WAVELENGTH DIVISION MULTIPLEXING OF YTTRIA-ALUMINA-SILICA DOPED WITH THULIUM OPTICAL FIBER AMPLIFIERS

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ABSTRACT

This work describes the Amplification characteristics (small signal gain) and the Noise figure (NF) of theYttria Alumina-Silica glass doped with Thulium. 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 $^3F_4$ (upper laser level) and $^3H_4$ (lower laser level), these characteristics were worked through numerical simulation based on a comprehensive rate equation modeling. Gain flatness was investigated and the results strongly confirm the feasibility of using Yttria Alumina Silica glass doped with Thulium in practical ultralarge capacity WDM networks.

Keywords: *Thulium doped fiber amplifier- Yttria Alumina Silica- wavelength division multiplexing- optical fiber communication.*

1. INTRODUCTION

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 amplifiers (TDFAs) for S-band have been studied extensively in recent years, as the candidates for the next generation amplifiers competing/compromising L-band EDFA's, Raman amplifiers [1], [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], also 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 [5], [6]. This structure makes the glass highly promising as laser gain media for Thulium doped fiber amplifiers [7].In this paper, we report the amplification properties of Yttria Alumina Silica glass doped with Thulium for WDM signals using 20 m-long of Thulium doped fiber and various values of wavelength of the signal and pump and the various values of pump power at 1.04 and 1.55 µm.We achieved a Gain exceeding 25 dB, a Noise Figure (NF) of less than 7 dB for a total pump power at (1550 nm) of 40 mW (30 nm bandwidth).

2. MODEL

1.04- and 1.55- µm Pumping

From Fig. I(a) and (b), the rate equations for the ion populations at each level are expressed as follows [9].

$$\frac{dN_0}{dt} = -(W_{p1} + W_{p4} + W_{18} + W_8)N_0 + (A_{10} + W_{18})N_1 + (A_{30} + W_8)N_3 + A_{50}N_5 \tag{1}$$

$$\frac{dN_1}{dt} = -(W_{p4} + W_{18})N_0 - (A_{10} + W_{P2} + W_{sa} + W_{18})N_1 + A_{21}N_2 + W_{se}N_3 \tag{2}$$

$$\frac{dN_2}{dt} = W_{P1}N_0 - A_{21}N_2 + A_{52}N_5 \tag{3}$$

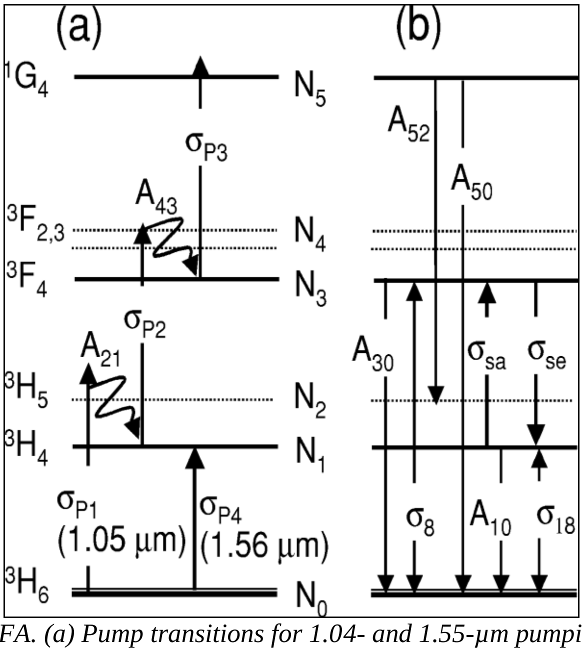

Figure 1 Numerical model of TDFA. (a) Pump transitions for 1.04- and 1.55-µm pumping. (b) Emission processes for 1.04- and 1.55-µm pumping [8].

$$\frac{dN_3}{dt}=W_8N_0+W_{sa}N_1-\left(A_{39}+W_{p3}+W_{SE}+W_8\right)N_3+A_{43}N_4 \tag{4}$$

$$\frac{dN_4}{dt}=W_{P2}N_1-A_{43}N_1 \tag{5}$$

$$\frac{dN_5}{dt}=W_{P3}N_3-\left(A_{50}+A_{52}\right)N_5 \tag{6}$$

$$\sum_i N_i=N_t \tag{7}$$

Where N_i is the ion population for level i(=0~5), W_{Pi}(i=1~4) is pump transition rate, W_{sa} and W_{se} are the absorption and emission rates in the signal band, W_8 and W_{18} are the transition rates of ASE at 800 nm and 1800 nm, respectively, A_{ij} is the spontaneous rate or nonradiative decay rate from level i to j, and N_t is the thulium ion concentration. The transition rates are expressed as follows.

