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CW room temperature operation of praseodymium-doped fluorozirconate glass fibre lasers in the blue-green, green and red spectral regions

R.G. Smart, J.N. Carter, A.C. Tropper, D.C. Hanna
Optoelectronics Research Centre, University of Southampton, Southampton SO9 5NH, UK

S.T. Davey, S.F. Carter and D. Szebesta
British Telecom Research Laboratories, Martlesham Heath, Ipswich IP5 7RE, UK

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We report room temperature, continuous-wave oscillation of Pr^{3+}-doped fluorozirconate fibre lasers at around 491 nm, 520 nm, 605 nm, 635 nm and 715 nm. An output power of 250 mW has been obtained at 635 nm for 800 mW of pump power from an argon ion laser operating at 476.5 nm. Tunable operation of the red transitions has been investigated, with output powers in excess of 30 mW being obtained. *Q*-switched pulses of 75 ns (fwhm) and 20 W peak power at 635 nm have also been generated.

1. Introduction

Rare earth doped fluorozirconate fibres are attracting interest as possible sources of tunable visible laser radiation. To date, visible laser emission has been obtained in the blue at 455 nm and 480 nm from Tm^{3+} [1], in the green at around 550 nm from Ho^{3+} [2], and in the red at 610 nm, 635 nm and 715 nm from Pr^{3+} [3]. The blue Tm^{3+} lasers were the first reported upconversion fibre lasers, being pumped by a krypton ion laser operating simultaneously at 647.1 nm and 676.4 nm. The Ho^{3+} fibre laser, which was also upconversion pumped by a krypton laser operating at 647.1 nm was much more efficient than the Tm^{3+} lasers, giving 11 mW of output for ≈ 50 mW of launched pump light, and also, unlike the Tm^{3+} laser which required liquid nitrogen cooling, operated at room temperature. Pr^{3+}-doped fluorozirconate fibres offer a large number of visible transitions. Pumping with an argon laser at 476.5 nm, Allain et al. [3] obtained oscillation on three transitions in the red. The convenience of these fibre sources suggests that they may find uses as alternatives to dye lasers, providing as they do, some tunability. With this potential in mind we have taken a further look at Pr^{3+}-doped fluorozirconate fibre and show that other transitions may be made to lase efficiently in the blue-green at 491 nm and in the green at 520 nm. We also show that useful output power, in the region of 20 mW, can be readily obtained from a tuned system. Our results show that with appropriate mirror design, efficient operation can be obtained on five transitions in the blue-green, green and red. We have observed thresholds for pumping at 476.5 nm and 472.7 nm of a few tens of milliwatts typically, with the prospect of a further reduction by a factor of at least four by a going to a smaller fibre diameter. This suggests that with a diode-pumped frequency doubled Nd:YAG laser operating at 946 nm as the pump, one could have an all solid state alternative to visible dye lasers. A further additional feature that the fibre lasers can offer is that of energy storage and hence the capability of producing high peak power via *Q*-switching. Preliminary results for *Q*-switched operation at 635 nm are described.

2. Spectroscopy

The fluorozirconate fibre used for the investigation of visible laser emission from the Pr^{3+} ion had a ZBLANP (ZrF_4-BaF_2-LaF_3-AlF_3-NaF-PbF_2) core doped with Pr^{3+} ions at a concentration of 560 ppm (by weight), and a cladding of ZBLAN glass. After chemical etching, the preform (which had been fabricated by the rotational casting technique) was pulled into a fibre of outer diameter 125 µm, $\Delta n = 0.007$, and cut-off for the LP_{11} mode at 0.9 µm implying a core diameter of 4.6 µm. The fibre was therefore multimode at all visible wavelengths. The background loss of the fibre was measured by the cut-black technique to be 4 dB over a 14 metre length and arose mainly from extrinsic scatter.

