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ABSTRACT

The trivalent thulium ion is an interesting activator for silica fiber lasers because of the near infrared transition which is broad-band tunable (>250nm), diode pumpable, can be operated with photon conversion efficiencies greater than 100% and has yielded in excess of 1W output power when pumped by a cw Nd:YAG laser. The paper will review progress on this system and indicate some potential future developments.

1. INTRODUCTION

The spectroscopic properties of the Tm^{3+} ion in a silica glass host present a sharp contrast with those of its neighbor in the lanthanide series, Er^{3+}. The importance of the "third window" wavelength of Er has generated great interest in this system, with relatively little attention being paid to the corresponding infrared transition in Tm. Nevertheless Tm offers some features which are unique among fiber lasers.

Whereas the $\approx 400 cm^{-1}$ width of the $^4I_{13/2}$-$^4I_{15/2}$ Er fluorescence band is amongst the narrowest observed for any lanthanide in a silica-based glass host, the $\approx 2000 cm^{-1}$ width of the $^3H_4$-$^3H_6$ Tm transition is amongst the broadest. The wavelengths at which laser action in Tm:silica fiber have been demonstrated span nearly $1200 cm^{-1}$, with continuous tunability over this range possible in principle although this has not yet been accomplished in a single resonator. This tuning range includes the central wavelengths of molecular absorption bands of carbon dioxide and water vapour, as well as a local maximum in the absorption spectrum of liquid water, suggesting applications in atmospheric sensing and medicine.

The large line broadening reflects a strong coupling of the electronic states of the Tm ion to random local strain in the silica host. An associated penalty is the rapid decay of the $^3H_4$ population by multiphonon emission which limits the lifetime of this level in silica to 500μs or less. By contrast the $^4I_{13/2}$ level of Er has an essentially radiative lifetime of ≈10ms, for low concentrations. The multiphonon emission process depends exponentially on the energy interval to the next lower level, which is smaller in Tm than in Er, and may be effectively further reduced by the large strain broadening of the ground $^3H_6$ multiplet. In addition, the electronic states of Tm are presumably more strongly coupled to the dynamic modes of the silica matrix than those of Er, just as they are more sensitive to static random strain.

The radiative quantum efficiency of the $^3H_4$ metastable level is estimated to be ≈12% in the best solution-doped fibers, fabricated in oxygen-rich conditions, and less than half that in early solution-doped fibre where the oxygen content was not controlled. Compared with the Er or Nd transitions the threshold for lasing of the Tm transition is therefore high. However above threshold the transition can exhibit high slope efficiency because of the peculiarly high pump quantum efficiency potentially available on the $^3H_6$-$^3F_4$ pump transition.

The ground, first, second and third excited multiplets of the Tm ion are shown in Figure 1 beside a spectrum showing the corresponding absorption bands for a solution-doped fibre containing 840ppm of Tm ions in the core. The strong absorption at the 790nm peak of the $^3H_6$-$^3F_4$ transition is pumpable by an AlGaAs diode. Whereas in Er-doped silica the AlGaAs diode pump band is subject to strong excited state absorption (ESA), for Tm ESA at this wavelength is negligible favouring efficient diode-pumped operation.

A further gain in efficiency can be realised when the Tm ion concentration is raised to a level at which Tm-Tm pair interactions become significant. A well-known cross-relaxation process populates the $^3H_4$ level from the pumped $^3F_4$ level with a quantum efficiency of 2.

Progress in efficient .8μm pumped operation of the infrared Tm transition is described in Section 2, which presents evidence for photon conversion efficiencies >100% in a system which is not yet optimised. High power operation is described in Section 3 and the potential for tunable operation is reviewed in Section 4.

2. EFFICIENT OPERATION

A silica-based fibre, fabricated by the MCVD technique, and given to us by Hong Po of the Polaroid Corporation, yields higher conversion efficiencies than any of the solution-doped fibres that we have investigated so far. The Tm ion concentration of this fibre is of order 3000ppm (≈7.10^{19} cm^{-1}) and the core diameter and numerical aperture are 12μm and 0.166 respectively, defining an LP_{11} mode cut-off wavelength of 2.6μm.

Efficient operation was demonstrated using a Ti:sapphire pump laser tuned to the 790nm absorption peak. The input end of the fiber was butted to a dielectric mirror with a reflectivity >99.5% at 1.9μm and a transmission >90% at 790nm. The output coupler, which transmitted 20% of the 1.9μm laser radiation, was also butted to the fiber. Approximately 65% of the pump power incident on the objective was launched into the fiber core, and of this at least 95% was absorbed.

