Gain-switched holmium-doped fibre laser

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Abstract: We demonstrate the first gain-switched, singly doped, single-mode holmium-doped silicate glass fibre laser that operates at 2.106µm. Using a gain-switched 1.909-µm thulium-doped fibre laser as the pump source, output pulses of energy 3.2 µJ and pulse duration of 150 ns were generated at 80 kHz and slope efficiency of 44%. Pulse stacking within the holmium-doped fibre laser resulted in significantly shorter 70 ns pulses.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3510) Lasers, fiber; (140.3538) Lasers, pulsed.

References

1. A. S. Kurkov, E. M. Sholokhov, O. I. Medvedkov, V. V. Dvoyrin, Yu. N. Pyrkov, V. B. Tsvetkov, A. V. Marakulin, and L. A. Minashina, "Holmium fiber laser based on the heavily doped active fiber," Laser Phys. Lett. **6** (9), 661-664 (2009).
2. S. D. Agger and J. H. Povlsen, "Emission and absorption cross section of thulium doped silica fibers," Opt. Lett. **14** (1), 50-57 (2006)
3. S. D. Jackson, "Midinfrared Holmium Fiber Lasers," IEEE J. Quantum Electron. **42**(2), 187-191 (2006).
4. S. D. Jackson, F. Bugge, and G. Erbert, "High-power and highly efficient diode-cladding-pumped Ho^{3+}-doped silica fiber lasers," Opt. Lett. **32** (22), 3349-3351 (2007).
5. M. Eichhorn and S. D. Jackson, "High-pulse-energy, actively Q-switched Tm^{3+}, Ho^{3+}-codoped silica 2µm fiber laser," Opt. Lett. **33**, 1044 (2008)
6. S. Kivistö, T. Hakulinen, M. Guina, and O. G. Okhotnikov, "Tunable Raman Soliton Source Using Mode-Locked Tm–Ho Fiber Laser," IEEE Photon. Technol. Lett. **19**(12), 934-936 (2007).
7. M. Eichhorn and S. D. Jackson, "High-pulse-energy actively Q-switched Tm^{3+}-doped silica 2 µm fiber laser pumped at 792 nm," Opt. Lett. **32** (19), 2780-2782 (2007).
8. M. Jiang and P. Taebati, "Stable 10 ns, kilowatt peak-power pulse generation from a gain-switched Tm-doped fiber laber," Opt. Lett. **32** (13), 1797-1799 (2007).
9. S. E. French, D. J. W. Brown, D. S. Knowles, and J. A. Piper, "Pulse-stacking technique for enhanced performance of a solid-state laser pumped by a high-pulse-rate source," Appl. Opt. **37** (3), 536-539 (1998).

1. Introduction

Pulsed fibre lasers operating in the 2 µm region of the spectrum are of particular interest to a range of applications in defence, medicine and telecommunications. Extensive research therefore has surrounded the development of thulium and holmium ion doped glasses for the generation of 2 µm output. To date, Tm^{3+}-doped silicate glass fibre lasers have dominated this research due to the commercial availability of high-power diode lasers for direct pumping of Tm^{3+} and the increased efficiency due to cross relaxation. However, the, development of Ho^{3+}-based fibre lasers is important because it provides an extension of the emission wavelength to beyond 2.1μm [1], a spectral region where Tm^{3+}-based fibre lasers significantly under perform [2].

A series of continuous wave (CW) singly-Ho^{3+}-doped fibre lasers operating at 2.1 μm have been reported [3,4], however for pulsed operation, the reported Q-switched [5] and mode-locked [6] Ho^{3+}-doped fibre lasers have involved Tm^{3+} as a sensitiser, which can compromise the overall efficiency because of energy transfer upconversion and may in fact limit the wavelength; the longest wavelength reported being 2.08 μm [7].

In this paper we extend the work associated with fibre lasers using singly Ho^{3+}-doped silicate glass because of the possibility of augmenting the overall efficiency as a result of separating the Tm^{3+}-based laser from the Ho^{3+}-based laser. To this end, we report, to the best of our knowledge, the first demonstration of a pulsed singly doped and single mode Ho^{3+}-doped silicate glass fibre laser operating at 2.106 μm that is pumped using a gain switched Tm^{3+}-doped silicate glass fibre laser.

