A cladding-pumped, tunable holmium doped fiber laser

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Abstract: We present a tunable, high power cladding-pumped holmium doped fiber laser. The laser generated >15 W CW average power across a wavelength range of 2.043 – 2.171 µm, with a maximum output power of 29.7 W at 2.120 µm. The laser also produced 18.2 W when operating at 2.171 µm. To the best of our knowledge this is the highest power operation of a holmium doped laser at a wavelength >2.15 µm. We discuss the significance of background losses and fiber design for achieving efficient operation in holmium doped fibers.

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

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#198023 - $15.00 USD Received 26 Sep 2013; revised 3 Nov 2013; accepted 5 Nov 2013; published 12 Nov 2013

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1. Introduction

Holmium and thulium doped fiber lasers provide an efficient method of generating high average power in the 1.8 – 2.2 µm spectral region. Sources in this spectral region experience excellent atmospheric transmission and have applications in LIDAR and remote sensing [1, 2]. Thulium doped fiber (TDF) lasers typically operate efficiently between 1.85 – 2.09 µm [3] and have been demonstrated at power levels exceeding 1 kW at 2.05 µm [4]. However these systems are not able to efficiently access longer wavelengths due to the diminishing emission cross-section of thulium in silica. Tm:Ho co-doped systems have been demonstrated at up to 83 W of output power at longer wavelengths, but these systems suffer from increased thermal loading and upconversion [5, 6]. Singly-doped holmium fiber lasers present the most power-scalable method for operation at 2.1 µm with >400 W demonstrated from a monolithic all-fiber system [7].

A number of tunable thulium and holmium lasers have been demonstrated addressing the wavelength region beyond 2.0 µm. A cladding-pumped thulium fiber laser was demonstrated with a tuning range from 1.85 – 2.09 µm and a maximum average output power of 7 W at 1.95 µm and 1 W at 2.09 µm [3]. The use of a higher reflectivity output coupler enabled the tuning range of a thulium fiber laser to be extended from 1.92 – 2.14 µm with a maximum average output power of 1 W at 1.99 µm and 200 mW at 2.135 µm [8]. A cladding-pumped Tm:Ho co-doped silica fiber was tuned from 1.90 – 2.15 µm achieving a maximum average power of 6 W at 2.05 µm and 1 W at 2.15 µm [9]. A singly doped, core-pumped holmium fiber laser was tuned from 2.0 – 2.15 µm with a maximum power of 2 W at 2.10 µm and 0.3 W at 2.15 µm [10]. An all-fiber, core-pumped, singly doped holmium laser was tuned from 2.045 – 2.10 µm achieving a maximum average power of 2 W and was limited in tuning range by the capability of the fiber Bragg grating (FBG) [11]. A $Tm:Sc_2O_3$ laser was tuned from 1.975 – 2.168 µm with a maximum of 4.2 W at 2.116 µm and less than 1 W at wavelengths > 2.15 µm [12]. A $Ho:Sc_2O_3$ laser was reported to operate at 2.158 µm however no spectral data or power curves were provided [13]. Recently a holmium doped fiber laser was reported to generate 0.13 W at 2.21 µm [14] – this laser was not tunable.

In this paper we describe the first tunable cladding-pumped holmium-doped fiber laser with an operating range of 2.043 – 2.171 µm. This robustly single mode fiber laser achieved >15 W of output power across the entire tuning range and a maximum output power of 29.7 W at 2.120 µm. We demonstrate how the cladding pumped architecture has enabled the power scaling of tunable holmium doped fiber lasers. We also consider the impact of the background absorption of silica and hydroxyl (OH^-) absorption on the operation of a silica fiber laser operating beyond 2.1 µm.

2. Holmium doped fiber design

2.1 Double clad fiber geometry

Figure 1(a) shows the possible pumping schemes and relevant energy levels for holmium doped silica [15–19]. A number of core-pumped systems have been reported utilizing holmium doped silica fibers. A 10 W laser has been demonstrated in systems that were core-pumped by 1.15 µm Yb^{3+} fiber lasers [19] and a 6 W laser was demonstrated by core-pumping with a Tm^{3+} fiber laser [18]. However demonstration and power scaling of resonantly pumped holmium doped fiber lasers has been limited by the absence of an efficient, power scalable, double clad fiber geometry.

