EFFICIENT AND TUNABLE OPERATION OF A Tm-DOPED FIBRE LASER

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We report on improved performance from a silica based thulium doped fibre laser. Under excitation at 810 nm this system has demonstrated a near theoretical maximum slope efficiency of 36% (84% photon conversion efficiency), corresponding to 44 mW of laser output power at 1900 nm for 167 mW of absorbed power. In addition we have used a birefringent filter to continuously tune the laser over a range of 276 nm, from 1780 to 2056 nm.

1. Introduction

Laser sources in the neighbourhood of 2 μm are currently being investigated with a view to applications in such diverse fields as medicine and eye safe laser radar. In pursuit of efficient, compact and cheap sources of laser radiation for this region the thulium doped fibre laser must be considered a serious contender. This point is illustrated by the results presented here which show that for pump wavelengths around 800 nm, where AlGaAs diode lasers are currently available, high efficiency performance is possible for quite modest powers.

To date three absorption bands have been identified as viable routes to the production of 2 μm laser radiation from thulium. To summarise, by pumping at 660 nm into the $^3F_{2,3}$ absorption band with a DCM dye laser a threshold of 50 mW absorbed was achieved with a slope efficiency of 1.3% [1]. The second by pumping at 1064 nm into the wings of the $^3H_5$ absorption band with a cw YAG laser a threshold of 60 mW absorbed has been demonstrated with a corresponding slope efficiency of 30% [2]. Finally by pumping at 797 nm into the $^3F_4$ absorption band with a Styryl 9M dye laser yielded a minimum threshold of 21 mW absorbed and a slope efficiency of 13% [3]. In this paper we report on an improved performance for the ≈800 nm pumping, with better than an order of magnitude improvement in the output power, and also a demonstration of the very wide tuning range available.

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2. Experimental

The experiments described here were performed using two different silica fibres. Those leading to the best threshold and slope efficiency were performed on a silica based fibre fabricated by the MCVD technique (provided by Hong Po of the Polaroid Corporation). Its characteristics are as follows, a dopant ion concentration of the order of 3000 ppm, numerical aperture 0.166, core diameter of 12 μm, and an LP_{11} mode cut-off wavelength of 2.6 μm. In contrast the best tuning performance was achieved using a germano-silica based fibre manufactured by the solution doping technique [4] (provided by J.E. Townsend, Optical Fibre Group, Southampton University). Its characteristics are as follows, a nominal dopant ion concentration of 830 ppm, numerical aperture 0.15, core diameter 8.3 μm, and an LP_{11} mode cut-off wavelength of 1.7 μm ensuring good launch of the pump and monomode operation of the laser over its entire tuning range.

The energy levels and absorption features for thulium in silica are shown in fig. 1. Pumping between 800–810 nm with a Styryl 9M dye laser thus excites population from the ground state, $^3H_6$, into the low energy side of the $^3F_4$ absorption band. From here

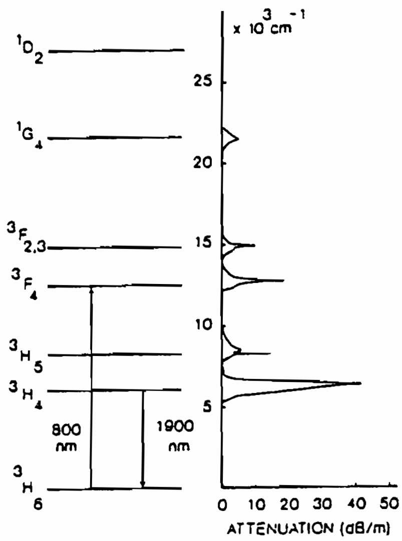

Fig. 1. Energy levels and absorption spectrum for Tm^{3+} in a silica host.

there is rapid non-radiative decay of the population to the upper laser level, $^3H_4$. Radiative decay then occurs from the $^3H_4$ level down to the ground with a characteristic lifetime of 500 μs for the MCVD fabricated fibre, whilst in the solution doped fibre it is found to be ≈ 200 μs [*1]. The reason for this variation in the two measured lifetimes is not completely clear, but it was noted that there were imperfections in the particular solution doped fibre used in this work [5]. Note also that there is a definite narrowing of the fluorescence spectrum from the MCVD fabricated fibre over that from the solution doped fibre, fig. 2. Measurements taken in sidelight, to avoid distortion due to reabsorption reveal that the MCVD fibre has a linewidth of ≈ 300 nm, and the solution doped fibre a linewidth of ≈ 340 nm. It is this broad linewidth that provides a strong interest in tuning this laser.

