Development of resonantly cladding-pumped holmium-doped fibre lasers

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ABSTRACT

The resonant pumping of holmium fibre lasers provides a fibre laser platform capable of addressing a wide range of applications that benefit from operation at wavelengths beyond 2.1 µm. This architecture can provide laser devices that promise high efficiency sources in the 2.1 µm spectral region with excellent beam quality and power scalability. This paper presents our recent results of resonantly pumped pulsed and CW holmium fibre lasers. We have demonstrated the first efficient resonantly cladding-pumped holmium fibre laser source. We have investigated both single mode and large mode area fibres and achieved CW output powers of ~140 W with excellent beam quality. In addition to these CW lasers we have investigated core-pumped, pulsed holmium fibre lasers and demonstrated output energies of up to 16 µJ at a repetition rate of up to 600 kHz. These developments provide an opportunity to build a high average power, pulsed 2.1 µm laser for the purpose of power scaling future mid-infrared sources.

Keywords: Fibre Laser, Mid-IR, Holmium, Thulium, Power Scaling,

1. INTRODUCTION

There are a range of applications that require laser sources in the 2 µm spectral region; remote sensing, LIDAR, non-linear frequency conversion and high power laser beam combination, all benefit from high power sources with excellent beam quality. Fibre laser based systems are of particular interest to these applications due to the high efficiency, excellent beam quality and potential for power scaling that they offer.

Of these applications non-linear frequency conversion into the mid-IR is of particular interest. High power sources in this spectral region have historically been demonstrated using $ZnGeP_2$ (ZGP) optical parametric oscillators (OPO's). A range of laser technologies have been demonstrated to pump ZGP OPO's. Initially all solid-state sources such as Tm:Ho:YAG [1] and Nd:YAG pumped KTP OPO [2, 3], were used to generate pulsed 2 µm pump sources for pumping the mid-IR OPO. The advent of high power thulium fibre lasers with excellent beam quality led to the development of hybrid pulsed 2.1 µm systems based on 1.91 µm thulium fibre laser pumped Ho:YAG [4, 5]. This pump architecture has led to the demonstration of the highest output powers from ZGP OPO's of up to 27 W, along with improved system efficiency in comparison to the all solid-state pump sources [6, 7]. These systems are operating on the limit of the output powers able to be generated by the Ho:YAG while still maintaining good beam quality. Further power scaling improvements require additional Ho:YAG rods in the laser cavity or amplifiers which add to system complexity. Moving to an all-fibre pump source is expected to enable further power scaling of ZGP OPO's without such an increase in system complexity. The most mature candidate for an all-fibre pulsed pump source is one based on thulium fibre lasers which have an efficient operation range of 1.95-2.05 µm [8]. However, defect related absorption in ZGP below 2.1 µm hinders such power scaling due to the associated thermal lensing and degradation of beam quality. This limits the use of thulium based fibre lasers as pump sources for high power. An alternate fibre laser pump source is required to extend the operation of these devices.

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Recently we have been developing resonantly cladding pumped holmium fibre lasers primarily for high power laser applications in the 2 μm spectral region [9]. The power scaling of fibre lasers in this spectral region is dominated by thulium fibre lasers and has resulted in output powers of up to 1050 W [10]. Further power scaling of these fibre lasers is currently limited by thermal issues and the brightness of pump diodes. The resonantly cladding–pumped holmium fibre laser architecture shows great promise for further power scaling of 2 μm high power lasers due to the ability to tandem pump with mature thulium fibre lasers. The scalability of the tandem pumping architecture has been demonstrated at 1 μm by an ytterbium pumped ytterbium fibre laser operating at 10 kW representing the highest power fibre laser to be reported [11]. The low quantum defect of the resonantly pumped holmium architecture promises a high power fibre laser stage with higher efficiency than that achievable from a thulium laser; either diode pumped at 0.79 μm or Er:Yb fibre laser pumped at 1.57-1.6 μm. In the resonantly pumped holmium architecture the majority of the thermal load is then distributed across the array of thulium fibre pump lasers reducing thermal issues associated with the high power laser stage. Tandem pumping also effectively increases the aperture for diode pumping across the array of thulium fibre lasers which alleviates limits to power scaling due to the brightness of currently available diodes. The all-glass fibre composition enabled by the high brightness fibre laser pump sources also provides flexibility in coating options for the fibre, which currently determines the thermal limit of thulium fibres.