$$W_{pi}=\frac{\sigma_{pi}\left(P_{P1}^{+}+P_{P1}^{-}\right)}{P_{\upsilon p1}A_{eff}}(i=1\sim 3) \tag{8}$$

$$W_{p4}=\frac{\sigma_{p4}\left(P_{P2}^{+}+P_{P2}^{-}\right)}{h\upsilon_{p2}A_{eff}}+\int\frac{\sigma_{p4}\left(P_{ASE}^{+}+P_{ASE}^{-}\right)}{h\upsilon_{ASE}A_{eff}}d\upsilon+\int\frac{\sigma_{p4}P_s}{h\upsilon_sA_{eff}}d\upsilon \tag{9}$$

$$W_{sa,se}=\frac{\sigma_{sa,se}P_s}{h\upsilon_SA_{eff}}+\int\frac{\sigma_{sa,se}\left(P_{ASE}^{+}+P_{ASE}^{-}\right)}{h\upsilon_{ASE}A_{eff}}d\upsilon \tag{10}$$

$$W_{8,18}=\frac{\sigma_{8,18}\left(P_{ASE}^{8,18^{+}}+P_{ASE}^{8,18^{-}}\right)}{h\upsilon_{ASE}^{8,18}A_{eff}} \tag{11}$$

Where σ_{pi} (i=1~4) is the pump absorption cross section, σ_8 and σ_{18} are the stimulated emission cross sections (assumed to be the same as respective absorption cross sections) at 800 nm and 1800 nm, and A_{eff} is the effective cross-sectional area. Subscripts of plus and minus signs denote forward and backward propagation, respectively.

The lightwaves propagating along the thulium fiber (Z-axis) can be expressed as the following set of coupled ordinary differential equations.

$$\frac{dp^{\pm}_{p1}}{dz} = \mp\Gamma(\lambda_{p1})(\sigma_{p1}N_0 + \sigma_{p2}N_1 + \sigma_{p3}N_3)\times P^{\pm}_{P1} \mp \alpha P^{\pm}_{p1} \tag{12}$$

$$\frac{dp^{\pm}_{p2}}{dz} = \mp\Gamma(\lambda_{p2})\sigma_{p4}N_0 P^{\pm}_{P2} \mp \alpha P^{\pm}_{p2} \tag{13}$$

$$\frac{dp_s}{dz} = \Gamma(\lambda_s)(\sigma_{se}(\lambda_s)N_3 - \sigma_{sa}(\lambda_s)N_1 - \sigma_{P4}(\lambda_S)N_0)P_S - \alpha P_s \tag{14}$$

$$\begin{aligned}\frac{dP^{\pm}_{ASE}}{dz} &= \pm\Gamma(\lambda_{ASE})(\sigma_{se}(\lambda_{ASE})N_3 - \sigma_{sa}(\lambda_{ASE})N_1 - \sigma_{P4}(\lambda_{ASE})N_0)P^{\pm}_{ASE} \\ &\pm\Gamma(\lambda_{ASE})2h\upsilon\Delta\upsilon\sigma_{se}(\lambda_{ASE})N_3 \mp \alpha P^{\pm}_{ASE}\end{aligned} \tag{15}$$

$$\frac{dP^{8\pm}_{ASE}}{dz} = \pm\Gamma(\lambda_8)\sigma_8(\lambda_8)(N_3 - N_0)P^{8\pm}_{ASE} \pm \Gamma(\lambda_8)2h\upsilon\Delta\upsilon\sigma_8(\lambda_8)N_3 \mp \alpha P^{8\pm}_{ASE} \tag{16}$$

$$\frac{dP^{18\pm}_{ASE}}{dz} = \pm\Gamma(\lambda_{18})\sigma_{18}(\lambda_{18})(N_1 - N_0)P^{18\pm}_{ASE} \pm \Gamma(\lambda_{18})2h\upsilon\Delta\upsilon\sigma_{18}(\lambda_{18})N_1 \mp \alpha P^{18\pm}_{ASE} \tag{17}$$

