High power operation of cladding pumped holmium-doped silica fibre lasers

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Abstract: We report the highest power operation of a resonantly cladding-pumped, holmium-doped silica fibre laser. The cladding pumped all-glass fibre utilises a fluorine doped glass layer to provide low loss cladding guidance of the 1.95 µm pump radiation. The operation of both single mode and large-mode area fibre lasers was demonstrated, with up to 140 W of output power achieved. A slope efficiency of 59% versus launched pump power was demonstrated. The free running emission was measured to be 2.12-2.15 µm demonstrating the potential of this architecture to address the long wavelength operation of silica based fibre lasers with high efficiency.

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

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1. Introduction

The development of high power laser sources in the 2 μm spectral region is of particular interest for a range of scientific, medical, and industrial applications. Operation in this wavelength region allows access to atmospheric transmission windows as well as water absorption features which are of interest for remote sensing and the atmospheric propagation of high power lasers [1–3].

Over the last decade work on thulium fibre laser development at 2 μm has provided a mature platform for the development of both pulsed and CW fibre laser sources, suitable for frequency conversion [4–6], and kW level power scaling [3]. Diode pumping of thulium fibre lasers at 0.79 μm relies on a cross-relaxation mechanism to produce efficient 2 μm operation [7]. Efficient exploitation of this energy transfer mechanism requires a highly doped core with a correspondingly high refractive index and thus core numerical aperture (NA). This high core NA limits the core sizes, and hence mode areas, over which good beam quality operation can be produced. To maintain good beam quality a pedestal structure around the core can be implemented, reducing the effective NA of the core [8]. However, this approach also increases the complexity of the fibre fabrication, and imposes practical limits on the NA, and subsequently the mode areas that can be fabricated.

In comparison to thulium fibre lasers, investigations into holmium fibre lasers have been limited. The use of holmium as the active rare earth ion presents several advantages over thulium fibre lasers for operation around 2 μm. Holmium fibre lasers allow access to an operating wavelength range extending beyond 2.1 μm, which is not efficiently addressed by thulium fibre lasers, and is of interest for mid-IR frequency conversion using $ZnGeP_2$ optical parametric oscillators. Holmium fibre lasers also offer the potential to be tandem pumped using mature thulium fibre lasers. Tandem pumping has been widely used to power scale fibre lasers [9–11], with up to 10 kW of output power with good beam quality having been demonstrated at 1 μm [12]. This architecture provides a robust route for the further power scaling of fibre lasers limited by the brightness of current laser diodes. Furthermore, the use of holmium as the active ion enables a simple core composition with a low dopant concentration to be used. This allows fibres with low NA cores and large mode areas to be fabricated without the need for a pedestal structure. Large mode area holmium fibres are required for producing long wavelength fibre laser sources capable of high pulse energy output, and high average power narrow linewidth operation.

For the direct pumping of singly doped holmium, the absorption bands of interest lie at ~1.15 μm, ($^4I_7$ level), and at ~1.95 μm, ($^5I_7$ level). Pumping of the $^4I_7$ level can be addressed by 1.15 μm laser diodes [13], or long wavelength operation of ytterbium fibre lasers [14]. The large quantum defect of this pumping scheme limits its efficiency and power scaling

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potential. The $^5I_7$ level can be accessed by thulium fibre lasers which can provide a mature pump source demonstrated at the kW power level. However, absorption of this pump wavelength by standard polymer coatings has precluded the demonstration of an efficient resonantly cladding pumped holmium fibre laser. This has limited the power scaling of holmium fibre lasers in comparison to other rare-earth ion doped silica fibre lasers which have benefitted from the implementation of a cladding pumped fibre.

Previous investigations of holmium fibre lasers have demonstrated core pumped operation, in both free-space [15] and monolithic fibre laser formats [16, 17] with output powers of up to 10 W [16]. Diode pumping of sensitised holmium based fibre lasers using Tm:Ho co-doping has produced 83 W output power, with a slope efficiency of 35% [18], but further power scaling is limited by thermal issues and complex dynamics in this core composition.

