Polarization Dependent Gain in Pr^{3+}/Yb^{3+} Doped Fluoride Fibre

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ABSTRACT

Fibre amplifiers and lasers are formed by introducing rare-earth ions into silica and fluoride fibre material. The advantage of fluoride glasses is the much more efficient upconversion lasing in co-doped systems such as the Praseodymium/Ytterbium system used in this work. We investigate the gain properties of Pr^{3+}/Yb^{3+} doped fluoride fibres with the ultimate goal of developing a blue polarized fibre laser. When a probe with state of polarization parallel to the major axis of the elliptical fibre core is injected, no rotation of its output polarization is observed with pump injection and a higher gain is achieved for a given pump power. Moreover if both probe and pump polarization are aligned with the major axis, the onset of the gain is found to occur at lower pump power.

Keywords: fluoride fibre, fibre amplifier, fibre laser, praseodymium, ytterbium, polarization.

1. INTRODUCTION

The development of lasers emitting in the visible spectral range has been driven by a wide array of applications, including colour displays, data storage, printing, confocal microscopy and medicine. In particular sources in the blue region of the spectrum often rely on expensive and bulky gas lasers with high power consumption. Because they are cheaper and more efficient, fibre lasers are important alternative sources to the standard Argon-ion lasers. To date they suffer from a lack of polarization selectivity resulting in a large noise characteristic. Since the fibre material is uniform and regular fibres have circular symmetry, the output of fibre lasers are generally unpolarized, or randomly polarized. However introducing birefringence by using a fibre with an elliptical core allows stable propagation of linearly polarized signals aligned with the main axes of the fibre. If the gain of these two polarization modes can be made sufficiently different, then one of the modes will dominate and single polarization lasing will occur. The system under investigation is based on upconversion in a Pr^{3+}/Yb^{3+} co-doped fluoride fibre, which has shown potential for the development of lasers operating at a number of wavelengths in the visible region of the spectrum [1-3]. The praseodymium ions (Pr^{3+}) have a strong emission in the blue region of the spectrum around 490 nm but suffer from weak absorption at typical pump diode laser wavelengths, around 800 – 900 nm. Successful visible upconversion [4] can be obtained by co-doping the fibre with ytterbium ions (Yb^{3+}), which strongly absorb the diode laser pump and efficiently transfer the absorbed energy to the Pr^{3+}. In this paper we investigate the polarization dependent gain in the blue region of the spectrum for a Pr^{3+}/Yb^{3+} co-doped fluoride fibre with an elliptical core.

2. EXPERIMENTAL SET-UP

The fibre under test is a 50 cm long Pr^{3+}/Yb^{3+} co-doped fluoride fibre. The core diameter is about 1.4 µm with an ellipticity giving a beat length of 4.8 m. The active core doping concentrations are 3000 ppm Pr^{3+} and 20000 ppm Yb^{3+}. A pump probe set-up is used in order to investigate the polarization dependent gain provided by the blue transition in the Pr^{3+}. The pump is provided by a Titanium:Sapphire laser set at 840 nm, while the probe is provided by the 488 nm line of an argon ion laser. The state of polarization (SOP) of the pump and probe signals can be controlled independently of one another. The output probe signal is measured by lock-in detection using a spectrometer and a photomultiplier tube. The measurements are performed as a function of pump and probe states of polarization as well as pump input power.

The spectrum of the pumped fibre output is shown on Fig.1, as well as an energy diagram of the Pr^{3+}. The fluorescence peaks corresponding to different transitions of the Pr^{3+}can clearly be seen. These transitions occur from the thermally coupled $^3P_0$, $^3P_1$ and $^1I_6$ levels of Pr^{3+}. The 489 nm, 520 nm, 603 nm and 634 nm transitions originate from the $^3P_0$ level and terminate on the $^3H_4$, $^3H_5$, $^3H_6$ and $^3F_2$ levels respectively, while the 535 nm transition originates from the $^3P_1$ level and terminates on the $^3H_5$ level. As mentioned before one of the laser lines of the Argon ion laser lies at 488 nm, providing a very close match to the $^3P_0 \rightarrow {}^3H_4$ transition.

