Thulium-doped fiber amplifier for optical communications at 2 μm

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Abstract: We report the first experimental realization and detailed characterization of thulium doped fiber amplifiers (TDFAs) specifically designed for optical communications providing high gain (>35 dB), noise figure as low as 5 dB, and over 100 nm wide bandwidth around 2 μ m. A maximum saturated output power of 1.2 W was achieved with a slope efficiency of 50%. The gain dynamics of the amplifier were also examined. Our results show that TDFAs are well qualified as high performance amplifiers for possible future telecommunication networks operating around 2 μ m.

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References and links

- 1. P. Winzer, "Beyond 100G Ethernet," IEEE Commun. Mag. 48(7), 26–30 (2010).
- A. D. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear Shannon limit," J. Lightwave Technol. 28(4), 423–433 (2010).
- 3. D. J. Richardson, "Applied physics. Filling the light pipe," Science 330(6002), 327–328 (2010).
- 4. T. Morioka, Y. Awaji, R. Ryf, P. Winzer, D. Richardson, and F. Poletti, "Enhancing optical communications with brand new fibers," IEEE Commun. Mag. **50**(2), s31–s42 (2012).
- S. Randel, R. Ryf, A. Sierra, P. J. Winzer, A. H. Gnauck, C. A. Bolle, R.-J. Essiambre, D. W. Peckham, A. McCurdy, and R. Lingle, Jr., "6×56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6×6 MIMO equalization," Opt. Express 19(17), 16697–16707 (2011).
- V. Sleiffer, Y. Jung, V. Veljanovski, R. van Uden, M. Kuschnerov, Q. Kang, L. Grüner-Nielsen, Y. Sun, D. Richardson, S.-u. Alam, F. Poletti, J. Sahu, A. Dhar, H. Chen, B. Inan, T. Koonen, B. Corbett, R. Winfield, A. Ellis, and H. De Waardt, "73.7 Tb/s (96X3x256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA," in *ECOC* (2012), paper Th.3.C.4.
- D. C. Hanna, R. M. Percival, R. G. Smart, and A. C. Tropper, "Efficient and tunable operation of a Tm-doped fibre laser," Opt. Commun. 75(3-4), 283–286 (1990).
- S. D. Jackson and T. A. King, "Theoretical modeling of Tm-doped silica fiber lasers," J. Lightwave Technol. 17(5), 948–956 (1999).
- D. Y. Shen, J. K. Sahu, and W. A. Clarkson, "High-power widely tunable Tm: fibre lasers pumped by an Er, Yb co-doped fibre laser at 1.6 mum," Opt. Express 14(13), 6084–6090 (2006).
- S. D. Jackson, "The spectroscopic and energy transfer characteristics of the rare earth ions used for silicate glass fibre lasers operating in the shortwave infrared," Laser Photonics Rev. 3(5), 466–482 (2009).
- A. Bellemare, M. Karasek, C. Riviere, F. Babin, G. He, V. Roy, and G. W. Schinn, "A broadly tunable erbiumdoped fiber ring laser: experimentation and modeling," IEEE J. Sel. Top. Quantum Electron. 7(1), 22–29 (2001).
- C.-H. Yeh, C.-C. Lee, and S. Chi, "120-nm bandwidth erbium-doped fiber amplifier in parallel configuration," IEEE Photon. Technol. Lett. 16(7), 1637–1639 (2004).
- S. D. Jackson and T. A. King, "High-power diode-cladding-pumped Tm-doped silica fiber laser," Opt. Lett. 23(18), 1462–1464 (1998).
- S. D. Jackson, A. Sabella, and D. G. Lancaster, "Application and development of high-power and highly efficient silica-based fiber lasers operating at 2 μm," IEEE J. Quantum Electron. 13(3), 567–572 (2007).
- E. R. Taylor, L. N. Ng, N. P. Sessions, and H. Buerger, "Spectroscopy of Tm3+-doped tellurite glasses for 1470 nm fiber amplifier," J. Appl. Phys. 92(1), 112–117 (2002).
- P. Peterka, B. Faure, W. Blanc, M. Karasek, and B. Dussardier, "Theoretical modelling of S-band thulium-doped silica fibre amplifiers," Opt. Quantum Electron. 36(1-3), 201–212 (2004).
- F. Poletti, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. Numkam Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavík, and D. J. Richardson, "Towards high-capacity fibre-optic communications at the speed of light in vacuum," Nat. Photonics 7(4), 279–284 (2013).

