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# Development of thulium-doped fibre amplifiers for the 2 $\mu$ m waveband

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## ABSTRACT

In this paper we show the analysis of Thulium Doped Fibre Amplifier(TDFA) gain dependence on pump laser wavelength and thulium doped fibre length. Thulium doped fibres of lengths varying from 0.5m to 3m are pumped with 785nm and 1550nm lasers in single and dual pumping schemes. Small signal gain up to 16dB was achieved at 2 $\mu$ m for a low pump power of 150mW. A potential wide amplifications bandwidth ranging from 1680nm to 2025nm is observed in the Amplified Spontaneous Emission(ASE) spectrum.

**Keywords:** Thulium Doped Fibre Amplifier, TDFA, 2 $\mu$ m Waveband, Optical Amplifier, Optical Gain, Rare Earth Doped Fibre

## 1. INTRODUCTION

Utilizing the 2 $\mu$ m waveband has become increasingly useful for applications in telecommunications and optical sensing. These applications require broad wavelength amplification, which can be provided by Thulium Doped Fibre Amplifiers(TDFAs). CO<sub>2</sub>, HCl and H<sub>2</sub>O all have absorption peaks within the range of 1700nm to 2025nm. For example, CO<sub>2</sub> sensing using the broad output of a TDFA was shown [1]. These sensing applications benefit from broad wavelength sources, allowing for absorption to occur across a continuous broad spectrum. This allows for sensing of various molecules using a single optical source. Another emerging application is communications at 2 $\mu$ m. In the past, moving the minimum transmission to longer wavelengths, away from Rayleigh scattering, was a potential avenue to achieve further loss reductions (when doped fibre amplifiers were not available). These were possible with fluoride, chalcogenite and ZBLAN fibres, with minimum attenuation shifted towards 2 or 3 microns [2]. Some of the issues with these fibres were nonlinearities, however, limiting the total capacity, but they were also brittle and difficult to handle. Recently, a new type of fibre, a hollow core photonic bandgap fibre (HC-PBGF) offers a low loss shifted towards 2microns too, but with the advantage of much improved nonlinearities and low latency, due to propagation confined within the air core [3].

In order to enable communications at this new waveband, a suite of components and devices are required such as modulators, laser sources and, in this case, amplifiers. TDFAs are currently the best available option for amplification around 2 $\mu$ m for telecommunications as they have high potential gain and a very large bandwidth allowing for WDM across a wide range of wavelengths, approximately twice the bandwidth of their 1550nm counterpart, Erbium Doped Fibre Amplifiers[4-9]. Through the results in this experiment the available bandwidth of TDFAs will be shown as well as the effect of design choices such as pump wavelength and fibre length on achievable gain around 2 $\mu$ m with the aim of demonstrating a large potential amplification region using low cost and relative low power pump lasers.

## 2. THULIUM DOPED FIBRE AMPLIFIERS

TDFAs consist of a strand of thulium doped silica fibre which is optically excited using a pump laser creating a gain medium which amplifies signals with wavelengths contained in the emission spectrum of thulium. Thulium has a very wide emission spectrum from its lowest excited state, the  $^3F_4$  energy level as shown in figure 1. This is due to stark splitting which increases width the energy levels[10]. Looking at the energy structure, there are two potential pump laser wavelength options, 1550nm and 785nm. Pumping at 1550nm excites the  $^3F_4$  energy level which is wide enough to absorb at 1550nm and emit at 2um. Due to the wide availability of high power low cost 1550nm lasers this is an attractive option.

