S+C band optical amplification in Er^{3+}-Tm^{3+} co-doped fiber

Jun Chang (常 军)[1,2], Qingpu Wang (王青圃)[1], Xingyu Zhang (张行愚)[1], Zejin Liu (刘泽金)[1], Zhaojun Liu (刘兆军)[1], and Gangding Peng[2]

[1]*School of Information Science and Engineering, Shandong University, Ji'nan 250100*

[2]*Photonics & Optical Communications Group, School of Electrical Engineering & Telecommunications, the University of New South Wales, Sydney 2052, Australia*

Received April 15, 2005

A new type of optical amplifier based on co-doping erbium in thulium doped fiber is proposed to realize S+C band gain by dual-wavelength (800+1410 nm) pumping scheme which is obtainable from laser diode. A novel model is established for the co-doped fiber considering the Er^{3+} to Tm^{3+} energy transfer process. Using appropriate fiber parameters and energy transfer parameters, the coupled rate equations are analyzed and solved; the concentrations of Er^{3+} and Tm^{3+} and fiber length were optimized to get more uniform gain. The results predicted that the S+C band gain can be achieved at the same time by co-doping erbium in thulium doped fluoride fiber.

OCIS codes: 060.0060, 060.2320, 060.2330.

The commercial availability of dry fiber opens new transmission window[1]. In order to broaden the bandwidth of fiber amplifier, Er^{3+} and Tm^{3+} co-doped glass material has been studied recently. Amplified spontaneous emission (ASE) with a 3-dB bandwidth from 1460 to 1550 nm was observed from Er^{3+}-Tm^{3+} co-doped silica fiber[2], and broadband 1.4—2.0 nm luminescence from Er^{3+}-Tm^{3+} co-doped silicon-rich silicon oxide films was demonstrated[3]. Although the experiment and theoretical study have been widely developed for erbium doped fiber amplifier (EDFA)[4,5] and thulium doped fiber amplifier (TDFA)[6−8], Er^{3+} has absorption in S-band, and Tm^{3+} has absorption in C-band[9], and there is energy transfer process between Er^{3+}:${}^4I_{13/2} \rightarrow Tm^{3+}$:${}^3F_4$[10]. It is necessary to establish theoretical model for Er^{3+} and Tm^{3+} co-doped fiber amplifier to optimize fiber parameters in order to get broadband amplification.

We established the theoretical model for Er^{3+}-Tm^{3+} co-doped fiber amplifier. Based on the diagram of Er^{3+} and Tm^{3+} energy levels which is shown in Fig. 1[9], the rate equations for the Tm^{3+} population densities, N_{T0}, N_{T1}, N_{T2}, N_{T3}, N_{T4}, are established as

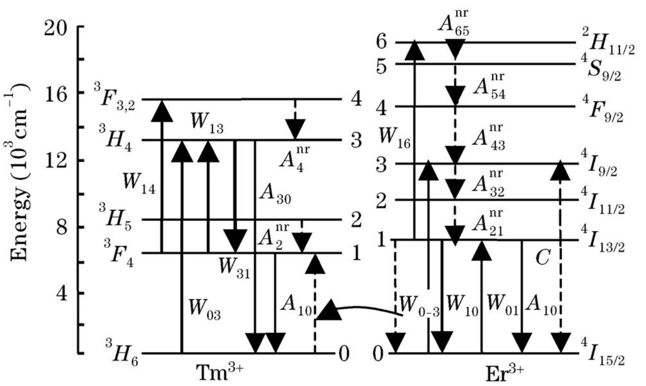

Fig. 1. Energy level diagram of thulium and erbium with transitions involved in the model[8].

$$\begin{aligned}\frac{dN_{T1}}{dt} &= N_{T0}W_{T01} + N_{T2}A^{nr}_{T21} + K_{ET1}N_{T0}N_{E1} \\ &-N_{T1}(W_{T10} + W_{T13} + W_{T14} + A^{r}_{T10}) \\ &+N_{T3}(W_{T31} + A^{r}_{T31}), \end{aligned} \quad (1)$$

$$\frac{dN_{T2}}{dt} = N_{T0}W_{T02} - N_{T2}A^{nr}_{T21}, \quad (2)$$

$$\begin{aligned}\frac{dN_{T3}}{dt} &= N_{T0}W_{T03} + N_{T1}W_{T13} \\ &+N_{T4}A^{nr}_{T43} - N_{T3}(W_{T31} + A^{r}_{T30}), \end{aligned} \quad (3)$$

