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Full length article

Continuous-wave oscillation of Tm^{3+}-doped fluorozirconate fibre lasers at around 1.47 μm, 1.9 μm and 2.3 μm when pumped at 790 nm

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Continuous-wave operation of Tm^{3+}-doped fluorozirconate fibre lasers at around 1.47 μm, 1.9 μm and 2.3 μm has been demonstrated when pumping at around 790 nm with a Ti:sapphire laser. The efficiency of the 1.9 μm $^3H_4$–$^3H_6$ transition was found to be significantly increased by enforcing simultaneous oscillation on the $^3F_4$–$^3H_5$ transition at 2.3 μm as this effectively enhances the branching ratio for pumping the $^3H_4$ level. An upconversion process leading to blue emission has also been observed. The efficiency of this process is enhanced by more than an order of magnitude as soon as laser oscillation takes place at 2.3 μm, indicating the potential application of manipulating branching ratios via lasing.

1. Introduction

The trivalent thulium ion is an interesting activator for solid state lasers since it offers many radiative transition on which laser oscillation may be demonstrated. By incorporating the Tm^{3+} ion into the core of an optical fibre it is possible to produce devices of low threshold and high efficiency. To date, Tm^{3+}-doped fibre lasers have been operated on seven different transitions with wavelengths ranging from 455 nm [1] to 2.35 μm [2,3].

We have previously reported the results obtained with Tm^{3+}-doped silica fibre lasers operating on the $^3H_4$–$^3H_6$ transition at wavelengths near 2 μm [4,5]. This transition is of great interest since it has been shown capable of widely tunable operation between 1.65 μm and 2.05 μm [5,6], covering the absorption bands of important molecules such as water vapour (1.88 μm, 1.91 μm), liquid water (1.94 μm) and carbon dioxide (1.96 μm, 2.01 μm and 2.06 μm) [7] and thus offers the possibilities of sensor applications. Additionally it should be noted that output powers in excess of 1 W have been demonstrated for Tm^{3+}-doped fibre lasers operating on this transition when pumped with a Nd:YAG laser at 1.064 μm [8]. However, a major disadvantage of the silica host is that all levels suffer from non-radiative decay via multiphonon emission and most transitions have a low radiative quantum efficiency and while this does not affect the output slope efficiency it does lead to an increased threshold. Indeed, the radiative quantum efficiency of the $^3H_4$ level may be less than 10% [5]. Furthermore, this is the only level from which laser emission has been observed in a silica fibre.

Optical fibres fabricated from the low phonon energy fluoride glasses, originally developed for ultra-low loss communications systems, make extremely good hosts for rare earth ions since they offer many more fluorescing metastable multiplets than a silica fibre. This is a result of the reduced multiphonon emission rates arising from the lower phonon energies. By incorporating the Tm^{3+} ion into the core of a monomode fluorozirconate fibre Allain et al. have demonstrated laser action at wavelengths between 455 nm [1] and 2.3 μm [3] when pumping with a krypton ion laser operating at 676.4 nm and/or 647.1 nm. The 455 nm operation represents the first reported upconversion fibre laser.

Clearly, from the point of view of practical devices it would be desirable to pump with an AlGaAs semiconductor diode laser and to date diode-pumped Tm^{3+}-doped fluorozirconate fibre lasers have been

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reported by Allen and Esterowitz operating at 2.3 μm [9] and by Carter et al. operating at 1.97 μm [10]. To investigate further the prospects for transition amenable to diode pumping we have used a Ti:sapphire laser operating at around 790 nm to pump Tm^{3+}-doped fluorozirconate fibre. In this way, we were recently able to achieve efficient lasing at ≈0.8 μm, on the same transition, $^3F_4$–$^3H_6$, that is responsible for the pump absorption [11]. This has interesting prospects for diode-pumped fibre amplifiers at 0.8 μm. In this paper we report results obtained on transitions at 1.47 μm, 1.9 μm and 2.3 μm and in particular show that significant increases in the efficiency of the latter two transitions can be achieved by ensuring their simultaneous oscillation.