This paper describes the efficient operation of a resonantly cladding pumped holmium fibre laser. The fibre features an all-glass fibre design utilising a fluorine-doped second cladding to provide low-loss pump guidance for resonant pumping of the holmium fibre laser at 1.95 μm. We have demonstrated both robustly single-mode and large mode area fibre lasers running at 140 W, pump power limited. The slope efficiencies of these lasers were 59% and 55% with respect to launched pump power and the lasers operated at 2.12-2.15 μm. To the best of our knowledge these are the highest power solid-state holmium lasers reported. These initial demonstrations show great promise for further power scaling of fibre lasers in the 2 μm spectral region.

2. Experiment

The cladding pumped holmium fibre laser demonstrations are based on the holmium doped silica fibre depicted in Fig. 1. Two fibre geometries were drawn from a single preform, producing a robustly single-mode (SM) fibre, and a large mode-area (LMA) fibre. The details of the fibre geometries are listed in Table 1.

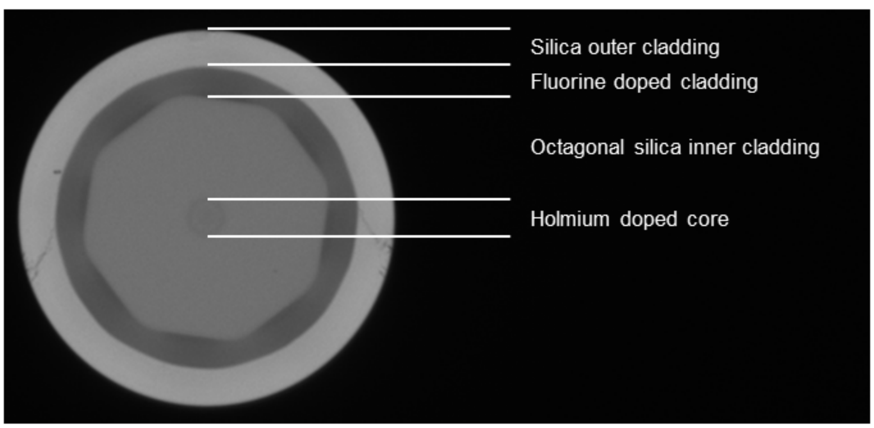

Fig. 1. Fluorine-doped glass clad holmium-doped silica fibre.

Table 1. Description of the Fibres under Investigation

Fibre Parameter	Fibre #1, (SM)	Fibre #2, (LMA)
Core Diameter	18 μm	40 μm
Core NA	0.08	0.08
Inner Cladding Diameter	114 μm	250 μm
Inner cladding NA	0.22	0.22
Second Cladding Diameter	144 μm	320 μm
Fibre Outer Diameter	180 μm	400 μm
Coating diameter	250 μm	550 μm
V-number @ 2.1 μm	2.35	4.75

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The lasers were operated in a free-space configuration to allow characterisation of the fibres described above and to ascertain the free-running wavelengths of these lasers. A schematic of the laser set-up is shown in Fig. 2.

The laser set-up allows for both single and double-ended pump architectures to be implemented. The core absorption of the fibre was ~64 dB/m at 1.95 µm. The holmium fibre length was chosen to correspond to an absorption of ~10 dB for single-ended and ~14 dB for double-ended pumping. Both the cladding-pumped holmium fibre and thulium pump laser output fibres were held in water cooled v-groove mounts. The high reflectivity (HR) end of the holmium laser cavity consisted of an Infrasil aspheric lens (f = 15 mm, AR @ 1.85-2.15 µm) and a dichroic mirror (HR @ 2.05-2.2 µm, HT @ 1.95 µm). The Fresnel reflection from the output fibre facet served as the output coupler. A pair of aspheric lenses was used to focus the output of each of the thulium pump lasers into the cladding of the holmium fibre. Residual 0.79 µm diode pump light from the 1.95 µm thulium fibre lasers was reflected by a dichroic mirror (HR @ 0.79 µm, HT @ 1.95 µm). The reflected 1.95 µm signal from these optics was monitored to determine the pump power incident on the holmium fibre. The pump coupling efficiency was determined by replacing the holmium fibre with a non-absorbing matched passive germanium doped fibre and comparing the incident and transmitted powers. The transmitted power was ~91% including Fresnel losses. A further pair of dichroic mirrors were used to separate any residual 1.95 µm pump from the holmium output before directing it onto a thermal power meter. A CaF_2 wedge split off a portion of the output beam to enable monitoring of the output beam quality with a pyro-electric camera (Pyrocam III, Spiricon) and the holmium laser wavelength was monitored using an optical spectrum analyzer (AQ6375, Yokogawa).

