Study on the Gain Excursion and Tilt Compensation for 1.4- and 1.5-μm Dual Wavelength Pumped TDFA

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***Abstract*—In this letter, we analyze the gain excursion and tilt function of the thulium doped fiber amplifiers (TDFAs) for the 1.4- and 1.5-μm dual-wavelength pump approach. We also reveal that those two pump wavelengths act as independent control factors for gain level and tilt function, because each pumps influence the populations of the first and second excited states ($^3H_4$–$^3F_4$) in a different manner. Gain excursion and gain tilt control of the TDFAs under the channel add–drop situations are demonstrated, revealing a suitable approach and inner dynamics of the gain/tilt excursion and compensation mechanisms for TDFAs.**

***Index Terms*—Gain control, optical fiber communication, thulium-doped fiber amplifiers (TDFAs), wavelength-division multiplexing.**

I. Introduction

THE INCREASING demand for traffic expansion, originating from various needs and exploding contents supply sources, now became an inevitable and irresistible trend in modern society. Optical communication systems, which form the fundamental physical layer for this global network cannot be exempted from this megatrend. In this sense, thulium-doped fiber amplifiers (TDFAs) for S-band applications can be considered as one of the key vehicles, which will enable even larger transmission capacity in the near future. Even though there exist several different pumping approaches [1]–[8] for S–S^+ band of the TDFAs with its rather complex transition band structures, the underlying physics can be summarized relatively in a simple manner—overcome the short lifetime of the 1.5-μm signal ground state ($^3F_4$–$^3H_6$), to achieve a good inversion for the amplification process. Considering the recent achievements and intensive research efforts to find effective pumping configurations so far, there should also be followed equivalent efforts to reveal the inner dynamics for the intelligent system applications of TDFAs. Still, so far, there have not been serious investigations on system related dynamics for TDFAs, resulting from the lack of understanding and difficulties in constructing appropriate characterization setup.

In this letter, we investigate some of the key issues for TDFA application in wavelength-division-multiplexing (WDM) systems, such as gain tilt and gain excursion—which have been studied extensively for the case of erbium-doped fiber amplifiers (EDFAs) [9]—along with the compensation techniques for these impairments. In particular, we focus on the 1.4- and 1.5-μm (main and subsidiary) pump approach, and note its advantages over other pumping schematics in terms of the rather independent, straightforward control over signal transient levels ($^3H_4$ with 1.4 μm, and $^3F_4$ with 1.5-μm pump). Results show that the overall gain level depends primarily on the main pump power, while the amount of gain tilt depends strongly on the subsidiary pump power above some critical value. Proper approaches for gain tilt and level control will be discussed and experimentally demonstrated to achieve excellent level of multichannel gain control.

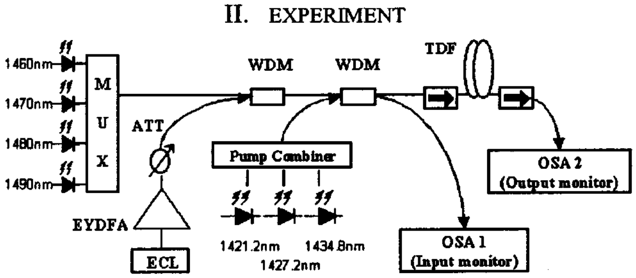

Fig. 1. Experimental setup. ATT: Attenuator. ECL: External cavity laser. OSA: Optical spectrum analyzer.

II. Experiment

The experimental setup is illustrated in Fig. 1. The 20 m of thulium-doped fluoride fiber (TDFF, Δn: 2.5%, 2000 ppm) was used as the gain medium, to amplify multiple signal waves provided by 1460-, 1470-, 1480-, and 1490-nm laser diodes. Combined with the main pumps [1421-, 1427-, and 1434-nm laser diodes (LDs)], a tunable laser followed by a high-power Erbium–Ytterbium-doped fiber amplifier has been also used as a tunable subsidiary pump source (1540–1570-nm band). Two sets of optical spectrum analyzers were used to monitor the input and output spectrum of the TDFA. Care was been taken to rescale the exact power level over a wide spectral range (1400–1600 nm), with the precision power meter and appropriate rescaling procedures.

