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Gain characteristics of Tm-doped fiber amplifier by dual-wavelength pumping with a tunable L-band source

Setsuhisa Tanabe *, Takeshi Tamaoka

Graduate school of Human and Environmental Studies, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

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Abstract

Gain characteristics of Tm-doped fiber amplifier were investigated by pumping with 1.05 μm and tunable L-band lasers. Red-shift and improved gain were observed by the pumping wavelengths in the 1.54–1.65 μm range. The gain values in the 1.44–1.50 μm range were improved by optimized pumping wavelengths and the optimized wavelengths were varied with the signal wavelength.

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Keywords: Thulium; Fluoride fiber; Amplifier; Dual pumping scheme; Gain characteristics; S-band

1. Introduction

As the information traffic in wavelength-division-multiplexing (WDM) optical communication systems is increasing rapidly, it is necessary to extend the telecommunications wavelength range and to develop broadband amplifiers. Especially, the extension of the wavelength region toward the shorter side (S^+, S-band; 1450–1530 nm) of the conventional band (C-band; 1530–1560 nm) has been attracting much attention in recent years. While the Er^{3+}-doped fiber amplifiers (EDFA) are used for the C-band, one of the possible amplifiers for the S^+-band is the Tm^{3+}-doped fiber amplifier (TDFA), which provides a gain band of 1450–1480 nm, by using an upconversion pumping scheme [1]. The gain-shifted Tm-doped fiber amplifiers (GS-TDFA) are attracting a great interest, because they can utilize the wavelength region between the C-band and the S^+-band. The development of the S-band (1480–1520 nm) amplifiers is important, because few other amplifiers can operate in this unexplored region of the low-loss window and the loss is lower than in the S^+-band or the L-band (1560–1610 nm). GS-TDFA, operating in the S-band, have recently been demonstrated by two kinds of schemes. One is the dual-wavelength pumping scheme [2–5] and the other is a high Tm^{3+} concentration doping scheme [6]. Since the excellent proposal of a dual-wavelength pumping scheme by Kasamatsu et al. [2], great efforts have been made to optimize it, because of its superiority in power conversion efficiency (PCE) over the high doping scheme. The key principle of the former

* Corresponding author. Tel.: +81-75-753-6832; fax: +81-75-753-6634.
E-mail address: stanabe@gls.mbox.media.kyoto-u.ac.jp (S. Tanabe).

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scheme is the use of an auxiliary pumping laser at 1.56 or 1.2 μm to control the population inversion factor between the initial $^3H_4$ and the terminal $^3F_4$ level, in addition to the main pumping laser source at 1.05 or 1.4 μm, which is used for the excited state absorption (ESA) [2]. The comparison of the 1.05 μm pumping and 1.4 μm pumping was discussed in terms of PCE and the noise figure performances [7,8]. The spectral properties and upconversion characteristics of Tm^{3+}-doped glasses are well studied [9,10], also by using tunable lasers [11,12]. The spectroscopic tunability of rare earth doped glasses is based on the inhomogeneous broadening and variations of the Stark splitting of 4f-electronic levels. It is known that the absorption spectrum to the first-excited $^3F_4$ level shows a broadband at around 1.7 μm, which is longer than the wavelength of the auxiliary pump of the previous dual-wavelength-pumped GS-TDFA [2,7,8]. The absorption coefficient of the Tm^{3+}: $^3F_4 \leftarrow {}^3H_6$ transition in a fluoride glass increases rapidly from 1.55 to 1.65 μm [12]. This fact suggests much improved pumping efficiency by an L-band laser, which has a wavelength longer than 1.56 μm. In this study, the gain characteristics of a TDF were investigated with a 1051 nm laser and a tunable L-band source, to investigate the optimization of a dual-wavelength pumping scheme.