An energy level diagram for the Pr^{3+} ion is shown in fig. 1, with the approximate energy of each multiplet being indicated in cm^{-1}. As pointed out by Allain et al. [3] there is a near-perfect energy match between the $^3P_1$ and $^1I_6$ levels and so for simplicity the label $^3P_1$ is used to represent either $^3P_1$ or $^1I_6$ throughout the rest of this paper. As indicated in fig. 1, it can be seen that the $^3P_0$ level at 20877 cm^{-1} may be effectively excited by the 476.5 nm line from an argon ion laser. It should be noted that since the $^3P_0$ and $^3P_1$ levels are only separated by ≈800 cm^{-1} the $^3P_1$ level will be thermally populated from the $^3P_0$ level, and hence may also be considered as metastable. An emission spectrum for light emitted transversely from a 560 ppm (by weight) Pr^{3+}-doped ZBLANP fibre is shown in fig. 2. This spectrum was recorded for a pump wavelength of 472.7 nm (corresponding to absorption to the high energy side of the $^3P_0$ level). A 0.25 m Bentham monochromator with a 500 nm blazed grating was used for wavelength dispersion, and the signal was detected with a Thorn EMI model 9658A photomultiplier. The spectrum shown in fig. 2 has not been corrected for the response of the detection system. It can be clearly seen that there is strong radiative emission at ≈490 nm, 520 nm, 610 nm, and 715 nm. The transitions responsible for the various emission bands are also indicated in fig. 2. It is interesting to note that the emission bands appear to be narrower than in the spectrum shown by Allain et al. [3], with the peaks at ≈520 nm and ≈535 nm being better resolved in our spectrum. The spectrum shown in fig. 2, however, closely resembles that reported by Eyal et al. [4], for Pr^{3+}-doped ZBLA glass. The lifetime of the $^3P_0$ level in Pr^{3+}-doped ZBLA glass at room tem-

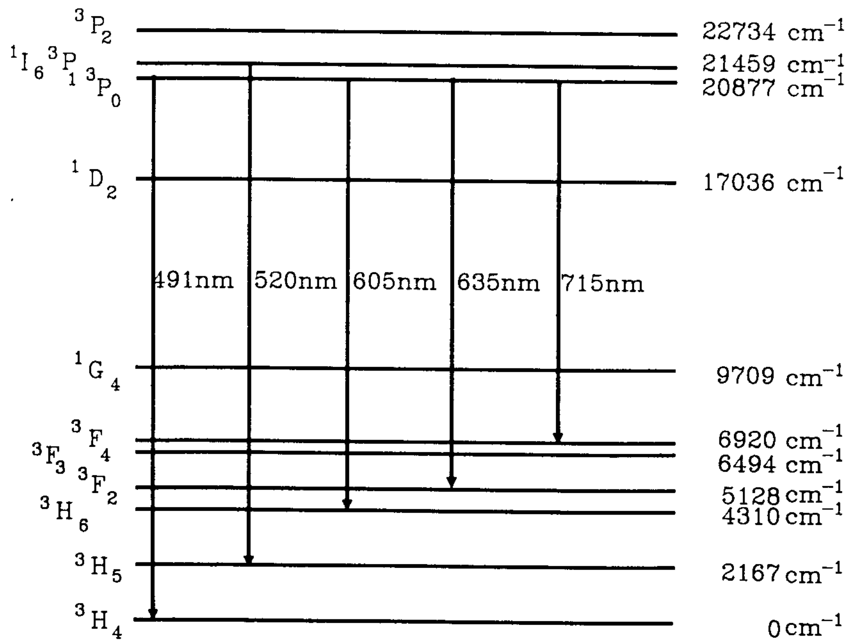

Fig. 1. Energy level diagram for Pr^{3+}-doped ZBLANP glass.

