

Comparative Studies of the Thulium and Erbium Doped from 1480-1650 nm with Different Host Materials as Optical Fiber Amplifiers

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Abstract- This work describes the comparison of the amplification characteristics (gain) and the Noise figure (NF) of the Thulium and Erbium in three different host materials which the Ytria Alumina-Silica glass, Fluoride and Tellurite fiber glass. The gain using these host materials covers the range 1.45-1.65 μm . Thulium doped fiber amplifier (TDFAs) operated in the region of wavelength (1480-1510 nm) which is called S-band. The main pump source is 1.04 and 1.55 μm which creates population inversion between 3F₄ (upper laser level) and 3H₄ (lower laser level), and erbium doped fiber amplifier (EDFA) operated in the region (1510-1650 nm) which is called L -band with the pump wavelength 980 nm. It is found that the erbium doped yttria-alumina silicate fiber amplifier exhibits a maximum gain of 40.3 dB at the central wavelength 1540 nm and minimum noise figure 14 dB, but the broadening in the gain curve is 20 nm. Also it is found that the thulium doped yttria-alumina silicate fiber amplifier exhibits a maximum gain of 27.5 dB at the central wavelength 1467 nm and minimum noise figure 2.5 dB, with the broadening in the gain curve is 41 nm. Gain flatness was investigated and the results strongly confirm the feasibility of using different hosts' glass doped with Thulium in practical ultralarge capacity WDM networks.

Key word: Optical amplifiers, EDFA, TDFA, Ytria-doped, Tellurite-doped, Fluoride doped.

1- 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 1.5 μm communication windows in conventional single-mode fibers (SMF) [1]. 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. Increasing demands on the capacity of WDM transmission system now require newly developed transmission windows beyond the amplification band width supported by erbium doped fiber amplifiers (EDFAs). So Thulium doped fiber

in recent years, as the candidates for the next generation amplifiers competing / com - promising L-band EDFA's, Raman amplifiers [2], [3]. Thulium doped fiber amplifiers are promising amplifiers for the 1400 nm band, they are reported to have high gain and low noise characteristics in the 1450-1480 nm region [4], Thulium-doped fiber amplifiers (TDFAs) are a promising candidate for the S-band amplification because the amplification bandwidth of the TDFA is centered at 1470 nm [5], which falls within the S-band. A 1050 nm pumping scheme can be used to obtain the population inversion in a Thulium-doped fiber (TDF) [6]. The TDF length and pump power are the important parameters that determine the attainable gain and noise figure in TDFA. Thulium-doped fiber amplifier (TDFA), which provides gain in the S- and S+ band, can be a potential candidate for such systems. Many different pumping schemes have been proposed to exploit the complex energy level transitions of Thulium in the -band, either by single-wavelength upconversion pumping [7], [8] or dual-wavelength pumping [9]. The most efficient (highest gain for lowest pump power) scheme to date has been a combination of 800 and 1050 nm, which takes advantage of the strong ground state absorption (GSA) at 800 nm [10]. However, it has been reported in [11] that GSA in thulium at 690 nm is even stronger than that at 800 nm.

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amplifiers (TDFAs) for S-band have been studied extensively

2-MODEL

Gain and Noise Figure

The gain and noise figure equations for EDFA and TDFA are given in [11].

EDFA

The gain at the output of the amplifier is:

$$G_k^+ = \frac{P_L^+}{P_o^+} = \exp \left[\frac{\alpha_k}{\alpha_p} \left\{ \frac{\eta_k - \eta_p}{1 + \eta_p} (q_o^+ - q_L^+) - \log \left(\frac{q_o^+}{q_L^+} \right) \right\} \right] \quad (1)$$

where P_o^+ and P_L^+ are the normalized input and output signal powers, respectively, one gets the following relation between the normalized input and output pump powers:

$$q_o^+ - q_L^+ = \alpha_p L - \log \left(\frac{q_o^+}{q_L^+} \right) \quad (2)$$

Eliminating $q_o^+ - q_L^+$ from Eqs.(3) and (4) gives:

$$q_L^+ = q_o^+ \exp(-A_G L), \quad (3)$$

where A_G is the gain-dependant pump absorption coefficient, defined through as:

$$A_G = \alpha_p \left(\frac{1 + \eta_p}{1 + \eta_k} \right) \left(\frac{\eta_k - \eta_p}{1 + \eta_p} - \frac{\log G_k^+}{\alpha_k L} \right) \quad (4)$$