where P_{P1} is the pump power at 1.04 µm, P_{P2} is the pump power at 1.55 µm, P_S is the signal power, P_{ASE} ,P^8_{ASE} , and P^{18}_{ASE} are the ASE powers in the S-band, 800 nm, and 1800 nm, respectively, α is the background scattering loss assumed to be constant for any wavelength, Γ(λ) is an overlapping factor at wavelength λ,λ_{P1} ,λ_{P2} , and λ_S are the main pump wavelength (1.04 µm), the auxiliary pump wavelength (1.55 µm), and signal wavelength, respectively, λ_{ASE} ,λ^8_{ASE} , and λ^{18}_{ASE} are the ASE wavelengths of signal, 800 nm, and 1800 nm, and υ is the frequency of each lightwave.

3. NUMERICAL CALCULATION

Assuming a steady state condition [the time derivatives to be zero in (1)–(6)], we numerically integrated the coupled differential equations [(12)–(17)] using the fourth-order Runge-Kutta method with a set of two-boundary conditions at Z =0 at the input end and Z=L at the output end of the fiber, where $P_s(Z=0)$ is input signal power, $P^{\pm}_{P1,P2}(0,L)$ are forward and backward launched pump powers of both wavelengths, and ASE powers, $P^{+}_{ASE}(0)$, $P^{+8}_{ASE}(0)$, $P^{+18}_{ASE}(0)$, $P^{-}_{ASE}(L)$, $P^{-8}_{ASE}(L)$, $P^{-18}_{ASE}(L)$ are all set to be zero. Calculation was terminated when all the power converged to certain accuracy. Typically, 10 iterations with 200 divisions along the fiber.

In some cases we noticed a very slow convergence, particularly when we simulated deeply saturated gain-shifted operations, probably due to the nature of stiffness of the aforementioned coupled equations.

The parameter set used in the calculation, shown in Table I, was mostly obtained from published literature [9]. The nonradiative transition rates (A_{43} and A_{21}) were calculated using the empirical energy-gap law [9]. While the emission cross section σ_{se} varies as reported in the literature[10], we choose σ_{se} to be 4.8x 10^{-21} cm^2 [10] based on a preliminary evaluation where we compared calculated results with experimental measurements by changing the cross section. In order to reasonably estimate the absorption cross section from the emission cross section, we used the McCumber relationship, i.e., $\sigma_{se}(\upsilon)= \sigma_{sa}(\upsilon)\exp[(\varepsilon-h\upsilon)/Kt]$, here ε is the temperature-dpendent excitation energy, is the Boltzmann constant, and is the temperature [8], and found the absorption cross section peak to be approximately 70% of the emission peak.

Table 1: Parameters used in numerical simulation.

Parameter	Unit	Symbol	Value	Ref.
Thulium concentration	$1/cm^3$	N_t	$2.8x10^{19}$	
Core diameter	µm	2a	1.9	[9]
Refractive index difference		Δ	3.7%	[9]
Fiber length	cm	L	2000	[9]
Signal wavelength	nm	λ_s	1450-1540	[9]
Division along the fiber			200-1300	
ASE wavelength	nm	λ_{ASE}	1380-1550	[9]
ASE band	nm	Δν	2	[9]
Spontaneous emission rate	1/s	A_{10}	172.4	[9]
	1/s	A_{30}	702.8	[9]
	1/s	A_{50}	676.3	[9]
	1/s	A_{52}	492.9	[9]
Nonradiative decay rate	1/s	A_{43}	52977	
	1/s	A_{21}	195628	
Background loss	dB/cm	α	0.15	
Stimulated emission cross section	cm^2	σ_{se}	$4.8x10^{-21}$	[cal.,[10]]
Absorption cross section				
Pump abs. cross section	cm^2	σ_{sa}	$4x10^{-21}$	[cal.,[10]]
	cm^2	σ_{p1}	$1.1x10^{-23}$	[9]
	cm^2	σ_{p2}	$8.2x10^{-21}$	[9]
	cm^2	σ_{p3}	$2.5x10^{-23}$	[9]
	cm^2	σ_{p4}	$2x10^{-22}$	[9]
	cm^2	σ_8	$6x10^{-21}$	[9]
Overlapping factor	cm^2	σ_{18}	$5x10^{-21}$	[9]
		Γ(λ)	0.762	1.04µm
			0.441	1.5 µm

Pump absorption cross sections of $\sigma P1=1.1x10^{-23} cm^2$, $\sigma P2=8.2x10^{-21} cm^2$, and $\sigma P4=2.0x10^{-22} cm^2$ were taken from [9]. Pump cross section was estimated to be 2.5 $10^{-23} cm^2$ in another preliminary calculation. We estimated the waveguide parameters of a thulium-doped fiber by using catalogue specifications. The overlapping factors between each radiation and the fiber fundamental mode were calculated by using parameters [9].