$$\frac{dN_{T4}}{dt} = N_{T1}W_{T14} - N_{T4}A^{nr}_{T43}, \quad (4)$$

$$N_T = N_{T0} + N_{T1} + N_{T2} + N_{T3} + N_{T4}. \quad (5)$$

The rate equations for the Er^{3+} population densities, N_{E0}, N_{E1}, N_{E2}, N_{E3}, N_{E4}, N_{E5} and N_{E6}, are given by

$$\begin{aligned}\frac{dN_{E1}}{dt} &= W_{E01}N_{E0} + A^{nr}_{E21}N_{E2} - 2CN^2_{E1} \\ &-K_{ET1}N_{T0}N_{E1} - (W_{E10} + A^{r}_{E10})N_{E1}, \end{aligned} \quad (6)$$

$$\frac{dN_{E2}}{dt} = A^{nr}_{E32}N_{E3} - A^{nr}_{E21}N_{E2}, \quad (7)$$

$$\frac{dN_{E3}}{dt} = W_{E03}N_{E0} + CN^2_{E1} - A^{nr}_{E32}N_{E3}, \quad (8)$$

$$\frac{dN_{E4}}{dt} = A^{nr}_{E54}N_{E5} - A^{nr}_{E43}N_{E4}, \quad (9)$$

$$\frac{dN_{E5}}{dt} = A^{nr}_{E65}N_{E6} - A^{nr}_{E54}N_{E5}, \quad (10)$$

$$\frac{dN_{E6}}{dt} = W_{E16}N_{E1} - A^{nr}_{E65}N_{E6}, \quad (11)$$

$$N_E = N_{E0} + N_{E1} + N_{E2} + N_{E3} + N_{E4} + N_{E5} + N_{E6}. \quad (12)$$

Here A^{r}_{ij} and A^{nr}_{i} are the radiative and nonradiative decays of Tm^{3+} or Er^{3+}, W_{ij} describes the interaction of the electromagnetic field and the ions, and can be written as[6]

$$W_{ij}(z) = \int_0^\infty \lambda\Gamma(\lambda)\sigma_{ij}\frac{\left(P_\lambda^+(z,\lambda)+P_\lambda^-(z,\lambda)\right)}{hc\pi b^2}\mathrm{d}\lambda, \quad (13)$$

$P_\lambda^\pm$ are the spectral power densities of the laser propagating in the positive and negative directions of the fiber axis, σ_{ij} is respective transition cross-section, and Γ is so called overlap factor defined by[6]

$$\Gamma(\lambda) = \frac{\int_0^\infty |E(r,\varphi,\lambda)|^2 N(r) r\mathrm{d}r}{N\int_0^\infty |E(r,\varphi,\lambda)|^2 r\mathrm{d}r}, \quad (14)$$

where $N(r)$ denotes $N_{\mathrm{Tm}}(r)$ or $N_{\mathrm{Er}}(r)$, the concentration distribution of Tm^{3+} or Er^{3+}, depending on whether Tm^{3+} or Er^{3+} ions is involved in the process of W_{ij}. Similarly N denotes N_{T} or N_{E}, $N_{\mathrm{T}} = \int_0^\infty N_{\mathrm{T}}(r)r\mathrm{d}r$ and $N_{\mathrm{E}} = \int_0^\infty N_{\mathrm{E}}(r)r\mathrm{d}r$. Powers along the fiber length can be expressed by propagation equations

$$\frac{\mathrm{d}P^\pm(\lambda)}{\mathrm{d}z} = \Gamma(\lambda)P^\pm(\lambda)\sum_{ij}\left(N_i\sigma_{ij}(\lambda) - N_j\sigma_{ji}(\lambda)\right) + \Gamma(\lambda)\sum_{ij} 2h\nu_{ij}\Delta\nu N_i\sigma_{ij}(\lambda). \quad (15)$$

Considering the Er^{3+} and Tm^{3+} absorption cross-section, we choose the pumping scheme 800 nm (0.3 W) +1410 nm (0.15 W), these wavelengths are now available from laser diode. Parameters chosen are based on ZEBLAN host, and they are summarized in Table 1. The transition cross-section spectra of Er^{3+} and Tm^{3+} are collected in Refs. [12,13]. Equations (1)—(12) and (15) are solved numerically and the spectral gain can be calculated.