To investigate, first the effects of main and subsidiary pump powers upon the multichannel gain profile, main pump, and subsidiary pump powers were changed while monitoring the signal gains at multiple waves (Fig. 2). Fig. 2(a) shows the output

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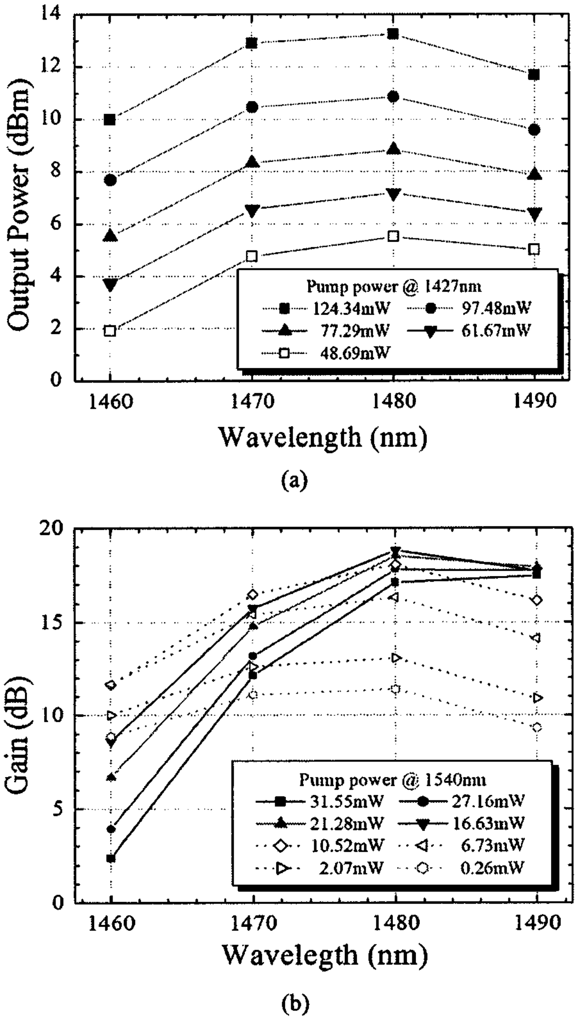


Fig. 2. (a) Multichannel output power changes as a function of main pump power (signal input power at −5.5 dBm/Ch, subsidiary pump power 5 mW). (b) TDFA multichannel gain as a function of subsidiary pump power (signal input power at −6 dBm/Ch, main pump 195 mW total).

power spectra as a function of main pump power change for 1427-nm main pump and 5 mW of 1550-nm subsidiary pump. The major role of the main pump power was found to be the gain level shifts. Data sets taken at other main pump wavelengths also exhibited a similar behavior, difference only on the gain tilt level and overall power conversion efficiencies. In contrast, the adjustments on subsidiary pump power mainly resulted in gain band shift (to longer wavelength) and severe gain tilt effects after some threshold values [Fig. 2(b): for example, 1540 nm, after ~15 mW].

For Fig. 2(b), when the subsidiary pump power was relatively small, the multichannel gain of TDFA showed quite a flat spectrum, increasing in the gain as the subsidiary pump power increase. While, as the 1540-nm pump power increases, the gain band shifted to longer wavelength and the amount of gain tilt was also increased with reduced gain for shorter wavelengths [3]. This gain shift behavior is due to the effect of gain enhancement from the increased numbers of the Tm^{3+} ions participating in the amplification process, plus the effect of decreased population inversion(after the threshold level) induced by over-populated (than main pump photons can handle) $^3F_4$ state.

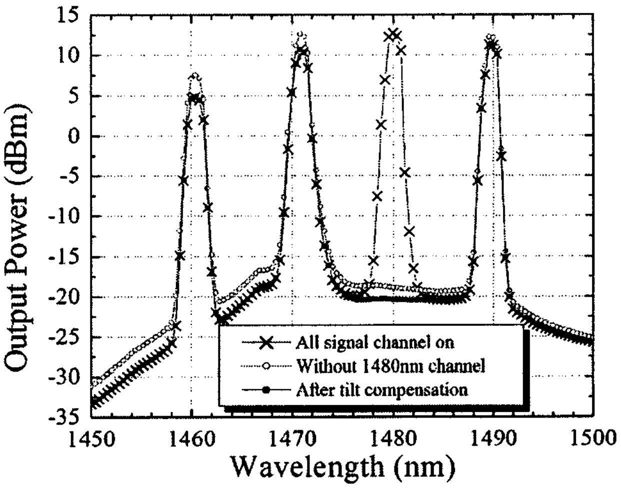


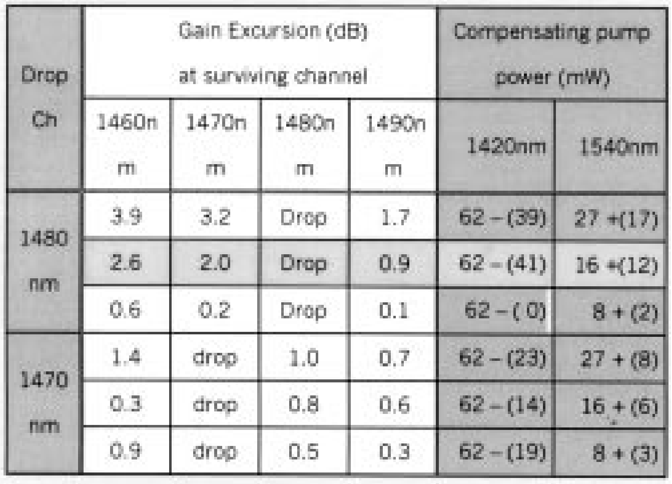
Fig. 3. The spectral responses of TDFA. Before and after the 1480-nm signal channel drop and its compensation (signal input power at −6 dBm/Ch).