4. RESULTS and DISCUSSION

The absorption and emission cross-section of Yttria-alumina silica glass doped with Thulium is shown in figure2 and figure3 respectively [10].

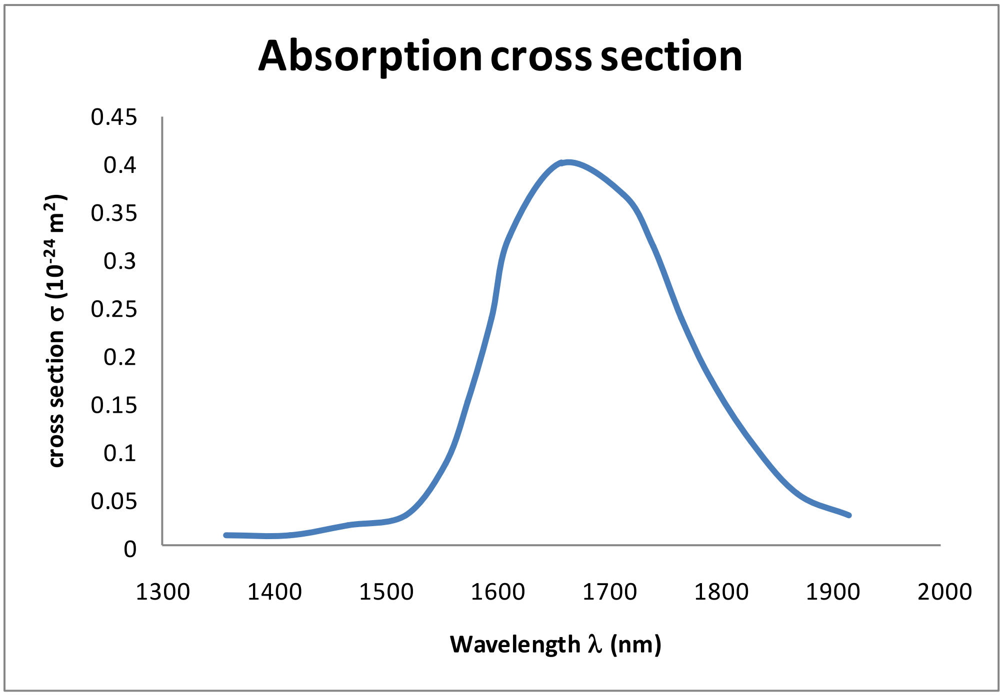

Figure 2 Absorption cross section of Yttria-Alumina-Silica glass doped with Thulium

In general, the key to achieving gain in fiber amplifier, we must make inversion population in fiber, which is defined by this fraction $\Delta N = N_u/(N_u + N_l)$, where N_u and N_l are the upper and lower level populations, respectively. The gain per unit length can be expressed as $g(\lambda) = (N_u \sigma_{se} - N_l \sigma_{sa})$, where σ_{sa} and σ_{se} are the absorption and emission cross-section as given in figures 1 and 2 respectively. Figure 4 shows the gain per unit length as a function of wavelength for different fractional inversion levels of Yttria-alumina silica glass doped with Thulium. The top curve means full inversion where N_l is considered to be very small (i.e., the fractional inversion of unity as in the case of ordinary four-level systems), being essentially the same as the emission cross section [8].
while the bottom curve indicate zero inversion i.e the absorption cross section. Fractional inversion of larger than 0.7 provides an S^+ - band gain profile (1450-1480 nm) with its peak at around 1.46 µm, while fractional inversion of approximately 0.4 provides gain whose peak is located at 1.49 µm.