- 18. M. N. Petrovich, F. Poletti, J. P. Wooler, A. M. Heidt, N. K. Baddela, Z. Li, D. R. Gray, R. Slavík, F. Parmigiani, N. V. Wheeler, J. R. Hayes, E. Numkam, L. Grüner-Nielsen, B. Pálsdóttir, R. Phelan, B. Kelly, M. Becker, N. MacSuibhne, J. Zhao, F. C. Garcia Gunning, A. D. Ellis, P. Petropoulos, S. U. Alam, and D. J. Richardson, "First demonstration of 2µm data transmission in a low-loss hollow core photonic bandgap fiber," in *ECOC* (2012), paper Th.3.A.5.
- E. N. Fokoua, F. Poletti, and D. J. Richardson, "Analysis of light scattering from surface roughness in hollowcore photonic bandgap fibers," Opt. Express 20(19), 20980–20991 (2012).
- P. Roberts, F. Couny, H. Sabert, B. Mangan, D. Williams, L. Farr, M. Mason, A. Tomlinson, T. Birks, J. Knight, and P. St J Russell, "Ultimate low loss of hollow-core photonic crystal fibres," Opt. Express 13(1), 236–244 (2005).
- J. K. Lyngsø, B. J. Mangan, C. Jakobsen, and P. J. Roberts, "7-cell core hollow-core photonic crystal fibers with low loss in the spectral region around 2 microm," Opt. Express 17(26), 23468–23473 (2009).
- N. MacSuibhne, Z. Li, B. Baeuerle, J. Zhao, J. P. Wooler, S. U. Alam, F. Poletti, M. N. Petrovich, A. M. Heidt, I. P. Giles, D. J. Giles, B. Pálsdóttir, L. Grüner-Nielsen, R. Phelan, J. O'Carrol, B. Kelly, D. Murphy, A. D. Ellis, D. J. Richardson, and F. C. G. Gunning, "Wavelength division multiplexing at 2μm," in *ECOC* (2012), paper Th.3.A.3.
- 23. S. R. Nagel, "Fiber materials and fabrication methods," in *Optical Fiber Telecommunications II*, S. E. Miller, and I. P. Kaminow, eds. (Academic Press Inc, 1988).
- P. L. Higby, I. D. Aggarwal, and E. J. Friebele, "Low loss glass and optical fibers therefrom," U.S. Patent 5305414 (1994).
- 25. W. Heitmann and K.-F. Klein, "Glass for optical waveguides or the like," U.S. Patent 6490399 B1 (2002).
- J. H. Lee, U.-C. Ryu, S. J. Ahn, and N. Park, "Enhancement of power conversion efficiency for an L-band EDFA with a secondary pumping effect in the unpumped EDF section," IEEE Photon. Technol. Lett. 11(1), 42– 44 (1999).
- 27. J. M. O. Daniel, M. Tokurakawa, and W. A. Clarkson, "Power-scalable wavelength-agile fibre laser source at two-microns," in 5th EPS-QEOD Europhoton Conference (2012).
- S. D. Agger and J. H. Povlsen, "Emission and absorption cross section of thulium doped silica fibers," Opt. Express 14(1), 50–57 (2006).
- C. R. Giles, E. Desurvire, and J. R. Simpson, "Transient gain and cross talk in erbium-doped fiber amplifiers," Opt. Lett. 14(16), 880–882 (1989).
- E. Desurvire, "Analysis of transient gain saturation and recovery in erbium-doped fiber amplifiers," IEEE Photon. Technol. Lett. 1(8), 196–199 (1989).

1. Introduction

Over the past few decades, breakthroughs in low loss, single mode transmission fiber, erbium-doped fiber amplifiers (EDFAs), wavelength division multiplexing (WDM), and more recently digitally coherent transmission, have shaped today's internet infrastructure and successfully pushed the record transmission capacity within a factor of 2 of the nonlinear Shannon limit [1–3]. However, as a result of the exponentially increasing volume of internet traffic, today's telecom networks are rapidly being driven towards their capacity limits, sparkling concerns over a potential future "capacity crunch" [3]. Therefore, new physical layer technology for communication networks will soon be necessary. In the search for solutions, the research community is investigating various radical approaches [4]. For instance, multi-mode (MM) communication systems with mode division multiplexing have recently attracted much interest and shown impressive data transmission performance [5, 6]. Most of the research effort directed towards enhancing network capacity, nevertheless, has been devoted to the 1.55 μ m optical waveband, which falls in the well-known low-loss transmission window of silica fiber and the amplification band of the EDFA.

