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Abstract. In this study, the performance of a thulium-doped fiber amplifier is investigated for optical telecom at 2 μm with the pump wavelength of 1570nm. The influence of energy up-conversion transitions has been built up on the theoretical model. A heavily thulium doped concentration has been chosen in order to consider this ion-ion interaction. The rate and propagation equations have been developed to study and evaluate the characteristics of a thulium doped fiber amplifier with considering the effects of amplified spontaneous emission noise, cross relaxation process and energy up-conversion. A MATLAB program has been developed to optimise the fiber length and compute the amplifier gain and noise figure. Through the numerical results it is indicated that a short thulium fiber length is require which is a one attractive advantage to choose a thulium fiber with high concentration. However, the results also showed that increasing of thulium doping concentration reduces the signal gain when pumped at 1570nm.

1. Introduction

Recently, extensive efforts have gone towards fiber laser sources at 2 μm wavelength region. There are numerous applications for this region such as laser radar, longer-wavelength laser pumping, gas detection, atmospheric measurements, spectral sensing, material processing, laser surgeries, ophthalmic procedures and laser lithotripsy [1,2,3,4,5]. In addition, this wavelength region has been suggested as attractive way to increase the data transmission capacity and overcome the internet traffic. Thulium-doped fiber amplifier (TDFA) is the best available way for amplification at this wavelength region. This amplifier has been demonstrated and characterized for optical telecom, offering high gain, low loss amplification and ultra-amplification bandwidth (1700-2100nm) [6]. This bandwidth covers about 30 THz which is higher two times than erbium-doped fiber amplifier (EDFA) at current transmission window. Moreover, the dynamic performance of TDFA is better than EDFA which makes the telecom system with TDFA more stable, leading to increase the transmission distance and capacity [7]. For enhancing the amplification performance of TDFA, numerical studies are strongly suggested to develop and find a deep understanding of the amplification. This study should contain theoretical amplifier modelling that describes the important transitions of thulium doped fiber. Despite of there are many theoretical studies of TDFA for optical communication at 2 μm [8] but it is not devoted to investigating for a heavily thulium doped fiber. The thulium doping concentration strongly effects on occurrence of ion-ion interaction such as cross-relaxation process CR which is one attractive feature of thulium doped fiber. CR process is a non-radiative transition, leading to emit two ions of a thulium at the upper state level $^3H_4$ from one excited ion at the energy state $^3F_4$. This transition has been experimentally demonstrated to enhance the optical efficiency from thulium doped fiber laser when pumped at 793nm pumping wavelength [9]. However, the other interaction of ions will occur at increasing of doping concentration which is not studied before such as the

fluorescent quenching and the energy transfer up-conversion. Thus, the need to extend the current amplifier model to consider these interactions as well as investigate the amplifier performance.

This study investigates the effect of energy transfer up-conversion on the amplifier performance at highly thulium concentration when pumped at 1570nm. A TDFA model operating at 2 µm is presented with taking into account the influences of energy up-conversion. The commercial IXBlue Tm-doped silica fiber (IXF-TDF-5.5-125-v_2) is used which its thulium concentration about $2.6*10^{26}$ ion/m^3. The suggested model investigates the influence of the thulium doped fiber length and the amplified spontaneous emission noise.

2. Theoretical modelling of a TDFA

The main optical element of a TDFA is the thulium doped fiber in which a gain medium is created when the thulium ions are optically excited via a pump laser. A very wide emission spectrum exits on the thulium from it is lowest excited state $^3F_6$ as illustrated in energy diagram figure 1. In addition to the non-radiation, laser and pump transitions, there are transitions from the upper energy state $^3H_4$ to the highest energy state $^3F_4$ which is called energy transfer up-conversion ETU. Then, the transition ions from ETU are relaxed to the lower energy level through non-radiative transition and cross relaxation process CR. The theoretical modelling describes the main ions transition of thulium doped fiber through the rate equations which defines the interactions of the pump transition, signal transition and the amplified spontaneous emission (ASE) for a TDFA. In our model, we ignore the population density N_2 at the energy level $^3H_5$ due to its short life time about 0.007 µs in silica host material as compared to the lifetime of other levels [8]. In our model, the pump transitions are indicated W_{p01} and $W_{p10;}$ W_{s01} and W_{s10} for signal transitions; ETU and CR are referred to the energy transfer up-conversion and cross relaxation, respectively.