2. Spectroscopy

A multimode fluorozirconate (ZBLANP) fibre has been used for the experiments described in this paper. The fibre, which was prepared by a casting technique [12], had core and cladding diameters of 40 μm and 80 μm, respectively, and the core was doped with 740 parts per million by weight of Tm^{3+} ions.

An energy level diagram for the Tm^{3+} ion is shown in fig. 1, with the approximate energy of each level being indicated in cm^{-1}. From fig. 1 it can be seen that the Tm^{3+} ion may be excited by many readily available laboratory lasers such as argon and krypton ion lasers (to the $^1G_4$ and $^3F_{2,3}$ multiplets, respectively) or Ti:sapphire and AlGaAs diode lasers (to the $^3F_4$ multiplet). An emission spectrum for fluorescence guided by a 30 cm length of Tm^{3+}-doped fluorozirconate fibre when excited at 800 nm is shown in fig. 2a. This spectrum was recorded using a lead sulphide detector and 0.25 m Applied Photophysics monochromator with a grating blazed at 2 μm. This spectrum has not been corrected for the system response. The emission bands at ≈ 1.46 μm, ≈ 1.82 μm and ≈ 2.3 μm correspond to the $^3F_4$–$^3H_4$, $^3H_4$–$^3H_6$ and $^3F_4$–$^3H_5$ transitions, respectively. Since the emission at ≈ 1.8 μm corresponds to a three-level transition, this light suffers a reabsorption loss while propagating down the fibre core. To observe a spectrum free from this reabsorption, the spectrum of light emitted radially from the fibre was recorded by placing the fibre directly against the entrance slit of the monochromator. The resulting "side-light" emission spectrum is shown in fig. 2b, where it can now be seen that the emission at ≈ 1.8 μm is enhanced relative to that at ≈ 1.46 μm.

The lifetimes of the emission from the $^3F_4$ and $^3H_4$

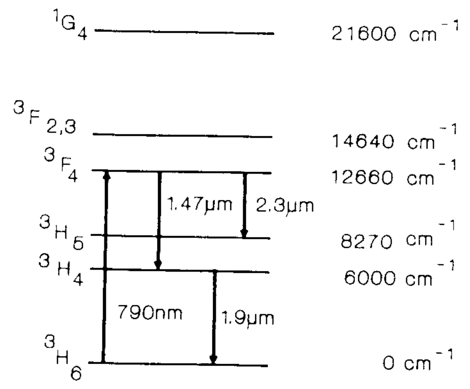

Fig. 1. Partial energy level diagram for Tm^{3+}-doped fluorozirconate (ZBLANP) glass.

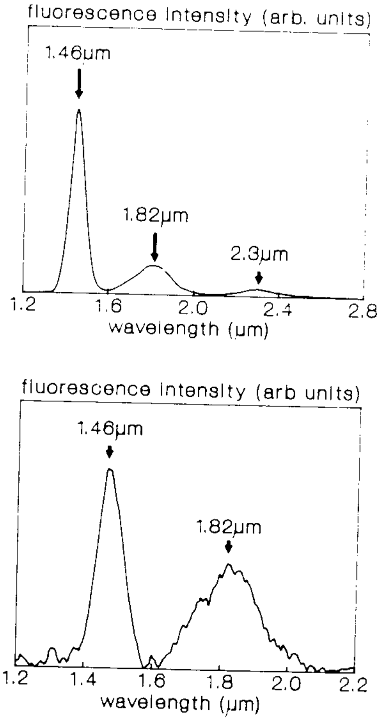

Fig. 2. Emission spectra for Tm^{3+}-doped fluorozirconate fibre when excited at 800 nm: (a) for guided light and (b) for radially emitted light ("side-light").

