Exploiting the short wavelength gain of silica-based thulium-doped fiber amplifiers

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Short wavelength operation (1.65–1.8 µm) of silica-based thulium-doped fiber amplifiers (TDFAs) is investigated. We report the first demonstration of an in-band diode-pumped silica-based TDFAs working in the 1.7–1.8 µm waveband. Up to 29 dB of small-signal gain is achieved in this spectral region, with an operation wavelength accessible by diode pumping as short as 1710 nm. Further gain extension towards shorter wavelengths is realized in a fiber laser pumped configuration. A silica-based TDFA working in the 1.65–1.7 µm range with up to 29 dB small-signal gain and noise figure as low as 6.5 dB is presented.

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The quest for increasing the transmission capacity of optical communication networks has stimulated interest in radical new approaches to data transmission, for example, through space division multiplexing [1]. Recently, the 2 µm spectral region has attracted growing attention as a potential new transmission window for optical communications [2]. This is underpinned by emerging technologies such as hollow-core photonic bandgap fibers (HC-PBGFs). These fibers offer a transmission medium with ultra-low nonlinearity, low latency, and potentially an ultra-low loss window covering both the conventional 1.5 µm and the emerging 2 µm wavebands [3,4]. As the background loss of HC-PBGFs is continually improving, it becomes pertinant to envisage a future optical communication network operating seamlessly from 1.5 µm to 2 µm. In order to realize such a system, high quality optical amplifiers are required. It is worth noting that a high performance small-signal amplifier in this waveband should also find applications in sensing, medicine, and nonlinear optics amongst others [5,6].

Although operation of silica fiber lasers has been demonstrated from 1650–2200 nm [7,8], the differing requirements for high performance small-signal amplification necessitate specialized configurations for amplifiers. We previously demonstrated diode pumped thulium-doped fiber amplifiers (TDFAs) providing high gain, low noise amplification in the wavelength range 1810–2050 nm [9], however this source took advantage of just a fraction of the potential; gain spectrum of thulium (Tm^{3+}) ions doped in silica glass [10]. While the long wavelength gain edge of the TDFA was close to the practical limit for high performance amplification in Tm^{3+}, the short wavelength amplification of the TDFA terminated at ~1810 nm, limited by the insertion loss of the 2 µm passive components available at the time [9]. To realize the full potential of the TDFA, it is essential to develop practical configurations that offer high quality amplification in the 1.65–1.8 µm band. At these wavelengths, thulium-doped silica exhibits a strong three-level behavior and therefore requires a large inversion to achieve appreciable gain. Moreover, the upper laser level lifetime is significantly reduced by multi-phonon non-radiative decay [11], further increasing the challenge of obtaining the very large population inversion required for operation at <1.8 µm. In addition, a high inversion will result in substantial gain at 1.8–2.0 µm and management of parasitic amplified spontaneous emission (ASE) at these longer wavelengths becomes essential to achieve shorter wavelength gain. Consequently prior to this work small-signal amplification in the 1.65–1.8 µm range could only be obtained using fluoride-based TDFAs (with distributed loss at longer wavelengths) [12], or via nonlinear approaches (e.g., Raman amplifiers [13,14]). It is however interesting to note that a recently reported bismuth-doped fiber amplifier has also shown amplification in this band [15].

In this contribution, we report to the best of our knowledge the first demonstration of silica-based diode-pumped TDFAs operating below 1800 nm with gain extended to wavelengths as short as 1710 nm, which corresponds to a bandwidth enhancement of ~8 THz compared with previous results [9]. Another ~5 THz bandwidth extension of the TDFA towards 1.65 µm is achieved as a result of more effective ASE management and higher pump power through fiber laser pumping, which presents to the best of our knowledge the first demonstration of a silica-based TDFA working in the 1.65–1.7 µm waveband.

