Continuous-Wave Tunable and Superfluorescent Operation of a Monomode Ytterbium-Doped Fiber Laser

D. C. Hanna, R. M. Percival, I. R. Perry, R. G. Smart, P. J. Suni,
and A. C. Tropper

Department of Physics, The University of Southampton,
Southampton SO9 5NH, United Kingdom

ABSTRACT

Efficient laser action has been observed in a monomode Yb^{3+}-doped fibre at 974nm (three level transition) and at 1036nm, with output powers of 9.3mW and 15.7mW respectively and slope efficiencies of 67% and 77% respectively. Q-switched operation yielded pulses of 25ns at 974nm and 100ns at 1041nm. Tunable cw operation from 1010nm to 1162nm has been demonstrated. In addition, efficient superfluorescent emission has been observed at 974nm and around 1040nm with output powers of 10mW and 31mW respectively and slope efficiencies of 45%.

INTRODUCTION

Silica-based optical fibres are useful host media for laser active rare-earth dopantions, providing an amorphous environment in which rare-earth optical transitions are considerably broadened spectrally. This offers the possibility of wide tuning ranges for laser operation and wide spectral ranges suitable for pumping. Yb^{3+} is of interest in that its broad absorption makes it a good candidate as an activator for energy transfer to another ion and also shows a broad fluorescence from around 940nm to 1200nm making it suitable as a candidate for tunable laser action. Laser action at 1015nm in Yb^{3+}-doped silicate glass cooled to 77K was reported in 1962 [1] and subsequently at 1060nm in silicate glass co-doped with Nd^{3+} [2]. More recently we reported preliminary results for laser action on the four level transition in a monomode Yb^{3+}-doped silica fibre tunable over the range 1015-1140nm [3]. Operation on the three level transition around 980nm in a fibre has also been reported [4,5]. We present here a more detailed investigation of this system and show that it has an extended tuning range (1010-1162nm), low threshold operation and the potential for pumping with GaAlAs diode lasers. Efficient laser operation has been achieved both on the three level and four level transitions at 974nm and 1036nm respectively. In addition, efficient superfluorescent emission has been observed at 974nm and around 1040nm

SPECTROSCOPY

The energy levels are shown in Fig 1. The $^2F_{5/2}$ multiplet is the only relevant excited state, lying about 11000cm^{-1} above the $^2F_{7/2}$ ground state multiplet. Other excited states correspond to a different configuration and thus have much higher energies. So for infra red pumping there is no possibility of excited state absorption (ESA) of the pump, nor is there ESA of the emitted radiation.

Fig 2 shows the absorption and fluorescence spectra at room temperature. Two of the excited state Stark levels are resolved in absorption: the peak centred at 910nm corresponds to transition a to e in Fig 1: the peak centred at 974nm corresponds to transition a to d. Pumping into level e is followed by rapid non-radiative decay to level d, from which fluorescence to the ground state occurs with a lifetime measured as 0.77ms. The fluorescence spectrum was recorded by observation of light emitted from the side of the fibre to avoid the spectral distortion of light guided along the fibre by self-absorption in the ground state. The peak centred at 974nm (FWHM. 10nm) arises from the pure three-level transition d to a, whereas the broader peak centred at 1036nm (FWHM 50nm) is a result of emission from level d to levels b and c and is quasi four-level in nature, since the population

1-55752-111-5/89/$2.00 © Optical Society of America

of level b at room temperature is approximately 4% of the total population. Levels c are unresolved but give rise to the long-wavelength tail where tuned laser operation is possible.

Fluorescence spectra were recorded for various excitation wavelengths in the range 800-920nm using a Styryl 9M dye laser as a pump source. We note that neither the relative heights of the peaks nor the linecentre positions showed any change with excitation wavelength in this region.

