Power Scalable and Efficient 790nm pumped Tm^{3+}-Doped Fibre Lasers

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ABSTRACT

This report presents a discussion of the engineering issues and results of high power 2µm Tm^{3+}-doped fibre lasers pumped at 790nm. To date we have achieved up to 85W from such devices with 54% slope efficiency relative to launched pump.[1] More recently, through using Tm^{3+} concentrations of approximately 4(wt.)% to enhance the cross-relaxation process ($^3H_4,^3H_6 \rightarrow ^3F_4,^3F_4$) we have demonstrated slope efficiencies of up to 67% relative to launched power. This represented ~170% quantum slope efficiency for the 790nm pumped 2µm laser.

KEY WORDS: Thulium, double-clad, fibre laser, fiber laser.

1. INTRODUCTION

For applications requiring 1.9 ~ 2.1µm emission, 790nm pumped Tm^{3+}-doped double-clad silica fibre lasers present excellent candidates as high efficiency sources. In eye-safe applications they exhibit higher conversion efficiency than current Er^{3+} and Er^{3+}:Yb^{3+} codoped fibres. Clarkson *et al*[2] showed the wavelength diversity of these devices by demonstrating the ability to tune the output wavelength from 1860 to 2090nm using a diffraction grating in Littrow configuration. Over 15dB gain has been reported from an amplifier operating at 1995nm by Imeshev *et al*.[3] The highest slope efficiency reported to date has been 74% relative to absorbed pump by S. Jackson.[4]

Figure 1 illustrates the cross relaxation (CR) process responsible for the well known “two-for-one” excitation of the upper laser level in Tm^{3+}-doped silica fibre lasers.[5] It has been shown that increasing the concentration of Tm^{3+} ions whilst minimising the detrimental effects from energy transfer upconversion (ETU) is vital for maximisation of the CR process and hence the slope efficiency.[6] While ETU is highly nonresonant in silica, a high degree of clustering leads to ETU reducing the population inversion and hence the beneficial effects from CR. Optimisation of the CR process has lead to reduced quantum defect and heat load allowing lasers to be scaled to much higher powers. A summary of the fibres we refer to in this report are listed in table 1. The first two fibres listed were manufactured by the Optical Fibre Technology Centre (OFTC) Australia. They both had a reported Tm^{3+} concentration of 2.2(wt.)%. The other fibres were manufactured by a commercial supplier and had Tm^{3+} concentrations of approximately 2(wt.)% and 4(wt.)%. All fibres had similar Tm^{3+}/Al^{3+} ratios of approximately 10:1.

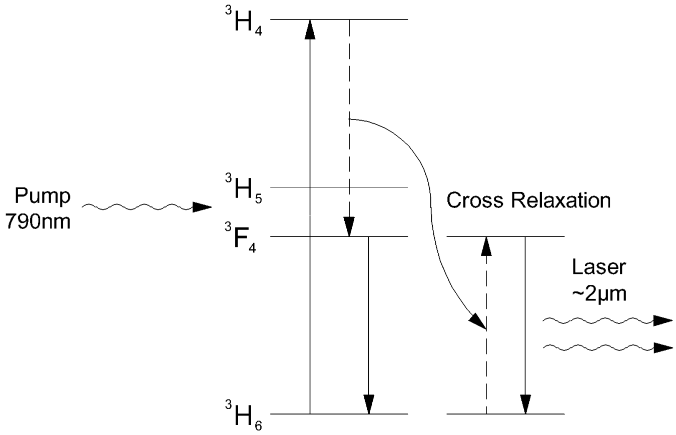

Figure 1. Level diagram for Tm^{3+}-doped silica showing the cross relaxation energy transfer process $^3H_4, ^3H_6 \rightarrow ^3F_4, ^3F_4$.

