# Broadband silica-based thulium doped fiber amplifier employing multi-wavelength pumping

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**Abstract:** A multi-wavelength pumped thulium doped fiber amplifier is investigated. Through the use of 791 nm, 1240 nm, and 1560 nm laser diode pumping, we achieved a broadband and gain-flattened silica-based thulium-doped fiber amplifier. A nominal gain of 15 dB is achieved over a bandwidth of more than 250 nm spanning from 1700 to 1950 nm with a maximum gain of 29 dB and a noise figure of less than 5 dB.

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

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## 1. Introduction

The explosive increases in internet speed and usage are steadily pushing today's telecom networks towards their capacity limits [1, 2]. As a result of the growing demand, the 2 m wavelength region has been proposed as an attractive new transmission window for optical communications, motivated mainly by the demonstrations of low-loss, low nonlinearity, and low latency hollow-core photonic band-gap fibers which are predicted to have a minimum loss around 2 μm [3-6]. Thulium doped silica fiber amplifiers (TDFAs) can support amplification over a very broad bandwidth at 2 μm and several different TDFA configurations have been presented offering high gain and low noise figure performance across the wavelength range 1800 – 2050 nm [7]. To exploit as much of the available bandwidth as possible, the short-wavelength amplification edge has been further extended down to 1650 nm which opens the intriguing possibility of bridging the gap between the long wavelength edge of the L-band erbium doped fiber amplifier and short wavelength edge of the TFDA [8-10]. However, it is to be appreciated that the wide spectral coverage of the TDFA has only been realized by concatenating several different TDFA configurations as individual amplifiers can only deliver a limited fraction of the full amplification bandwidth. Typically 15 dB gain bandwidths are limited to ~100 nm at wavelengths around 1750 – 1800 nm while a slightly broader bandwidth can be achieved at longer wavelengths around 1900 nm.

Here we present a novel broadband TDFA operating in the 1680 – 1950 nm region, achieved by employing a simultaneous dual-wavelength or triple-wavelength pumping scheme. Multi-wavelength pumping of TDFAs has previously been investigated in the context of S-band (1450 – 1520 nm) operation [11-13]. Such schemes utilize upconversion or excited state absorption (ESA), and proved to be a successful means to effect the desired gain shift towards the S-band region, but no multi-wavelength pumped TDFAs working in the 1.7 – 2 μm region have been reported so far to the best of our knowledge. The proposed TDFAs, pumped by a combination of 791 nm, 1240 nm, and 1560 nm laser diodes (LDs), can extend gain to wavelength shorter than 1.7 μm whilst providing a much broader amplification window, lower noise figure (NF) of less than 5 dB and a simpler implementation as compared to the prior art.

## 2. 791 nm and 1560 nm pumping

We consider 791 nm and 1560 nm dual-wavelength pumping first. Figure 1(a) shows the energy level diagram of the 791 / 1560 nm dual-wavelength pumping scheme. The 1560 nm radiation populates the $^3F_4$ level directly and creates a population inversion for signal amplification. However, it is hard to create a large population inversion using in-band pumping thereby compromising the gain at the blue edge of the gain bandwidth. The791 nm pump radiation however helps to increase the population of the $^3F_4$ manifold, thereby promoting gain at the short wavelength edge of the TDFA and increasing the overall gain bandwidth. Fig. 1(b) shows a schematic of our experimental setup which allowed us to compare the 791 / 1560 nm dual-wavelength pumping scheme with that of 791 / 791 nm and 1560 / 1560 nm bidirectional pumping. All configurations were seeded by either a tunable laser source (TLS) provided by Yenista (Tunics T100S-HP) covering the wavelength range 1500 – 1680 nm, or an in-house built thulium doped fiber laser (TDFL) covering the range 1710 – 1950 nm [14]. A variable optical attenuator (VOA) was used to adjust the input power levels from -20 dBm to 0 dBm to simulate small signal and saturated signal scenarios respectively. Isolators were used at both the input and output ends of the TDFA to suppress parasitic lasing and any unwanted feedback into the seed lasers, thereby improving the stability of the amplification. The single-mode TDF (OFS TmDF200) has a mode-field diameter of ~6.5 μm at 2 μm and a core absorption of ~20 dB/m at 1.56 μm. We used a 50 cm length of TDF in our experiments which was core pumped in a bidirectional configuration by two laser diodes. The length of the TDF was chosen following an initial sequence of cut-back measurements that looked to find the optimal amplifier length in terms of maximum gain bandwidth for 791 / 1560 bidirectional pumping configuration. Laser diodes operating both at 791 nm (Lumics) and at 1560 nm (Princeton Lightwave) were capable of delivering up to 250 mW (24 dBm) of pump power. For the pump power at 791 nm and 1560 nm, the actual power delivered into the TDF was ~ 230 mW and 210 mW, due to the 0.3 and 0.8 dB loss of the WDM couplers, respectively. Two different WDM couplers were used to combine the signal and pumps at different wavelengths. An 800 / 1700 nm fused WDM coupler was used for 791 nm pumping whilst a 1550 / 2000 nm thin-film filter based WDM coupler was used for 1560 nm pumping. A power meter (Ophir 3A-FS) and an optical spectrum analyzer (Yokogawa AQ6375) were used to measure the input (just before the isolator) and output signals. The gain and NF were calculated from the measured input and output signals.

