Thulium-doped Fiber Amplifier for Optical Communications at 2 µm

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Abstract: We report the realization of a thulium doped fiber amplifier designed for optical communications providing high gain (>35dB) and low noise figure (<6dB) over 1910nm-2020nm with a maximum saturated output power of more than 1W.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.2330) Fiber optics communications

1. Introduction

Over the past few decades, breakthroughs in low loss, single moded transmission fiber, erbium-doped fiber amplifiers (EDFA), wavelength division multiplexing (WDM), and (coherent) phase encoding, have shaped today's Internet infrastructure and successfully pushed the record transmission capacity within a factor of ~2 of the nonlinear Shannon limit for current fiber technology [1, 2]. However, as the ever increasing Internet traffic [3] is rapidly pushing systems towards the nonlinear Shannon limit, a "capacity crunch" is foreseeable unless radical approaches will be adopted [1]. Therefore, new physical layer technology for the communication network will soon be necessary in order to meet the fast growing Internet traffic demand. The research community has started looking for solutions already. For instance, multi-mode (MM) communication systems have recently aroused much interest [4, 5] and shown good data transmission performance [5]. Most of the research effort in enhancing the network capacity, nevertheless, has been devoted to 1.5 µm, which falls in the well-known transmission window of silica fiber and the amplification band of EDFA.

The vast emission band of thulium (Tm^{3+}) around 2 µm covers ~28THz (1750 nm - 2100 nm), almost a factor 2 more than that of erbium (Er^{3+}). Therefore, the enormous bandwidth resource of the TDFA is waiting to be exploited. Despite thulium-doped fiber sources having found many applications such as eye safe radar, remote sensing, photo-medicine, and mid-IR generation [6], they have received little attention from the optical communication community apart for its S-band emission properties. This is largely due to the lack of a suitable transmission medium, since the background loss of silica fiber is considerably higher at 2 µm. Recently, data transmission experiments have been conducted at 2 µm waveband over both conventional solid core fiber and hollow core photonic band-gap fiber (HC-PBGF) which is predicted to exhibit its minimum loss window in this waveband [7, 8], achieving 20 Gbit/s and 8 Gbit/s transmission rates, respectively. These preliminary results clearly indicate the potential of 2 µm fiber communication systems. In this paper, we report the detailed characterization of the TDFA used in these transmission experiments and examine its performance over the band ranging from 1910 nm – 2020 nm for telecom application. We demonstrate low noise, high gain operation of the TDFA over the entire band indicating that the TDFA is well placed as an amplification medium for 2 µm communication systems. To the best of our knowledge, this is the first time TDFAs have been studied in the context of 2 µm optical fiber communications.

2. Experimental setup

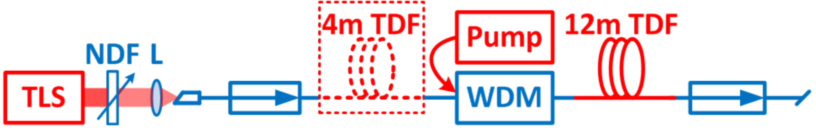
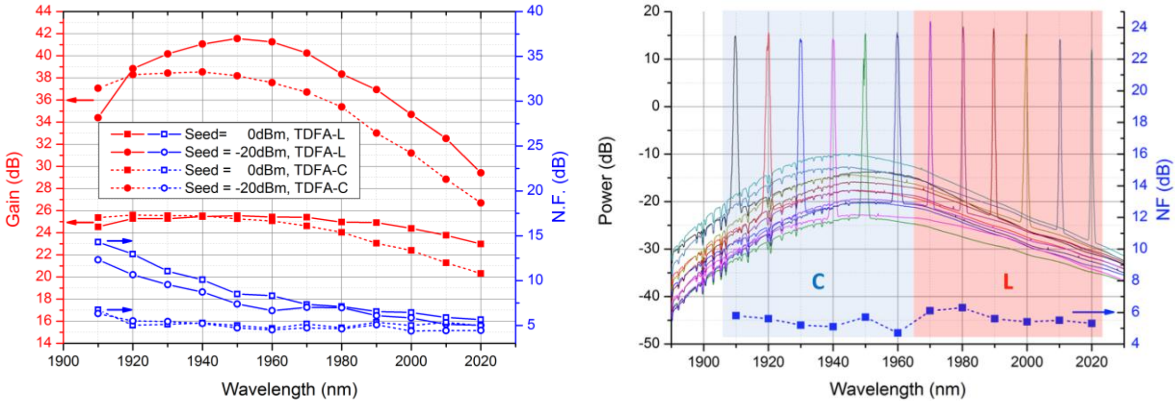