Narrow line-width operation of these devices in the 2 μm region for applications such as coherent beam combination is also of interest. The power scaling of thulium fibre lasers has also been accompanied by the demonstration of efficient, high power, narrow line-width operation below the stimulated Brillouin scattering (SBS) gain bandwidth of silica. Recent results have shown up to 608 W narrow line-width output, which was pump power limited [12]. The inherent advantages associated with operating at a 2 μm compared to 1 μm in terms of SBS suppression may allow scaling of narrow line-width sources to beyond the kilowatt level [13].

As well as offering a scalable architecture suitable for power scaling, resonantly pumped holmium lasers are also able to operate efficiently beyond 2.1 μm. This spectral region has excellent atmospheric transmission which suits applications requiring free-space atmospheric propagation, as well as being preferred for pumping ZGP. A fibre amplifier based on the efficient cladding pumped holmium fibre under investigation here will enable amplification of a pulsed holmium master laser, producing an all-fibre source suitable for pumping ZGP OPO's beyond 2.1 μm. The scalability of such devices should enable further power scaling of ZGP OPO's.

In this paper we present results of the development of resonantly pumped holmium fibre lasers. We have demonstrated cladding pumped robustly single-mode and LMA fibre lasers with output powers up to ~140 W. These lasers represent the highest reported power for a holmium laser source and the first resonantly cladding pumped holmium fibre lasers. These results demonstrate the viability of this laser architecture for potential power scaling to the kiloWatt regime using a tandem pumping architecture. We also report on a linearly polarised gain switched holmium fibre laser. This is to our knowledge the first all-fibre polarised pulsed holmium laser to be demonstrated. Pulse energies up to 16 μJ were achieved at 300 kHz and 5.1 W output power was demonstrated at a repetition rate of 600 kHz. This laser demonstrates the utility of the resonantly pumped holmium architecture for the development of all-fibre pulsed master laser sources suitable for amplification with the aforementioned cladding pumped fibre. The pulsed pump sources produced will be suitable for the further power scaling of ZGP OPO's.

2. GAIN SWITCHED HOLMIUM FIBRE LASERS

Pulsed operation of holmium doped fibre lasers has mainly been achieved by Q-switching Tm:Ho co-doped fibres. However this complex composition suffers from up-conversion and energy transfer effects that limit the inversion and, consequently, the achievable pulse energy output [14].

Pulsed fibre lasers with holmium as the sole rare-earth dopant have not been widely investigated. One of the major deterrents has been the lack of a power scalable cladding-pumped fibre to amplify these pulsed sources. As a result there have only been demonstrations of core pumped devices with limited output powers. Passive Q-switching of highly doped holmium fibre lasers operating at 2.05 μm pumped by 1.15 μm ytterbium fibre lasers were demonstrated producing an average power of ~1.35 W, pulse durations of 20 ns and pulse energies of 7 μJ [15]. Gain switching of a holmium doped fibre laser operating at 2.1 µm by a pulsed thulium doped fibre laser has also been demonstrated with 250 mW average output power, with pulse durations of 70 ns and energies of 3 µJ [16].

In our preliminary experiments we have achieved linearly polarized operation of a gain-switched holmium fibre laser at 2.104 µm. The system output power was 2.7 W at a repetition rate of 300 kHz and 5.1 W at 600 kHz, with pulse energies of up to 16 µJ and typical pulse durations of 85 ns.

Experiment

A schematic of the gain switched holmium fibre laser is shown in Figure 1. The laser consists of a 2-stage Er:Yb amplifier which amplifies a high peak power semiconductor laser diode. This pulsed output gain switches a 3 m long Tm laser operating at 1.95 µm. The thulium laser produces pulses with energies of up to 25 µJ and durations of ~150 ns, which are finally used to core pump and gain-switch the polarized holmium laser.