The input pump power is then expressed as a function of the forward gain G_k^+ by eliminating q_L^+ from Eqs.(4) and (5) as:

$$q_o^+ = \alpha_p L \frac{Q_k}{1 - \exp(-\alpha_p L(1 - Q_k))}, \quad (5)$$

With

$$Q_k = \frac{1 + \eta_p}{1 + \eta_k} \left(1 + \frac{\log(G_k^+)}{\alpha_k L} \right) \quad (6)$$

The output pump power is then rewritten, using Eqs.(5) and (6), in terms of Q_k as:

$$q_L^+ = q_o^+ \exp(-\alpha_p L(1 - Q_k)). \quad (7)$$

For forward pumping case, q_L^+ is always smaller than q_o^+ and hence Q_k must be smaller than one. Eq. (6) gives the following condition for the peak gain as:

$$G_k < \exp \left(\frac{\eta_k - \eta_p}{1 + \eta_p} \alpha_k L \right) \quad (8)$$

which sets the upper limit for the gain, G_{max} , through which the amplifier length and the rest of the performance

parameters can be determined. It is worth noting that in the case of backward pumping all the power equations are consistent in their physical interpretation through q_o and q_L and have to be interchanged.

The gain in dB can be calculate from the relation

$$G = 10 \log_e (G_k \cdot L) \quad (9)$$

Noise figure is generated by spontaneous emission and therefore is closely related to ASE. The number of spontaneous photon is given by:

$$\eta = \frac{\frac{\sigma_{SE} N_3}{\sigma_{SA}}}{\frac{\sigma_{SE} N_3 - N_2}{\sigma_{SA}}} \quad (10)$$

The noise figure (NF) of the TDFA at the signal wavelength is calculated as [12], [13]

$$NF(\lambda_k) = \frac{1 + 2\eta [G - 1]}{G} \quad (11)$$

The parameters used in the modeling of the erbium doped with different hosts materials are given in table 1.

TABLE 1

THE OPTICAL PARAMETERS OF ER-DOPED FIBER GLASS.

Physical meaning	Symbol	Value
pump wavelength	λ_p	980 nm
pump input power	P_{in}	18.4 dBm
signal wavelength	λ_s	1550 nm
length of EDFA	L	27 m
core radius of EDFA	r	1.277 μ m
core area of EDFA	A	5.1 \times 10 ⁻¹² m ²
overlap factor of EDFA	Γ	0.5
fluorescence time of EDFA	τ	10.5 ms
ion density of EDFA	ρ	1.14 \times 10 ²⁴ ions/m ³

TDFA

For 1.05- and 1.56- μ m pumping, the rate equations for the ion populations at each level of TDFA and the gain and noise figure are expressed in [11].

TABLE 2

:PARAMETERS USED IN NUMERICAL SIMULATION FOR Tm IN THREE DIFFERENT HOSTS MATERIALS.

Parameter	Unit	Symbol	Value
Thulium concentration	1/cm ³	Nt	2.8x10 ¹⁹
Core diameter	μm	2a	1.9
Refractive index difference	cm	Δ	3.7%
Fiber length	nm	L	2000
Signal wavelength	nm	λ _{ASE}	1450-1540
Division along the fiber	nm	Δv	200-1300
ASE wavelength	1/s	A10	1380-1550
ASE band	1/s	A30	2
Spontaneous emission rate	1/s	A50	172.4
	1/s	A52	702.8
	1/s	A43	676.3
	1/s	A21	492.9
	1/s	A21	52977
	1/s	A21	195628
	dB/cm	α	0.15
	cm ²	ose	4.8x10 ⁻²¹
Nonradiative decay rate	cm ²	osa	4x10 ⁻²¹
Background loss	cm ²	op1	1.1x10 ⁻²³
Stimulated emission cross section	cm ²	op2	8.2x10 ⁻²¹
Absorption cross section	cm ²	op3	2.5x10 ⁻²³
Pump abs. cross section	cm ²	op4	2x10 ⁻²²
Overlapping factor	cm ²	o8	6x10 ⁻²¹
	cm ²	o8	5x10 ⁻²¹
		σ18	0.762
		Γ(λ)	0.441

different hosts material glass fiber amplifier, the gain of Tm-doped is higher than that of Er-doped in the yttria- alumina-silica glass, the signal wavelength for both is 1467 and 1540 nm respectively.

The noise figure as a function of the pump power at 34 m fiber length for the two signal wavelength 1540 and 1467 nm for both Er and Tm doped for the three hosts glass fiber amplifier respectively is plotted in Fig.3.

