A linearly polarised, pulsed Ho-doped fiber laser

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Abstract: We report the highest power operation of a monolithic polarised gain-switched holmium fiber laser. In this paper we describe the pulsed operation of two monolithic holmium fiber lasers, which were gain-switched by a pulsed thulium fiber laser. The first holmium laser produced pulses with a minimum pulse duration of 85 ns, maximum pulse energy of 16 µJ and repetition rate of 600 kHz. This laser was linearly polarised with an extinction ratio of >18.5 dB under all operating conditions and achieved average powers of up to 5.1 W at 2.104 µm. The second laser demonstrated shorter pulses with a minimum duration of 38 ns at a maximum repetition rate of 300 kHz. This laser produced up to 1.5 W of average power at 2.112 µm.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3460) Lasers; (140.3510) Lasers, fiber; (140.3538) Lasers, pulsed.

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1. Introduction

Pulsed 2 µm lasers are required as pump lasers for frequency conversion to generate mid-infrared radiation, as well as for remote sensing, and medical applications. Gain-switching of a thulium fiber laser has been demonstrated to be an efficient, all-fiber method of achieving short pulses around 2 µm [1–3] that are suitable for these applications. Gain-switched thulium lasers have subsequently been used to seed large mode area (LMA) thulium amplifiers, the output of which have been used as a pump source for optical parametric oscillators (OPOs) based on Zinc Germanium Phosphide (ZGP) [1, 4]. The conversion efficiency achieved by these OPOs has demonstrated that the spectral and temporal characteristics of such gain-switched master oscillators are suitable for non-linear frequency conversion.

ZGP is widely used for frequency conversion into the mid-IR due to its excellent physical properties and high non-linear co-efficient. However, ZGP also exhibits strong defect related absorption at wavelengths <2.1 µm [5]. Pulsed thulium fiber lasers are limited to efficient operation at wavelengths <2.05 µm [6], and the subsequent pump absorption at these wavelengths by the ZGP leads to strong aberrations due to thermal lensing and will ultimately limit the scalability of thulium pumped ZGP mid-IR sources. Attempts to operate pulsed thulium fiber lasers at longer wavelengths have resulted in poor efficiency due to a vanishing gain cross section, and the onset of amplified spontaneous emission and parasitic lasing at ~1.98 µm.

Co-doping of thulium fibers with holmium has extended the operation of pulsed thulium based fiber lasers to 2.07 µm because the addition of the holmium ions enhances the gain at the longer wavelengths and absorbs ASE at around 1.95 – 2 µm [7]. Other techniques can also be used to suppress the ASE at the shorter wavelengths such as using more complicated Bragg fiber geometries – these techniques have been successfully demonstrated in extending the operation of ytterbium doped fibers out to 1.178 µm [8].

Currently, singly doped holmium lasers provide the most efficient fiber laser platform for pulsed operation at wavelengths beyond 2.1 µm. Thulium fiber laser core-pumped holmium doped silica fiber lasers have previously been demonstrated with output powers less than 5 W [9, 10]. More recently a cladding pumped holmium doped fiber laser was demonstrated with 140 W output at 2.11 – 2.14 µm [11]. As well as reducing the pump absorption experienced in ZGP, operating in this wavelength region also provides access to atmospheric transmission windows, which are important for LIDAR and free-space optical communications. The holmium emission can also be used to target a variety of water absorption lines for medical or environmental monitoring applications which otherwise could not be accessed by thulium fiber lasers.

Gain-switching of a holmium fiber laser by a pulsed thulium fiber laser has been demonstrated previously [12], however this system was pump power limited to <0.3 W and operated in an un-polarised regime with a maximum repetition rate of 150 kHz. In the current work we describe the gain-switched operation of two holmium lasers. The first laser operated with an average power of 5.1 W at repetition rates of up to 600 kHz, and produced linearly polarised pulses with durations as short as 85 ns. The second un-polarised laser was optimised for shorter pulses and produced 1.5 W of average output power at a repetition rate of 300 kHz, with pulse lengths as short as 38 ns.

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2. Experiment

2.1 Pulsed thulium laser system at 1.95 µm

The holmium fiber lasers were gain-switched by a pulsed 1.95 µm polarised thulium fiber laser system [3]. The thulium fiber laser system consists of a 1.55 µm seed diode, two stages of amplification in erbium/ytterbium co-doped fiber amplifiers and a thulium gain-switched fiber laser operating at 1.95 µm. A schematic of the laser system is shown in Fig. 1.