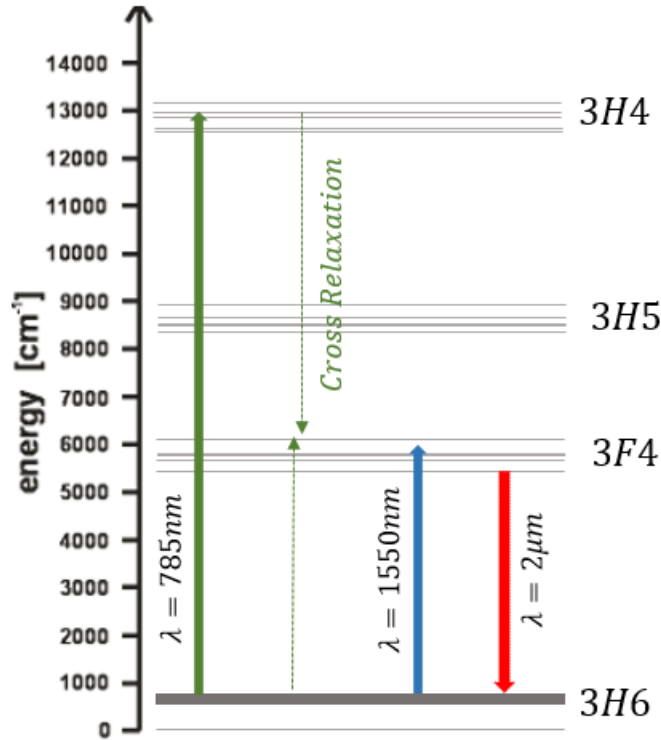


Figure 1. Energy levels of Thulium with 1550nm and 785nm pumping schemes

The second option is to pump at 785nm which excites the  $^3H_4$  band. Electrons in this band can relax to the  $^3F_4$  band through cross relaxation, a non-radiative process where an electron relaxes to a lower level through exciting another ground state electron. This is a dipole interaction so the distance between Thulium ions affects the efficiency of this transition. This requires the doping density of Thulium to be high enough for 785nm to be an efficient pump wavelength. Due to the high absorption peak at 785nm, amplifiers with shorter doped fibres can be more efficient as the absorption occurs over a shorter length.

### 3. EXPERIMENTAL SETUP

Here we designed TDFAs using three pumping schemes and lengths of Thulium doped fibre varying from 0.5m to 3m. The pumping schemes used were (a) single pump at 1550nm (b) single pump at 785nm (c) dual pump with 1550nm and 785nm lasers. The 1550nm pump laser chosen had an output power of 150mW and the 785nm pump laser output power was varied from 150mW and 250mW. The single pump schemes used forward pumping, i.e. in the same direction as the signal, while for the dual pump scheme the 1550nm source forward pumped and the 785nm source reverse pumped the Thulium doped fibre. These were designed to compare the effects of pump laser wavelength and Thulium doped fibre length on potential gain around  $2\mu\text{m}$  as well as the spectral width of the amplified spontaneous emission(ASE) produced. By analysing the ASE spectrum, one can estimate the gain profile of the TDFA.

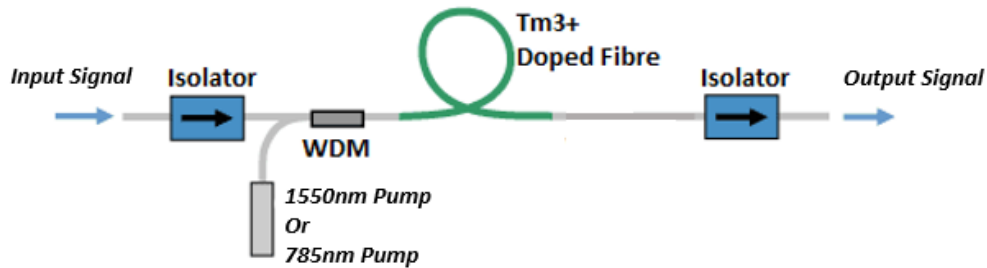


Figure 2. Single Pump TDFA design

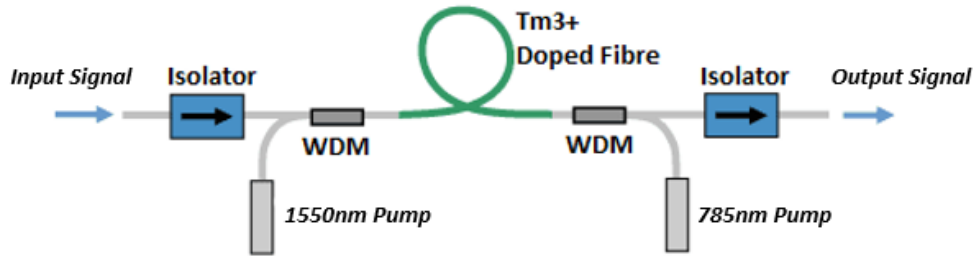


Figure 3. Dual pump TDFA Design

In figure 2-3, the blue arrow labeled input signal represents the optical signal at  $2\mu\text{m}$ . The Blue arrow labeled output signal represents the amplified input signal and the accompanying amplified spontaneous emission from the Thulium doped fibre. In this experiment amplified spontaneous emission without an input signal was also measured. This was measured by exciting the Thulium doped fibre with the various pumping schemes and recording the optical output from the TDFA. The output of the TDFA was monitored by an optical spectrum analyzer(OSA) which collected data over the wavelength range between 1600nm to 2100nm. For both pump lasers specific WDMs were designed to allow for the best coupling of pump and signal lasers with minimal loss. Isolators were in place to prevent ASE from reaching the pump or signal laser, which would reduce efficiency and potentially damage the laser sources. A single mode laser operating at 1998nm was used as the signal to be amplified.

