Development of high power holmium-doped fibre amplifiers

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ABSTRACT

Resonantly pumped holmium fibre lasers present a range of opportunities for the development of novel fibre laser and amplifier devices due to the availability of mature, efficient high power thulium fibre pump lasers. In this paper we describe the operation of a large mode area holmium-doped fibre amplifier. The master-oscillator is an all-fibre linearly polarised, core pumped single mode laser operating at 27 W at 2.11 µm. This laser was amplified in a large mode area fibre producing up to 265 W of output power. This system is the first demonstration of a resonantly pumped holmium-doped fibre amplifier. It is also the highest power fibre amplifier that is capable of operating in an atmospheric transmission window >2.05 µm. This monolithic all-fibre system is able to address a wide range of remote sensing, scientific, medical and defence applications.

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

1. INTRODUCTION

There are a range of applications that require high power 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. Eye-safety is also an important concern with maximum exposure values at 2 µm being several orders of magnitude larger than at 1 µm. Fibre laser based systems are of particular interest due to the high efficiency, excellent beam quality and potential for power scaling that they offer.

High power operation of laser and amplifier sources in the 2 µm spectral region has progressed greatly due to the advances made in thulium and holmium fibre lasers compared to previous solid state laser sources in this wavelength region. The highest power sources demonstrated at 2 µm have been based on thulium fibres with more than 1 kW of output power and 608 W narrow line-width operation reported [1, 2]. The utilization of holmium extends the range of operation of silica based fibre sources past 2.1 µm providing access to the improved atmospheric transmission characteristics in this wavelength region. To enable high power operation of holmium fibre lasers, a cladding pumped geometry is required. A Fluosil glass cladding is employed rather than the standard polymer coatings typically used in conventional double clad fibres due to the absorption of pump power by these polymer coating materials at 1.95 µm. Recently we have demonstrated a range of resonantly pumped pulsed and CW holmium sources operating in the spectral region across 2.05-2.17 µm [3-5].

In this paper we describe a 27 W resonantly core pumped holmium fibre laser and its subsequent amplification to more than 265 W. We also discuss the development of components essential to the construction of monolithic high power amplifiers. The amplifier system presented here is transferrable to pulsed and narrow line-width operation at medium and high power.

Fiber Lasers XI: Technology, Systems, and Applications, edited by Siddharth Ramachandran,
Proc. of SPIE Vol. 8961, 89611A · © 2014 SPIE · CCC code: 0277-786X/14/$18
doi: 10.1117/12.2042963

2. POLARISED RESONANTLY PUMPED HOLMIUM LASER

Experiment

The polarised master laser utilises fibres with Panda stress features to enable polarisation maintaining (PM) operation. The fibres have a 15 μm core diameter, 0.09 core numerical aperture (NA) and 250 μm cladding diameter. The fibre core has a V-number of 2.0 at 2.1 μm, and provides single-mode operation above 1.75 μm. This fibre geometry is matched to the high power single mode thulium fibre lasers we have reported previously [6]. The thulium fibre lasers are capable of providing more than 150 W of output power at 1.95 μm in a 15/250 μm, 0.09NA fibre.

A schematic of the polarised holmium fibre laser is shown in Figure 1. The laser is pumped by a single-mode thulium fibre laser coupled through a 1.95/2.1 μm wavelength division multiplexer (WDM). The WDM is fabricated in-house using matching fibres. This device is used to spectrally de-couple the thulium and holmium lasers, providing protection for the 1.95 μm pump laser from any reverse propagating holmium emission at 2.11 μm. The WDMs were fabricated on a custom hydrogen torch glass processing station using a parallel fusion technique. The specification of the WDM used in this experiment is <0.4 dB insertion loss with a coupling ratio of >15 dB at 1.95 μm and 2.11 μm.

The pump output of the WDM was spliced to the high reflector (HR) fibre Bragg grating (FBG) which was then spliced to the active holmium-doped silica fibre with a standard PM splice orientation.. The output coupler (OC) is then spliced onto the holmium fibre with a 90° rotation offset between the two fibres. The wavelength of the HR and OC FBGs were tuned in the FBG fabrication process to match the fast axis of the HR with the slow axis of the OC. The rotated splice then forms a robust cavity for only one polarization at a single wavelength [7].

A 1 mm long 300 μm fused silica end-cap was used to limit Fresnel reflection from the end fibre facet for initial characterization of the master oscillator. For further amplifier experiments, a fibre coupled PM isolator (Shinkosha) was spliced to the output coupler FBG. This device is pigtailed with matching PM 15/250 μm fibre and is rated up to 20 W of average power with an insertion loss of 1.2 dB.