The gain profile as a function of signal wavelength is shown in figure 5, the input signal power was -30dBm, the pump power at 1047 nm was maintained at 100mW, while the power at 1550 nm was varied from 20 to 100 mW. The gain profile exhibited a peak at 1460 nm with approximately 27 dB at a pump power 20 mW and becomes more flattened, the gain peak also slightly shifted to a longer wavelength region around 1480 nm. Finally, at the 1550 nm power of 100 mW, the gain profile shifted to the 1480- 1510 nm band, although the magnitude of the peak gain was reduced to less than 10 dB, at the wavelength less 1480 nm, its magnitude becomes negative values.

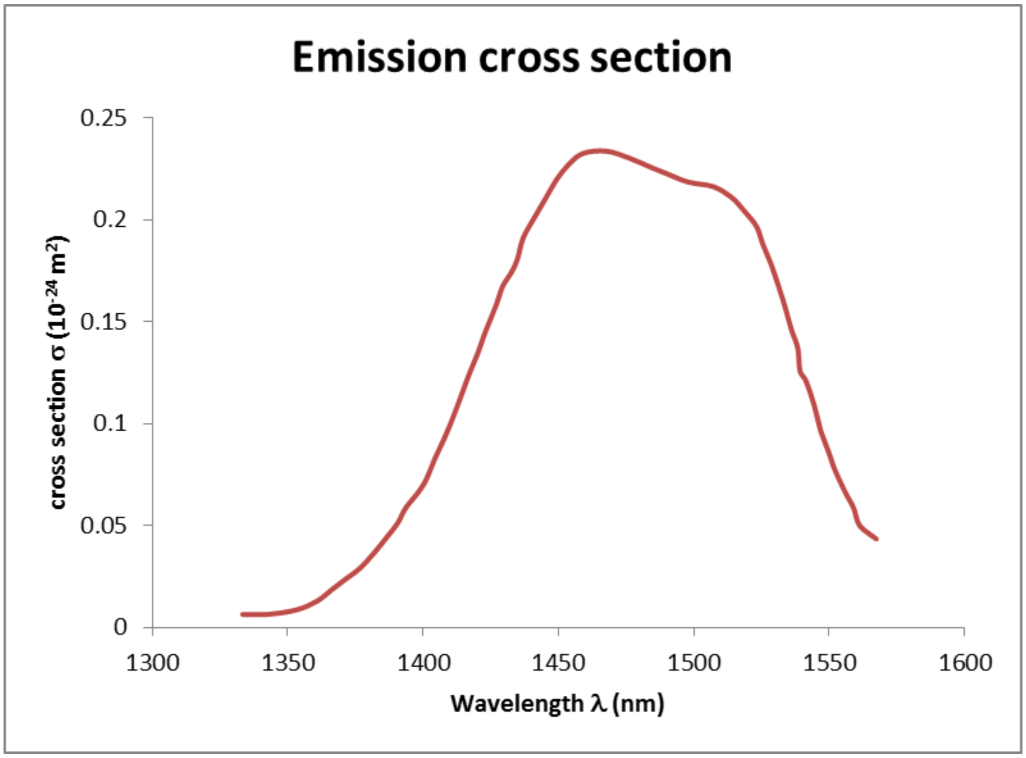

Figure3 Emission cross section of Yttria-Alumina-Silica glass doped with Thulium

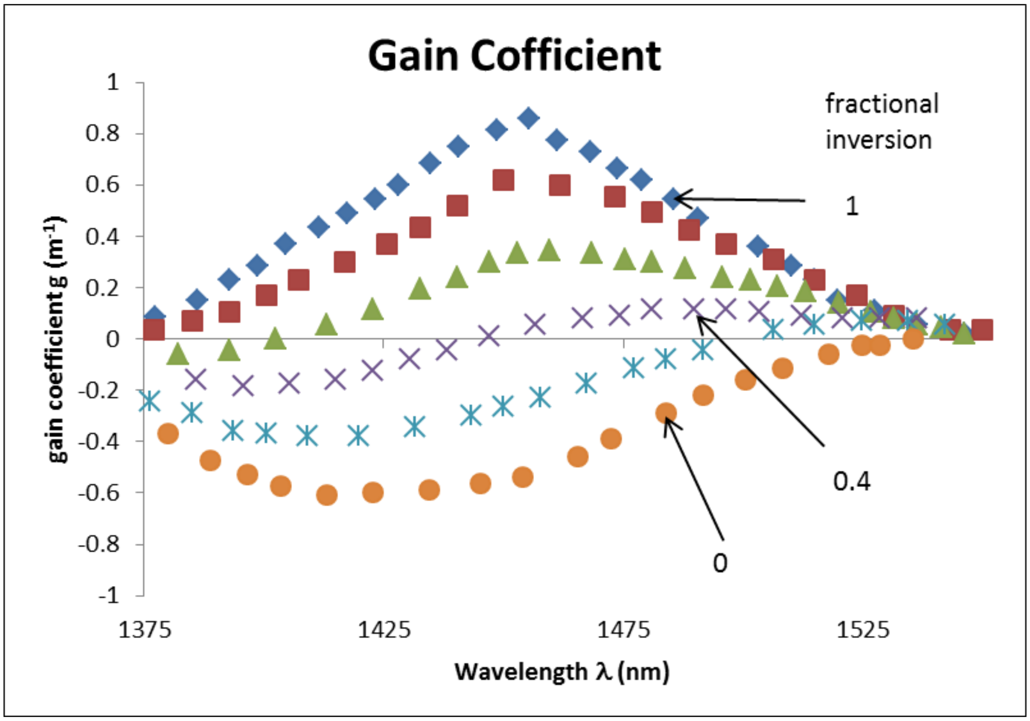

Figure 4 Gain coefficient as a function of wavelength for Yttria-Alumina-Silica glass doped with Thulium at different fractional inversion levels.

