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Thulium Doped Fiber Amplifier (TDFA) for S-band WDM Systems

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Abstract— A comprehensive numerical model based on solving rate equations of a thulium-doped silica-based fiber amplifier is evaluated. The pump power and thulium-doped fiber (TDF) length for single-pass Thulium-Doped Fiber Amplifiers (TDFA) are theoretically optimized to achieve the optimum Gain and Noise Figure (NF) at the center of S-band region. The 1064 nm pump is used to provide both ground-state and excited state absorptions for amplification in the S-band region. The theoretical result is in agreement with the published experimental result.

Keywords-component; Thulium-Doped Fiber Amplifiers, Rate Equations, Gain, Noise Figure

I.

1. Introduction

The increase demands on the capacity of WDM transmission system now require newly developed transmission windows beyond the amplification bandwidth supported by erbium-doped fiber amplifiers (EDFA's). Thulium-doped fiber amplifier (TDFA) provides high-power optical amplification in the S+ (1450–1480 nm) and S-bands (1480–1530 nm) [1-3], hence the TDFA is expected to complement C- (1530–1560 nm) and L-band (1560–1580 nm) amplification based on EDFAs in high-capacity dense wavelength division multiplexed (DWDM) systems [4, 5]. The additional bandwidth, modularity, inherent higher pumping efficiency, and lower nonlinear signal degradation (compared with alternatives such as S-band Raman amplification [6,7] offered by TDFA enables applications such as coarse wavelength-division multiplexing (CWDM) and fiber to the home (FTTH).

The TDFA length and Pump power are the important parameters that determine the achievable gain and NF in TDFA [8]. In this paper, we detail the observation and modeling of TDFA where TDFA gain and NF are optimized by solving the rate equations.

2. Configuration of the TDFA

The basic architecture used to model TDFA in the WDM system consists of 16 input signals (channels), an ideal multiplexer, a pump laser , pump coupler, Thulium-doped fiber (TDF), Optical spectrum analyzer and dual port WDM analyzer. The input of the system is 16 equalized wavelength multiplexed signals (channels) in the wavelength region of 80 nm (1450 nm-1530 nm) with 5 nm channels spacing. The power of each channel is -20 dBm. The pumping at 1064 nm is used to excite the doped atoms to a higher energy level. The TDF used is a glass based one with thulium density of 15.6×10^{-24} m^2, core radius is 1.3μm, doping radius is 1.3 μm and Numerical aperture (NA) is 0.3. The simulation done with maximum number of iterations is 150 and relative error is 5×10^{-4}.

3. Theory of the TDFA

The rate equations describe the interaction between signal, pump, and ASE light in the TDFA. The rate equations are used to analyze theoretically the populations in the energy levels of Tm^{3+} ions under 1064 *nm* pump and signal power conditions. The absorption and stimulated emission cross sections define the absorption coefficient for pump light and gain coefficient for signal light [9]. The transition cross-sections of thulium are shown in Fig. 1 [8]. The transition cross-sections were calculated in fluoride based TDF [10]. The Judd–Ofelt analysis shows that the transition strengths obtained were consistent with those for silica.

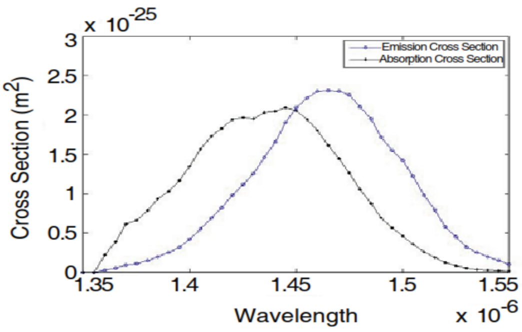


Figure 1. Absorption and emission cross-sections spectra of the fluoride-based TDFA.

An analysis of a six energy levels system is shown in Figure 2, where the energy levels of trivalent thulium ion in fluoride glass are displayed. The absorption and emission transitions are shown in fig. 2(a) and (b), respectively for the TDFA with 1064 *nm* pump wavelength. For S-band amplification, the main transition is from $^3H_4 \rightarrow {}^3F_4$ energy levels. Pumping at 1064 nm range takes benefit of the excited state absorption (ESA) $^3F_4$ at the level to excite electrons to the upper energy state. On the other hand, as 1064 nm is the main source of excitation, ground state absorption (GSA) of 1064 nm and /or WDM signals at the $^3H_6$ ground state must be nonzero in order to populate $^3H_5$ energy level and then relaxed to the $^3F_4$ energy level by non-radiative decay [11]. By exciting the TDFA at a fixed level (at 1064 nm), increasing the input WDM signals power further populates the lower energy state ($^3F_4$), from which the excited ions are raised to the upper energy state ($^3H_4$) because of excess pump power [11]. The pumping transition $^3F_4 \rightarrow {}^1G_4$ is (ESA). The energy level of the $^3F_2$ and $^3F_3$ are very close nearly the same and can be regarded as one level for simplicity. So the $^3F_4$ energy level ions are re-exited to the $^3F_2$ energy level and experience non-radiative decay to the $^3H_4$ energy level via exited state absorption [12, 13].