In order to measure the gain excursion level and the amount of gain tilt, we dropped one of the WDM channels (1480 nm) and observed the output spectrum changes. Depending on the channel wavelength, 2–4 dB of gain excursion was observed with corresponding gain tilt behavior (Fig. 3).

To compensate for induced gain tilt resulting from channel dropping, we adjusted the main and subsidiary pump powers while monitoring the overall spectrum in the optical spectrum analyzer. As can be inferred from the previous data in Fig. 2, most of the power change has been made to the main pump (1420 nm, from 62 to 21 mW: no changes for 1427 nm, and 1434-nm pumps—fixed at 64 and 69 mW). The necessary power change in subsidiary pump wavelength was much smaller than that of the main pump (in absolute value: 1540 nm, from 16 to 28 mW), and mainly was used to make corrections on the tilt error function in the output spectrum. As an example, a maximum 3.9-dB signal gain excursion was controlled by approximately 20% changes of total pump power. After minor adjustments with the subsidiary pump, the total gain deviation was controlled under 0.1 dB over the whole spectral range. Complete overlap of the spectrum over the entire gain bandwidth is evident from Fig. 3 after the compensation. Reminding that it was impossible to restore gain profile with only a main pump or subsidiary pump, this behavior suggests the necessity of a gain tilt control for TDFAs, which different from that of EDFAs, where the gain tilt/excursion level is tightly related with the total pump power. Gain excursion values/compensation pump conditions for dropping different signal channels, at different pump conditions are summarized in Table I (the main pump power setting is identical to Fig. 3, but with different initial subsidiary pump power conditions). Different in absolute values, but the overall behavior was identical to that of Fig. 3, and the error functions were again negligible after the compensation.

This seemingly complex behavior can be understood in a simple manner by considering the effect of the subsidiary pump upon the TDFA dynamics. When the subsidiary pump power is small, the 1.5-μm photons generate just enough photons to increase participating ions in the amplification process [3]. But, when the subsidiary pump power gets larger above some critical

TABLE I
THE AMOUNT OF GAIN-EXCURSION AND COMPENSATION PUMP POWER FOR 1480 OR 1470 NM CHANNEL DROP (SIGNAL INPUT POWER AT -6 dBm/Ch, FROM MAIN PUMP POWER 195 mW TOTAL TO BEGIN WITH)



Drop Ch	Gain Excursion (dB) at surviving channel				Compensating pump power (mW)	
	1460nm	1470nm	1480nm	1490nm	1420nm	1540nm
1480 nm	3.9	3.2	Drop	1.7	62 – (39)	27 +(17)
	2.6	2.0	Drop	0.9	62 – (41)	16 +(12)
	0.6	0.2	Drop	0.1	62 – (0)	8 + (2)
1470 nm	1.4	drop	1.0	0.7	62 – (23)	27 + (8)
	0.3	drop	0.8	0.6	62 – (14)	16 + (6)
	0.9	drop	0.5	0.3	62 – (19)	8 + (3)

value, the subsidiary photons at 1.5 μm starts to affect the inversion state (and thus the gain tilt of the TDFA starts to occur), providing more than enough ions for the 1.4-μm main pump photons to excite from $^3F_4$ level to $^3H_4$ levels (in general, this regime also corresponds to the average inversion level of ~0.5 to 0.6, which provides gain over 1460–1510-nm bands). To state the issue clearly, after some critical value of subsidiary pump power, the power of the subsidiary pump directly controls the inversion, and thus the gain tilt function of the amplifier. This relationship also implies that the most effective controller for gain tilt in this regime goes to the subsidiary pump power. Considering the gain excursion/tilt control applications for other combinations of pump wavelengths, the addition of 1.5-μm subsidiary pump source will be beneficial for the independent predictable control of inversion state.

III. CONCLUSION

We have investigated and explained the gain excursion and tilt behavior of TDFA under 1.4- and 1.5-μm (main and subsidiary) pump scheme, and found that it is necessary to control both wavelengths to completely compensate the induced gain excursion from the channel add–drops. With coarse tuning of the main pump power for gain level control, together with subsidiary pump power control for gain tilt fine tuning, it was found possible to reduce the gain excursion within 0.1 dB over the entire multichannel gain bandwidth (1460 to 1490 nm), up to 4 dB of gain excursions. Even the current investigations have been limited by the experimental setup, we believe that this algorithm can be applied to wider gain excursion values, and can be used to develop a practical gain tilt control algorithm that differs from that of the EDFAs.

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