levels were measured to be 1.1 ms and 6.4 ms, to be compared with calculated radiative lifetimes of 1.3 ms and 6.8 ms, respectively. It is interesting to compare the lifetime of these levels in the fluorozirconate host to those observed in a silica host. In a silica host both the $^3F_4$ and $^3H_4$ levels suffer from non-radiative decay via phonon emission with the observed lifetime of the $^3F_4$ level being ≈ 20 μs and that of the $^3H_4$ level ≈ 500 μs. Obviously, this fast non-radiative decay from the $^3F_4$ level would make it difficult to achieve laser oscillation on a transition from this level in a silica host, whereas in a fluorozirconate host laser action has been demonstrated on the $^3F_4$–$^3H_5$, $^3F_4$–$^3H_4$ and $^3F_4$–$^3H_6$ transitions.

The rate of non-radiative decay from the $^3F_4$ level also affects the performance of a laser operating on the $^3H_4$–$^3H_6$ transition. In a silica host nearly all of the ions initially excited to the $^3F_4$ level decay non-radiatively through multiphonon emission to the $^3H_5$ level and then to the $^3H_4$ level. Thus the pumping quantum efficiency of the $^3H_4$ level, ϕ_p, defined as the fraction of ions excited to the $^3H_4$ level for each pump photon absorbed, is approximately unity. However, in a fluorozirconate host the principal decay route from the $^3F_4$ level is through the radiative $^3F_4$–$^3H_6$ transition at around 800 nm. From a Judd–Ofelt analysis similar to that of Guery et al. [13] we have calculated a branching ratio of $\approx 88\%$ for the $^3F_4$–$^3H_6$ transition in Tm^{3+}-doped ZBLANP glass. Thus the pumping quantum efficiency for the $^3H_4$ level in the fluorozirconate host is only $\approx 12\%$. It should be noted, however, that the radiative quantum efficiency, ϕ_r, of the $^3H_4$ level is nearly an order of magnitude greater for the fluorozirconate host compared to the silica host. Thus the threshold for laser oscillation (which is inversely proportional to the product $\phi_p\phi_r$) will be similar provided other parameters of the fibres such as core size and numerical aperture are similar. However, the slope efficiency is only dependent upon ϕ_p and not on ϕ_r since above threshold stimulated emission provides an alternative route to the non-radiative decay. Hence the silica fibre would be expected to have a higher slope efficiency.

The high branching ratio for the $^3F_4$–$^3H_6$ transition in the fluorozirconate host can, on the other hand, be exploited for the construction of efficient laser oscillators and fibre amplifiers in the 0.8 μm region. Indeed, our recently reported results on this, using a 780 nm Ti:sapphire laser as a pump laser, demonstrated a slope efficiency of $\approx 45\%$ with respect to absorbed power and an output power of 125 mW at 806 nm [11].

3. Laser oscillation at around 1.9 μm

Laser oscillation at around 1.9 μm in Tm^{3+}-doped fluorozirconate fibre was first reported by Allain et al. [3], who, using a krypton ion laser operating at 676.4 nm as the pump source, obtained tunable operation from 1.84 μm to 1.94 μm and a maximum output power of 1.3 mW. We have subsequently reported the operation of a laser diode-pumped Tm^{3+}-doped fluorozirconate fibre laser at 1.97 μm [10]. This device has a slope efficiency of less than 1% with respect to launched pump power. This low slope efficiency was attributed to the combined effect of a low branching ratio from the $^3F_4$ level (to which ions were initially excited) to the $^3H_4$ level and the use of an output coupler of low transmission (less than 1%). The small output coupling was a consequence of the need to bring the threshold down to a level comparable to the output from the diode laser. In an attempt to determine the degree to which the low value of output coupling limited the performance of the device we have investigated the performance of Ti:sapphire-pumped Tm^{3+}-doped fluorozirconate fibre laser for differing values of output coupling