Manufacturer	OFTC		Commercial		
Notation in text	20/300	27/400	MM-25/250	LMA-25/250	MM-30/400
Core	20μm	27μm	25μm	25μm core + raised pedestal (see section 2.5)	30μm
Tm^{3+} concentration	2.2(wt.)%	2.2(wt.)%	~2(wt.)%	~2(wt.)%	~4(wt.)%
Tm^{3+}/Al^{3+}	10:1	10:1	~10:1	~10:1	~10:1
Core NA	0.24	0.24	0.21	0.10 (effective)	0.21
Cladding	300μm D-shaped	400μm hexagonal (see section 2.3)	250μm octagonal	250μm octagonal	400μm octagonal

Table 1. Summary of fibres and their notation as referred to in this report

2. RESULTS

2.1 Three-level behaviour

The three-level nature of the $^3F_4 \rightarrow {}^3H_6$ transition of Tm^{3+} is well known in solid state hosts.[7] In figures 2 to 5 we show the magnitude of this three-level nature in Tm^{3+}-doped silica fibre lasers. Experiments were conducted by end-pumping the 20/300 fibre at 795nm through a dichroic mirror butted to one of the cleaved facets. The dichroic mirror had high reflectivity from 1.8 to 2.1µm and was highly transmissive for the pump wavelength. Output coupling was provided by the Fresnel reflection of the opposite fibre facet only. Spectra were recorded using a 0.5m monochromator fitted with a 600mm^{-1} grating blazed at 2µm and a TE-cooled ZnHgCdTe detector.

We observed that as the fibre was cut shorter, the free running wavelength was blue shifted due to decreasing reabsorption. To investigate the effects of fibre temperature, we placed the fibre within a PVC water jacket and circulated controlled temperature water through it. As the fibre was heated we observed a red shift of the output spectrum due to changes in the thermal population of Stark levels in accordance with Boltzmann statistics.

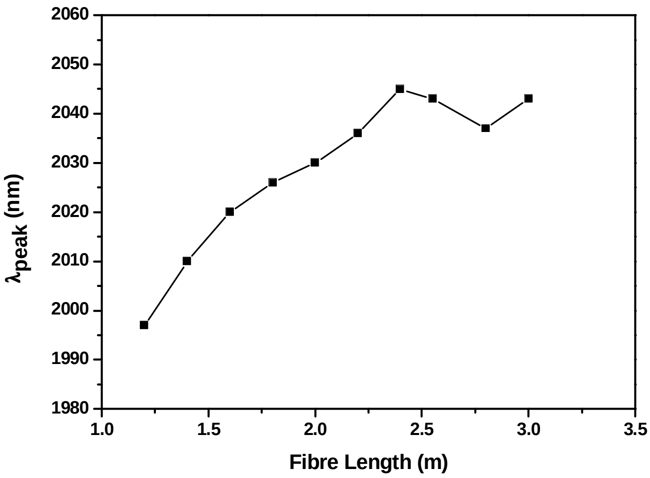

Figure 2. Peak wavelength of laser emission measured during cutback experiment.

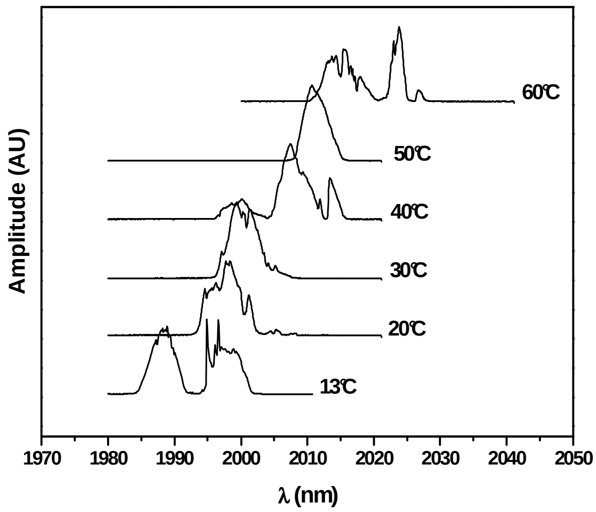

Figure 3. Measured output spectra for various coolant temperatures

In Figures 4 and 5 we show how the laser slope efficiency and threshold were affected by altering the fibre temperature. As the water temperature was increased from 15 to 61°C we observed a linear increase of the laser threshold. We also observed significant changes to the slope efficiency as the temperature was altered. Most notable was the increase in slope efficiency from 40% to 52% by lowering the water temperature from 27°C to 15°C. This indicates how crucial the effective removal of heat from the fibre is to high efficiency operation of Tm^{3+}-doped lasers when pumped at around 790nm.