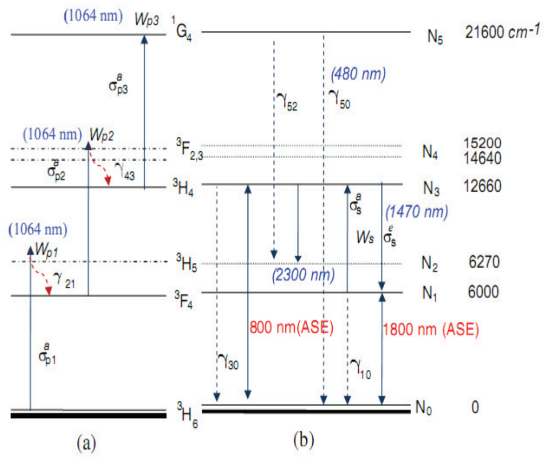


Figure. 2. Energy levels with pumping mechanism 1064 nm of trivalent ion (Tm^{3+}) in fluoride glass. (a) Pump absorption, (b) signal and ASE emission transitions.

The Thulium doped fiber ions can be considered homogeneously broadened in amplification system and also characterized by the variables N_0, N_1, N_2, N_3, N_4 and N_5 which are used to represent population ions in the $^3H_6$, $^3F_4$, $^3H_5$, $^3H_4$, $^3F_2$, and $^1G_2$ energy levels, respectively. For simplicity, γ_{31} and γ_{32} are ignored because they are very small compared with γ_{30} . γ_{51} and γ_{53} are also ignored because they are small compared with γ_{50} and γ_{52} . γ_{20} and γ_{4j} (j = 0,1,2) are very small and can be disregarded because γ_{21} and γ_{43} are multiphonon decay. On the basis of the energy level diagram as in Fig. 2. The rate equation for Tm^{3+} population density can be written as follows [14]:

$$\frac{dN_0}{dt} = -W_{p1}N_0 + \gamma_{10}N_1 + \gamma_{30}N_3 + \gamma_{50}N_5 \tag{1}$$

$$\frac{dN_1}{dt} = -(\gamma_{10} + W_{p2} + W_s)N_1 + \gamma_{21}N_2 + W_s N_3 \tag{2}$$

$$\frac{dN_2}{dt} = W_{p1}N_0 - \gamma_{21}^{nr}N_2 + \gamma_{52}N_5 \tag{3}$$

$$\frac{dN_3}{dt} = W_s N_1 - (\gamma_{30} + W_{p3} + W_s)N_3 + \gamma_{43}N_4 \tag{4}$$

$$\frac{dN_4}{dt} = W_{p2}N_1 - \gamma_{43}^{nr}N_4 \tag{5}$$

$$\frac{dN_5}{dt} = W_{p3}N_3 - (\gamma_{50} + \gamma_{52})N_5 \tag{6}$$

$$N_t = \sum_{i=1}^{5} N_i \tag{7}$$

where W_{p1}, W_{p1}, and W_{p3} are transition rates of $^3H_6 \rightarrow {}^3H_5$, $^3H_4 \rightarrow {}^3F_2$, and $^3F_4 \rightarrow {}^1G_4$ pumping transition. The signal of the central S-band is 1470 nm as signal stimulated absorption and emission is described by transition rate W_s . The non-radiative transition rate from $^3F_2 \rightarrow {}^3F_4$ and from $^3H_5 \rightarrow {}^3F_4$ energy levels are defined as γ_{43}^{nr}, and γ_{21}^{nr} , respectively. γ_{ij} is the radiative rate from level i to level j .

