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Holmium-doped 2.1 µm waveguide chip laser with an output power > 1 W

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Abstract: We demonstrate the increasing applicability of compact ultra-fast laser inscribed glass guided-wave lasers and report the highest-power glass waveguide laser with over 1.1 W of output power in monolithic operation in the short-infrared near 2070 nm achieved (51% incident slope efficiency). The holmium doped ZBLAN chip laser is in-band pumped by a 1945 nm thulium fiber laser. When operated in an extended-cavity configuration, over 1 W of output power is realized in a linearly polarized beam. Broad and continuous tunability of the extended-cavity laser is demonstrated from 2004 nm to 2099 nm. Considering its excellent beam quality of $M^2 = 1.08$, this laser shows potential as a flexible master oscillator for single frequency and mode-locking applications.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3580) Lasers, solid-state; (140.3390) Laser materials processing; (230.7380) Waveguides, channeled.

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1. Introduction

Compact lasers emitting near 2.1 µm are desirable owing to a spectral overlap with strong liquid water absorption lines that are located in a high atmospheric transmission window. Lasers in this waveband are used for applications including medical ablation of hard and soft tissues, remote sensing of atmospheric CO_2 and H_2O, coherent LIDAR, and infrared countermeasures. There is also the prospect raised of a second communication band in optical fiber centered near 2 µm [1].

The $^5I_7$ to $^5I_8$ ground-state terminated transition in holmium is the dominant laser emitting near the ~2.1 µm band, but is hampered by the scarcity of high brightness diode-laser pump sources to directly excite holmium at 1.15 µm or in-band pump at 1.95 µm. Fan *et al.* [2] demonstrated the first thulium sensitized holmium solid-state laser which could be pumped near 780 nm. However, increasing the efficiency of this excitation scheme has been challenging. A maximum slope efficiency of ~29% (P = 381 mW) has been achieved in a crystal host [3], whereas a 20% slope efficiency (P = 100 mW) was demonstrated in a ZBLAN glass waveguide laser [4].

In-band pumping of holmium lasers provides a low quantum defect hence reduced thermal load. The ready availability and technology maturity of thulium silica fiber lasers has enabled in-band pumped holmium fiber lasers to achieve over 400 Watts [5], and a thulium microchip laser in-band pumped Ho: $KLu(WO_4)_2$ microchip laser achieve 84% slope efficiencies (P = 201 mW) [6].

In the last two decades, waveguides structures in bulk materials have emerged as a complementary combination of solid-state bulk lasers and fiber lasers [7], trading average power to achieve compact geometries [8,9]. Like solid-state lasers, they can reach considerable levels of energy storage in a small active volume. Like fiber lasers, they have a high efficiency due to the engineered spatial overlap of the pump and gain volumes, and excellent beam quality owing to their waveguide confinement. By incorporating a depressed-cladding guiding structure in a straight waveguide (where bend loss is not relevant), single transverse mode operation of large core diameters can be achieved [10]. This reduced power density, coupled with a large gain bandwidth opens up the possibility of high peak-power diffraction-limited mode-locked output from compact resonators. Furthermore the ~cm long active length of waveguide gain media results in a large longitudinal mode spacing which enables single longitudinal mode lasing in fs-laser written waveguide lasers either by using external waveguide [11] or fiber Bragg gratings [12], or via directly inscribed Bragg gratings [13]. For these reasons, waveguide lasers appear as an ideal miniature platform for monolithic integration of a range of laser functionality.

Our motivation for this work was to demonstrate a practical and compact waveguide laser architecture that could achieve watt level emission in the short infrared atmospheric transmission window. By using a simple thulium fiber laser pump we achieve a relatively low-cost high-brightness pump source, in contrast to power limited 790 nm single emitter diode lasers (< 350 mW), or expensive semiconductor optical amplifier chips. This compact

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guided-wave laser is an efficient gain module that can be configured in a range of cavities designed for single frequency, q-switched, or mode-locked operation.

In past work we reported a Tm^{3+} sensitized holmium-doped chip laser that achieved 80 mW of output power, pumped by a high beam-quality 790 nm Ti-sapphire laser as a pump source [4]. To substantially improve the power available and efficiency from a compact chip laser, we now demonstrate the first in-band pumping of a Ho^{3+} only doped fluorozirconate chip laser by a fiber Bragg grating (FBG) stabilized thulium fiber laser operating at 1945 nm. We first demonstrate a monolithic cavity producing 1.1 W of 2.06 µm continuous-wave emission with a slope efficiency of 51%, and a threshold of 180 mW.