Conventional low index polymers are unsuitable for guiding the 1.95 µm pump light due to the strong absorption of common low index polymers at this wavelength. The use of an internal fluorine-doped layer has enabled cladding-pumping of holmium doped fibers by thulium fiber lasers [20]. This approach has produced a monolithic fiber laser with an output power of >400 W at 2.12 µm [7]. The holmium doped fiber used in this paper has an 18 µm, 0.083 NA single mode core and a 112 µm octagonal shaped fused silica cladding. The inner silica cladding was jacketed by a 10 µm Fluosil layer, which was over-clad by a fused silica layer out to a diameter of 180 µm. Figure 1(b) shows the view of the end-face of the fiber. The V-number for the core is 2.25 at 2.1 µm resulting in a robustly single-mode fiber in this wavelength region.

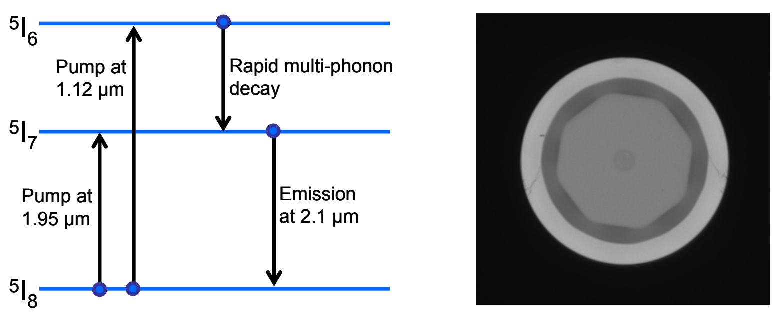

Fig. 1. (a) Common pumping schemes in holmium doped silica. (b) End face view of a double clad holmium fiber.

2.2 Holmium cross-sections and background losses

The holmium absorption and emission cross-sections are shown in Fig. 2. The absorption cross-section was measured by using a super-continuum source (Koheras SuperK) and an optical spectrum analyzer (Yokogawa AQ6375). The emission cross-section was derived from the measured absorption cross-section via the McCumber reciprocity relation [21]. The cross-sections agree with previously published results [22]. Also shown in Fig. 2 are the significant background losses in this spectral region due to silica [23, 24], as well as hydroxyl contamination [25]. As shown in Fig. 2 a hydroxyl level of ~1 ppm is sufficient to ensure that the background loss due to OH^- is significantly lower than the silica infrared absorption.

The core absorption of the fiber used in the tuning experiment was measured using the above technique and determined to be 70 dB/m at 1.95 µm. The hydroxyl concentration in the core was determined by a similar measurement of the absorption feature at 1.38 µm. The strength of the absorption at 1.38 µm was then compared to the standard silica value of 62 dB/(ppm km) [24]. The OH^- concentration of the holmium doped fiber used in this experiment was measured to be 1.4 ± 0.3 ppm.

#198023 - $15.00 USD Received 26 Sep 2013; revised 3 Nov 2013; accepted 5 Nov 2013; published 12 Nov 2013

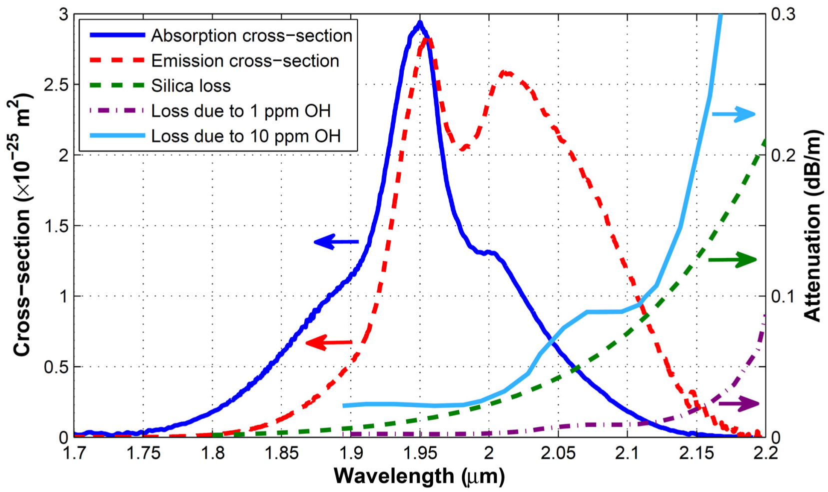

Fig. 2. Ho:silica measured absorption and derived emission cross. Also shown are the silica [23, 24] and hydroxyl [25] absorptions in this wavelength region.