The thulium (Tm³⁺) doped fiber amplifier (TDFA) offers a route to significantly enhanced amplification bandwidths. The remarkably broad emission spectrum of the ${}^{3}F_{4} - {}^{3}H_{6}$ transition in Tm-doped silica covers about 30 THz (~1700 to ~2100 nm [7–10]), which is a particularly attractive feature compared to the ~15 THz (~1480 to ~1610 nm [11, 12]) offered by the ${}^{4}I_{13/2} - {}^{4}I_{15/2}$ transition in erbium (Er³⁺) doped silica. Therefore, the enormous potential bandwidth resource of the TDFA is there to be exploited. Despite the fact that Tm-doped fiber sources have found many applications such as spectroscopy, remote sensing, photo-medicine, material processing, and mid-IR generation in the context of high power lasers [13, 14], they have received little attention from the optical communication community other than for its S-band emission properties [15, 16]. This is largely due to the lack of a suitable transmission

medium, since the background loss of silica fiber is considerable at $2 \mu m$. However, for local area networks, where fiber loss is not a crucial issue, conventional fiber can be used to carry the signals across a significant fraction of the TDFA bandwidth. As for long haul transmission, radically new fiber types will be necessary.

Encouraging developments have recently been reported in the design and fabrication of hollow core photonic band-gap fibers (HC-PBGFs) [17, 18], in which surface scattering at the air-glass interfaces rather than material absorption determines the lowest achievable loss [19]. HC-PBGFs are predicted to exhibit their minimum loss window in the waveband around 2 μ m [20, 21], and provide realistic prospects for achieving similar loss levels to conventional fibers at 1.5 µm while maintaining a large transmission bandwidth of more than 100 nm [17, 18]. Moreover, HC-PBGFs possess the advantages of a very low nonlinearity and low latency compared with conventional fibers [17]. Recently, data transmission experiments have been conducted at 2 um over both conventional solid core fiber and HC-PBGF, achieving 20 Gbit/s [22] and 8 Gbit/s [18] transmission rates, respectively. These preliminary results clearly indicate the potential of 2µm fiber communication systems. It is also worth commenting that other material systems exist with potential for low loss at wavelengths around 2 μ m [23–25] providing yet further motivation to consider the telecommunications potential of the TDFA. In this paper, we report the detailed characterization of TDFAs developed for these first transmission experiments and examine their performance over the band ranging from 1910 -2020 nm for telecom applications. We demonstrate low noise, high gain operation of the TDFA over this entire band indicating that the TDFA is well placed as an amplification medium for 2 µm communication systems. We also discuss the small signal performance in the saturation regime as well as the gain dynamics in the event of the add/drop of WDM channels. To the best of our knowledge, this is the first time that TDFAs have been studied in the context of 2 um optical fiber communications.

2. Experimental setup



Fig. 1. Experimental setup. TLS: tunable laser source. NDF: neutral density filter. L: lens. TDF: Tm^{3+} -doped fiber. WDM: wavelength division multiplexer.

Figure 1 illustrates the experimental setup of the core pumped Tm-doped fiber amplifier. The TDFA was built with a commercially available Tm³⁺-doped fiber (OFS TmDF200) having a mode field diameter of $\sim 6.2 \,\mu\text{m}$ at 2000 nm and a core absorption of $\sim 20 \,\text{dB/m}$ at 1565 nm. Two TDFA configurations were developed to provide maximum gain at short and long wavelength bands, respectively. The first design, entitled TDFA-C, consisted of a 12 m long TDF, which was forward pumped by an in-house built fiber Bragg grating (FBG) stabilized single mode Er³⁺/Yb³⁺ co-doped fiber laser operating at 1565 nm. Pump and signal wavelengths were combined using a 1570 / 2000 nm WDM coupler. Isolators were placed both at the input and output ends to prevent parasitic lasing. The second design, named as TDFA-L, included an additional 4 m TDF (dotted line in Fig. 1) inserted between the input isolator and the WDM coupler. This additional piece of fiber was indirectly pumped by the backward-travelling amplified spontaneous emission (ASE) generated from the directly pumped 12m TDF section and provided additional signal gain at longer wavelengths. This pumping scheme is similar to what has been used in L-band EDFA designs [26]. The TDFAs were seeded using an in-house built tunable laser source (TLS) [27]. 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. The free space laser beam from the TLS was coupled to the input end of the TFDAs through an 8 mm focal length lens.