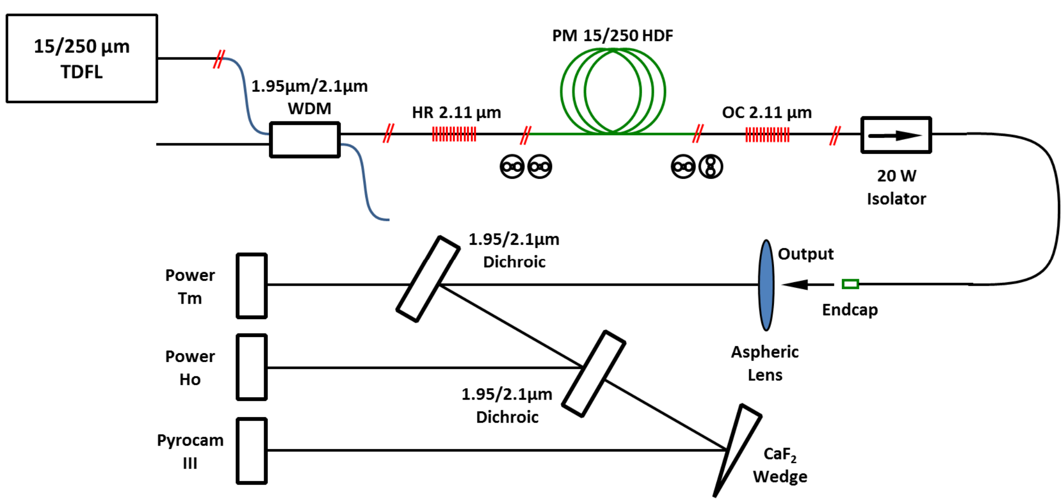

Figure 1: Schematic of polarised holmium fibre laser experimental set-up.

Results

The core-pumped laser produced 27 W of output power with a slope efficiency of 59%, as shown in Figure 2. The output exhibited single transverse mode operation and the polarization extinction ratio (PER) was measured to be >12 dB using a Wollaston prism. The inset in Figure 2 shows the spectral content of the laser. It is operating at 2.106 µm with a 3-dB band-width of <0.05 nm.

For further experiments, the laser was operated at an output power of 20 W corresponding to the input power rating of the isolator. In this configuration the laser produced 16 W at the output of the isolator as input for the high power amplifier stage.