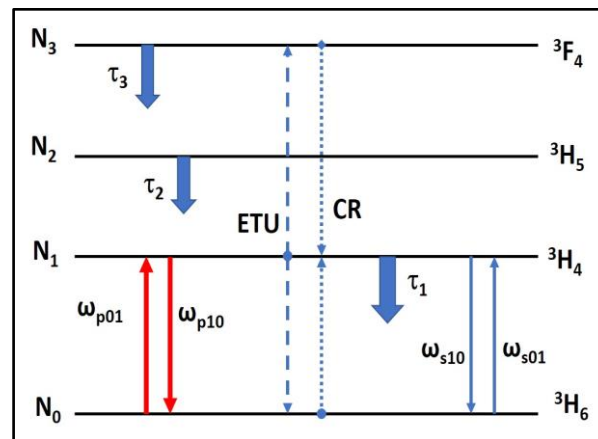The rate equations modelling of a TDFA are described as [8]:

Figure 1. Four lowest energy state diagram for thulium-doped silica fiber. The terms ω_{p01}, ω_{p01}, ω_{p01} and ω_{p01} are indicated for the pump and laser transitions; τ_1, τ_2 and τ_3 are referred to non-radiative transitions; CR and ETU are the cross-relaxation and energy transfer up-conversion.

$$\frac{dN_3(z,t)}{dt} = -\frac{N_3(z,t)}{\tau_3} - C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

$$\frac{dN_1(z,t)}{dt} = w_{p01} - w_{p10} - \frac{N_1(z,t)}{\tau_1} + \frac{\beta_{31}N_3(z,t)}{\tau_3} - w_{s10} + w_{s01} + 2C \quad \ldots\ldots\ldots.. (2)$$

$$N_0(z,t) = N_T - N_1(z,t) - N_3(z,t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3)$$

where C is combined of the energy transfer up-conversion and cross-relaxation process which is defined as:

$$C = k_{3101} N_0(z,t) N_3(z,t) - k_{1310} N_1^2(z,t)$$ …………………………………….. (4)

here the spontaneous lifetime of $^3F_4$ and $^3H_4$ energy states are indicated as τ_3 and τ_1, respectively; and the population densities of energy states $^3F_4$, $^3H_4$ and $^3H_6$ are referred as $N_3(z,t)$, $N_1(z,t)$ and $N_0(z,t)$, respectively; the thulium concentration is N_T which is assumed constant; k_{3101} and k_{1310} are the constants of CR and ETU, respectively. β_{31} is the transition branching ratio from level 3 to 1. The pump and signal transitions are described as:

$$w_{p01} = \frac{\lambda_p \Gamma_p}{hcA_{core}} \sigma_a(\lambda_p) N_0(z,t) \left[p_p^-(z) + p_p^+(z) \right]$$ …………………………….. (5)

$$w_{p10} = \frac{\lambda_p \Gamma_p}{hcA_{core}} \sigma_e(\lambda_p) N_1(z,t) \left[p_p^-(z) + p_p^+(z) \right]$$ ……………………………. (6)

$$w_{s01} = \frac{\lambda_s \Gamma_s}{hcA_{core}} \sigma_a(\lambda_s) N_0(z,t) [p_s(z) + ASE_f(z) + ASE_b(z)]$$ ………………..……… (7)

$$w_{s10} = \frac{\lambda_s \Gamma_s}{hcA_{core}} \sigma_e(\lambda_s) N_1(z,t) [p_s(z) + ASE_f(z) + ASE_b(z)]$$ ……………………. (8)