3. Results and discussion

3.1 Noise figure, gain, tunability, and efficiency characteristics



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

Figure 2(a) compares the (external) noise figure (NF) and gain performances of TDFA-C and TDFA-L respectively at a pump power of 31 dBm. Small (-20 dBm) and saturated (0 dBm) signal gain characteristics for both amplifier configurations are presented. TDFA-C provided a maximum small signal gain of \geq 38 dB at a peak wavelength of 1930 nm. Whereas the maximum small signal gain of TDFA-L was measured to be 41 dB, ~3 dB higher than TDFA-C due to the added length of gain fiber incorporated in between the input isolator and the WDM coupler, however the gain peak was red-shifted to 1950 nm in this instance. Except for the short wavelength edge of the amplification band, TDFA-L in fact exhibited a small signal gain enhancement approaching ~3-4 dB for wavelengths beyond 1950 nm. Additionally, TDFA-L effectively improved the flatness of the saturated gain curve and consistently provided 23-26 dB saturated gain over the entire amplification bandwidth. In contrast, the saturated gain of TDFA-C dropped significantly for wavelengths above 1960 nm. Note that the gain enhancement offered by TDFA-L on the long wavelength side of the amplification band was achieved without paying any significant penalty in terms of NF. Both amplifier configurations exhibited NFs between 5 and 7 dB for wavelengths above 1980 nm. However, moving towards the shorter wavelength side, the NF of TDFA-L increased considerably and reached a value of 12-14 dB at 1910 nm, while TDFA-C consistently exhibited 5-6 dB NF over the entire amplification band. Note that even higher gain was available at higher pump power (e.g. 45 dB small signal gain was recorded for TDFA-L at 1950 nm for 32 dBm of pump power), but the system became sensitive to parasitic lasing especially when operating at the edge of the gain band where isolator performance was compromised.

The introduction of the additional indirectly pumped section of gain fiber in TDFA-L therefore had two distinct effects. Firstly, the amplifier gain was notably enhanced, particularly for longer wavelengths, and the saturated gain flatness was improved. This can be attributed to the reabsorption of the otherwise lost backward travelling ASE, which enhanced the amplifier efficiency, and the overall longer length of gain fiber, which shifted the gain peak towards longer wavelengths. Secondly, the NF increased 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 full 110 nm band investigated at 2μ m can be achieved by combining TDFA-C and TDFA-L in a transmission system, where shorter wavelength signals up to 1960 nm are 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 30 dB small signal gain, NF below 6.3

dB and more than 30 dB optical signal-to-noise ratio (OSNR) were achieved over the entire wavelength range investigated in this work. Note that the amplifier performance could not be investigated below 1910 nm due to the limited tunability of the TLS. Neither the gain curve nor the noise figure in Fig. 2(a) showed any tendency of rapid degradation, which leads us to expect that the true operating window of the TDFAs will ultimately prove to be much broader than that physically demonstrated here: particularly with further customization of the amplifier design and the availability of the sorts of filtering and gain flattening components now routinely available for erbium based systems.



Fig. 3. Gain and NF of TDFA-L at 2000 nm at different (a) pump and (b) input signal power levels.

Seeding at 2000 nm was chosen as an example to demonstrate the performance of TDFA-L in terms of gain and NF at different pump and input signal levels. Figure 3 shows that >35dB small signal gain was achieved for 33 dBm pump power. As expected, the gain increases for increasing pump power (see Fig. 3(a)) or decreasing input signal power (see Fig. 3(b)). The NF did not exhibit a strong dependence on pump or input signal power, and remained around 6 dB.



Fig. 4. Efficiency and spectrum of TDFA-L at 1950 nm.

