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Ytterbium-Codoping in Thulium Doped Silica Fiber

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Abstract

A novel ytterbium-thulium codoping scheme is presented taking advantage of the fact that ytterbium codoping in thulium could facilitate population inversion between the relevant energy levels, through a cross energy transfer process between Tm^{3+} and Yb^{3+} . A set of nonlinear coupled ODEs which govern the dynamics of optical amplification in the ytterbium-thulium codoped material system was established based on the rate equations and propagation equations. The results demonstrated that the ytterbium to thulium energy transfer process is significant and beneficial. PACS: 42.81; 42.70.HJ

1. Introduction

The development of the so-called ‘dry fiber’ opens up opportunity for optical communication in the S-band [1]. The emission associated with Tm^{3+} transition 3H_4 to 3F_4 covers the spectral range 1440nm-1520nm [2]. Hence Tm^{3+} doped fiber amplifier (T DFA) is desirable for the S-band (1460-1520nm) optical amplification and has attracted considerable attention as a means of extending the transmission bandwidth of optical fibers beyond the range available from Er^{3+} -doped fiber amplifiers (EDFA) [3]. Several types pumping schemes and methods have been developed for Tm^{3+} doped optical fibre amplifiers. In terms of T DFA’s gain in the S-band, it has been reported that around 20dB has been achieved in thulium doped telluride fiber [4] and fluoride fibers [5,6] using various upconversion pumping methods. However these thulium doped fibers have difficulties in practical implementation and application, mainly due to the host material instability, problems in fabrication and in connection with silica fiber system.

These difficulties have stimulated further development of thulium doped silica fibers. Although the lifetime of its upper level is significantly shorter compared to that of telluride and fluoride host materials, remarkable amount of progress has been made in recent years. In thulium doped silica fiber, gain excess of 20dB has been predicted by theoretical modeling and simulation [7] and gains as high as 10dB [8], 12dB [9], have been achieved by various experiments. Nevertheless, there remain many challenges such as improving gain, gain bandwidth, pump efficiency, etc.

Yb^{3+} has the advantage to present only two multiplets: the ground-state level $^2F_{7/2}$ and the excited-state level $^2F_{5/2}$, corresponding the highly efficiency absorption in the range of 900nm-1000nm [10]. This particular energy level structure is highly desirable for efficient absorption of commercially available laser diodes emitting around 980nm and avoiding any undesirable excited-state absorption under intense optical pumping.

Based on the above consideration, as a first attempt as far as we know, we investigate ytterbium codoping in thulium doped silica fibers in this paper, a generic model of ytterbium-thulium codoped S-band silica fiber amplifier is established for the first time taken into consideration the $\text{Yb}^{3+} \rightarrow \text{Tm}^{3+}$ energy transfer process and investigated the relevant aspects of ytterbium codoping in silica T DFAs. A new computational strategy was developed to solve the rate and propagation equations, which are nonlinear coupled ordinary differential equations (ODE). From the simulation results, it is shown that Yb^{3+} codoped T DFA produce improved performance for S-band optical amplification.

2. Modelling of Yb^{3+} - Tm^{3+} codoping

With the selection of the 980nm and 1064nm co-pumping scheme, the relevant absorption and emission transitions and the energy transfer process between Tm^{3+} and Yb^{3+} are shown as in Fig.1. The energy levels 3F_2 and 3F_3 of Tm^{3+} are very close and thus they are treated as a single level (level 4). The stimulated absorption and emission rates between levels i and j are W_{ij} . Spontaneous decay processes are described by the radiative and nonradiative decays, A_{ij}^r and A_i^{nr} , respectively. Branch ratio β_{ij} is the probability of a radiative transition from upper level i to lower level j. Since the nonradiative decay rates from 3F_3 and 3H_5 to the respective underlying level are very high ($\gg 10^5/\text{s}$), the atomic population density N_2 and N_4 of both bands