The noise figure as a function of signal wavelength is plotted in figure 6, the noise figure was 5 dB in the 1450-1510 nm at 1550 nm power of 40 mW and when the pump power of 1550 nm increase to 100 mW, the noise figure reduce to about 2-4 dB in the 1450- 1510 nm band. Figures 7 and 8 show, the gain and noise figure as a function of pump power for a 1.04 µm- Yttria-alumina silica glass doped with Thulium with 20-m fiber, each curve plotted in the range of wavelength 1470-1510 nm, the values of the gain at 1470 nm shows a saturation around 35 dB, while the gain values at saturation decreased as the wavelength increase to 1510 nm.

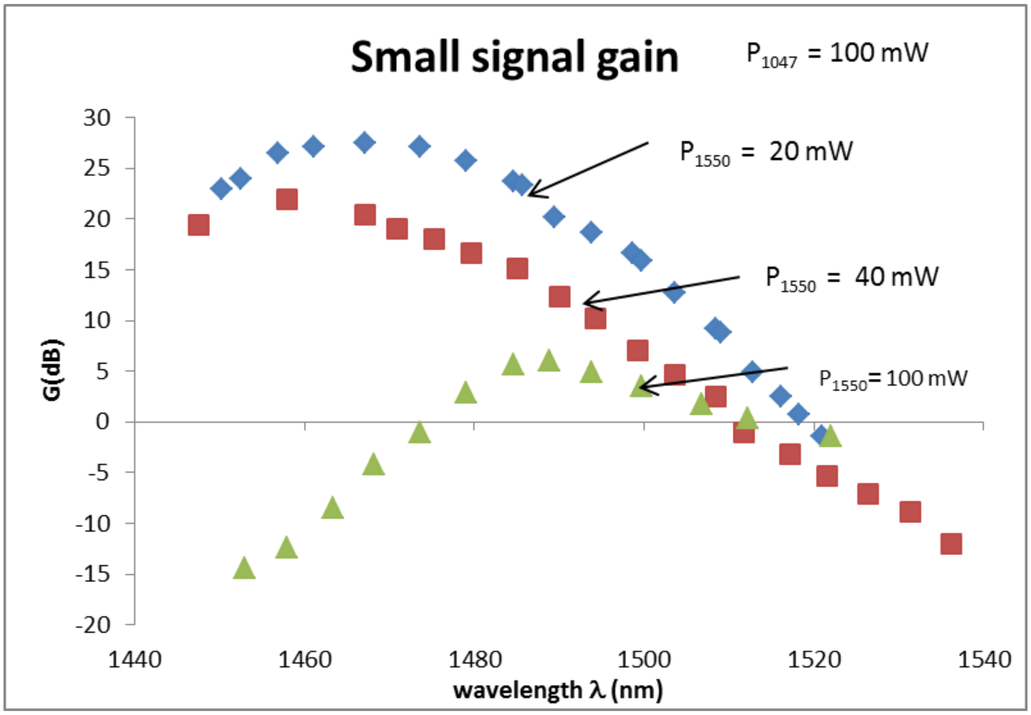

Figure 5 Small-signal gain for a 1.04 and 1.55-µm-pumped Yttria-Alumina-Silica glass doped with Thulium with 20-m fiber at different wavelengths.