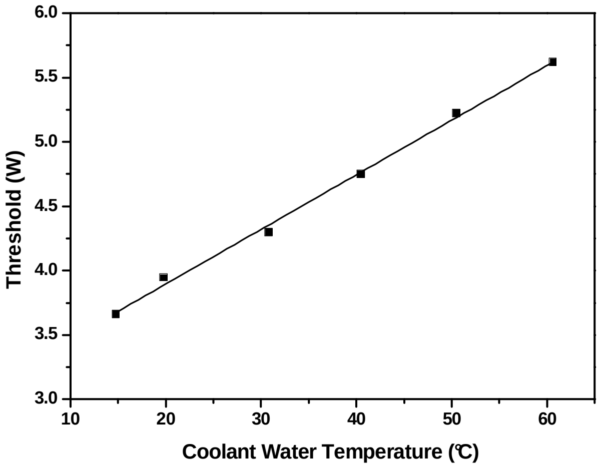

Figure 4. Laser threshold for various fibre temperatures.

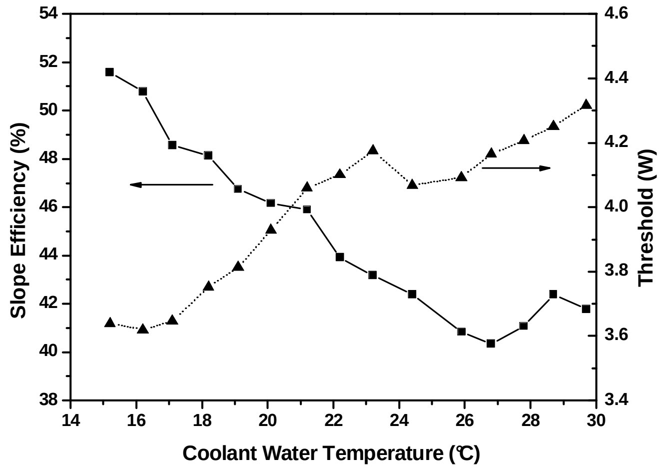

Figure 5. Laser performance for 15~30°C. Solid line shows slope efficiency, dotted line shows threshold

Fibres with similar composition but larger core/cladding ratios have intrinsically higher cladding absorption and in such fibres we found that the thermal effects were even greater. In figure 6 we show a comparison of cooling techniques for the MM-25/250 fibre. In this case over 50% increase in the slope efficiency was observed by simply air-cooling the fibre with a fan.

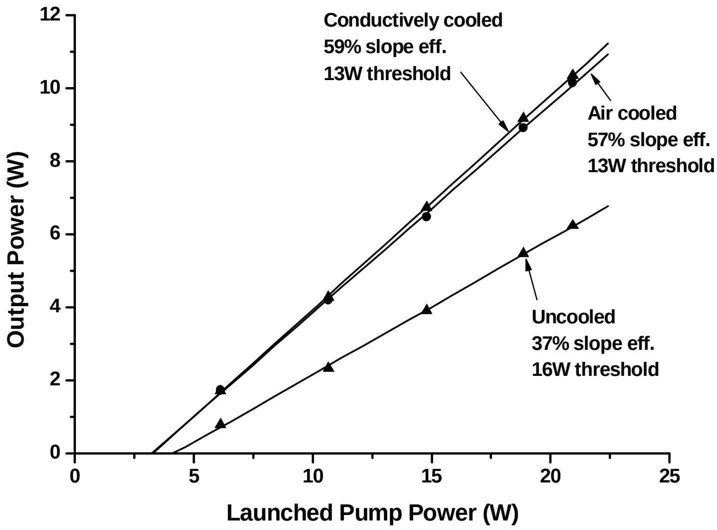

Figure 6. Comparison of cooling techniques for MM-25/250 fibre

2.2 Fibre composition and geometry

Figure 7 shows a comparison of two fibres, both approximately 2(wt.)% Tm^{3+}, but with different geometries. The MM-25/250 fibre had a core/cladding area ratio that was 2.5 times greater than the 27/400 fibre. This fibre was specifically designed to be more efficient at an operating wavelength 1.9µm by increasing the pump absorption and so reducing reabsorption at the emission wavelength. We show this effect by comparing the free-running wavelengths. Unfortunately the higher absorption of this fibre makes mitigation of thermal issues more difficult. While the 27/400 fibre with a much lower core/cladding ratio had a linear slope, the MM-25/250 fibre showed roll-off for powers greater than about 30W. By placing a low duty cycle chopper into the pump beam we have determined that the observed roll-off was a thermal phenomenon.

