing (WDM) systems, optical amplification outside the conventional band (C-band, 1540-1560 nm) and L-band (1560-1610 nm) is required and the various parameters which affected the gain such optimum length of the fiber and the temperature must be studied. The short wavelength band (S-band, 1480-1520 nm) is particularly attractive, being characterized by low loss in silica optical fiber. Many techniques have been developed to realize S-band amplification such as thulium-doped fluoride fiber amplifier (TDFFA) and a fiber Raman amplifier (Gerlas et al., 1997; Cheng and Min, 2005).

While these amplifiers have enabled impressive gain, noise figure and system performance, they have not matched conventional Erbium-Doped Fiber Amplifiers (EDFAs) in terms of efficiency, simplicity, reliability and cost.

To calculate the maximum gain at different values of temperature the approximate McCumber (1964) procedure is often used to predict the emission cross-section spectrum of the 1.5 μm transition of Er-doped glass fibers from the transition's measured absorption spectrum at different values of temperature (Osama, 2007).

A transcendental equation for the Maximum Gain ($G_{\text{max}}$) at Optimum Length ($L_{\text{opt}}$) of single-channel Erbium Doped Fiber Amplifiers (EDFAs) with fixed pump power was arrived by Ruhl (1992) and, independently, Lin and Chi (1992), Desurvire (1994) also arrived to the same equations in his first book (Desurvire, 1994). The equivalent equations for Gmax and Lopt are Eqs. (10) and (11) in (Ruhl, 1992), (7) and (10) in (Lin and Chi, 1992), and (1.139) and (1.157) in (Desurvire, 1994), respectively. Importantly, it was shown in (Riezni and Arellano, 2003) that these equations, deduced in principle for single-channel amplifiers, could be easily extended to the case of EDFAs operating under Wavelength Division Multiplexing (WDM) conditions.

In this article, we study the effect of temperature on the optimum fiber length for maximum gain of Erbium doped almino-germanosilicate, aluminum oxide and yattria-silicate glass, with fixed pump power.

MATERIALS AND METHODS

This theoretical work was done in 2008 at Faculty of Science, University of Alexandria, Alexandria, Egypt.

Model:

Calculation of maximum gain: The McCumber (1964) relation states that the absorption cross section $\sigma_\text{a}(\nu)$ and the emission cross section $\sigma_\text{e}(\nu)$ spectra between a ground state (manifold of eight sublevels of energy $E_\text{i}$) and the excited state (is a manifold of seven sublevels of energy $E_\text{e}$) are related by (Gigonnet et al., 2002):

$$\sigma_\text{a}(\nu) = \sigma_\text{e}(\nu) \exp\left(-\frac{\nu}{kT}\right)$$

(1)

where; $k$ is the Boltzmann constant, $T$ the absolute temperature, and $\nu$ the optical frequency. The parameter $\epsilon$ (Gigonnet et al., 2002) is defined as:

$$\epsilon = \sum_{j=1}^{8} \frac{\exp\left(-\frac{E_j}{kT}\right)}{\sum_{j=1}^{8} \exp\left(-\frac{E_j}{kT}\right)} - \exp\left(-\frac{E_\text{e}}{kT}\right) - \exp\left(-\frac{E_\text{i}}{kT}\right)$$

(2)
where \( E_i = E_{i1} - E_{i2} \) is the energy difference between the lowest energy levels of the two manifolds (McCumber, 1964) and Table 1.

If \( \eta_p \) and \( \eta_s \) are the ratio of the emission to the absorption cross section for the pump and the signal, respectively, where:

\[
\eta_k = \frac{\sigma_s(v)}{\sigma_a(v)}
\]  

(3)

We can neglect ESA also because it is absent for a pump at 980 nm. For simplicity, we assume that the gain spectrum is homogeneously broadened. Within these limits, the most fundamental limitation is due to the energy conservation,

\[
G \leq 1 + \frac{\lambda_p^m \cdot \lambda_s^m}{\lambda_k^m}
\]  

(4)

Where \( \lambda_p^m \) and \( \lambda_s^m \) is the input power for the pump and signal respectively, and \( \lambda_k \) the pump and signal wavelength.

In actual amplifiers, the absorption of pump photons (and therefore gain) is limited by the finite number of rare earth ions existing in the medium, the maximum signal gain corresponding to a three-level laser medium of length \( L \) is given by:

\[
G = \frac{\rho \cdot \alpha_{sat}}{\alpha_p} \theta(\alpha \cdot \epsilon(\lambda_k) \cdot L)
\]  

(5)

In addition if we consider how many active ions are available in the medium for certain pump, we have the following expression:

\[
G \leq \exp \left( \frac{\eta_k - \eta_p}{1 + \eta_k} \cdot \alpha_k \cdot L \right)
\]  

(6)

Where \( \alpha_k \) is the absorption coefficient for the signal, (for pump at 980 nm \( \eta_p = 0 \)) (Yahya et al., 2004).