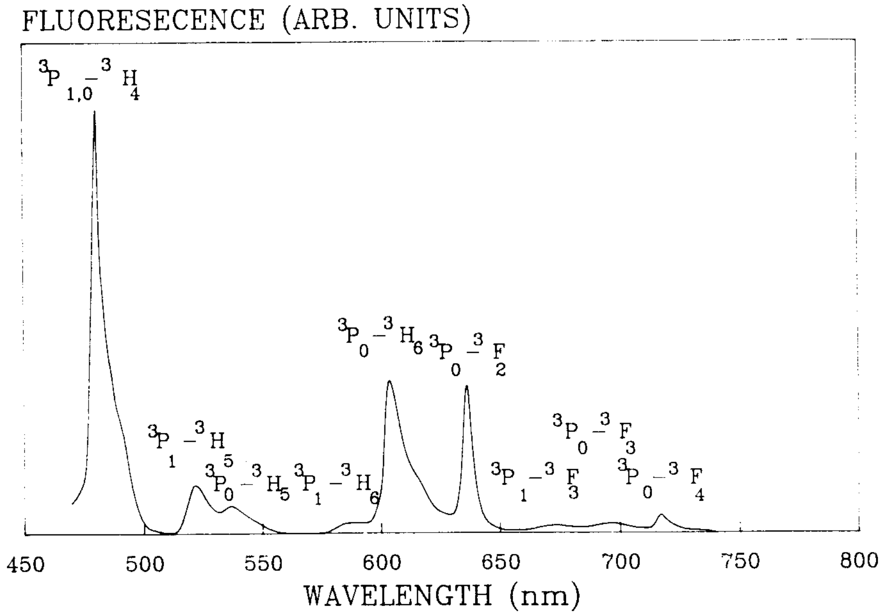

Fig. 2. Emission spectrum for Pr^{3+}-doped ZBLANP glass under excitation at 472.7 nm.

perature has been measured by Eyal et al. to be 15 μs and by Adam and Sibley [5] to be ≈40 μs. Since the $^3P_0$ level is separated by 3800 cm^{-1} from the $^1D_2$ level it is not expected to be quenched by non-radiative decay via multiphoton emission. The situation is rather different in a silica fibre host where the higher phonon energies (≈1100 cm^{-1} compared to ≈500 cm^{-1} in ZBLAN glasses) mean that the $^3P_0$ level is quenched by non-radiative emission as observed by Percival et al. [6]. Hence, most of the visible emission observed from Pr^{3+}-doped silica excited by light from an argon laser originates from the $^1D_2$ multiplet. However, since the radiative branching ratio from $^3P_0$ to $^1D_2$ is very low (a few percent at most [4]) hardly any of the visible emission from Pr^{3+}-doped fluorozirconate fibres originates from $^1D_2$ when an argon laser is used for excitation. As pointed out by Eyal et al. [4], a contribution to the emission near 590 nm may arise from the $^1D_2$–$^3H_4$ transition.

3. Efficient laser emission at 635 nm

The cavity initially used for investigating laser emission incorporated an ≈1 m length of fibre, a length which allowed essentially complete absorption of the launched pump. The fibre was butted against a dielectric mirror of ≈90% transmission at 476.5 nm and ≈10% transmission at 635 nm. The cavity was completed by the ≈3.5% Fresnel reflection arising from the glass/air interface. Light from an argon laser operating at 476.5 nm was launched into the fibre by a ×10 microscope objective with an efficiency of 65% (determined by a cut-back measurement). Laser oscillation was observed at 635 nm with a threshold power of 200 mW from the argon laser (130 mW launched). A plot of the output power as a function of incident pump power is shown in fig. 3, from which it can be seen that ≈250 mW at 635 nm was obtained for 800 mW of incident pump power. This corresponds to a slope efficiency of 42% with respect to incident pump power (64% with respect to launched power). Both the slope efficiency and maximum output power represent more than a factor of two improvement on the values previously reported by Allain et al. for this transition [3]. An output power of 250 mW is, we believe, the highest reported to date for a fluoride fibre laser. This output power was limited by damage to the input mirror

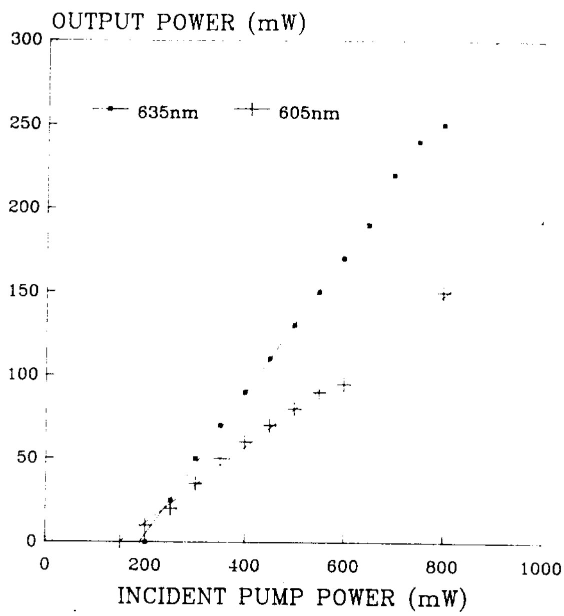

Fig. 3. Output power as a function of pump power for a Pr^{3+}-doped ZBLANP fibre laser operating at 635 nm or 605 nm.

and so using a mirror with a higher damage threshold it should be possible to extract even higher powers. The overall conversion efficiency of blue pump light to red fibre laser output is in excess of 30% and is a very good illustration of the high efficiencies obtainable with fibre lasers.