Figure 1: Pump scheme of ytterbium-thulium, energy transfer process between ytterbium-thulium

are neglected in this model. The thulium concentration in TDFAs is usually low and the self-quenching process ${}^3H_4 + {}^3H_6 \rightarrow {}^3F_4$ is neglected. Based on these considerations, the rate equations for the Tm^{3+} population densities, N_1 , N_3 and N_5 are established as follows:

$$\frac{dN_1}{dt} = N_0 W_{01} - N_1 (W_{13} + W_{14} + A_1^{nr} + A_{10}^r) + N_3 (W_{31} + A_3^{nr} + A_{31}^r) + N_5 (A_{51}^r + A_{52}^r) + K_1 N_0 N_{Yb1} - K_2 N_1 N_{Yb1} \quad (1)$$

$$\frac{dN_3}{dt} = N_1 (W_{13} + W_{14}) + N_5 (A_5^{nr} + A_{54}^r + A_{53}^r) - N_3 (W_{35} + W_{31} + A_3^{nr} + \sum_{j=0}^2 A_{3j}^r) + K_2 N_1 N_{Yb1} \quad (2)$$

$$\frac{dN_5}{dt} = N_3 W_{35} - N_5 (A_5^{nr} + \sum_{j=0}^4 A_{5j}^r) \quad (3)$$

$$N_{Tm} = N_0 + N_1 + N_3 + N_5 \quad (4)$$

The rate equations for the Yb^{3+} population densities, N_{Yb0} , and N_{Yb1} are given by:

$$\frac{dN_{Yb1}}{dt} = N_{Yb0} W_{Yb01} - N_{Yb1} W_{Yb10} - K_1 N_0 N_{Yb1} - K_2 N_1 N_{Yb1} - N_{Yb1} / \tau_1 \quad (5)$$

$$N_{Yb} = N_{Yb0} + N_{Yb1} \quad (6)$$

Here N_{Tm} and N_{Yb} are the total Tm^{3+} and Yb^{3+} concentrations in the fiber. N_1 , N_3 , N_5 are the population densities of the energy levels 3F_4 , 3F_3 , 1G_4 . N_{Yb0} and N_{Yb1} are the population densities of the energy levels ${}^2F_{7/2}$ and ${}^2F_{5/2}$. K_1 is the energy transfer parameter for ${}^3H_6(Tm^{3+}) + {}^2F_{5/2}(Yb^{3+}) \rightarrow {}^3H_5(Tm^{3+}) + {}^2F_{7/2}(Yb^{3+})$, and K_2 is the energy transfer parameter for ${}^3F_4(Tm^{3+}) + {}^2F_{5/2}(Yb^{3+}) \rightarrow {}^3F_3(Tm^{3+}) + {}^2F_{7/2}(Yb^{3+})$. W_{ij} describes interaction of the electromagnetic field and the ions, it can be written as [7]:

$$W_{ij}(z) = \int_0^\infty \lambda \Gamma(\lambda) \sigma_{ij} \frac{(P_\lambda^+(z, \lambda) + P_\lambda^-(z, \lambda))}{hc\pi b^2} d\lambda \quad (7)$$

Here $P_\lambda^\pm$ are the spectral power densities of the radiation propagating in the positive and negative directions of the fiber axis, is so called overlap factor defined by [7]:

$$\Gamma(\lambda) = \frac{\int_0^\infty |E(r, \varphi, \lambda)|^2 N(r) r dr}{N_{Tm} \int_0^\infty |E(r, \varphi, \lambda)|^2 r dr} \quad (8)$$

Where $N(r)$ is the Tm^{3+} concentration distribution with $N_{Tm} = \int_0^\infty N(r)rdr$

As ASE is not significant, we can derive the propagation equation of each partial wave,

$$\frac{dP^\pm(\lambda)}{dz} = \Gamma(\lambda)P^\pm(\lambda) \sum_{ij}^{(N_i\sigma_{ij}(\lambda) - N_j\sigma_{ji}(\lambda))} \quad (9)$$

The spectroscopic parameters used in our analysis and design are summarized in Table 1. The absorption and emission cross-section spectra of ytterbium and thulium are collected in Ref. [7, 11]. Since there is no

