A 1-Watt thulium-doped cw fibre laser operating at 2 μm

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We report efficient high power (> 1 W) single transverse mode continuous-wave laser action at 2 μm in a thulium-doped silica-based fibre laser pumped by a Nd:YAG laser at 1.064 μm. The highest measured output power was 1.35 W. A threshold of 600 mW absorbed and slope efficiency of 37% with respect to absorbed power were observed.

1. Introduction

Fiber lasers have recently been receiving considerable attention as efficient and convenient laser sources and amplifiers for a wide range of wavelengths, from the visible to the mid-infrared. The small pump power requirement is an outstanding feature, and emphasis has been given to devices that exploit this, for example in optical amplifiers pumped by lasers of a few milliwatts power [1]. So far relatively little attention has been paid to the capabilities of continuous-wave fibre lasers for much higher power operation (say 1 W and above), although the favourable thermal conditions have been discussed [2,3]. As a contribution to the growing interest in high power operation of fibre lasers we report here a thulium-doped silica-based fibre laser (pumped by a 1.064 μm Nd:YAG laser) which has produced an output of 1.35 W at a wavelength of 2 μm. Lasers operating in this spectral region are expected to find a number of applications in LIDAR, remote sensing of gases, and in the medical field. The availability of much higher Nd:YAG powers than we have used suggests that even higher cw outputs from such a Tm fibre laser should be achievable.

A typical absorption spectrum of the Tm^{3+} ion in a silica host is shown in fig. 1. The first reports of lasing in a Tm^{3+}-doped silica fibre used the pump absorption $^3H_6$–$^3F_2$, $^3F_3$ at around 0.67 μm [4] and the $^3H_6$–$^3F_4$ absorption at around 0.79 μm [5], with the latter yielding a slope efficiency (with respect to absorbed power) of 36% in recent work [6]. More recently still the feasibility of pumping via the $^3H_6$–$^3H_5$ transition using a 1.064 μm Nd:YAG laser was demonstrated [7], pointing to the possibility of high

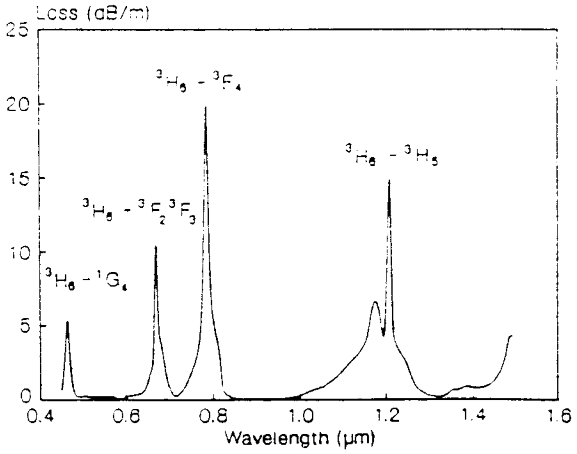

Fig. 1. Absorption spectrum for 840 ppm Tm^{3+} in a silica host.

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power operation. Although the absorption at 1.064 µm is weak, being in the extreme wing of the $^3H_6$–$^3H_5$ transition, some 1000 cm^{-1} from linecentre, the efficient laser performance reported in the present work (37% slope efficiency) provides a good illustration of how the long absorption path in a fibre geometry enables weak absorption to be exploited effectively. The absorption spectrum (fig. 1) shows an extended absorption wing on the short wavelength side of $^3H_6$–$^3H_5$, rather unexpected feature that varies with host composition and preparation. In Tm^{3+}-doped fluorozirconate glass for example, the wing is much reduced in extent.

The energy levels are shown in fig. 2. Pump light at 1.064 µm excites population from the $^3H_6$ ground state into the high energy wing of the $^3H_5$ level, followed by rapid nonradiative decay into the $^3H_4$ upper laser level. The measured fluorescence lifetime of this level is 200 µs, but population is also removed by pump excited state absorption (ESA). Despite laser action taking place from $^3H_4$ to the ground state $^3H_6$, the transition is essentially 4-level in nature since the lower level is a Stark-split component of the ground manifold. Fig. 3 shows the fluorescence spectrum in the 2 µm region for light emitted from the side of the fibre. In such an arrangement the fibre is optically thin so that there is no spectral distortion by reabsorption.