The second part of this work reports an investigation into extended cavity operation of this gain chip where we report a slope efficiency of 44.9%, 1.02 W of power in a single linear polarization, beam quality of $M^2_{x,y} = 1.08$, and a tunable range of ~95 nm. The slightly lower efficiency of the extended cavity is believed to be caused by the larger cavity-mode extending into the un-pumped waveguide depressed-cladding structure.

2. Monolithic cavity Ho^{3+} ZBLAN guided-wave chip laser

The ZBLAN chip used in this work was fabricated in-house, starting as a 50 g ingot of 2.0 mol % HoF_3: ZBLAN (ZrF_4; BaF_4; AlF_3; LaF_3; NaF_3). The waveguides were directly inscribed via the femtosecond laser direct-write technique into a plane parallel polished chip with a length of L = 20 mm as described in [14]. The chip includes 8-waveguides with cores varying from 26 to 52 µm, all located 300 µm below the surface. The depressed claddings are ~52 µm wide, and this cladding width has been demonstrated to achieve low-loss confinement out into the mid-infrared at 2.9 µm [15]. The propagation loss for these waveguides has been estimated at ~0.4 ± 0.2 dB/cm [14].

We custom-built a fiber Bragg grating stabilized 1.945 µm Tm: ZBLAN fiber laser to pump the holmium chip laser. For the monolithic configuration (see Fig. 1 (a)), the pump laser was focused to a 36 µm diameter spot with a numerical aperture of NA = 0.03, which is below the acceptance angle for the waveguides (f = 30 mm AR-coated Plano-convex lens). The holmium-doped chip absorption at 1.945 µm was measured to be 6.3 dB/cm (Agilent, Cary 5000). To reduce losses at the laser wavelength, an anti-reflection (AR) coating was applied to the chip facets. A measurement of the AR coating on the chip determined that it was less than ideal with a residual reflection of > 4% per surface at 2060 nm, which was well above the specification. However, we proceeded with the monolithic cavity experiment and accepted the additional intra-cavity loss. For this work the waveguide chip was not actively cooled but bonded with UV curable acrylate to an uncooled aluminum block (8 mm thick). Thermal conductivity to the mount was improved by sandwiching a 100 µm thick indium sheet under the chip.

A monolithic laser cavity (Fig. 1(a)) was formed by butting an input-coupler (IC) mirror with 95% transmittance at 1.94 µm and almost 100% reflectance at 2.07 µm, and an output-coupler (OC) mirror with 98% reflectance at 1.94 µm (for double-pass pump) and 75% reflectance at 2.07 µm. To monitor the incident pump power, an un-coated wedge was inserted into the beam at an angle of < 5°.

The performance of the monolithic holmium chip laser is shown in Fig. 1(b) with a slope efficiency of 50.9% of incident power, and a threshold of 104 mW. Incident power is defined as the pump power incident on the chip facet after the IC mirror. In this experiment we could operate the holmium fiber laser only up to 350 mW for extended periods of time as its 790 nm pump diode could only be conductively cooled due to a failure of the water chiller. We did however have an opportunity to briefly run it at higher power and achieved an output of 1.1 W for a period of approximately 2 minutes before having to allow the pump diode to cool. Unfortunately this experiment could not be redone to improve the overall efficiency as after this experiment the waveguide ends were re-polished with a wedge on one end of the chip and a new design AR coating was applied in order to realize an extended cavity guided-wave chip

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laser setup (Fig. 2). During the re-polishing/ re-coating a replacement cooling system for the thulium pump fiber laser was procured.

