Pulsed operation of a resonantly pumped, linearly polarised, large mode area holmium-doped fibre amplifier

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Abstract: We present the design of a polarisation maintaining, resonantly and cladding pumped, large mode area holmium-doped fibre. We describe the operation of this fibre in a pulsed amplifier configuration. The amplifier produced pulses with energy of 2.25 mJ and duration of 20 ns at a repetition rate of 20 kHz and average power of 45 W. The holmium-doped fibre provided >10 dB of gain at 2.09 µm and the polarisation extinction ratio was >11.5 dB. The beam quality of the output (M^2) was 1.6. To the best of our knowledge this is the highest pulse energy achieved from any singly holmium-doped fibre by an order of magnitude.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3510) Lasers, fiber; (140.3460) Lasers.

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1. Introduction

Pulsed 2 μm lasers are required for a variety of applications including LIDAR and remote sensing, material processing, medical applications, and as pump lasers for mid-infrared generation via optical parametric oscillators. Some of these applications also require the source to be linearly polarised. Traditionally pulsed sources in this region have been based on crystalline gain media with thulium and/or holmium dopants. Fibre lasers offer an attractive alternative with the ability to create a monolithic rugged system and to allow for further power scaling while preserving beam quality.

Several groups have produced sub-100 ns pulses from polarisation maintaining (PM), large mode area (LMA) Tm:silica fibres in both Q-switched laser and master oscillator power amplifier (MOPA) configurations. The fibres used in these experiments had a 25 μm diameter core and a 400 μm diameter cladding and were limited to modest pulse energies ranging from 0.2 – 0.4 mJ [1–5].

A master oscillator power amplifier (MOPA) configuration was used to produce 15 ns, 0.5 mJ single frequency pulses at 1.918 μm in a thulium doped germinate fibre. The M^2 was ~1.2 and the polarisation extinction ratio was 13 dB. The repetition rate of this system was <°500 Hz [6]. Linearly polarised, 0.6 mJ pulses at a 10 kHz repetition rate were also demonstrated from a thulium-doped silicate MOPA operating at 1.95 μm [7].

Recently another approach to scaling the peak power from thulium doped fibres was demonstrated. Pulsed and tunable operation of a PM thulium-doped large pitch fibre (LPF) was demonstrated with an output of 0.435 mJ at 1.9 – 1.95 μm and a significant reduction in efficiency when attempting to operate at wavelengths >2 μm [8]. The fibre had a 50 μm diameter core with a 0.04 NA and boron-doped stress rods. The laser operated at repetition rates of 10-50 kHz and produced 7 W output with a diffraction limited beam quality ($M^{2°}$<°1.15). Pulse durations as short as 49 ns were reported [8].

A Q-switched Tm-doped LPF with an 81 μm core achieved 2.4 mJ output energy at a repetition rate of 13.9 kHz (33 W average power) [9]. The pulse duration was 15 ns and the spectrum extended from 1.85 – 1.95 μm. A near-diffraction limited beam quality was demonstrated with an M^2 of <1.3. This laser was not linearly polarised [9].

In contrast, pulsed holmium-doped sources have not been as widely investigated. A Tm:Ho co-doped fibre was Q-switched to produce 0.264 mJ pulses at 2.07 μm with duration of 45 ns at a repetition rate ranging from 10 – 100 kHz and average power up to 15 W [10, 11]. To the best of our knowledge, all other reported pulsed holmium-doped fibre sources have been limited in pulse energy to <100 μJ and average power <5 W by small mode field areas and core-pumped fibre designs.

In this paper, we describe the operation of a holmium-doped fibre in a pulsed MOPA configuration. The master oscillator is a Q-switched Ho:YAG laser at 2.09 μm which provides 200 μJ, 21 ns pulses at 20 kHz to the input of the fibre amplifier. This is amplified by a resonantly cladding pumped, PM, LMA holmium-doped silica fibre. The MOPA system produces pulses with 2.25 mJ energy and 20 ns duration. The output is linearly polarised with a polarisation extinction ratio (PER) > 11.5 dB. The output power is 45 W and the $M^2 = 1.6$.

2. Experimental arrangement

2.1 Holmium-doped fibre design

An end view of the holmium-doped fibre is shown on Fig. 1. The fibre has a 45 µm diameter core with a 0.075 numerical aperture (NA). The V-number is ~5 at 2.1 µm and as a result the core is not single mode. The holmium concentration is similar to fibres presented in [12] with a peak absorption at 1.95 µm of ~70 dB/m. The inner silica cladding has a diameter of 250°µm. A fluorine doped silica (fluosil) layer is used to provide the pump guidance with a 0.24 NA [12]. The fluosil is further overclad with silica out to a 400 µm diameter. Two features located in the inner silica cladding created a stress-induced birefringence of 1.5×10^{-4}.

