Temperature Effect on Erbium Doped Fiber Amplifier in a Multichannel System for Different Glass Hosts

[2]Mohamed M. Keshk, [2]Moustafa H. Aly, [1]Ali M. Okaz and [1]Aly M. El-Rasheedy

[1]Faculty of Engineering, University of Alexandria, Alexandria, Egypt.
[2]College of Engineering and Technology, Arab Academy for Science & Technology and Maritime Transport, Alexandria, Egypt, Member of OSA.

Abstract: Temperature effect on the gain of mulitchannel (ten channels) erbium-doped fiber amplifiers (EDFAs) is analyzed based on a linear extrapolation. In order to use the model for gain shaped calculations, some simplifications are demonstrated. Forward pumping is considered taking both amplified spontaneous emissions (ASE) and scattering loss into account. The amplifier gain at the optimum length is given for each channel and hence, the temperature effect is calculated for a wide range of temperature. This procedure is repeated for six different glass hosts, namely; alumino-germanosilicate, bismuth, fluoride phosphate, oxyfluoride silicate, tellurium and aluminum oxide.

Key words:

INTRODUCTION

In a typical WDM system, most components exhibit some temperature dependence in loss shape and/or magnitude. Early system often had enough margins in performance that such changes could be tolerated. However, as systems evolve toward more wavelengths, higher bit rates and grater distances. Such temperature dependences are no longer acceptable. While several authors have recognized the presence and significance of this dependence[1,3], no general rule for predicting the temperature dependence of a particular EDFA has been presented.

Linear extrapolation has been used by several authors[1,2] to model the temperature dependence of EDFAs. While this approach can be used for a small temperature variation, a better approach is needed in order to achieve a good accuracy for a wide temperature range. In order to use the model for gain shaped calculations, some simplifications are demonstrated. Such an approach based on the physical model will be developed below.

In the present paper, the multichannel EDFA is analyzed for a different number of spectral channels (ten channels with a spacing 1 nm), approximate analytical solutions of steady state rate equations have been used to investigate the behavior of different host materials. In the described model, the maximum gain (at optimum amplifier length) for all channels is studied for different host materials. Six different host materials are considered to select the best one which can be used in WDM systems with small temperature dependence.

In the next section, the mathematical model, as well as its linear extrapolation, is presented. Section displays the obtained results and discussion. Finally, some general conclusions are given in section IV.

MATERIALS AND METHODS

Concentration Calculation: Before going into a description of the energy levels of an erbium ion in a glass host, consider first a simple system with discrete levels. The levels of this system can be degenerate. Let N be the concentration of active ions in the media and n_i be the probability of electron to be at level i. By definition of probability[4]

$$\sum_i n_i = 1 \qquad (1)$$

If a plane wave with frequency f and intensity I propagates along the z-axis through the medium, its evolution can be described by[5]

Corresponding Author: Mohamed M. Keshk, College of Engineering and Technology, Arab Academy for Science & Technology and Maritime Transport, Alexandria, Egypt, Member of OSA.
E-Mail: mohk444@hotmail.com

$$I(z) = I_0 e^{gz} \qquad (2)$$

where g is the gain coefficient defined by[6]

$$g = \sigma_{ul} N \left[n_u - \frac{w_u}{w_l} . n_l \right] \qquad (3)$$

Here, σ_{ul} is the stimulated emission cross section, w_i is the statistical weight of the ith level, and the electron transition occurs between the upper level with i = u and the lower level with i = l, separated by an energy difference $E_{ul} = h_s$.

In particular, the relative occupation of two levels in thermal equilibrium follows Boltzmann law

$$\frac{P(E_2)}{P(E_1)} = e^{-[E_2 - E_1 / kT]} \qquad (4)$$

where T is the temperature in K and k is Boltzmann constant. The most general form of the function P(E) which satisfies condition (4) is

$$P(E) = e^{\left(-\frac{E}{kT}\right)} \cdot f(T) \qquad (5)$$

where *f(T)* is an arbitrary function of temperature.

Suppose that there are two identical manifold u and l, and E is the distance between those manifolds. The probability density within each manifold takes the form

$$P_u(E) = e^{\left(-\frac{E - \Delta E}{kT}\right)} \cdot f_u(T) \qquad (6)$$

$$P_l(E) = e^{\left(-\frac{E}{kT}\right)} \cdot f_l(T) \qquad (7)$$

and

$$f_u(T) = f_l(T) \qquad (8)$$

Hence, the erbium ion level density is different for different manifolds and, as a result, (8) is not valid; but (6) and (7) can be used for definitions of P_u and P_l. This is especially valuable in the case that the level densities for the upper and lower manifolds are not very different, and functions f_u and f_l are similar.

