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An ytterbium-doped monomode fibre laser: broadly tunable operation from 1·010 μm to 1·162 μm and three-level operation at 974 nm

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Abstract. Continuous-wave laser action has been observed from an ytterbium-doped monomode fibre laser on the three-level transition at 974 nm and on the four-level transition at 1036 nm with slope efficiencies of 67% and 77% respectively, with respect to absorbed power. Tuning behaviour is described, in which polarisation control by means of fibre loops has allowed smooth continuous tuning from 1·010 μm to 1·162 μm.

1. Introduction

Laser action in Yb^{3+}-doped silicate glass was first observed in 1962 [1] using a flash-pumped rod cooled to 77 K, with oscillation occurring at 1·015 μm. Subsequently, laser action at 1·06 μm in a silicate glass co-doped with Nd^{3+} was described [2]. Recently we reported preliminary results on laser action in a silica-based fibre [3] doped with Yb^{3+} by the solution-doping technique [4]. An attractive feature of this system is that it provides a very broad fluorescence in the 1 μm region without excited state absorption, thus offering the potential of broadly tunable laser operation. We have reported [3] a tuning range of 1·015 μm to 1·140 μm on the four-level transition, but with large fluctuations of output power across this range. Further investigation revealed that these fluctuations were due to wavelength-dependent changes of polarisation in the non-polarisation-preserving fibre.

In this paper we report results obtained with polarisation control applied to the fibre, resulting in a smooth tuning behaviour on the four-level transition over an extended range of 1·010 μm to 1·162 μm. We also describe results of laser action at 974 nm on the three-level transition [5], which we previously reported as a superfluorescent source [6] (i.e. with one mirror only and no feedback). With the addition of a second butted mirror to provide feedback, a very high laser slope efficiency with respect to absorbed power has now been observed on this transition (see also [7]). *Q*-switched operation of both the three-level and four-level transitions is also described.

2. Spectroscopy

Yb^{3+} is described by a relatively simple energy level scheme (figure 1), comprising the multiplets $^2F_{7/2}$ and $^2F_{5/2}$ separated by around 11000 cm^{-1}. Low-temperature (20 K) spectroscopy of Yb^{3+}-doped bulk glass samples [8] completely resolves the degeneracies, but at room temperature only two of the four ground-state Stark levels are resolved in fluorescence. A spectrum taken at room temperature by

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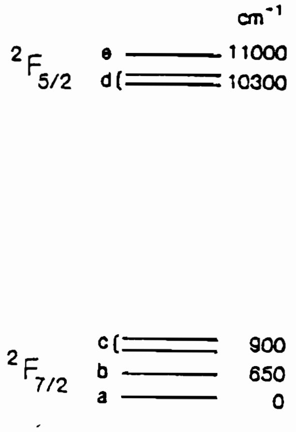

Figure 1. Yb^{3+} energy levels.

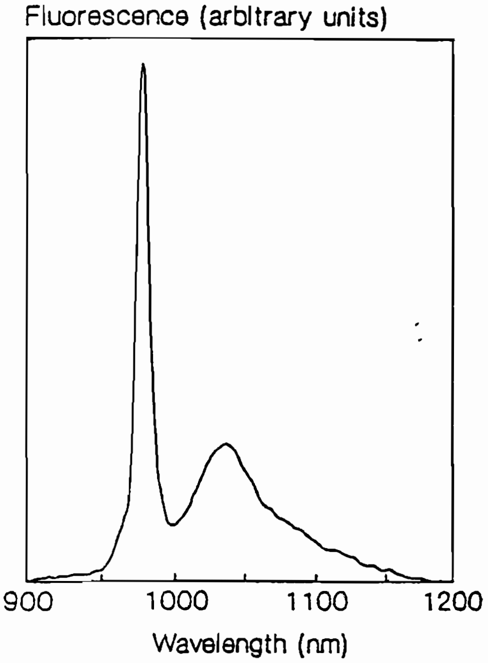

Figure 2. Yb^{3+} fluorescence spectrum at room temperature.

observation of light emitted out of the side of a fibre is shown in figure 2. This 'side-light' undergoes negligible self-absorption by thermally populated Stark levels, whereas light travelling along the fibre suffers reabsorption which produces a red-shift so that the end-light spectrum is significantly distorted. The two resolved transitions (referring to figure 1) are at 974 nm (three-level transition d to a) and 1036 nm (quasi-four-level transition d to b), with f.w.h.m. 10 nm and 50 nm respectively. The remaining unresolved transitions are contained in the long wavelength tail where tunable laser operation is possible. The lifetime of level d was measured as 0·77 ms. Absorption is strongest at 915 nm (45 db m^{-1} for this fibre) and

974 nm (70 dB m^{-1}), whereas at the upper wavelength limit for GaAlAs laser diodes that are currently available commercially (around 840 nm) the absorption is 2 dB m^{-1}. Since considerable interest centres on the performance of fibre lasers under diode-laser pumping, a Styryl 9M dye laser operating at 840–850 nm was used to simulate such pump conditions, in addition to operation at 900 nm, closer to the Yb^{3+} absorption peaks.

