2.1 μm waveguide laser fabricated by femtosecond laser direct-writing in Ho^{3+}, Tm^{3+} : ZBLAN glass

D. G. Lancaster,[1,*] S. Gross,[2] H. Ebendorff-Heidepriem,[1] A. Fuerbach,[2] M. J. Withford,[2] and T. M. Monro[1]

[1]IPAS and School of Chemistry & Physics, University of Adelaide, SA, 5005, Australia

[2]CUDOS and MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, New South Wales 2109, Australia

*Corresponding author: david.lancaster@adelaide.edu.au

Received November 18, 2011; revised January 20, 2012; accepted January 24, 2012; posted January 25, 2012 (Doc. ID 158383); published March 6, 2012

We report the first Ho^{3+} doped waveguide laser, which was realized by femtosecond direct-writing of a depressed cladding structure into ZBLAN glass. Tm^{3+} sensitizing allows the 9 mm long Ho^{3+} gain medium to be conveniently pumped at 790 nm, achieving an optical-to-optical slope efficiency of 20% and a threshold of 20 mW. The potentially widely tunable laser produces up to 76 mW at 2052 nm and also operates at shorter wavelengths near 1880 nm and 1978 nm for certain cavity configurations.

OCIS codes: 140.3580, 130.2755.

The ready availability of compact, efficient, and low-cost lasers operating in the short IR spectral region around 2 μm is critical to many applications such as laser ranging, coherent LIDAR, trace gas spectroscopy, and testing of IR defense systems.

While thulium (Tm) and holmium (Ho) fiber [1] and solid-state lasers [2,3] are established in this spectral region, there has been limited work to date on Tm waveguide (WG) lasers [4,5,6] and no reported Ho WG lasers (to the best of our knowledge). The attractive features of WG lasers include an inherently small foot-print, the confinement and beam-quality characteristic of a single transverse mode fiber laser, and high efficiency with a low laser threshold [7].

Direct writing of WGs in glass enables the rapid and reproducible fabrication of the WG structures required to create lasers in bulk glasses and crystals [8,9]. The ultrafast direct-write process uses focused femtosecond (fs) laser pulses to induce a highly localized and permanent refractive index change in dielectric media. Typically fs direct-writing in ZBLAN glass (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) results in a reduced refractive index, thus allowing us to write a depressed cladding WG structure. This structure allows enhanced mode discrimination due to the differential confinement losses of the fundamental and higher-order leaky modes [10].

We recently reported the highest power (48 mW at 1.89 μm—pump power limited) and most efficient glass WG laser at a wavelength >1.6 μm [6]. We report here a new study pursuing wavelengths beyond 2 micrometers utilizing a rare-earth Tm, Ho co-doped waveguide. We demonstrate the potentially widely tunable WG laser operating on either the Tm (1.89 μm) or Ho (2.05 μm) transition, and improved mechanical integrity of the waveguide laser, the latter viewed as being critical for future power scaling of this class of device.

For efficient operation of Ho-doped gain materials, in-band pumping at ~1.94 μm is the dominant technique; however the lack of low-cost diode or fiber laser pump sources is a shortcoming to this approach. By co-doping with Tm as a sensitizer, the well known Tm cross-relaxation process can be exploited to improve efficiency, and the laser can be pumped by readily available 790 nm diode lasers. A further benefit of Tm, Ho doped glass lasers is the wide tunability possible, with up to 280 nm reported from a Tm, Ho silica fiber laser [11].

For this WG laser demonstration, a 50 g block of Ho^{3+}, Tm^{3+} : ZBLAN (0.22 mol% HoF_3 and 1.96 mol% TmF_3) was fabricated in-house and diced into rectangular sections (9 mm long, 8 mm wide, and 2.7 mm high), where the top and bottom surfaces were polished to optical grade. The Tm concentration and dopant ratio was chosen based on spectroscopic analysis of Tm, Ho co-doped glasses [12], and was consistent with the Tm, Ho ratio reported for a ZBLAN fiber laser in [13].

15 WGs were written into the doped glass with core diameters from 15 to 45 μm using an ultrafast Ti:sapphire laser oscillator [6]. After WG writing, the end faces were polished back by 250 μm to reveal the WG ends. A microscope image of the polished end face with 2 WGs is depicted in Fig. 1, with the inset showing a transmission differential interference contrast image taken from the top. Each WG is defined by 24 partially overlapping direct-written longitudinal channels to create a "*W*" refractive index profile, with a measured cladding Δn

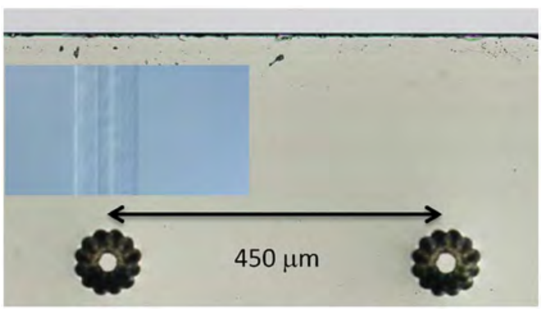

Fig. 1. (Color online) End-on microscope image of the direct-write WG structures in Ho, Tm:ZBLAN, which are made up of 24 partially overlapping modifications. The WGs are located 300 μm below the surface. The inset is a top view of the WG structure.