Table 1. Parameters Used in the Numerical Simulations

Parameter	Symbol	Value
Tm Concentration (ppm)		1200
Er Concentration (ppm)		0—600
Core Diameter (μm)	$2a$	2.8
Tm Spontaneous Emission	A_{10}	172.4
Rate[11] (s^{-1})	A_{30}	702.8
	A_{50}	676.3
	A_{52}	492.9
Er Spontaneous Emission		
Rate[11] (s^{-1})	A_{10}	70
Tm Non-Radiative Decay	A_{43}	52986
Rate[11] (s^{-1})	A_{21}	195626
Er Non-Radiative Decay	A_{21}	1.5×10^5
Rate[12] (s^{-1})	A_{32}	2×10^8
	A_{43}	1.6×10^8
	A_{54}	1.4×10^6
	A_{65}	$> 10^7$
Tm Pump Absorption	$\sigma_{02}(1410)$	0.23×10^{-27}
Cross-Section[7] (m^2)	$\sigma_{14}(1410)$	1.45×10^{-25}
Er Cross-Section[11] (m^2)	$\sigma_{03}(800)$	0.97×10^{-25}
	$\sigma_{16}(800)$	0.9×10^{-25}
Energy Transfer[10] (m^3/s)	K_{ET1}	0.9×10^{-24}

Spectral gain of 17 channels from 1450 to 1560 nm with each channel input power 10^{-5} W is shown in Fig. 2. Six lines represent Tm^{3+} concentration of 1200 ppm with Er^{3+} 0, 100, 200, 300, 400, 500, 600 ppm. With the increase of Er^{3+} concentration, C-band gain increases quickly, while S-band gain drops a little. When Er^{3+} concentration is above 500 ppm, gain around 1490 nm drops quickly, this might because of the fast increase of ground state $^4I_{15/2}$ population of Er^{3+}. For a certain Tm^{3+} concentration, there exists an optimal Er^{3+} concentration, in Fig. 3, Tm^{3+} concentration is 1200 ppm, 12 lines represent signal wavelengths from 1450 to 1560 nm respectively, Er^{3+} concentration changes from 0 to 600 ppm, we can see that the best concentration is 1200 ppm Tm^{3+}, and 500 ppm Er^{3+}.

Spectral gain along fiber is shown in Fig. 4, 12 lines represent signal wavelengths from 1450 to 1560 nm; Tm^{3+} concentration is 1200 ppm and Er^{3+} is 500 ppm. Signal from 1490 to 1530 nm drops fast after reaching their peak because of ground state absorption (GSA) of Er^{3+}; and there exists optimized fiber length which the gain is more uniform.

There is energy transfer process between Er^{3+} and Tm^{3+}, Er^{3+}:$^4I_{13/2} \rightarrow Tm^{3+}$:$^3F_4$[10], because the concentrations of Er^{3+} and Tm^{3+} are very low, the transfer parameter is very small and it has very limited influence on the results according to the simulation.

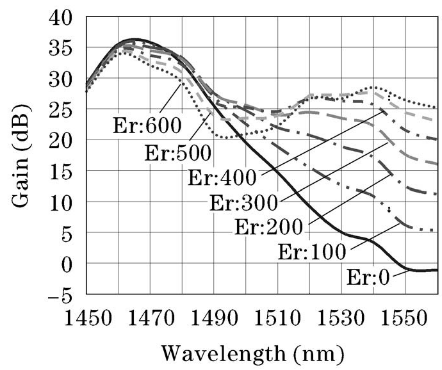

Fig. 2. Spectral gain of different Er^{3+} concentrations, 800 nm (0.3 W) + 1410 nm (0.15 W) pump scheme.

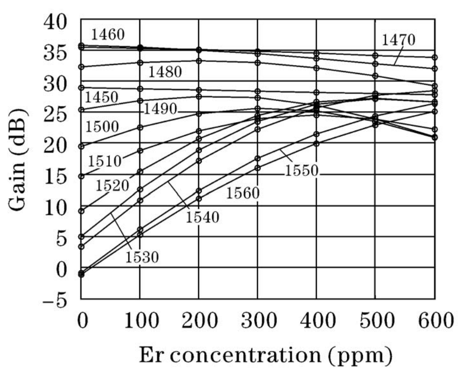

Fig. 3. Spectral gain versus Er^{3+} concentration.

