Diode-pumped Wideband Thulium-doped Fiber Amplifiers for Optical Communications in the 1800 – 2050 nm Window

Z. Li, A. M. Heidt, S. U. Alam, N. Simakov, Y. Jung, J. M. O. Daniel, D. J. Richardson

Optoelectronics Research Centre, University of Southampton, SO17 1BJ, United Kingdom
zl3g10@orc.soton.ac.uk

Abstract *We present the first in-band diode-pumped TDFAs operating in the 2 µm wavelength region and test their application as high performance amplifiers in potential future telecommunication networks. We demonstrate amplification over a 240 nm wide window in the range 1810 – 2050 nm with up to 36 dB gain and noise figure as low as 4.5 dB.*

Introduction

As a result of the exponentially increasing volume of internet traffic, today's telecom networks are rapidly being driven towards their capacity limits. The quest for increasing transmission capacity has stimulated interest in radical approaches, which may eventually justify a shift away from the traditional operating wavelengths around 1.55 µm [1].

Thulium-doped fiber amplifiers (TDFAs) operating around 2 µm offer the broadest gain spectrum of all rare-earth doped fiber amplifiers and represent an attractive route towards significantly enhanced transmission bandwidths[2]. Additionally, their operating region overlaps with the predicted minimum loss window of hollow-core photonic bandgap fibers (HC-PBGFs), which hold great promise as a transmission medium due to their ultra-low nonlinearity and faster transmission speed as compared to conventional solid core fibers[3]. Recently, the first amplified data transmission system at 2 µm using TDFAs and HC-PBGFs has been demonstrated, confirming the viability/practicability of this approach[4].

TDFAs have recently been characterized extensively in an optical communications context, demonstrating high gain, low noise amplification over more than 100 nm bandwidth around 2 µm [5]. The current implementations are typically in-band fiber laser pumped, which would limit their applicability in real-life transmission systems. Ultimately, TDFAs will have to reach the same level of compactness, reliability and efficiency as current Erbium-based systems in order to be considered as a true alternative solution, i.e. laser diode pumping is indispensable. Diode-pumped TDFAs have been developed for emission in the S-band at 1470 – 1500 nm [6], but to date no such pumping scheme has been demonstrated suitable for optical communications in the new waveband of interest at 2 µm.

In this contribution we present the first implementations of TDFAs operating in the 2 µm wavelength region, in-band pumped by laser diodes at 1550 nm. We demonstrate amplification over a 240 nm wide window with up to 36 dB gain, noise figure as low as 4.5 dB and up to 100 mW saturated output power by combining three TDFA designs optimized for short, central and long wavelength operation, respectively. These results represent a major stepping stone in the assessment of such a radically new solution for next generation transmission systems.

Fig. 1: Experimental setup. TLS: tunable laser source; LD: laser diode; WDM: wavelength division multiplexer; TDF: thulium-doped fiber.

Experimental setup

The experimental setup of the diode-pumped TDFA is shown in Fig. 1. We employed a commercially available single-mode Tm^{3+}-doped fiber (OFS TmDF200) with ~6.2 µm mode-field diameter at 2000 nm and core absorption of ~20 dB/m at 1565 nm. Three TDFA implementations were investigated using 2 m, 4 m, and 8 m of gain fiber, denoted TDFA-S/C/L, which optimize the amplifier performance at short, central, and long wavelength bands, respectively. The fiber was core pumped in a bidirectional configuration by two Fabry–Pérot (FP) laser diodes (Princeton Lightwave) operating at 1550 nm with 3 dB bandwidth of ~4 nm, each delivering up to 210 mW (23.2 dBm) of pump power. Pump and signal wavelengths were combined using two 1570 / 2000 nm WDM couplers. Isolators were placed both at the input and output ends to prevent parasitic lasing. For characterization, the TDFAs were seeded by an in-house built tunable laser source (TLS) providing narrow linewidth operation in the range 1790 – 1990 nm. Additionally, we used three discrete-mode (DM) laser diodes (Eblana

