Analysis on the Transient Response of 1.55-μm/1.4-μm Dual-Wavelength Pumped Thulium-Doped Fiber Amplifiers

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***Abstract*—The transient response of S- and S^+-band thulium-doped fiber amplifiers with 1.4-μm/1.5-μm dual-wavelength pumping scheme was investigated both experimentally and theoretically. In contrast to conventional Erbium-doped fiber amplifiers, two characteristic time-constants related with $^3F_4$ and $^3H_4$ level lifetime were observed, implying the need of much complex transient control algorithm for the future applications. The amount of surviving channel gain, gain excursion, and related time constants showed changes in their response characteristics, depending on the combinations of main pump, subsidiary pump, and signal powers. A simplified numerical approach for the analysis of transient response in Thulium-doped fiber amplifiers under average inversion framework, will be provided.**

***Index Terms*—Optical amplifiers, simulation, thulium, transient response.**

I. Introduction

WITH the recent explosion of data traffic demands, there have been many efforts to develop novel amplifiers with different gain band from conventional Erbium-doped fiber amplifiers (EDFA) for *C/L* band, to expand transmission capacity per a line of fiber. Among these approaches, Thulium-doped fiber amplifiers (TDFA) have a distinctive merit when compared with Raman or other rare earth-based hybrids, with their excellent positioning in the supporting band [1.46–1.51 μm: where the laser diode (LD) technology is mature] and high-power conversion efficiency inherited from their rare earth-based nature [1]–[5]. Out of several pumping schemes possible for the operation of TDFA, the recently proposed combination of the 1.4-μm main pump with the 1.5-μm subsidiary pump [1] has advantages over other approaches with the readily available high-power pump LDs operating in these wavelengths. Successfully enough, this lead to the latest demonstration of 11-Tb/s wavelength division multiplexed (WDM) transmission experiment possible, even without the inclusion of S^+ bands in the total gain bandwidths [6]. Still, with the shortest development history among the various types of optical amplifiers, there is lack of sufficient back-up data and understandings on the dynamics of TDFA to support highly intelligent WDM networks. This includes such fundamental characteristics as transient responses, which have to be well understood for modern optical amplifiers to support wavelength add–drops in optically switched networks. Proper characterization and compensation techniques for this transient property would ensure the safe and stable operation of the network.

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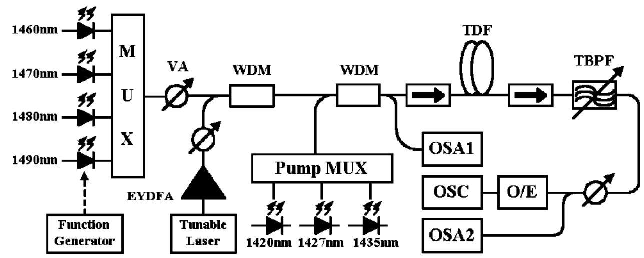
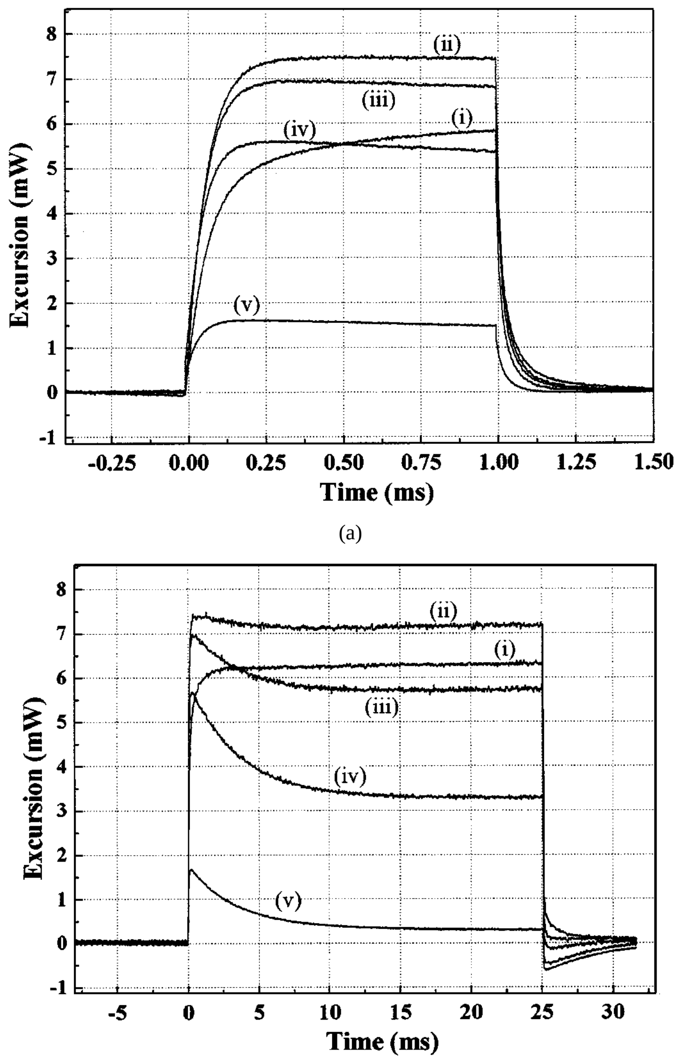


Fig. 1. Experimental setup (VA: variable attenuator, EYDFA: erbuim/ytterbuim co-doped fiber amplifier, TDF: thulium-doped fiber, TBPF: tunable bandpass filter, O/E: optical-to-electrical converter, OSC: oscilloscope, OSA: optical spectrum analyzer).