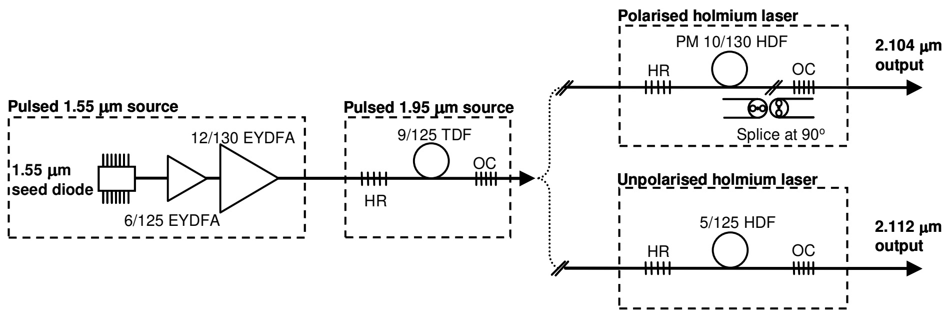

Fig. 1. Schematic of 1.55 µm pulsed pump source and gain-switched thulium fiber laser. Also shown is the 90° splice to the strain tuned output coupler (OC) which enables single polarisation operation.

The pulsed 1.55 µm source is similar to that presented in [3]. This source provides pulses with energies of up to 50 µJ and durations of ~50 ns at 1.55 µm. These pulses core-pump and gain-switch the thulium fiber laser. The thulium fiber laser is formed between a high reflectivity (HR) fiber Bragg grating (FBG) at 1.95 µm and an output coupler (OC) with a 5% reflectivity at 1.95 µm. 3 m of active thulium doped fiber with a 9 µm diameter, 0.15 NA core and a 125 µm cladding (Nufern) was used. A low dopant concentration (0.3 wt.%) of thulium ensured that the heat load was distributed over a long length of fiber. This prevented any thermal issues that were previously observed when using shorter lengths of fiber with larger thulium dopant concentrations [3]. The output of the pulsed polarised thulium fiber laser system was then used to core-pump and gain-switch the holmium fiber lasers.

The output fibres were cladding stripped to remove any light not propagating in the core and then dichroic mirrors (HR $\lambda > 2.05$ µm, AR $\lambda < 1.55$–2.00 µm) were used to separate the holmium output from the remaining 1.95 µm and 1.55 µm output.

2.2 Linearly polarised pulsed holmium fiber laser at 2.104 µm

A schematic of the linearly polarised holmium fiber laser is shown in Fig. 1. This laser was composed entirely of fiber with a PANDA polarisation maintaining (PM) structure, a 10 µm diameter, 0.15 NA core and a 130 µm diameter cladding. The laser consisted of a HR FBG written in PM passive photosensitive fiber which was spliced to ~1.2 m of PM holmium (~0.25 wt.%) doped fiber (PM HDF). The small signal absorption of this fiber at 1.95 µm was ~25 dB/m. This in turn was spliced with a 90° rotational offset of the stress-rods to an OC grating, also written in PM passive photosensitive fiber. An output coupler reflectivity of 20% was used. In this configuration a cavity is formed for only one polarisation mode at one wavelength as shown in Fig. 2 [3, 13–15]. The total cavity length including the pigtails from the FBGs is 1.6 m.

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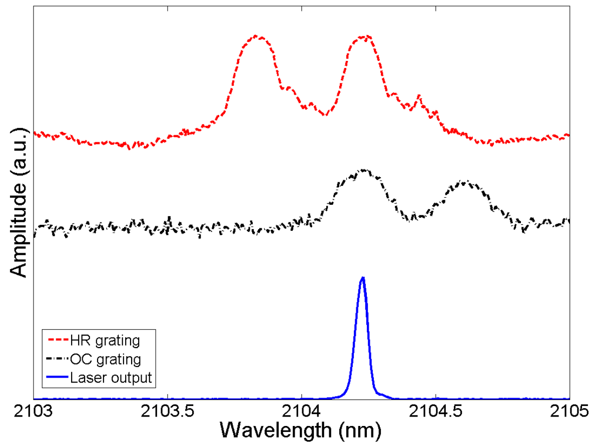

Fig. 2. Shown are the grating spectra as measured by an un-polarised super-continuum source and an optical spectrum analyser with a 0.05 nm resolution. The 2 peaks correspond to the fast and slow axes of the highly bi-refringent fiber. The gratings were strain tuned during the writing process such that the output coupler slow axis overlapped with the high reflector's fast axis.