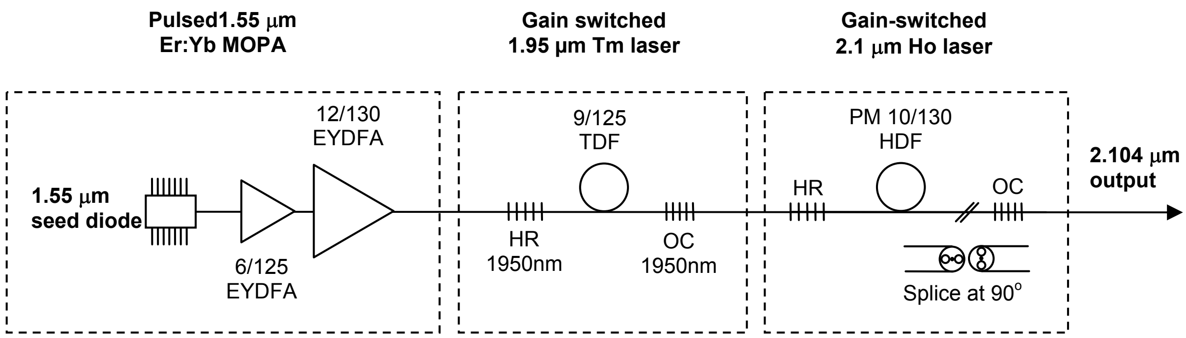

Figure 1: Schematic of gain switched holmium fibre laser system

The holmium laser is formed between a high reflector (HR) and output coupler (OC) fibre Bragg gratings (FBGs) written in PM passive fibre. The output coupler is strain tuned during the writing process and spliced at 90° to the doped fibre and high reflector. This forms a cavity at a given wavelength for a single polarization [17]. Spectra of the HR FBG, OC FBG and the laser output are shown in the inset of Figure 2. The OC FBG was strain tuned in-situ to optimize overlap with the HR FBG. A core-less end-cap is used to suppress reflection from the end-facet and allow the output mode to expand reducing the risk of optical damage.

Results

The laser operated at up to 5.1 W of output power at a repetition rate of 600 kHz, as shown in Figure 2. The output wavelength spectrum is shown and confirms that the cavity is formed by the HR and OC in the presence of the coreless end-cap. Excellent polarization performance was observed with a polarization extinction ratio of >18.5 dB maintained over the whole range of operating conditions at 300 kHz, confirming the robust PM nature of this cavity design. The fibre that was used is single mode at wavelengths beyond 1.9 µm and as a result the beam quality of the output was found to be close to diffraction limited with an $M^2_{x,y}$ = 1.05, 1.07.

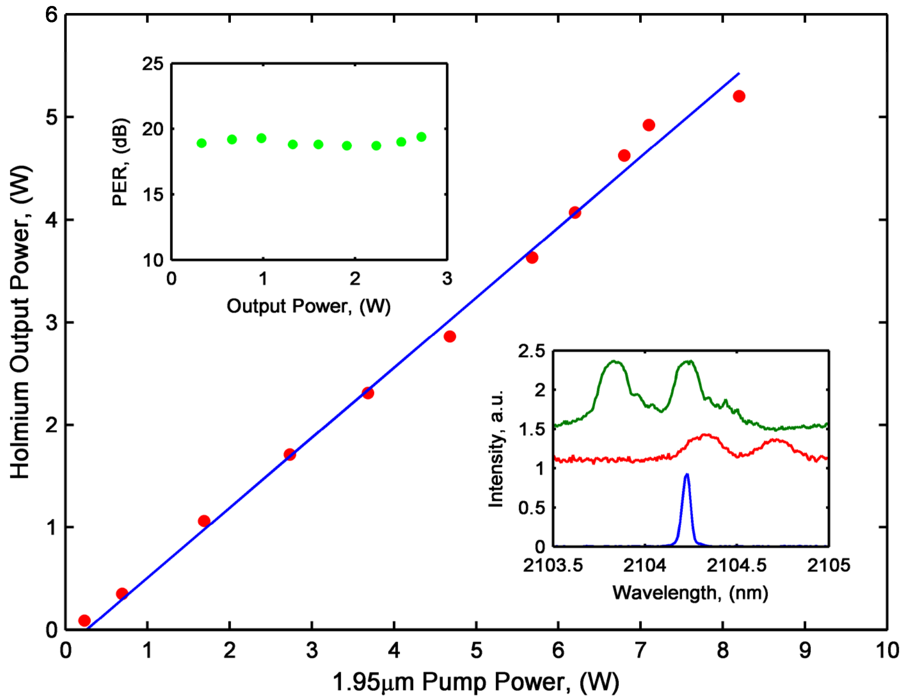

Figure 2: Output power of gain switched Holmium fibre laser. Top Inset - Polarization extinction ratio as a function of output power for 300kHz operation. Bottom Inset – Spectra of: HR FBG (Top-green), OC FBG (Middle-red) laser output (Bottom-blue).