Table 1: Parameters used in the numerical simulations

Parameter	Unit	Symbol	Value	Ref
Tm concentration	ppm		1000~3000	Specification
Yb concentration	ppm		2500~15000	Specification
Core diameter	$\mu\text{ m}$	2a	2.6	Specification
Fluorescence Lifetimes (Thulium)	$\mu\text{ s}$	τ_5	784	[7]
	$\mu\text{ s}$	τ_3	45	[7]
	$\mu\text{ s}$	τ_1	430	[7]
Radiative Lifetimes(Thulium)	$\mu\text{ s}$	$1/\sum_{i=1}^4 A_{5i}^r$	860	[7]
	$\mu\text{ s}$	$1/\sum_{i=1}^2 A_{3i}^r$	650	[7]
	$\mu\text{ s}$	$1/A_{10}$	3500	[7]
Fluorescence Lifetimes (Ytterbium)	$\mu\text{ s}$	τ_1	1500	[11]
Branching Ratios (Thulium)		β_{54}	0.03	[7]
		β_{53}	0.11	[7]
		β_{52}	0.30	[7]
		β_{51}	0.06	[7]
		β_{50}	0.5	[7]
		β_{32}	0.03	[7]
		β_{31}	0.09	[7]
		β_{30}	0.88	[7]

data available for the energy transfer parameters K_1 and K_2 in ytterbium-thulium codoped silica materials, we collected the energy transfer parameters K_1 and K_2 determined in Ref.[10] and delineated them in terms of the product of the total Tm^{3+} and Yb^{3+} concentrations, N_{Tm} and N_{Yb} , the values of K_1 and K_2 is estimated by the extrapolation method.

3. Result and Discussion

Firstly, we investigated the gain characteristics of ytterbium-thulium codoped silica fibers with dual wavelength pumping 1064nm (1w) and 980nm (0.4w), the ytterbium and thulium concentrations are 15000ppm and 3000ppm respectively, input signal power is $10\mu\text{W}$. The spectral gain in S-band is shown in Fig.2; the solid curve represents the gain of the ytterbium-thulium codoped fiber amplifier, while the dotted curve represents the spectral gain of a TDFA as a reference for comparison. The reference TDFA has exactly the same parameters as the ytterbium-thulium codoped fiber amplifier, except without the ytterbium codoping and 980nm pump. It is shown that, with a total pump power increase by only 1.5dB; ytterbium codoping improves the maximum gain by about 2dB at 1470nm.

Figure 2: Spectral gain in the S-band of TDFA and Ytterbium codoped TDFA

Figure 3: Dependence of gain versus Yb and Tm concentration

The relation of gain versus Yb^{3+} and Tm^{3+} concentrations is shown in Fig.3. Here the signal wavelength is 1470nm and the input signal is $10\mu\text{W}$. The pump powers are as in the case of Fig.3. It is shown that fibers with higher ytterbium-thulium concentration will produce a higher gain.

The gain characteristics with respect to the pump power are demonstrated in Fig.4. In this case, the thulium concentration is 3000ppm and the ytterbium concentration 15000ppm, the signal wavelength is 1470nm and the input signal is $10\mu\text{W}$. It is clear that the higher the main pump power at 1064nm is the higher gain will be. It is noted that there is an optimal 980nm pump power given a certain 1064nm pump power level. The value of the optimal 980nm pump power increases with the 1064nm pump power. When the main pump powers are 0.5W, 0.75W and 1W, the corresponding optimal 980nm pump powers are 0.27W, 0.33W and 0.4W respectively.

Figure 4: Dependence of gain versus pump power

Conclusions

We proposed a novel ytterbium-thulium codoping scheme, expecting that ytterbium codoping can facilitate population inversion between the relevant energy levels 3H_4 and 3F_4 of Tm^{3+} , through a cross energy transfer process between Tm^{3+} and Yb^{3+} . A set of nonlinear coupled ODEs, which govern the dynamics of optical amplification in the ytterbium-thulium codoped material system, were established based on the rate equations and propagation equations taken into consideration of the energy transfer process between Tm^{3+} and Yb^{3+} in silica fiber host. A novel computational strategy to solve the set of rate equations and propagation equations is developed to study various cases of ytterbium-thulium codoping under different parametrical conditions.

From our simulation results, we have demonstrated that the gain characteristics and pump efficiency can be improved by ytterbium codoping and using an auxiliary pump at 980nm. It has been shown that higher values of the parameters from higher doping concentrations would produce a higher gain improvement. This suggests that fabrication techniques for higher doping concentrations should be pursued in future.

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