0146-9592/12/060996-03$15.00/0

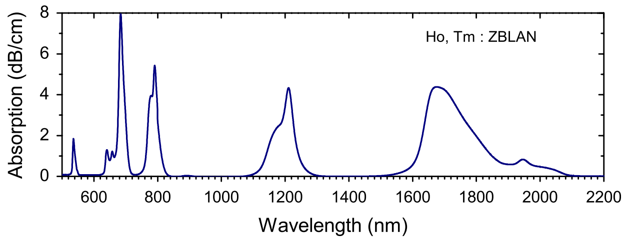

Fig. 2. (Color online) Measured absorption spectrum of the 0.22 mol% HoF_3 and 1.96 mol% TmF_3 doped ZBLAN glass.

of -0.0016 ± 0.0003, compared to the bulk glass and the unmodified core, and a cladding width of 32 μm. In the previous work [6] stress fractures were apparent and occurred during the writing process. By increasing the spacing between adjacent WGs from 150 μm to 450 μm, and increasing the depth from 150 μm to 300 μm, we have produced multipass WGs with no evidence of fractures (which could have led to failure). To estimate the pump and laser ground state absorption the measured absorption of a polished Ho, Tm:ZBLAN sample is shown in Fig. 2 (CARY 5000 spectrophotometer).

Figure 3 details the setup we used to conduct the WG laser characterization. A CW Ti:sapphire laser tuned to 790 nm ($\alpha = 5.4$ dB/cm) was focused into the uncoated WG slab using a $f = 50$ mm lens giving a spot size of ~29 μm. We subsequently found that the 24 μm diameter WG performed best for this pump focusing condition, and it was thus used throughout this work. Flat dielectric coated cavity mirrors were butted up to either end of the slab, where the input coupler was highly transmitting at 790 nm, and highly reflecting from 1.8 to 2.1 μm. Several output couplers (OCs) were tried. To isolate the Ti:sapphire laser from feedback an optical isolator was used (22 dB of isolation). To further reduce feedback to the pump laser, and to quantify the unabsorbed pump light, a $\lambda/4$ plate converted the incident light on the WG to circular polarization and the unabsorbed counter propagating pump-beam was in turn converted to a vertical linear polarization and directed out of the beam path via a polarizer onto a power meter.

The spectral [Fig. 4] and power [Fig. 5] characteristics of the Ho, Tm:ZBLAN laser were found to be dependent on the OC used. When the $R = 77\%$ OC was used, the laser operated on random lines between ~1880 nm and ~2000 nm (alignment dependent), coinciding with the broad Tm fluoresence, as shown in Fig. 4(a) (Yokogawa AQ6375 OSA). The absorbed-power slope efficiency [Fig. 5] was up to 29% (where the absorbed power was calculated by measuring the depleted pump power), with the thulium ions reaching laser threshold at 145 mW absorbed pump power. The $R = 77\%$ OC was the only OC being highly reflective at 790 nm and thus double-passing the pump, resulting in a more uniform population inversion.

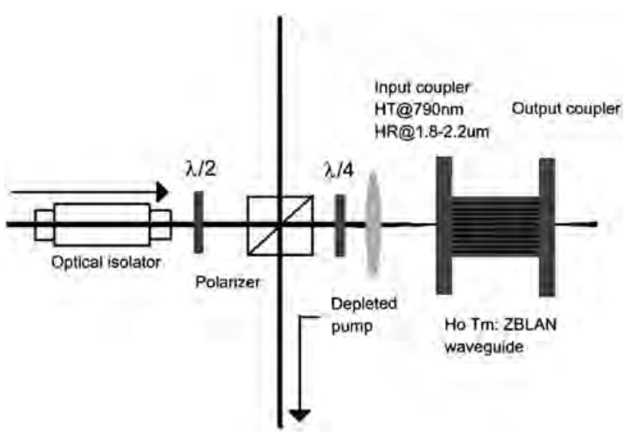

Fig. 3. The experimental configuration used to characterize the Tm^{3+} sensitized Ho^{3+} : ZBLAN laser.