3. CLADDING PUMPED HOLMIUM FIBRE LASERS

Previous development of cladding pumped holmium fibre lasers has been limited to diode or ytterbium fibre laser pumping of the $^5I_6$ transition in holmium at ~1.15 μm [18, 19]. Availability and the limited output power of these pump sources has restricted the output powers demonstrated by these double clad fibre lasers to <10 W. The work described here utilizes an all-glass fluorine doped cladding to provide low loss guidance of the 1.95-2.05 μm pump radiation required for resonant pumping of the $^5I_7$ transition in holmium. This all-glass fibre design allows rapidly maturing thulium fibre lasers to be used as efficient, scalable pump sources for resonantly pumping double-clad holmium fibre lasers.

We describe recent experiments that have demonstrated free-space operation of both robustly single-mode and LMA resonantly cladding-pumped holmium-doped fibre lasers. These demonstrations represent the first demonstration of cladding pumped operation of this laser transition.

3.1 Single Mode Fibre Laser

Experiment

A schematic of the free-space laser set-up is depicted in Figure 3. The free-space setup consists of two LMA thulium fibre lasers pumping each end of the holmium fibre laser through dichroic mirrors. These LMA thulium pump lasers are grating stabilized at 1.95 μm and utilise 25/400 μm/0.09 NA LMA thulium doped fibre (Nufern). At the HR end of the cavity the normal incidence dichroic mirror forms a high reflector in combination with an AR coated aspheric lens, while admitting pump power to the fibre laser. At the output end of the cavity the 45° dichroic mirror separates the pump and laser output. The laser output spectrum is measured by diffuse reflection from the power meter using a fibre patch-cord coupled to a Yokogawa AQ-6375 optical spectrum analyzer (OSA).

The fibre used was nominally single-mode at 2.1 µm and consisted of an 18 µm core with 0.08 NA, corresponding to a V-number of 2.2. The core was surrounded by a standard octagonal silica inner cladding of 112 µm flat-flat diameter. Low loss 1.95 µm pump guidance in the inner cladding was achieved by the use of a 180 µm diameter all-glass fluorine-doped outer cladding providing an NA of 0.22. The fibre was then overclad with silica to produce an outer fibre diameter of 250 µm.

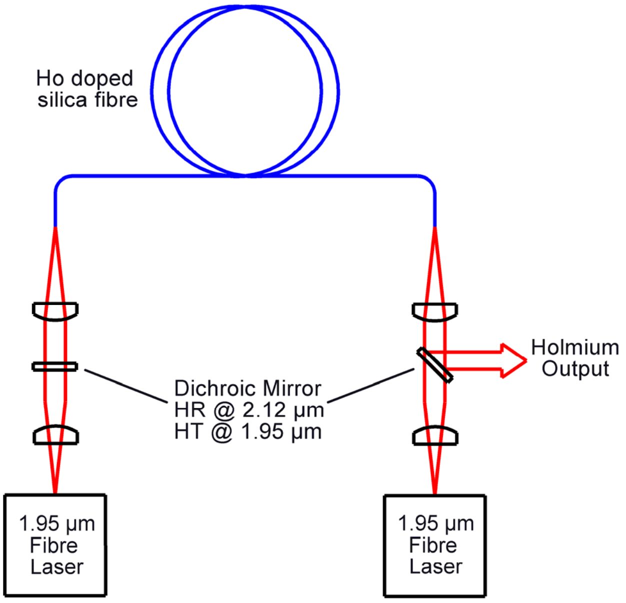

Figure 3: Experimental setup used to investigate the performance of double-clad holmium fibre lasers.