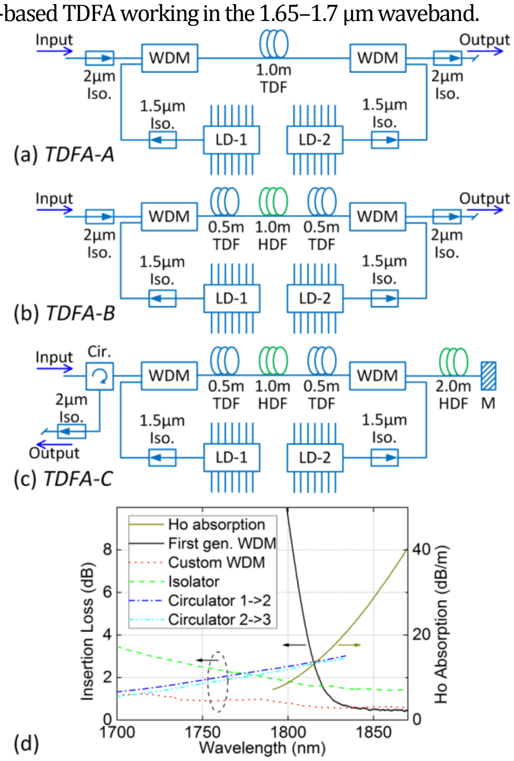

Fig. 1. (a)–(c) Schematic of the experimental setup for diode pumped TDFAs working in the 1.7–1.8 µm region, denoted as TDFA-A/B/C respectively. Iso.: isolator; Cir.: circulator; LD: laser diode; WDM: wavelength division multiplexer; TDF: thulium-doped fiber; HDF: holmium-doped fiber. (d) Right axis: absorption of the HDF. Left axis: measured insertion losses of passive components, including a custom-made WDM coupler, an isolator, and a circulator. For comparison, the insertion loss of a first-generation WDM coupler is also shown.

Figure 1(a)–(c) shows a schematic of the diode-pumped TDFA designs denoted as TDFA-A/B/C, respectively. TDFA-A/B both have a single-pass configuration, with TDFA-A having 1.0 m of single mode thulium-doped fiber (TDF) and TDFA-B having 1.0 m of heavily-doped, in-house fabricated, holmium-doped fiber (HDF) spliced in-between two 0.5 m lengths of TDF. The HDF acts as an absorber of >1.8 µm ASE (see Fig. 1(d)) with negligible absorption below 1750 nm in contrast to ~10 dB/m and ~30 dB/m absorption at 1800 nm and 1850 nm, respectively. TDFA-C employs a double-pass cavity (whereby the signal to be amplified passes the gain region twice) with an additional 2.0 m of HDF and a fiber retro-reflector to enhance short wavelength gain through additional filtering of the long wavelength ASE. For TDFA-A/B, isolators were placed both at the input and output ends to prevent parasitic lasing. In TDFA-C, an isolator was placed at the output end (port 3 of the circulator). The circulator itself provides ~15 dB isolation at the input of the amplifier. This helps in suppressing parasitic lasing and any feedback to the signal seed lasers, and is beneficial in terms of ensuring stable amplifier performance. The single-mode TDF used has a ~6.5 µm mode-field diameter at 2000 nm and core absorption of ~20 dB/m at 1565 nm. A relatively short total length of TDF (1.0 m) was used to reduce reabsorption of the short wavelength signal. The fiber was core-pumped in a bidirectional configuration by two Fabry–Pérot (FP) laser diodes operating at 1560 nm with a 3 dB bandwidth of ~4 nm, each delivering up to 250 mW (24 dBm) of pump power. Pump and signal wavelengths were combined using two custom-made filter-based 1550/2000 nm wavelength division multiplexer (WDM) couplers, each having ~1 dB insertion loss for both pump and signal wavebands. Compared with the high loss first generation WDM couplers (see Fig. 1(d)), this custom-made prototype allows us to access the 1.7–1.8 µm region for the first time. For characterization, the TDFAs were seeded by an in-house built tunable laser source (TLS) providing narrow linewidth (<0.1 nm) operation in the wavelength range 1700–1960 nm. A thermal power meter and an optical spectrum analyzer (OSA) were used to measure the gain and noise figure (NF) of the amplifiers.

Figure 2 shows a detailed characterization of the TDFA-A implementation. Figure 2(a) presents the wavelength dependence of the small-signal gain (measured with an input signal power of -20 dBm), the saturated gain (measured with an input signal power of 0 dBm), as well as the NFs for both gain curves. Note that all gain and NF values quoted are external values throughout the paper. The total pump power delivered by both pump diodes was 27 dBm in all cases. The amplifier provides a maximum small-signal gain of 35 dB at 1840 nm and gain over a more than 225 nm wide window spanning the range 1730–1955 nm. Measurements at longer wavelengths could not be performed due to the lack of a suitable seed source. The saturated gain curve is flat and only varies by 2 dB (between 18–20 dB) over the 1780–1955 nm waveband. There is no significant difference in the NF between small and saturating input signal powers, varying by 5 dB (between 5–10 dB) over the entire spectral range tested.