If several energy levels are separated by equal distance h_s, then a summation over all such levels is required

$$g(\mathbf{f}) = \sum_{E_i - E_j = hf} \sigma_{ij} N \left[n_i - \frac{w_i}{w_j} n_i \right]$$

Also, the electron transition occurs between the upper level with i = u and the lower level with j = l.

Hence, this equation can be transformed for a continuous erbium ion spectrum by changing the summation into an integration over E, substituting (E)P(E) for n_i and substituting $(E + h_s)/(E)$ for $\sigma(E + h\nu_s, E)N$

$$g(\nu_s) = \int_0^\infty \left[\rho(E + h\nu_s)P(E + h\nu_s) - \frac{\rho(E + h\nu_s)}{\rho(E)} \rho(E)P(E) \right] dE$$

From the previous equations (6), (7) and (10), gain coefficient can be calculated easily as shown in the next numerical model.

Numerical Model: To get the gain coefficient from equation (10), great simplifications are needed in order to use the formula. A first assumption is in the calculation of f_l. Because the results of the computation should not depend on the energy reference level, one can put $E_l^L = 0$. Taking the $E_l^H \rightarrow \infty$ can find that

$$f_l(T) = \frac{C}{T} \qquad (11)$$

where C is some constant in temperature, but varying with wavelength.

A second assumption is to substitute the integration in (10) by a finite summation. Moreover, because of the relative short temperature range of interest (about 120 ºC), we would like to keep only two terms in that sum. Thus, the whole expression can be replaced by a very simple sum

$$g = \frac{C}{T} \left(\sigma(E_2)N\rho(E_2)e^{-\frac{E_2}{kT}} - \sigma(E_1)N\rho(E_1)e^{-\frac{E_1}{kT}} \right) \qquad (12)$$

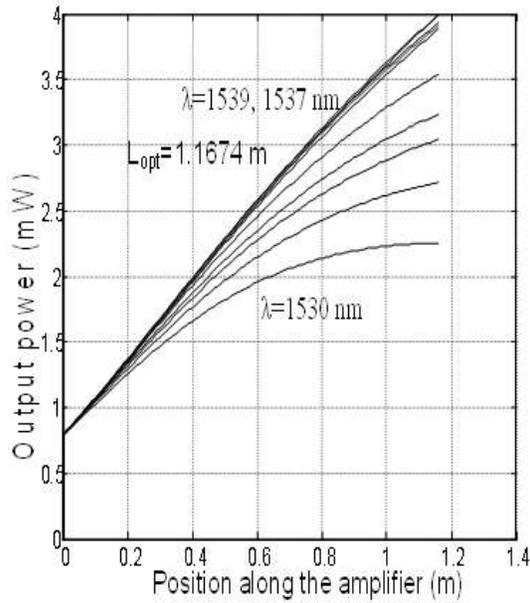where E_1 and E_2 are the lower and upper energy levels, respectively.

Fig. 1: Signal power for ten channels, pump power = 60 mW, input signal power = 0.8 mW at the optimum amplifier length for bismuth.
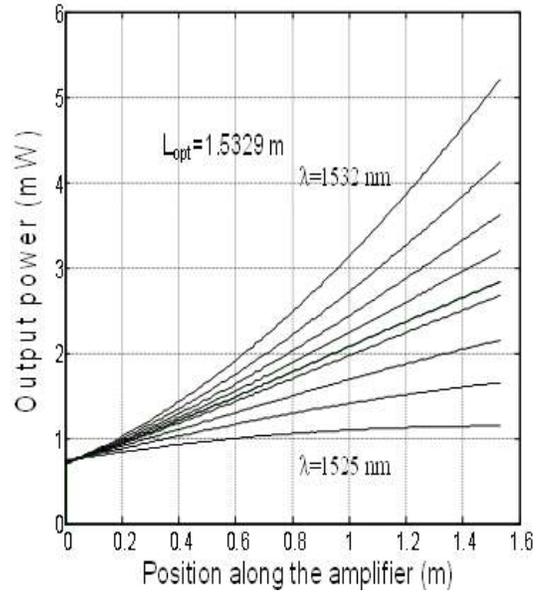

