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Upconversion Laser Action in Pr^{3+}-Doped ZBLANP Fiber Pumped by an Yb-Doped Silica Fiber Laser

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Abstract

Laser action at 491, 520, and 635nm from Pr^{3+}-doped ZBLANP fibre is reported for pumping at 840 and 1020nm with the output of an 840nm-pumped Yb-doped silica fibre laser.

1. Introduction.

Upconversion-pumping of laser materials is an attractive route to converting infrared laser output to visible laser output. If the infrared pump light can be derived from a diode source, then this can be an efficient means of generating visible laser output for a wide range of applications. Fluorozirconate fibres are an attractive medium for realising upconversion pumping. The long interaction length results in good pump absorption, the phonon energy is sufficiently low that the lifetimes of intermediate levels are long enough for sequential absorption of infrared photons, and the linewidths are broad enough to give flexibility in the design of pump schemes.

Pr^{3+}-doped ZBLANP is a particularly interesting host, since laser action at blue, green, orange and red wavelengths can all be obtained using the same pump scheme. There have been several reports of upconversion-pumped laser action in Pr^{3+}-doped ZBLANP [1,2,3]. As shown in figure 1, two infrared wavelengths are required to excite Pr^{3+} to the $^3P_{0,1}$ and $^1I_6$ levels from which several visible laser transitions emanate. Previous pump schemes have employed two Ti-sapphire lasers [1] or two diode lasers [2] which have been polarisation-coupled into the doped fibre. Allain et. al. [3] obtained laser action at

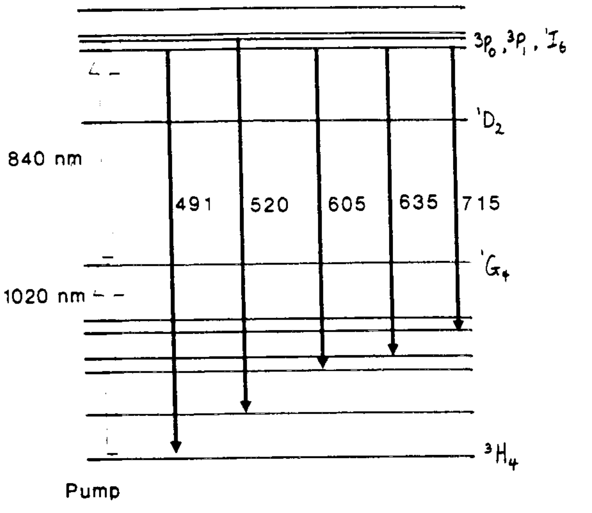


Figure 1. Energy level diagram for Pr^{3+} in a ZBLAN host.

635nm in an Yb^{3+} co-doped fibre by pumping at 850nm only.

In this work, the pump source is an Yb-doped silica laser, pumped at 840nm with the output of a Ti-sapphire laser and operating at 1020nm. Laser action has been demonstrated at 491, 520 and 635nm, and the output at each of these wavelengths is significantly more efficient than has been reported previously.

2. Spectroscopy of Pr^{3+}-doped ZBLANP

The Pr^{3+}-doped fibre used in this work had a standard ZBLAN composition, with PbF_2 added to increase the index of the core and HfF_2 added to decrease the index of the cladding. The core was doped with Pr^{3+} ions at a measured concentration of 480ppm by weight. The fibre diameter was 3.25μm, and the numerical aperture (NA) ~ 0.2.

An energy level diagram for Pr^{3+} in a ZBLANP host is shown in figure 1. The peak ground-state absorption occurs at 1.02μm [4]. The lifetime of the intermediate ($^1G_4$) level was determined from the decay of 1.3μm fluorescence to be 125 +/- 5 μs. This measurement was made by chopping the 1020nm pump (~10mW) acousto-optically and detecting the end-light fluorescence from a 20cm length of fibre. The lifetime was calculated from the best exponential fit to the decay.

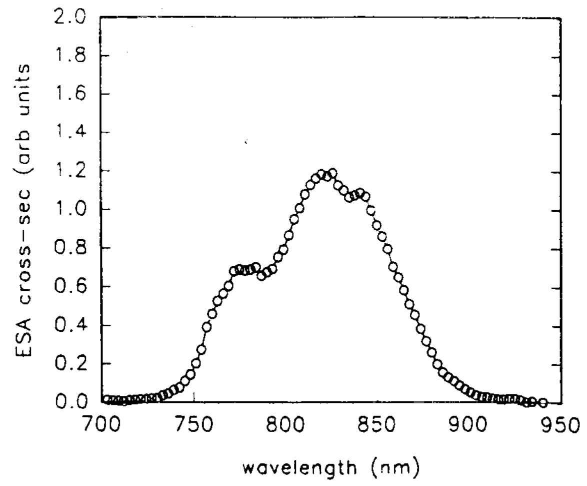


Figure 2. Measured excited-state absorption spectrum for $^1G_4$-$^3P_{0,1,2}$ and $^1I_6$.