Fig.1 Schematic of the experimental setup. TLS: tunable laser source. NDF: neutral density filter. L: lens. WDM: wavelength division multiplexer. Improve display of pump, TDF, output

Fig. 1 illustrates the experimental setup. The TDFA was built with a commercially available Tm^{3+}-doped fiber (OFS TmDF200) having a mode field diameter of 5 µm at 1700 nm and a core absorption of 200 dB/m at 790 nm. Two TDFA configurations were developed, which were optimized to provide maximum gain at short and long wavelength bands, respectively. The first design (TDFA-C) used a 12 m long TDF forward pumped by a fiber Bragg grating (FBG) stabilized single mode Er^{3+}/Yb^{3+} co-doped fiber laser operating at 1565 nm. Pump and signal wavelength were combined using a 1570 / 2000 nm WDM and isolators at both input and output ends prevented instabilities and parasitic lasing. The second design (TDFA-L) included an additional 4 m TDF (dotted line in Fig.1) inserted between the input isolator and the WDM combiner. This additional piece of fiber was indirectly pumped by the amplified spontaneous emission (ASE) travelling backwards from the directly pumped 12m TDF and increases the signal gain at longer wavelengths. The TDFAs were seeded using an in-house built tunable laser source (TLS) [9]. The laser wavelength was tuned by an external cavity acousto-optic tunable filter (AOTF), providing narrow linewidth wavelength coverage from 1910 nm to 2020 nm. A tunable neutral density filter was used to adjust the input signal power. Light from the TLS was free space coupled into the TFDAs through a lens with 8 mm focal length and 0.5 NA.

3. Results and discussion



(a) (b)

Fig. 2 Performances of TDFA-C and TDFA-L at 31dBm pump power. (a) Noise figure and gain; the solid lines represent TDFA-L, whereas the dotted lines show TDFA-C performance. (b) Output spectra and noise figure when amplifiers were seeded by -10 dBm signal.

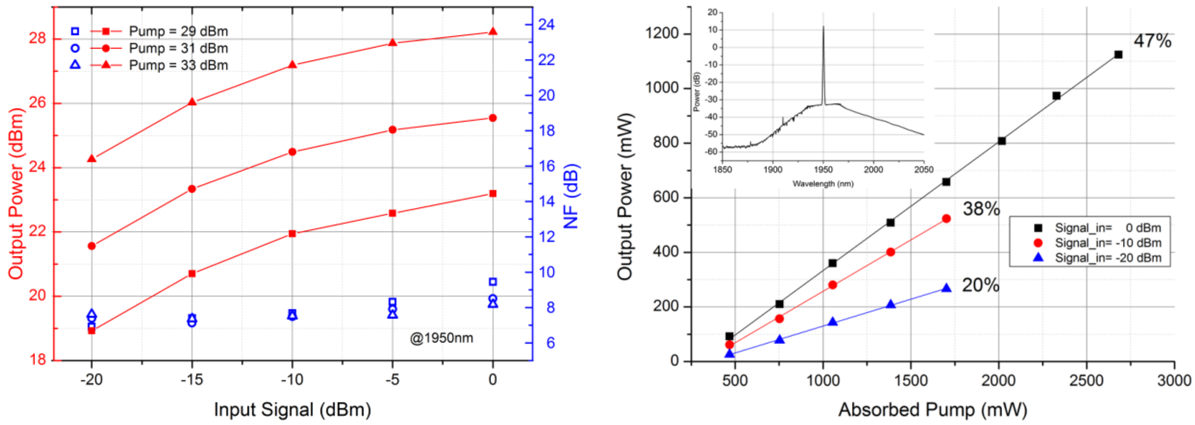
Fig. 2(a) compares the performances of TDFA-C and TDFA-L in terms of noise figure (NF) and gain at 31dBm pump power. The small signal gain and saturated gain characteristics for both amplifier configurations are displayed using input signal levels of -20 dBm.and 0 dBm, respectively. TDFA-C provides a maximum small signal gain of more than 38 dB at a peak wavelength of 1930 nm. Due to the additional section of gain fiber inserted into TDFA-L, the gain peak for this amplifier design shifts to 1950 nm, where it provides 41 dB small signal gain. Except for the short wavelength edge of the amplification bandwidth, TDFA-L exhibits a small signal gain enhancement that approaches 3 – 4 dB for wavelengths beyond 1950 nm. Additionally, TDFA-L effectively improves the flatness of the saturated gain curve and consistently provides 23 – 26 dB saturated gain over the entire amplification bandwidth. In contrast, the saturated gain of TDFA-C drops significantly for wavelengths above 1960 nm. In particular at the long wavelength side of the amplification band, this gain enhancement is achieved without paying any significant penalty in terms of NF. Both amplifier configurations exhibit a NF between 5 – 7 dB for wavelengths above 1980 nm. However, for shorter wavelengths the NF of TDFA-L increases considerably and reaches 12 – 14 dB at 1910 nm, while the TDFA-C configuration consistently exhibits 5 – 6 dB NF over the entire amplification bandwidth