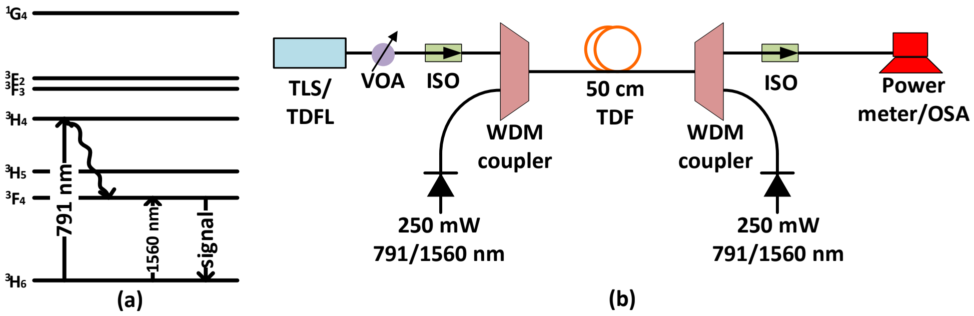
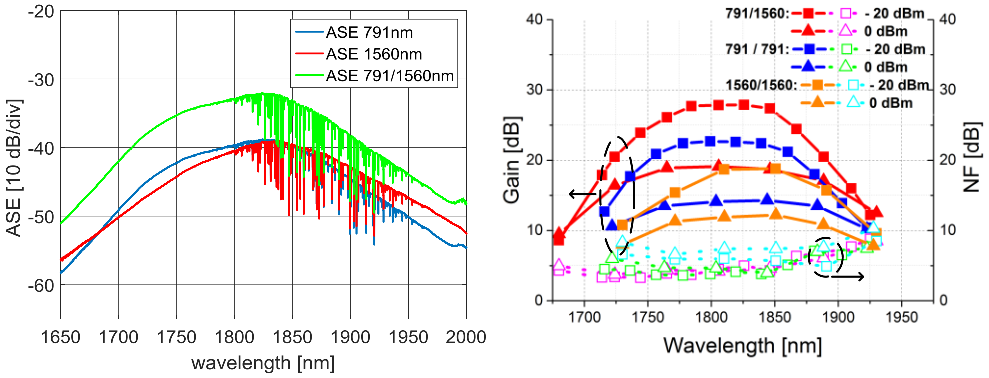


Fig. 1. (a) Energy-level diagram of Tm ions in a silica glass host with a dual-wavelength pumping scheme. (b) Schematic of the 791 / 791 nm pumped and 791 / 1560 nm LD pumped TDFA. TLS: tunable laser source; TDFL: thulium doped fiber laser; VOA: variable optical attenuator; ISO: isolator; WDM: wavelength division multiplexer; TDF: thulium doped fiber; LD: laser diode.

