CW DIODE-PUMPED OPERATION OF 1·97 μm THULIUM-DOPED FLUOROZIRCONATE FIBRE LASER

Indexing terms: Lasers and laser applications, Semiconductor lasers

Operation of a diode-pumped continuous-wave thulium-doped fibre laser on the $^3H_4$–$^3H_6$ transition at ≅1·97 μm is reported. The absorbed pump power at threshold for a multimode fibre with 40 μm core diameter was measured to be ≅20 mW.

Introduction: CW lasing at around 1·9 μm has been reported in both Tm^{3+}-doped silica[1–3] and fluorozirconate[4] fibres. The pump sources used have been a Styryl 9M dye laser,[1,2] a Nd:YAG laser[3] and a krypton-ion laser.[4] It is desirable to use a semiconductor diode laser as the pump source. Previous diode-pumped fluorozirconate fibre lasers have operated at 1·05 μm and 1·346 μm in Nd^{3+} [5] and in Tm^{3+} at 2·3 μm on the $^3F_4$–$^3H_5$ transition[6]. We report diode-pumped operation on the $^3H_4$–$^3H_6$ transition at ≅1·9 μm, for which applications in fields such as medicine and eyesafe laser radar are anticipated.

Experimental: The fibre used in these experiments was of the standard ZBLANP composition and was fabricated by a casting technique.[7] The fibre was doped with 740 ppm by weight thulium (Tm^{3+}) ions and had core and cladding diameters of 40 and 80 μm, respectively.

Initial spectroscopic measurements were carried out using a Styryl 9M dye laser operating at 800 nm corresponding to absorption from the $^3H_6$ ground state to $^3F_4$ excited state as shown in the partial energy level diagram, Fig. 1. Emission at

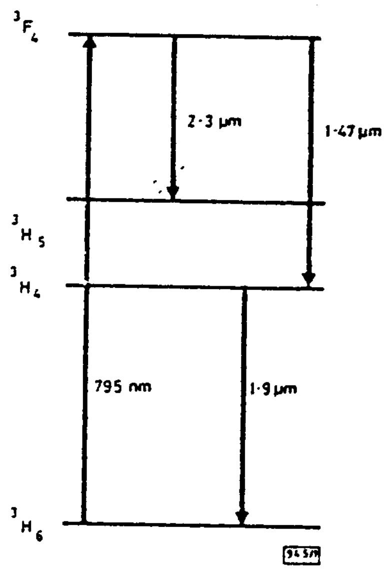

Fig. 1 *Energy level diagram*
Tm^{3+}-doped ZBLANP fibre

around 2·3 μm and 1·47 μm (corresponding to decay from the $^3F_4$ to $^3H_5$ and $^3H_4$ levels, respectively) and at around 1·9 μm (decay from the $^3H_4$ to $^3H_6$ level) is observed. A fluorescence spectrum for the $^3H_4$ to $^3H_6$ transition is shown in Fig. 2. This was taken by looking at light scattered out of the side of the fibre and so was not distorted by reabsorption. We attribute the ripple on our spectrum to noise although Allain *et al.*,[4] who excited this transition with a krypton laser, observed ripple which was repeatable and suggested that it was not caused by noise. The lifetimes of the $^3F_4$ and $^3H_4$ levels were measured to be 1·1 ms and 6·4 ms, respectively.

The pump source used for obtaining laser oscillation was a Sony SLD 303V broad stripe diode operating at 795 nm with a nominal maximum operating power of 500 mW. The diode output was collected by a 8 mm focal length diode collimating lens and reshaped by a 45 mm focal length cylindrical lens.

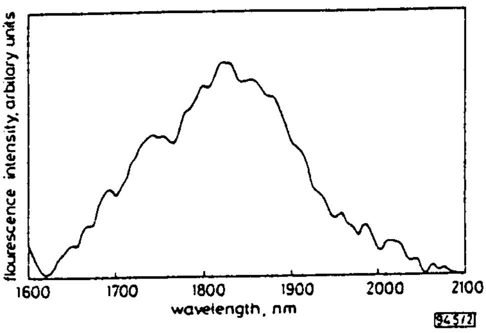

Fig. 2 *Sidelight fluorescence spectrum*
$^3H_4$–$^3H_6$ transition in Tm^{3+}-doped ZBLANP fibre
Excitation at 800 nm

Light was launched into the fibre by means of a ×10 microscope objective. The positions of the optics were determined by mode-matching calculations.[5] The launch efficiency was determined by launching into undoped fibre as described in Reference 5.

A standard Fabry–Perot cavity was constructed by butting the cleaved ends of a 30 cm length of fibre against mirrors of high reflectivity (>99%) at the lasing wavelength. Index matching fluid was used to minimise the butting losses. The fibre length was a compromise between ensuring good absorption of the pump, and minimising reabsorption losses at the lasing wavelength. For the 30 cm fibre length chosen for this experiment approximately 50% of the launched power was absorbed.

