All-fibre widely tunable thulium laser
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ABSTRACT

We present results from an all-fibre thulium laser system that can be tuned to any wavelength between 1710 – 2110 nm, without using any moving mechanical parts. An Acousto-Optic Tunable Filter (AOTF) is used as the tuning element, which allows for the wavelength to be tuned in ~ 20 µs. Core-pumped and cladding pumped thulium fibres are used to enable lasing action across the wavelength range.

We use in-house fabricated fused fibre couplers and combiners that have a flattened coupling response with wavelength to allow for the system to be built in an all fibre design. These couplers have a coupling response that only varies by +/- 10% over the 400 nm operating range.

The laser can output powers between 1-5 mW over 1710 – 2110 nm and has a linewidth of <0.2 nm. An Acousto-optic modulator is used as a switch on the output of the laser to switch the signal between core-pumped and cladding-pumped amplifier stages. This allows for the output signals to be amplified to ~1W levels.

Keywords: Thulium, fiber laser, fused fiber, AOTF, tunable

1. INTRODUCTION

The broad emission spectrum of thulium fibres, which can extend from 1600-2200 nm makes a thulium fibre laser an excellent choice for building widely tunable fibre lasers [1]. An intra-cavity or external selective element, such as a Fabry-Perot filter [2] or an Acousto-Optic Tunable Filter (AOTF) [3] can be used to select the wavelength. Tuning ranges of >100 nm have been demonstrated [4] as well as all-fibre architectures [5]. These lasers were developed primarily with gas sensing and LIDAR applications in mind [4, 5] but have also found a potential use in optical communications [6]. Another application area for tunable swept lasers is in Swept Source Optical Coherence Tomography (SS-OCT) [7]. In particular, Thulium swept sources are particularly suited for non-invasive investigation of paintings [8].

The aim of this work was to achieve the widest possible tuning range from a single mode fibre output and to build a laser in an ‘all-fibre’ design as far as possible. The laser was designed to not have any moving parts, making it suitable for high-reliability applications. Currently, tuning ranges of 330 nm [9] and 380 nm [10] have been demonstrated.

2. LASER DESIGN

Our laser consists of two ring cavities that share a common path through an Acousto Optic Tunable Filter (AOTF). To obtain the widest possible tuning range, it was necessary to use both a core pumped and cladding pumped thulium fibres. Cladding pumping at 793 nm has been shown to favour longer emission wavelengths (1950-2100 nm), whereas core pumping at 1565 nm favours shorter emission wavelengths (1700 – 1950 nm) [11]. The layout of the laser is shown in Figure 1.

The oscillator was designed to be two lasers with a shared cavity. It is important to note that only one laser is active at a time, so as to avoid a coupled cavity situation. The two lasers were then combined through a wide-band 50:50 coupler into a single output fibre. The output from this fibre was then collimated using a silver off-axis parabola and then the beam was coupled into the AOTF. A polariser was placed in front of the AOTF to linearly polarise the beam to improve the diffraction efficiency. The other output of the 50:50 coupler was used as a power monitor.
The collimated beam had a 7 mm diameter to maximise the diffraction efficiency in the AOTF. The diffracted beam was then re-captured onto a single-mode fibre using another silver off-axis parabolic mirror. Another wideband 50:50 coupler would then split the light into the two different ring lasers of the core and cladding pumped lasers respectively.

This arrangement allowed for an ‘all-fibre’ arrangement (excluding the AOTF), but did mean that the maximum oscillator efficiency was 25% as 50% of the input light was lost at each coupler (into the other output fibre of the coupler). The polariser in front of the AOTF also reduced the efficiency of the oscillators. The oscillator was not built using polarisation maintaining fibres (PM) due to the added cost of the fibres and the increased difficulty of manufacturing wideband fused fibre devices using PM fibres.

The pump source for the 793 nm pumped laser was a fibre coupled 6 W 793 nm pump diode. A 2+1x1 combiner manufactured in-house was used to couple in the pump light and the feed through fibre on the combiner was CorActive DCF-UN-8/125-18 that was the matched passive fibre to the active fibre (CorActive DCF-TM-10/128). After the active thulium fibre, singled clad matched passive fibre (CorActive SCF-TM-8/125) was spliced in so as to remove any remaining pump light that was in the active fibre.