Results

The results obtained for this laser are shown in Figure 4. Running in a free-space configuration the laser produced 140 W of output power, pump limited, with a slope efficiency versus launched power of 57%, and a laser threshold of 7 W. The spectrum displayed a cluster of peaks in the range 2.125-2.135 µm typical of a free running fibre laser, indicating the peak of the laser gain in this free running mode of operation. A typical near field beam profile at 100 W is also shown.

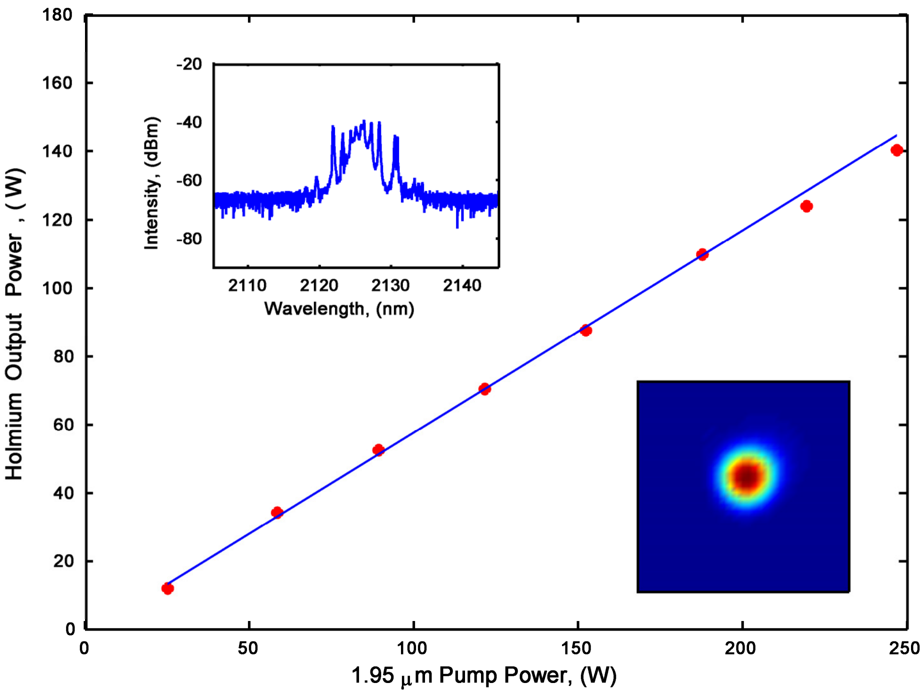

Figure 4: Output power of single-mode holmium fibre laser. Top Inset - Lasing spectrum at 100W output power. Bottom Inset - Typical near-field beam profile.

3.2 Large Mode Area Fibre Laser

Experiment

The fibre laser setup for the LMA fibre experiments was the same configuration as used for the SM laser, Figure 3. The fibre was again pumped from both ends by 1.95 μm thulium LMA fibre lasers as described previously.

These experiments used a LMA fibre design consisting of a 40 μm, 0.08 NA core in a 250 μm inner silica cladding. This is surrounded by a 0.22 NA fluorine doped glass second cladding of diameter 320 μm. A further silica cladding of diameter 400 μm was added to increase the fibre outer diameter and increase the thermal power handling during high power operation that is anticipated to be achieved with this LMA fibre.

Results

An output power of 140 W was achieved with a slope efficiency versus launched pump power of 55%, Figure 5. This output power was pump power limited and showed no sign of roll over at this output power level. Laser threshold was 24 W, and is higher than that observed for the SM fibre presumably due to the increased number of holmium ions in the laser cavity. The spectral output consists of a comb of wavelengths in the 2.120-2.145 μm range as shown in the inset of Figure 5. A typical near field beam profile of the laser output at 140 W is also shown.