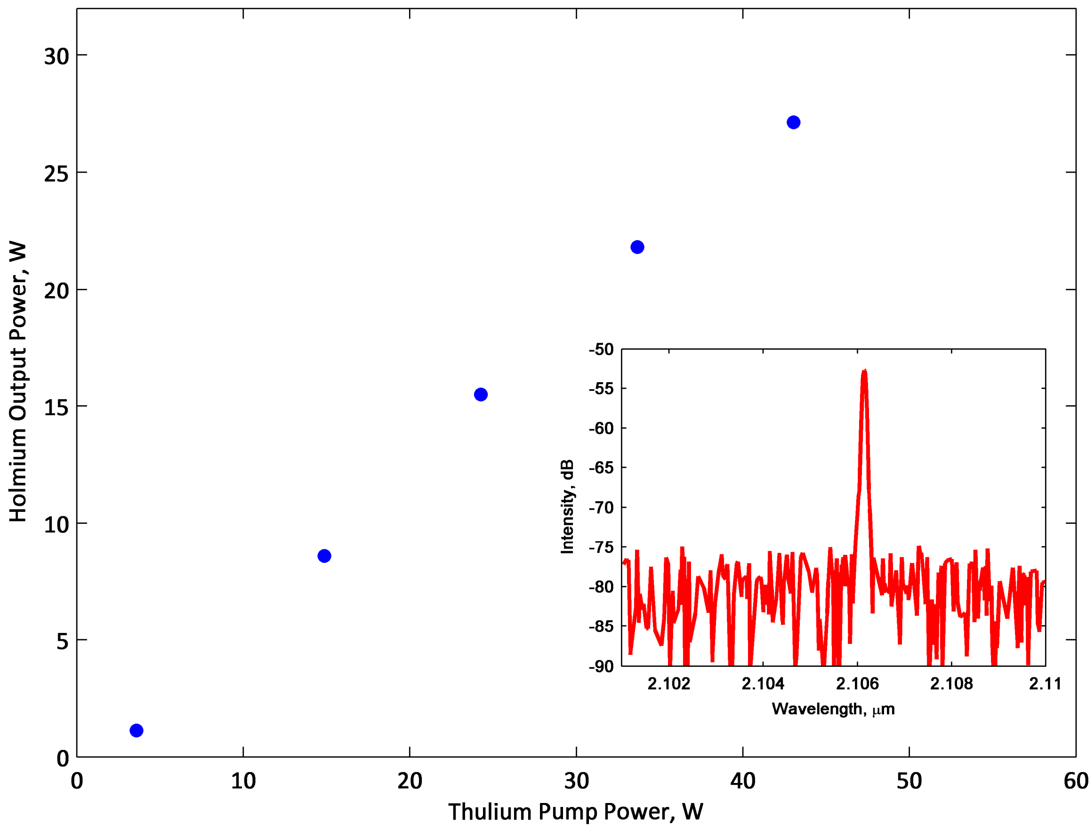

Figure 2: Output power of PM holmium fibre master oscillator. Inset: Output spectrum of master oscillator.

3. HIGH POWER HOLMIUM AMPLIFIER

Experiment

A schematic of the resonantly pumped holmium-doped fibre amplifier is shown in Figure 3. The holmium amplifier uses an LMA fibre consisting of a 40 µm core diameter, 250 µm octagonal inner cladding, 320 µm diameter Fluosil layer and a 400 µm outer silica cladding. This fibre is similar to that described in [4]. The master laser described in Section 2 was spliced to a 17/110/140/170 µm to 40/250/320/400 µm taper to efficiently couple the single-mode master laser to the LMA combiner. The 10+1 → 1 combiner device was fabricated in-house using a hydrogen torch based glass processing station and comprises 10 pump ports and a central LMA signal feed-through. In this experiment 9 ports were spliced to high power thulium fibre pump lasers. The combiner was then spliced to an 8 m length of the holmium fibre described above and end-capped using a 2 mm long section of 400 µm coreless fused silica fibre. The active fibre was heat-sunk and water-cooled. The output beam from the amplifier was collimated using a 15 mm focal length Infrasil aspheric lens. Dichroic mirrors (HR @ 2.1 µm , HT @ 1.95 µm) were then used to separate residual pump and signal powers, which were directed onto thermal power meters. A CaF_2 wedge was used to direct the leakage beam from the second 1.95 µm/2.1 µm dichroic mirror onto a Pyrocam III pyroelectric camera.

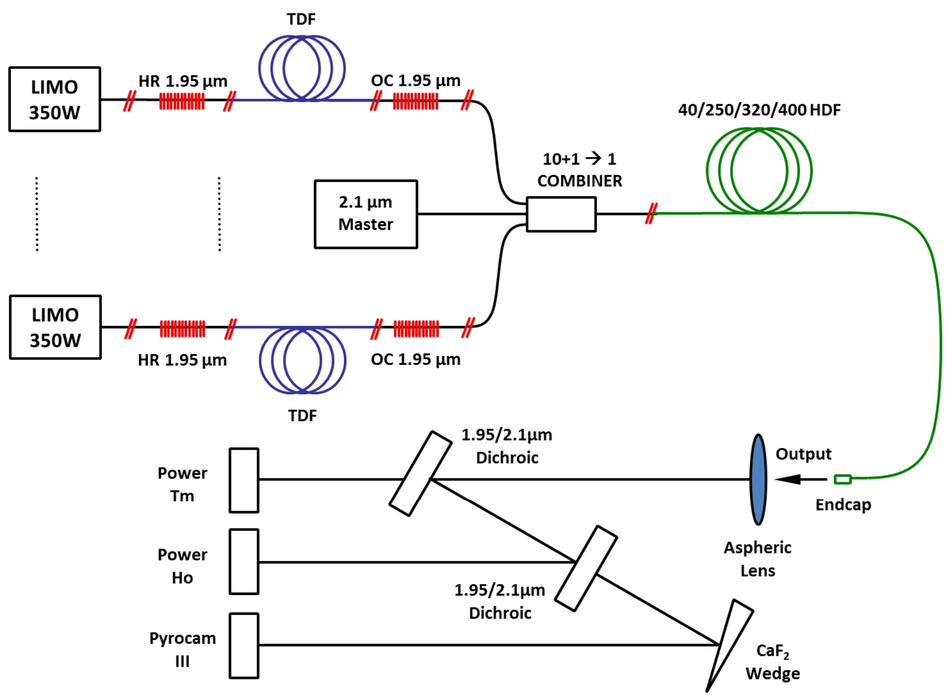

Figure 3: Experimental setup of the LMA holmium amplifier.