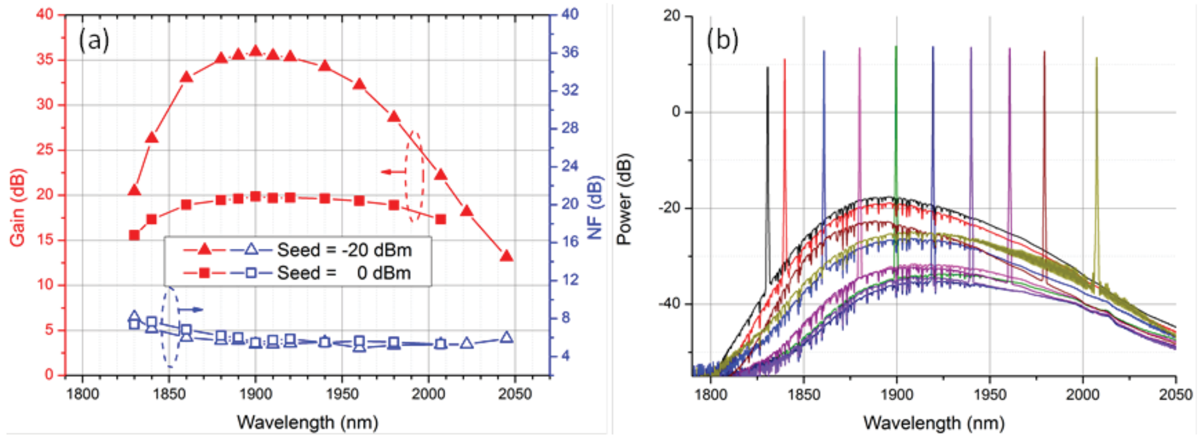

Fig. 2: Detailed wideband performance of TDFA-C using 4 m of gain fiber. (a) Wavelength dependence of small signal gain (seed power: -20 dBm), saturated gain (seed power: 0 dBm), and noise figure (NF) for both gain curves. (b) Output spectra over the tested wavelength band for 0 dBm seed power.

Photonics) emitting at 2008 nm, 2025 nm, and 2045 nm to evaluate the TDFA performance at the long wavelength edge of the amplification bandwidth. A power meter and an optical spectrum analyzer were used to measure gain and noise figure (NF) of the amplifiers.

Results and discussion

Fig. 2(a) shows the detailed characterization of the TDFA-C implementation, which uses 4 m of gain fiber. The figure presents the wavelength dependence of the small-signal gain (measured with an input seed power of -20 dBm), the saturated gain (measured with an input seed power of 0 dBm), as well as the external NF for both gain curves. The total pump power delivered by both pump diodes together is 26.2 dBm in all cases. The amplifier achieves a small-signal peak gain of 36 dB at 1900 nm and provides gain over a more than 215 nm wide window in the range 1830 – 2045 nm. Note that we could not perform measurements at longer wavelengths due to the lack of a suitable seed source. The saturated gain curve is flat and only varies between 18 – 20 dB in the 1840 – 2010 nm waveband. We could not perform saturated gain measurements using the DM diodes at 2025 nm and 2045 nm, because their output power level is below 0 dBm. There is no significant difference in NF between small and saturated input signal powers, varying between 5 and 7 dB over the entire tested spectral range.

A single, compact and diode-pumped TDFA is therefore able to deliver more than 20 dB small-signal gain and less than 7 dB NF over a nearly 200 nm wide transmission window in the 2 µm wavelength region. The resulting amplified spectra have more than 30 dB optical signal to noise ratio (OSNR), as shown in Fig. 2(b).

The amplifier performance at the short and long wavelength edge of the amplification band can be improved by varying the length of employed gain fiber. Fig. 3 compares the external small-signal gain and NF performance of all three different amplifier configurations. As the gain fiber length is increased, the maximum of the gain curve shifts from 1880 nm for TDFA-S (2 m of TDF) to 1950 nm for TDFA-L (8 m of TDF). This behavior is due to the fact that at room temperature Tm^{3+} is effectively a three level laser system resulting in the reabsorption of short wavelength components with the increase in fiber length.

In comparison to the performance of TDFA-C discussed above, TDFA-S provides up to 10 dB gain enhancement and up to 3 dB improvement in NF for wavelengths below 1860 nm. Similarly, TDFA-L provides up to 4 dB higher gain and up to 1 dB lower NF than TDFA-C for wavelengths beyond 1970 nm. TDFA-L also exhibits the lowest overall measured NF of 4.5 dB at 2025 nm. However, in this amplifier configuration the NF rises sharply for wavelengths below 1900 nm. We found that increasing the length of gain

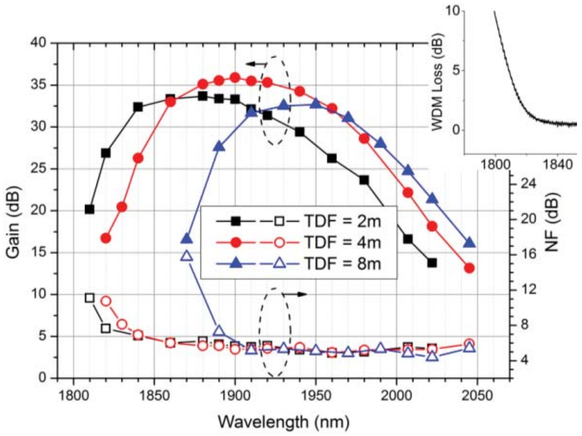

Fig. 3: Small-signal gain and noise figure (NF) of the TDFA incorporating different lengths of fibers. The inset shows the measured signal loss of the WDM coupler.