To reduce the threshold, the output end of the fibre was butted against an output coupler of ≈ 20% transmission at 635 nm. This reduced the threshold to ≈ 40 mW of incident pump power. A slope efficiency of 24% with respect to incident pump power (37% wrt launched power) was measured with this arrangement. The lowest threshold of 15 mW incident power was observed using an output coupler of < 1% transmission at 635 nm. The maximum power issuing from this output coupler was of the order of a few mW. A similar threshold was also observed when pumping at 472.7 nm. Since this cavity had a transmission loss at the lasing wavelength of ≈ 10% at the input mirror, it is clear that it should in principle be possible to construct a Pr^{3+}-doped fluorozirconate fibre laser operating at 635 nm with both a low threshold and a high efficiency given a cavity with a high reflectivity mirror at the input and a 10% transmission output coupler. It should also be noted that a factor of four reduction in threshold should be possible if a fibre with a cut-off wavelength near 0.5 μm is used.

4. Efficient laser emission at 605 nm

A simple Fabry-Perot cavity consisting of the same 1 m length of fibre was also used for investigating laser operation on the $^3P_0$–$^3H_6$ transition. The same mirror as had been used for the 635 nm laser was used at the launch end of the cavity, having 95% reflectivity at the lasing wavelength of 605 nm. The output coupler used had 40% reflectivity at 605 nm, and only 20% reflectivity at 635 nm. This difference in reflectivity was sufficient to ensure that laser emission only occurred at 605 nm rather than on the higher gain transition at 635 nm. A plot of 605 nm output power as a function of incident 476.5 nm pump power is shown in fig. 3. The threshold incident pump power was measured to be 150 mW (≈ 100 mW launched), and the slope efficiency was 21.5% with respect to incident pump power (33% wrt launched power). The maximum output power at 605 nm was 150 mW for 800 mW of pump power incident on the launch microscope objective. This is a much higher conversion efficiency than that recently reported by Allain et al. [3] where the maximum output power obtained was ≈ 25 mW for ≈ 800 mW of pump power, and confirms that high efficiency is not limited to the 635 nm transition.

5. Laser emission at 715 nm

Laser emission at 715 nm on the $^3P_0$–$^3F_4$ transition was observed when pumping at 476.5 nm. A 1 m length of fibre was used. A mirror of high reflectivity (> 99%) at 715 nm and ≈ 70% transmission at the pump wavelength was used at the input end of the cavity. The output coupler used to complete the cavity had 30% transmission at 715 nm. The threshold incident pump power was 80 mW (40 mW of which was launched into the fibre) and the slope efficiency was 15% with respect to incident pump power (30% wrt launched power). The maximum output power at 715 nm was 25 mW for 250 mW of incident pump power. This value of output power was limited by damage to the high reflector occurring at pump powers greater than 250 mW. Allain et al. were able to extract 50 mW of 715 nm output for 800 mW of pump power, with a threshold of ≈230 mW. The laser described here is, therefore, more efficient with a significantly lower threshold, although the maximum output is lower as a consequence of the high reflector coating suffering damage at a relatively low pump power.

6. Laser emission at 520 mm

Laser emission has also been observed at 520 nm, corresponding to the $^3P_1$–$^3H_5$ transition, this being the first report of lasing on this transition in a fluorozirconate host. The $^3P_1$–$^3H_5$ transition has a higher gain than the $^3P_0$–$^3H_5$ transition since the latter transition has a very low cross-section. Thus, despite the fact that the population of the $^3P_1$ level is only 5% that of the $^3P_0$ level (based on a simple Maxwell-Boltzmann distribution between these two thermally coupled levels [3]), the much higher cross-section for the $^3P_1$–$^3H_5$ transition more than compensates for the lower population of the $^3P_1$ level.