THREE AND FOUR LEVEL OPERATION

For inversion on the three level transition it is necessary to pump with an intensity at least equal to the saturation intensity $I_{sat} = h\nu/\sigma\tau$ where ν is the pump frequency, σ is the absorption cross-section for the a to e transition and τ is the fluorescence lifetime of level d. With A_{eff} the effective area of the fibre core we can calculate the saturation power $P_{sat} = I_{sat}A_{eff}$ that must be launched to produce inversion at the input end. With a pump source operating at 900nm, P_{sat} for our fibre is about 5mW. Significantly higher powers were available from the Styryl 9M dye laser and we were able to invert the three level transition over lengths of about 50cm (i.e. about 5 times the small signal extinction length). Although level d is also inverted with respect to level b, the fluorescence spectrum shows that the ratio of the emission cross-sections at 974nm (three level) and 1036nm (four level) is about 4:1, so for fibre lengths shorter than about 50cm the three level gain is higher than the four level gain.

If the fibre length is increased beyond the length at which the pump power at the output end falls to the saturation power, the three level gain decreases because of reabsorption in this non-inverted region. This imposes an optimal length for maximum gain on the three level transition where the pump power emerging at the output end is just equal to the saturation power. For such a length, transition d to b is still inverted, since this inversion only requires about 4% of the total population to be in the upper level. Increasing the length increases the four level gain until all the pump power is absorbed. Further increase of length for the perfect four level case (i.e. empty lower level) would lead to no change in overall gain. In practice however the fibre length cannot be arbitrarily long since the thermal population of the lower level is not negligible and leads to significant reabsorption.

EXPERIMENT

Laser Emission

The fibre used in these experiments was fabricated by the solution doping technique [6] and was characterised by a nominal Yb^{3+} concentration of 580ppm, a numerical aperture of 0.16, a core diameter of 3.7µm and an LP_{11} mode cut-off wavelength of 800nm.

To observe laser action a length of fibre was butted at the input end against a dielectric mirror with reflectivity >99.5% in the range 930-1200nm. Feedback was provided by Fresnel reflection from the output end-face of the fibre, calculated as 3.5%. Pump light at 900nm was launched into the fibre using an 18X microscope objective. This detuning from the absorption peak at 910nm was found to give more output power due to the higher pump power available at this wavelength. For a fibre length of 0.5m laser action was observed at 974nm, whereas for a 1m piece the laser emission was at 1036nm. The maximum output power at 974nm was 9.3mW for an absorbed pump power of 25.3mW and the threshold absorbed power was 11.5mW. The slope efficiency with respect to absorbed power was 67%. In the case of the 1036nm emission, maximum output power was 15.7mW for 30.6mW absorbed with a threshold absorbed power of 9.4mW. The slope efficiency with respect to absorbed power was 77%. Output power versus absorbed pump power is shown for both transitions in Fig 3.

Preliminary results for Q-switched performance were obtained by inserting an acousto-optic Q-switch between the fibre output and a second mirror which now provided the feedback. Optimum results for the three level transition were achieved with a 0.25m fibre pumped at 884nm with 20% output coupling. The output energy was 200nJ at 974nm in a 25nsec. pulse, indicating a peak power of 8W. For the four level transition a 1m length of fibre was pumped at 850nm with output coupling of 25%. The output energy was 8µJ at 1041nm in a 100nsec. pulse, indicating 80W peak power.

Superfluorescent Emission

We have also observed efficient superfluorescent emission from the Yb^{3+}-doped fibre at 974nm and around 1040nm [7]. Superfluorescence (or Amplified Spontaneous Emission) occurs when the gain is so high that in a single pass the ASE can grow to a significant fraction of the saturation intensity. Calculation shows that, for the fibre we have used a gain of 30-40dB in a single pass is sufficient for the onset of strong superfluorescence. For a double pass arrangement, such as we have used with a feedback mirror at one end of the fibre, the gain requirement for superfluorescence is halved.

To observe superfluorescence we pumped the of level b at room temperature is approximately 4% of the total population. Levels c are unresolved but give rise to the long-wavelength tail where tuned laser operation is possible.

Fluorescence spectra were recorded for various excitation wavelengths in the range 800-920nm using a Styryl 9M dye laser as a pump source. We note that neither the relative heights of the peaks nor the linecentre positions showed any change with excitation wavelength in this region.