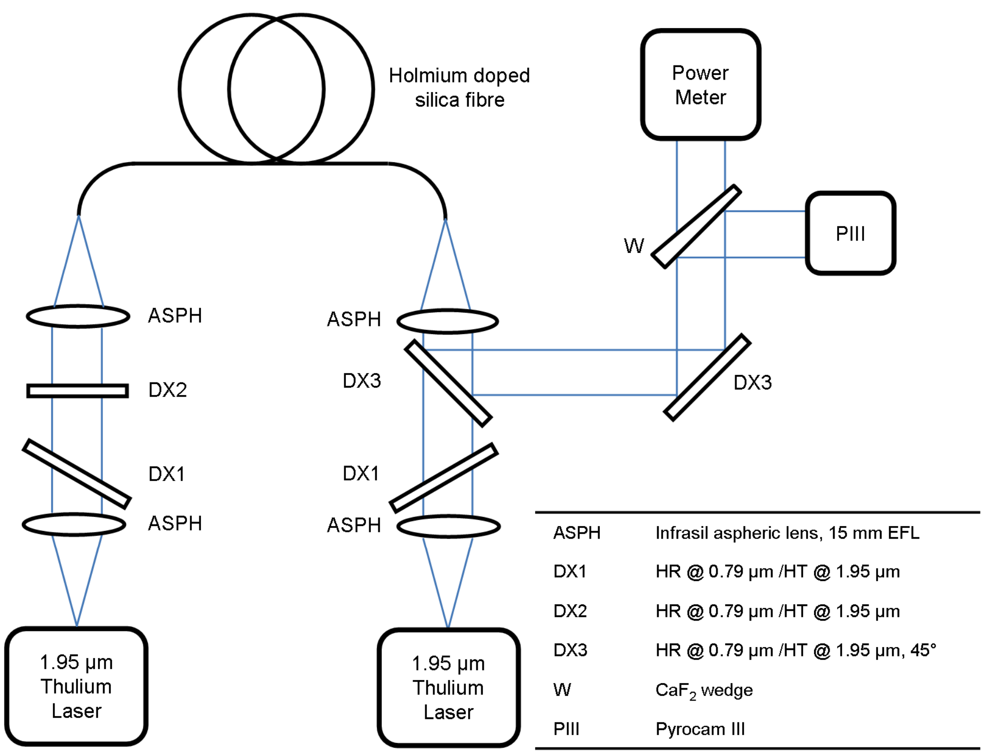

Fig. 2. Schematic of experimental laser layout.

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3. Results

The output power achieved using the single-mode fibre is plotted in Fig. 3. Both single-end and double-end pumped results are shown. The slope efficiency versus launched pump power of the single-end pumped laser was 59%, and the double-end pumped laser achieved 57%. The operating wavelength was measured to be a broad feature between 2.12 and 2.13 µm, as shown in Fig. 4.

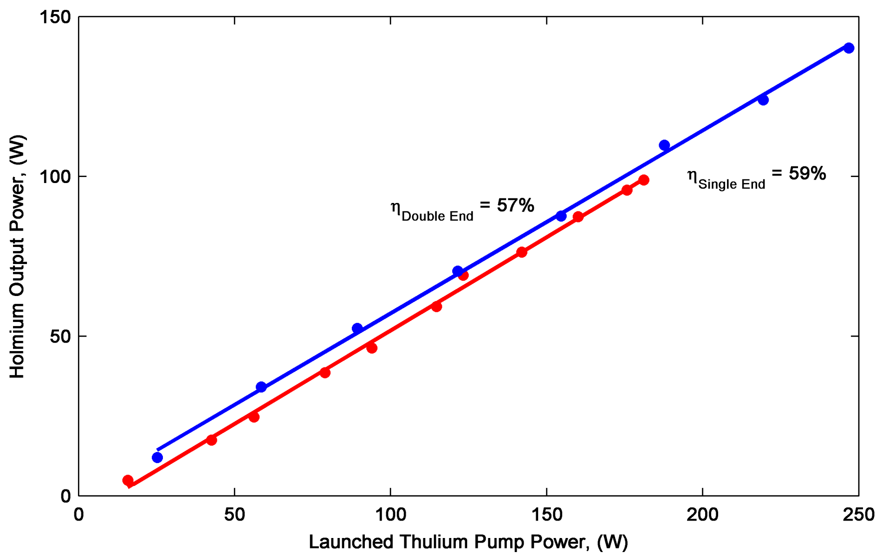

Fig. 3. Output power from single (red) and double (blue) end pumped SM holmium fibre lasers.