The cavity used for demonstrating laser emission at 520 nm had a mirror of high reflectivity (>99%) at 520 nm butted at the input end of a 1 m length of fibre. This mirror was the same as that used in the 605 nm and 635 nm laser experiments and so had a reflectivity of ≈95% at 605 nm and ≈90% at 635 nm. Since the gain for the 520 nm transition is much less than for the transitions in the red at 635 nm and 605 nm, this choice of high reflector meant that the output coupler needed to discriminate strongly against the red transitions. The mirror used to complete the cavity had >99% reflectivity between 450 nm and 550 nm, and ≈30% reflectivity at 605 nm and 635 nm. With this cavity the threshold for laser oscillation at 520 nm was 200 mW of incident pump power (130 mW launched). The maximum output power extracted at 520 mW was of the order of 2 mW for 500 mW of pump power. Clearly the performance of this green laser could be much improved by using mirrors of appropriate design. For example, the low efficiency of the 520 nm transition has been simply the result of the very low output coupling used. Also the available mirrors did not give an adequate discrimination against the red transitions. In fact, by altering the butt at the output end of the cavity it was possible to alter the lasing transition to that at 635 nm. Indeed, it was also possible to have simultaneous operation in the green and the red. So, in principle, it should be possible to improve significantly on the efficiency by using an output coupler of a few per cent transmission at 520 nm, together with an input mirror of high reflectivity at 520 nm but low reflectivity in the red.

7. Laser emission at 491 nm

Laser emission has also been observed at 491 nm when pumping at 476.5 nm with an argon ion laser. This is, we believe, the first report of lasing on this $^3P_0$–$^3H_4$ transition in a fluorozirconate host. A simple Fabry-Perot cavity was again used with mirrors butted at either end. The input mirror had ≈50% transmission at 476.5 nm, and was highly reflecting (>99%) at 491 nm. The reflectivity of this mirror was ≈99% at 520 nm and ≈60% at 605 nm and 635 nm. The output coupler used had a nominal 4% transmission at 491 nm although, as discussed below, this reflectivity was thought to change on butting against the fibre. This mirror was highly reflecting at the pump wavelength and had ≈20% transmission at 520 nm and ≈60% transmission at 610 nm and 635 nm. Since the $^3P_0$–$^3H_4$ transition at 491 nm corresponds to a three-level laser scheme, the fibre could not be made arbitrarily long as the 490 nm fluorescence experiences a reabsorption loss on passing down the fibre. For this reason an 80 cm length of fibre was used, providing a compromise between good absorption of the pump and minimal reabsorption of fluorescence. Since the available input mirror was approximately 8 mm thick, a 5× microscope objective was used for launching light into the fibre as it had a longer working distance than the ×10 objective used for the previous experiments. However, since the ×5 objective focused to a larger spot size than the ×10 objective and the input mirror only had a transmission of 50% at the pump wavelength the launch efficiency (measured using a cut-back technique) was found to be only 22%.

The minimum threshold for laser oscillation at 491 nm was measured to be 150 mW of incident pump

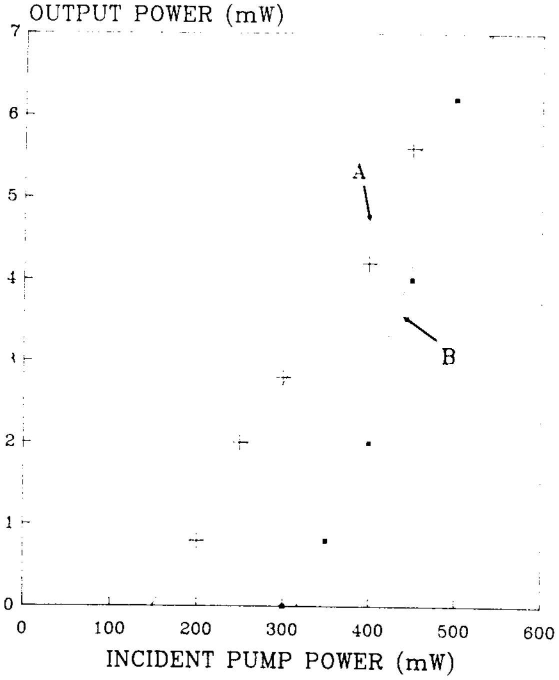

Fig. 4. Output power at 491 nm as a function of pump power for a Pr^{3+}-doped ZBLANP fibre lasers (see text for explanation of data sets A and B).

power (33 mW launched). The maximum output power extracted was ≈6 mW for 450 mW of incident pump power (100 mW launched). A graph of output power against incident pump power is shown as line A in fig. 4, with the slope efficiency being 2% with respect to incident pump power (9% wrt launched pump power). It was noted however that a higher slope efficiency could be obtained by careful adjustment of the butt at the output end of the cavity. These results are shown as line B in fig. 4. The most likely explanation for the output being such a sensitive function of the butt condition is that the lasing wavelength of 491 nm was at the extreme long wavelength edge of the mirror's high reflectivity range. Thus the etalon effect arising from the mirror surface/fibre end may significantly alter the effective reflectivity of the output mirror, with a corresponding change in the fibre laser performance.