#### 4. RESULTS

First a comparison was made between single pump TDFAs using fibers of length ranging from 0.5m to 3m. Both the 785nm and 1550nm pump lasers were operating at 150mW. The signal power was set to -5dBm for this portion of the experiment. This was considered the large signal regime.

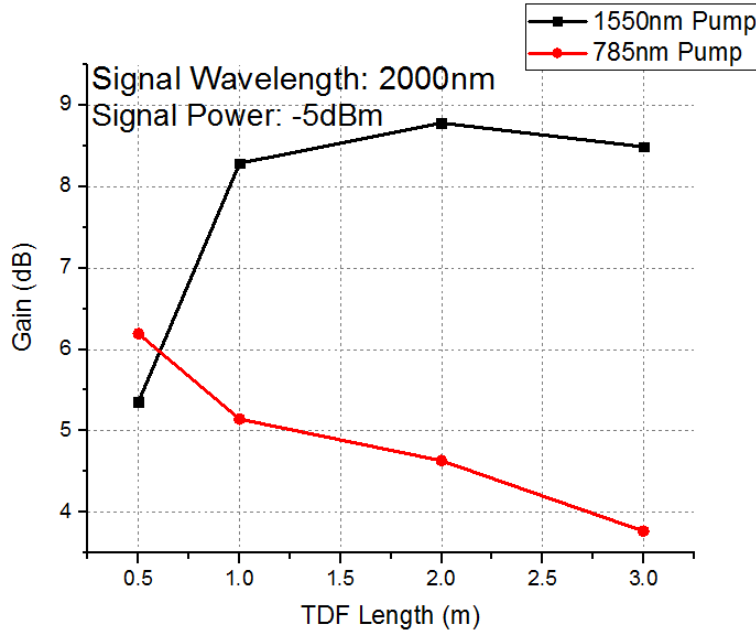


Figure 4. Thulium doped fiber length vs gain for 1550nm and 785nm pump source

It can be seen in figure 4 that for 785nm pump wavelength, increasing fibre length reduces signal gain, with the optimal length being 0.5m. For a 1550nm pump the gain increases with fiber length to a point and then begins to decrease, with an optimal length 2m. The variation in these two results is mainly caused by the power distribution of pump laser power along the fibre length. The power distribution along the fibre is dependent on the absorption coefficient. Light at 785nm has an absorption cross section of approximately  $8.5 \times 10^{-25}m^2$ , while at 1550nm it is approximately  $1 \times 10^{-25}m^2$ [12]. A higher coefficient results in the pump power being fully absorbed over a shorter length of fibre, leaving any additional unexcited fibre to absorb the stimulated and spontaneous emissions, reducing the power output at the end of the fibre. These results are in good agreement with current theoretical models describing this power distribution[11]. For 785nm pump wavelength to compete the cross relaxation process would need to be very efficient in populating the  $^3F_4$  energy level. This energy transfer process is dependant on distance between  $Tm^{3+}$  ions in the silica fibre so is dependant on the doping density. The doping density of thulium is limited in silica glass so pumping with 785nm alone will not achieve high gain in these fibres. The high phonon energy in silica glass also limits the effectiveness of the non-radiative transitions required to make 785nm pumping a viable option for amplification around  $2\mu m$ . A spectral output was taken from the TDFAs for both pump wavelengths fig 7-8. The effect of power distribution in the fiber on fiber power output can be seen and will be discussed next..

Figure 5 Shows the output spectra for a 0.5m and 3m TDFAs pumped at 1550nm with pump power of 150mW. Thulium has an absorption overlap which can reabsorb wavelengths up to 1800nm. This overlap can be seen in the ASE spectrum. As the length of the fiber increases greater re-absorption occurs, greatly reducing the output power around 1700nm-1800nm. However, due to the efficient power distribution in the fiber, the achievable gain is increased around  $2\mu m$  as the re-absorbed light emits at the longer wavelengths.