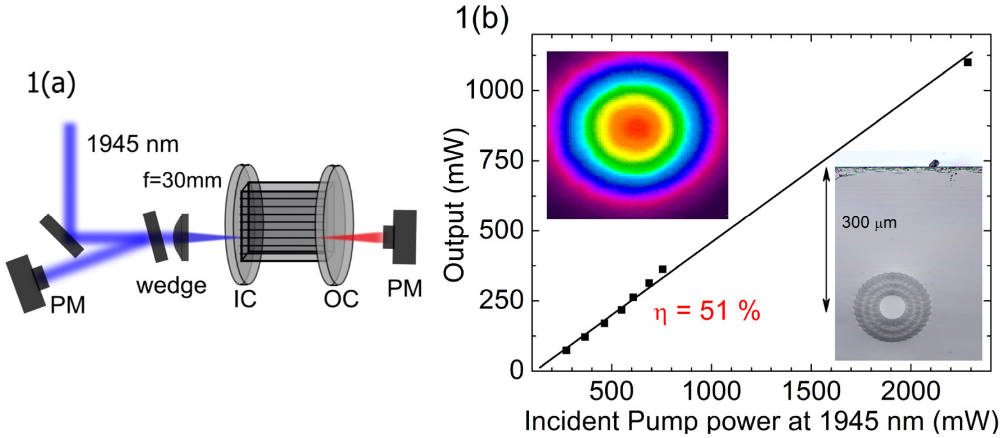

Fig. 1. (a) Ho:ZBLAN waveguide laser configured for monolithic cavity operation. PM: powermeter, IC: input coupler, OC: output coupler. (b) Slope efficiency of the monolithic configured holmium ZBLAN waveguide laser. Insets include a near-field image of the output beam (D~3mm), as well as the 52 µm diameter waveguide written into the ZBLAN chip.

The inset to Fig. 1(b) shows the near-field mode-profile of the holmium laser output for a power of 350 mW, which displays a high beam-quality with a single transverse mode, characteristic of close to diffraction-limited beam-quality. This is consistent with past beam-quality measurements we have made where the M^2 of monolithic configured chip lasers is M^2 ~1.2 [8]. The free running spectrum of this laser was measured to be centered at 2070 nm with a FWHM of 8 nm for 350 mW output.

3. Extended-cavity guided-wave chip laser

To operate the holmium-doped chip in an extended cavity configuration (Fig. 2) the non-HR end of the chip was re-polished at 2.5° from normal to the waveguide (in the horizontal plane) to eliminate the etalon effect of the chip in the extended cavity (which manifests itself as spectral structure [16]). Unfortunately this meant monolithic operation was not possible any longer using this modified chip. The new chip AR coating was measured to have a loss of < 0.4% at 2.06 µm. Cavity stability was achieved by use of a f = 30 mm plano-convex AR coated lens placed approximately ~28 mm from the end of the angled waveguide face. Out-coupling is provided by the same T = 25% OC mirror used for the monolithic cavity. The IC mirror was butted up to the perpendicular end of the chip. To investigate single linear-polarization operation of the laser, an AR-coated cube polarizer was placed into the cavity between the intra-cavity lens and the OC mirror. The 790 nm wavelength diode-laser for the thulium fiber pump laser was temperature-stabilized via conduction to a thermo-electric chiller.

To measure the gain bandwidth available from this holmium-only doped chip, the OC was replaced by a diffraction grating orientated in Littrow configuration. The grating has 600 lines/ mm and is blazed at 1.6 µm. The grating was oriented such that the 1st-order diffracted light was reflected back into the standing wave cavity. The 0th-order diffracted light provided the output beam. The aluminum coated grating was specified to have an absolute diffraction efficiency of ≈90% for light polarized perpendicular to the grooves, and < 35% for parallel polarized light. Hence it is apparent that when using the grating as an OC the laser will be horizontally polarized as the parallel polarized-mode will not achieve threshold.

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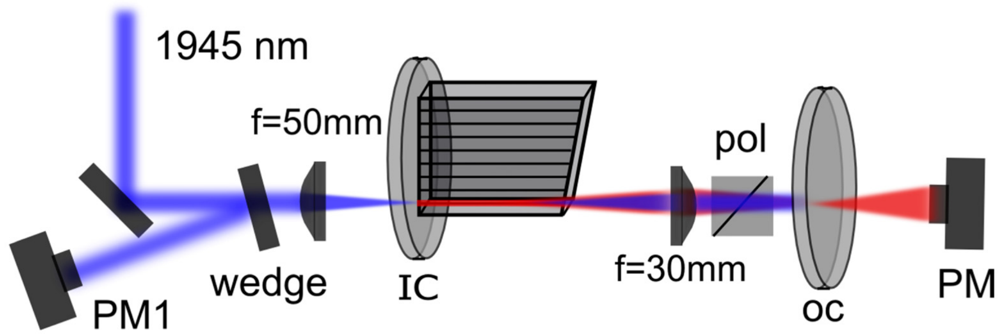

Fig. 2. Ho: ZBLAN chip laser configured for extended cavity operation. pol: polarizer, PM: power meter.