8. Tunable operation at around 605 nm and 635 nm

Allain et al. [3] have previously reported tunable operation of Pr^{3+}-doped fluorozirconate fibre lasers at around 610 nm, 635 nm, 695 nm, 715 nm, 885 nm and 910 nm. However, output powers from these devices were typically of the order of 1 mW only, as a result of using high reflectivity output couplers in order to keep the threshold down. To investigate the possibility for much higher power output under tuned operation, we have used an output coupler of ≈25% transmission between 600 nm and 650 nm. The resonator used for investigating tunable operation is shown in fig. 5. The fibre was butted against the same mirror as used for the demonstration of efficient laser oscillation at 605 nm and 635 nm as described above. Light exiting the fibre was collected by a ×10 microscope objective. This light was focused onto the output coupler having been dispersed by two high dispersion glass prisms. The prisms were positioned close to Brewster's angle in order to minimise the losses of the cavity. Tuning was accomplished by making small angular adjustments to the output coupler to feed back fluorescence of the required wavelength. The operating wavelength of the tunable fibre laser was monitored by passing light reflected from the first prism through a monochromator. The tuning curve resulting for a pump power of 550 mW and fibre length 50 cm is shown in fig. 6. It can be seen that tunable operation was observed from 599 nm to 611 nm and from 631 nm to 636 nm. The threshold for operation on both transitions was ≈100 mW of incident pump power (65 mW launched). In both cases the limits for the tuning range were set by laser oscillation shifting back to the peak of the gain curve, suggesting that a higher degree of dispersion (by using more prisms) could be required. Nevertheless the tuning ranges demonstrated were of the order of the linewidths (fwhm) observed in the fluorescence spectrum and, as seen in fig. 6 output powers of up to 25 mW were obtained. Polarisation-controlling loops could in principle be used to compensate for the effects of fibre birefringence to produce a smoother tuning curve (as discussed in ref. [7] for an Yb^{3+}-doped silica fibre laser) but we have not attempted this with fluorozirconate fibre.

9. *Q*-switched operation at 635 nm

An initial investigation of *Q*-switched perform-

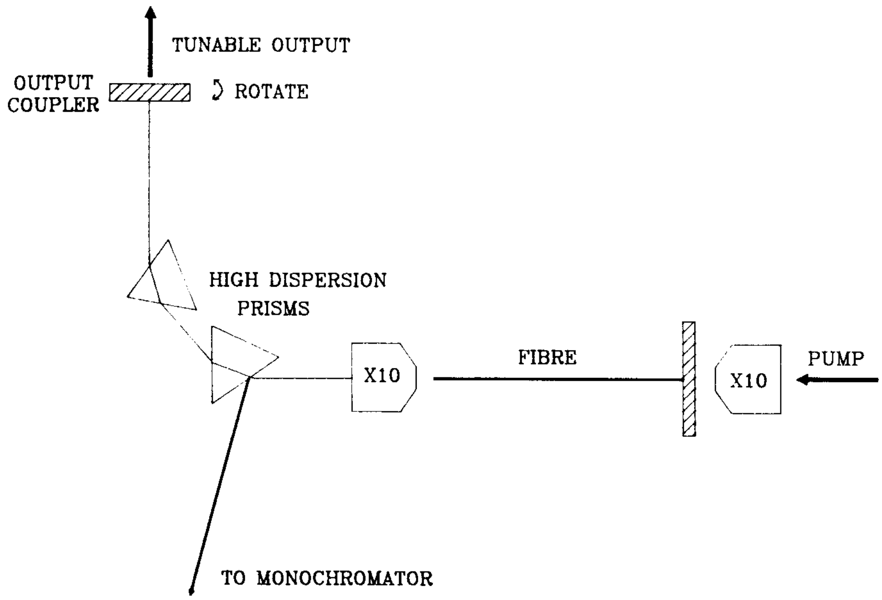

Fig. 5. Experimental arrangement used for investing tunable operation of Pr^{3+}-doped ZBLANP fibre lasers.