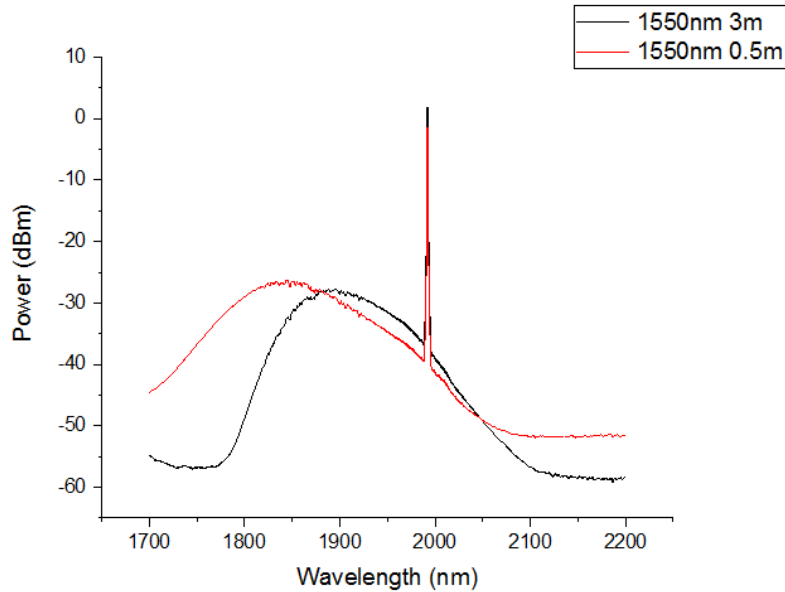


Figure 5. TDF output spectra for 0.5m and 3m TDF pumped at 1550nm

Figure 6 shows the output spectra for a 0.5m and 3m TDF pumped at 785nm with pump power of 150mW. Like in figure 5, it can be seen that the shorter wavelengths are reabsorbed for longer length of Thulium doped fibre. However, this reabsorbed light does not produce any additional amplification as the pump power density through the fibre length is insufficient. This limits the 785nm pumped TDFAs to shorter lengths of Thulium doped fibre. As well as poor amplification for longer lengths, the spectral width is also greatly reduced.

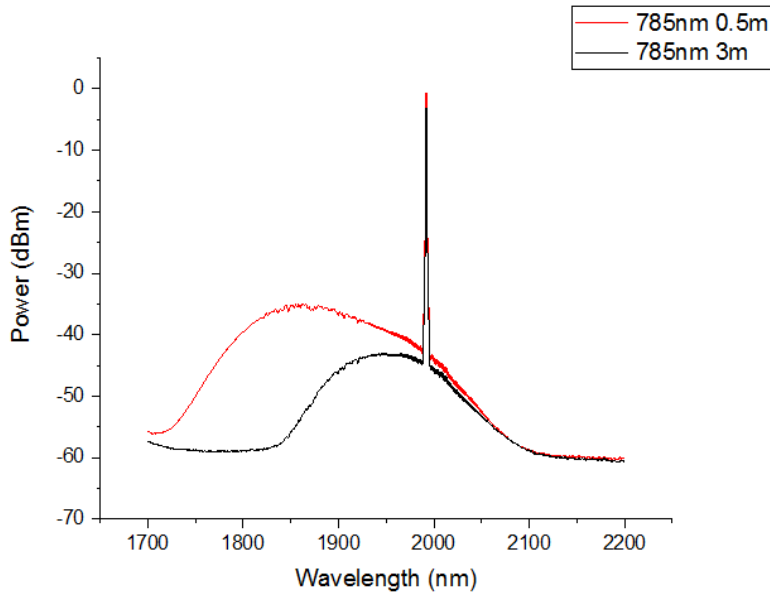


Figure 6. TDF output spectra for 0.5m and 3m TDF pumped at 785nm

Gain vs length was also characterized for a dual pumping scheme using both 785nm and 1550nm pump sources in a bi-directional pumping setup with 1550nm forward pumping and 785nm reverse pumping. This setup was used to amplify a -15dBm signal at  $2\mu\text{m}$ .

