An Efficient TDFA Model for Improved Gain Enhancement by Improving Doping Schemes

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Abstract:

A novel scheme has been proposed by the way of improved doping concentration of Tm+3. With this configuration maximum gain of 32.5 dB over 1460-1540nm for 6500ppm of Tm+3 for 22m long TDFA is achieved.

1. Introduction

The DWDM systems have proven themselves beneficial for triggering off the rapid demand of communication. As per the ITU recommendations (ITU-T G.692), the channel spacing for DWDM systems is0.8 to 0.1nm at 1550nm. This requires implementation of high quality, stable, temperature and wavelength controlled laser diode light sources. Optical fiber amplifier being the most powerful and advanced amplification media has played as a core factor in the widespread implementation of DWDM systems. Optical Fiber amplifiers may be either thulium doped (TDFA) or erbium doped fiber amplifier (EDFA). EDFA uses C-Band and TDFA uses S-Band.

In today's technological era, TDFA offers more advantages over EDFA such as low absorption loss due to OH- ions, low fiber loss and low dispersion. In order to overcome the increasing demand of information traffic in WDM communication systems, it is primarily required to increase the wavelength range of telecommunication. This means it is the time to explore optical amplifiers in the S-band along with already existing optical amplifier i.e. EDFA in the C-Band and L-Band. One of the feasible answers for utilizing S-Band is Thulium Doped Fiber Amplifier. An emission occurs at 1.47µm between the two excited levels 3H4 and 3F4 [1-4] of TDFA. This emission exactly matches the range of S-Band. So, with TDFA high gain, high efficiency and low noise can be achieved [5-6]. The energy diagram of TDFA revels that Tm+3 ions has three energy levels [7]. It has been observed that the gain and NF, ASE are dependant not only on ESA and SE but also on GSA. The GSA in TDFA decreases the efficiency of TDFA. This pumping scheme consists of the two step excitation of 3H6 to 3 F4 and 3F4 to 3H4 with the same pump wavelength as shown in figure1. With this upconversion pump scheme a population inversion state between 3F4 to 3H4 exists. It has been observed that the excitation of 3H6 to 3 F4 depends on the pump power, so the total population at upper and lower level (N2 +N1) of thulium ions is increased. To lower the ground state absorption (GSA) of TDFA, phonon energy in Tm+3 must be lowered. It is important to use either fluoride or aluminum is added, rather than conventional pure silica glass. By adding aluminum improvement in quantum efficiency has been observed without lowering its maximum phonon energy. An improved model of TDFA is developed in this paper by the way of improved doping level of Tm+3 ions. The normal doping level considered in various research papers was 600ppm. In this paper various doping concentrations were performed keeping all realistic parameters into consideration. The impact of length, pump power on gain of TDFA was carried out for different doping levels for obtaining optimized gain enhancement.

2. Need of the Work and Methodology

It has been observed that the prime factor for performance of TDFA is GSA. The GSA is affected by the number of ions present in ground state (N0) which in turn depends on the doping level of Tm+3 ions. In the present work a mathematical model has been developed and analyzed for improved gain enhancement using optimized doping concentration of Tm+3 ion. To achieve the improved gain spectrum of TDFA, we have to vary the doping level of Tm+3 ions. It is known that radiative transition involves the absorption and emission of photons while non-radiative transition involves the absorption and emission of phonons. Tm+3 ions doped silica fiber is found inefficient due to relatively high phonon energy which leads to non-radiative quenching. So, a need was felt to improve the quantum efficiency of this optical transition. In this paper a mathematical model is proposed which considers all possible realistic impairments. Impact of doping level on the performance of TDFA is carried out. A simulated model has been developed using MathCAD for verification of proposed mathematical model. The gain of TDFA is given as

$$G(\lambda) = exp[(\sigma_e(\lambda)N_2 - \sigma_a(\lambda)N_1 - \sigma GSA \lambda N0 \ \eta L \qquad (1)$$

Where η is the confinement factor, L is the length of TDF, N0, N1 and N2 are the population densities of the thulium ions(Tm+3) in ground, lower and upper state respectively. These densities can be averaged along the complete length of TDF, can be given as

$$Ni = \int_0^L n(z)dz \qquad (2)$$

The total population of thulium ions (Tm+3) which is a function of time only, is given as

$$N_{Total} = (N_0 + N_1 + N_2) \qquad (3)$$

The ratio of thulium ions(Tm+3) in excited state and total population density (α) is considered as 0.4, the population inversion coefficient between upper and lower excitation states (β) is considered as 0.55. The three population densities of thulium ions i.e. at ground state, lower excitation state and upper excitation state are derived as:

$$\frac{\delta n_0}{\delta t} = \Big(-P_{01}\ n_0 - S_{01}\ n_0 + S_{10}\ n_1 + \frac{n_1}{\tau} + P20n2 + n2\tau' \qquad (4)$$

$$\frac{\delta n_1}{\delta t} = \left(S_{01}\, n_0 \;\; - S_{10} n_1 \; - \right.$$
$n1\tau{+}P21n2$ (5)

$$\frac{\delta n_2}{\delta t} = \left(P_{02}\;\, n_0 \;\; - P_{21}\;\, n_2 \;\; - \right.$$
$P20n2 - n2\tau'$ (6)