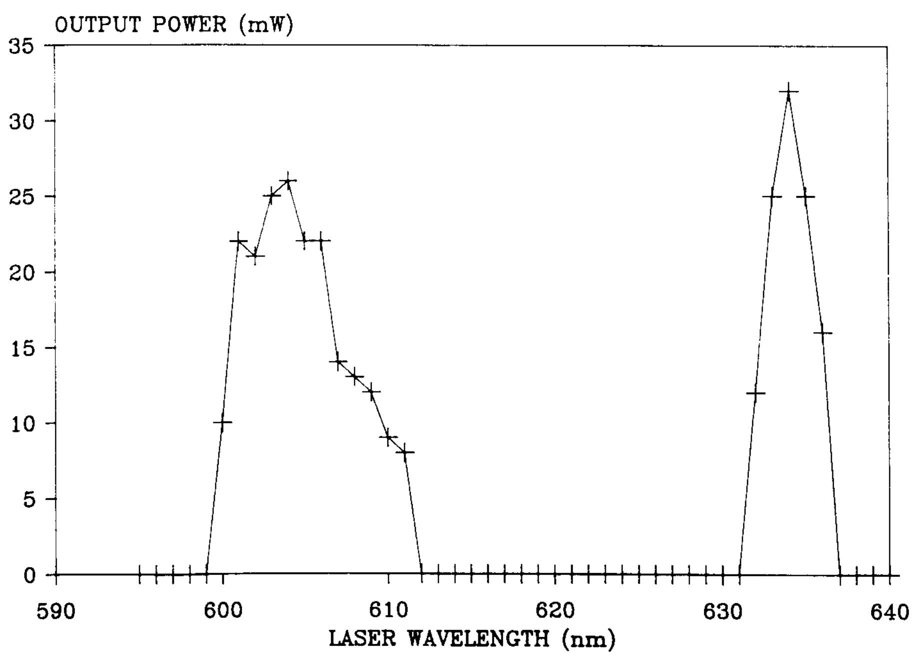

Fig. 6. Tuning curve for a Pr^{3+}-doped ZBLANP fibre laser.

ance on the $^3P_0$–$^3F_2$ transition has been undertaken using a mechanical chopper as the Q-switch. The resonator used was similar to that previously used by Alcock et al. [8] for the Q-switching of a Nd^{3+}-doped silica fibre laser. The fibre was again butted at the input end against the same dielectric mirror as used for the high efficiency operation experiments described above. The fibre end was index-matched to a silica flat to prevent oscillation occurring from the fibre/air Fresnel reflection. Light exiting the fibre was collected by a ×10 microscope objective before being focused on to a 30% transmission output coupler. The chopper used for these experiments operated at a maximum frequency of 125 revolutions per second. Q-switching was achieved using a small aperture of ≈0.5 mm diameter at the edge of the chopper wheel. Thus energy was stored except for the time when the cavity was completed as the beam passed through the small aperture. This gave rise to pulses of 75 ns duration (fwhm) and a peak power of ≈20 W at a repetition rate of 125 Hz for an incident pump power of 400 mW. No subsidiary pulses were found to follow the initial pulse as had been observed by Alcock et al. Significant improvements in pulse duration, power and repetition rate should be possible when using an acousto-optic modulator as the Q-switch.

10. Conclusions

We have demonstrated laser oscillation on five visible transitions in a Pr^{3+}-doped fibre. Operation on the blue-green transition at 491 nm and the green transition at 520 nm has, to our knowledge, not been reported in a glass host before. We have been able to achieve 250 mW output at 635 nm, and 150 mW output at 605 nm when pumping with 800 mW from an argon ion laser, showing that Pr^{3+}-doped fluorozirconate fibres may be very efficient convertors of blue light to red. Tunable operation has been demonstrated, with 30 mW of tunable output being possible near 635 nm and >20 mW near 605 nm. Preliminary investigations of Q-switching have been made, with pulses of ≈75 ns duration and ≈20 W peak power being produced. The pump powers and wavelength required (476.5 nm and 472.7 nm have been used for the experiments described in this paper), are close to that of a frequency-doubled 946 nm Nd:YAG laser. Since these Nd:YAG laser may be AlGaAs diode-pumped Pr^{3+}-doped fluorozirconate fibres offer a potential route to all solid-state laser sources operating at red, green and blue wavelengths, offering the advantage of tunability when compared to frequency-doubled source alone.

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