2. Experimental

The gain and noise figure measurement setup of a fluoride TDF (NEL, 2000 ppm, 20 m) is shown in Fig. 1. The signal input power was −30 dBm in the region of 1420–1500 nm. The pump light of a Yb-fiber laser (1051 nm) and a tunable L-band source (Santec, TSL-210, 1545–1645 nm) were both introduced from the forward side of the fiber and the output spectra of the TDF was monitored with an optical spectrum analyzer (Anritsu, MS9780A) to search the peak and ASE power levels, which were used for calculation of the gain and noise figure at each signal wavelength by the following equations:

$$G = (P_p - P_{ase})/P_{sig}, \quad (1)$$

$$NF = (1 + P_{ase}/h\nu\Delta\nu)/G \quad (2)$$

where P_p is the peak power, P_{ase} is the ASE power, $h\nu$ is the signal photon energy, and $\Delta\nu$ is the resolution of the optical spectrum analyzer at the measuring condition.

For the gain excitation spectra measurement, we conducted the step-scan of the L-band source under a constant signal wavelength of the S^+-band source. The energy level and pumping scheme of Tm^{3+} is shown in Fig. 2.

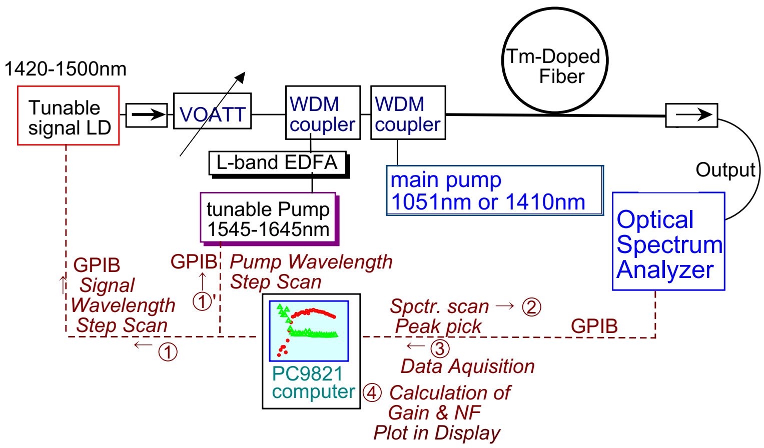

Fig. 1. Measurement setup of dual-pumped TDFA.

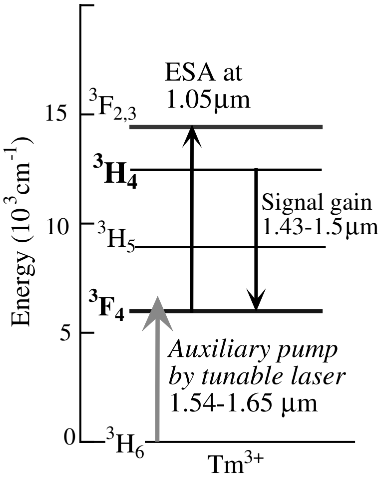

Fig. 2. Energy levels and upconversion pumping scheme of Tm^{3+} ion.

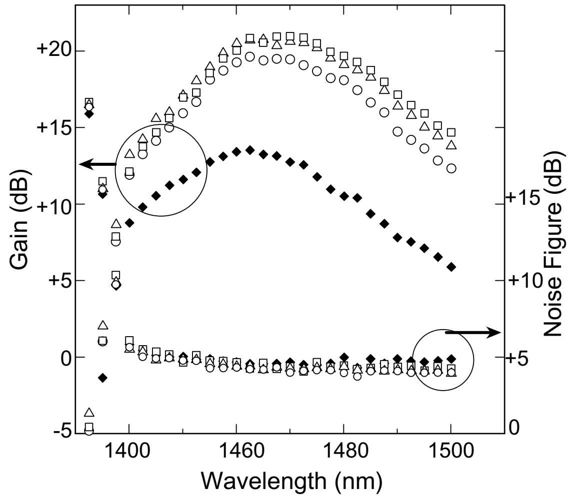

Fig. 3. Variation of gain spectra and noise figure of TDF with single and dual-wavelength pumping schemes. Auxiliary pump wavelength: (○) 1640 nm, (△) 1600 nm, (□) 1560 nm, (◆) no auxiliary pump (Yb-single). Auxiliary pump power: 5 mW. Yb-laser power: 150 mW. Signal input power: −30 dBm.