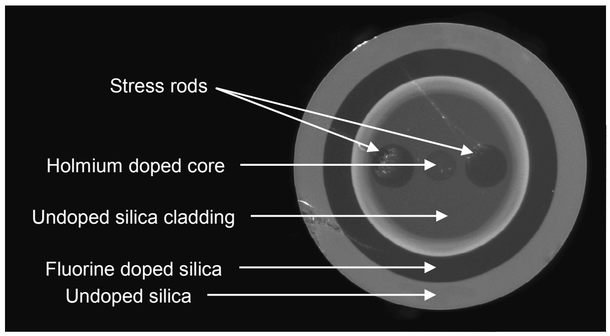

Fig. 1. End view of the PM, LMA Holmium-doped fibre. The labels detail the various types of glasses used to provide pump guidance and birefringence.

2.2 Q-Switched Ho:YAG Master Oscillator

The master oscillator is a Q-switched Ho:YAG laser similar to the design presented in [13]. A schematic of the laser is shown in Fig. 2. A 1.908 µm thulium-doped fibre laser is used to resonantly pump a 30 mm Ho:YAG (0.7 wt%) rod through a dichroic mirror (TFP1: HT @ 1.908 µm, HR @ 2.09 µm S-pol, HT @ 2.09 µm P-pol). The laser cavity is formed between a highly reflective mirror (HR) and a 70% reflective output coupler (OC, radius of curvature = 100 mm). The HR also ensures that the thulium pump is double passed through the rod. A quarter-wave plate (QWP) provides hold-off and a Rubidium Titanyl Phosphate (RTP) Pockels cell acts as the Q-switch.

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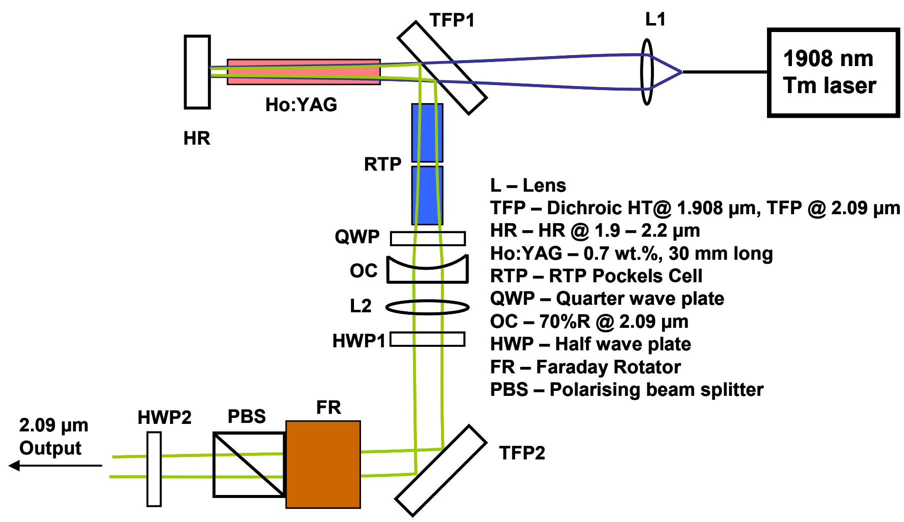

Fig. 2. Schematic of the Q-switched Ho:YAG laser used as the master oscillator.

The output from the laser is collimated by a 100 mm lens (L2). A combination of a half-wave plate (HWP1) and thin film polariser (TFP2) provides control of the energy output of the system. A Faraday rotator (FR) and a polarising beam splitter (PBS) provide isolation protection for the master oscillator from reverse propagating signal and reflections from the amplifier. A second half-wave plate (HWP2) is used to adjust the polarisation incident onto the fibre amplifier.

2.3 Amplifier design

A schematic of the amplifier is shown in Fig. 3. The holmium-doped fibre is counter-pumped with a 150 W thulium-doped fibre laser at 1.95 μm [14]. The length of the holmium-doped fibre used is 10 m. A 1.5 mm long, 400 μm diameter undoped silica end-cap with a 4° cleave is used at the output end. A similar dimension end-cap but with a 0° cleave is used at the input end. The fibre is spooled on a water-cooled mount with a diameter of 30 cm.