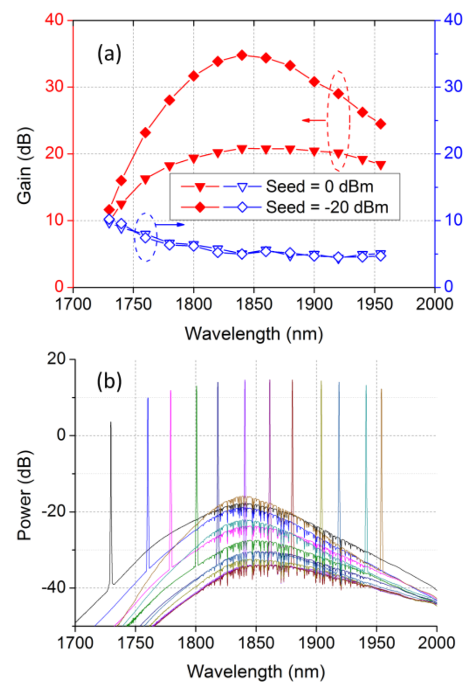

Fig. 2. Detailed wideband performance of TDFA-A shown in Fig. 1. (a) Wavelength dependence of the small-signal gain (-20 dBm seed power), saturated gain (0 dBm seed power), and noise figure (NF) for both gain curves. (b) Output spectra over the tested wavelength region for 0 dBm seed power, measured with 0.5 nm spectral resolution.

A single, compact, diode-pumped TDFA is therefore capable of delivering more than 20 dB small-signal gain with a NF of less than 8 dB over a 200 nm wide transmission window (1750–1950 nm) in the 2 µm wavelength region. The saturated amplified spectra show more than 45 dB in-band optical signal-to-noise ratio (OSNR) for the entire waveband tested as shown in Fig. 2(b).

In order to enhance the gain for signals at short wavelengths (<1.76 µm) where the Tm^{3+} emission is low and signal reabsorption is high, the >1.8 µm long wavelength ASE needs to be effectively suppressed. TDFA-B was constructed and tested in this context. As can be seen in Fig. 3, the gain peak is shifted to 1790 nm and the small-signal gain for <1760 nm signals is clearly increased, with up to 6 dB gain improvement at 1730 nm compared with TDFA-A. Interestingly, this is achieved without any noticeable NF penalty. The amplifier gain curve now reaches 1710 nm for >10 dB small-signal gain. These results clearly show the effectiveness of the HDF filtering.

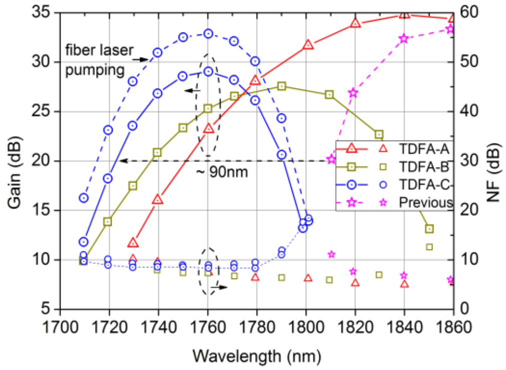

Fig. 3. Gain and NF of TDFA-A/B/C in the 1710–1850 nm region in comparison with those of a previously reported TDFA [9]. A seed power of -20 dBm was used in all cases.

Further gain enhancement for <1.76 µm short wavelength signals is realized using a double-pass cavity to increase the strength of the ASE filtering (TDFA-C). It can be seen from Fig. 3 that TDFA-C has a gain peak located at 1760 nm and offers small-signal gains as high as 29 dB. 23.5 dB gain is achieved at 1730 nm with TDFA-C, which is 6 dB higher than TDFA-B and 12 dB over TDFA-A. The NF penalty is 0.5–1 dB compared to a single-pass configuration. To compare with earlier results, the gain and NF performance of a previously reported TDFA [9] is also plotted in Fig. 3. This particular TDFA has the same structure as TDFA-A except that it incorporates 2.0 m of TDF. Its performance was limited by the first generation WDM coupler used and this degraded rapidly below 1810 nm (see Fig. 1(d)). Using the 20 dB gain point as a benchmark, we found that TDFA-C successfully extends the working window of diode-pumped silica-based TDFAs by ~8 THz (~90 nm) with the 20 dB short wavelength gain point shifting from 1810 nm to ~1720 nm.