The silica-based fibre used in these experiments was fabricated using the solution doping technique [4] and had the following characteristics: nominal dopant concentration 580 p.p.m.; numerical aperture 0·16; core diameter 3·7 μm, and LP$_{11}$ mode cut-off 800 nm.

3. Experimental

Several factors determine whether laser action occurs on the three-level or four-level transition. To avoid significant re-absorption losses on the three-level transition, the fibre must be bleached throughout a substantial part of its length, so it is necessary to pump with an intensity in this region at least equal to the pump saturation intensity. For a given pump level, this requirement imposes a restriction on the length of fibre: increasing the fibre length beyond the point at which the pump power emerging from the output end is just equal to the saturation power causes a reduction in the three-level gain due to re-absorption in the non-inverted (with respect to levels a and d) region. Level d will be inverted with respect to level b provided that more than about 4% of the total population is in the upper level. However, the fluorescence spectrum shows the ratio of the emission cross-sections at 974 nm (three-level) and 1036 nm (four-level) to be 4 : 1, so the three-level gain is higher unless the fibre length is such that re-absorption losses reduce the gain below that of the four-level transition. The four-level gain increases with length until all the pump power is absorbed. Emission would then propagate without gain or loss in the remaining fibre in the pure four-level case, but here the transition is, strictly speaking, quasi-four-level in nature since the thermal population of Stark levels in the ground-state multiplet presents a re-absorption loss and prevents the fibre being made arbitrarily long.

3.1. *Three-level operation*

We have recently reported superfluorescent emission on the pure three-level transition in Yb^{3+} at 974 nm [7], but it is also possible to operate the system as a conventional laser oscillator at this wavelength. To investigate this we chose a pump wavelength of 900 nm (absorption 41 dB m^{-1}) where the large absorption cross-section means a low pump saturation power of about 5 mW. This wavelength is slightly detuned from the absorption peak at 915 nm, since the dye laser tuning range did not extend to this wavelength.

A fibre length of 0·5 m was found to be optimum for emission of fluroescence at 974 nm when pumped with 30 mW of launched power. With this length of fibre, a resonator was formed by butting it against a mirror of > 99% reflectivity in the range 930–1200 nm at the input end and the cavity was completed using the 3·5% Fresnel reflection at the output end. With the pump laser operating at its power limit of about 65 mW incident upon the launch optics, a maximum output power of 9·3 mW was achieved from the fibre laser for 25 mW absorbed. The slope efficiency with respect to absorbed power was 67%, and the threshold power was 11·5 W absorbed. Output power against absorbed pump power is shown in figure 3.

Laser action on this transition was also observed when pumping at 850 nm, a wavelength chosen to simulate high-power diode lasers. The low pump absorption (3 dB m^{-1}), limited amount of pump power (145 mW incident on the launch optics), and the need to avoid a non-inverted region at the end of the fibre restricted the fibre length to about 20 cm. In addition to the input mirror, a second high reflector was butted at the output to reduce the cavity loss. The maximum output power was 1·4 mW for 68 mW launched, with a threshold of 26 mW launched.

3.2. *Four-level operation*

Pumping again at 900 nm, we return to the resonator with a single high reflector, plus the end face reflection for feedback, but an increase of fibre length to 1 m. Under these conditions we observe a change in the laser wavelength to 1036 nm, where the laser transition has switched from three-level (d to a) to four-level (d to b and c). The maximum output power was 15·7 mW for 31 mW absorbed. The slope efficiency with respect to absorbed power was 77%, and the threshold power was 9·4 mW absorbed. Output power against absorbed pump power is shown in figure 4.

The pump laser wavelength was again changed to 850 nm for diode laser simulation. The weaker absorption here presents less of a problem than in the three-level case, since the four-level nature allows a longer fibre length to be used to absorb more pump power. The maximum output power for a 4 m fibre was 27·7 mW at 1050 nm for an absorbed power of 67·6 mW (the longer wavelength being due to re-absorption in the ground-state Stark levels). The slope efficiency with respect to absorbed power was 61%, and the threshold power was 22·3 mW absorbed.