THREE AND FOUR LEVEL OPERATION

For inversion on the three level transition it is necessary to pump with an intensity at least equal to the saturation intensity $I_{sat} = h\nu/\sigma\tau$ where ν is the pump frequency, σ is the absorption cross-section for the a to e transition and τ is the fluorescence lifetime of level d. With A_{eff} the effective area of the fibre core we can calculate the saturation power $P_{sat} = I_{sat}A_{eff}$ that must be launched to produce inversion at the input end. With a pump source operating at 900nm, P_{sat} for our fibre is about 5mW. Significantly higher powers were available from the Styryl 9M dye laser and we were able to invert the three level transition over lengths of about 50cm (i.e. about 5 times the small signal extinction length). Although level d is also inverted with respect to level b, the fluorescence spectrum shows that the ratio of the emission cross-sections at 974nm (three level) and 1036nm (four level) is about 4:1, so for fibre lengths shorter than about 50cm the three level gain is higher than the four level gain.

If the fibre length is increased beyond the length at which the pump power at the output end falls to the saturation power, the three level gain decreases because of reabsorption in this non-inverted region. This imposes an optimal length for maximum gain on the three level transition where the pump power emerging at the output end is just equal to the saturation power. For such a length, transition d to b is still inverted, since this inversion only requires about 4% of the total population to be in the upper level. Increasing the length increases the four level gain until all the pump power is absorbed. Further increase of length for the perfect four level case (i.e. empty lower level) would lead to no change in overall gain. In practice however the fibre length cannot be arbitrarily long since the thermal population of the lower level is not negligible and leads to significant reabsorption.

EXPERIMENT

Laser Emission

The fibre used in these experiments was fabricated by the solution doping technique [6] and was characterised by a nominal Yb^{3+} concentration of 580ppm, a numerical aperture of 0.16, a core diameter of 3.7μm and an LP_{11} mode cut-off wavelength of 800nm.

To observe laser action a length of fibre was butted at the input end against a dielectric mirror with reflectivity >99.5% in the range 930-1200nm. Feedback was provided by Fresnel reflection from the output endface of the fibre, calculated as 3.5%. Pump light at 900nm was launched into the fibre using an 18X microscope objective. This detuning from the absorption peak at 910nm was found to give more output power due to the higher pump power available at this wavelength. For a fibre length of 0.5m laser action was observed at 974nm, whereas for a 1m piece the laser emission was at 1036nm. The maximum output power at 974nm was 9.3mW for an absorbed pump power of 25.3mW and the threshold absorbed power was 11.5mW. The slope efficiency with respect to absorbed power was 67%. In the case of the 1036nm emission, maximum output power was 15.7mW for 30.6mW absorbed with a threshold absorbed power of 9.4mW. The slope efficiency with respect to absorbed power was 77%. Output power versus absorbed pump power is shown for both transitions in Fig 3.

Preliminary results for Q-switched performance were obtained by inserting an acousto-optic Q-switch between the fibre output and a second mirror which now provided the feedback. Optimum results for the three level transition were achieved with a 0.25m fibre pumped at 884nm with 20% output coupling. The output energy was 200nJ at 974nm in a 25nsec. pulse, indicating a peak power of 8W. For the four level transition a 1m length of fibre was pumped at 850nm with output coupling of 25%. The output energy was 8μJ at 1041nm in a 100nsec. pulse, indicating 80W peak power.

Superfluorescent Emission

We have also observed efficient superfluorescent emission from the Yb^{3+}-doped fibre at 974nm and around 1040nm [7]. Superfluorescence (or Amplified Spontaneous Emission) occurs when the gain is so high that in a single pass the ASE can grow to a significant fraction of the saturation intensity. Calculation shows that, for the fibre we have used a gain of 30-40dB in a single pass is sufficient for the onset of strong superfluorescence. For a double pass arrangement, such as we have used with a feedback mirror at one end of the fibre, the gain requirement for superfluorescence is halved.

To observe superfluorescence we pumped the fibre through a butted dielectric mirror with reflectivity >99.5% in the range 930-1200nm. The output end was terminated in a cell containing index-matching fluid to prevent feedback and hence laser oscillation from the fibre end-face. The length dependence of the emission wavelength follows similar considerations to those above for laser emission: for output on the three level transition to dominate, the fibre must be substantially bleached throughout its length with a pump intensity at least equal to the saturation intensity. To investigate the length dependent behaviour the fibre was progressively cut back while measuring the amount of superfluorescence on the three and four level transitions and also the residual pump power at the fibre output. Approximately 30mW of pump at 900nm was launched into the fibre for these measurements. Output power versus fibre length is shown in Fig 4. We see that for short lengths the three level emission at 974nm predominates, whereas for lengths greater than about 0.75m the four level emission around 1040nm is favoured, this behaviour being in good agreement with the qualitative description given above. We note that the peak in the 974nm emission occurs where the residual pump power is approximately 5mW, i.e. equal, as expected, to the calculated saturation power.