A standard Fabry–Pérot cavity was constructed by butting the cleaved fibre ends of a length of fibre against dielectric mirrors. Pump light from a Ti:sapphire laser was launched into the fibre by a ×5 microscope objective. The mirror at the input end of the cavity had a transmission of greater than 80% at the pump wavelength of 791 nm (chosen as this gave the maximum output power from the fibre laser) and greater than 99% reflectivity between 1.7 μm and 2.1 μm. Three different values of output coupling were used for these experiments: $<1\%$, $\approx 5\%$ and $\approx 10\%$ transmission at around 1.9 μm. Several lengths of fibre were tried (between 0.5 m and 1.5 m) with a length of 1 m giving the highest values of fibre laser output power. For lengths shorter than this the efficiency of pump absorption was reduced while for longer lengths reabsorption caused the effective loss to increase.

The output power as a function of launched pump power is shown in fig. 3 for a 1 m length of fibre for the three values of output coupling used. The fibre laser wavelengths were measured to be 2.000 μm, 1.963 μm and 1.960 μm for the < 1%, 5% and 10% transmission output couplers, respectively. The reason for the laser wavelength being dependent upon the output coupler used was that the 5% and 10% transmission mirrors had a maximum reflectivity at around 1.9 μm whereas the < 1% transmission mirror had a flat transmission band from 1.7 μm to 2.1 μm. The fact that laser oscillation occurred at wavelengths significantly longer then the peak spontaneous emission wavelength is a consequence of the quasi-three-level nature of the $^3H_4$–$^3H_6$ transition, with wavelengths shorter than ≈ 1.9 μm experiencing a significant reabsorption loss.

It is interesting to note that the laser wavelengths recorded for the multimode fibre used in this experiment fall outside the tuning range reported by

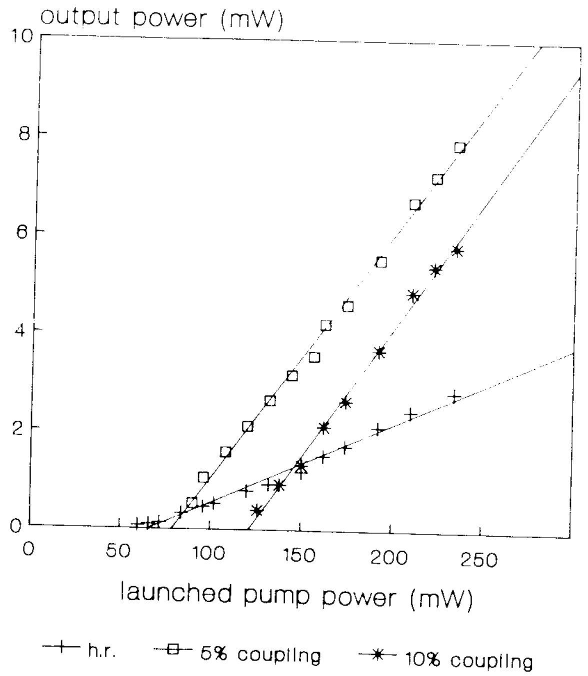

Fig. 3. Output power as a function of launched pump power for a Tm^{3+}-doped fluorozirconate fibre laser operating on the $^3H_4$–$^3H_6$ transition. The results for three values of output coupling are shown.

Allain et al. for the $^3H_4$–$^3H_6$ transition in a monomode fluorozirconate fibre [3]. For a monomode fibre the peak in the gain spectrum is shifted to shorter wavelengths since it is easier to saturate the ground state absorption and hence bleach the fibre so that shorter wavelengths experience only a small reabsorption loss. The fact that oscillation in a multimode fibre in a cavity with no wavelength selective elements took place at wavelengths outside the previous published tuning range suggests that it should be possible to tune a monomode fibre over a much wider tuning range.

As expected the highest slope efficiency (3.2% with respect to incident power, 5.3% with respect to launched power, 5.9% with respect to absorbed power) was recorded for the 10% transmission output coupler, although the highest output power (7.9 mW) was obtained when using the 5% output coupler as a consequence of the lower threshold.