Where c and *h* are the vacuum light speed and Planck constant; the pump and signal wavelengths are given as λ_p and λ_s, respectively; Γ_p and Γ_s are the pump and signal overlapping factor. A_{core} is the core area of the thulium fiber; the pump and signal absorption cross sections are given by $\sigma_a(\lambda_p)$ and $\sigma_a(\lambda_s)$, respectively; the distirbution of the signal and the pump power at location z are denoted as $p_s(z)$ and $p_p^\pm(z)$, respectively which are computed as follow [8]:

$$\frac{dp_p^\pm}{dz} = \pm p_p^\pm(z) [\, \Gamma_p(\sigma_e(\lambda_p) N_1(z) - \sigma_a(\lambda_p) N_0(z)) - \alpha_p]$$ …………………………….. (9)

$$\frac{dp_s}{dz} = p_s(z) [\, \Gamma_s(\sigma_e(\lambda_s) N_1(z) - \sigma_a(\lambda_s) N_0(z)) - \alpha_s]$$ ………………………………. (10)

The forward and reverse direction of the pump power are referred to positive and negative signs in equation 9. The ASE power distribution along a thulium fibre length should be calculated by [10]:

$$\frac{dASE_f}{dz} = ASE_f(z) [\, \Gamma_s(\sigma_e(\lambda_s) N_1(z) - \sigma_a(\lambda_s) N_0(z)) - \alpha_s] + 2\sigma_e(\lambda_s) N_1(z) \frac{hc^2}{\lambda_s^3} \Delta\lambda$$ ……(11)

$$\frac{dASE_b}{dz} = -ASE_b(z) [\, \Gamma_s(\sigma_e(\lambda_s) N_1(z) - \sigma_a(\lambda_s) N_0(z)) - \alpha_s] - 2\sigma_e(\lambda_s) N_1(z) \frac{hc^2}{\lambda_s^3} \Delta\lambda$$ ……..(12)

Where the pump and signal intrinsic absorption for a thulium fibre are referred as α_p and α_s, respectively; the optical bandwidth of the ASE at the transition window 2 μm is given by $\Delta\lambda$. The gain and noise figure of a TDFA can be computed from the following:

$$G = \frac{amplified\ output\ power}{seed\ input\ power}$$ …………………………………………………………..(13)

$$NF = \frac{1}{G} + \frac{P_{ASE}}{G\,h\,v\,\Delta v}$$ ………………………………………………………………… (14)

3. Simulation results

The rate equations (1-3) are set to zero at the steady state condition. The distribution of the signal and the pump power take a form of the first order differential equations which are solved by applying of the Runge-Kutta method. We initially assume the entire population densities at the lowest energy level $^3H_6$ and all other populations are set to zero. A thulium-doped fiber (IXF-TDF-5.5-125-v_2) is used as an active fiber in the numerical modelling and all required parameters are summarized in table 1 [11].

Table 1. The required parameters for the numerical simulations.

Symbol	Parameter	Value
N_T	Thulium ion concentration	$2.6\times10^{26}\,\text{m}^{-3}$
τ_3	Lifetime of level $^3F_4$.	$14\mu s$
τ_1	Lifetime of level $^3H_4$.	$485\mu s$
A	Core cross sectional area	$2.2\times10^{-11}\,\text{m}^2$
λ_p	Pump wavelength	1570nm
λ_s	Signal wavelength	1950nm
$\sigma_a(\lambda_p)$	Pump absorption cross section.	$1\times10^{-25}\,\text{m}^{-3}$.
$\sigma_a(\lambda_s)$	Signal absorption cross section	$0.02\times10^{-25}\,\text{m}^{-3}$.
$\sigma_e(\lambda_p)$	Pump emission cross section	$2\times10^{-25}\,\text{m}^{-3}$.
$\sigma_e(\lambda_s)$	Signal emission cross section.	$0.001\times10^{-25}\,\text{m}^{-3}$.
α_p	Pump intrinsic absorption	$1\times10^{-2}\,\text{m}^{-1}$
α_s	Signal intrinsic absorption	$2.3\times10^{-2}\,\text{m}^{-1}$
K_{0131}	Cross relaxation constant	$1.8\times10^{-22}\,\text{m}^3\text{s}^{-1}$
K_{1310}	Energy up-conversion constant	$0.084\,K_{0131}$

The initial conditions for the signal, pump and ASE power for both directions are set as described in table 2. We use the relaxation algorithm to solve the boundary equations and less than 0.001% of accuracy can be achieved. A MATLAB program is developed to study and optimize the amplifier performance.