Fig. 3: Output signal power for ten channels (1525-1534 nm). Input signal power is 0.8 mW per channel and pump power is 60 mW.
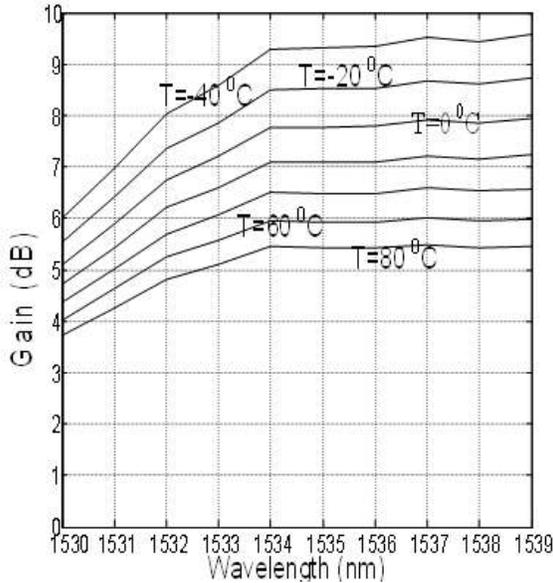

Fig. 2: Gain versus wavelength (10 channels) in the temperature range from -40°C to 80°C.
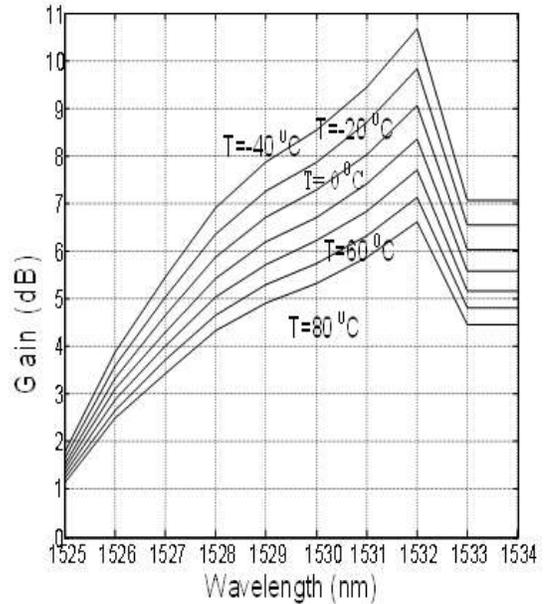

Fig. 4: Gain versus wavelength (10 channels) in the temperature range from -40°C to 80°C.

Also, T_1 can be replaced by $T_1 = (E_1/k)$ and T_2 by $T_2 = (E_2/k)$, where T_1 and T_2 are above and below the temperature region of interest. The optimum values of T_1 and T_2 are found 90 K and 650 K[1].

So, (12) takes the form

$$g = \frac{C}{T}\left(\sigma_a(E)N_2 e^{-\frac{T_1}{T}} - \sigma_e(E)N_1 e^{-\frac{T_2}{T}}\right)$$

where $_a$ and $_e$ are absorption and emission cross sections, respectively.

Hence, from the previous model, the absorption and emission cross sections for each host material and electron concentrations in upper and lower energy levels are used to calculate the gain coefficient at different values of temperature as shown in the next section.

RESULTS AND DISCUSSION

This section introduces a set of examples for the gain calculation at optimum amplifier length of multichannel EDFAs with different host materials near the central frequency of each material and temperature effect on that gain. Ten channels with a spacing 1nm are introduced using the previously described linear extrapolation model.

The change in temperature is taken in the range from T= - 40 °C to T= 80 °C which is an interesting range. The used host materials include: alumino-germanosilicate, bismuth, fluoride phosphate, oxyfluoride silicate, tellurium and aluminum oxide. Through calculations, the erbium concentration, N, is set at 1×10^{25} m^{-3}.

The first host material is chosen as bismuth which has a good response in WDM. Tanabe *et al.*[7] reported some kinds of bismuth-based glasses, which present good broadband properties. Also, thermal stability and flattened gain of bismuth-based glass are important properties of the bismuth-based glass host material. The signal power at the optimum amplifier length for ten channels (from 1530 to 1539 nm) and the maximum output power at that length are displayed in Fig.1 at the central wavelength, $_o$= 1535 nm.