The pump source for the core pumped laser was an Erbium Doped Fibre Amplifier (EDFA) built in-house, producing a maximum output power of 1.87 W at 1550 nm. The 1550 nm output was coupled to the active fibre (CorActive SCF-TM-8/125) using an in-house manufactured wideband WDM, with CorActive SCF-UN-8/125 used as the signal fibre.

![Diagram of the laser layout](image)

Figure 1. Diagram of the laser layout

### 3. WAVELENGTH FLATTENED COUPLERS

To enable lasing over as large a wavelength range as possible, fused couplers that had a flattened wavelength response were manufactured. These were manufactured by varying the coupling constant between the two fibres by pre-tapering the fibres. The flatter spectral response is needed in this laser as otherwise the losses at the wavelengths at the ends of the tuning ranges would be so high as to prevent lasing. Figure 2 shows the coupling response with wavelength for the different types of couplers used in the laser.
4. NON-FREQUENCY SHIFT AOTF

A novel G&H non-frequency shift AOTF was used as the tuning element in the laser. A standard AOTF would impose a 200 Hz up-shift in frequency every round trip. This can cause the laser to pulse [12, 13] and also broadens the linewidth [14]. To overcome this, we developed a non-frequency shift AOTF. This was essentially two matched AOTFs with the second AOTF providing a frequency down shift that compensated for the upshift of the first AOTF. This AOTF allowed us to tune the laser wavelength without experiencing any linewidth broadening or self-pulsing effects.
5. RESULTS

The first experiment was to determine the tuning range of the laser. The drive frequency to the AOTF was varied and the signal monitored. For the cladding-pumped oscillator, the longest lasing wavelength was 2110.2 nm and the shortest was 1912.0 nm. In the core-pumped oscillator, the longest lasing wavelength was 1918.0 nm and the shortest wavelength was 1710.0 nm. In total, the continuous tuning range of the laser was 400.2 nm between 1710 and 2110.2 nm, with the two oscillators over-lapping between 1912 and 1918 nm. The wavelength could be tuned in <20 μs, which was the switching time of the AOTF, and the linewidth was <0.2 nm. Figure 4 shows the tuning ranges for the two different pumping schemes, with measurements taken on an Optical Spectrum Analyser in 10 nm intervals.

Figure 3. Photograph of the non-frequency shift AOTF

Figure 4. The tuning range of the core-pumped cavity (a) and the cladding pumped cavity (b).
The efficiency of the laser was very low, primarily due to 75% of the light being lost at the two 50/50 couplers (although the unused output arms were used as power monitors). The maximum output power was 5 mW at 1970 nm.

An amplifier section was added to the laser to increase the signal output power of the 1910 – 2110 nm wavelengths. The amplifier stage that was built used a 6W 793 nm diode laser to cladding pump a 6.0 m length of thulium fibre. The fibre length was chosen to improve the amplification of the weaker signals between 1910-1940 nm. Amplification using a cladding-pumped thulium fibre is less efficient at the shorter wavelengths, so the amplifier was optimised to work here to flatten the output spectrum and gain profile.

The amplifier also included an in-house built isolator and 2+1x1 pump combiner. The output from the active fibre was spliced onto the matched single-clad fibre to remove any residual pump light. The output fibre end was then angle cleaved to prevent back reflections.

![Figure 3. The output power of the cladding-pumped amplifier (a) and the gain (b).](image)

### 6. SUMMARY

A laser consisting of two oscillators, sharing components but operating separately, that can be tuned to lase at any wavelength between 1710 – 2110 nm has been demonstrated. This is believed to be the largest laser tuning range from a thulium fibre output from a single fibre that has not used non-linear processes (such as super-continuum generation) to generate the wavelengths. The output power across the tuning range was >1 mW for the majority of the wavelength range.

Such a wide operating range was possible due to the use of in-house fabricated fused devices designed to have a flat coupling ratio with wavelength. Without these devices, losses at the wavelengths at the ends of the tuning range would have been too high to allow for laser action. We have also used a novel null frequency shift AOTF as the tuning element to suppress any self-pulsing or linewidth broadening processes.

### REFERENCES