Figure 2(a) illustrates that both the highest small signal gain and the maximum saturated gain were achieved by TDFA-L at 1950 nm. Therefore, we chose this wavelength to test the power scaling capability of the TDFA. Figure 4(a) shows the output power with respect to absorbed pump power for different input signals. Up to 1.2 W of saturated output power was obtained for 1 mW input signal at 2.7 W of pump power, corresponding to a power conversion efficiency of 44% and slope efficiency of 50%. An optical signal-to-noise ratio (OSNR) of more than 40 dB was obtained, as shown in Fig. 4(b).

Note that each of the isolators used in the setup had an insertion loss of ~ 1 dB at 2 μ m, whereas the WDM had an insertion loss of ~ 0.5 dB at 2 μ m. The amplifier noise figure, gain,

and efficiency are therefore limited by the relatively high insertion losses of the first generation of passive optical components at $2 \,\mu m$.



3.2 Small signal performance in the saturation regime

Fig. 5. Small signal performance in the saturation regime. (a) Influence of the saturating channel on the gain and noise figure of the probe channel. (b) Spectra of 1970 nm probe channel with 2008 nm channel on/off.

Next, we examined the behavior of TDFA-L in the presence of two wavelength channels. The small signal gain and NF in the saturation regime were tested by injecting one saturating wavelength channel with high input power and probing with a small tunable signal channel across the gain bandwidth. The saturating signal was provided by a laser diode at 2008 nm, which was coupled into the amplifier through a fiber tap coupler together with the small signal from the TLS. The input powers of the saturating 2008 nm channel and the probe channel were kept at 0 dBm and -20 dBm, respectively. The pump power was 31 dBm.

Figure 5 shows the influence of the saturating channel on the gain and NF performance as well as the spectra of the probe channel. In the presence of the saturating channel, the gain of the probe channel dropped by about 10 dB in the intended operating window of TDFA-L between 1970 – 2020 nm, and up to 20 dB at the short wavelength edge of the gain bandwidth (see Fig. 5(a)). However, the gain curve roughly preserved its shape, especially in the \geq 1970 nm region. Note that the presence of the saturating channel did not affect the NF significantly. Figure 5(b) compares the spectra of the probe channel located at 1970 nm when the saturating channel was turned on and off. Clearly the power of the probe channel decreased by ~10 dB when the 2008 nm channel was switched on, but the optical signal-to-noise ratio (OSNR) at the probe wavelength remained almost unchanged.

3.3 Gain dynamics

Here we investigate the gain dynamics of the TDFA in the presence of two wavelength channels in order to examine both power excursions due to cross gain modulation and transient settling times.

TDFA-L was seeded with two input channels combined by a 10 dB fiber tap coupler. A directly modulated discrete mode laser diode at 2008 nm, which we refer to as Ch1, was used to generate square wave with 50% duty cycle to simulate the impact of adding/dropping one (or multiple) channels. A pulse generator (8131A, HP) was used to modulate the laser diode at different frequencies and various power levels. The other channel (Ch2), which we refer to as the surviving channel, was another discrete mode laser diode at 2000 nm with a constant power of -15 dBm. Two fiber Bragg grating (FBG) based filters with 2 nm bandwidths were used to separate the individual channels at the output of the amplifier. The temporal response of each channel was recorded using 10 GHz InGaAs PIN detectors (ET-5010-F, EOT) and a digital oscilloscope (TDS5032B, Tektronix). The results are summarized in Fig. 6.



Fig. 6. Gain dynamics of TDFA-L. (a) Normalized input and output signal in the event of signal channel power modulation. Top: modulation channel input; Middle: modulation channel output; Bottom: surviving channel output. (b) Power excursion at different modulation frequencies. (c) Power excursion with respect to pump power (red) and modulation channel power (blue) at 10 Hz modulation frequency. (d) Rise time with respect to pump power (red) and modulated channel power (blue) at 10 Hz modulation frequency.

Figure 6(a) shows the normalized transient response of the channels. Ch1 input was modulated at 10 Hz with an 'on' level of -4 dBm (equivalent in power terms to ~ 12 data streams each of -15 dBm power) and an 'off' level of null. Ch2 input was kept at -15 dBm. The pump power used was 27.5 dBm. When Ch1 was switched on, Ch2 experienced gain competition due to the depletion of population inversion by Ch1. The output power of Ch2 therefore dropped and was subsequently restored to the original level when Ch1 was switched off. In the following paragraphs the characteristic parameters of this transient response, power excursion and rise time, are discussed.