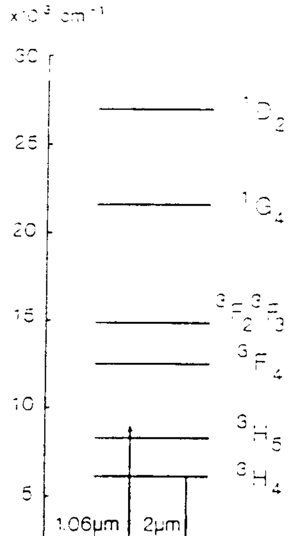

Fig. 2. Energy levels for Tm^{3+} in a silica host.

2. Experiment

The fibre used in this work had a nominal Tm^{3+} concentration of 840 parts per million introduced by the solution-doping technique [8], and had a numerical aperture of 0.15. The host glass composition was 94 (mole %) SiO$_2$, 6 (mole %) GeO$_2$, with the core index raised by 0.008 above the cladding. Initial results on 1.064 µm pumping [7] used a fibre core diameter of 8.6 µm (LP$_{11}$ mode cut-off at 1.7 µm), thus ensuring monomode operation at 2 µm. To avoid optical damage by focused pump light incident on the butted input mirror, the pump power was limited to 1 W, yielding 50 mW of output at 2 µm. With improved mirrors less susceptible to damage we have since increased the output power from this same fibre to 209 mW for an incident power of 3.6 W (1.3 W absorbed). Under these conditions the cw pump intensity incident on the mirrors is about 10 MW/cm^2.

To further increase the output power, two possibilities were considered: either use a larger core fibre to allow a higher pump power before the onset of damage, or use a resonator arrangement where the pump input mirror is separated from the fibre end, with an intra cavity lens between the fibre and input mirror. This latter approach however increases the threshold and reduces the laser efficiency due to the higher resonator losses introduced by an intra cavity element. In fact it is clear that for efficient operation of this 1.064 µm pumped Tm fibre laser the requirements on resonator losses are much more demanding than in most other fibre lasers. In practice we have only been able to achieve the required low loss using mirrors butted directly against the fibre ends with a very high quality cleave. This critical dependence on loss arises because strong ESA occurs from the $^3H_4$ level. This is evidenced by blue fluorescence at 467 nm, and also by the observation of 2.35 µm fluorescence (fig. 3) from the $^3F_4$–$^3H_5$ transition. This depletion by ESA of the $^3H_4$ upper laser level has a detrimental effect on laser operation at 2 µm, and to minimise the effect it is important to keep the population of this level as low as possible. This means

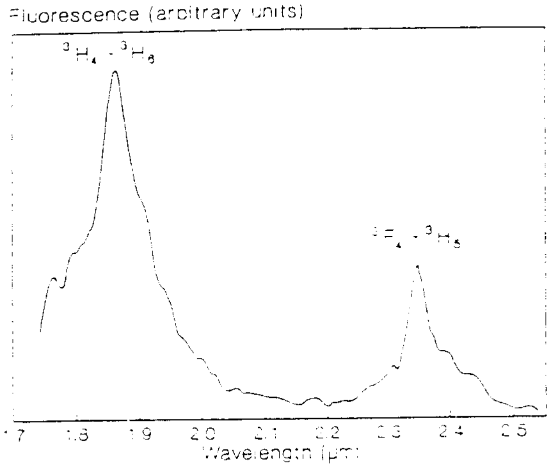

Fig. 3. Infrared fluorescence spectrum for light emitted from the side of the fibre.

operating with a low loss resonator so that only a small population in the upper laser level is needed.

Therefore, to achieve high power operation of this fibre laser we have retained the butted mirror arrangement and increased the core diameter to 17 μm, giving around four times the core area of the previous fibre. A potential penalty entailed by the larger core is that more than one propagating mode can be supported. As our results show however, in practice the output of this laser has remained monomode.