In order to explore the maximum gain achievable with the current TDFA-C setup, the pump diodes were replaced by a fiber laser emitting at 1565 nm (forward pumping configuration). The small-signal gain and NF performances of this setup are also plotted in Fig. 3. At a launched pump power of 660 mW (28.2 dBm), a ~4 dB gain enhancement compared with the gain obtained under diode-pumping is observed across nearly the full operating window (except at the long wavelength edge). The peak gain increased to as high as 33 dB and the gain at 1710 nm increased to 16 dB. Due to the forward pumping scheme and higher pump power, the NF is improved by ~0.5 dB. The unabsorbed pump power for all measurements varied in the range 78–85 mW. Further gain enhancement was limited by parasitic lasing at ~1760 nm at higher pump powers.

Hence we have demonstrated high performance silica-based diode-pumped TDFAs working at wavelengths as short as 1710 nm, leaving a ~80 nm gap between the TDFA and erbium doped fiber amplifier (EDFA) operating windows. It is therefore of immense interest to further extend silica-based TDFA gain to <1.7 µm and possibly to 'bridge the gap' between the EDFA and TDFA. Next we discuss the development and characterization of a silica-based TDFA operating in the 1.65–1.7 µm spectral region.

A schematic of the TDFA is shown in Fig. 4(a). The amplifier employs a double-pass cavity design similar to that of TDFA-C. The gain region comprises two 0.5 m lengths of TDF (the same as is used above) spliced to each end of an in-house fabricated ASE filter. The short-pass ASE filter is realized by exploiting the bend loss of a dispersion compensating fiber (DCF). This filter provides high loss for >1.7 µm wavelengths suppressing long wavelength ASE and the potential for parasitic lasing. The DCF was chosen because of its strong bend loss dependence on wavelength. The transmission loss for the ASE filter is shown in Fig. 4(b). It can be seen that the transmission curve is relatively flat with a 3–7 dB insertion loss for wavelengths <1700 nm. The loss increases dramatically for wavelengths >1700 nm, exhibiting over 20 dB transmission loss for 1720 nm, over 30 dB loss at 1730 nm, and effectively no light is guided at wavelengths >1750 nm. A second ASE filter was used to further filter any long wavelength ASE. A 1565 nm fiber laser operating at 5 W (37 dBm) was used as a pump source to forward core-pump the TDF. For characterization, the TDFA was seeded by either of the two narrow linewidth (<0.1 nm) TLSs. One TLS was a commercially available laser covering the range 1500–1680 nm and the other one was an in-house built laser covering 1690–1800 nm.

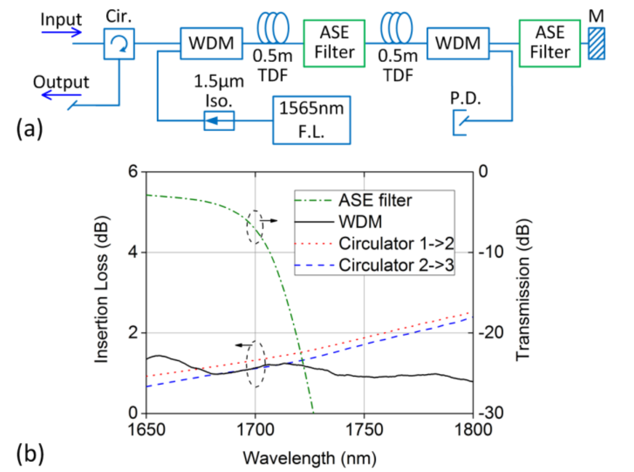

Fig. 4. (a) Schematic of the TDFA working in the 1.65–1.7 µm region. Cir.: circulator; WDM: wavelength division multiplexer; TDF: thulium-doped fiber; ASE: amplified spontaneous emission; Iso.: isolator; F.L.: fiber laser; P.D. power dump; M: Mirror. (b) Left: insertion losses of the circulator and WDMs; Right: transmission loss of the in-house built ASE filters.