The threshold for laser action was ≈50mW, and above threshold a slope efficiency of 32% was measured, specified in each case with respect to power incident on the launch objective. This value of the slope efficiency implies a photon conversion efficiency above threshold of ≈120%.

The possibility of laser operation with quantum efficiency >1 arises by virtue of a cross-relaxation process that provides an alternative decay path for the $^3F_4$ multiplet when the excited ion is sufficiently close to an adjacent Tm ion in the ground multiplet. The decay path may be written symbolically

$$(^3F_4, ^3H_6) - (^3H_4, ^3H_4)$$

where the bracketed terms represent the states of the two interacting ions before and after cross-relaxation.

The level of concentration at which cross-relaxation becomes a significant effect is dependent on the host. In garnet crystals the $^3F_4$ term populates the $^3H_4$ term with a quantum efficiency ≈2 for Tm ion concentrations $>8.10^{20}$ cm^{-3} and this effect has been used to demonstrate diode-pumped operation of a Tm:YAG crystal at 2.02μm with a slope efficiency of 56%[1]. In a glass host the possibility that clustering of the dopant ions reduces the actual separation between adjacent ions must be considered, and this effect is known to give rise to biexponential decays in Nd:silica fiber and degrade the performance of Er:silica fiber amplifiers for dopant concentrations above 1000ppm.

It is therefore surprising that in solution-doped Tm:silica fibres with concentrations of ≈1000ppm no spectroscopic evidence for cross-relaxation (biexponential decays, concentration-dependent branching ratios) has been detected. The experiment described here was repeated substituting a fiber of this type for the MCVD fabricated fiber, and although the threshold for laser operation was similar, the slope efficiency was smaller by a factor of ≈2.

So far no attempt has been made to fabricate solution-doped fibers with much higher Tm ion concentrations and this will be the subject of future work.

3. HIGH POWER OPERATION

An output power of 1.3W at 2.01μm has been demonstrated for Tm:silica fibre lasing on the $^3H_4$-$^3H_6$ transition[2]. This experiment exploited the weak absorption at 1.064μm ($2dBm^{-1}$ for 840ppm) in the high energy wing of the $^3H_6$-$^3H_5$ transition, using a cw Nd:YAG laser as the pump source. The 1.064μm pump wavelength, unlike 780nm, is subject to strong excited state absorption, and blue emission from the fibre appears under Nd:YAG laser pumping. To achieve high output power it was found essential to observe rigorous precautions to minimize cavity losses and keep the inversion at threshold as small as possible. The resonator was constructed with dielectric mirrors butted directly against fiber ends prepared with a high quality cleave.

To overcome the limitation which mirror damage imposes on high power operation the size of the fiber core was increased from that reported in earlier work[3]. A fiber with core diameter of 17μm was used in conjunction with a x10 launch objective, ensuring that with the maximum incident pump power of 9.6W the threshold for mirror damage was not exceeded. The Nd:YAG beam was launched into the large area core with an

overall efficiency of 55%.

The fiber was fabricated by solution-doping with 840ppm of Tm ions in a germanosilicate core. An LP_{11} cut-off wavelength of 2.7μm was predicted for this fibre, implying that two modes can propagate at the laser wavelength. However investigation of the intensity profile of the laser output showed that operation on the fundamental mode was observed up to the highest powers demonstrated.

The maximum output power of 1.35W was achieved with a fiber length of 0.7m and 9.6W of incident pump power of which ≈4.5W was absorbed in the core. The performance was found to be extremely sensitive to adjustments of the cavity mirrors. Threshold for this laser was typically reached with ≈600mW of absorbed power, and the photon conversion efficiency above threshold was estimated to be ≈70%, a value which presumably reflects losses due to pump excited state absorption.

Future prospects for this system include the extension to multimode YAG laser pumping at higher power, perhaps using a cladding pumping scheme[4], and developing alternative core compositions, tailoring the Tm level structure to enhance 1.064μm ground state absorption and reduce excited state absorption. It seems likely that multiwatt cw operation at around 2μm will eventually be achieved.

4. TUNABLE OPERATION

Continuously tunable operation of a Tm-doped fiber laser over the range 1.780-2.056μm has been demonstrated using an intracavity Lyot filter[5]. The dependence of output power on wavelength is shown in Figure 2. This result was obtained using a solution-doped germanosilicate fiber with a Tm ion concentration of ~840ppm in the core. This fiber was preferred for the tuning experiment because the infrared fluorescence spectrum of Tm in solution-doped germanosilicate and aluminosilicate fibers is found to be ~15% broader than that in the MCVD fabricated fiber.