To investigate laser performance in the MCVD fibre the input end of a ≈ 30 cm length of fibre was butted to a dielectric mirror with a reflectivity

[*1] Solution doped fibres of various concentrations were fabricated with both higher and much lower concentrations but with no variation in the measured fluorescence lifetime of 200 μs.

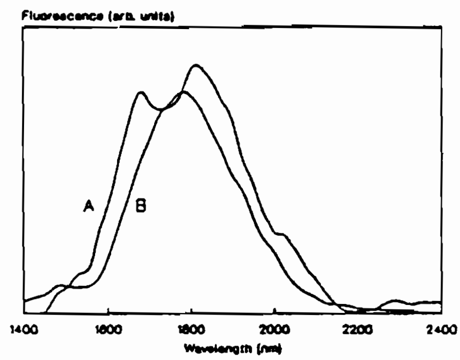

Fig. 2. Side-light fluorescence spectrum for the two fibres used in the experiments. A: solution doped fibre; B: MCVD doped fibre.

> 99.5% from 1.7–2.1 μm and better than 90% transmission in the range 800–810 nm. To complete the cavity a second mirror with the above specification was butted to the output end of the fibre. With this arrangement the threshold for laser oscillation was ≈ 17 mW absorbed power, and the lasing wavelength was ≈ 2.01 μm. Under these conditions the cavity losses were measured by means of the relaxation oscillation technique [6], to be between 10–20% per pass. The losses were measured beyond 2 μm since laser operation can be considered virtually four-level, with minimal reabsorption losses. The observed loss is rather greater than measured in a number of earlier experiments on fibre lasers, and suggests that this fibre also has imperfections.

On replacing the high reflector at the output with an output coupler of 20% transmission the threshold increased to 44 mW absorbed and the lasing wavelength shortened to 1900 nm for a ≈ 22 cm fibre length. The slope efficiency for this arrangement was 36% with respect to absorbed power, or a photon conversion efficiency of 84%, fig. 3. This slope corresponds to a maximum output power of 44 mW at 1900 nm for 167 mW of absorbed power at 810 nm where the performance was optimum.

In order to investigate the tuning in this system a resonator was set up, fig. 4, in which a three plate birefringent filter from a commercial dye laser was used for wavelength selection. The two mirrors used for the tuning were high reflectors (R > 99.5%) from 1.7–

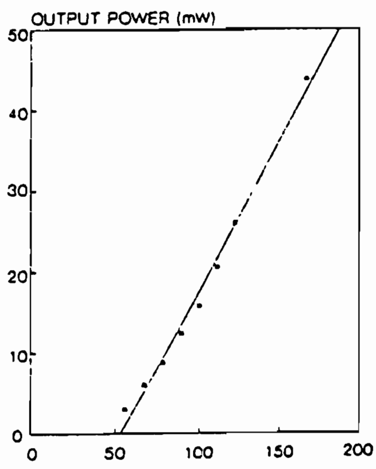

Fig. 3. Fibre laser output power against absorbed pump power. HR: high reflector; 10× : 10× microscope objective.

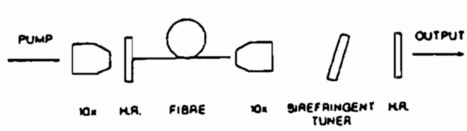

Fig. 4. Resonator configuration used for tuning the fibre laser.