The gain cross-section as a function of inversion is shown in Fig. 3. In resonantly pumped lasers the effective pump absorption is a function of the density of ions in the ground state and in the upper lasing level. In order to overcome background transmission losses and achieve transparency at 2.1 µm, >14% of the holmium ions are required to be in the upper lasing level. At this significant level of inversion, the effective pump absorption at 1.95 µm is weaker in comparison to that when all of the ions are in the ground state. It is important to ensure that the laser cavity design considers the pump absorption at the required inversion level during operation.

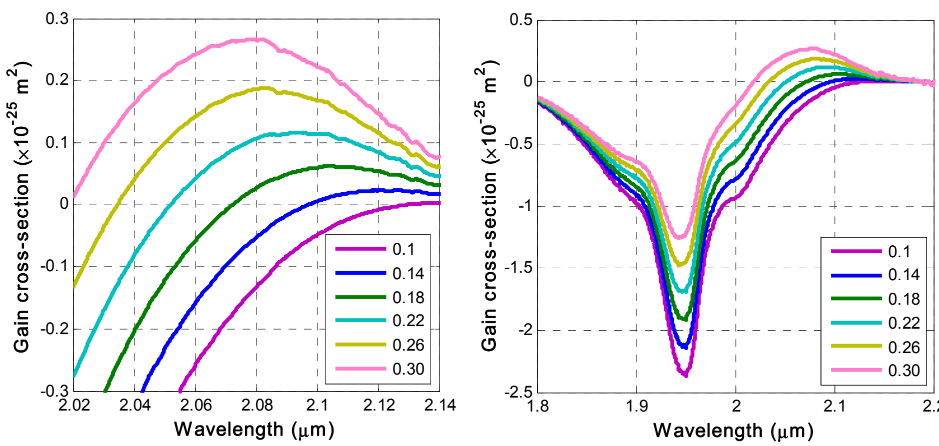

Fig. 3. Ho:silica gain cross-sections as a function of wavelength for various inversion ratios (a) showing the gain cross-section around 2.1 µm and (b) showing the change in the gain cross-section at 1.95 µm.

3. Experiment

A schematic layout of the experimental set-up is shown in Fig. 4. The output of a single-mode 1.95 µm fiber laser is collimated and focused into the cladding of a 6.5 m long holmium doped fiber (HDF). The thulium fiber laser is fabricated in-house and operates with a slope efficiency of 60% with respect to launched pump power at 0.79 µm [26].

#198023 - $15.00 USD Received 26 Sep 2013; revised 3 Nov 2013; accepted 5 Nov 2013; published 12 Nov 2013

Care was taken to ensure that the 1.95 µm pump light was focused into the cladding and not the core of the holmium doped fiber. This was achieved by imaging the thulium fiber core onto the end-face of the holmium doped fiber and scanning transversely to misalign from the core of the holmium doped fiber. A dichroic mirror (Dx: HR @ 2.04 – 2.2 µm, HT @ 1.95 µm) was placed in between the two ZnSe lenses (L, focal length = 15 mm) to separate the pump and laser light. This dichroic was angle tuned to minimize feedback between the holmium and thulium oscillators.

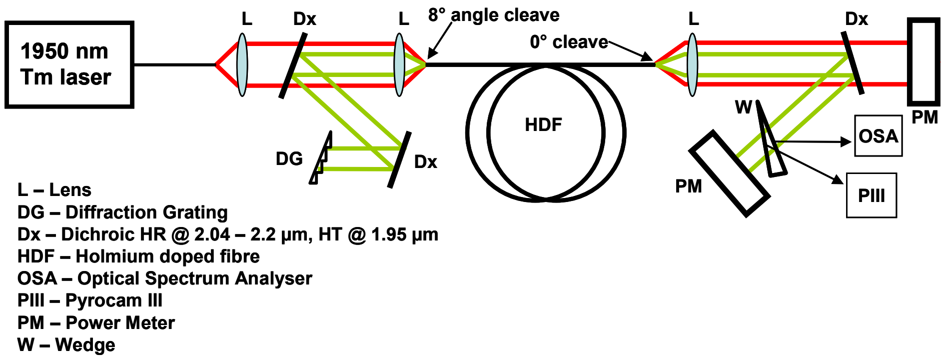

Fig. 4. Schematic of tunable laser experiment.