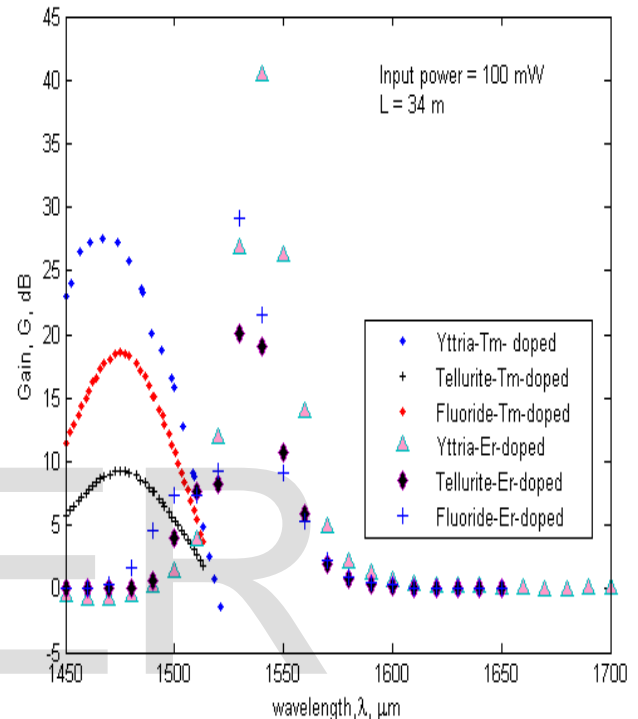


Fig.1 the gain spectrum for Er and Tm doped three hosts glass fiber amplifier

3-RESULTS AND DISCUSSION

In this section we will make a comparison between the three level dopant (Er³⁺) and the four level dopant (Tm³⁺) in the three different hosts material which yttria- alumina- silica, tellurite and fluoride glass as an optical fiber amplifiers. Fig.1 shows the gain in dB as function of the signal wavelength at input pump power 100mW (for Tm the second pump [dual pump]1550 pump power also at 100mW) and fiber length 34 m for both Er and Tm doped for the three glasses fiber amplifier. From the figure the central wavelength for Er is 1540 nm at which the gain maximum 40.3 dB, with bandwidth 20 nm, while for Tm the central wavelength is 1467 nm at which the maximum gain is 27.5 dB with bandwidth 41 nm, this mean that erbium doped gives higher gain than thulium doped but the gain flatness in thulium is higher than erbium for the same glasses fiber doped.

Fig.2 shows the relation between the gain and pump power at 34 m fiber length for both Er and Tm doped for the three

As in figure, the noise figure decreases with pump power increases for both erbium and thulium but the decrease in noise for erbium is higher than thulium doped with the given glass.

Fig.4 shows the dependence of the gain of the erbium and thulium doped for the three hosts on the fiber length at pump power 100 mW, as the fiber length increases, the gain increases to reaches a maximum value then begins to decreases, also the gain increases with increases in pump power values as in figure.

There is a limit of the length increases after it the gain decreases, this limit is at 32.8 m, this because with longer fiber length the amplification process increase also the spontaneous emission and stimulated absorption as well as excited state absorption (ESA) increase, which led to gain decreases.

As a summary we report our results for erbium and thulium doped in different glass hosts and the comparison between the gain and noise figure for both in table 3.

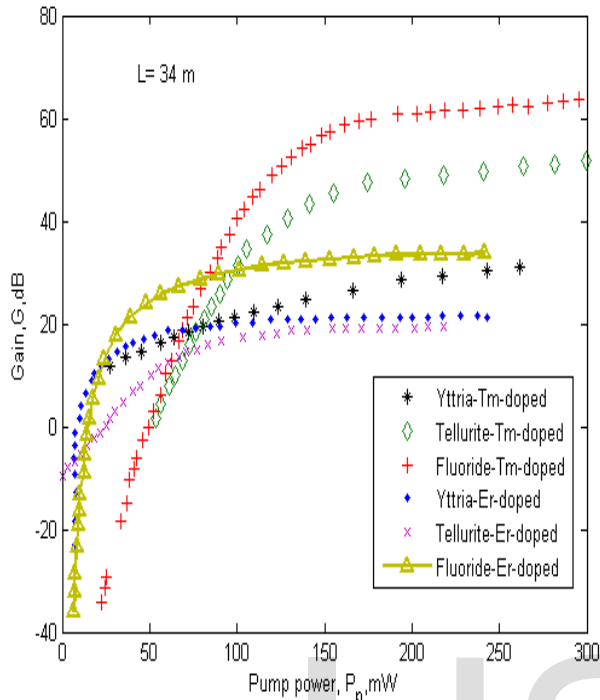


Fig.2 gain against the pump power for Er and Tm doped three hosts glass fiber amplifier