The slope efficiencies measured for a Tm^{3+}-doped fluorozirconate fibre laser operating on the $^3H_4$–$^3H_6$ transition are significantly less than those reported for a Tm^{3+}-doped silica fibre laser operating on this same transition (≈ 35% with respect to absorbed pump power). As we have indicated earlier, this is a consequence of the much smaller branching ratio from the $^3F_4$ level to the $^3H_4$ upper laser level in the fluorozirconate fibre when compared to a silica fibre.

Perhaps the best way of enhancing the pumping efficiency of the $^3H_4$ level in a fluorozirconate host would be to use a much higher dopant concentration (> 1%). At high dopant levels cross relaxation between neighbouring Tm^{3+} ions can become efficient, resulting in two ions being excited to the $^3H_4$ level for each pump photon absorbed. This scheme has been shown to operate extremely well in Tm^{3+}-doped YAG lasers, where slope efficiencies of 59% with respect to absorbed pump power have been observed when a Tm^{3+} doping level of 12% is used [7]. Sufficiently high doping concentrations for this process to be efficient are possible in Tm^{3+}-doped fluorozirconate glass. However, at the time of these experiments, fibre with the appropriate Tm^{3+} concentration was not available, so an alternative scheme for enhancing the branching ratio from the $^3F_4$ level to the $^3H_4$ upper laser level needed to be considered. The method chosen was to enforce laser oscillation simultaneously on the $^3F_4$–$^3H_5$ and $^3H_4$–$^3H_6$ transitions, with stimulated emission from $^3F_4$–$^3H_5$ followed by rapid non-radiative decay via multiphonon emission being used to enhance the branching ratio to $^3H_4$.

4. Simultaneous laser oscillation at around 1.9 μm and 2.3 μm

A Fabry–Pérot cavity was constructed with an 86 cm length of fibre (the same piece as used for the measurements described above but with the ends recleaved) with the input end butted against a mirror of >99% reflectivity between 1.8 μm and 2.4 μm. An output coupler of ≈3% transmission between 1.8 μm and 2.4 μm was used to complete the cavity. The Ti:sapphire pump wavelength was again 791 nm. Using this arrangement simultaneous laser oscillation at 1.94 μm and 2.305 μm was observed, corresponding to the $^3H_4$–$^3H_6$ and $^3F_4$–$^3H_5$ transitions, respectively, with both transitions having a threshold of approximately 200 mW pump power incident on the launch microscope objective (corresponding to approximately 120 mW launched into the fibre core). The fact that the threshold for the two transitions was the same was entirely coincidental; for example, when a longer fibre length was used the threshold for oscillation on the $^3H_4$–$^3H_6$ transition increased as a consequence of increased reabsorption losses while that for oscillation on the $^3F_4$–$^3H_5$ transition decreased as a consequence of more pump light being absorbed for the longer fibre length and hence an increase in gain for this transition.

The slope efficiencies at 1.942 μm and 2.305 μm were measured to be 8.3% and 18.8%, respectively, with respect to launched power (5.0% and 11.3% with respect to incident power) with a maximum output power of ≈26 mW at 2.305 μm and ≈17 mW at 1.942 μm being obtained. Thus the efficiency of oscillation of the $^3H_4$–$^3H_6$ transition was found to be enhanced by simultaneous oscillation of the $^3F_4$–$^3H_5$ transition, as expected. In passing it is interesting to note that despite using higher excitation intensities than those reported by Allen and Esterowitz [9], unlike them we observed no decrease in slope efficiency with respect to pump power. They attributed the saturation of output power to a build-up of population in the $^3H_4$ level. In the work described here this is not a problem since laser emission on the $^3H_4$–$^3H_6$ transition rapidly removes population from the $^3H_4$ level to the ground state, which may then be re-excited to the $^3F_4$ level. Thus simultaneous oscillation actually enhances the performance of lasers operating on both transitions.