Table 2. The initial condition.

Parameter	Value
$P_p^+\,(z=0)$ = launched pump power at the forward direction	Initial condition at z=0 for 1570nm pumping.
$P_p^-\,(z=L)$ = launched pump power at the backward direction.	Initial condition at z=L for 1570nm pumping.
$P_s\,(z=0)$ = input power.	Initial condition at z=0 of the input power
$ASE_f\,(z=0)=0$	Initial condition at z=0 of forward ASE.
$ASE_b\,(z=L)=0$	Initial condition at z=L of backward ASE.

In this investigation, the forward pumping scheme is used with the total power of 2 W and the seed power of -10dBm at the wavelength of 1950nm. The optimum thulium fiber length is initially evaluated when pumped at 1570nm pump wavelength. Figure 2 describes the theoretical value of the pump and output power pumped at 1570nm. It is clearly notice that the optimum fiber length is 0.7m. Figure 4 illustrates the computed signal gain at the wavelength of 1950nm which is equal 35dB when

the optimum fiber length is 0.7m. Also, the noise figure of the amplifier is equal to 5dB which is calculated according to the equation 14 and taking the data of the ASE power (from figure 3) and the signal gain (from figure 4). It is clearly seen from this optimization that the required fiber length is shorter than that in case of lower doping concentration [8], leading to reduce the effect of fiber losses on amplifier performance. In addition, the gain dynamic is reduced with a shorter fiber length which makes the WDM system more stable with longer transmission distance [12], [13]. So, these are the main advantages of utilizing of high thulium doping concentration.
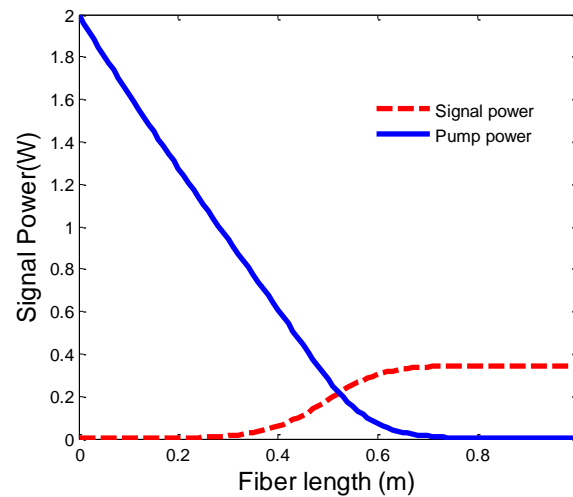

Figure 2. The pump and signal power distribution at the signal wavelength of 1950nm and a seed power of -10dBm and a pump power of 2W.
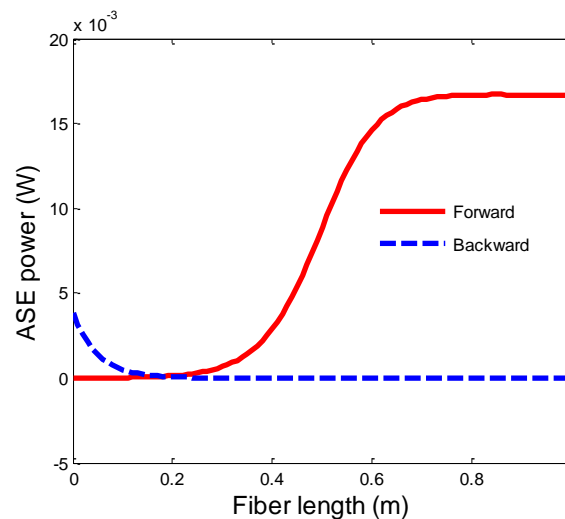