The laser cavity consisted of a length of fibre butted at both ends against plane dielectric mirrors. The input mirror was highly reflecting (>99.5%) in the range 1.6–2.1 μm and 90% transmissive at the pump wavelength. The output coupler had a transmission of 7% (nominal figure in air) at 2 μm and 80% at the pump wavelength. The fibre ends were cleaved with a vibrating diamond blade and inspected interferometrically to ensure flatness and end-face angles of 0.5 degrees or less to keep losses to a minimum. Pump light was focused into the fibre through the input mirror with a 10× microscope objective. By monitoring the amount of transmitted pump power as a function of length it is possible to determine both the small signal absorption and the power launched into the fibre. For the fibre used in our experiments the absorption was 2 dB/m at 1.064 μm and the overall launch efficiency (ratio of power launched into core to power incident on the launch objective) was 55%. By accounting for the transmissions of the launch objective and the input mirror we obtain a coupling efficiency (ratio of power launched into core to power incident on fibre endface) of about 75%.

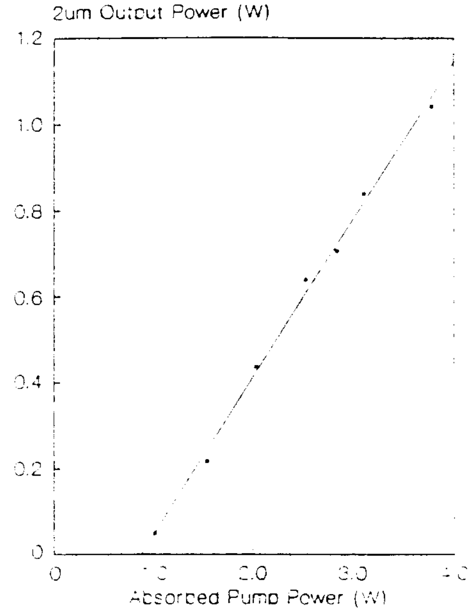

Fig. 4. Output power at 2 μm versus absorbed pump power.

Fig. 4 shows 2 μm laser power versus absorbed pump power for a fibre length of 1.4 m (the actual laser wavelength was 2.010 μm). The threshold for laser action was 600 mW absorbed and the slope efficiency with respect to absorbed power was 37%, representing an internal quantum efficiency of 70%.

Absorbed powers were calculated by subtracting the measured unabsorbed pump power escaping through the output coupler from the pump power coupled into the fibre at the input end (93% of the launched pump light was absorbed in this length). These input powers are found by using the measured launch efficiency of 0.55. Throughout these measurements the incident pump power was varied with an optical attenuator while keeping the lamp current in the Nd:YAG laser fixed at the value used to measure the launch efficiency, since current variations alter the pump beam characteristics and yield a different launch efficiency. However, the maximum observed output power for this fibre length was achieved by slightly increasing the lamp current to give a pump power of 9.6W incident on the launch objective, yielding 1.24 W at 2 μm from the fibre laser, although since the launch efficiency (and hence absorbed power) was not known accurately under these conditions this point is not shown in fig. 4.

A somewhat higher power of 1.35 W, again for 9.6 W incident, was achieved by reducing the fibre length to 0.7 m, suggesting that host absorption and reabsorption in the thermally populated lower laser level is significant for longer lengths. We estimate the absorbed power to be about 4.5 W (assuming 55% launch efficiency). It should be noted that to achieve this high power very careful adjustment of the cavity mirrors was required, and the performance was especially sensitive to longitudinal movement of the fibre against the output coupler. Index-matching fluid between the end-face and the mirror would reduce the sensitivity, but the high power levels at this location make this impractical. Direct dielectric coating of the fibre ends to form the mirrors would be the ideal solution to the problem.