A further increase in efficiency for the $^3H_4$–$^3H_6$ transition was observed when using an output coupler of higher transmission (≈5%) at 1.9 μm and lower transmission (≈1.5%) near 2.3 μm. The latter, by increasing the intracavity intensity at 2.3 μm, further enhances the branching ratio from $^3F_4$ to $^3H_4$ via $^3H_5$. A plot of output power at 1.92 μm and 2.33 μm as a function of launched pump power is shown in fig. 4. It should be noted that a higher-power Ti:sapphire laser was used for recording the data shown in fig. 4 than for the work described above and that a higher launch efficiency (70% compared to 60%) of pump light into the fibre was measured. The results shown in fig. 4 correspond to a slope efficiency of 18.2% with respect to launched power at

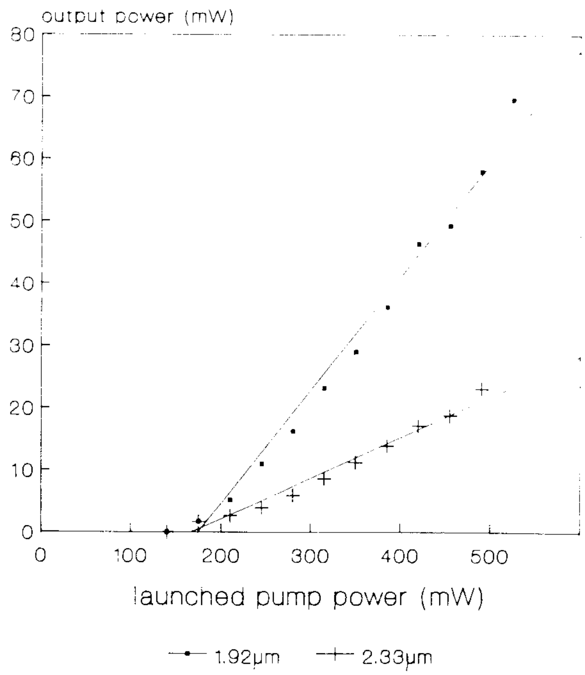

Fig. 4. Output power at 1.92 μm and 2.33 μm as a function of launched pump power for a Tm^{3+}-doped fluorozirconate fibre laser operating on the $^3H_4$–$^3H_6$ and $^3F_4$–$^3H_5$ transitions simultaneously.

1.92 μm and 6.5% at 2.33 μm (12.7% and 4.5%, respectively, with respect to incident pump power). A maximum output power of ≈ 70 mW was measured at 1.92 μm. The slope efficiency at 1.92 μm, although a significant improvement (a factor of three) on that obtained when the $^3H_4$–$^3H_6$ transition lasers without simultaneous oscillation on the $^3F_4$–$^3H_5$ transition, is still only approximately half that obtained for Tm^{3+}-doped silica fibre lasers operating on this transition.

Further improvements to the slope efficiency may result from increasing the output coupling at around 1.9 μm since increasing the output coupler transmission from ≈ 3% to ≈ 5% approximately doubled the slope efficiency. However, it seems likely that the most dramatic improvement in slope efficiency for Tm^{3+}-doped fluorozirconate fibre lasers operating on the $^3H_4$–$^3H_6$ transition will be obtained when a sufficiently high Tm^{3+} concentration is used to ensure rapid cross relaxation between neighbouring Tm^{3+} ions, with the prospect of a pumping quantum efficiency of 2. This scheme will offer as high a branching ratio to the $^3H_4$ level as in a silica host but with the advantage of a near unity radiative quantum efficiency for the $^3H_4$ upper laser level. Thus the fluorozirconate fibre may still prove to be the preferred host for a Tm^{3+} laser operating on the $^3H_4$–$^3H_6$ transition since the threshold will be only around one fifth of that when using a silica host.

