Continuous-Wave Oscillation of a Monomode Thulium-Doped Silica Fiber Laser

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ABSTRACT

A Tm^{3+}-doped silica fibre laser has been tuned from 1.81μm to 2.01μm when pumped with a Styryl 9M dye laser at 800nm. The pump powers required are compatible with those available from high brightness laser diodes.

INTRODUCTION

To date several low threshold tunable lasers based on rare-earth-doped silica optical fibres have been demonstrated. The first such device was based on a Nd^{3+}-doped fibre and was tunable from 0.900μm to 0.945μm and from 1.070μm to 1.135μm [1,2]. The largest tuning range reported to date is for an Yb^{3+} doped silica fibre laser [3] which operated between 1.01μm and 1.16μm. The longest wavelength reported to date for a tunable fibre laser was for an Er^{3+}-doped system which tuned from 1.53μm to 1.60μm [1].

Tm^{3+} is an interesting activator ion for a tunable silica fibre laser since it has a broad emission near 1.9μm, a region where such lasers have not previously operated. Additionally, Tm^{3+} has an absorption band at around 800nm and is thus a candidate for pumping with an AlGaAs laser diode. We have recently reported [4] the operation of Tm^{3+}-doped silica fibre laser which emitted at discrete wavelengths between 1.88μm and 1.96μm. In this paper we report the operation of a Tm^{3+}-doped fibre laser which is tunable continuously from 1.81μm to 2.01μm.

SPECTROSCOPY

In the experiments described here a germano-silica based fibre produced by the solution doping technique [5] was used. The fibre was characterised by a Tm^{3+} concentration of approximately 830ppm, numerical aperture of 0.15, cut-off wavelength of 1.7μm and core diameter 9μm.

The absorption spectrum of a fibre of the above characteristics is shown in Fig. 1. There are, therefore, several possible pump wavelengths with the most attractive being at around 800nm corresponding to absorption from the $^3H_6$ ground state to the $^3F_4$ level. This wavelength is attractive because cheap high power laser diodes are available in this region. In the experiments described in this paper a Styryl 9M dye laser was used to simulate such a device. The presence of an absorption band at around 670nm ($^3H_6$ to $^3F_2$, $^3F_3$) means that a DCM dye laser is also a possible pump source. Laser diodes which emit at 670nm are also becoming available but are more expensive and of much lower power (4mW), than those at around 800nm. Millar et al [6] have previously reported the observation of photochromic effects in Tm^{3+}-doped silica fibres when pumping with an Ar^+ laser. The excess loss induced in this way precludes the use of an Ar^+ laser for pumping a Tm^{3+}-doped silica fibre laser.

The fluorescence spectrum of Tm^{3+} under excitation at 800nm is shown in Fig 2. The curve labelled 'end-light' shows the spectrum of light which has been guided down a 27cm length of fibre; that labelled 'side-light' shows the spectrum of light scattered perpendicular to the fibre axis. The effect of self-absorption (from thermally populated Stark levels in the ground state multiplet) is evident on comparing the two curves, the wavelength of peak emission having been shifted to longer wavelengths for light which has been longitudinally guided. This is due to the emission at shorter wavelengths having

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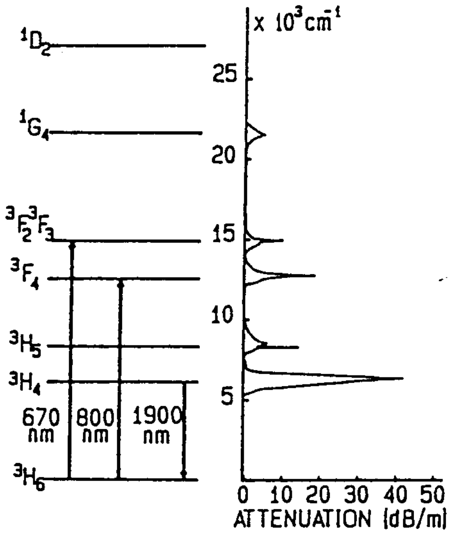

Figure 1. Energy levels and absorption spectrum for the Tm^{3+}-doped fibre used in this experiment

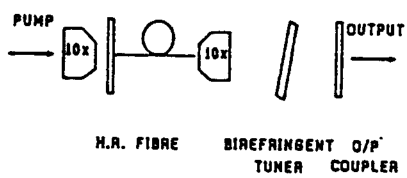

Figure 3. Resonator for tunable operation

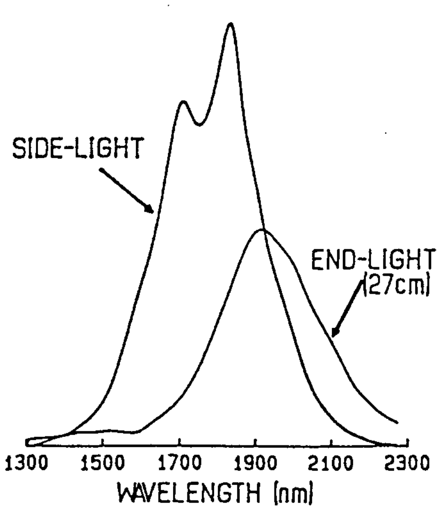

Figure 2. Fluorescence spectra for the $^3H_4$ to $^3H_6$ transition in Tm^{3+}-doped silica