**Calculation of optimum length at maximum gain**: The expression for \( G_{max} \) derived from the TPE model is a transcendental equation, while \( L_{opt} \) is explicitly given in terms of the fibers intrinsic parameter and \( G_{max} \). We stress that the advantages in using the TPE model is not just to have a simple transcendental equation for the gain as a function of the input powers and fiber parameters (avoiding the tedious and time-consuming numerical integrations of the SCD model), but also that these fiber parameters are combined into just two easily-measurable constants per wavelength: the absorption constant \( \alpha_s \) and the saturation power, at wavelength \( \lambda_s \). To stress this fact, we write the equations for \( G_{max} \) and \( L_{opt} \) in terms of these two spectral constants (Rieznik et al., 2006):

\[
G_{max} = \exp \left( A \cdot \lambda_k^m \cdot (G_{max} - 1) \right) = \frac{1}{\beta_p^m} \cdot \exp \left( \frac{\alpha_k}{\alpha_p} \cdot \left( \lambda_k^m - B \right) \right)
\]  

(7)

and

\[
L_{opt} = \frac{1}{\alpha_p} \cdot \left( \lambda_k^m - B + \ln(\beta_p^m) \right) + \frac{\alpha_p}{\alpha_p} \cdot \frac{\lambda_k^m}{\lambda_k^m} \cdot \alpha_s \cdot (G_{max} - 1)
\]  

(8)

Where:

\[
A = \frac{\alpha_k}{\alpha_p} \cdot \frac{\lambda_k^m}{\alpha_p} \cdot \frac{\lambda_k^m}{\alpha_p} - \alpha_s \cdot \frac{\lambda_k^m}{\alpha_p} \cdot \frac{\lambda_k^m}{\alpha_p}
\]

\[
B = \frac{\alpha_k}{\alpha_p} \cdot \frac{\lambda_k^m}{\alpha_p} \cdot \frac{\lambda_k^m}{\alpha_p}
\]

with

\[
\frac{\lambda_k^m}{\alpha_p} = \frac{\lambda_k^m}{\alpha_p}
\]

and \( \alpha_s \cdot \alpha_p \) are the absorption and pump coefficients respectively, \( \lambda_k^m \) is input pump power and \( \lambda_k^m \) is the input signal power, \( \lambda_k^m \) is the saturation power of the pump and signal, respectively.

**RESULTS**

The parameters used in calculations McCumber cross section is given in Table 1 (Gigonnet et al., 2002) and the parameters used in calculations the maximum gain and optimum amplifier length also given in Table 2 and 3 (Osama et al., 2009).
Table 3: The parameters used in this calculation of optimum length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s )</td>
<td>0.2 m</td>
</tr>
<tr>
<td>( p )</td>
<td>0.1 m</td>
</tr>
<tr>
<td>( s_{\text{sat}} )</td>
<td>0.02 mW</td>
</tr>
<tr>
<td>( p_{\text{sat}} )</td>
<td>0.01 mW</td>
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<tr>
<td>( s_{\text{min}} )</td>
<td>64 mW</td>
</tr>
<tr>
<td>( p_{\text{min}} )</td>
<td>20 mW</td>
</tr>
</tbody>
</table>

McCumber emission cross section

Fig. 1: Emission spectrum with the experimental absorption cross section for erbium doped alumino-germanosilicate glass fiber amplifier, calculated for different values of temperature

Maximum gain

![Graph showing maximum gain for different values of \( \lambda \)](image)

Fig. 3: The maximum gain for erbium doped alumino-germanosilicate glass fiber amplifier, calculated for different values of maximum wavelength at room temperature

The normalized experimental values of the absorption cross section and the McCumber (1964) theory calculation for the erbium doped alumino-germanosilicate glass fiber amplifier at temperature range 290-310ºK is represented in Fig. 1. This figure shows that as the temperature slightly increases the emission cross section increases but the wavelength at maximum gain not shifted with temperature changes. So that the window at which the signal is amplified not affect by slightly temperature changes.

The maximum gain values in dB for the erbium doped alumino-germanosilicate glass fiber amplifier are plotted against wavelength range from 1530 to 1560 nm at input power 64 mw at temperature range 290-310 ºK as shown in Fig. 2. Also the gain is plotted with length at different values of wavelength in Fig. 3, where the relation is found to be linear between the gain and the length. The Optimum length for the erbium doped alumino-germanosilicate glass fiber amplifier is calculated for fixed pump power and the maximum gain of the amplifier studied before. Since the maximum gain studied at different values of temperature, also the optimum length is studied at different values of temperature in Fig. 4.