The introduction of the additional indirectly pumped section of gain fiber in TDFA-L therefore has two distinct effects. Firstly, the amplifier gain is notably enhanced, particularly for longer wavelengths, and the saturated gain flatness is improved. This can be attributed to the reabsorption of backward travelling ASE from the directly pumped gain fiber, which enhances the amplifier efficiency, and the overall longer length of gain fiber, which shifts the gain peak towards longer wavelengths. Secondly, the NF increases for short wavelengths due to the increased initial absorption of the input signal in the indirectly pumped section before the amplification takes place in the directly pumped gain fiber.

The above discussion suggests that high gain, low noise amplification over the investigated 110 nm band can be achieved by combining TDFA-C and TDFA-L in a transmission system, where shorter wavelength signals up to 1960 nm will be amplified by TDFA-C, while TDFA-L provides amplification for the longer wavelengths. The resulting amplified spectra are shown in Fig. 2 (b). More than 35 dB gain, NF below 6 dB and more than 30 dB signal-to-noise ratio were achieved over the entire wavelength range tested.

Fig. 3 illustrates the power transfer characteristics of TDFA-L at 1950 nm. At 33 dBm pump power, the amplifier was able to produce 45 dB small signal gain and 27 dBm saturated output power (see Fig. 3(a)). Note that for all the pump and signal power levels listed in Fig. 3(a), the amplifier maintained relatively good noise figures of around 8 dB.

Fig. 3(b) shows the efficiency and power scaling capability of TDFA-L. Up to 47% efficiency with respect to the absorbed pump power was achieved, which enables the amplifier to provide a total output power of 1.1 W for a 1 mW input signal at 2.9 W absorbed pump power. This demonstrates the power scaling capability of the TDFAs, which will contribute towards the development of high power laser systems covering the Thulium amplification band.



(a) (b)

Fig. 3 TDFA-L performance at 1950 nm. (a) Power transfer characteristics. (b) Slope efficiencies at different input signal levels. The inset shows the spectrum at the highest output power.

4. Conclusion

We have demonstrated and extensively tested the performance of TDFAs for application as high performance amplifiers in future telecommunication networks operating around 2 μm wavelength. The TDFAs are analogous in implementation and function to the current EDFA, but capable of operating over a far more extended bandwidth in this new waveband of interest. By choosing two different designs optimized for short and long wavelength operation, respectively, we were able to demonstrate small signal gains of more than 35 dB and NF lower than 6 dB over 110 nm bandwidth. The peak gain was measured to be 45 dB at 1950 nm and -20 dBm input signal level. We have also demonstrated the ability of the TDFAs to operate at high powers and achieved 1.1 W output power with 47 % slope efficiency.

The authors would like to acknowledge B. Pálsdóttir and L. Grüner-Nielsen from OFS Denmark for providing the thulium doped fiber. This work was supported by the EU 7th Framework Program under grant agreement 258033 (MODE-GAP) and by the UK EPSRC through grants EP/I01196X/1 (HYPERHIGHWAY).

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