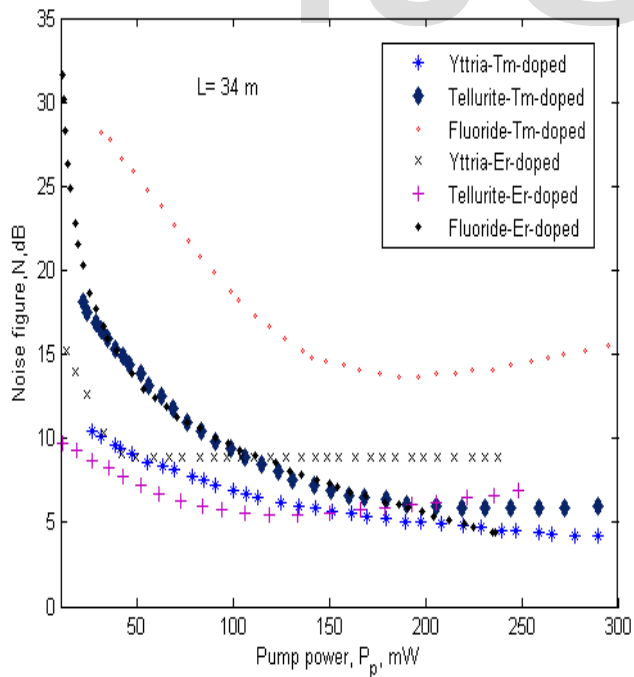


Fig.3 the noise figure against the pump power for Er and Tm doped for three hosts glass fiber amplifier

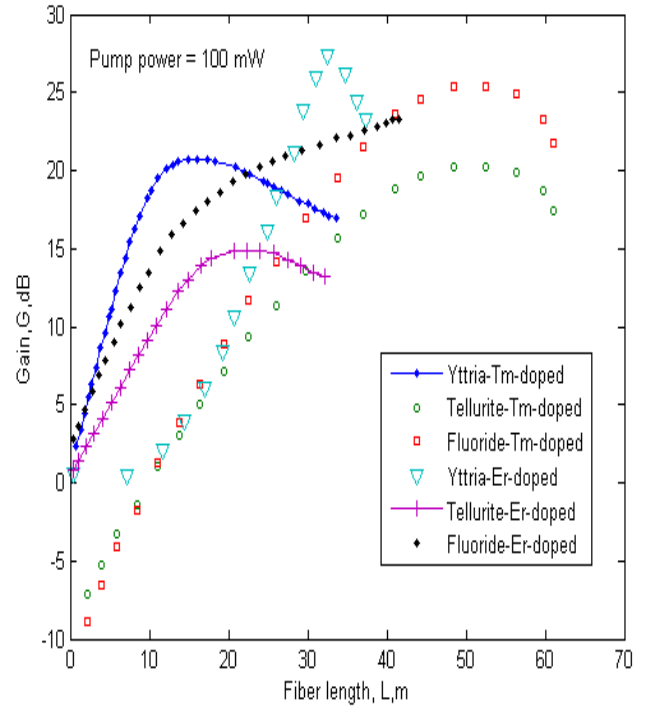


Fig.4 the gain against the fiber length for Er and Tm doped for three hosts glass fiber amplifier

TABLE 3
 GAIN AND NOISE COMPARISON FOR ERBIUM AND THULIUM
 DOPENTS IN DIFFERENT GLASS HOSTS

Dopa nt	Host glasse s	Fibe r leng th (m)	Pum p pow er (m W)	Centr al wavel ength (nm)	Max. gain (dB)	Gain band widt h (nm)	Mi n. noi se (dB)
Er3+	Yttria- alumi na- silica	34	100	1540	40.3	20	14
	Fluori de	34	100	1530	29.1	20	3.1 2
	Telluri te	34	100	1530	20	20	8
Tm3 +	Yttria- alumi na- silica	34	100	1467	27.5	41	2.5
	Fluori de	34	100	1474	18.6	40	3.1 6
	Telluri te	34	100	1474	9.29	42	2.3 8

4- CONCLUSION

In this paper we make the comparison of the amplification characteristics (gain) and the Noise figure (NF) of the Thulium and Erbium in three different host materials which the Yttria Alumina-Silica glass, Fluoride and Tellurite fiber glass. The gain using these host materials covers the range 1.45-1.65 μm . It is found that the erbium doped yttria-alumina silicate fiber amplifier exhibits a maximum gain of 40.3 dB at the central wavelength 1540 nm and minimum noise figure 14 dB, but the broadening in the gain curve is 20 nm. Also it is found that the thulium doped yttria-alumina silicate fiber amplifier exhibits a maximum gain of 27.5 dB at the central wavelength 1467 nm and minimum noise figure 2.5 dB, with the broadening in the gain curve is 41 nm.