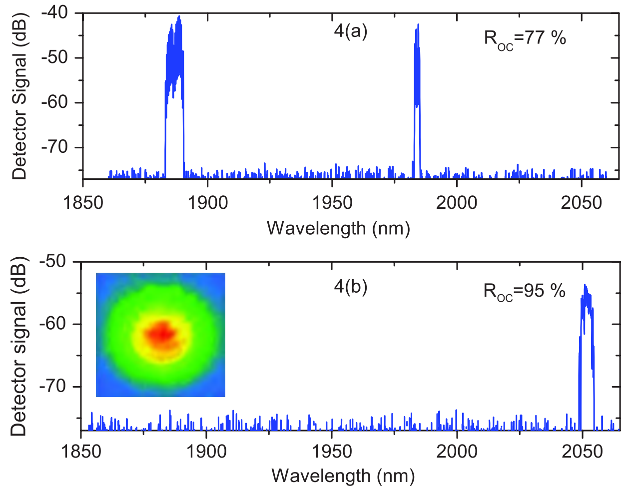

Fig. 4. (Color online) Spectral characteristics of the Ho, Tm: ZBLAN laser for two resonator OCs (a) $R = 77\%$, (b) $R = 95\%$. Figure 4(b) (inset) is the uncollimated output from the Ho, Tm:ZBLAN laser operating at 2052 nm (note the WG writing direction was from the top of the image).

When the 95% and 98% OCs were used, the laser operated at ~2052 nm [see Fig. 4(b)], which is near the peak of the Ho^{3+} fluorescence emission [12]. For this low OC cavity the Ho transition reaches threshold first (20 mW) and dominates as a high Ho population inversion is achieved due to efficient energy transfer from the higher dopant density Tm ions (~9×). The operation of this waveguide laser on either Tm or Ho transitions is consistent with the demonstrated wide tunability of a Tm,Ho co-doped silica fiber laser [11].

The absorbed-power slope efficiencies for these OCs are shown in Fig. 5. It can be seen that the 95% OC provided the best performance with 20% slope efficiency and 20 mW threshold (incident slope efficiency was 12%). The 98% OC slope efficiency was lower at 15% until an absorbed power of 250 mW was reached; at pump power >250 mW the efficiency is reduced, which is likely due to increased losses from a combination of energy transfer upconversion and excited-state absorption.

While a slope efficiency of 20% is reasonable for a WG laser, it is lower than the efficiency achieved in our recent report of a 50% slope efficiency Tm:ZBLAN WG laser, and the 36% reported from a Ho, Tm:ZBLAN fiber laser [13]. The lower efficiency is consistent with the unoptimized and lossy cavity used here composed of the uncoated WG ends with mirrors butted up, and a low output coupling of 5%. For a cavity round trip the four Fresnel intracavity reflections are estimated to add up

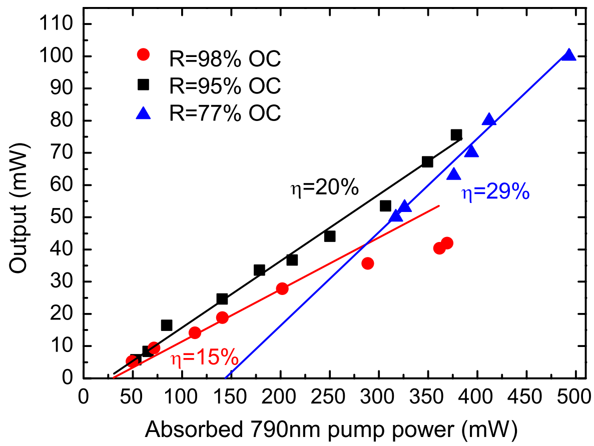

Fig. 5. (Color online) Slope efficiencies for the Ho, Tm:ZBLAN WG laser for a range of resonator OC mirrors.

to ~15%. However due to the collinear geometry, these reflections still substantially contribute to the laser mode-field subject to scattering due to surface imperfections and polishing defects on the end-faces.

The beam quality of the laser was measured using a Spiricon Pyrocam camera. A single transverse mode was observed, with a measured $M = 1.6 \pm 0.2$. A near-field image of the uncollimated beam is shown in Fig. 4(b) (inset). A high spatial frequency intensity modulation is present in the mode-field, which is more apparent close to the surface of the slab (i.e., the writing direction) and is most likely responsible for the nondiffraction limited beam quality. This artifact may be due to spatial etalon effects from the uncoated WG ends, stress-induced refractive index variations in the WG cladding region, or a nonuniform cladding refractive index. Cavity improvements discussed in a following paragraph should provide more insight into this issue.