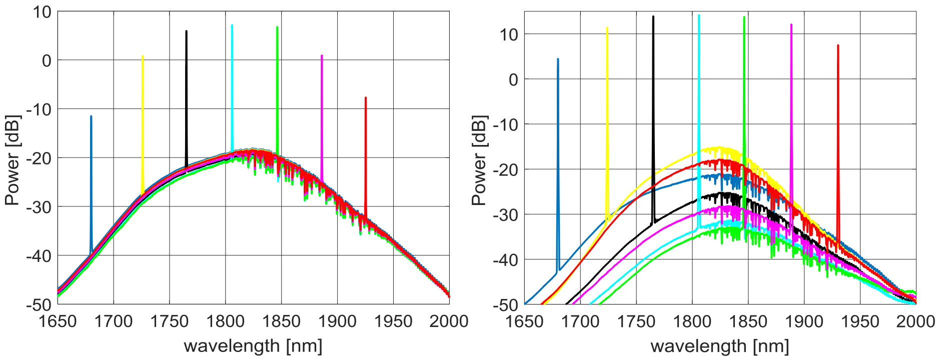
Figure 2(a) shows the amplified spontaneous emission (ASE) for different pumping schemes. The ASE spectrum for 791 nm is measured in the forward pumping configuration while that for 1560 nm is measured in the backward pumping configuration. The ASE spectrum clearly indicates that 791 nm pumping provides higher gain at shorter wavelengths while 1560 nm pumping results in a higher gain at longer wavelengths. Fig. 2(b) shows the detailed characterization plots of all three different TDFA schemes, i.e. 791 / 791 nm, 1560 / 1560 nm, and 791 / 1560 nm LD pumping. All of the configurations employed bi-directional pumping, however for 791 / 1560 nm dual wavelength pumping, the 791 nm pump is coupled in the forward direction whilst the 1560 nm pump coupled in the backward direction. The total pump power launched into the TDF was fixed at 460 mW, 420 mW, and 440 mW, respectively. The external small signal gain (measured with an input signal power of -20 dBm) and saturated gain (measured with an input signal power of 0 dBm), along with the external NFs are shown for each pumping scheme. The 1560 / 1560 nm pumping provides only a small-signal peak gain of 19 dB at 1830 nm, and 125 nm 15 dB gain bandwidth as the total absorption is relatively low at this wavelength due to the short length of TDF used (almost 100 mW of unabsorbed pump power were measured in each direction). The 791 / 791 nm pumping provides a small-signal peak gain of 23 dB at 1800 nm and maintains >15 dB gain over a 175 nm wide window extending from 1725 nm to 1900 nm. The spectral gain profile is flat over a 130 nm wide window spanning from 1740 – 1870 nm. The saturated gain has a similar amplification window and varies between 11 – 14.5 dB in the 1710 – 1930 nm waveband. The external NFs for both small and saturated signals are below 5 dB from 1710 – 1860 nm. Note that the NF increases at longer wavelengths are due to the fact that the insertion loss of our passive components (WDM couplers and isolators) increases at longer wavelengths., By contrast the 791 / 1560 nm LD pumping provides a 5 dB higher peak gain and a 35 nm broader relative to the 791 / 791 nm pumping case with a 15 dB gain bandwidth spanning from 1700 – 1920 nm. No significant difference in NFs was observed between these two later pumping schemes.



**(a)** **(b)**

Fig. 2. (a) ASE spectrum of 791 nm, 1560 nm and 791/1560 nm pumping. (b) Detailed broadband performance of the 791 / 791 nm and 791 / 1560 nm pumped TDFAs. The gas absorption lines around 1850 – 1900 nm are due to air path in the OSA.

Figure 3(a) and 3(b) shows the amplified small and saturated signal spectra for the 791 / 1560 nm pumped TDFA. The amplified small signal has 26 – 30 dB in-band optical signal-to-noise ratio (OSNR) across the entire amplification band. The amplified saturated signal has 48 – 50 dB in-band OSNR and up to 50 dB out-of-band OSNR.



**(a)** **(b)**

Fig. 3. Amplified (a) small and (b) saturated signals for dual-wavelength pumping. Measured with 0.5 nm optical spectrum analyzer resolution.

## 3. 791 nm, 1240 nm and 1560 nm pumping

We then added an additional 1240 nm pump to the 791 / 1560 nm dual-wavelength pumping scheme. Figure 4(a) shows the energy level diagram of the 791, 1240 and 1560 nm triple-wavelength pumping scheme. The 1240 nm radiation creates population at the $^3H_5$ level which rapidly decays to the $^3F_4$ level (non-radiative multi-phonon decay) to further increase the population inversion. Fig. 4(b) shows a schematic of the experimental setups. We used an additional WDM coupler to combine the 1240 nm and 1560 nm pumps. The laser diode operating at 1240 nm (INNOLUME) delivered up to 500 mW (27 dBm) of pump power.