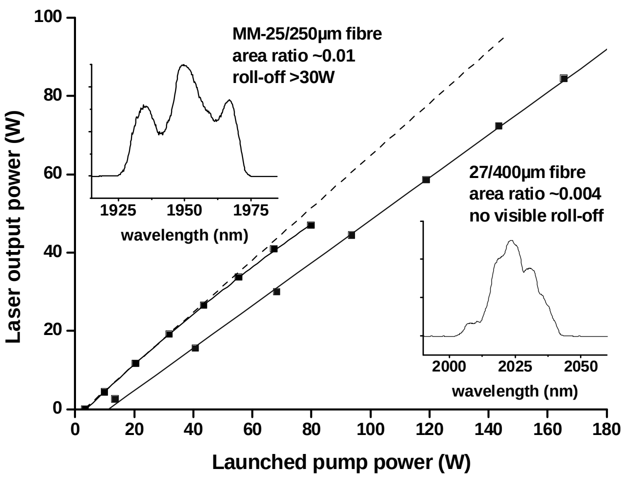

Figure 7. Comparison of ~2(wt.)% fibres with different core/cladding ratios

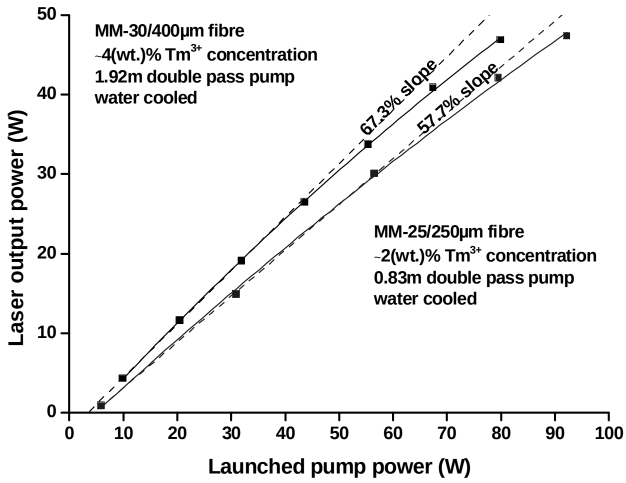

Figure 8. Comparison of ~2(wt.)% and ~4(wt.)% Tm^{3+}-doped fibres

During laser development, the lowest performance we observed was ~45% slope efficiency from a fibre with only 1.4(wt.)% Tm^{3+}. We show a comparison of fibres with different active ion concentration in figure 7. The MM-25/250 fibre had an initial slope efficiency of ~58%. By doubling the Tm^{3+} concentration we observed a higher initial slope efficiency of about 67%. This represented 173% quantum slope efficiency for the 793nm pumped 2µm laser.