It is useful at this point to compare the Ho WG laser with other reported Ho-doped compact lasers. These include a gain-guided microchip laser and a fiber laser. A Tm, Ho:YLF microchip laser ($L = 2.5$ mm) operating near 2.1 μm is described in [2]. This laser employed a 792 nm pump laser to define the laser mode, threshold power of 0.4 W, and output power of ~1 W (beam quality not reported). Wu *et al.* [14] reported a FBG stabilized single-frequency Ho-doped germanate fiber laser producing up to 60 mW of power with in-band pumping of the $L = 2$ cm gain medium (threshold and slope-efficiency not stated). Our WG geometry has a 20× lower threshold than the microchip laser and intrinsically high beam quality. Compared to the fiber laser a WG laser is a more flexible geometry, and can be conveniently packaged. Monolithic narrow linewidth operation of these WGs will require a waveguide-Bragg grating structure to realize a distributed feedback laser architecture [15].

To enhance the laser efficiency we are investigating the feasibility of directly coating dielectric mirrors to the ends of the WG chip, which may also improve the beam quality. In addition we expect to improve the overall device efficiency by optimizing the length of the gain medium and by double-passing the pump light using an optimized OC.

In conclusion we report the first Ho WG laser. The laser emits 76 mW at a wavelength of 2052 nm and has a ~20% optical-to-optical slope efficiency.

This work was produced with the assistance of the Australian Research Council under the Centres of Excellence and Linkage Infrastructure, Equipment and Facilities programs. T. Monro acknowledges the support of an ARC Federation Fellowship. The authors appreciate Benjamin Ung and Derrick Abbot for making available the Ti:sapphire laser, and Kevin Kuan for glass fabrication. This work was performed in part at the OptoFab node of the Australian National Fabrication Facility utilizing Commonwealth and SA State Government funding.

References

1. S. D. Jackson, A. Sabella, and D. G. Lancaster, IEEE J. Sel. Top. Quantum Electron. **13**, 567 (2007).
2. G. L. Bourdet and R. A. Muller, Appl. Phys. B **70**, 345 (2000).
3. P. A. Budni, L. A. Pomeranz, M. L. Lemons, C. A. Miller, J. R. Mosto, and E. P. Chicklis, J. Opt. Soc. Am. **17**, 723 (2000).
4. F. Fusari, R. R. Thomson, G. Jose, F. M. Bain, A. A. Lagatsky, N. D. Psaila, A. K. Kar, A. Jha, W. Sibbett, and C. T. A. Brown, Opt. Lett. **36**, 1566 (2011).
5. K. Van Dalfsen, S. Aravazhi, D. Geskus, K. Wörhoff, and M. Pollnau, Opt. Express **19**, 5277 (2011).
6. D. G. Lancaster, S. Gross, H. Ebendorff-Heidepriem, K. Kuan, T. M. Monro, M. Ams, A. Fuerbach, and M. J. Withford, Opt. Lett. **36**, 1587 (2011).
7. C. Grivas, Prog. Quantum Electron. **35**, 159 (2011).
8. R. R. Gattass and E. Mazur, Nat. Photon. **2**, 219 (2008).
9. J. Siebenmorgen, T. Calmano, K. Petermann, and G. Huber, Opt. Express **18**, 16035 (2010).
10. J. Hu and C. R. Menyuk, Adv. Opt. Photon. **1**, 58 (2009).
11. A. Hemming, S. D. Jackson, A. Sabella, S. Bennetts, and D. G. Lancaster, Electron. Lett. **46**, 1617 (2010).
12. X. Zou and H. Toratani, J. Non-Cryst. Solids **195**, 113 (1996).
13. S. D. Jackson, Electron. Lett. **37**, 821 (2001).
14. J. Wu, Z. Yao, J. Zong, and A. Chavez-Pirson, *Fiber Lasers VI: Technology, Systems and Applications*, D. V. Gapontsev, ed. (SPIE, 2009), Vol. **7195**.
15. M. Ams, P. Dekker, G. D. Marshall, and M. J. Withford, Opt. Lett. **34**, 247 (2009).

Optics Letters

Title Details | Table of Contents

Related Titles

- Alternative Media Edition (4)

Lists

Marked Titles (0)

Search History

0146-9592
1440-2440

Save to List Email Download Print Corrections Expand All Collapse All

Basic Description

Title	Optics Letters
ISSN	0146-9592
Publisher	Optical Society of America
Country	United States
Status	Active
Start Year	1977
Frequency	Semi-monthly
Volume Ends	Jan - Dec
Language of Text	Text in: English
Refereed	Yes
Abstracted / Indexed	Yes
Serial Type	Journal
Content Type	Academic / Scholarly
Format	Print
Website	http://www.opticsinfobase.org/ol/journal/ol/about.cfm
Description	Covers the latest research in optical science, including atmospheric optics, quantum electronics, fourier optics, integrated optics, and fiber optics.

- Subject Classifications
- Additional Title Details
- Publisher & Ordering Details
- Price Data
- Online Availability
- Other Availability
- Demographics
- Reviews

Save to List Email Download Print Corrections Expand All Collapse All