Fig 4. shows the optimal length for emission at 974nm to be 0.5m when pumped with 30mW launched power. Using this length, the fibre yielded 10mW of superfluorescent output at 974nm (when pmped at slightly higher powers). The slope efficiency was about 45%. For the four level transition the choice of fibre length is not critical. Since most pump power was available at 850nm, we used this pump wavelength and a sufficient length of fibre, 5m in this case, to ensure complete absorption of the pump. This arrangement discriminated against the 974nm emission since the small absorption cross-section and hence saturation intensity, for 850nm reduced the inversion of the three level transition. The maximum output power was 31mW with a slope efficiency of about 45%. Output power versus absorbed pump power for both transitions is shown in Fig 5.

The bandwidth (FWHM) of the 974nm emission was measured as 2nm, but the four level emission bandwidth and indeed linecentre position exhibited a dependence on pump power and wavelength: in the high power regime (70mW absorbed at 850nm) the emission is centred at 1040nm with a 20nm bandwidth; the wavelength increases with decreasing power such that below threshold it has shifted to 1049nm with a bandwidth of 25nm. Pumping at 900nm reduces the bandwidth to 9nm for high power pumping. We believe these effects to be due to a site-dependent effect and will be investigated further.

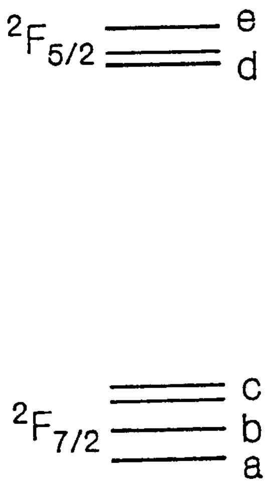

Fig 1. Energy levels for Yb^{3+} in a silica host

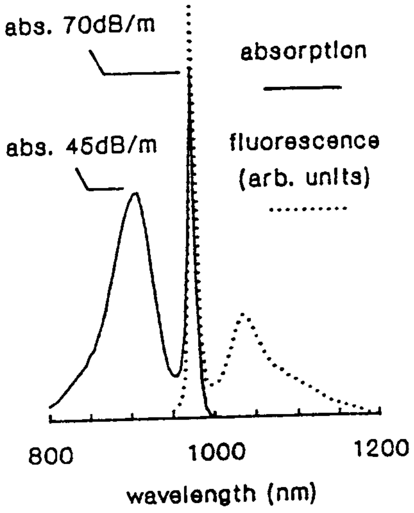

Fig 2. Absorption and fluorescence spectra for the Yb^{3+}-doped fibre

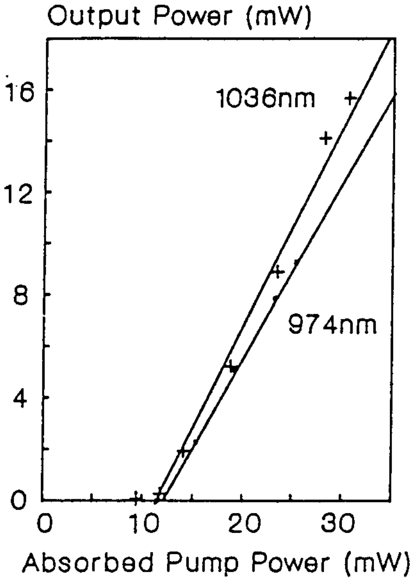

Fig 3. Laser performance: output power versus absorbed pump power

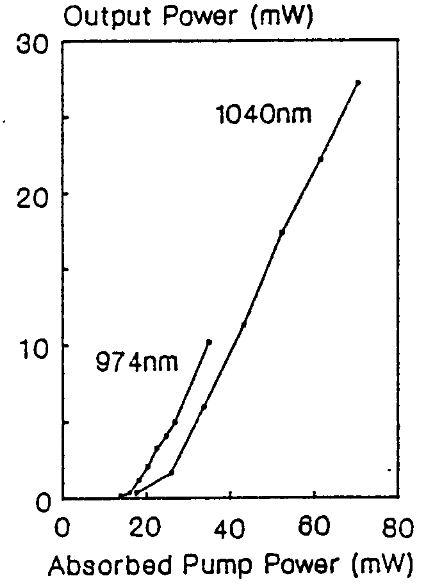

Fig 5. Superfluorescent performance: output power versus absorbed pump power

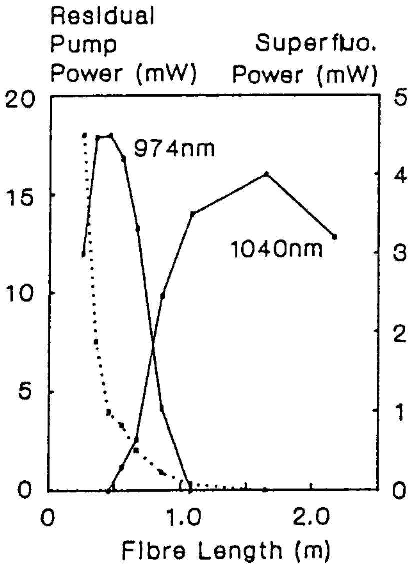

Fig 4. Variation of superfluorescent power with fibre length

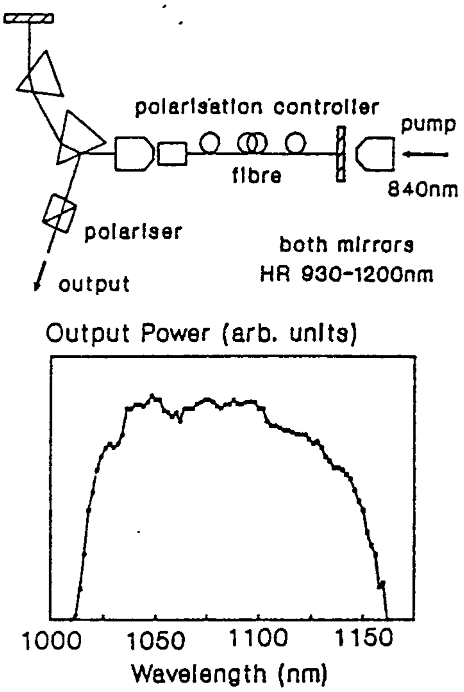

Fig 6. Resonator for tunable operation and tuning curve

TUNABLE OPERATION