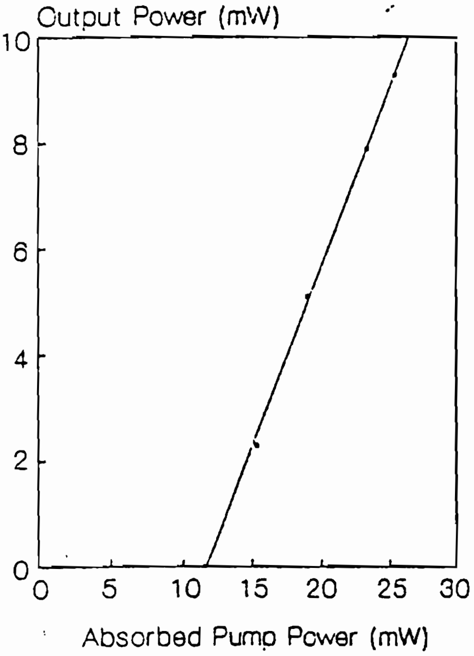

Figure 3. Output power against absorbed pump power for the three-level transition.

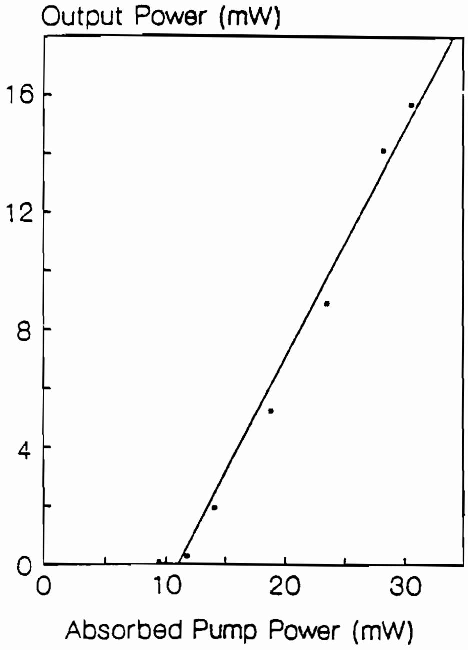

Figure 4. Output power against absorbed pump power for the four-level transition.

3.3. *Tunable operation*

Preliminary investigations of the tuning range available from the potentially broad gain curve of the four-level transition were made using a prism as the dispersive element. The pump wavelength was set at 840 nm to simulate GaAlAs diode laser wavelengths. About 100 mW of pump power was launched into a 3 m fibre, with about 75% of this power absorbed. The input end of the fibre was butted against a mirror with reflectivity >99% in the region 930–1200 nm. The output end was fixed into a glass capillary tube and mounted into a cell containing index-matching fluid to prevent reflections from the end face of the fibre. The high dispersion prism was located between the index-matching cell and a feedback mirror (identical to that at the input), with tuning achieved by small angular adjustments of the mirror. The low output coupling of the mirrors meant that it was more practical to detect radiation by observation of the reflection from one face of the prism.

The fibre laser wavelength was tuned in steps of 2 nm with careful adjustment of the resonator at each step to optimise the output signal. A typical tuning curve is shown in figure 5. Laser operation was observed continuously over the range 1020–1150 nm, but the output power was modulated with a period of about 7 nm. The possibility that this was caused by an étalon in the cavity was investigated by systematic adjustment of all elements within it, but the modulation remained. It was noticed that by applying slight bends or twists to the fibre at minima in the tuning curve the signal could be increased, indicating that the output is sensitive to changes in stress-induced birefringence. In fact, as we describe below, the modulation can be significantly reduced by using this effect to control the polarisation state of light in the cavity.

Spontaneous emission in the fibre is unpolarised. The fibre is non-polarisation preserving and in general its output is unpolarised. The prism, aligned close to