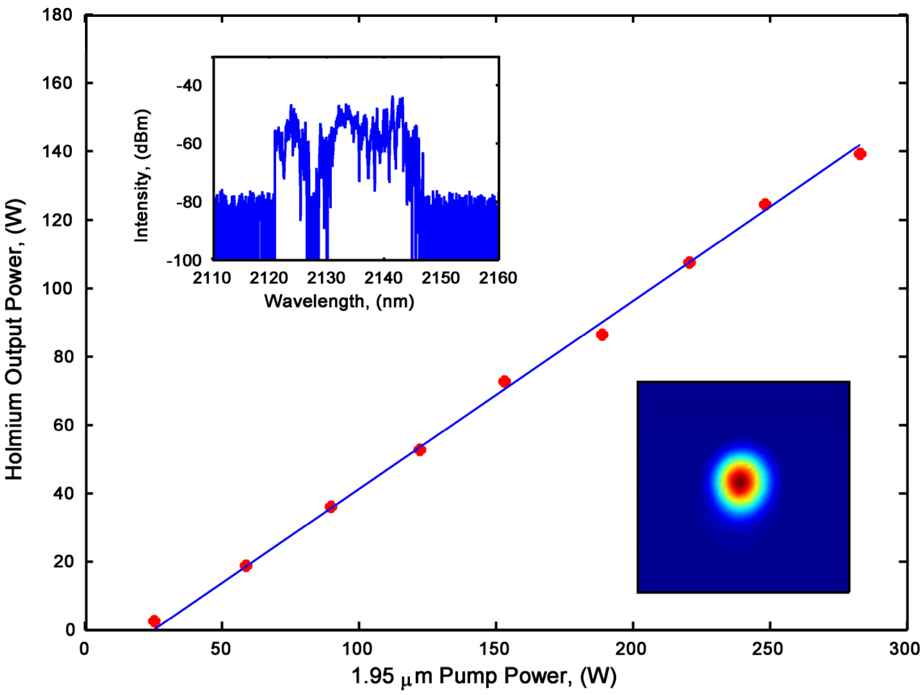

Figure 5: Output power of LMA holmium doped fibre laser. Top Inset - Free-running laser spectrum at 140 W output power. Bottom Inset – Typical near-field beam profile.

4. DISCUSSION

We have demonstrated a gain switched pulsed holmium laser and CW holmium cladding pumped fibre lasers. The gain switched holmium laser delivers pulse energies suitable for further amplification to enable frequency conversion in ZGP OPO's. The reduced absorption due to operation beyond 2.1 μm and the subsequent reduction of thermal lensing observed in ZGP, should enable the output power and scalability of these systems to be increased in comparison to ZGP OPO's based on thulium fibre laser pump sources. The slope efficiency achieved was 68% and does not include Fresnel losses from the output end-cap and splice losses. These losses indicate that the internal slope efficiency is >70%, and further work is underway on compositional optimization and minimization of OH^- concentration in the fibre, which is expected to increase this efficiency further.

The demonstration of resonantly pumped double-clad holmium fibre lasers has produced ~140 W from both single mode and LMA fibres. These lasers demonstrate the use of a fluorine-doped glass cladding to enable efficient operation of resonantly cladding pumped holmium fibre lasers. The slope efficiency of the cladding-pumped lasers was 55-60% with respect to launched power. The power levels demonstrated represent the highest reported output power achieved by a holmium laser. The lasers demonstrate the potential for further power scaling of this class of sources that emit beyond 2.1 μm, by pumping with an array of thulium fibre lasers using a fused combiner device. A single-ended pump architecture will also minimize fibre length and the subsequent impact of any fibre losses on the laser performance. The operating wavelength of 2.125-2.145 μm may also be the source of some of the reduction in efficiency of the LMA laser in comparison to the SM device. The core compositions of these two fibres are nominally identical having being drawn from the same preform. The longer operating wavelength may be due to the laser operating in a re-absorption region, red-shifting the emission due to the increased number of holmium ions in the LMA cavity.

5. CONCLUSION

Resonantly pumped holmium fibre lasers hold much promise for a range of applications. Operation of holmium fibre lasers beyond 2.1 μm has benefits that are advantageous for a range of remote sensing applications and high power laser beam propagation. We have demonstrated both CW fibre lasers and pulsed sources based on this architecture, both with the ability to be realized in an all-fibre system. These devices demonstrate the applicability of the tandem pumping architecture to these applications. The CW fibre demonstrations indicate that the potential power scaling of these devices to the kW class is feasible in an all-fibre platform. Leveraging this cladding pumped holmium fibre laser technology will also enable the development of high power all-fibre pulsed sources suitable for the power scaling of mid-IR sources using non-linear frequency conversion in OPO's.

6. ACKNOWLEDGEMENTS

We would like to thank Alan Davidson, Sophie Hollitt, Len Corena and Dmitrii Stepanov for their contributions.

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