In this paper, within our knowledge, we report for the first time, the transient response of the TDFA, to provide an understanding path for the future development of transient control and gain clamping techniques. Different from the surviving channel responses of conventional EDFA, we observed two different time constants (~60 μs, and 8 ms) involved in the process, with close relationships to the characteristic lifetimes of first excited state and second excited state ($^3F_4$, and $^3H_4$), which appear with different weights depending on the TDFA operating conditions. This result implies the need for an even more complex algorithm for the control of the TDFA transient, when compared to that of an EDFA

II. Experiments and Analysis

Fig. 1 shows the experimental configuration for the analysis of the transient response, in a 1.4-μm/1.5-μm dual-wavelength pumped TDFA. To investigate the multichannel gain transient responses of TDFA, we used four LDs at the wavelength of 1460, 1470, 1480, and 1490 nm as signal sources. The input signal power at each wavelength was set at −6 dBm (total input power of 0 dBm), making the TDFA operate in a saturated regime. 20 m of Tm-doped Zr-based fluoride fiber was used in our experiment. The doping concentration and Δn of the TDF were 2000 ppm and 2.5%, respectively. Three high-power LDs stabilized with fiber bragg (FBG) at 1420, 1427, 1435 nm were used as the main pumping source at 1.4-μm band [1], providing the total combined power of 210 mW. As a subsidiary pump



(a)

(b)

Fig. 2. Measured 1490 nm surviving channel transient response with on/off modulation of 1480 nm LD at different frequency of (a) 500 Hz (b) 20 Hz. (1550 nm subsidiary pump/1490 nm signal channel power—(i) 37/14.9 mW, (ii) 26/15.2 mW, (iii) 21/14.1 mW, (iv) 17/13.4 mW, (v) 10.5/8.9 mW).

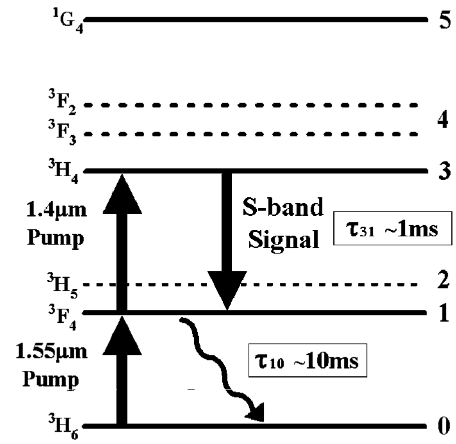


Fig. 3. Energy level diagram of thulium ion in Zr-based fluoride fiber.

source at 1.5-μm band [1], a tunable laser was used together with a high power Erbium/Ytterbium co-doped fiber amplifier (EYDFA) in combination with an optical attenuator. The EYDFA was pumped with a high-power Ytterbium fiber laser at 1060 nm. Two optical-spectrum analyzers in combination with a precision power meter were used, to exactly scale the input powers to the TDFA and to measure the output spectrum of the main pump, subsidiary pump, and signal, simultaneously.

While applying a on/off keying amplitude modulation to the 1480-nm LD with a function generator, a tunable band-pass filter was tuned to the surviving channel wavelength to monitor the transient responses with high-speed O/E converter and digital oscilloscope. Fig. 2(a) shows the measured transient response of an 1490-nm signal channel with on/off amplitude modulation of 1480 nm signal channel at frequency of 500 Hz, adjusting the 1550-nm subsidiary pump from 10.5 mW to 37 mW. Seemingly similar to the transient response curve of a conventional EDFA, the measured response curve at a 500-Hz modulation shows under a $\sim$100-μs response time at both rising and falling edges. This shorter time constant resulted from a shorter spontaneous life time of second excited state $^3H_4$ as illustrated in Fig. 3 (τ_{31} $\sim$ 1 ms: to compare, case of EDFA 10 ms). Still, when looked at in detail, the response curves at high subsidiary pump powers exhibited increasing trace behavior before the falling edges, while the curves taken from low subsidiary pump powers showed decreasing upper trails before the falling edges.