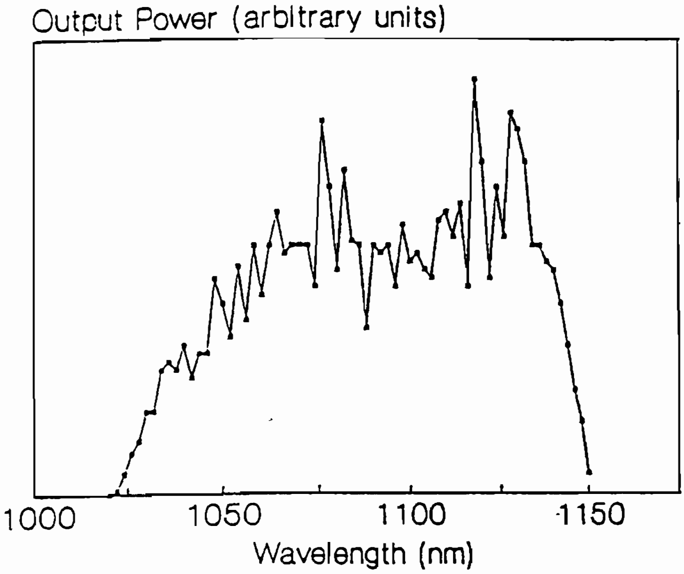

Figure 5. Tuning curve with no polarisation control.

Brewster's angle with respect to radiation incident from the fibre in order to minimise the cavity loss, transmits almost all of the horizontal component whereas a proportion of the vertical component suffers from reflection and is lost from the cavity. The prism therefore favours laser action on the low-loss horizontal component. However, the lack of complete circular symmetry in the cross-section of the fibre core, together with anisotropies due to thermal and mechanical stresses, renders the fibre a birefringent medium. The horizontal component launched into the fibre via the prism after reflection at the feedback mirror can be resolved into two orthogonal components with respect to the axes of the birefringence, and so the polarisation state within the fibre evolves cyclically as these two modes beat together. After one round trip, light at the prism has developed a vertical component which suffers from reflection loss. Since the phase shift between the two polarisation components is wavelength-dependent, the polarisation state at the fibre output is also wavelength-dependent. This causes the cavity loss to vary as the laser is tuned and leads to the observed power oscillations.

To prevent this effect, the birefringence must be controlled so that horizontally polarised light launched into the fibre from the tuning mirror through the prism emerges after one round trip through the fibre with the same polarisation.

The natural birefringence is unpredictable, being sensitive to twists and bends in the fibre. Correctly aligned high-birefringence polarisation-preserving fibre could eliminate these problems, but with typical fibre a means of controlling the polarisation state is required. A remedy was found in the application of fibre loop polarisation controllers. We use here the method developed by Lefevre [9] for control of the birefringence of single-mode silica fibre by bending it in a series of loops to make devices analogous to fractional wave plates in bulk devices.

Birefringence can be induced in a fibre by coiling it into a loop of radius R with a number of turns N such that the total phase delay between the two modes corresponds to that given by a λ/m wave plate, where $m=2, 4, 8$, and so on. The relationship is given by $R(m, N) = 2\pi a r^2 Nm/\lambda$, where λ is the wavelength, r is the fibre radius (inclusive of the cladding) and a is a factor derived from consideration of the difference between the extraordinary and ordinary refractive indices as a function of $(r/R)^2$. For propagation in silica at a wavelength of 633 nm Lefevre gives $a = 0{\cdot}133$. We assume this value to be valid at longer wavelengths. Control of the polarisation state is achieved by rotating the plane of the loops. This twists the fibre and rotates the orientation of the axes of the induced birefringence and consequently rotates the angle of the polarisation state at the loop.

For a single-turn $\lambda/4$ device we take the values $\lambda = 1{\cdot}090\,\mu\text{m}$, $N = 1$, $m = 4$ and $r = 62{\cdot}5\,\mu\text{m}$, giving a loop radius of $R = 1{\cdot}2$ cm. A $\lambda/2$ device of the same radius simply requires two turns (or alternatively a single-turn of half the radius).

For a further investigation of the tuning range a device was constructed consisting of two $\lambda/4$ loops and one $\lambda/2$ loop, all having radius 1·2 cm. For each 2 nm step in the tuning curve the polarisation state at the prism can be made horizontal for minimum reflection losses by adjustment of the angle of the loops. With the prism aligned at a slight deviation from Brewster's angle there exists a horizontal component of reflection which forms the laser output. This passes through a Glan–Taylor polariser and then a monochromator before reaching a Ge photodetector.

A problem encountered with the single-prism arrangement (with and without the loop polarisers) was that of simultaneous oscillation on more than one wavelength. The consequent depopulation of the upper laser level reduces the gain available at the tuned wavelength. The insertion of a second prism to increase the dispersion is sufficient to allow efficient tuning.