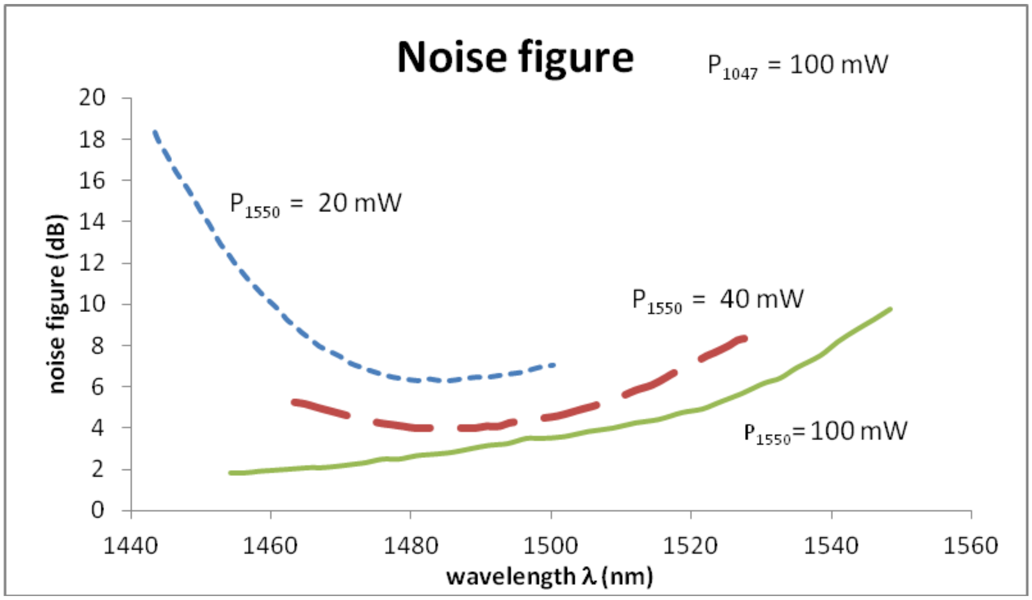

Figure 6 Noise figure for a 1.04 and 1.55-µm-pumped Yttria-Alumina-Silica glass doped with Thulium with 20-m fiber at different wavelengths.