Others radiative transitions are not included in the rate equations because they have an ignorable effect on the S-band amplification. For simplicity, γ_{31} and γ_{32} are ignored because they are very small compared with γ_{30} . γ_{51} and γ_{53} are also ignored because they are small compared with γ_{50} and γ_{52} . γ_{20} and γ_{4j} (j = 0,1,2) are very small and can be disregarded because γ_{21} and γ_{43} are multiphonon decay [15, 16]. Rate equations can be solved by considering the steady state regime where the populations are time independent, $\frac{dN_i}{dt} = 0$, (i = 0, 1, 2,......., 5) . The average thulium ion concentration in the core N_t is calculated by [17]

$$N_t = \frac{2}{b^2}\int_0^\infty N(r) r dr \tag{8}$$

where b is the doping radius , i.e. the half of the concentration profile FWHM. In general, the variable N_i is functions of position *r, z* and time *t*. *N(r)* is the thulium ions concentration profile. N_2 and N_4 are very small compared to other N_i values. Therefore the total population density N_t is expressed as:

$$N_t = N_0 + N_1 + N_3 + N_5 \tag{9}$$

The transition rates, which describe the interaction of the electromagnetic field with the Tm^{3+} ions for a TDFA can be written as [14]:

$$W_{p1} = \frac{P_p \sigma^a_{p1}}{h\nu_p} \quad (10)$$

$$W_{p2} = \frac{P_p \sigma^a_{p2}}{h\nu_p} \quad (11)$$

$$W_{p3} = \frac{P_p \sigma^a_{p3}}{h\nu_p} \quad (12)$$

$$W_s = \frac{P_s \sigma^a_s}{h\nu_s} \quad (13)$$

where P_p is the pump power intensity and P_s is the signal power intensity. σ^a_{p1}, σ^a_{p2}, and σ^a_{p3} are ${}^3H_6 \rightarrow {}^3H_5$, ${}^3H_4 \rightarrow {}^3F_2$, and ${}^3F_4 \rightarrow {}^1G_4$ stimulation absorption cross sections where the Tm^{3+} ions are excited homogeneously across the fiber cross-section. So;

$$\gamma_{30} = 1l\,\tau_3 \quad (14)$$

$$\gamma_{10} = 1l\,\tau_1 \quad (15)$$

where τ_3 and τ_1 are the lifetimes of the ${}^3F_4$ and ${}^3H_4$ levels, respectively. *h* is the Planck constant, ν_p is pump light frequency and ν_s is signal light frequency. The light wave propagation equations along the thulium fiber in the z-direction can be recognized as follows [8]:

$$\frac{dP_p}{dz} = -\Gamma_p(\sigma_{p1}N_0 - \sigma_{p2}N_1 - \sigma_{p1}N_3)P_p - \alpha P_p \quad (16)$$

$$\frac{dP_s}{dz} = \Gamma_s(\sigma^e_s N_3 - \sigma^a_s N_1 - \sigma_{01}N_0)P_s - \alpha P_s \quad (17)$$

$$\frac{dP_{ASE}}{dz} = \pm\Gamma_{ASE}(\sigma^e_s N_3 - \sigma^a_s N_1 - \sigma_{01}N_0)P_{ASE} \pm \Gamma_{ASE}\, 2h\upsilon\Delta\upsilon\sigma^e_s N_3 \mp \alpha P_{ASE} \quad (18)$$

where α is the background scattering loss which assumed to constant for all wavelength. P_{ASE} is the amplified spontaneous emission (ASE) at S- band in forward (+) and backward (-) directions a along the fiber. σ_{01} is transition cross section from background level N_0 to the first level N_1 for 1800 nm wavelength. $\Gamma_{s,p,ASE}$ is the overlapping factor between each radiation and the fundamental mode for the signal, the pump, and ASE respectively, Γ can be given by [15,18]:

$$\Gamma = 1 - e^{-\frac{2b^2}{w_0^2}} \quad (19)$$

where w_0 is the model field radius and b is the thulium ion-dopant radius.

$$w_0 = a(0.761 + \frac{1.237}{V^{1.5}} + \frac{1.429}{V^6}) \quad (20)$$

where *a* is the core diameter, *V* is the normalized frequency. In eq. (17) the term $\sigma_{01}N_0$ is ignored because the σ_{01} is very small, so eq. (17) becomes as:

$$\frac{dP_s}{dz} = \Gamma_p(\sigma^e_s N_3 - \sigma^a_s N_1)P_s - \alpha P_s \quad (21)$$

The gain (*G*) is given by integration eq. (21) along z-direction from 0 to *L*;

$$G(dB) = 10\log_{10}\left[\exp[\Gamma_s(\sigma^e_s N_3 - \sigma^a_s N_1)L] - \exp(\alpha L)\right] \quad (22)$$

where *L* is the length of the TDFA. The gain in decibel (dB) From a practical point of view, the noise figure (*NF)* characteristic is very important in an optical amplifier's performance. The rate equation analysis predicts a low-noise characteristic in the optical amplification. Therefore, the *NF* was calculated using fiber by an optical method [19]. NF is given by

$$NF = \frac{1}{G} + \frac{P^{out}_{ASE}(\lambda_s)}{Gh\nu\,\Delta\nu} \quad (23)$$

where $P^{out}_{ASE}(\lambda_s)$ is the output ASE spectral density (W/Hz) at the signal wavelength. For each signal wavelength, the *NF* in dB is given by:

$$NF(dB) = 10\,x\,\log_{10}\left[\frac{1}{G} + \frac{P^{out}_{ASE}(\lambda_s)}{Gh\nu\Delta\nu}\right] \quad (25)$$