From Fig.1, it can be seen that the optimum amplifier length is L_{opt} =2.2377 m which corresponds to the maximum output signal power for the lowest channel in the range (from 1530 to 1539 nm). It is important to note that the absorption and emission cross sections for the central wavelength $_o$= 1535 nm are collected from Ref.[7].

In Fig.2, the gain for different temperatures is displayed for ten channels from - 40 °C to 80 °C with 20 °C spacing. As shown, the gain is more flat in the higher wavelengths (used in WDM system) and more affected by temperature in that range, nearly increases by ≈ 0.025 dB/°C. But, at lower wavelengths, the effect of temperature is lower ≈ 0.005 dB/°C. Also, as expected, for higher temperatures, a higher gain is obtained because the population inversion at high temperatures.

The second host material is alumino-germanosilicate which has many advantages. As compared to the semiconductor laser amplifier, the advantage of using an alumino-germanosilicate EDFA includes high gain[8,9], high saturation output power[8], polarization independent gain[8], no crosstalk, low noise figure and low insertion loss. Also, for practical optical fiber communication systems, the EDFA must be pumped at most interested pump power at 0.81 at which the excited state absorption implies a high pump power and causes a high gain[10].

The output signal power at the optimum amplifier length (L_{opt}= 1.5329 m) for ten channels is shown in Fig. 3 at central wavelength $_o$=1535 nm. The gain of these channels is not flat, which means that such material is not widely used in WDM systems.

Figure 4 displays the amplifier gain with wavelength, from which it can be noted that, the temperature has not the dominant effect on the lower wavelength (≈ 0.5 dB for 120 °C), but the major effect of temperature occurs in a flat gain or nearly flat regions.

The third investigated material aluminum oxide which has many useful properties. The performance of an EDFA is affected the magnitude and wavelength dependence of the emission and absorption cross sections. Together with the Er concentration profile, the knowledge of the optical intensity profile and the waveguide loss enables a first-order estimate of the potential optical gain. Aluminum-oxide waveguide films on silicon wafers are interesting as a host material for Er because waveguide fabrication technology is well developed for this material[11]. Low-loss, single-mode waveguide can be fabricated using standard photolithographic techniques[12].

Figure 5 displays the output signal power for the ten channels as a function of amplifier length. The gain is calculated at the optimum value of the amplifier length (L_{opt} = 4.5814 m) for maximum output signal power for the lowest channel in the range.

Figure 6 gives the effect of temperature from - 40 to 80 °C on the gain. This effect is dominant in the mid range of wavelengths (from 1528 to 1532 nm) which corresponds to a nearly flat gain. While, at the wavelengths that give no flat gain, temperature has lower influence.

The following table shows the effect of temperature on the calculated gain for the different host materials of EDFA at central wavelengths of each material, max gain and optimum amplifier length.

Table 1: Features of EDFA for different hosts.

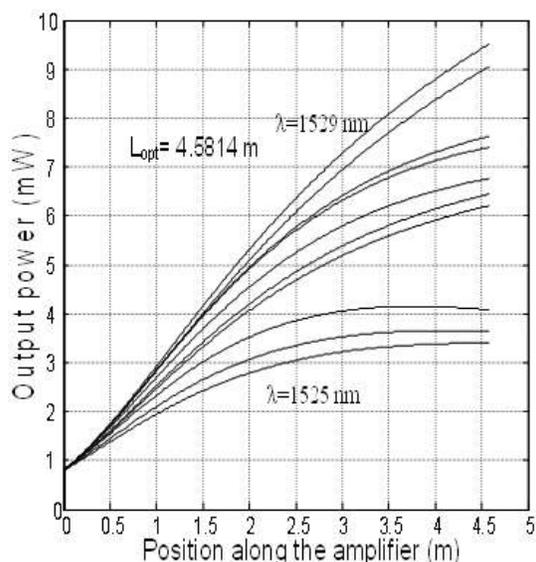| Host Material	Central Wavelength (nm)	Wavelength at G_{max} (nm)	L_{opt} (m)	Gain differenceat G_{max} (dB)
Alumino-Germanosilicate	1530	1532	1.5329	4.07
Bismuth	1535	1537	1.1674	4.12
Fluoride Phosphate	1535	1537	1.5611	4.29
Oxyfluoride Silicate	1530	1531	2.3195	4.04
Tellurium	1535	1537	2.1172	3.88
Aluminum Oxide Waveguides	1530	1529	4.5814	2.55