The laser cavity was formed between a diffraction grating (DG) and the 4% Fresnel reflection at the opposite end of the fiber. The tuning arrangement was in a Littrow configuration. The reflectivity of the diffraction grating was >80% for P-polarized light and >90% for S-polarized light at 2.0 – 2.2 µm. This allowed for continuous tuning with minimal dependence on polarization. In order to increase the threshold for parasitic lasing, the end of the HDF facing the pump laser was cleaved at an 8° angle. Another dichroic mirror was then used to separate the pump and laser light at the output. An uncoated CaF_2 wedge at near normal incidence provided two low power reflections which enabled monitoring of the spectrum and beam profile of the laser output on an optical spectrum analyzer and a pyroelectric beam profiler (Ophir Pyrocam III). Calibrated thermal power meters (Ophir, Thorlabs) were used to monitor the residual pump power and output laser power throughout the experiment.

4. Results

4.1 Tuning ranges

Typical lasing spectra for a number of operating wavelengths are shown in Fig. 5. The 3 dB line-width of the laser output was measured to be ~3 nm at each operating point. At the extremes of the tuning ranges, an ASE feature was observed at 53 dB below the intensity of the main signal. When attempting to operate at 2.177 µm, parasitic lasing occurred at 2.089 µm and there was a significant increase in output ASE as depicted in Fig. 5.

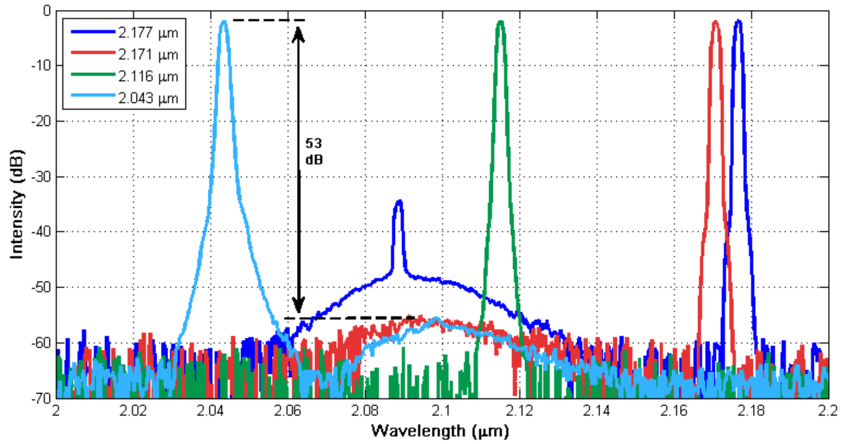

Fig. 5. Typical output spectra of the holmium fiber when the grating is tuned to the wavelengths in the legend while the laser is pumped at 74 W. The resolution setting of the OSA for these measurements was 2 nm. The peak intensity is normalized to the same level for ease of comparisons between the noise levels in each measurement.

The results of the tuning experiments are shown in Fig. 6. The fiber laser could be tuned from 2.043 µm to 2.171 µm. Only those data points where the signal-to-noise ratio of the spectrum was not degraded are included in the tuning graph of Fig. 6.

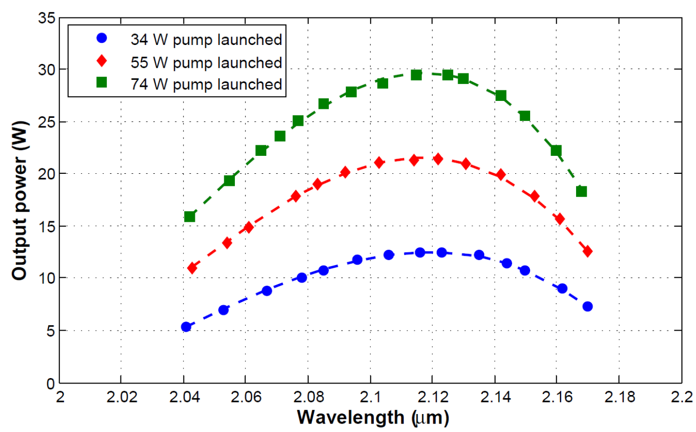

Fig. 6. Tuning ranges of the laser under different pumping rates. Only operating points with the signal-to-noise ratio > 53 dB are shown.

4.2 Output power at 2.120 µm and 2.171 µm

The output power with respect to launched pump power is shown in Fig. 7. The most efficient operating point of the laser was at 2.120 µm. The laser operated with a slope efficiency of 43% with respect to launched pump power (56% with respect to absorbed pump power) and achieved up to 29.7 W of output power.

At 2.171 µm, the laser operated at 27% with respect to launched pump power (45% with respect to absorbed pump power) and produced up to 18.2 W of output power. The pump absorption when operating at 2.120 µm was 80% and when operating at 2.171 µm decreased to 60%.