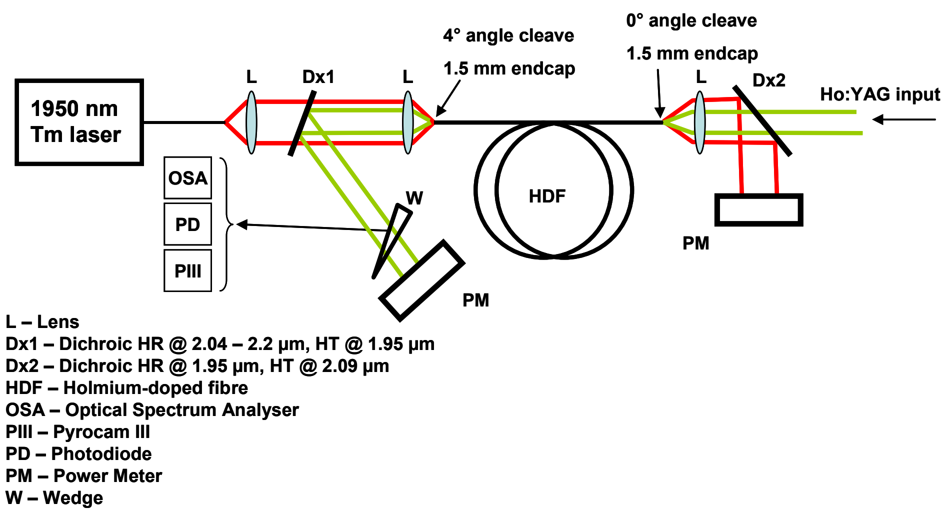

Fig. 3. Schematic of holmium fibre amplifier experiment. The fibre amplifier is operating in a counter-pumped configuration.

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A dichroic (Dx1: HR @ 2.1 µm, HT @ 1.95 µm) reflects the holmium output to the diagnostics. A CaF_2 wedge provides a pick-off for imaging (PIII: Ophir Pyrocam III), spectral (OSA: Yokogawa OSA) and temporal (PD: Discovery Semiconductors) measurements. The power transmitted through the wedge is measured on a calibrated thermal power meter (Ophir). A second dichroic (Dx2: HT @ 2.1 µm, HR @ 1.95 µm) further protects the master oscillator from any residual pump power transmitted through the amplifier. A ZBLAN patch-cord is used as the input to the OSA in order to avoid attenuation at wavelengths >2.1 µm due to absorption that would be present in a silica patch-cord.

2.4 Amplified spontaneous emission measurement

In order to quantify the amplified spontaneous emission (ASE) at the output of the amplifier, a configuration as shown in Fig. 4 was used. An acousto-optic modulator (AOM) is inserted in an attenuated beam to effectively gate the amplifier output. For a pulse measurement, images are taken with the AOM triggered to a 100 ns window around the laser pulse, and for the ASE measurement, the trigger is set to a 50 µs window in between the pulses. The relative intensity of the 1st order beams in each triggering condition represents the ratio of the power in the pulse to the power not contained in the pulse.

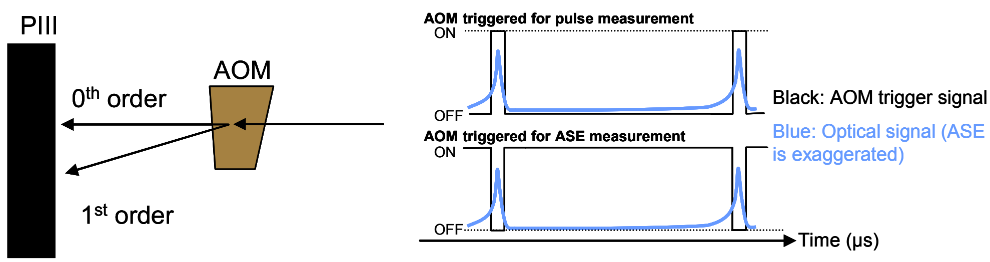

Fig. 4. Schematic of ASE measurement. A pick-off beam is chopped with an AOM at 2 different triggering conditions. Both the undiffracted and the diffracted 1st order are monitored on a relatively slow detector (in this case a Pyrocam).

3. Results

3.1 Master Oscillator characterization

The master oscillator provided stable pulses when operating at 20 kHz and 10 W output power. The pulse duration is shown in the inset of Fig. 5 and is 21 ns at full-width half-maximum (FWHM). The beam quality of the Ho:YAG laser is diffraction limited and the polarisation extinction ratio (PER) is > 20 dB. HWP1 was adjusted so as to launch 200 µJ at 20 kHz (4 W) into the PM, LMA fibre amplifier.