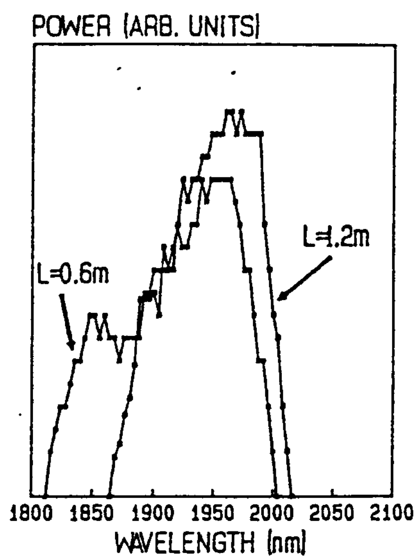

Figure 4. Output power as a function of tuned wavelength for Tm^{3+}-doped fibre laser

been reabsorbed in the fibre. The most striking feature of these curves is the very large linewidth of ≈300nm for the $^3H_4$ to $^3H_6$ transition. Additionally a weak second peak at ≈1.4μm is resolved in end-light. We believe this corresponds to emission from the $^3F_4$ level to the $^3H_4$ level.

The lifetimes of the $^3F_4$ and $^3H_4$ levels were measured by chopping the pump beam and monitoring the fluorescence decay. The life time of the $^3F_4$ level was measured to be ≈10μs which suggests significant decay by non-radiative routes from this level. The lifetime of the $^3H_4$ level was measured to be ≈200μs. By integrating over the $^3H_6$ to $^3H_4$ absorption, the radiative lifetime of the $^3H_4$ level was estimated to be 3.4ms. This suggests a radiative quantum efficiency of just 6% for the $^3H_4$ to $^3H_6$ transition in silica.

On pumping at 660nm with a DCM dye laser a similar fluorescence spectrum to that shown in Fig 2 was obtained. Additionally blue emission at ≈460nm and u.v. emission at ≈370 nm was observed with emission at both wavelengths having a quadratic dependence on pump power, thus implying a two photon upconversion process. This is believed to be due to absorption of the pump from the $^3F_2$ and $^3F_3$ excited levels to the $^1D_2$ level. The blue emission thus corresponds to decay from the $^1D_2$ to $^3H_4$ levels with the u.v.emiasion corresponding to decay from the $^1D_2$ level to the $^3H_6$ level. In both cases the fluorescence lifetime was measured to be ≈200μs. This upconversion process will be described in more detail elsewhere [7] along with details of upconversion in Yb^{3+}-sensitised Tm^{3+}-doped silica fibres.

LASER OPERATION

A laser cavity was formed by butting dielectric mirrors against either end of a cleaved fibre. Light from the dye laser was launched into the fibre by a 10x microscope objective. Optimal results were obtained with a 27cm length of fibre. Pumping at 797nm, near the peak of the $^3H_6$ to $^3F_4$ absorption band, and using mirrors of greater than 99% reflectivity at the lasing wavelength c.w. oscillation was observed at 1.96μm with an absorbed pump threshold of 21mW (30mW incident). On changing the output coupling to about 3%, laser emission was seen at 1.94μm. Here the threshold absorbed power was unchanged at 21mW (30mW incident) and a slope efficiency, with respect to absorbed power, of 13% was measured. The maximum extracted power in this configuration was 2.7 mW.

As an alternative to pumping at ≈800nm, the effect of pumping with a DCM dye laser at 660nm was also examined. With this pump source the threshold absorbed pump power increased to 50mW, with a slope efficiency of 1.3%. It should be noted that output coupling was only about 1% for this laser. We believe the relatively poor performance for this pump wavelength is due to excited state absorption of the pump as described earlier.

In order to obtain tunable operation of this fibre laser we used a 3-plate birefringent tuner from a Coherent 599 dye laser as an intracavity tuning element. The resonator used to obtain tunable operation is shown in Fig 3. In this resonator the input mirror had >99% reflectivity over the observed tuning range. Output coupling was about 1% over the entire tuning range.

Initial measurements of tunable behaviour were made with a 1.2m length of fibre. With this length the minimum incident threshold pump power for laser oscillation was found to be 80mW. It was possible to tune this laser over a 150nm range from 1.864μm to 2.014μm. The extracted power as a function of lasing wavelength is shown in Fig 4. The maximum output power was ≈100μW for an incident power of 210mW at 800nm. We believe that significant improvements in extracted power should be possible with a resonator of lower loss and with optimised output coupling. The fibre length was then cut back to 0.6m. In this case, with an incident power of 250mW, the tuning range extended down to 1.81μm owing to reduced self-absorption losses for the shorter length. The power extracted as a function of tuned wavelength is also shown in Fig 4. The long wavelength limit of this tuning curve is less than that for the 1.2m case as there is less pump power absorbed in the fibre for the shorter length and consequently less gain at these wavelengths.

CONCLUSIONS

We have demonstrated, we believe for the first time, a widely tunable fibre laser at around 1.9μm based on Tm^{3+}-doped silica fibre. Additionally Tm^{3+}-doped fibre lasers have been shown to operate with slope efficiencies of up to 13% in this region. These results have all been obtained by pumping at around 800nm and at power levels compatible with high brightness diode lasers. It should, therefore, be possible to construct an all solid-state tunable laser operating near 2μm which is based on Tm^{3+}-doped fibre.

The reason for the high threshold relative to other fibre lasers is mainly due to significant decay by non-radiative routes from the upper laser level. Generally nonradiative decay is much reduced in fluoride glasses so a Tm^{3+}-doped fluoride fibre laser could be expected to have a lower threshold than the laser described here.

Future work will be aimed at increasing the present tuning range by pumping with Styryl 8 dye nearer the $^3H_6$ to $^3F_4$ absorption peak at ≅790nm. These improvements may allow saturation of the ground state absorption and with the consequent reduction in re-absorption losses allow the tuning range to be extended to significantly shorter wavelengths.

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