1 W diode-pumped tunable Ho^{3+}, Pr^{3+}-doped fluoride glass fibre laser

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A 1 W Ho^{3+}, Pr^{3+}-co-doped fluoride glass fibre laser was operated narrowband (<0.5 nm) and was tuned between 2825 and 2900 nm using cleaves that were perpendicular to the fibre axis. A maximum slope efficiency of 28.5% was generated as a function of the launched pump power.

Introduction: Mid-infrared photonics is a fast-growing field within integrated optics as a result of the large number of potential applications that will benefit from light sources and detectors that are arranged in a planar geometry. To support this growth, a wide range of pump and probe sources are required to develop the integrated optical components that are necessary for medicine, defence and astronomy. Shortwave infrared (SWIR) fibre lasers based on mature fluoride glass optical fibre technology have been shown to provide high power radiation in the 2.7 to 2.95 μm region; a region of the infrared spectrum that is not covered by the emission from quantum cascade lasers. Er^{3+}-doped fluoride (ZBLAN) glass fibre lasers operating on the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition offer high power [1, 2] and broad tunability [3–5] in a diode pumped format with multiple Watt output power levels recently produced between 2.71 and 2.88 μm from a tunable laser arrangement [6].

Holmium-doped ZBLAN fibre lasers operating on the $^5I_6 \rightarrow {}^5I_7$ transition [7] offer a comparatively longer emission wavelength and a higher Stokes efficiency limit when the diode is pumped at 1150 nm [8]. To date, the highest power generated from this transition is 2.5 W using Pr^{3+} ions for lower laser level de-excitation [7, 8], however higher output power levels are expected with increased levels of pumping. The fluorescence spectrum of the $^5I_6 \rightarrow {}^5I_7$ transition when Ho^{3+} is doped into ZBLAN glass is shown in Fig. 1. It can be observed that the fluorescence peak is located at 2.856 μm and the fluorescence extends up to and beyond 3 μm. Ho^{3+}-doped ZBLAN fibre lasers offer the opportunity to create a high power diode pumped fibre laser with true mid-infrared (>3 μm) emission. In this Letter, we describe experiments relating to the performance of a tunable Ho^{3+}, Pr^{3+}-doped ZBLAN fibre laser. We show that despite the fact that an angled cleave was not used to suppress feedback from a fibre facet, broad (75 nm) tuning up to a wavelength of 2.9 μm was achieved.

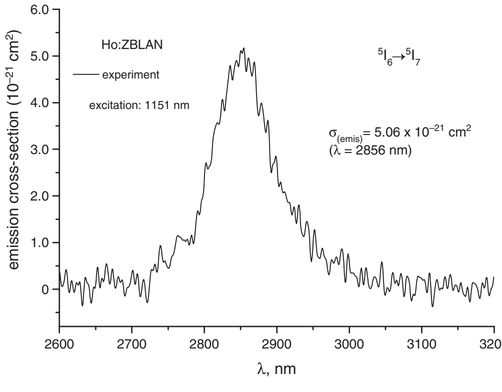

Fig. 1 *Measured fluorescence spectrum of Ho^{3+}-doped ZBLAN glass when pumped with optical parametric oscillator emitting 1151 nm*

Experiment: Tuning of the transition was carried out using a Littrow configuration with a diffraction grating added to the experimental setup used for our first demonstration of a high power diode-cladding-pumped Ho^{3+}, Pr^{3+}-doped ZBLAN fibre laser [8]; see Fig. 2. For the present demonstration only one end of the fibre was pumped. The core of the double clad fluoride fibre had Ho^{3+} and Pr^{3+} ion concentrations of 30000 ppm molar and 2500 ppm molar, respectively. The core of the fibre had a diameter and numerical aperture (NA) of 10 μm and 0.2, respectively, and supported singlemode operation down to a wavelength of 2.61 μm. The background loss between 1 and 2 μm was reasonably uniform at 0.1 dBm^{-1}. The pump core was D-shaped and had a diameter of 125 μm (and truncated diameter of 104 μm) which was surrounded by a low index polymer providing an NA of 0.5 for the pump core. The diffraction grating was an Au-coated 300 lines/mm ruled grating that was illuminated from the non-pumped end of the fibre with collimated light from a CaF_2 uncoated lens (f = 50 mm). Both ends of the fibre were cleaved near-perpendicularly to the axis of the fibre using a York FK11 cleaver; further tuning is expected with an angle cleave placed at the diffraction grating end to the fibre. The fibre laser was pumped with two high power diode lasers operating at 1150 nm (Eagleyard Photonics, Berlin) that were combined together using a polarising beam splitter. The pump light was focused into the fibre using a standard off-the-shelf microscope objective (Melles Griot 10 ×, 0.25 NA). The laser output was measured with a power meter and monochromator after reflection from a dichroic mirror which was placed at ~45° to the fibre axis between the focusing lens and pumped end of the fibre. The coupling efficiency into the fibre, i.e. taking into account mirror, lens and launch losses, was estimated to be 60%.