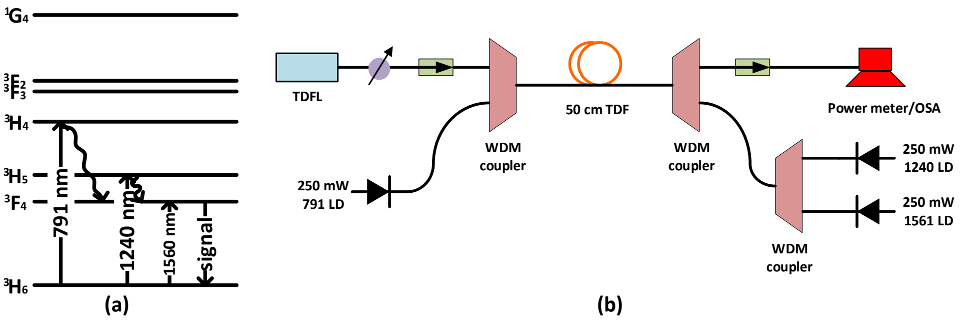


Fig. 4. (a) Energy-level diagram of Tm ions in silica glass host and the triple-wavelength pumping scheme. (b) Schematic of the triple wavelength pumped TDFA. TLS: tunable laser source; TDFL: thulium doped fiber laser; VOA: variable optical attenuator; ISO: isolator; WDM: wavelength division multiplexer; TDF: thulium doped fiber; LD: laser diode.

Figure 5 shows the detailed characterization plots of the triple-wavelength pumped TDFA. The external small signal and saturated signal gains along with the external NFs are shown. The total pump power launched into the TDF was fixed at 665 mW – 230 mW, 226 mW, and 210 mW for pump at 791 nm, 1240 nm, and 1560 nm, respectively. The triple-wavelength pumping provides a small-signal peak gain of 28 dB at 1825 nm and maintains 15 dB gain over a 250 nm wide window ranging from 1700 nm to 1950 nm. The spectral gain profile is flat over a 130 nm wide window spanning from 1750 – 1880 nm. The saturated gain has a similar amplification window and varies between 11 – 20 dB in the 1710 – 1900 nm waveband. The external NFs for both small and saturated signals are <5 dB from 1750 – 1860 nm. The NF increases gradually at the edge of the amplification window.

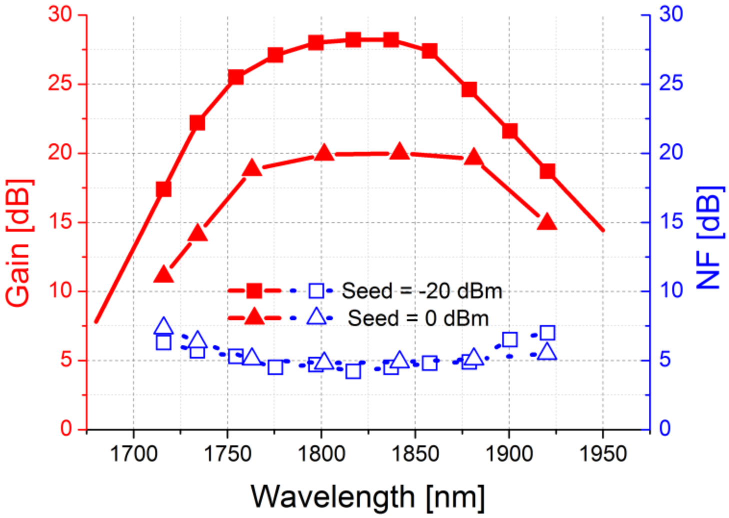
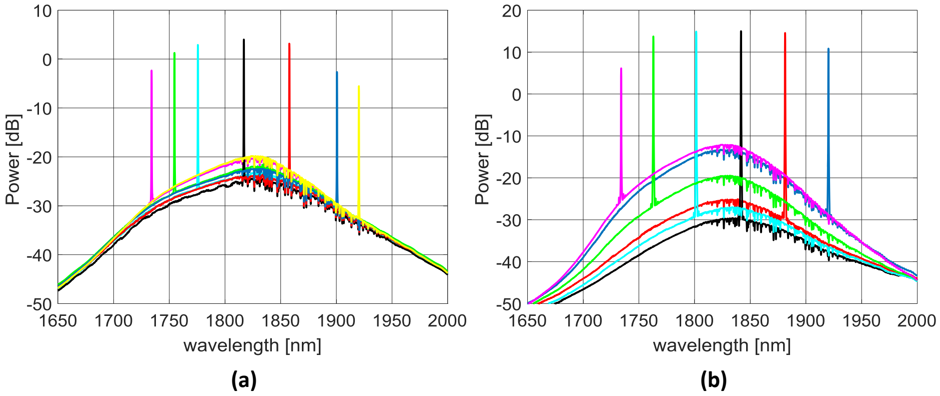


Fig. 5. Detailed broadband performance of the triple-wavelength pumped TDFA. Gain: red; NF: blue.