A spectral characterization of the TDFA is shown in Fig. 5. Figure 5(a) presents the wavelength dependence of the small-signal gain (measured with an input signal power of -20 dBm), the saturated gain (measured with an input signal power of 0 dBm), as well as the NF for both the gain curves. A small-signal gain of up to 29 dB was achieved at 1690 nm. The 20 dB small-signal gain window covers a ~35 nm band (1670–1703 nm), which corresponds to ~3.7 THz bandwidth. The 15 dB small-signal gain window spans 1660–1710 nm, corresponding to a bandwidth of as much as 5.3 THz. The TDFA provides 8 dB of gain at wavelengths as short as 1650 nm. The saturated gain is above 10 dB in most of the waveband with up to 19 dB saturated gain achieved at 1690 nm. Both the small-signal gain and saturated gain decrease rapidly at wavelengths >1.7 µm due to the rapidly increasing transmission loss imposed by the ASE filters. The small-signal NF was below 10 dB for almost the whole wavelength region with a value as low as 6.5 dB achieved at 1690 nm. The amplified signal spectrum is of high quality. The amplified small-signal has over 25 dB in-band OSNR in the 1660–1700 nm region and over

20 dB in-band OSNR at the edges of the amplification band as shown in Fig. 5(b). The in-band OSNR for the amplified saturated signal is found to be over 40 dB throughout the range of 1650–1700 nm.

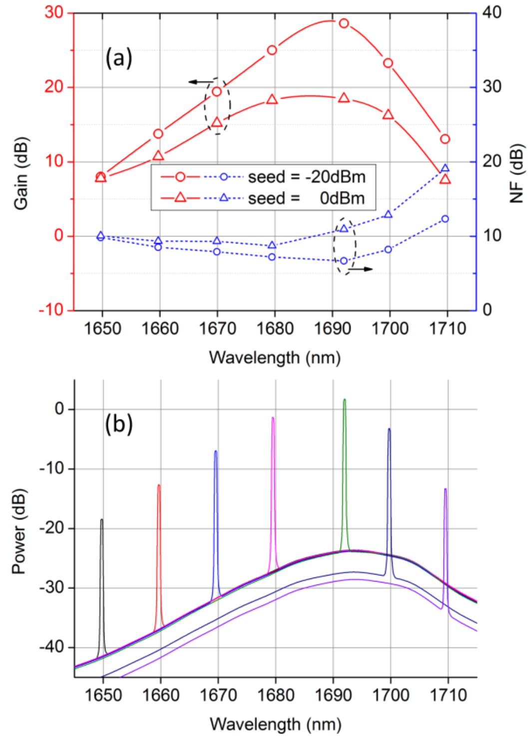

Fig. 5. (a) Gain and NF characteristics of the TDFA shown in Fig. 4. (b) Spectra of amplified small signals (0.5 nm spectral resolution).

In conclusion, we have developed several TDFA configurations designed for operation at wavelengths below 1800 nm. Taking advantage of effective ASE management, the diode pumped TDFA can offer up to 29 dB gain at 1760 nm and achieve 15 dB gain at wavelengths as short as 1715 nm. In order to effectively amplify even shorter wavelengths higher-power pumping has to be adopted, currently using a fiber laser. Up to 29 dB gain has been achieved at 1690 nm using using this approach. It is interesting to see that this particular TDFA can provide 8 dB gain at 1650 nm – an extremely short operating wavelength for Tm^{3+}. This body of work greatly extends the useful gain band of our previously demonstrated TDFAs [9,16]. The diode pumping method is now able to give seamless access to the 1715–2050 nm waveband, offering >15 dB gain with a NF of 5–10 dB over the entire range. The fiber laser pumping scheme can not only boost the gain in this range but also further extends the TDFA gain to extreme wavelengths approaching the long wavelength edge of the accessible EDFA gain band.

Presently amplifier performance is predominantly limited by the passive components employed in these experiments. For example, in the diode-pumped TDFA setups, the isolators and circulators showed a relatively high insertion loss of 1.5–3.5 dB at <1800 nm whereas the WDM couplers had an insertion loss of 0.5–1.5 dB (see Fig. 1). Taking this into account, we estimate the internal NF values of the diode-pumped TDFAs to be of the order of 2 dB lower in this region than the external NF values we have quoted indicate. The gain is also seriously compromised by the total insertion loss, which sums up to ~8–10 dB for both single-pass and double-pass configurations. A similar situation applies to the fiber laser pumped TDFA. From Fig. 4(b) it can be seen that at the input coupling side of the setup (Fig. 4(a)) the circulator and WDM coupler both introduced ~1 dB insertion loss per component.; the total round-trip insertion loss from the amplifier input to output totaled to 18 dB at 1650 nm and 26 dB at 1690 nm. Hence the internal small-signal NF values are estimated to be 1~2 dB less than the external NF; the gross small-signal gain is estimated to be over 25 dB at 1650 nm and above 50 dB at the 1690 nm gain peak (note that achieving this level of high gain would require enough isolation, usually more than that typically obtainable). We therefore envisage that the TDFA performance can be further improved with the future availability of better passive components.

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