The launched power necessary to obtain CW laser oscillation at 1·972 μm was found to be approximately 40 mW (20 mW absorbed). A maximum output power of ≅200 μW was measured for the maximum available launched power of 100 mW (Fig. 3). This corresponds to a slope efficiency of approximately 0·3% with respect to launched power (0·6% with respect to absorbed power). Significant improvements are anticipated with optimum output coupling and fibre length and by enhancing the pumping quantum efficiency.

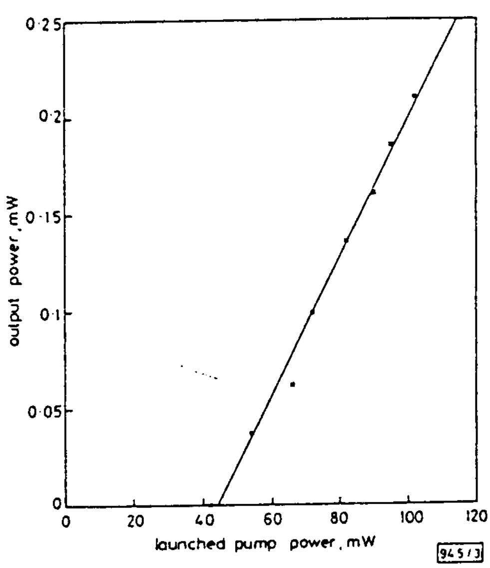

Fig. 3 *Output power against launched pump power*
Diode pumped Tm^{3+}-doped ZBLANP, fibre laser at 1·972 μm

Discussion: It is interesting to compare the performance of Tm^{3+}-doped fluorozirconate fibre with that of silica fibre. The threshold of 20 mW absorbed power can be significantly reduced by reducing the core diameter. With a small core fibre as described by Allain *et al.*,[4] a threshold of a few milliwatts should be obtainable. Using a krypton laser as a pump Allain *et al.*, demonstrated tuning from 1·84 to 1·94 μm. This range should be extendable. It is interesting to note that the operating wavelength of our diode-pumped laser, at 1·97 μm already falls outside this range. The overall tuning range is likely to be less than that available from Tm^{3+}-doped silica fibre (1·78 to 2·056 μm has already been achieved[2]) since the fluorescence linewidth in fluorozirconate fibre is less than that in silica.

The slope efficiency demonstrated here is much lower than has been achieved with silica fibre. This is partly because of the very low transmission of the output mirror. Another feature affecting this is the small branching ratio for Tm^{3+} ions to decay to the $^3H_4$ level from the $^3F_4$ level. This arises from the low rate of nonradiative multiphonon decay from the $^3F_4$ pump level to $^3H_5$ level in fluorozirconate glass compared with that of silica, a consequence of the lower phonon energy of the fluoride host. As a result, Tm^{3+} ions excited to the $^3F_4$ level mostly (≅90%) decay radiatively back to the ground state and only around 10% (estimates based on the data of Guery *et al.*[8]) decay to the $^3H_4$ upper laser level. Consequently the threshold for lasing on the $^3H_4$ to $^3H_6$ transition is raised by a factor of ≅10 and the slope efficiency decreased by a similar factor because of the poor pumping quantum efficiency. In silica the rapid nonradiative decay from the $^3F_4$ to $^3H_5$ levels ensures a high pump efficiency and high slope efficiencies have been observed.[2] The threshold for silica fibre is increased by virtue of the shortened lifetime of the $^3H_4$ level (between 200 and 500 μs has been observed where the calculated radiative lifetime of the $^3H_4$ level in a silica host is ≅3 ms). In fluorozirconate glass the $^3H_4$ level has an observed lifetime of ≅6·4 ms which agrees well with the calculated radiative lifetime.

It may be possible to improve the slope efficiency of the $^3H_4$–$^3H_6$ Tm^{3+} fluorozirconate fibre laser. This would involve having mirrors which have reflectivity for the $^3F_4$–$^3H_5$ transition so that both transitions lase simultaneously. The branching ratio for decay from $^3F_4$ to $^3H_5$ and then to $^3H_4$ could be enhanced. If the $^3F_4$ to $^3H_5$ transition is pumped to n times the threshold value then the branching ratio of the $^3F_4$ to $^3H_5$ is approximately n times larger. The laser threshold for $^3F_4$ to $^3H_5$ is calculated to be similar to that of $^3H_4$ to $^3H_6$ (experimental results[6] confirm this) so it appears feasible to enhance the slope efficiency of the $^3H_4$ to $^3H_6$ laser transition to tens of percent. This technique for enhancing the slope efficiency will also reduce the threshold.

Conclusions: We have demonstrated a CW diode-pumped Tm^{3+}-doped fibre laser operating at 1·97 μm. Considerable improvements in performance can be anticipated with the use of smaller core fibre, using optimised output mirror transmission and by enforcing simultaneous lasing on the 2·3 μm $^3F_4$–$^3H_5$ transition so as to enhance the effective pumping quantum efficiency.

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