The laser tuning range of the broad four level fluorescence was investigated using the resonator shown in Fig 6. About 100mW was launched into a 3m length of fibre from a Styryl 9M dye laser operating at 840nm, a wavelength chosen because high pump powers were available here and also to simulate a GaAlAs diode laser. The input end of the fibre was butted against a dielectric mirror with reflectivity >99.5% in the range 930-1200nm, and the output was terminated in an index-matching cell to prevent lasing off the fibre end-face. The resonator uses two prisms as the dispersing elements: we found that one prism provided insufficient dispersion to prevent simultaneous laser action at more than one wavelength. Feedback was provided by a second high reflector which could be rotated through small angles to select the lasing wavelength from the dispersed beam leaving the second prism. The low output coupling of the mirrors meant that it was necessary to extract laser output in the form of reflection from the first prism.

The resonator also incorporates a fibre loop polarisation controller as described by Lefevre [8]. To minimise cavity losses the prisms are set close to Brewster's angle so that laser action is favoured on the horizontal polarisation state. However, the fibre acts like a birefringent medium and the polarisation state will in general be modified after a round trip through the fibre. The phase retardation resulting from the birefringence depends on the fibre laser wavelength and thus so also does the polarisation state of light at the prism. Thus without polarisation control the losses, and hence output power, would vary with wavelength in a complex manner. This effect is counteracted by use of the fibre loop polarisation controller consisting of three discs of appropriate radii around which the fibre is wound. These loops in the fibre induce a radial stress which produces additional birefringence in the fibre. Rotation of the plane of the discs has the effect of rotating the co-ordinate axes for the birefringence and in essence a single loop in the fibre acts as a quarter waveplate and a loop of two turns behaves like a half waveplate. Light can thus be made to emerge after one round trip with its original polarisation state. In practice the output prism was deliberately off-set from Brewster's angle so that the output power in the form of horizontally polarised light could be monitored (the output is passed through a Glan-Taylor polariser to remove the vertical component). It should be noted that by using fibre fabricated in such a way as to have a deliberately high birefringence, the need for these fibre loops would be elimintated.