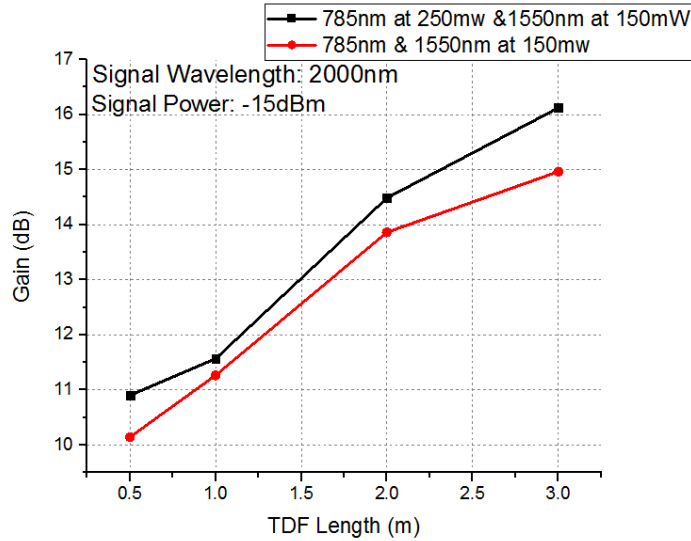


Figure 7. Gain vs Length for dual pumped TDFA configuration

Figure 7 shows that the maximum gain achieved for this low pump power TDFA design was 16dB at  $2\mu\text{m}$ . This maximum gain was achieved for 3m of Thulium doped fibre. The plot also shows how increasing the power of the 785nm pump laser produces an increase in gain. As a single pump source the 785nm laser produced very low gain for 3m of Thulium doped fibre due to low power density in the fiber, but when combined with a 1550nm pump laser the combined power density in the fiber prevents the losses seen in figure 6. The ASE spectrum of the dual pumped TDFA was compared to that of the single 1550nm pumped TDFA to see if any spectral changes occurred when combining the pump lasers. Figure 8 shows the ASE spectra for dual pumped and single 1550nm pumped regimes. The addition of the 785nm pump greatly increases the amplification bandwidth of the TDFA. The amplification edge moves from 1780nm down to 1680nm. As the power of the 785nm laser increases there is very little change in the ASE power around  $2\mu\text{m}$  but around 1700nm the ASE power continue to increase, this shows the increasing potential for amplification across a spectrum ranging from 1680nm to 2025nm.

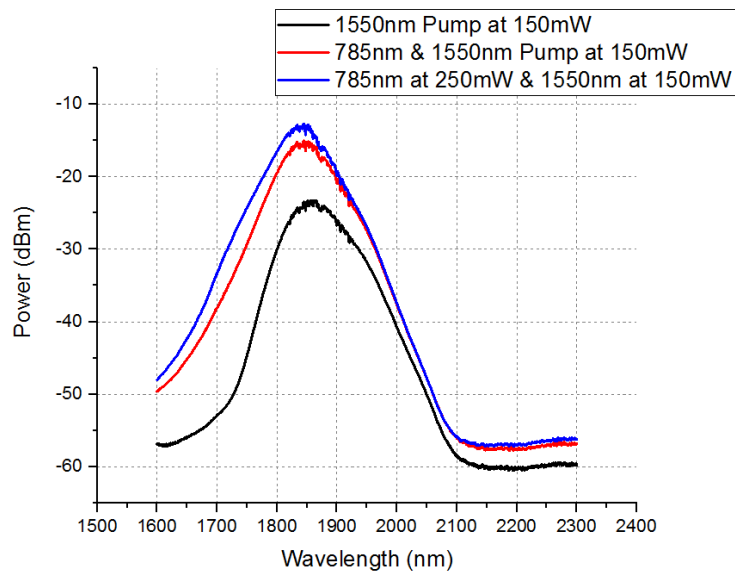


Figure 8. ASE spectra of dual and single pumped TDFA

## 5. CONCLUSION

After comparing the the effect of thulium doped fiber length and pump wavelength on gain around  $2\mu\text{m}$ , it was seen that for increasing fiber length 785nm pumped TDFAs decreased in gain output and 1550nm Pumped TDFAs increased in gain output. This was due to the relationship between optical power distribution and pump wavelength. The optimum length for a T DFA operating with a 785nm pump at 150mW was found to be 0.5m. The optimum length for a T DFA operating with a 1550nm pump at 150mW was found to be 2m. These results were in good agreement with theoretical models of this system[11]. For dual pumped T DFA designs, using both a 1550nm and 785nm pump laser, a maximum gain of 16dBm was achieved. The ASE spectrum of the dual pumped T DFA also demonstrated a potential amplification bandwidth ranging from 1680nm to 2025nm.

## ACKNOWLEDGMENTS

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