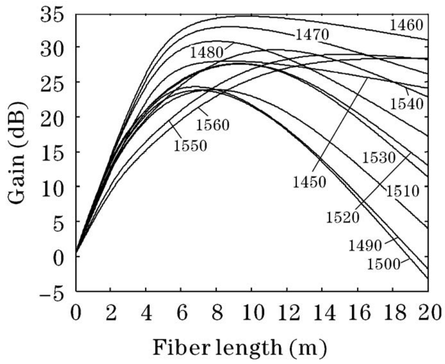

Fig. 4. Spectral gain versus fiber length.

In conclusion, we have developed a theoretical model for Er^{3+}-Tm^{3+} co-doped fiber. A set of nonlinear coupled ordinary differential equations (ODEs), which govern the dynamics of optical amplification in the Er^{3+}-Tm^{3+} co-doped material system, were established based on the rate equations and propagation equations taking into consideration of the energy transfer process between Er^{3+} and Tm^{3+}.

From simulation results, we predicted that gain as high as 20 dB can last from 1450 to 1560 nm by 800 nm (0.15 W) + 1410 nm (0.3 W) pump scheme in fluoride ZEBLAN fiber, the gain wavelength range is wider than the experimental result in Ref. [2] because of the low phonon energy and larger emission cross-section bandwidth in ZEBLAN host.

Er^{3+}-Tm^{3+} co-doped silica fiber[2], tellurite fiber[14] and fluoride glass[10] have been successfully fabricated recently, so it is possible to fabricate Er^{3+}-Tm^{3+} co-doped fluoride fiber in the future, and the splicer between silica fiber and fluoride fiber is now practical[15], in addition, 800 + 1410 nm pump scheme is available by laser diode, consequently this scheme could be feasible to have practical use in next-generation wavelength division multiplexing (WDM) networks.

This work was supported by the China Scholarship Council, the Natural Science Foundation of Shandong Province of China (No. Y2003G01, Y2002G06), and the Research Found for the Doctoral Program of High Education of China (No. 20020422048). J. Chang's e-mail adress is j.chang@unsw.edu.au or changjun@sdu.edu.cn.

References

1. G. A. Thomas, B. I. Shraiman, P. F. Glodis, and M. J. Stephen, Nature **404,** 262 (2000).
2. H. Jeong , K. Oh, S. R. Han, and T. F. Morse, Opt. Lett. **28,** 161 (2003).
3. S.-Y. Seoa, J. H. Shin, B.-S. Bae, N. Park, J. J. Penninkhof, and A. Polman, Appl. Phys. Lett. **82,** 3445 (2003).
4. Q. Jiang, X. Liu, Q. Wang, and Y. Wang, Chin. Opt. Lett. **1,** 451 (2003).
5. J. Li, Y. Guo, T. Wang, Y. Shun, B. Bai, X. Li, and G. Hu, Chin. Opt. Lett. **1,** 503 (2003).
6. P. Peterka, B. Faure, W. Blanc, M. Karasek, and B. Dussardier, Opt. and Quantum Electron. **36,** 201 (2004).
7. C. Floridia, M. T. Carvalho, S. R. Lüthi, and A. S. L. Gomes, Opt. Lett. **29,** 1983 (2004).
8. J. Chang, Q. Wang, X. Zhang, Z. Liu, and G. Peng, Opt. Express **13,** 3902 (2005).
9. M. J. F. Digonnet, *Rare Earth Doped Fiber Lasers and Amplifiers* (Marcel Dekker, New York, 2001).
10. C. Y. Chen, R. R. Petrin, D. C. Yeh, W. A. Sibley, and J. L. Adam, Opt. Lett. **14,** 432 (1989).
11. T. Kasamatsu, Y. Yano, and T. Ono, J. Lightwave Technol. **20,** 1826 (2002).
12. W. J. Miniscalco, J. Lightwave Technol. **9,** 234 (1991).
13. M. Naftaly, S. Shen, and A. Jha, Appl. Opt. **39,** 4979 (2000).
14. L. Huang, A. Jha, S. Shen, and X. Liu, Opt. Express **12,** 2429 (2004).
15. F. J. Mcaleavey, J. Ogorman, J. F. Donegan, J. Hegarty, G. Mazé, and H. Poignant, Opt. and Quantum Electron. **33,** 151 (2001).