The excited state absorption spectrum was measured by co-launching ~50mW of pump light at 1020nm and chopped white light from a tungsten lamp into ~1m Pr^{3+}-doped fibre. The transmission of the white light was measured using a lock-in amplifier with and without the pump light launched. The form of the spectrum was determined from the difference in transmission, and is shown in figure 2 where a broad peak is seen to occur at ~840nm.

3. Pump source: Yb^{3+}-doped silica fibre laser

Yb^{3+}-doped silica fibre lasers have been demonstrated [6,7] to be very efficient at converting pump light at a wide range of pump wavelengths (840nm to 1064nm) to wavelengths in the range 1-1.2μm. An Yb^{3+}-doped silica fibre laser was pumped in the absorption wing at 840nm. This fibre was fabricated with ~200ppm Yb^{3+}. Germania was added to the fibre core to produce an NA of ~0.17. The fibre length was 6.0m, and the core diameter was 3μm. To force laser action to occur at 1020nm, it was necessary to splice fibre gratings to the doped fibre. Angle-polishing of the launch end was found to be beneficial in suppressing the free-running wavelength (1040nm). The gratings were fabricated in photosensitive silica fibre by side illumination with two interfering beams from a KrF excimer laser, using a technique described previously [8].

The length of doped fibre was chosen so that roughly equal amounts of laser output at 1020nm, and unabsorbed pump at 840nm were obtained. The performance of the laser is shown in figure 3, where it is seen that for

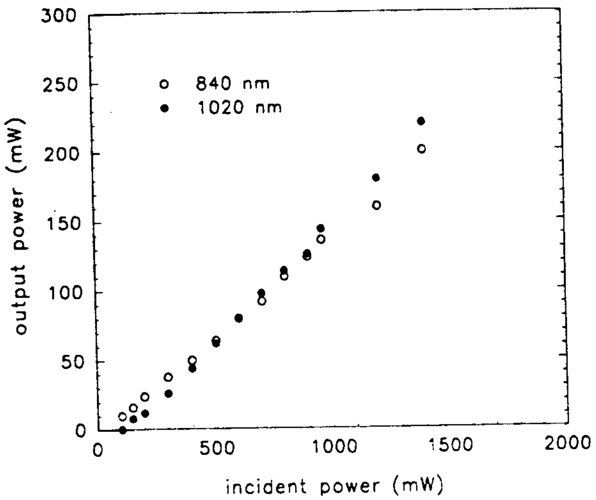


Figure 3. Performance characteristic of upconversion laser pump source: Yb^{3+}-doped silica fibre laser.

1.4W of incident power at 840nm, >200mW of power (measured after a collimating objective) can be obtained at each of the wavelengths required for upconversion pumping. The laser threshold occurred for 100mW of incident power at 840nm, and the slope efficiency with respect to absorbed power was ~60%. Each splice was measured to have a loss of 0.2dB; therefore it is anticipated that the slope efficiency of the laser could be improved by ~20% by writing gratings directly into the doped fibre core.

4. Performance of Pr^{3+} upconversion laser

The dual-wavelength output of the Yb^{3+}-doped silica laser was launched into the Pr^{3+}-doped ZBLANP fibre, via two x10 microscope objectives to allow spot-size matching of the beam and the fibre mode, with a launch efficiency of ~60%. The characteristics of the ZBLANP fibre were: NA~0.2, fibre diameter 3.25μm, Pr^{3+} concentration ~480ppm (by weight) and background loss at 1.2μm ~0.03μm. The fibre is singly-moded at both pump wavelengths, but will support several transverse modes at the laser wavelengths.

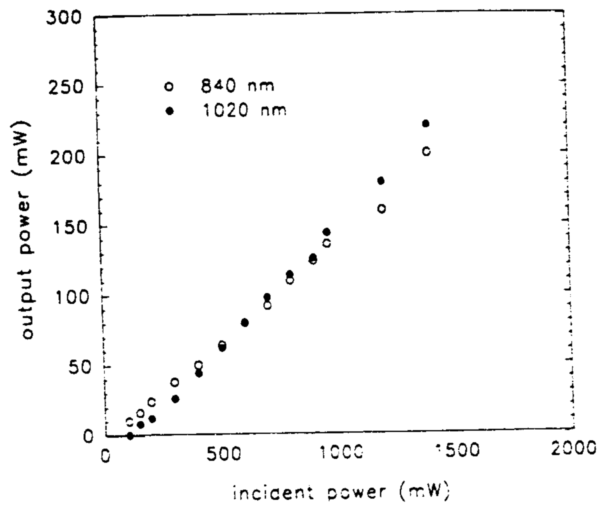
When pumped, the Pr^{3+} fibre fluoresced strongly at the visible wavelengths indicated in figure 1. Since all of these transitions emanate from the same manifold of levels, they compete for the upper level population. The highest gain occurs on the 635nm transition: to achieve oscillation at the other wavelengths it was necessary to introduce wavelength selection into the laser cavity, in this case by using dielectric mirrors.