5. Laser oscillation at 1.47 μm

Laser sources and amplifiers operating near 1.5 μm are of great interest in the context of telecommunications in silica fibres. From the emission spectra shown in figs. 2a and 2b it can be seen that Tm^{3+}-doped fluorozirconate offers a transition which emits in this region. The only previous report of oscillation on this transition in fluorozirconate fibre had used a krypton ion laser operating at 676.4 nm as the pump source [3], so it was decided to investigate the performance of this $^3F_4$–$^3H_4$ transition when pumping at diode laser wavelengths.

Both self-terminating and continuous-wave oscillation at 1.47 μm was observed in the Tm^{3+}-doped fluorozirconate fibre when pumping at around 790 nm. A Fabry–Pérot cavity was again constructed using a 70 cm length of fibre butted at either end against dielectric mirrors of approximately 85% transmission at the pump wavelength and < 1% transmission at the fibre laser wavelength. The pump light was mechanically chopped and launched into the fibre by a ×5 microscope objective. Pulsed laser emission was observed at 1.47 μm with an incident pump threshold of 250 mW (175 mW launched). The reason for this transition being self-terminating is that the lower laser level has a longer lifetime (6.4 ms) than the upper laser level (1.1 ms). However, it was found that if the fibre was pumped sufficiently hard, continuous wave oscillation could be enforced. The threshold for continuous wave oscillation was measured to be 480 mW incident on the launch objective (≈ 330 mW launched into the fibre). In view of the lower values of output coupling, the efficiency of this device was found to be rather low with output powers of less than 1 mW being measured.

Clearly by going to a monomode fibre, whose area could be around two orders of magnitude smaller than in the present fibre, one could expect power requirements to be reduced to the few milliwatt level. The power requirement could also be reduced by rapidly removing population from the $^3H_4$ lower laser level. Allain et al. [3] have accomplished this by enforcing oscillation on the $^3H_4$–$^3H_6$ transition. An alternative scheme for enforcing cw operation on the $^3F_4$–$^3H_4$ transition has been reported by Rosenblatt et al. [14], who used energy transfer to the $^7F_0$ level in a Tb^{3+} codopant to remove population. Such a scheme could be easily extended to a fluorozirconate fibre.

6. Upconversion in thulium-doped fluorozirconate fibres when pumping at around 790 nm

Allain et al. [1] have previously reported a Tm^{3+}-doped fluorozirconate upconversion fibre laser operating at 455 nm and 480 nm when pumping by a krypton ion laser operating at 647.1 nm and 676.4 nm simultaneously. Clearly, from the viewpoint of constructing a practical device it would be desirable to pump with a semiconductor diode laser and the highest powers from such devices are available from AlGaAs diodes operating near 800 nm. In practice we have found that the efficiency of upconversion of

≈ 800 nm photons in Tm^{3+}-doped fluorozirconate fibre was extremely low, with only a weak blue spontaneous emission at around 479 nm (corresponding to a transition between the $^1G_4$ and $^3H_6$ levels) being observed. However, the efficiency of upconversion was found to be significantly enhanced (by more than an order of magnitude) by enforcing laser oscillation at ≈ 2.3 μm on the $^3F_4$–$^3H_5$ transition.

A plot of the intensity of blue emission at 479 nm as a function of pump power is shown in fig. 5. The yield of ≈ 2.3 μm laser power with respect to pump power is also shown. It was observed that the yield of blue fluorescence with respect to pump power increased significantly as soon as the threshold for oscillation at 2.3 μm was reached.

The proposed mechanism for the upconversion/excited state absorption of pump photons is shown in fig. 6. Absorption of a pump photon causes excitation of Tm^{3+} ions to the $^3F_4$ level. The second pump photon is absorbed from the $^3H_5$ level, giving rise to population of the $^1G_4$ blue emitting level. Below threshold the branching ratio for the $^3F_4$–$^3H_5$ transition is only about 3% (this value being calculated form a Judd–Ofelt analysis). However, once the threshold for laser oscillation on the $^3F_4$–$^3H_5$ transition is reached stimulated emission significantly increases the ratio of ions decaying to the $^3H_5$ level, with a proportionate increase in the number of pump photons undergoing excited state absorption to the $^1G_4$ level. However, the overall efficiency of this process is low because of the short lifetime (measured by us to be less than the 20 μs resolution of our detection system and to be less than ≈ 10 μs by Allen and Esterowitz [9]) of the $^3H_5$ level, which suffers fast non-radiative decay to the $^3H_4$ level (an energy gap of only ≈ 2200 cm^{-1}) via multiphonon emission. This short lifetime means that most ions decay non-radiatively before a second pump photon can be absorbed.