2.1 µm, output coupling was therefore minimal. As a consequence at the peak of the tuning curve the maximum observed laser power was only of the order of 100 µW. For the MCVD fabricated fibre the tuning range extended from 1.84–2.04 µm for a single fibre length of ≈20 cm, but suffered from large variation of the laser output with wavelength. This behaviour has been previously noted while tuning the ytterbium fibre laser, and was ascribed to variations in the polarisation state as the wavelength is varied due to birefringence in the fibre [7]. In the referenced work we were able to counteract this effect, and subsequently improve the tuning range, by inserting a series of fibre loops by which the required polarisation state could always be maintained. However in this instance we were unable to use the loop polarisation controllers since they would require too

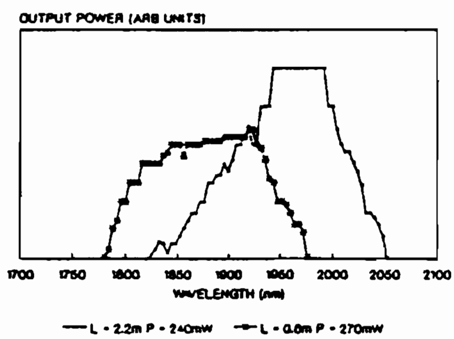

Fig. 5. Tuning curves for the thulium fibre laser. A: 2.2 m fibre, incident power 240 mW; B: 0.6 m fibre, incident power 270 mW.

great a length of fibre, thus introducing so much reabsorption loss that laser operation would not be achievable.

Despite the higher threshold and lower slope efficiency from the solution doped fibre in the simple butted mirror cavity [2], we have obtained a wider tuning range, 276 nm, from two pieces of this fibre, fig. 5. Using the same resonator described above a 2.2 m length of fibre was tuned from 1820–2056 nm for an incident power of 240 mW. The fibre length was then cut-back to 0.6 m. In this case, with an incident power of 270 mW it was found that the tuning range could be extended down to 1780 nm by virtue of the reduced self-absorption losses. The long wavelength limit was reduced however, since a shorter length also means less absorbed power, hence less gain at the longer wavelengths. Although fibre lengths were more appropriate for the inclusion of the polarisation controllers it proved unnecessary for this solution doped fibre. One can only assume that this particular fibre fabricated by the solution doping technique was coincidentally polarisation preserving.

3. Discussion

These results clearly indicate that the most efficient absorption band in thulium is the $^3H_6$–$^3F_4$ transition around 800 nm, since at this wavelength there is no significant excited state absorption (ESA). This cannot be said for the alternative pumping schemes which involve the $^3H_6$–$^3F_{2,3}$ transition at 660 nm and the $^3H_6$–$^3H_5$ transition which was pumped at 1064 nm, where in each case upconversion of the pump light led to strong emission in the blue [8].

From a practical point of view the logical extension of this work would be to investigate the laser performance using an AlGaAs diode laser, targetted to the peak of the $^3H_6$–F_4 absorption band (785–795 nm), as the pump source. We note that the prospect exists for much lower thresholds since the quantum efficiency of the $^3H_4$–$^3H_6$ transition observed in these fibres can in principle be increased by an order of magnitude. We estimate the radiative lifetime for this transition in the solution doped fibre, calculated from the observed integrated absorption, to be 3.4 ms. Thus the observed lifetime of 200 μs implies a quantum efficiency of ≈6%. The MCVD fibre showed a significantly longer fluorescence lifetime, 500 μs, and this was reflected in its improved performance. For thulium doped fluorozirconate glass observed fluorescence lifetimes are many milliseconds indicating essentially 100% quantum efficiency. This suggests that low threshold diode-pumped operation will be a practical reality in fibres made of fluorozirconate glass or other glasses for which high quantum efficiencies can be achieved.

Another direction in which one might hope to improve performance is to extend the tuning range towards shorter wavelengths, in fact the fluorescence emission (fig. 2) extends below 1600 nm. If sufficient pump power were used to invert the $^3H_6$–$^3H_4$ transition, thus removing the self-absorption at short wavelengths, then laser operation in the quasi three-level region should in principle be possible. However it should be pointed out that ESA of the emitted light from the upper laser level $^3H_4$, to the $^3F_4$ level, might prevent tuning into this short wavelength region. Further measurements are needed to investigate this question.

4. Conclusion

We have demonstrated the highest efficiency to date for a thulium doped glass laser, this being achieved by utilising the $^3H_6$–$^3F_4$ absorption band around 800 nm where there are no problems with ESA. The system exhibited a slope efficiency of 36% (photon conversion efficiency 84%), with a maximum output power of 44 mW at 1900 nm for 167 mW of absorbed power at 810 nm. In addition this system has also demonstrated one of the widest tuning ranges of any fibre laser, covering 276 nm from 1780 to 2056 nm.

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