The laser performance at each wavelength has been investigated in some detail, eg. for a range of output couplings, and for fibre lengths of ~2.5, 5.5 and 9m, as discussed below. The best performance achieved to date is summarised in table 1. λ denotes the laser wavelength, L the fibre length and R1 and R2 the mirror reflectivities at the launch and output ends respectively. Note that thresholds and slope efficiencies are both in terms of power incident on the launch objective. P_{max} denotes the maximum output powers that were measured for each wavelength, P_{Yb} the corresponding total power (at 840nm and 1020nm) from the Yb^{3+} silica laser and $P_{Ti\text{-}S}$ the power from the TiSapphire laser.

It is worth comparing the performance of the Pr^{3+}-doped ZBLANP upconversion laser reported here with that reported in [1], where fibre of similar diameter and NA was upconversion-pumped at the same wavelengths with the outputs of two Ti-sapphire lasers. The lower thresholds and higher slope efficiencies reported in the present work are believed to be largily due to significant improvements in the fibre quality. The fibre loss quoted in [1] was ~0.3dB/m at 1.2μm, while that in the present work is ~0.03dB/m at 1.2μm.

635nm

The highest laser output powers have been obtained at 635nm on the $^3P_0$-$^3F_2$ transition; this is the dominant channel for radiative decay from $^3P_0$. Laser action has been



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635nm

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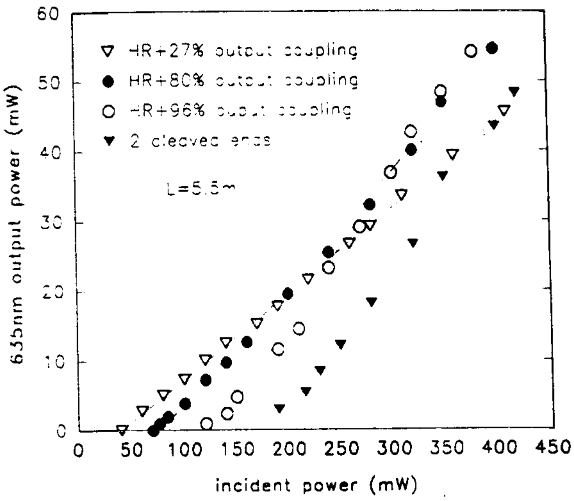

Figure 4. Laser performance at 635nm for various cavity configurations.

520nm

Laser action at 520nm on the $^3P_1$-$^3H_5$ transition was achieved in all three lengths of fibre, and performance with output couplings up to 11% has been investigated to date. In the 8.5m length of fibre, simultaneous laser action at 520nm and 635nm was frequently observed. The best performance was achieved with the 5.7m length of fibre in a cavity with 8% output coupling. The length dependent performance of this transition is understood to arise from the fibre loss, which at 520nm, was estimated from measurements of relaxation oscillation frequency versus pump power in a high-Q cavity, to be ~0.5+/-0.2dB/m.

491nm

Laser action at 491nm on the 3-level $^3P_0$-$^3H_4$ transition has been achieved to date only in the 2.5m length of fibre, and with up to 12% output coupling. Since this transition terminates on the ground-state, there will clearly be an optimum fibre length which, on the grounds of previous work [1], may be

λ (nm)	L (m)	R1	R2	THRESHOLD (mW)	SLOPE EFF	P_{max} (mW)	P_{Yb} mW	P_{Ti-S} (mW)
635	5.5	100%	4%	120	23%	54	380	1300
520	5.0	98%	93%	180	8.5%	18	380	1300
491	2.0	99%	95%	260	5.7%	6.5	380	1300

Table I Best laser performance acheived with Pr^{3+} ZBLANP upconversion laser shorter than 2.5m. Therefore there are prospects for improving the performance at this wavelength.

5. Conclusions

The Yb^{3+}-doped silica laser is an efficient means of obtaining the two wavelengths required for upconversion from a single 840nm source. If a 1W diffraction-limited diode output, eg. a MOPA were to become available at 840nm, then our results show that significant powers at 491nm, 520nm and 635nm could be achieved.

6. References

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