Fig. 5 and 9 represents the normalized values of the emission cross section of Er-doped \( \text{Al}_2\text{O}_3 \) fiber amplifier and yttria-Alumina-Silicate Erbium Doped Fiber Amplifier as calculated using McCumber (1964) theory at different temperatures, from 290 to 310ºK respectively. It is clear that, the emission cross-section increases with temperature. The maximum gain values in dB for the Er-doped \( \text{Al}_2\text{O}_3 \) fiber amplifier and yttria-Alumina-Silicate
Fig. 4: The Optimum length variation for erbium doped alumino-germano-silicate glass fiber amplifier, calculated for different values of temperature at maximum gain of the amplifier.

Fig. 5: The normalized values of the emission cross section of Er-doped Al₂O₃ fiber Amplifier as calculated using McCumber theory at different temperatures.

Erbium Doped Fiber Amplifier are plotted against wavelength range from 1530 to 1560 nm at input power 64 mw at temperature range 290-310ºK respectively as shown in Fig. 6 and 10. Also the gain for the Er-doped Al₂O₃ fiber amplifier and yttria-Alumina-Silicate Erbium Doped Fiber Amplifier respectively is plotted with length at different values of wavelength in Fig. 7 and 11, where the relation is found to be linear between the gain and the length. The Optimum length for the Er-doped Al₂O₃ fiber amplifier and yttria-Alumina-Silicate Erbium Doped Fiber Amplifier is calculated for fixed pump power and the maximum gain of the amplifier studied before. Since the maximum gain studied at different values of temperature, also the optimum length is studied at different values of temperature in Fig. 8 and 12, respectively.
Fig. 8: The Optimum length variation for erbium doped Al₂O₃ glass fiber amplifier, calculated for different values of temperature at maximum gain of the amplifier.

Fig. 9: The normalized values of the emission cross section of yttria-Alumina-Silicate Erbium Doped Fiber Amplifier as calculated using McCumber theory at different temperatures.

Fig. 10: The maximum gain spectrum for yttria-Alumina-Silicate Erbium Doped Fiber Amplifier, calculated for different values of amplifier length at room temperature.

Table 4: Features of the EDFA with three different hosts

<table>
<thead>
<tr>
<th>Host</th>
<th>λₑ (nm)</th>
<th>Gₘₐₓ (dB)</th>
<th>T(K)</th>
<th>290</th>
<th>294</th>
<th>298</th>
<th>300</th>
<th>305</th>
<th>310</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.48</td>
<td>3.82</td>
<td>5.81</td>
<td>7.13</td>
<td>11.8</td>
<td>19</td>
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</tr>
<tr>
<td>Al₂O₃</td>
<td>1537</td>
<td>2.11</td>
<td>3.27</td>
<td>5.01</td>
<td>6.17</td>
<td>10.3</td>
<td>16.8</td>
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<tr>
<td>yttria-Alumina-Silicate</td>
<td>1550</td>
<td>1.45</td>
<td>2.24</td>
<td>3.41</td>
<td>4.2</td>
<td>6.96</td>
<td>11.3</td>
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</table>
CONCLUSION

We can summarize the features of the erbium doped with the three different hosts material at temperature range 290 to 310°K and the optimum length of the amplifier to improve the performance of the optical amplifier where the results given in the Table 4 and 5.

It is found that the erbium doped alumino-germanosilicate fiber amplifier exhibits large value of gain 7.13 dB at center wavelength 1560 nm and temperature 300°K relative to erbium doped aluminum-oxide fiber amplifier which exhibits a value of gain 6.17 at center wavelength 1537 nm and temperature 300°K and for erbium doped yttria-silicate fiber amplifier which exhibits a value of gain 4.2 at center wavelength 1550 nm and temperature 300°K.

Also it is found that the erbium doped alumino-germanosilicate fiber amplifier exhibits a more broadening in the gain curve (= 40 nm). The broadening in gain is required in amplification of the signal at large range of wavelengths.

For the optimum fiber length it is found that the erbium doped alumino-germanosilicate fiber amplifier exhibits value of 18.1 m at center wavelength 1560 nm and temperature 300°K relative to erbium doped aluminum-oxide fiber amplifier which exhibits a value of gain 15.3 at center wavelength 1537 nm and temperature 300°K and for erbium doped yttria-silicate fiber amplifier which exhibits a value of gain 11.8 at center wavelength 1550 nm and temperature 300°K.

REFERENCES


Table 5: Features of the EDFA with three different hosts

<table>
<thead>
<tr>
<th>Host</th>
<th>λc (nm)</th>
<th>T(°K)</th>
<th>290</th>
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<th>298</th>
<th>300</th>
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<td>9</td>
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<tr>
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<td>13.2</td>
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</tr>
<tr>
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<td>6.8</td>
<td>8.2</td>
<td>10.3</td>
<td>11.8</td>
<td>16.7</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Fig. 12: The Optimum length variation for yttria-Alumina-Silicate Erbium Doped Fiber Amplifier, calculated for different values of temperature at maximum gain of the amplifier.