The fibre laser was tuned in steps of 2nm and the polarisation controller adjusted at each wavelength to maximise the output power. The tuning curve is shown in Fig 6. Laser action was observed continuously over the range 1010-1162nm at room temperature. By immersing the fibre in liquid nitrogen, the lower wavelength limit could be extended to 1000nm due to the reduction in the thermally excited population of the ground state manifold, thus reducing self-absorption at short wavelengths. The typical incident power threshold for the room temperature laser was about 60mW. Since the feedback mirror was essentially a total reflector, the output power from this mirror was only about 3μW over most of the tuning range and could obviously be greatly increased by using an optimum transmission (although this will to some extent reduce the tuning range).

CONCLUSION

An Yb^{3+}-doped monomode fibre has demonstrated efficient low threshold (about 10mW) cw laser action on the three level transition at 974nm with an output power of 9.3mW and slope efficiency of 67%. The four level transition, when untuned, has produced 30.6mW at 1036nm with a slope efficiency of 77%. A tuning range of 1010-1162nm has been achieved on the four level transition. Pump wavelengths for this transition are in the range provided by commercially available diode lasers. Q-switched performance on both transitions has also been demonstrated. Superfluorescent emission has been observed at 974nm and around 1040nm with output powers of 10mW and 31mW respectively and slope efficiencies of about 45% in both cases.

Both laser operation and superfluorescent emission are highly efficient, due mainly to the lack of ESA in the Yb^{3+} system. This freedom from ESA also offers the possibility of scaling to much higher powers since the output powers we have observed are limited only by the available pump power.

We note that the three level emission at 974nm may find uses in pumping Er^{3+}-doped fibre lasers and amplifiers, since Er^{3+} has an absorption band centred at 980nm (with a bandwidth of about 40nm) which is free from the problems of pump ESA encountered in other Er^{3+} absorption bands.

ACKNOWLEDGMENTS

Financial support for this work as well as Research Fellowships (P.S., R.P.) and studentships (I.P. and R.S.) was provided by the United Kingdom Science and Engineering Research Council. We also acknowledge the Optical Fibre Group at Southampton University for providing the Yb-doped fibre.

REFERENCES

1. H.W.Etzel, H.W.Gandy, and R.J.Ginther, "Stimulated emission of infra-red radiation from ytterbium activated silicate glass", Appl.Optics 1, 534-536 (1962).
2. E.Snitzer, "Laser emission at 1.06μm from Nd^{3+}- Yb^{3+} glass", IEEE J.Quantum Electron. QE-2, 562-567 (1966).
3. D.C.Hanna, R.M.Percival, I.R.Perry, R.G. Smart, P.J.Suni, J.E.Townsend, A.C.Tropper, "Continuous-wave oscillation of a monomode ytterbium fibre laser", Electron Lett. 24, 1111-1113 (1988).
4. D.C.Hanna, "Physics of fibre lasers", Lasers 88, (Lake Tahoe, 1988), paper TG2.
5. J.R.Armitage, R.Wyatt, B.J.Ainslie, and S.P. Craig-Ryan, "Highly efficient 980nm operation of an Yb^{3+}-doped silica fibre laser", Electron.Lett.25 298-299 (1989).
6. J.E.Townsend, S.B.Poole, and D.N.Payne, "Solution-doping technique for fabrication or rare-earth doped optical fibres", Electron.Lett.23, 329-331 (1987).
7. D.C.Hanna, I.R.Perry, R.G.Smart, P.J.Suni, and A.C.Tropper, "Efficient Superfluorescent emission at 974nm and 1040nm from an Yb-doped fiber", submitted to Opt. Comm.
8. H.C.Lefevre, "Single-mode fibre fractional wave devices and polarisation controllers", Electron.Lett.16, 778-780 (1980).