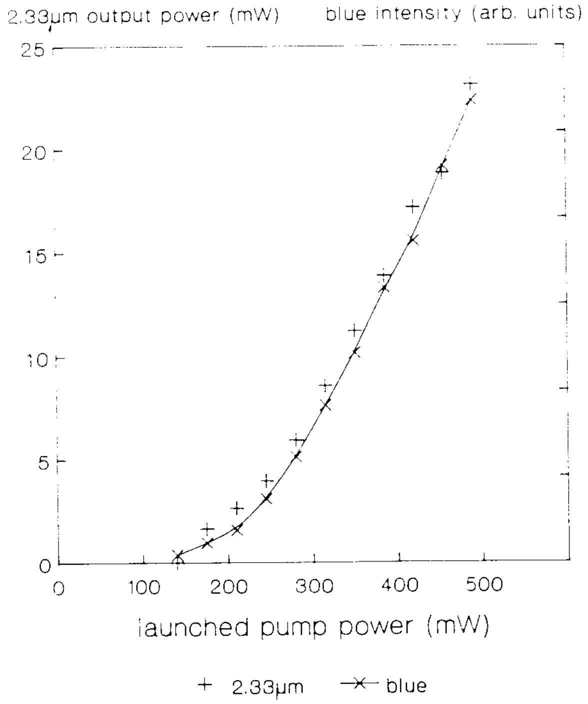

Fig. 5. Intensity of 479 nm spontaneous emission and 2.33 μm laser power as a function of launched pump power.

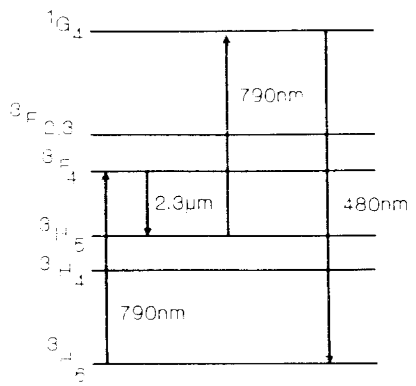

Fig. 6. Proposed upconversion mechanism for ≈ 790 nm pump photons giving rise to blue emission.

More efficient upconversion would require a host having lower phonon energies. However, even if such a host were available it is possible that this upconversion process would not lead to a blue laser since a blue fibre laser would require a fibre of small core size, which may mean a poor degree of overlap between the pump and 2.3 μm laser mode profiles, which would make oscillation at 2.3 μm extremely inefficient.

7. Conclusions

We have demonstrated cw operation of Tm^{3+}-doped fluorozirconate fibre lasers at around 1.47 μm, 1.9 μm and 2.3 μm when pumping at around 790 nm, with output powers at 1.9 μm and 2.3 μm being much greater than those previously reported. The efficiencies of lasers operating both at 1.9 μm and 2.3 μm were found to be significantly enhanced by enforcing simultaneous oscillation at these wavelengths (the 1.9 μm transition by a factor of three). Additionally the efficiency of upconversion of 790 nm pump photons has been observed to be significantly increased when laser oscillation takes place at 2.3 μm. The results for both the 1.9 μm laser transition and those on upconversion illustrate the general point that in a host such as a fluorozirconate glass, where there are many radiative transitions, it is possible to manipulate branching ratios by laser oscillation allowing the efficiency of processes related to transitions of low branching ratios to be significantly enhanced.

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