This experiment indicated the potential of the Tm: silica system even though the tunable laser was very far from being optimised. A Styryl 9M dye laser was used as a pump source, giving incident power of 240mW at 810nm, a wavelength which represented a compromise between diminishing Tm absorption and diminishing dye laser output. The transmission sidebands of the 3 plate Lyot filter limited the tuning range achievable with a single fiber length, so that a shorter piece of fiber had to be used to cover the high energy end of the range where the transition has a more nearly 3-level character. An intracavity x10 microscope objective was used to define a low divergence mode through the Lyot filter, and this had poor transmission at 2μm and introduced a large resonator loss. In this experiment both resonator mirrors were high reflectors (>99.5%) and with this minimal output coupling the greatest output power observed at the peak of the tuning curve was only of the order of 100μW.

More recently an extension of the tuning range to shorter wavelengths (1.65μm) has been reported[6] using a Ti:sapphire pump laser at 788nm and a grating-tuned resonator. Further optimisation of this system is clearly possible.

5. ACKNOWLEDGMENTS

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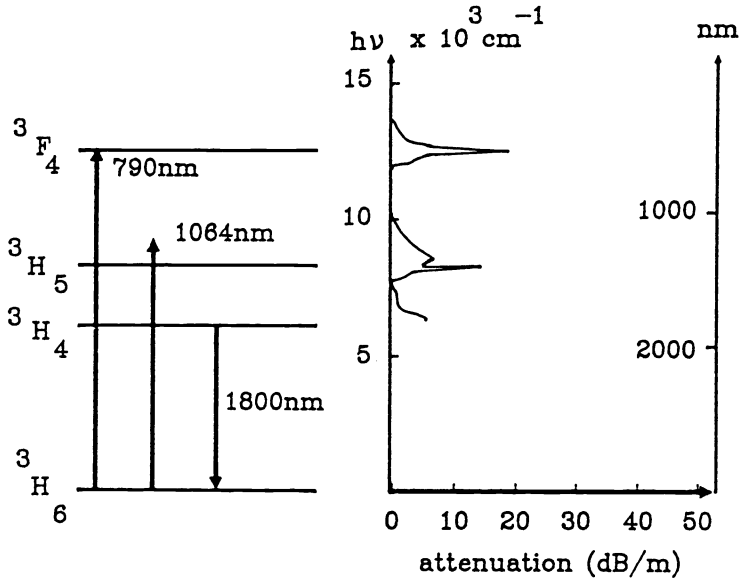

Figure 1. Partial term diagram for the Tm^{3+} ion, with absorption spectrum showing pump bands in 840ppm solution-doped fiber.

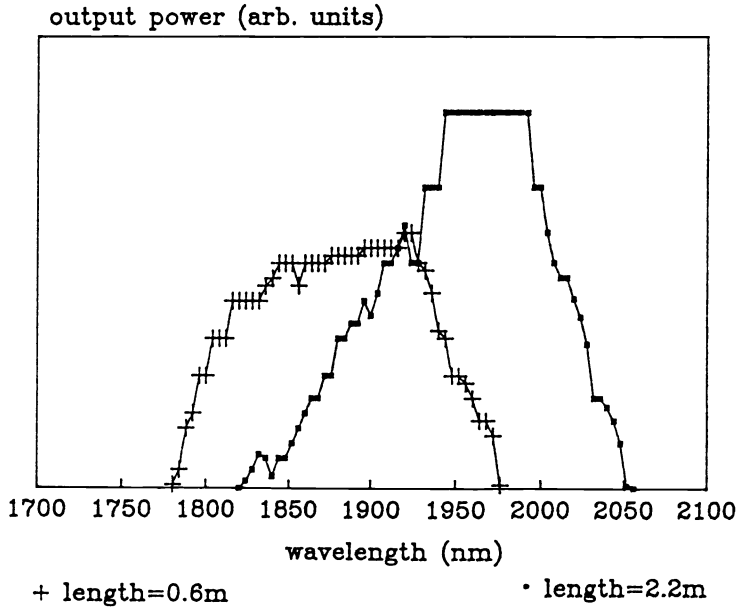

Figure 2. Wavelength dependence of output power from the $^3H_4$-$^3H_6$ transition for two lengths of 840ppm Tm-doped germanosilicate fibre.