Figure 3. The power distribution of the forward and backward ASE at the wavelength 1950nm and a seed power of -10dBm lunched with a pump power of 2W.
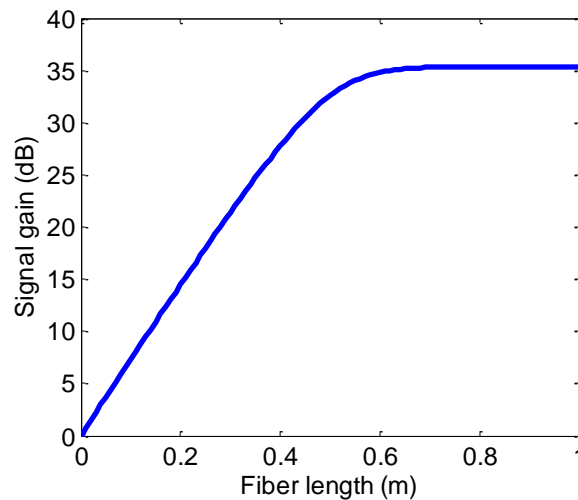
Figure 4. The calculated signal gain versus a fiber length at the wavelength
1950nm and a seed power of -10dBm lunched with a pump power of 2W.

The last investigation in this study is to study the effect of ETU in the TDFA performance. The fiber length and seed input power are fixed to 0.7m and -10dBm, respectively. The signal gain is computed at different lunch pump power. Figure 5 shows the dependence of the signal gain with the pump power with/without considering of the ETU influence. It is clearly seen that the signal gain reduces with considering of ETU because some of population densities should go out the excited energy level $^3H_4$ and therefore reducing of population inversion. As a result, increasing of the thulium concentration doesn't assist to enhance the amplifier efficiency and these findings are different to that in the case of the pump wavelength at 793nm as reported in [9].
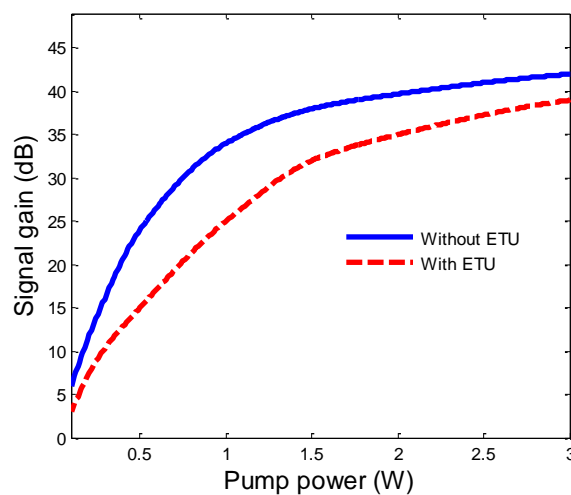

Figure 5. The calculated signal gain versus lunched pump power at the
wavelength 1950nm and a seed power of -10dBm lunched with a pump power
of 2W.

4. Conclusion
In this study, the influence of energy up-conversion transitions has been investigated on the performance of a thulium doped-fiber amplifier. A heavily thulium doped concentration has been chosen in order to consider this ion-ion interaction. The rate and propagation equations have been developed to study and evaluate the static characteristics of a TDFA with considering the effects of

amplified spontaneous emission noise, cross relaxation process and energy up-conversion. A MATLAB program has been applied to optimise the fiber length and compute the amplifier gain and noise figure. The simulation results illustrated that a short thulium fiber length is require which is about 0.7m when pumped at 2W. This is one attractive advantage of choosing a thulium fiber with high concentration. However, the results also indicated that increasing of thulium doping concentration reduces the signal gain when pumped at 1570nm. This fact is different to the reported results with the other pump wavelength at 793nm which enhances the optical efficiency with the doping concentration via utilizing of the cross-relaxation process.

5. References

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