When investigated with lower modulation speed to the 1480-nm signal LD, it was observed that another time constant overlaid to the overshoot curve generated from $^3H_4$ level lifetime showed in Fig. 2(a). Fig. 2(b) shows the 1490-nm surviving channel transient response, with a 20-Hz modulation to the switching channel at 1480 nm. It is evident from this figure that there exists a relatively slow 4–10-ms transient time after the fast overshoot coming from the response of $^3H_4$ level. We attribute these phenomena to the infiltration of $^3F_4$ level spontaneous lifetime of $\sim$10 ms. When the subsidiary pump power is small, the 1.5-μm photons generate just enough photons to increase participating ions to the amplification process [1]. But, when the subsidiary pump power is larger than some critical value, the subsidiary photons at 1.5-μm start to affect the inversion state of the TDFA providing more ions than 1.4-μm main pump photons to excite the ions from $^3F_4$ level to $^3H_4$ levels. Roughly stated, in the low subsidiary pump regime, the TDFA operates in a locally full inversion state, while for the case of high-subsidiary pump regime TDFA is in operation at the incomplete inversion state (as most of the EDFA do). This leads to a similar response curve for the TDFA in the high-subsidiary pump regime, when compared with that of EDFA—for example, curve (i) at the 37 mW of subsidiary pump power does not show the overshoot profile, as a single EDFA does.

To confirm our experimental results and further investigate surviving channel power transients in a TDFA, a numerical analysis has been performed. Fig. 3 shows the atomic energy level diagram of Thulium ion with 1.4-μm/1.5-μm pump transition with S^+ band signal amplification transition. By applying the average inversion analysis method (used for the modeling of EDFA transient) to steady-state model of Zr-based TDFA [7]–[9], the rate equations governing the operation

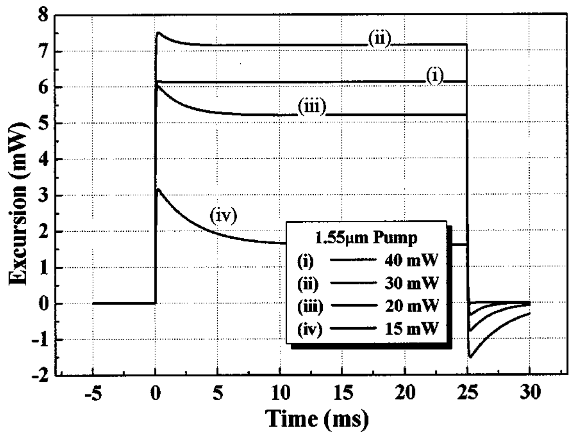


Fig. 4. Simulated 1490-nm surviving channel transient response with on/off modulation of 1480-nm LD at different frequency of 20 Hz.

of 1.4-μm/1.5-μm dual-wavelength pumped TDFA can be simplified as follows:

$$\begin{aligned}\frac{dN_0}{dt} &= -W_{01}\cdot N_0 + A_{10}\cdot N_1 + A_{30}\cdot N_3\\ \frac{dN_1}{dt} &= W_{01}\cdot N_0 - (A_{10}+W_{13})\\ &\quad \cdot N_1 + (A_{31}+W_{31})\cdot N_3\\ \frac{dN_3}{dt} &= W_{13}\cdot N_1 - (A_{30}+A_{31}+W_{31})\cdot N_3\end{aligned}$$

where N_i is the fractional population of level i, and A_{ij} is the spontaneous emission probability given in [8]. Here, W_{ij} is the absorption/emission transition rate given by

$$W_{ij} = \int_\lambda \frac{\Gamma(\lambda)\sigma_{ij}P(\lambda)}{h\upsilon A_{\text{eff}}(\lambda)}d\lambda$$

where Γ is the overlap factor, σ_{ij} is the cross-section, $P(\lambda)$ is the optical intensity at the wavelength of λ, and A_{eff} the effective interaction area. In this equation, the up-conversion and multiphoton decay related with levels 2, 4, and 5 have been ignored.

Fig. 4 shows the simulated TDFA transient responses with the proposed equation at various subsidiary pump powers, exhibiting a behavior similar to those in Fig. 2(b). With relatively small subsidiary pump power, the measured transient curve shows the large overshoot and ~10-ms relaxation time. In contrast, the overshoot disappears in the large subsidiary pump regime as in the case of common EDFAs.

III. Conclusion

For the first time, we characterized the transient responses of a TDFA, as a function of 1.55-μm subsidiary pump power in combination with 1.4-μm-band main pump. A simplified numerical method employing average inversion analysis for the analysis of transient behavior of TDFA was developed. Results show the existence of a signature from the lower state (i.e., first excited state 3F4) lifetime in the transient curve, making the response curve characteristics different from that of an EDFA. We have also found that the transient response of the TDFA depends on the relative strength between main/subsidiary pump power and signal power. Different time constants at ~60 μs and ~8 ms time has been characterized to explain these phenomena. Our results suggest that transient gain control algorithm different from that used for EDFA should be used in future applications of TDFA.

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