2. Experiment

Gain switching a laser offers a simple method for achieving moderate peak power pulses with durations between 10 ns to 100 ns with high repetition rates from a simple robust cavity. Recently, it has been demonstrated that pulsed pumping directly into the upper lasing level of Tm^{3+} produces stable pulses of 10 ns pulse duration [8] because in-band pumping creates a rapid population inversion that can be depleted by a single short duration gain switched pulse. Extending this concept to holmium-based fibre lasers involves pumping the absorption transition between the $^5I_7$ and $^5I_8$ states that has peak absorption at 1.95 μm [2], which is easily achieved using a pulsed Tm^{3+}-doped fibre laser. Thus the experimental setup of our gain-switched Ho^{3+}-doped fibre laser, which is shown in Fig. 1, employs a gain-switched Tm^{3+}-doped fibre laser, which was pumped by a pulsed 1.55 μm laser source.

The 1.55 μm laser consisted of a pulsed, single-mode, distributed feedback diode laser amplified by a two-stage erbium-doped fibre amplifier. The output from the 1.55 μm source consisted of a 100 kHz pulse train of 100 ns pulses with an average power of 1.3 W. The 1.55 μm output was launched into the core of single mode Ge-doped fibre that was spliced to the Tm^{3+}-doped fibre. A fibre Bragg grating was written (using a phase-mask and UV laser) into the core of the Ge-doped fibre to provide high reflection at $\lambda = 1.909$ μm. The Tm^{3+}-doped fibre (Nufern, Connecticut) was double-clad with a single-mode core (NA=0.16). A partially reflective fibre Bragg grating was spliced onto the other end of the Tm^{3+}-doped fibre to close the cavity. The entire length of Tm^{3+}-doped fibre was water-cooled.

The output of the Tm^{3+}-doped fibre laser was injected into the core of the Ho^{3+}-doped fibre through a fibre Bragg grating designed to highly reflect light at 2.106 μm. The Ho^{3+}-doped fibre (from the former Optical Fibre Technology Centre, Sydney) was a single-clad single-mode core with a Ho^{3+} concentration of 0.5% wt% (i.e., 4×10^{25} m^{-3}). A partially reflective dichroic mirror (R = 70% at 2.1 μm) was butted against the holmium-doped fibre to close the cavity. This mirror was highly reflecting (R > 99%) at the Tm^{3+} wavelength and retro-reflected unabsorbed pump light back into the Ho^{3+}-doped fibre. At the output, a second dichroic mirror (R > 99% at 1.55 μm, AR at 2.1 μm) was used to filter the 2.1μm emission and any unabsorbed 1.55-μm light. A fast InGaAs detector (1 ns rise time, Thorlabs) was used to monitor the 1.55 μm source, while an InAs detector (300 MHz bandwidth, Judson) was used to measure both the Tm^{3+} and Ho^{3+} output. (As the Tm^{3+}-doped fibre laser was directly spliced onto the Ho^{3+}-doped fibre laser, direct monitoring of the output of the Tm^{3+}-doped fibre laser output was not possible.) The 2.1 μm emission was monitored relative to the unabsorbed 1.55 μm pump pulse on a 1 GHz digital oscilloscope.

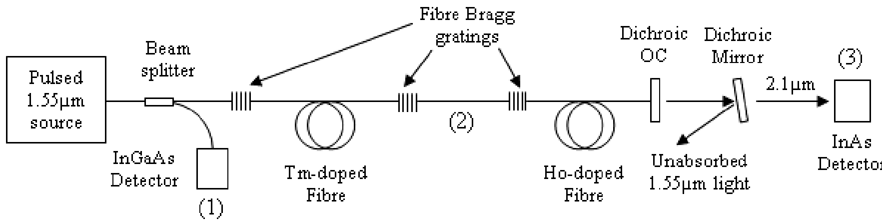

Fig. 1. Schematic of the gain-switched Ho^{3+}-doped fibre laser.

3. Results

3.1 Tm^{3+}-doped fibre laser

A stable pulse train was obtained from the Tm^{3+}-doped fibre laser when pumped by 100 ns 100 kHz pulses from the 1.55-µm source. Sample pulses from each laser are shown in Fig. 2 and are measured with respect to the 1.55 µm pulse. The Tm^{3+}-doped fibre length was optimised for maximum output power and the optimum length was found to be 25 cm. The pulse width was observed to decrease as the fibre length was reduced from an excessive length to the optimum length. This is due to a shorter cavity and reduced cavity loss, and hence reduced pulse build-up time. This was also observed when optimising the Ho^{3+}-doped fibre laser. An average output power of 720 mW was achieved, corresponding to a pulse energy of 7.2 µJ. A pulse width of 60 ns FWHM was obtained, corresponding to a peak power of 120 W. In this configuration, the slope efficiency was 60% with a threshold of 135 mW, as shown in Fig. 3. The lasing spectrum of the Tm^{3+}-doped fibre laser is shown in the inset to Fig. 3 and is centred at 1.909 µm with a FWHM of 1 nm. This spectrum was measured using a 32 cm monochromator at a resolution of <0.1 nm. (Horiba iHR320).