Where P and S refer to the transition rates related with the pump and signal respectively. Here n0, n1 and n2 represent the population densities of thulium ion (Tm+3) at ground state, metastable state and excited state respectively, which are function of time as well as linear distance z. Practically, the transition from upper to lower state has more probability of occurrence as compared to that from lower state to ground state or from upper to ground state. So, by assuming P21»P20 , P21»1/τ' and P21»P02, equation (6) becomes:

$$\frac{\delta n_1}{\delta t} = \left(S_{01}\; n_0 \;\; - \right.$$
$S10n1 - n1\tau{+}P02n2$ (7)

On integrating equation (7) over z,

$$\frac{\delta N_1}{\delta t} = \left(P_s\;(0,t) - P_s\;(L,t) - \right.$$
$n1\tau{+}PP0{,}t{-}PPL{,}t$ (8)

At Steady state,

$$\frac{\delta n_0}{\delta t} = 0 = \frac{\delta n_1}{\delta t} = \frac{\delta n_2}{\delta t}$$
(9)

Using equations (6) & (7) we get,

$$N_2 \;= \frac{P_{02}}{P_{02}+\tau} N_0$$
(10)

Equation(10) explains that in order to obtain population inversion between state 2 and state 1 the necessary condition is that $\tau > \tau'$. Here, τ and τ' represent lifetime from state 2 to sate1 and from state 1 to state 0 respectively. These lifetimes are inversely proportional to the relaxation rates. If this condition is satisfied then minimum pumping rate required to achieve population inversion is given as

$$P_{min} \;= \frac{\tau\tau'}{\tau - \tau'}$$
(11)

From equations (3),(10) & (11) we get,

$$\frac{N_1 \; - N_0}{N_{Total}} = \frac{P_{02} - \tau'}{P_{02} + \tau'}$$
(12)

From equation (12) it is concluded that when P02 is small then population inversion is dependent on I1, because:

$$P_{02} \;= \frac{\pi^2 - c^2}{h\omega^2 n_0{}^2} R_{10}\, f_{0(}\omega) I_1$$
(13)

Where R10 is radiative relaxation rate between 0 & 1,f0 (ω) is lineshape function representing transition between state 0 & 1.

3. Model Analysis, Figures and Result

For the proposed model the active fibers used for the model were 10m long ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF3) fibers having thulium ion concentration ranges from 5000ppm to 6500ppm. The cutoff wavelength for TDF at 950nm and a relative refractive index difference (Δn) has been set up. The forward pumping at 1390nm is used. The numerical aperture and core diameter 0.27 and 2.55µm were considered. 250mW was fixed as forward pump power. The absorption (σa) and emission (σe) cross section were taken as 0.17X10-25m2 and 1.2X10-25m2 respectively. With this configuration optimized gain of 32.5 dB over 1460-1540nm for 6500ppm of Tm+3 for 22m long TDFA is achieved.

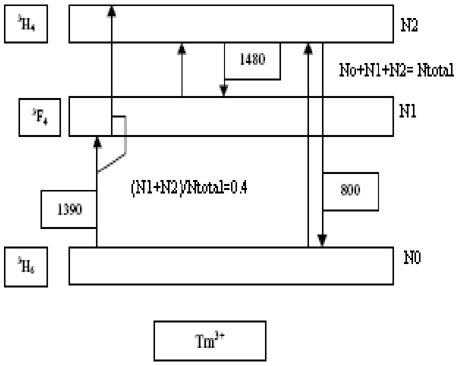

Figure1: Energy Level Diagram of TDFA

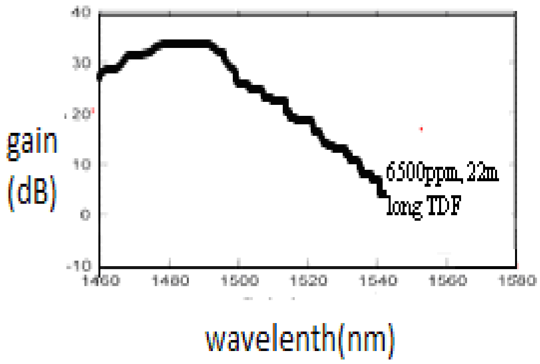

Figure2: Gain Spectrum of TDFA

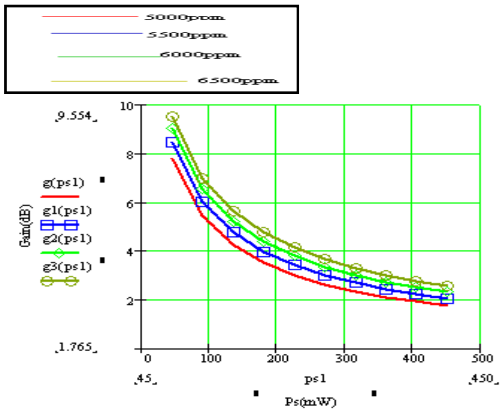

Figure3: Impact of Signal Power on Gain for Different doping concentration of Tm+3

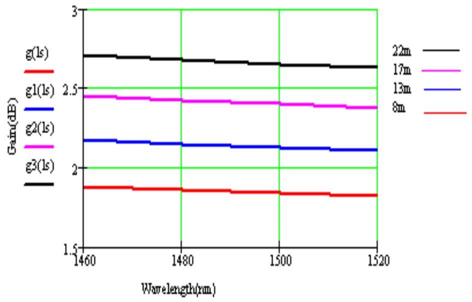

Figure4: Impact of length of TDF on Gain

4. Conclusion

By implementing this model optimized gain of 32.5 dB over 1460-1540nm for 6500ppm of Tm+3 for 22m long TDFA is achieved. It has been observed that as signal power is increased the gain is reduced exponentially.

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