The measured incident slope efficiency for the free-running extended cavity is 44.9% as plotted in Fig. 3(a). The threshold for this laser is 144 mW, and the passively cooled laser was operated up to 1.105 W, with maximum incident power of 2.58 W.

A key characteristic to enable maximum versatility of the extended cavity configuration is the beam quality. The beam quality factor M^2 was determined by focusing the beam using a f = 500 mm lens and measuring the evolution of the beam diameter along the propagation direction. For this, the beam profile was fitted by a Gaussian function to determine the $1/e^2$ beam diameter (second moment of the intensity profile) at various locations behind the lens. The M^2 factor was then determined by fitting a hyperbolic function to the beam radius through the waist region of the focused beam [17]. The inset to Fig. 3(b) shows an image (Ophir Pyrocam III) of the Gaussian-profile at the beam waist. The results of this measurement are shown in Fig. 3(b), with a resultant high beam-quality of M^2 = 1.08 measured in both x and y planes.

Efficient linearly-polarized operation of extended-cavity lasers is a critical requirement for many applications. To characterize the performance of this chip laser operating on a linear polarization an AR-coated polarizing cube (EOT Polarizer, 2000-2100 nm) was placed in the extended-cavity between the lens and the output-coupler. A single linear polarization is verified by analysis of the beam polarization outside the cavity by placing a crossed-polarizer which completely extinguished the beam. The performance of the polarized laser was close to performance of the un-polarized cavity (44.9 to 43.2%), and plotted in Fig. 3(a), with approximately the same threshold. From this result we conclude that the birefringence of the waveguide is negligible at up to 1 W of output power.

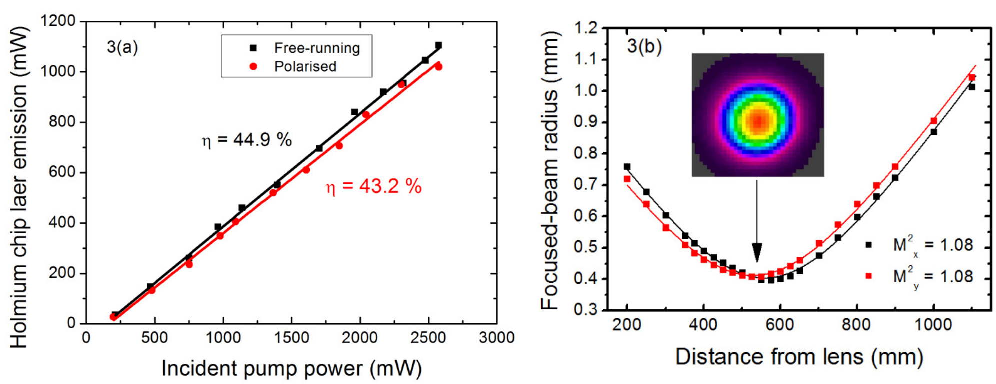

Fig. 3. (a) Measured slope efficiencies for extended cavity operation. (b) Measured beam-quality of the extended cavity laser at an output power of 100 mW. Inset is the far-field profile of the beam at the waist.

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The Littrow configured extended cavity laser had a slope efficiency of ~29% and a threshold of 110 mW. When rotating the grating in the horizontal plane, the laser tuned continuously from 2004 nm to 2099 nm (95 nm tuning range) at a pump power of 350 mW, as shown in Fig. 4 (a). The shortest possible wavelength was determined by a combination of the HR chip-coating reflectivity falling, decreasing gain, and increased ground state absorption. A typical output spectrum is shown in Fig. 4 (b) with a FWHM linewidth of 0.1 nm. For this spectral measurement a Bristol Instruments optical spectrum analyser (771B IR) with a resolution of 12 GHz (0.17 nm) was used, hence this measurement was instrument limited. At different points in the laser tuning curve the spectrum was measured to have up to a 0.38 nm spectral width. Due to the low dispersion of the diffraction-grating used for the extended cavity configuration, and the calculated mode spacing of 0.06 nm, it is expected that a number of longitudinal modes could be oscillating at any one wavelength. The sidebands apparent in the laser spectrum are spaced at 1.0 ± 0.05 nm, corresponding to an etalon with a thickness of 1.4 mm (n~1.5), which can be accounted for by a 'less than ideal' AR-coated intra-cavity lens.