4. Results and Discussions

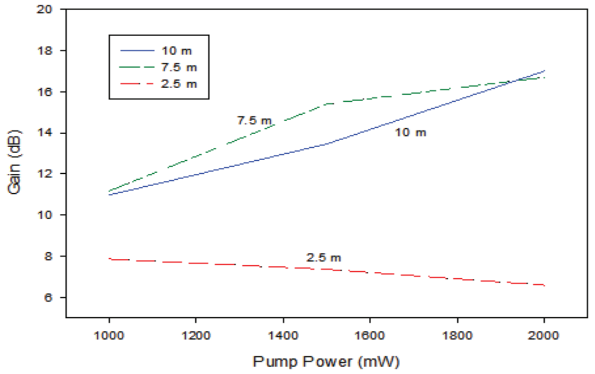
The proposed system amplifies a set of 16 channels in the S-band going from 1450 nm to 1525 nm. The parameters used in the simulation are listed in table 1.

Table 1: Parameters used in the simulation [12]:

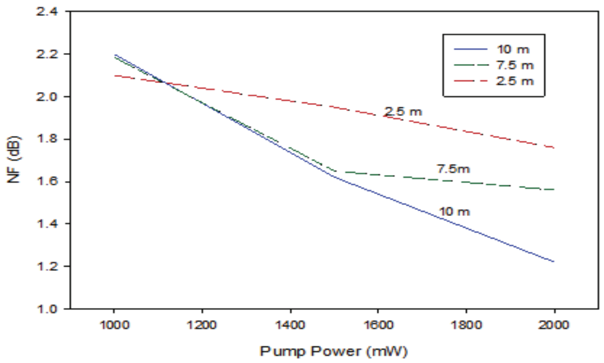
Parameter	Value
Thulium ion density	1.68e+025 1/m^3
Numerical aperture	0.4
Fiber Length	2.5, 7.5, 10 m
Core radius	1.3μm

Optimization of the length of the thulium-doped fiber (TDF) is one of the most important issues for optical networks that need to be considered for designing a TDFA in order to obtain the best gain with the lowest noise figure. The gain and noise figure of the TDFA are dependent on the TDF length and the operating pump power. The TDF length is selected carefully, when the TDF length is too short, the TDFA will be saturated at a low pump power and this does not provide a high gain. For a short TDF, the total population is very low and therefore the TDF is fully inverted by a low amount of pump power. When this low amount of pump power is used then the optimized TDF length is short. The length of the TDF is optimized by calculating the gain as a function of TDF length for various operating pump powers. The input signal power and wavelength is fixed at −20 dBm and 1470 nm, respectively and the pump power is varied from 1000 mW to 2000 mW. Three different amplifier lengths are simulated (2.5 m, 7.5 m, 10 m) and the gain and NF curves are plotted in Figure 3. It is clear from the results that the gain increases with increasing the pump power for L = 7.5m and 10 m and it stays almost constant at L =2.5 m. However, the best gain is achieved at L = 7.5 m. For the NF results, it is clear that increasing the pump power and the fiber length has a little impact on the NF.

Although the 10 m long TDFA design provides the highest gain (16.7 dB) at pump power of 2000 mW. However the use of a high pump power is in conflict with the main objective of the TDFA design which requires a smaller pump power especially for long haul applications. For this reason, a very



(a) Gain



(b) NF

Figure 3. Gain and Noise Figure (NF) versus pump power at different lengths L=2.5m, 7.5m and 10 m.

long TDF is not recommended to be considered as a reference TDF length during the design of single pass TDFAs. In the optical network, an amplifier is mainly designed to obtain a gain as high as possible with a low noise figure using a minimum pump power. So the optimum length is 7.5 m with optimum pump power of 1500 mw, where a gain of 15.4 dB and NF of 2.9 dB are achieved.

5. Conclusion

This paper has described in detail the relation between the operating 1064 nm pump power and TDFA length for single-pass TDFA. The simulation results are based on the rate equations to determine the gain and noise figures for TDFA. The simulated model was also used for optimizing of the TDFA parameters: fiber length, pump wavelength and pump power. The theoretical results obtained here is in agreement with the published experimental result. It is found that the optimum TDFA length is 7.5 m with optimum pump power of 1500 mW. The results show that silica-based TDFA amplifiers are interesting comparing to its competitors within the S-band optical amplifiers, namely the fluoride-fiber based TDFA and the Raman amplifiers.

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