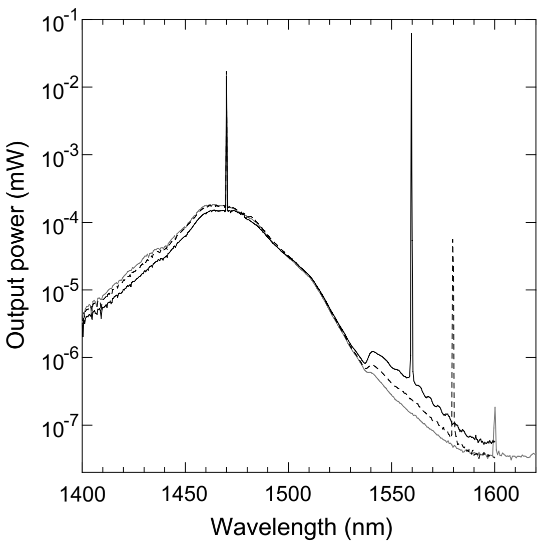

Fig. 4. Output power spectra of TDF by several dual-wavelength pumping schemes. Auxiliary pump wavelength: (—) 1560 nm, (– – –) 1580 nm, (- - -) 1600 nm. Auxiliary pump power: 5 dBm. Yb-laser power: 150 mW. Signal input power: −30 dBm. Signal wavelength: 1470 nm.

3. Results

Fig. 3 shows the gain and noise figure spectra of the TDF by 1051 nm single pumping (150 mW) and by the dual-wavelength pumping together with 5 mW light of 1560, 1600 or 1640 nm. All the latter three schemes achieve a gain-shift and gain improvement of 4–9 dB in the region of 1440–1500 nm. It is clear that the gain profiles of the three schemes are slightly different, i.e, the 1560 nm pumping shows the largest gain-shift and the 1640 nm pumping the smallest. The output power spectra of the dual-pumped TDF are shown in Fig. 4. The ASE spectra are also different with auxiliary pump wavelengths, λ_{AP}, although the power is constant (5 mW), by APC-mode in the L-band source. Also, the intensity of the transmitted auxiliary pump decreases with increasing λ_{AP} and no peak was observed in the region of $\lambda_{AP} > 1620$ nm.

4. Discussion

The degree of the gain-shift in the present study is smaller than the previous GS-TDFA [1,2], because the auxiliary pump power is much lower. However, we can clearly see the variation of the gain spectra with different λ_{AP} in Fig. 3, which should be correlated with the absorption efficiency of the pump light. In order to investigate the profile of the pumping efficiency, the output power of the L-band source was measured with and without the Yb-laser and the calculated loss spectra in the fiber are shown in Fig. 5. Both spectra show a drastic increase with increasing λ_{AP}, which reflects the absorption coefficient of the $^3F_4$-band [12]. The GSA efficiency increases with increasing λ_{AP}. The profiles were similar, irrespective of the 1051 nm pumping power. The excitation spectra of the loss at 1051 nm are also shown in Fig. 5, which shows different power dependence and an improved region at shorter λ_{AP}. These results indicate the presence of an optimum λ_{AP} for the ESA and GSA, as well as the nonlinear absorption response at the ESA wavelength.

The excitation spectra of the ESA loss are shown under a constant laser power at 1051 nm, for various auxiliary pump powers, P_{AP}, in Fig. 6. The ESA efficiency increases with increasing P_{AP}, owing to the increased population of the $^3F_4$ level. Although the GSA efficiency should increase with increasing λ_{AP}, the loss due to the ESA decreases. The gain excitation spectra of S-band signals are shown in Fig. 7. The profiles for all the signals show a broad and flat profile, which suggests the wide tolerance of λ_{AP} in the dual-pumping schemes.