The arrangement is shown in figure 6. A 3 m length of fibre was tuned in steps of 2 nm (under the same pump conditions as before) with the system carefully optimised at each stage. The tuning curve (figure 7) extends from 1010 nm to 1162 nm and is relatively free from the modulation observed previously. On the plateau of the tuning curve the output power coupled out of the resonator by the tuning mirror was 3 μW. Since this mirror was a high reflector, much higher output powers may be expected with an optimised transmission, although at the expense of some reduction in the tuning range. The threshold for laser action was about 30 mW absorbed.

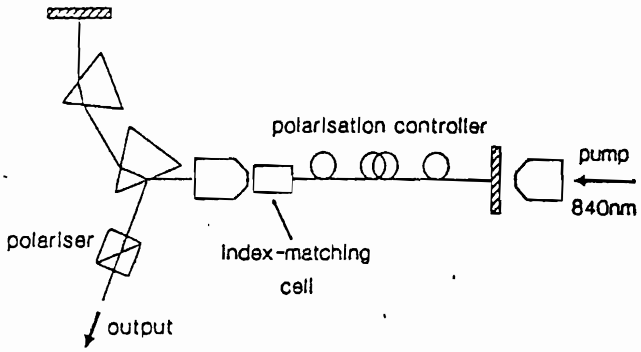

Figure 6. Arrangement for tuning, incorporating fibre loop polarisation controller.

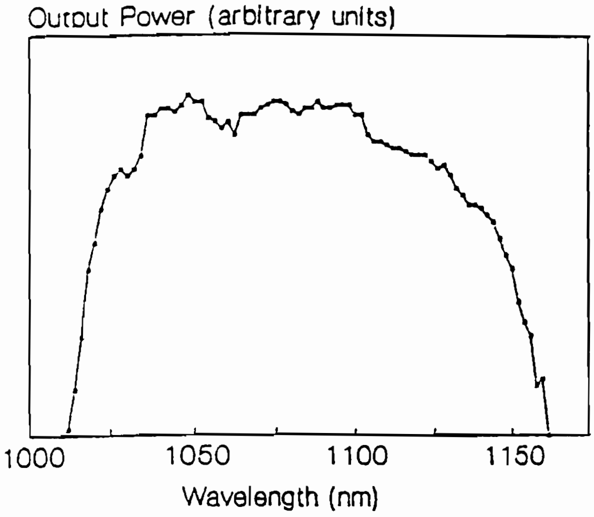

Figure 7. Tuning curve using fibre loop polarisation controller.

3.4. *Q-switched performance*

A resonator was constructed by butting one end of the fibre against a high reflector in the range 930–1200 nm. The other end was inserted into a cell containing index-matching fluid to prevent reflections from the end face. An acousto-optic Q-switch with a 1 ms repetition rate was inserted between the cell and a feedback mirror.

For the three-level transition a 25 cm length fibre was pumped with 38·8 mW absorbed at 884 nm. With an output coupler of 20% transmission, 25 ns pulses were observed at 974 nm. The pulse energy of 200 nJ indicates a peak power of 8 W. The fibre length was increased to 1 m for the four-level transition and the pump wavelength changed to 850 nm. An output coupler of 80% transmission was used, and the laser wavelength was 1041 nm. With 104 mW of pump absorbed, the output was 8 μJ in a 100 ns pulse, indicating a peak power of 80 W.

4. Conclusion

Tuned operation has been observed on the four-level transition in Yb^{3+}. Problems encountered due to a lack of polarisation control in a tunable fibre laser resonator have been demonstrated and a remedy in the form of fibre loop polarisation controllers has been shown to be effective. The tuning range of 1·010 μm to 1·162 μm is believed to suffer at the long wavelength end from fall-off in the mirror reflectivity towards 1·2 μm, and it may be possible to extend the range using more suitable mirrors.

We have also demonstrated efficient, low threshold (about 10 mW) c.w. laser action in Yb^{3+}-doped silica fibre on both the three-level and four-level transitions when pumped at 900 nm. The three-level transition yielded 9·3 mW at 974 nm with slope efficiency with respect to absorbed power of 67%. The four-level transition, when untuned, yielded 15·7 mW at 1036 nm with a slope efficiency with respect to absorbed power of 77%. The ability to achieve these high slope efficiencies is attributed to the lack of excited state absorption in the Yb^{3+} system, a particularly attractive feature of this laser that presents the possibility of scaling to higher powers.

Both transitions have also operated when pumped at 850 nm, a significant detuning from the absorption peak. Our results indicate that efficient diode laser pumped operation should be possible, both on the four-level transition and, with the help of recently available higher power diodes at 860 nm, on the three-level transition also.

Acknowledgments

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