2.3 Un-polarised pulsed holmium fiber laser at 2.112 µm

The PM HDF had a low concentration of holmium and a long laser cavity was required to efficiently absorb the 1.95 µm pump light. In order to investigate the production of shorter pulses, an active fiber with a larger holmium dopant concentration of 4 wt. % was used. This fiber did not have any polarisation maintaining features and as a result the laser operated in an un-polarised manner. The non-PM holmium doped fiber had a 5 µm diameter, 0.22 NA core and a 125 µm diameter cladding (Nufern). The small signal absorption of this fiber at 1.95 µm was ~300 dB/m. The FBGs used to form the cavity were written in passive, photosensitive fiber with a 10 µm diameter, 0.15 NA core and a 125 µm diameter cladding. The central wavelength for the FBGs was at 2.112 µm and two lasers with different output coupling fractions (30% and 80% reflectivity) were characterised. The total cavity length including the 20 cm of doped fiber and pigtails from the gratings was 54 cm.

3. Results

3.1 Pulsed thulium laser system at 1.95 µm

The dual amplifier 1.55 µm source produced pulse energies up to 50 µJ and durations of ~50 ns. The final Er:Yb amplifier achieved an average output power of up to 17 W with a slope efficiency of ~35% with respect to the total input pump power at 974 nm as shown in Fig. 3(a).

The thulium fiber laser operated with an efficiency of 48% as shown in Fig. 3(b). The pulse duration from the gain-switched thulium laser was ~150 ns due to the long cavity length [2, 16]. The thulium fiber laser operated with a stable output at pulse energies up to 25 µJ and a maximum repetition rate of 600 kHz. At larger pulse energies significant modulation instability was observed, resulting in super-continuum generation and a subsequent reduction in spectral density.

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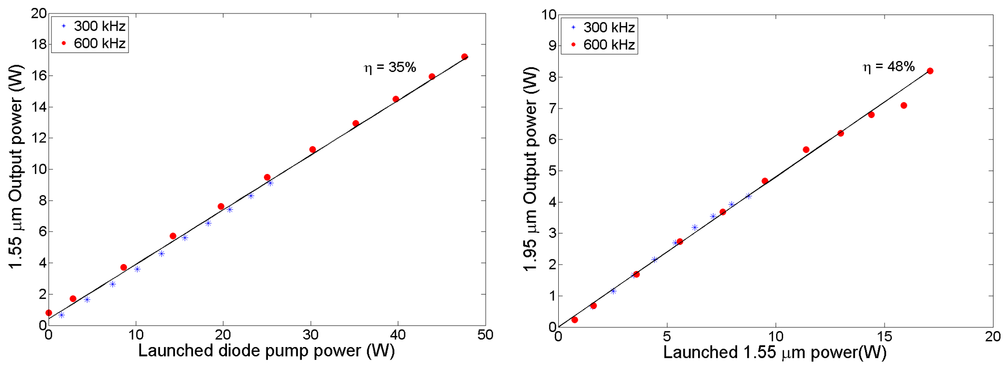

Fig. 3. (a) The second stage of the 1.55 μm pump operates at a slope efficiency of 35% with respect to incident diode power. The output power was measured at the output of a passive 10 μm diameter, 0.15 NA core fiber which contained the high reflectivity grating of the thulium laser. (b) The gain-switched thulium laser operated with a slope efficiency of 48% with respect to incident 1.55 μm pump.

3.2 Linearly polarised pulsed holmium fiber laser at 2.104 μm

The polarised holmium fiber laser operated with a slope efficiency of ~65% with respect to the launched pump power and achieved an average output power of 5.1 W as shown in Fig. 4(a). The fiber laser operated on a single line with a single polarisation as shown in Fig. 2. The polarisation extinction ratio was >18.5 dB under all operating conditions. Due to the long cavity length (1.6 m) the duration of the pulses was >85 ns as shown in Fig. 4(b).