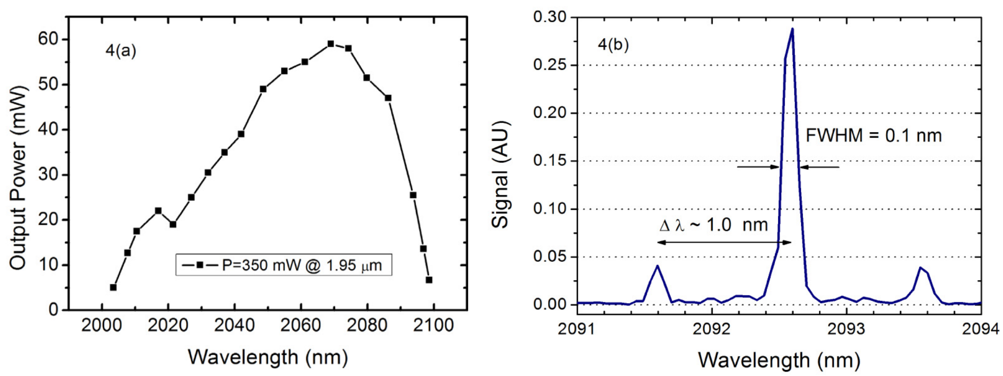

Fig. 4. (a) Measured tuning range of the Ho:ZBLAN chip. (b) Laser spectrum recorded when the laser is operating in a Littrow tuning configuration.

4. Discussion and conclusions

The extended-cavity laser has a slope-efficiency of 45%, which is less than the 51% slope-efficiency for the monolithic cavity laser (noting that the monolithic chip laser performance was also compromised by lossy AR coatings). The lower efficiency of the extended-cavity compared to the monolithic cavity requires some discussion; in both cases the pump configuration, gain available in the cavity, and input/ output couplers are the same.

If the monolithic waveguide resonator is considered, the cavity mode is built up from the multiple passes of the lowest-order (ie. lowest-loss) leaky-mode of the fs laser written waveguide (if the travelling wave representation is considered). As such it is confined to within the waveguide volume and there is high spatial overlap of the pump-volume and laser-mode in a similar way to a core-pumped optical fiber. This is consistent with the high slope-efficiency we see from this monolithic configuration (in spite of the lossy AR coating).

The extended cavity configuration is more complex and to first-order the intra-cavity f = 30 mm plano-convex silica lens collimates the holmium gain-chip emission, which then travels a set distance (typically 20 to 60 mm) to the OC, which reflects 75% of the light back into the cavity. However for this type of semi-monolithic waveguide/ free-space cavity, the free-space cavity-modes also need to be considered as the chip waveguides have only weak guiding provided by the depressed-cladding (NA of ~0.03). As such, the waveguide confines the single-pass pump to a cylindrical region (i.e. gain), but the 'leaky-mode' waveguide doesn't provide a definite edge to restrict the cavity-mode. Thus it is expected that the cavity mode will overfill the cylindrical gain volume and extend outside the gain region, hence

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suffering additional losses. In effect the mode will suffer ground-state absorption losses in the unpumped regions of the holmium chip, and as the cladding is not completely homogenous and of a lower index (i.e. anti-guiding), additional loss will be present which would account for the lower efficiency of the extended cavity.

In this work we have presented a broad characterization of a practical and re-configurable compact holmium-doped waveguide laser able to operate between 2.0 and 2.1 μm. This work has concentrated on characterizing the key parameters of this waveguide gain medium that are necessary for either widely-tunable single-frequency, or mode-locked operation. While these are quite different operating regimes, they both benefit from the unique characteristics of this waveguide-laser geometry: High efficiency due to high pump/signal beam overlap, excellent beam quality as well as increased longitudinal mode-spacing in the case of single-longitudinal mode operation. The broad tunability for the holmium doped ZBLAN waveguide chip laser is significant as it demonstrates a wide bandwidth available which is necessary for generation of ultrashort mode-locked pulses. In addition, as this is an important spectral region, it would also allow the laser (if configured for single frequency operation) to tune across overtone H_2O and CO_2 spectral absorption lines [18].

Furthermore, this waveguide gain media has achieved more than 1.1 W of output power and a large transverse-mode diameter, which are necessary conditions for high peak-power operation.

In conclusion we have demonstrated a compact waveguide laser operating at a critical wavelength centered around 2.06 μm, and capable of over 1.1 W of output power in both monolithic and extended-cavity configurations. We have also investigated extended-cavity operation of this guided-wave chip gain medium and demonstrated single-polarization operation, large cavity modes which are suitable for high peak-power generation, and a wide tuning bandwidth of ~95 nm.

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