Figure 6(b) shows the power excursion, defined as the ratio of the highest power to the lowest power of the surviving channel, as a function of modulation frequency. All other parameters were the same as in Fig. 6(a). For modulation frequencies lower than 1 kHz, the power excursion remained approximately constant at around 4 dB. For higher frequencies, the power excursion dropped to 1 dB at 100 kHz, because the surviving channel (Ch2) cannot follow the fast modulation of Ch1 and only a steady-state gain compression appears due to the slow response of the fiber amplifier's population inversion, which has an excited state lifetime (radiative) of \sim 4 ms [28]. Higher power excursion suggests a bigger influence of cross gain modulation effects on the surviving channel.

To simulate the effect of adding/dropping multiple data streams, the power of Ch1 was varied from -15 dBm (1 data stream) to -4 dBm (~representative of 12 data streams) with

-15 dBm power in Ch2 and 27.5 dBm of pump power. The modulation frequency of Ch1 was set at 10 Hz. The results are shown in Fig. 6(c) (blue curve). As more data streams were added/dropped, the power excursion increased accordingly. The power excursion for the addition of one data stream was ~0.5 dB, compared with ~3 dB when 8 data streams (-6 dBm Ch1 power) were added/dropped. More data streams therefore introduce larger cross gain modulation effects because the system operates in the large signal (saturated) regime and are in line with the observation made in Fig. 5(b).

We also studied the dependence of the power excursion on pump power, which varied from ~26 dBm to ~31 dBm while Ch2 was kept at -15 dBm and the 'on' level of Ch1 was kept at -4 dBm. The results are summarized in Fig. 6(c) (red curve). The power excursion increased with pump power and remained stable for pump powers exceeding 28.5 dBm. This indicates that the cross gain modulation in the TDFA is proportional to the overall gain experienced by the input signals, which is likely to increase with pump power until gain saturation occurs.

Finally, the rise time (defined as the time to transit from 10% to 90% of the maximum steady state power level) of the surviving channel was investigated. Figure 6(d) shows the results, with each data point taken under the same condition where its counterpart in Fig. 6(c) was recorded. The rise time exhibited a strong dependence on pump power and decreased from ~0.9 ms to ~0.2 ms as the pump power was increased from ~26 dBm to ~31 dBm. However, the rise time is largely unaffected by the change in power of the modulated channel and only a small increase (~0.1 ms) was observed when the power of Ch1 was increased from -15 dBm to -4 dBm. This confirms that the transient time of the surviving channel is directly linked to the gain it experiences, the higher the gain, the faster the response of the surviving channel and vice versa.

4. Conclusion

In conclusion, we have demonstrated and extensively tested the performance of two TDFA designs for application as high performance amplifiers in potential future telecommunication networks operating around 2 um. 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, namely TDFA-C and TDFA-L, optimized for short and long wavelength operation respectively, we were able to demonstrate small signal gains of more than 30 dB and NFs lower than 6.3 dB over a 110 nm bandwidth, and >35 dB gain over 90 nm (1910~2000 nm). The peak gain was measured to be 45 dB at 1950 nm for -20 dBm input signal power at 32 dBm pump power. We have also demonstrated high power operation of the TDFA with 1.2 W output power at 50% slope efficiency with respect to the absorbed pump power. The small signal performance in the presence of a saturating signal has also been studied. It was found that the gain curve of the probe signal preserved its shape whilst the NF values remained roughly unchanged. Furthermore, we have investigated cross gain and associated transient effects in a TDFA for the first time. Our measurements show that, just like the EDFA [29, 30], the power excursion increases whilst the transient response time decreases with increases in amplifier gain.

To the best of our knowledge, this is the first time a TDFA has been systematically evaluated for 2 μ m optical fiber communications, which from the amplifier perspective confirms the practicality of such a radical solution should future potential solutions to the "capacity crunch" problem currently under investigation require it. With the transmission loss of HC-PBGF getting lower and 2 μ m active and passive devices becoming more and more available, 2 μ m optical communications certainly offers interesting prospects. Note that such high performance amplifiers are also likely to find applications in a host of other application areas in the shorter term including within: high power fiber lasers systems, optical sensing and medicine amongst others.

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