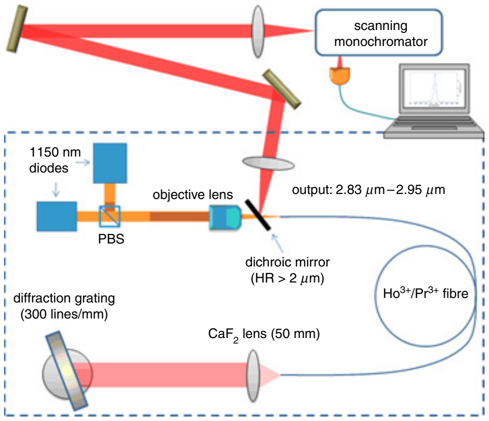

Fig. 2 *Schematic diagram of diode pumped external grating tuned Ho^{3+}, Pr^{3+}-doped ZBLAN fibre laser*

Results: The measured output power (uncorrected for mirror and collimating lens losses) against emission wavelength for two fibre lengths is shown in Fig. 3. A total tuning range of 70 nm was measured for the short (2.3 m) fibre and the output power was 360 mW. To enhance the absorption efficiency of the fibre laser, we increased the fibre length to 6.3 m and the tuning results for this arrangement are shown in Fig. 3 where we note the comparatively higher output power and relatively flat tuning characteristic. The threshold pump power for this fibre length was approximately 100 mW. The increased absorption efficiency resulted in a narrower tuning range compared to the short fibre length because the cavity with the resonator comprising the fibre ends reaches threshold easily and limits the tuning range. (The reduced power at 2895 nm results from fibre end reflection forcing emission towards the centre of the tuning range.) In the centre of the tuning range a slope efficiency of 28.5% was measured. The spectrum of the output at the centre of the tuning range is shown in the inset to Fig. 3. The FWHM of the emission is ~0.5 nm, which was limited by the distance of ~0.6 m between the CaF_2 lens and diffraction grating.

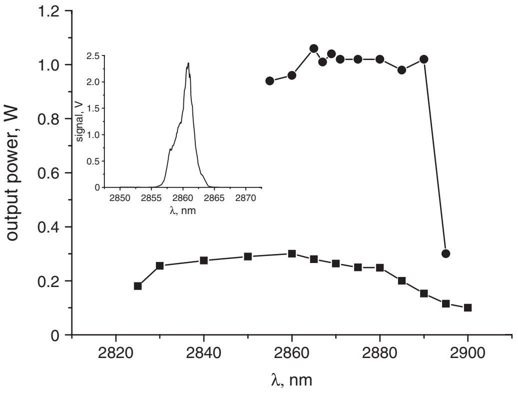

Fig. 3 *Tuning ranges from 2.3 and 6.3 m lengths of Tm^{3+}, Ho^{3+} fibre*
Inset: Spectrum of output when laser tuned to 2860 nm

Discussion: The first grating-tuned ~3 μm class fibre laser was demonstrated with this transition and provided tuning between 2.83 and 2.95 μm [9] and a maximum output power of 12.6 mW. In the current demonstration, with the use of high power diodes, double clad fibre and Pr^{3+} co-doping we have extended the output power to 1.27 W; however, because the fibre was not angle cleaved, we were not able to extend the emission wavelength of the output beyond 2.9 μm. It is interesting to note that our short wavelength limit was similar to the short wavelength limit of the pioneering demonstration [9] which indicates that it is difficult to stimulate transitions that terminate on Stark levels that are deep within the $^5I_7$ manifold without an angle cleave combined with Pr^{3+} co-doping. The slope efficiency of 28.5% measured for the long fibre length when the emission wavelength was 2860 nm makes the current tunable 3 μm class fibre laser system the most efficient reported to date.

The addition of Pr^{3+} ions to Er^{3+}-doped ZBLAN glass fibres has been shown to provide a wider tuning range compared to singly doped lasers over a broad range of pump powers. When Pr^{3+} desensitiser is added to Ho^{3+} a comparatively broader tuning range is expected but the tuning range will be narrower compared to the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition of Er^{3+}. The measured splitting of the $^5I_7$ level of Ho^{3+} is $\Delta E = 226\ cm^{-1}$ [10] which is smaller than the measured splitting of $\Delta E = 340\ cm^{-1}$ for the $^4I_{13/2}$ level of Er^{3+} [11] for YAG hosts. Thus, with higher pump powers and an angle cleave, we anticipate the measurement of a comparatively narrower but significantly red-shifted tuning range compared to Er^{3+}-doped ZBLAN fibre lasers.

Conclusion: We have demonstrated the first diode-pumped tunable Ho^{3+}-doped fluoride fibre laser operating in the 3 μm region. The fibre laser produced >1 W output power and the addition of Pr^{3+} desensitiser ions provided a slope efficiency of 28.5%. As a result of the red-shifted tuning range compared to Er^{3+}-doped ZBLAN fibre lasers, Ho^{3+}-doped fluoride fibre lasers complement Er^{3+}-doped ZBLAN fibre lasers and extend the capability of fluoride-glass-based fibre lasers.

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One or more of the Figures in this Letter are available in colour online.

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