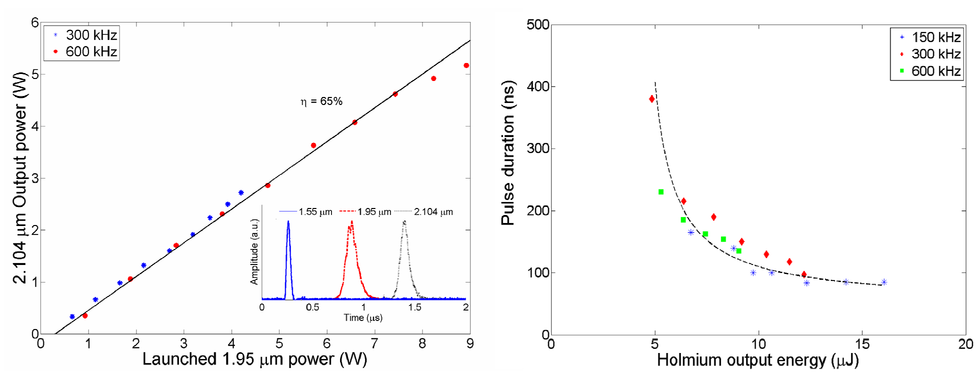

Fig. 4. (a) Holmium laser output power vs. 1.95 μm launched pump power at different repetition rates. Inset: Pulses from each stage of the laser. (b) Pulse duration vs. pulse energy of the gain-switched holmium fiber laser.

3.3 Un-polarised pulsed holmium fiber laser at 2.112 μm

Two configurations of the un-polarised holmium fiber laser were investigated with output coupler grating reflectivities of 30% and 80%. As shown in Fig. 5(a), the lasers operated with a 40% and 30% slope efficiency with respect to the launched pump power and achieved an average output power of 1.5 W. Pulses as short as 38 ns were generated by the laser with the 30% output coupler as shown in Fig. 5(b) and both of the lasers operated on a single line at 2.112 μm.

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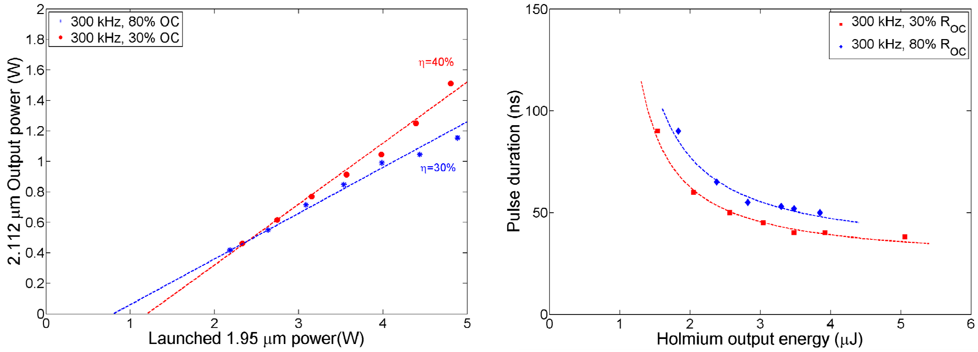

Fig. 5. (a) Average power output of gain-switched holmium-laser. (b) Pulse duration as a function of holmium fiber output energy.

We suspect that the reduced efficiency of the lasers using the 4 wt.% holmium fiber is due to the high rare-earth ion dopant concentration in the fiber. Similar reductions in the efficiency of heavily holmium doped silica fibers have been reported elsewhere [17]. However, unlike other rare-earth ions such as Er, Yb and Tm, there has been little reported on the mechanism responsible for the quenching of the upper laser level in holmium doped silica at high dopant concentrations.

4. Conclusion

We have to the best of our knowledge demonstrated the highest power operation of gain-switched holmium fiber lasers. Robust single polarisation operation was achieved in a monolithic all-fiber cavity. The polarised laser produced 85 ns pulses with maximum pulse energies of 16 µJ at a repetition rate of 600 kHz and an average output power of up to 5.1 W.

4 wt.% doped holmium fiber was used in order to produce shorter pulses by decreasing the cavity length of the laser. This laser demonstrated pulses as short as 38 ns, but at a reduced efficiency. Studies are ongoing to better understand the origin of the reduced efficiency in the higher doped fiber. The polarised and short pulsed lasers operated at wavelengths of 2.104 µm and 2.112 µm respectively.

With the recent demonstration of high power CW cladding pumped holmium fiber lasers operating in the 2.11 – 2.14 µm region [11, 18], it is anticipated that pulsed singly-doped holmium fiber lasers will find significant application alongside systems already incorporating thulium fiber lasers.

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