3.2 Amplifier operation

The output power versus launched pump power is shown in Fig. 5. The pump absorption was 95%. The amplifier operated with a slope efficiency of 45% with respect to launched pump power up to 35 W (1.7 mJ pulse energy) and a reduced slope of 25% up to 45 W (2.25 mJ). An ASE measurement as described in Section 2.4 confirmed that there was negligible (<100 mW) ASE at the 45 W output level. There was also no significant increase in reverse propagating power towards the master oscillator. Also shown in Fig. 5, the output pulse shape was very similar to the input pulse from the master oscillator. The duration of the output pulse was 20 ns.

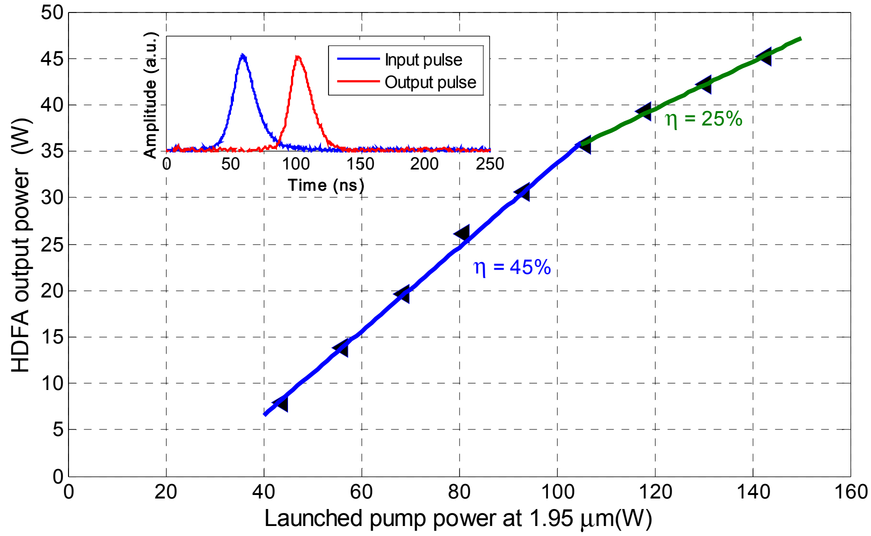

Fig. 5. Output power from the holmium fibre as a function of launched pump power. The launched power from the master oscillator was 4 W. Inset: Temporal traces of the pulses measured with a temporal resolution of 2 ns.

3.3 Temporal and spectral characterization

The spectrum of the amplifier output is shown in Fig. 6. As the pumping rate was increased, there was a broad-band output generated spanning from 2.05 – 2.4 µm. The central peak was maintained at 2.09 µm. The PER as a function of output energy is shown in the inset of Fig. 6. The PER was > 11.5 dB (93%) under all operating conditions.

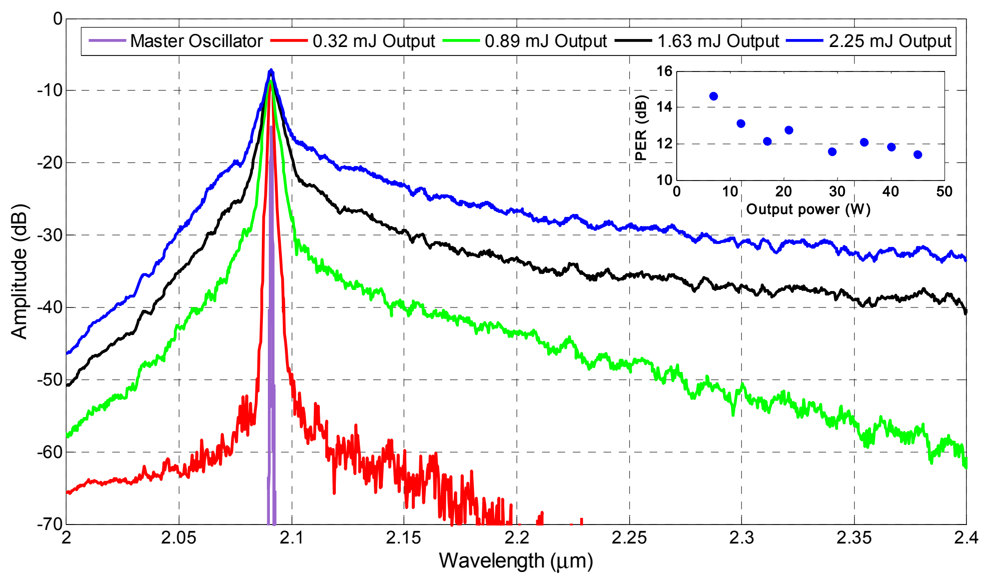

Fig. 6. Spectrum of the amplifier output at various output energies illustrating the spectral broadening. Inset: Polarisation extinction ratio as a function of power indicating that the laser is >11.5 dB (93%) linearly polarised at all operating levels.