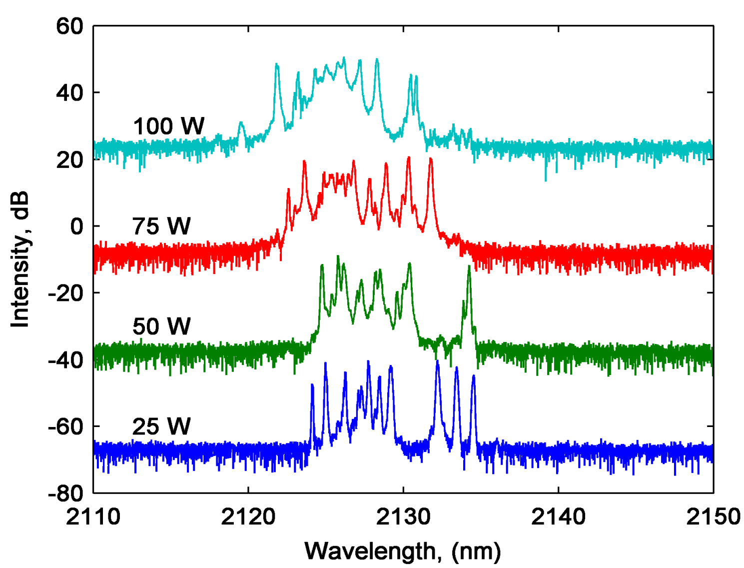

Fig. 4. Spectra of double-end pumped SM holmium fibre laser.

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The output power achieved with the LMA fibre is shown in Fig. 5. A double-end pumped laser was demonstrated. An output power of 140 W was achieved, with a slope efficiency of 55% versus launched 1.95 µm pump power. Typical spectra of the LMA laser are shown in Fig. 6(a), with the free-running operating wavelength being in the range 2.12–2.15 µm. A typical near field profile of the laser output from the double-end pumped LMA fibre laser is shown in Fig. 6(b) at 25 W and 140 W. The beam quality was measured using a pyro-electric camera and commercial beam quality measurement software (Pyrocam III, M^2-200, Spiricon-Ophir) and found to be $M^2 = 1.3$-1.5.

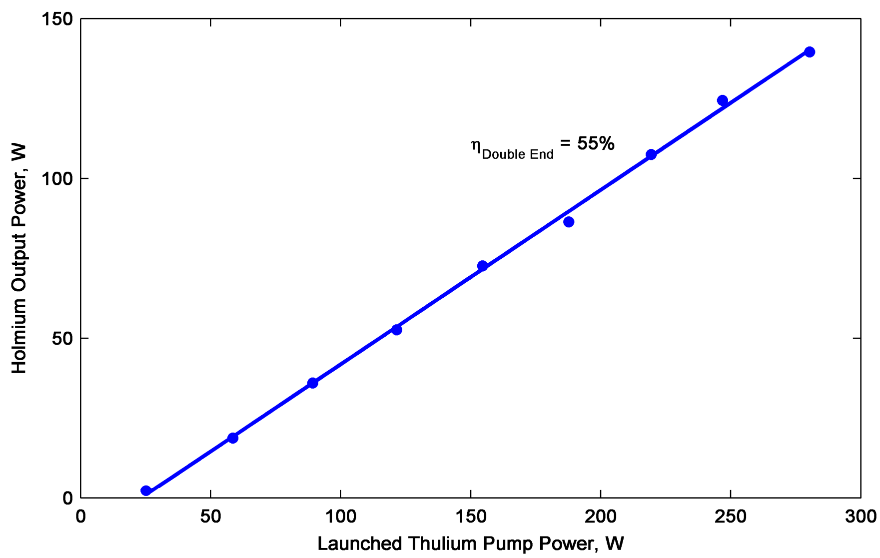

Fig. 5. Output power of the double-end pumped LMA fibre laser.