2.3 High power operation

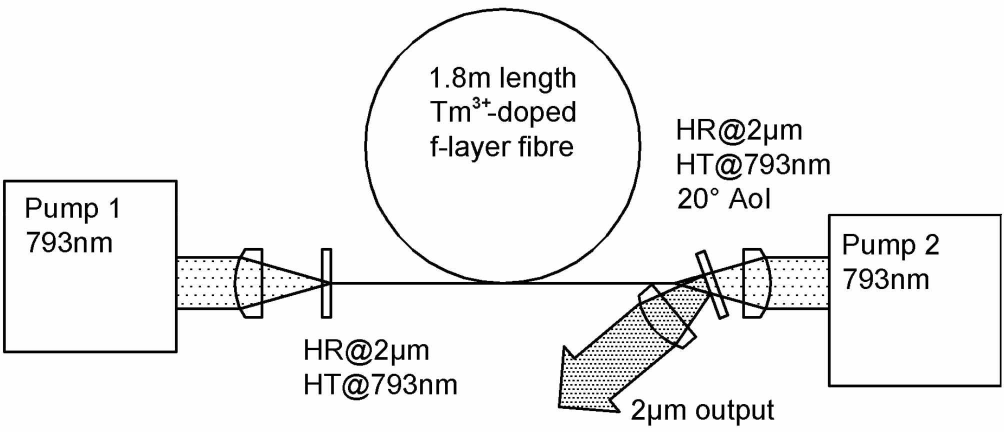

Figure 9. Efficient high power laser configuration

To date the highest power we have achieved from a 790nm pumped Tm^{3+}-doped fibre laser was 85W. The output was limited only by available pump and we did not observe any roll-off of the output power up to this value. For this experiment we used the 27/400 fibre; a 'triple-clad' design utilising two claddings for the pump. The first cladding was a fluorosilicate layer applied to the preform to give 0.24NA, the second cladding was a low refractive index UV cured polymer layer applied during drawing of the preform giving a total NA for the pump of 0.38. A high power collimated 793nm diode laser source was used to pump the fibre at each end. Rather than attempting to focus the pump and collimate the 2µm beam with a single lens, we butted a dichroic mirror directly to the fibre facet at one end and used two lenses with a dichroic beamsplitter at the other. The mirrors were manufactured with a damage threshold of ~400MW/cm² to withstand the high incident intensity from the fibre core. For efficient operation, the ends of the fibre were conductively cooled and the remainder of the fibre was water cooled at room temperature.

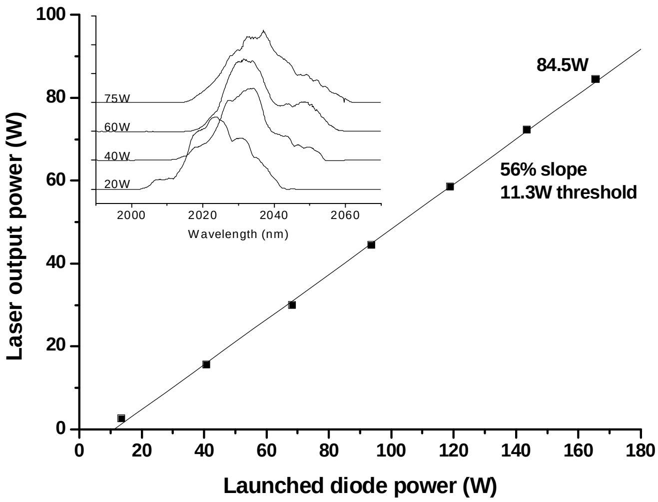

Figure 10. Slope efficiency and spectral output of laser

2.5 Fixed wavelength operation

One limiting factor of our high power laser configuration was the use of a dichroic reflector butted to the end of the fibre. Using a dielectric reflector resulted in broad wavelength emission and also a high degree of spectral instability. As a remedy this problem we investigated the use a fibre Bragg grating (FBG) as the cavity reflector. Our requirement of high concentrations of Tm and Al within the core resulted in fibres with highly multimode cores. Mizanumi *et al* showed that Bragg gratings in multimode fibres result in a spread spectrum of low reflectivity peaks due to coupling between laser modes.[8]

To achieve single transverse mode operation, the MM-25/250 fibre design was modified to incorporate a raised refractive index 'pedestal' around the fibre core. This resulted in an effective core NA of 0.10 (V~4.1 @ 1.9μm) and an M^2 of <1.3 indicating single transverse mode operation using slight coiling of the fibre.

Using a phase mask and 244nm laser, gratings were written into the core of a photosensitive passive fibre that was mode-matched to the pedestal (LMA-25/250) fibre. The active fibre was then spliced to the passive fibre containing the grating. Output coupling was from the Fresnel reflection of the cleaved fibre face only. Figure 11 shows the output spectrum of the laser at 1892nm. The line width was approximately 1.6nm FWHM with one observed side lobe. By writing a longer grating with apodisation we aim to suppress the side lobe and decrease the line width.