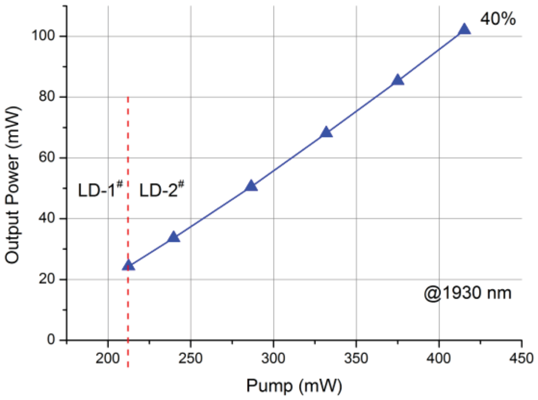

Fig. 4: TDFA-C efficiency at 1930 nm.

fiber above 8 m does not provide any further performance advantage at long wavelengths.

The above discussion highlights the possibility that high gain, low noise amplification over the entire 240 nm band investigated can be achieved by combining all three amplifier configurations in a transmission system, where short wavelengths up to 1860 nm are amplified by TDFA-S, the central waveband 1860 – 1970 nm by TDFA-C, and TDFA-L provides amplification for longer wavelengths. The combined amplifier system would provide more than 20 dB gain in the waveband 1810 – 2025 nm, and more than 16 dB at up to 2050 nm. These gain figures can be improved in the future using higher pump power. The NF for the combined system is flat at ~5 dB over almost the entire waveband tested, but rising rapidly below 1840 nm.

The degradation of gain and NF below 1840 nm in both TDFA-S and TDFA-C is caused by the exponentially increasing insertion loss of the WDM couplers, as shown in the inset of Fig. 3. We therefore stress that the reported performance, especially the NF, is mainly limited by the insertion loss and operating bandwidth of the first generation fiber components at 2 µm. There is no fundamental reason why TDFAs should be noisier than erbium based systems, and we expect the NF to approach the values known for EDFAs once a new generation of low-loss components becomes available for the 2 µm region. Therefore, we expect the true operating window of TDFAs to be even broader than physically demonstrated here, especially on the short wavelength side.

Seeding of TDFA-C at 1930 nm was chosen to demonstrate the power scaling capability of the amplifier. Fig. 4 shows the variation of output power with increasing pump power of the backward-pumping LD-2, while the forward-pumping LD-1 was fully powered up. We obtained more than 100 mW saturated output power at a total pump power of 420 mW with a slope efficiency of 40%.

Conclusions

We presented the first in-band diode-pumped TDFAs operating in the 2 µm region and tested their application as high performance amplifiers in potential future telecommunication networks. The TDFAs are analogous in implementation and function to current EDFAs, but offer a far more extended bandwidth in this new waveband of interest. By combining three different designs optimized for short, central and long wavelength operation, respectively, we demonstrated amplification over a 240 nm wide window in the range 1810 – 2050 nm with up to 36 dB gain, NF as low as 4.5 dB, and up to 100 mW saturated output power. Bandwidth and performance were limited by the insertion loss of the employed components.

Our results confirm the practicality of 2 µm optical fiber communications from an amplifier perspective, and represent a significant advancement in terms of compactness, robustness, controllability and power consumption of high performance TDFAs compared to earlier fiber-laser-pumped systems.

Acknowledgements

We acknowledge Eblana Photonics for providing the discrete mode laser diodes and OFS Denmark for providing fiber samples. A. M. Heidt acknowledges funding from the EU People Programme (Marie Curie Actions), grant agreement 300859 (ADMIRATION). Z. Li wishes to acknowledge the China Scholarship Council for its financial support. This work was supported by the EU 7th Framework Program, grant agreement 258033 (MODE-GAP) and by the UK EPSRC through grant EP/I01196X/1 (HYPERHIGHWAY).

References

[1] T. Morioka et al., IEEE Commun. Mag. **50**, 31 (2012).
[2] S. D. Jackson, Nat. Photonics **6**, 423 (2012).
[3] F. Poletti et al., Nat. Photonics **7**, 279 (2013).
[4] M. Petrovich et al., Proc. ECOC 2012, Th.3.A.5.
[5] Z. Li et al., Opt. Express **21**, 9289 (2013).
[6] T. Kasamatsu et al., Electron. Lett. **36**, 1607 (2000).