To investigate the intensity profile of the output beam a pinhole and lead sulphide detector were scanned across the far field. The profile is shown in fig. 5, where a gaussian fit to the data has been added. Using the separation of the $1/e^2$ points we find the half angle divergence to be 103 mrad which, assuming a diffraction-limited output, implies a 6.2 μm spot size for the fundamental mode. A prediction of the beam characteristics of this fibre can be made by employing the Equivalent Step Index technique [9] to derive two parameters, the equivalent core radius ρ_e and the equivalent numerical aperture NA_e, from a moment analysis of the refractive index profile of the fibre preform (we assume the index profile to remain unchanged in the transition from preform to fibre). These parameters allow us to simulate the refractive index profile as a step index, and from this predict the propagation characteristics of the actual profile.

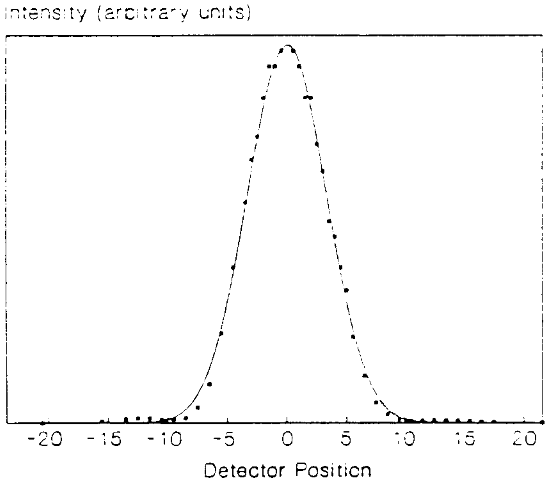

Fig. 5. Far field intensity profile of fibre laser output at 2 μm.

The moment analysis yields $\rho_e = 7.5$ μm and $\mathrm{NA}_e = 0.137$. The normalised frequency V [10] is given by

$$V = 2\pi\rho_e(\mathrm{NA}_e)/\lambda\,. \tag{1}$$

where λ is the free-space wavelength. For a step index fibre at cut-off, $V = 2.405$ and λ becomes the cut-off wavelength for single mode propagation. Substituting for ρ_e and NA_e in eq. (1) gives a LP_{11} cut-off wavelength of 2.7 μm, thus indicating the possibility of multimode operation at the lasing wavelength of 2 μm. In fact, for $\lambda = 2$ μm we have a V number of 3.23, so only the LP_{11} mode can propagate in addition to the LP_{01} mode. Using the gaussian approximation for mode field [11] gives a spot size w_0, for the fundamental mode, of

$$w_0 = \rho_e/(\ln V)^{1/2}\,. \tag{2}$$

Substituting or $V = 3.23$ in eq. (2) we obtain $w_0 = 6.9$ μm, in good agreement with the measured spot size of 6.2 μm.

The observed intensity profile indicates that in practice only the fundamental mode is excited, a condition that continues to hold for this fibre even when pumping at many times the threshold level, in this case up to 6 times threshold. No special precautions, such as holding the fibre straight, were required to achieve this monomode operation.

3. Conclusions

Despite a very weak (2 dB/m) absorption for pump light at 1.064 μm, a thulium-doped silica-based fibre laser pumped by a cw Nd:YAG laser has yielded > 1 W cw output at a wavelength of 2 μm. A threshold of 600 mW and slope efficiency of 37% (internal quantum efficiency 70%), both with respect to absorbed power, were observed. The highest measured output power was 1.35 W for about 4.5 W absorbed in a 70 cm fibre. We note that although this fibre can in principle support two modes at 2 µm, the output is in fact clearly single transverse mode.

There is considerable scope for further optimisation of this fibre laser. Further investigation is needed of the effect of fibre host on spectroscopic features, with the hope that ground state absorption of the pump can be enhanced and ESA reduced. Direct coating of mirrors onto the fibre ends should be particularly beneficial, and increased reflection of unabsorbed pump light at the output mirror would enhance performance. It is also possible that cladding-pumping schemes [12] will be effective for this laser. Finally, it should be noted that Nd:YAG laser powers well in excess of those used by us are available, particularly if multimode Nd:YAG operation is considered, so that multiwatt cw output at around 2 µm can be anticipated from a Tm^{3+}-doped fibre laser.

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