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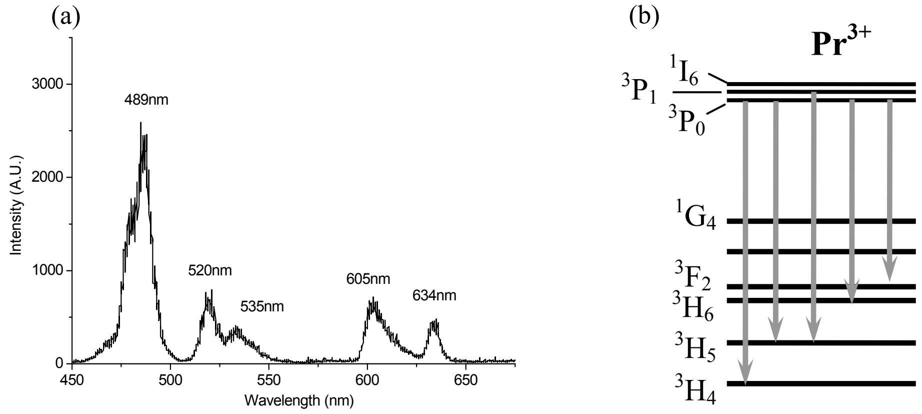

Figure 1. (a) Fluorescence spectrum of the fibre under test, pump wavelength 840nm, input power 50mW, and (b) Energy diagram of Pr^{3+} with observed transitions.

3. RESULTS AND DISCUSSION

The principal axis of the elliptical core fibre is determined by measuring the output pump intensity as a function of a linear input polarization orientation. A minimum and maximum were found, 90° from each other, therefore we can safely assume they correspond to the axes of the fibre. The state of polarization giving the highest (lowest) transmission is referred to as Max (Min). It is important to keep in mind here that the Min condition also corresponds to the maximum pump absorption and is therefore aligned with the major axis of the elliptical core of the fibre.

3.1 Pump polarization

A polarizer is placed at the output of the fibre, before detection, and the output signal is recorded as a function of the orientation of the polarizer. This allows us to estimate the state of polarization at the output of the fibre, both for the transmitted pump at 840 nm and the blue fluorescence at 489 nm. The output polarizer is rotated over 360° in steps of 10° and the results are presented as polar plots.

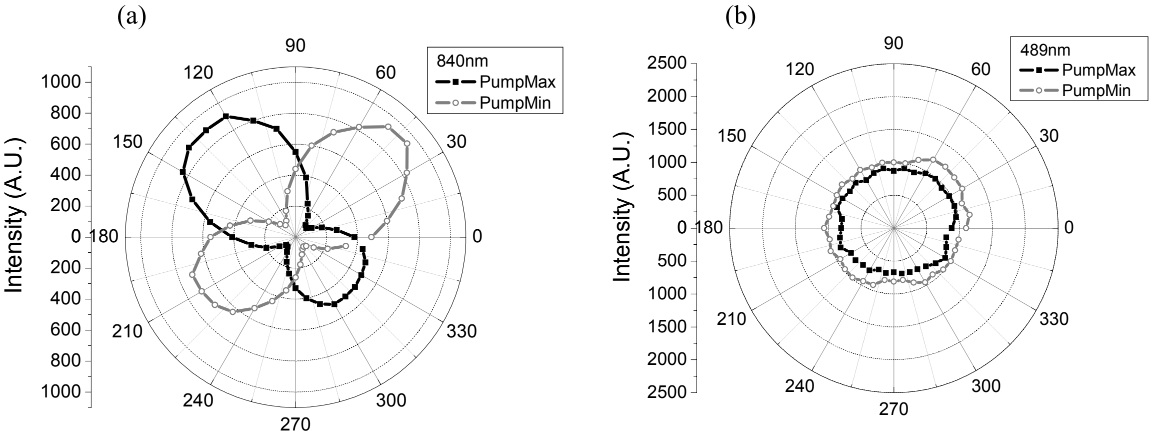

Figure 2. Polarization resolved output at (a) 840 nm and (b) 489 nm, pump 840 nm, 60 mW, for both polarizations.

As can be seen on figure 2(a), the pump signal at the fibre output remains almost linear, with only a small amount of ellipticity introduced during the propagation along the fibre. Similar results are obtained whether the pump input is polarized along the Max and Min polarizations. In addition, the angle between the two polarizations remains 90° at the output of the fibre.

On the other hand the fluorescence, shown on figure 2(b), is unpolarized, with an output intensity independent of polarizer orientation. This can be expected at this relatively low pumping power and small length since no saturation, due to pumping or amplified spontaneous emission, occurs.