REFERENCES

- [1] R. J. Mears, L. Reekie, I. M. Jauncey, and D. N. Payne, "Low-threshold erbium-doped fiber amplifier operating at 1.54 μm ," *Electron. Lett.*, vol.23, pp. 1026-1027, 1987.
- [2] Bumki Min, Hosung Yoon, Won Jae Lee, and Namkyoo Park, "Coupled Structure for Wideband EDFA with Gain and Noise Figure Improvement from C to L-band ASE Injection," *IEEE Photo. Techno. Lett.*, vol. 12, pp. 480-482, May 2000.
- [3] J.Kani, M.Jinno, "Wideband and Flat-Gain Optical Amplification from 1460 to 1510nm by Serial Combination of a Thulium-Doped-Fluoride Fiber Amplifier and Fiber Raman Amplifier," *Electron. Lett.*, vol. 35, pp. 1004-1006, 1999.
- [4] T. Komukai, T. Yamamoto, T. Sugawa, and Y.Miyajima, "Upconversion Pumped Thulium-Doped Fluoride Amplifier and Laser Operating at 1.47 μm ," *IEEE J.Quantum Electron.*, vol. 31, pp.1880-1889, Nov.1995.
- [5] Kozak, M. M., R. Caspary, and W. Kowalsky, "Thuliumdoped fiber amplifier for the S-band," *Proceedings of 2004 6th International Conference on Transparent Optical Networks*, 2004, Vol. 6, 51-54, 2004.
- [6] Scott S.-H. Yam, Youichi Akasaka, Senior Yoshinori Kubota, Hiroyuki Inoue, and Krishnan Parameswaran. "Novel Pumping Schemes for Fluoride-Based Thulium-Doped Fiber Amplifier at 690 and 1050 nm (or 1400 nm)," *IEEE PHOTONICS TECHNOLOGY LETTERS*, VOL. 17, NO. 5, MAY 2005.
- [7] T. Sakamoto, M. Shimizu, T. Kanamori, Y. Terunuma, Y. Ohishi, M. Yamada, and S. Sudo, "1.4- μm -band gain characteristics of a Tm-Ho-doped ZBLAN fiber amplifier pumped in the 0.8- μm band," *IEEE Photon. Technol. Lett.*, vol. 7, no. 9, pp. 983-985, Sep. 1995.
- [8] S. Aozasa, H. Masuda, H. Ono, T. Sakamoto, T. Kanamori, Y. Ohishi, and M. Shimizu, "1480-1510 nm band Tm-doped fiber amplifier (TDFA) with high power conversion efficiency of 42%," in *OFC 2001, Anaheim, CA, 2001, Paper PD1*.
- [9] T. Kasamatsu, Y. Yano, and T. Ono, "Laser-diode pumping highly efficient gain-shifted thulium-doped fiber amplifier operating in the 1480-1510nm band," in *OFC 2001, Anaheim, CA, 2001, Paper TuQ4*.
- [10] A. S. L. Gomes, M. T. Carvalho, M. Sundheimer, C. J. A. Bastos-Filho, J. F. Martins-Filho, M. B. Costa e Silva, J. P. von der Weid, and W. Margulis, "Characterization of efficient dual-wavelength (1050 + 800 nm) pumping scheme for thulium-doped fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 15, no. 2, pp. 200-202, Feb. 2003.
- [11] O. Mahran, M. EL Shahat, A. El Samahy and M. S. Helmi, "Wavelength Division Multiplexing of Yttria-Alumina-Silica doped with Thulium optical Fiber Amplifiers" *International Journal of Research and Reviews in Applied Sciences*, 10(2): 314 - 321 , 2012.
- [12] Emmanuel Desurvire, "Study of the Complex Atomic Susceptibility of Erbium-Doped Fiber Amplifiers," *J. Lightwave Technol.*, vol. 8, no. 10, pp. 1517-1527, 1990.
- [12] E. Desurvire, *Erbium Doped Fiber Amplifiers: Principles and Applications*, New York: Wiley, 1994.
- [13] R. M. Percival, D. Szebesta, and S. T. Davey, "Thulium doped terbium sensitized CW fluoride fiber laser operating on the 1.47 μm transition," *Electron. Lett.*, vol. 29, no. 12, pp. 1054-1056, 1993.

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