Fig. 5: Output signal power for ten channels (1525-1534 nm). Input signal power is 0.8mW per channel and pump power is 60 mW.
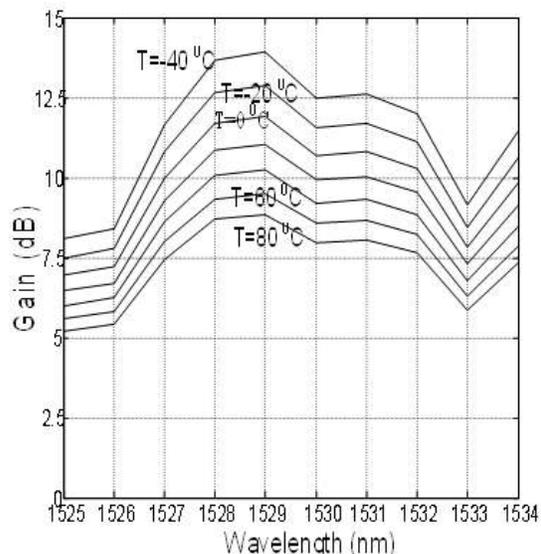

Fig. 6: Gain versus wavelength (10 channels) in the temperature range from -40ºC to 80ºC.

Conclusion: In this paper, the properties of multichannel EDFA are studied for six different glass hosts assuming large pumps and signal powers (compared to the ASE). Simple linear analytical expressions are used to calculate the temperature effects on the gain for the output signal power. From Table 1, it can be noted that.

- Aluminum oxide waveguides are less host materials affected by temperature ($\approx$ 0.02 dB/ºC).
- Fluoride phosphate is the most host materials affected by temperature especially in the wavelengths of high gain ($\approx$ 0.034 dB/ºC).

REFERENCES

1. Kagi, N., A. Oyobe and K. Nakamura, 1991. "Temperature Dependence of the Gain in Erbium-Doped Fibers," IEEE J. Lightwave Technol., 9: 261-265.

2. Yamada, M., M. Shimuzu, M. Horiguchi and M. Okayasa, 1992. "Temperature Dependence of Signal Gain in Er^{3+}-Doped Optical Fiber Amplifiers," IEEE J. Quantum Electron., 28: 640-648.

3. Lee, J. and N. Park, 1998. "Temperature Dependent Distortion of Multichannel Gain Flatnees for Silica and ZBLAN-Based Erbium Amplifiers," Tech. Digest OFC'98, Paper WGI, pp: 133-134.

4. Bolshtyansky, M., P. Wysocki and N. Conti, 2000. "Model of Temperature Dependence for Gain Shape of Erbium-Doped Fiber Amplifier," IEEE J. Lightwave Technol., 18: 1533-1540.

5. Silfvast, W.T., 1996. Laser Fundamentals, Cambridge, U. K.: Cambridge Univ. Press.

6. Govind, P., 1995. Agrawal, Nonlinear Fiber optics, Academic Press, 2nd ed..

7. Peter, W. Milonni and Joseph H. Eberly, 1988. LASER, John Wiley.

8. Pedersen, B., A. Bjarklev, J.H. Povlsen, K. Dybdal and C.C. Larsen, 1991. "The Design of Erbium-Doped Fiber Amplifiers," IEEE. J. Lightwave Technol., 9: 1106-1112.

9. Digonnet, M.J., E.E. Chutorian and D. Falquier, 2002. "Fundamental Limitations of the Mc-Cumber

Relation Applied to Er-Doped Silica and Other Amorphous-Host Lasers," IEEE J. Quantum Electron., 38: 1629-1637.

10. Barnes, W.L., R.I. Laming, E.J. Tarbox and P.R. Morkel, 1997. "Absorption and Emission Cross Section of Er^{3+} Doped Silica Fibers," IEEE J. Quantum Electron., 27: 1004-1010.

11. Myslinski, P., D. Nguyen and J. Chrostowski, 1997. "Effect of Concentration on the Performance of Erbium-Doped Fiber Amplifiers," IEEE J. Lightwave Technol., 15: 112-120.

12. Philipps, J., T. Töpfer, H.E. Heidepriem, D. Ehrt and R. Sauerbrey, 2001. "Spectroscopic and Lasing Properties of Er^{3+}: Yb^{3+} –Doped Fluoride Phosphate Glasses," Appl. Phys. B, 72: 399-405.