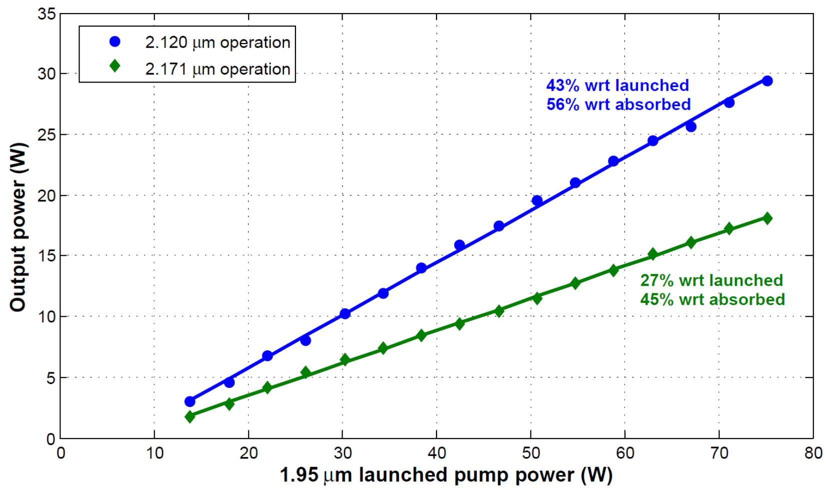

Fig. 7. Output powers for various operating conditions for the holmium doped fiber laser.

5. Discussion

5.1 Holmium double clad fiber design

A double clad geometry is achieved by the use of an internal Fluosil layer. The inner silica cladding has an octagonal shape to facilitate efficient scrambling of the pump radiation and prevent the formation of whispering gallery modes [27].

Due to the large silica transmission loss in this spectral region, it becomes essential to keep the length of the fiber gain medium as short as possible to produce efficient lasing. In order to achieve this, a large core:cladding area ratio is desirable. In this experiment the fiber has a core:cladding area ratio of 1:40. Even smaller area ratios are possible which would reduce the device length. The reduction in length of the gain medium has to be balanced with the increased thermal loading per unit length (W/m) onto the fiber in order to achieve operation at the desired output power level.

As shown in Fig. 2 the level of hydroxyl impurities must be kept to a minimum with levels of ~1 ppm sufficient to ensure a low background loss.

5.2 Tunable laser operation

The holmium laser could be tuned from 2.043 µm to 2.171 µm while maintaining excellent spectral quality. At wavelengths < 2.04 µm, there was an increase in power from the holmium fiber laser transmitted through the input dichroic mirror towards the thulium pump laser causing instabilities. A thulium laser operating at 1.95 µm has significant gain at 2.05 µm and is susceptible to power fluctuations when there is radiation present at this wavelength. For all other operating conditions, we did not observe instability in the thulium pump laser.

The pump transmission when operating at 2.171 µm was significantly larger than when operating at 2.120 µm indicating that a larger inversion was required to operate in the long wavelength region. This suggests that the limitation of the tuning range at longer wavelengths is the decreasing emission cross-section of the holmium ion. When attempting to operate at 2.177 µm, the signal-to-noise ratio severely degraded and a significant increase in ASE occurred. We believe that operation could be achieved at > 2.177 µm while maintaining a good spectral quality by the use of a higher reflectivity output coupler or fiber Bragg gratings. The line-width of the laser (~3 nm) could be reduced by using a telescope to expand the beam size incident onto the grating.

The laser produced 29.7 W at the peak of the emission, 2.120 µm, and achieved 18.3 W at 2.171 µm. The slope efficiency of the laser was at 56% with respect to absorbed pump power

#198023 - $15.00 USD Received 26 Sep 2013; revised 3 Nov 2013; accepted 5 Nov 2013; published 12 Nov 2013

which is substantially lower than the quantum defect. The source of this is currently under investigation.

6. Conclusion

We have demonstrated a tunable holmium doped silica fiber laser with >15 W of average output power across a wavelength range spanning 2.043 – 2.171 µm, and a maximum output power of 29.7 W at 2.120 µm. This is the highest power demonstration of a tunable holmium fiber laser and also the highest power operation of any holmium laser at wavelengths > 2.15 µm. The laser was able to produce 18.3 W at 2.171 µm while maintaining an excellent signal-to-noise ratio. This demonstrates a medium power fiber laser source which is able to address the important atmospheric transmission window beyond 2.1 µm.

#198023 - $15.00 USD Received 26 Sep 2013; revised 3 Nov 2013; accepted 5 Nov 2013; published 12 Nov 2013