3.2 Probe polarization

Polarization resolved measurements are now performed on the probe output signal and the results recorded for different pumping conditions. The probe signal is kept as low as possible, a few microwatts, so that it does not affect the gain of the doped fibre.

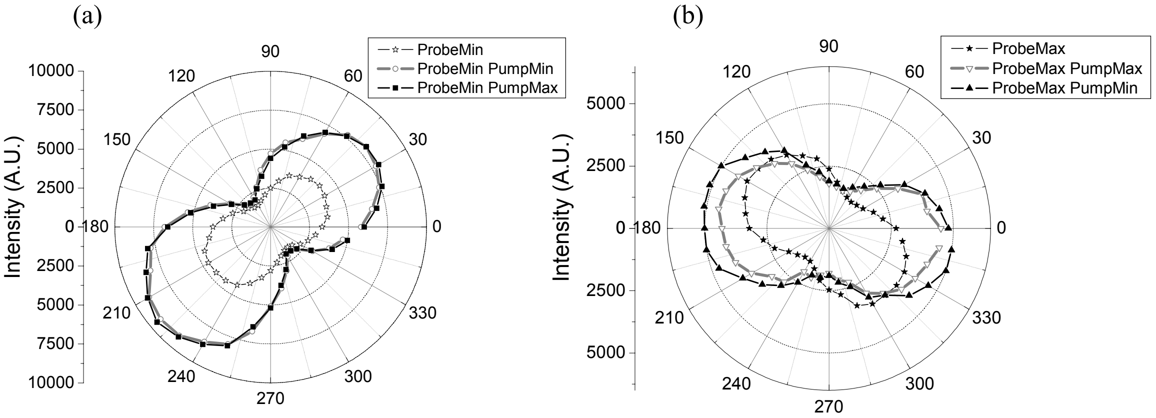

Figure 3. Polarization resolved output at 488nm, probe 488nm, without and with pump (840nm, 60mW) for the different combinations of pump and probe polarization. (a) Probe polarized along Min axis, (b) probe polarized along Max axis.

As can be seen on figure 3(a), when the probe SOP is aligned with the Min polarization its ellipticity increases as it travels through the fibre but no rotation is observed. When the pump signal is injected, gain is observed. The ellipticity of the probe decreases, again with no change in orientation, and the results are similar for both pump polarization conditions. On the other hand when the probe SOP is aligned with the Max polarization, shown on figure 3(b), rotation of the probe SOP occurs when the pump is present. The ellipticity of the probe output SOP in this case is higher and stays almost constant when the pump is present.

The difference in behaviour is most likely due to the elliptical core of the fibre. Its asymmetry causes light polarized along the major axis (Min) to be more tightly confined and experience a greater overlap with the core than light polarized along the minor axis (Max), causing gain anisotropy. In terms of lasing properties, a fibre laser with a pump aligned with its major axis tends to provide an output polarized along the same axis, while when pumped along its minor axis it provides an a laser output on both axis [5]. In our case when the probe polarization is aligned with the major axis, the higher confinement allows its polarization orientation to stay constant whatever the pump polarization may be, while for a probe polarization aligned with the minor axis the lower confinement and gain provided by the pump causes the orientation of its SOP to rotate.

3.3 Polarization dependent gain

The gain experienced by the probe for the different combinations of pump and probe SOP is shown on figure 4. The output probe intensity is measured as a function of pump input power and normalized by its value in the absence of the pump. The gain experienced by the probe is clearly polarization dependent, with a lower threshold achieved when pumping and probing the major axis. The slope of the gain curves above threshold is higher for the probe SOP along the major axis than along the minor axis, due to the better confinement in the first case. The saturation observed in the ProbeMin PumpMin case is unexpected and maybe due to the saturation of the detector due to the high amplified spontaneous emission signal at this wavelength.

Gain anisotropy in doped fibres can have different causes and is present even in circular core fibres [6]. This is due to the fact that even in an amorphous glass with no preferred ion orientation, each ion has some degree of spatial anisotropy. For example in the presence of a saturating pulse, the signal with a polarization orthogonal to that of the pulse will experience more gain due to polarization hole burning. However in the absence of saturation, signals with the same SOP as the pump experience more gain. As mentioned above this is further complicated in an elliptical core fibre where the orientation of pump and probe SOP with respect to the axis of the fibre is of primary importance.