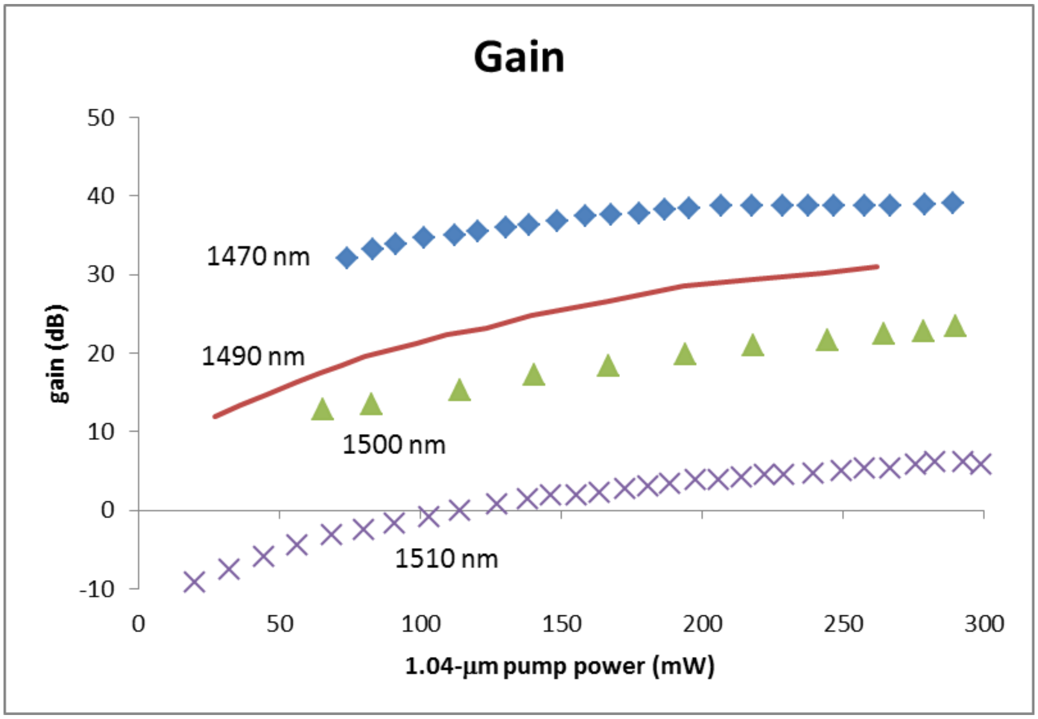

Figure 7 Gain for a 1.04 -µm-pumped Yttria-Alumina-Silica glass doped with Thulium with 20-m fiber at different pump power at power signal -30 dBm

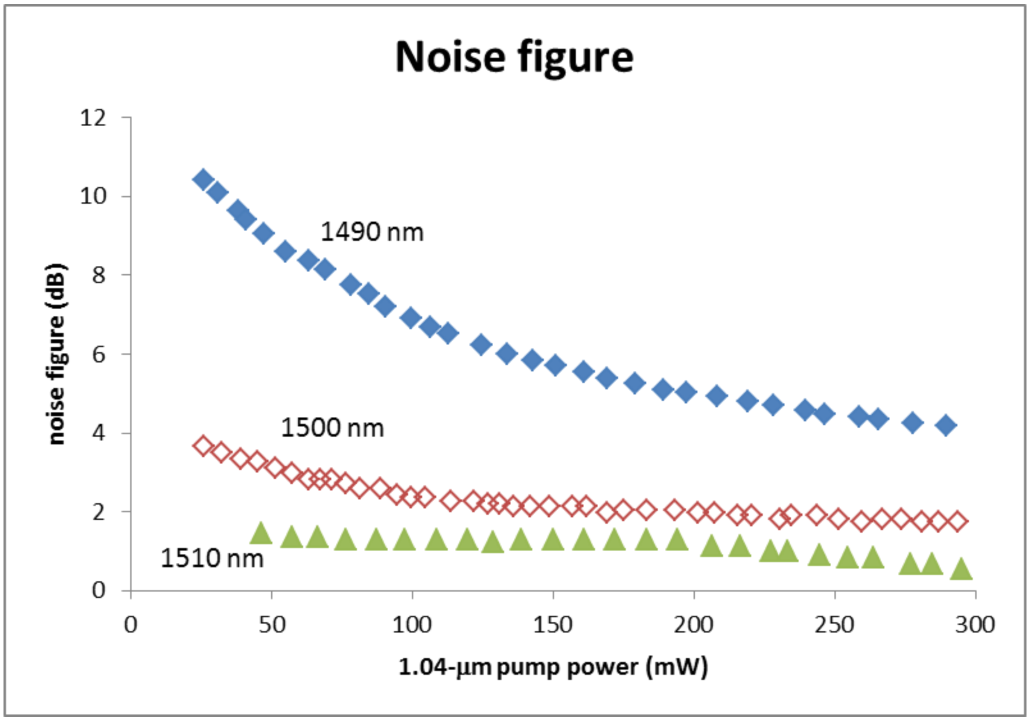

Figure 8 Noise figure for a 1.04 -µm-pumped Yttria-Alumina-Silica glass doped with Thulium with 20-m fiber at different pump power at power signal -30 dBm

The noise figure shows a decrease from approximately 10 dB to 2 dB as the wavelength increase from 1490 nm to 1510 nm as in fig.7, so the values of gain slightly increase as the pump power increase increases, while the values of noise figure decrease slightly as the fig.6 and fig.7 respectively.

5. CONCLUSION

This paper describe, the amplification characteristics and noise figure of the Yttria- alumina silica glass doped with Thulium with 20-m fiber as optical fiber amplifier, especially with a view toward application to WDM networks at the pump power 1.04 and 1.55 µm. These characteristics were calculated numerically through a model based on a full set of rate equations, gain flatness were observed through these calculations, which strongly confirm the feasibility of using Yttria-alumina silica doped with Thulium in practical ultralarge capacity WDM networks.

6. REFERENCES

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