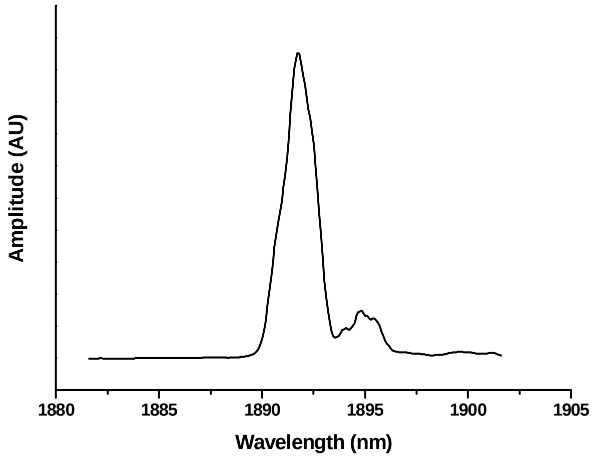

Figure 11. Wavelength spectrum of FBG tuned laser with LMA-25/250

2.6 Performance as an amplifier

Testing as an amplifier was performed using the MM-25/250µm fibre in a master oscillator/power amplifier configuration. The amplifier was seeded at 1.9µm using a multimode source with a broad spectral linewidth of ~3.5nm. Figure 12 shows the absorbed and launched slope efficiency for 6dB gain. As we can see, for low gain, broad linewidths we obtain similar efficiencies to the lasers.

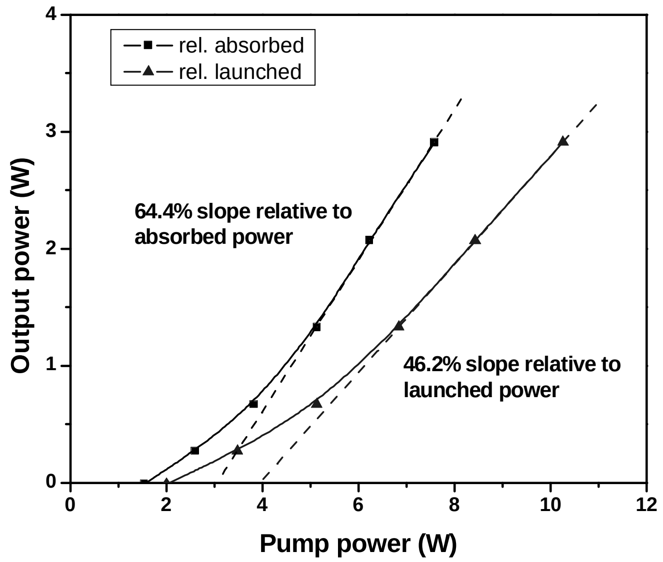

Figure 12. 1.9µm CW amplifier using the MM-25/250 fibre

3. DISCUSSIONS

Conversion efficiencies of Tm^{3+}-doped fibre lasers are rapidly approaching those of Yb^{3+}-doped which to date have been scaled beyond the 1kW level.[9] We have shown pump power limited performance up to 85W without evidence of roll-off. The key to achieving high powers with high efficiency lies within the ability to effectively extract heat from the fibres. Unlike Yb^{3+}-doped fibres where low dopant concentrations may be used to help distribute the heat load over a long length of fibre, Tm^{3+}-doped fibres require relatively high active ion concentrations to optimise the cross-relaxation process.

With appropriate thermal management of Tm^{3+}-doped fibres, we have demonstrated high powers and efficiencies are achievable. We have shown successful wavelength tuning of these devices to ~1.9µm using fibre Bragg gratings. Single mode operation was achieved in a relatively large, high refractive index core by using a raised refractive index ‘pedestal’ surrounding the core.

We predict that the solution to engineering these lasers to higher powers will require reduction of the fibre heat loading either by using small core/clad area ratios to distribute the pump over a longer length, or by pumping slightly off the peak absorption wavelength. As with any three-level laser, this will be at the expense of higher reabsorption losses which may restrict practical high power operation to wavelengths above 2µm where the $^3H_6 \rightarrow {}^3F_4$ absorption is lower.[10]

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