Results

The results obtained for the amplification of the master laser are shown in Figure 4. 265 W of output power was achieved with a slope efficiency of 41% versus absorbed thulium pump power. The spectra shown in Figure 4 demonstrate the preservation of the spectral content of the master laser and the absence of ASE. The LMA amplifier operated with multiple transverse mode structure apparent and this is ascribed to the quality of the splices in the LMA section of the amplifier.

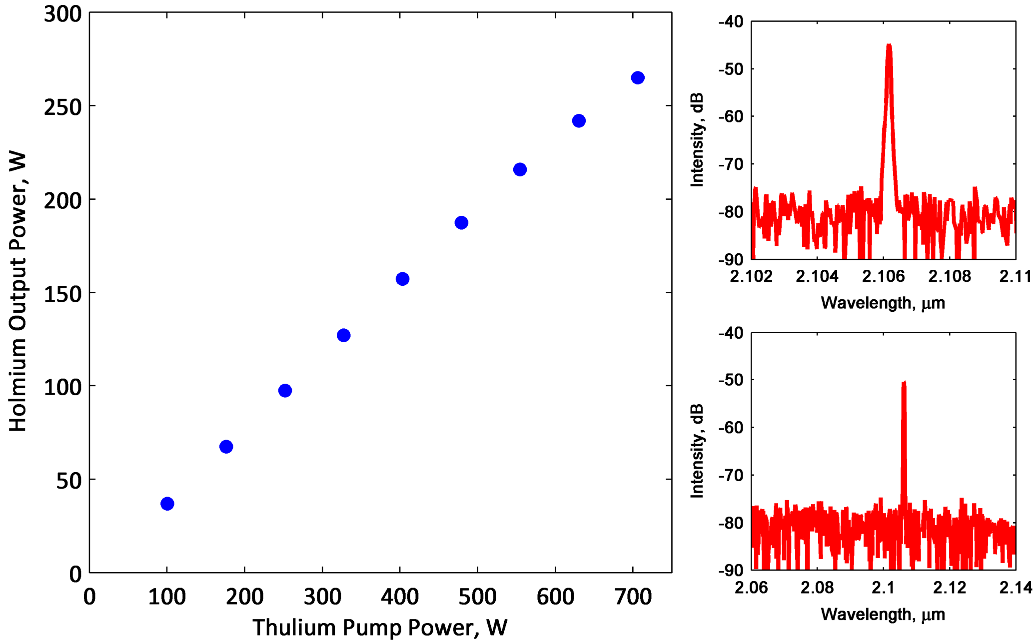

Figure 4: Output power of LMA holmium-doped fibre amplifier. Top Inset - Lasing spectra at 200 W output power. Bottom Inset: Large bandwidth scan at 200 W output power.

4. DISCUSSION

The monolithic, linearly polarised, single-mode holmium master laser demonstrated in Section 2 utilised robustly single mode fibres with a 15 µm core. The relatively large mode-field diameters are expected to enable the further development of robustly single-mode sources in both narrow line-width and pulsed formats at 2.1 µm by reducing the intensity and therefore non-linear effects in comparison to shorter wavelength fibre lasers.

The LMA amplifier demonstrated in Section 3 provided 12 dB of gain, resulting in 265 W of output power from a 16 W input at 2.11 µm. This was achieved in an all-fibre architecture enabled by in-house fabricated WDM and combiner technology. The amplifier operated at high power and was limited by thermal degradation of the input splice. The efficiency of this fibre is the subject of current investigations as the reported slope efficiency of 41% is well below the quantum limited efficiency of ~92%.

5. CONCLUSION

This is the first demonstration of a resonantly cladding-pumped holmium-doped fibre amplifier. The double clad all-glass design has enabled power scaling of holmium-doped amplifiers in a rugged, monolithic all-fibre format up to a power level of 265 W. We observed negligible power loss in the combiner due to high brightness output of the single mode thulium pump lasers. An in-house fabricated WDM was also demonstrated to operate at >40 W of power at 1.95 µm.

The amplifier architecture is transferrable to pulsed and narrow-line width systems. Further development of this approach will provide eye-safer fibre sources which are able to access the atmospheric transmission window >2.1 µm.

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