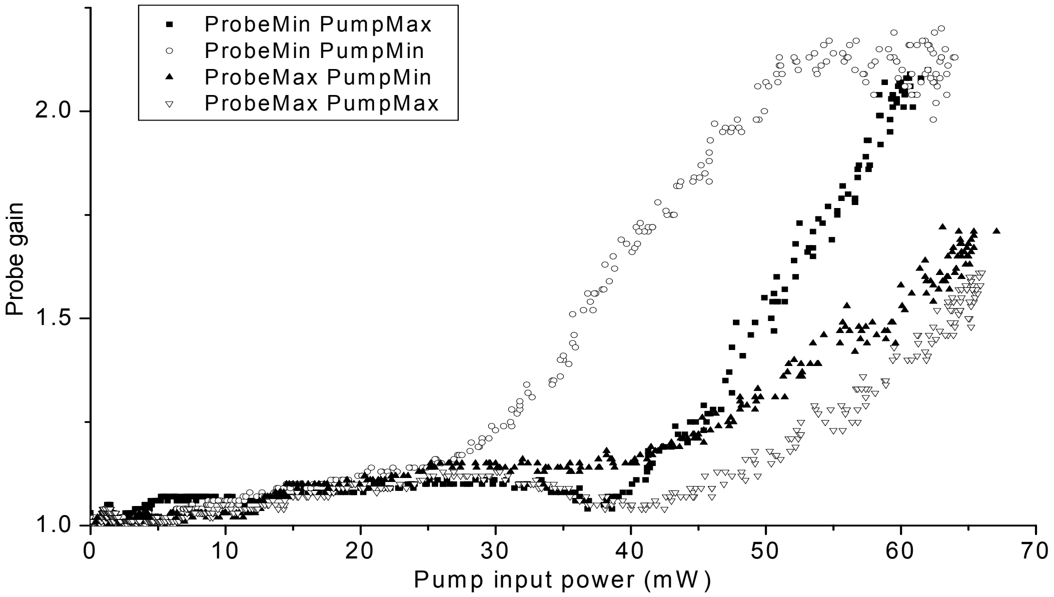

Figure 4. Gain curves as a function of input pump power for the different pump and probe SOP combinations. Probe wavelength 488nm, pump wavelength 840nm.

4. CONCLUSIONS

The alteration of the SOP of both pump and probe signals after propagation through a Pr^{3+}/Yb^{3+} fibre with an elliptical core were measured. A rotation of the probe SOP was observed when the probe is polarized along the minor axis of the elliptical core but not when aligned with the major axis, irrespective of pump SOP. The polarization dependence of the gain in the blue region of the spectrum was also investigated. It was found that the ProbeMin PumpMin condition provides a lower threshold and the highest gain for a given pump power.

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REFERENCES

[1] H. Scheife, G. Huber, E. Heumann, S. Bar, and E. Osiac, "Advances in up-conversion lasers based on Er $^{3+}$ and Pr $^{3+}$," *Optical Materials*, vol. 26, pp. 365-374, 2004.

[2] D. M. Baney, L. Yang, J. Ratcliff, and K. W. Chang, "Red and orange Pr^{3+}/Yb^{3+} doped ZBLAN fibre upconversion lasers," *Electronics Letters*, vol. 31, pp. 1842-1843, 1995.

[3] D. M. Baney, G. Rankin, and K. W. Chang, "Simultaneous blue and green upconversion lasing in a laser-diode-pumped Pr3+/Yb3+ doped fluoride fiber laser," *Applied Physics Letters*, vol. 69, pp. 1662, 1996.

[4] H. Zellmer, P. Riedel, and A. Tuennermann, "Visible upconversion lasers in praseodymium-ytterbium-doped fibers," *Applied Physics B: Lasers and Optics*, vol. 69, pp. 417-421, 1999.

[5] J. Hernández-Cordero, V. A. Kozlov, A. L. G. Carter, and T. F. Morse, "Polarization effects in a high-birefringence elliptical fiber laser with a Bragg grating in a low-birefringence fiber," *Applied Optics*, vol. 39, pp. 972-977.

[6] P. Wysocki, P. Wysocki, and V. Mazurczyk, "Polarization dependent gain in erbium-doped fiber amplifiers: computer model and approximate formulas," *Lightwave Technology, Journal of*, vol. 14, pp. 572-584, 1996.