Figures 6(a) and 6(b) show the amplified small and saturated signal spectra for the triple-wavelength pumped TDFA. The amplified small signal has 28 – 30 dB in-band OSNR across the entire amplification band, while the amplified saturated signal has 33 – 45 dB in-band OSNR. It is to be noted here that the addition of 1240 nm pump did not help in increasing the signal gain, instead strong upconversion was observed, as the fiber was glowing purple.



(a)

(b)

Fig. 6. Amplified (a) small and (b) saturated signals for triple-wavelength pumping. Measured with 0.5 nm optical spectrum analyzer resolution.

Table 1 summarizes results for different types of pumping configurations. Dual wavelength (791nm/1560nm) pumping offers the maximum signal gain and gain bandwidth while triple wavelength pumping makes no tangible difference to the amplifier performance.

**Table 1. A summary of different configurations**

| | **Pump power** | **Small signal peak gain** | **15 dB gain bandwidth** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 791 / 791 nm pumping | 460 mW @ 791 nm | 23 dB | 125 nm |
| 1560 / 1560 nm pumping | 420 mW @ 1560 nm | 19 dB | 175 nm |
| 791 / 1560 nm pumping | 230 mW @ 791 nm, 210 mW @ 1561 nm | 28 dB | 250 nm |
| 791 / 1240 / 1560 nm pumping | 230 mW @ 791 nm, 210 mW @ 1561 nm, and 226 mW @ 1240 nm. | 28 dB | 250 nm |

Figure 7 shows a comparison between 791/1560 nm pumping, 791/1240/1560 pumping, and the previous demonstrations of short wavelength TDFAs [8, 9]. As can be seen from the figure, the additional 1240 nm pump increases the gain at the longer wavelength edge, and both multi-wavelength pumping schemes offer similar gain and NF performance. We also noticed that the amplifier performance with the 1240 nm pump behaves in a similar way to the 1560 nm pump, and little real additional advantage was achieved by incorporating this further level of pumping complexity. Although previously demonstrated short wavelength TDFAs have shown higher gains over the shorter wavelength band these have only been achieved at the expense of bandwidth and NF. This is due to the fact that in these previous demonstrations a signal loss mechanism was introduced into the system to suppress ASE at longer wavelengths. A higher pump power was also required in these implementations necessitating the use of a high power single mode fiber laser.

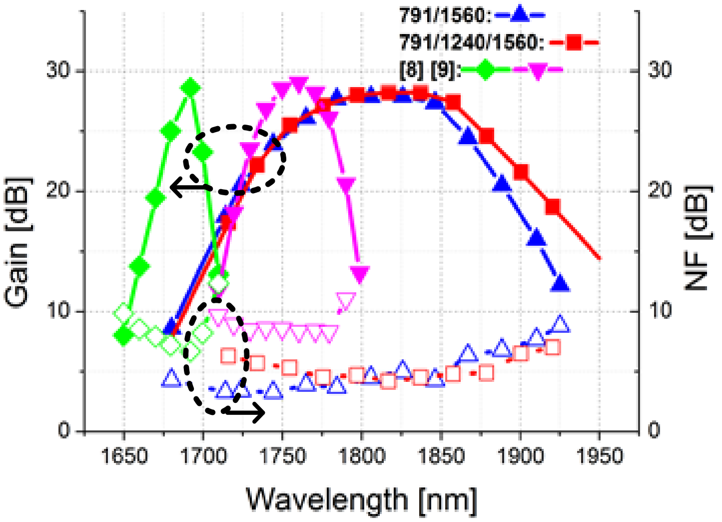


Fig. 7. A comparison between different pumping schemes and previous demonstrations.

## 4. Conclusion

We have demonstrated a low-noise broadband silica based TDFA employing multi-wavelength pumping. By using 791 nm and 1560 nm pumps in a bi-directional configuration, we have shown that the TDFA can cover an amplification window of more than 220 nm at wavelengths around 1800nm with a small signal gain as high as 29 dB and a NF as low as 3.3 dB. The amplification window can be further increased to 250 nm using an additional 1240 nm LD pump, which, to the best of our knowledge, represent the broadest bandwidth reported from a high gain TDFA operating in this waveband. The proposed TDFAs are compact, practical and have a flat-top gain profile with high spectral quality and as such should find use in various communication and sensing applications where optical bandwidth is the key defining parameter in this operating range.

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