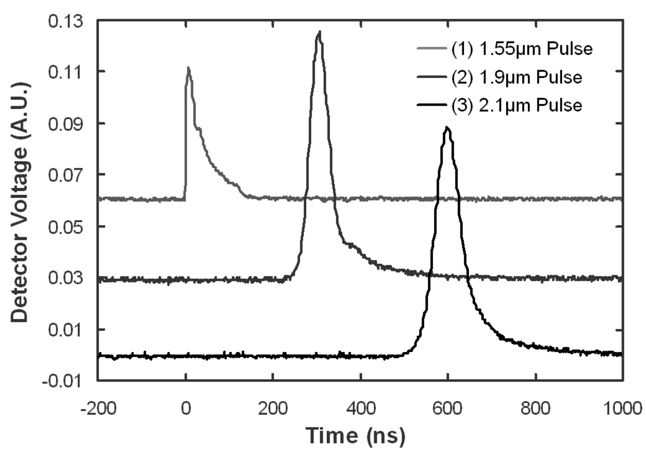

Fig. 2. Measured pulse sequence from the 1.55 µm source, the Tm^{3+}-doped fibre laser and the pulse-stacked Ho^{3+}-doped fibre laser.

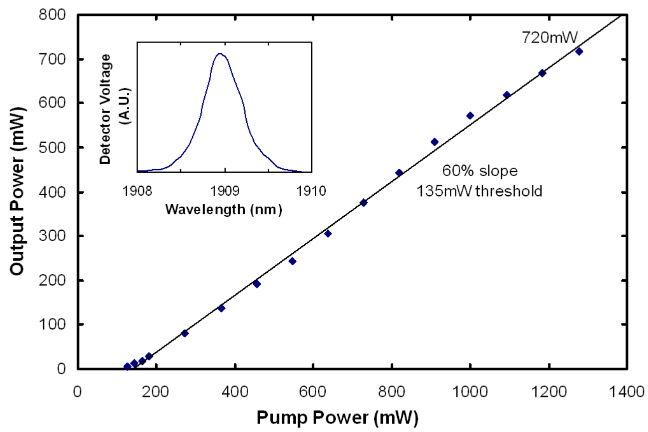

Fig. 3. All-fibre Tm^{3+}-doped fibre laser output power and spectrum.

Because the reflectivity of the grating output coupler was not optimised and estimated to be too high, the grating was replaced with an external dichroic mirror with a lower reflectivity (R = 35% at 1.9µm, R > 99% at 1.55 µm) in a separate experiment. A higher slope efficiency of 68% was achieved with a slightly higher threshold of 160 mW. This result indicates that the all-fibre Tm^{3+}-doped fibre laser could be made even more efficient by further optimisation.

3.2 Ho^{3+}-doped fibre laser

The maximum output power of 720 mW from the all-fibre Tm^{3+}-doped fibre laser at 100 kHz was used for the initial characterisation. Utilising Fresnel reflection from the cleaved fibre end resulted in weak unstable output pulses from the Ho^{3+}-doped fibre laser. Improved performance was achieved using an output coupler mirror (R >99% at 1.9 µm, R = 70% at 2.1 µm) butt-coupled to the end of the fibre to lower the laser threshold. The repetition rate of the Tm^{3+}-doped fibre laser was reduced to 80 kHz to increase the pump pulse energy. By cutting back the Ho^{3+}-doped fibre, the length was optimised to 40 cm for maximum output power for this output coupler.

The maximum average power produced was 254 mW, corresponding to output pulse energy of 3.2 µJ. The laser operated with a slope efficiency of 44% and a threshold of 150 mW, as shown in Fig. 4. The inset to Fig. 4 shows the emission spectrum of the Ho^{3+}-doped fibre laser which is centred at 2.106 µm with a narrow bandwidth of 1 nm FWHM (instrument resolution of < 0.1 nm). The output pulse widths were measured to be 150 ns, with a pulse-to-pulse fluctuation in peak power estimated to ±20%. At this pulse width, the peak power was ~21 W. The long pulse width is attributed to the relatively high reflectivity output coupler used and the low pump pulse energy. The efficiency of the Ho^{3+} fibre laser is well below the Stokes efficiency limit of 90%, and we attribute this to non-optimal resonator reflectivities. We currently have no ability to measure the absolute reflectivity of the fibre Bragg grating.