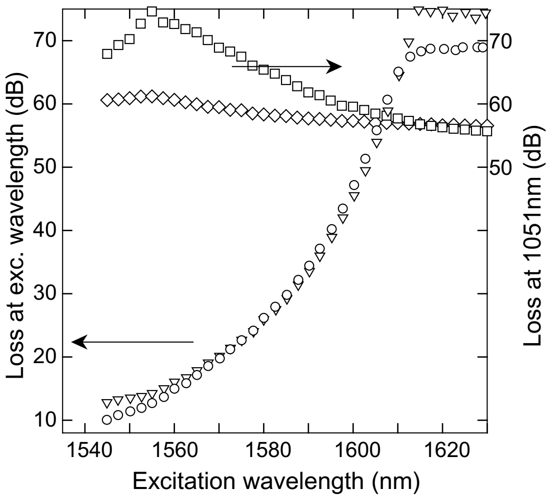

Fig. 5. Loss spectra of auxiliary excitation laser and loss excitation spectra at 1051 nm. Yb-laser power at 1051 nm: (□) 30 mW, (◇) 150 mW, (▽) 0 mW, (○) 150 mW. Auxiliary pump power: 5 mW.

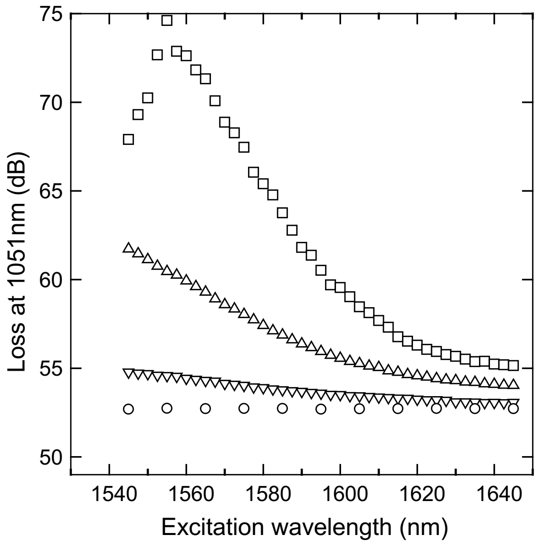

Fig. 6. Excitation wavelength dependence of loss of TDF at 1051 nm with various excitation power. Auxiliary pump power: (□) 5 mW, (△) 3 mW, (▽) 1 mW, (○) 10 μW. Yb-laser power: 30 mW.

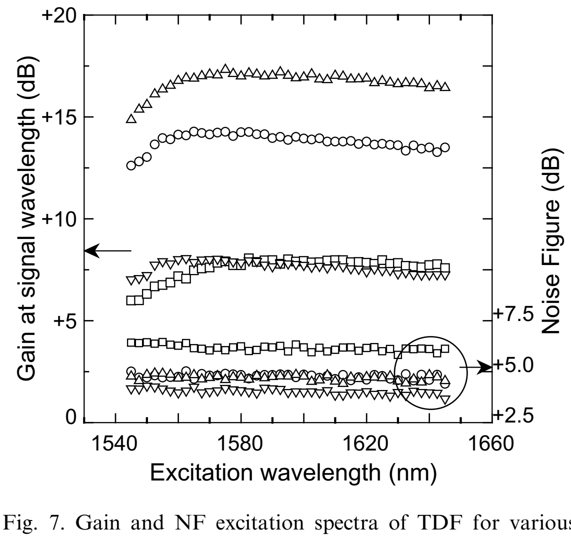

Fig. 7. Gain and NF excitation spectra of TDF for various signal wavelengths. Signal wavelength: (□) 1440 nm, (△) 1460 nm, (○) 1480 nm, (▽) 1500 nm. Auxiliary pump power: 5 mW. Signal input power: −30 dBm.

However, there exists an optimum region around 1.6 μm, for the 1.44 μm signal and around 1.57 μm, for the 1.46–1.50 μm signals. These differences can be attributed to the wavelength variations in the

GSA and ESA efficiencies and thus to the variation of population inversion in the Tm-level.

5. Conclusions

The gain profiles of a TDF showed different profiles with different pumping wavelengths. The GSA efficiency was higher for longer λ_{AP} and the ESA efficiency became higher for shorter λ_{AP} and for higher P_{AP}. The dual-wavelength pumping conditions affect the degree of population inversion and thus the gain spectra. Further research is under way, by using L-EDFA to obtain higher P_{AP} for further gain-shift.

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