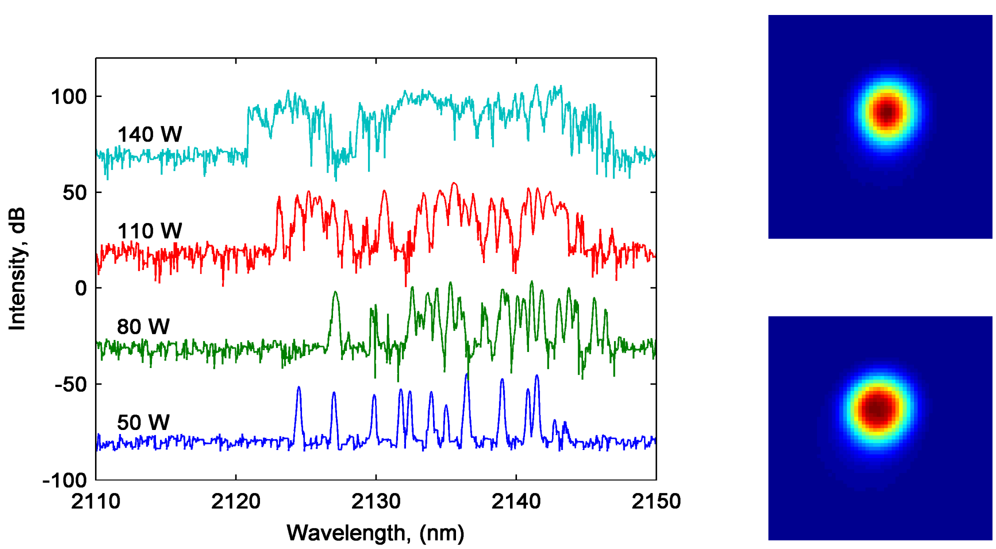

Fig. 6. (a) Spectra of the double-end pumped LMA holmium fibre laser. (b) Near field beam profile at 25 W (top) and 140 W (bottom).

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4. Discussion

Previous work into holmium doped silica fibre lasers has utilized 1.15 µm ytterbium fibre laser pumping [19]. That pump architecture has a quantum defect of 45%, and demonstrated slope efficiencies of ~45%, resulting in a quantum efficiency of ~82% at an output wavelength of 2.05 µm. The resonantly pumped architecture investigated in this work has a quantum defect of ~8%. If similar quantum efficiencies as those reported for ytterbium pumped holmium can be achieved then slope efficiencies of ~75% should be attainable. The lasers presented here demonstrate slope efficiencies of 55-59% versus launched pump power and are operating well below the quantum limit.

The sources of loss that contribute to this reduced efficiency are background IR silica losses (0.07-0.15 dBm^{-1}) [20], OH^- combination mode absorption (~0.05 $dBm^{-1}ppm_{OH}^{-1}$) [21], re-absorption and non-radiative decay processes of holmium in silica. Comparison of the slope efficiency versus launched 1.95 µm pump power for the single and double-end pumped SM lasers indicate that the double-end pumped laser suffers from losses associated with the longer fibre length. The differences in the SM and LMA spectra also provide some indications as to which mechanisms dominate and further work is underway to better understand these loss processes.

The experiments presented here are pump power limited with no sign of roll-over or thermal degradation. We anticipate that further power scaling is possible by increasing the output power from each thulium pump laser, or by increasing the number of thulium pump lasers in a monolithic tandem pumping scheme.

5. Conclusion

We have presented to our knowledge the highest output power resonantly cladding pumped holmium fibre lasers. Both single mode and large mode area fibre lasers were demonstrated with output powers of 140 W achieved, limited only by pump power. The efficiency of the lasers was 55-59% with respect to launched pump power. The holmium fibre laser architecture presented in this paper will allow power scaling of both CW and pulsed holmium fibre laser sources for a range of applications. In particular the resonantly pumped holmium fibre laser architecture, utilising mature thulium fibre lasers as pump sources, shows great promise for power scaling and high power narrow line-width operation. Future work will focus on understanding and improving laser efficiency and investigating the accessible wavelength range that this laser architecture can address.

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