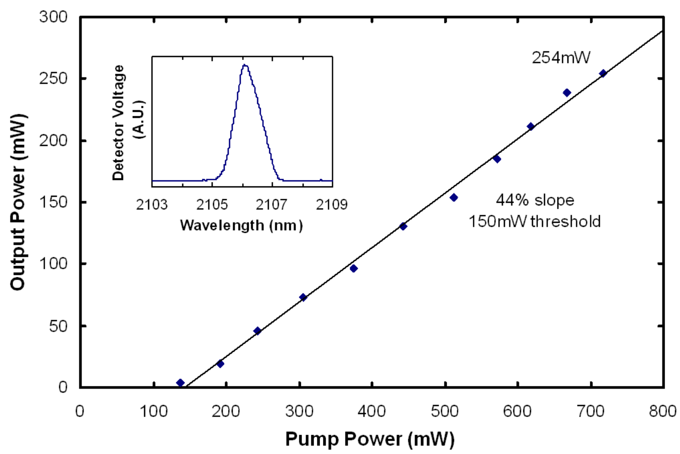

Fig. 4. Ho^{3+}-doped fibre laser output power and spectra.

3.3 Pulse stacking in Ho^{3+}-doped fibre laser

By introducing a slight gap between the dichroic output coupler and the fibre end, the laser was observed to operate in a two-to-one pulsing scheme (two pump pulses for each output pulse) at certain output coupler positions; one-to-one pulsing was re-established when the dichroic was butt-coupled to the fibre. Pulse stacking, where multiple pump pulses result in a single output pulse, has been previously demonstrated [9]. In our gain-switched laser, pulse stacking results from insufficient round trip gain is created from a single pump pulse and a second pump pulse is required. Since the pump pulse period is much shorter than the upper laser level lifetime, energy is stored from the first pump pulse producing high-energy output pulses from a source with lower pump pulse energies. With higher gain, the build-up time is reduced, resulting in narrower pulses with greater peak power.

Figure 2 shows a sample output pulse from the Ho^{3+}-doped fibre laser operating in the pulse-stacked regime whereby the repetition rate was halved to 40 kHz. The 2.1 μm output pulse had a reduced pulse width of 70 ns compared to 150 ns in the one-to-one pulsing scheme. The maximum average power was 120 mW, corresponding to 3-μJ pulse energy and a peak power of 43 W. The overall efficiency at maximum pump power was reduced to 17% compared to 35% for non-pulse stacked operation. The slope efficiency could not be obtained because pulse stacking requires the gap (i.e. loss) to be varied when the pump power was varied. The pulse-to-pulse variations for the pulse-stacked operation were observed to be significantly lower than the normal one-to-one operation, with the peak power fluctuations estimated to be ±8%.

Although this method resulted in an improved peak power, the overall efficiency was lower as light is lost to poor coupling rather than being extracted. In addition, the dichroic mirror was used to retro-reflect the pump light, and thus the gap reduced the amount of pump light reflected back into the fibre, reducing the total amount of pump light absorbed. A better method is to avoid using the gap and increase the out-coupling fraction of the mirror to match the round-trip losses required for pulse stacking. It is anticipated that as the pump power is increased, apart from having greater pulse energy, the output pulses generated will have narrower pulse widths and thus higher peak powers, as well as greater pulse-to-pulse stability. The characteristics of each stage of the laser are summarised in Table 1.

Table 1: Summary of the output properties for the 1.55µm source, Tm^{3+}-doped fibre laser and Ho^{3+}-doped fibre laser.

	1.55µm source	TDFL (All fibre)	TDFL (Ext. OC)	HDFL (normal)	HDFL (pulse stacked)
Repetition rate	100 kHz	100 kHz	100 kHz	80 kHz	40 kHz
Wavelength	1.548 µm	1.909 µm	1.909 µm	2.106 µm	2.106 µm
Linewidth	1 nm	1 nm	1 nm	1 nm	1 nm
Output power	1.3 W	720 mW	800 mW	250 mW	120 mW
Pulse energy	12 µJ	7.2 µJ	8.0 µJ	3.2 µJ	3.0 µJ
Efficiency (absorbed)	--	60% slope	68% slope	44% slope	17% absolute
Threshold	--	135 mW	160 mW	150 mW	--
Pulse width (FWHM)	100 ns	60 ns	55 ns	150 ns	70 ns
Peak power	120 W	120 W	130 W	21 W	43 W

4. Summary

We have demonstrated a gain-switched Ho^{3+}-doped fibre laser that emits at a wavelength of 2.106 µm. A maximum average power of 250mW, a slope efficiency of 44%, a pulse width of 150 ns and peak power of 21 W were obtained. Pulse stacking was demonstrated by varying the loss within the cavity, which resulted in a narrower pulse width of 70 ns and improved pulse-to-pulse stability, at the expense of repetition rate and overall efficiency.