3.4 Polarisation and beam quality

The beam quality was calculated from measurements of the beam profile through the focus of a 100 mm lens. The measured values of the beam diameter using the second moment are shown in Fig. 7. A magnification element was attached to the Pyrocam in order to resolve the waist. The evolution of the diameter as a function of distance corresponded to an M^2 of 1.6 in both axes, indicating that the amplifier was operating on multiple transverse modes.

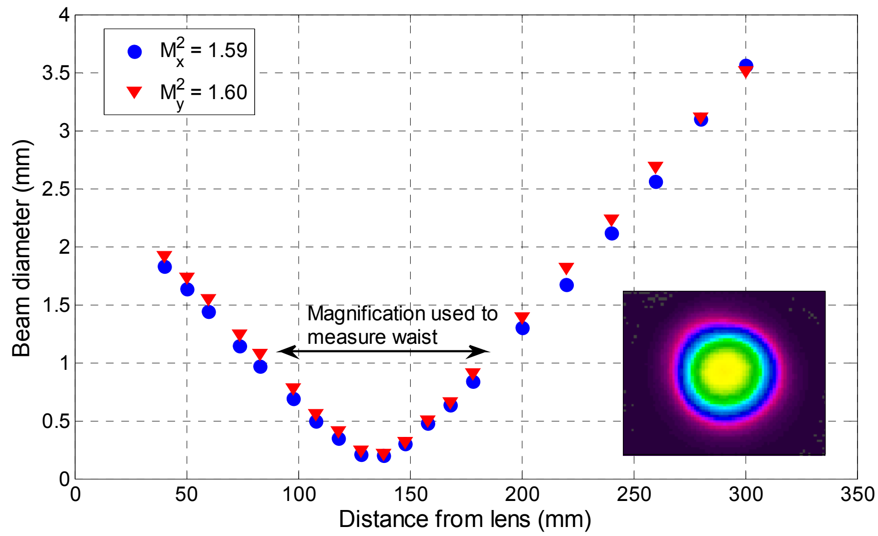

Fig. 7. Beam profile measured through the focus. Inset: An image of the near-field profile.

4. Discussion

The PM, LMA holmium-doped fibre amplifier produced pulses of energy of 2.25 mJ at a repetition rate of 20 kHz with negligible CW background or ASE. The output was linearly polarised with an extinction ratio of >11.5 dB and had a beam quality of M^2 = 1.6. The 20 ns FWHM pulse duration at the output was almost identical to the master oscillator input and we estimate that peak powers in excess of 100 kW were achieved.

There was significant spectral broadening observed with the output spectrum extending from 2.05 – 2.4 µm with a central peak at 2.09 µm. We attribute this effect to modulation instability leading to pulse break-up and super-continuum generation. Similar spectral broadening has been reported by other authors working in the 2 µm region [15]. No evidence of stimulated Brillouin scattering or stimulated Raman scattering was observed.

The reduction in slope efficiency at >35 W (1.75 mJ) output power is attributed to the increase in power at wavelengths >2.2 µm due to the super-continuum generation and subsequent absorption in the active fibre or the fused silica refractive optics before the power meter.

We believe that the efficiency at low powers (45%) is below the quantum efficiency (93%) due to a combination of energy transfer processes in the holmium ion population, residual hydroxyl contamination, and significant infrared absorption at wavelengths >2.15 µm. An improved composition should allow for a significant improvement in the efficiency of PM holmium-doped fibre amplifiers.

Significant gains in efficiency and improvement in beam quality have been demonstrated with distributed doping of the rare-earth in the core of LMA ytterbium doped fibres [16]. We expect that similar improvements are possible for LMA holmium-doped fibres.

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5. Conclusion

We have achieved 2.25 mJ pulses at a repetition rate of 20 kHz with a peak power >100 kW from a 2.09 μm holmium-doped fibre amplifier. To the best of our knowledge this is the highest power, linearly polarised operation of a pulsed fibre amplifier at 2 μm. This is also the first demonstration of a resonantly and cladding pumped, polarisation maintaining holmium-doped fibre.

In comparison to pulsed thulium fibre sources which have been demonstrated to operate efficiently only at wavelengths <2 μm, this fibre was able to operate at 2.09 μm. This demonstration provides a fibre platform that is uniquely capable of operating with high peak powers in the atmospheric transmission window >2.09 μm. With recent power scaling of monolithic CW holmium fibre lasers to >400 W [17], we anticipate similar improvements and monolithic demonstrations of pulsed holmium amplifiers.

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