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Eric C. Honea
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170W continuous-wave single-frequency single-mode green fiber laser

Alexey V. Avdokhin*, Valentin P. Gapontsev, Yuri S. Grapov
IPG Photonics Corp., 50 Old Webster Rd, Oxford, MA, USA 01540
*aavdokhin@ipgphotonics.com; phone +1 508 373-1234; www.ipgphotonics.com

ABSTRACT

170W of continuous-wave single-mode single-frequency low-noise emission at 532nm has been obtained using frequency doubling of linearly-polarized single-frequency ytterbium fiber laser in LBO crystal with SHG conversion efficiency of 76% and overall electrical-to-optical efficiency of 25%.

Keywords: Frequency doubling, fiber laser, CW green laser

1. INTRODUCTION

High-power CW green laser sources are used in a variety of applications, ranging from scientific (pumping of titanium-sapphire and dye lasers, cooling and trapping of atoms), to industrial (material processing, solar cell manufacturing, semiconductor industry, hologram production) to defense and security (LIDAR, dazzling, underwater communications). Many of these applications have traditionally utilized very inefficient and bulky 514-nm argon-ion lasers. As diode-pumped solid-state laser (DPSSL) technology is becoming more affordable, argon-ion lasers are rivaled by far more efficient and compact frequency-doubled DPSSLs. Two frequency-doubling approaches have been used to produce near-diffraction-limited CW green radiation with several tens of Watts of output power. One scheme involves intra-cavity second harmonic generation (SHG) in a diode-pumped solid-state laser. Both bulk and fiber lasers with intra-cavity SHG have been reported, with output powers up to 62 W for bulk [1] and 19 W for fiber [2]. Power scaling of bulk lasers with intra-cavity SHG above several tens of Watts of green output power is challenging due to thermal beam distortion in the laser crystal. Another approach involves using a stand-alone near-IR bulk or fiber laser to pump an external resonant cavity with a nonlinear crystal. Using this scheme, more than 20 W of green output power has been achieved with a fiber laser pump [3] and more than 130 W of green output power has been recently reported, limited by the power of the bulk near-IR laser pump [4]. In our work we utilize an external SHG cavity approach with IPG's single-frequency ytterbium fiber laser as a pump source. This approach brings all the advantages of reliable and affordable fiber laser technology, pioneered by IPG, to the high-power CW green laser market.

2. EXPERIMENTAL PART

We report a fiber laser based source generating 170W of CW single-mode single-frequency green power with a record-high electrical-to-optical efficiency of 25%. To the best of our knowledge, this laser also has the highest output power ever reported from a CW green single-mode solid state laser. A schematic of the setup is shown in Figure 1.

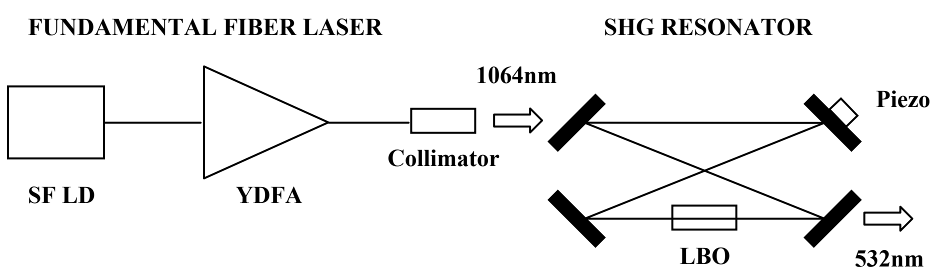

Figure 1. Experimental configuration

The fundamental fiber laser provided up to 230W of linearly polarized single-frequency emission at 1064nm and consisted of a linearly polarized seed laser diode with linewidth of ~140kHz and a single-mode polarization-maintaining multi-stage fiber amplifier. Owing to highly-effective side pumping configuration and fiber-pigtailed assembly of very high-brightness single-emitter pump diodes, the overall electrical-to-optical efficiency of the 1064nm laser was 33%. The output of the laser was then coupled into external bow-tie SHG resonator, which consisted of 4 mirrors and a high-quality IPG-grown LBO crystal. One of the mirrors was installed on piezo actuator in order to actively lock resonance frequency of the resonator to the stabilized frequency of the laser diode seed using Pound-Drever-Hall technique.

The reported laser exhibited very low optical noise - power fluctuation of green output was measured to be <1% peak-to-peak at 170W during 100s interval. Output power, SHG conversion efficiency and overall electrical-to-optical laser efficiency are shown in Figure 2.

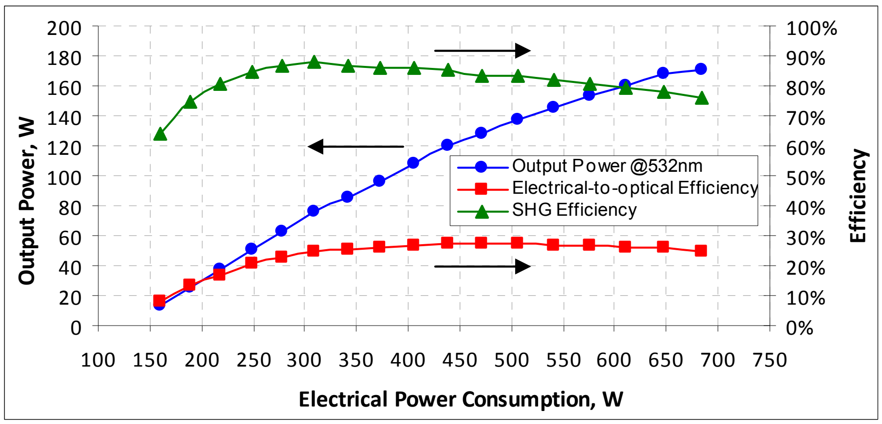

Figure 2. Output power at 532nm (blue circles), electrical-to-optical laser efficiency (red squares), and SHG efficiency (green triangles) as a function of electrical power consumption

SHG resonator used in this experiment was optimized for 75W of green power, at which SHG efficiency of 88% was reached..Further increase of pump power resulted in slow decline of SHG efficiency to 76% at 170W of green power. We expect that cavity optimization for higher output power will result in increase of SHG efficiency up to ~90% and electrical-to-optical efficiency up to ~30%.

3. CONCLUSION

In conclusion, we have demonstrated a compact and efficient high-power CW green fiber laser. With proper cavity optimization, output power is limited by the fundamental fiber laser. As we continue developing more powerful single-frequency ytterbium amplifiers, we intend to further scale CW green power to 500W and higher. We believe that emergence of such low-cost high-power sources will boost the existing applications of green lasers and create new ones.

REFERENCES

[1] L. McDonagh and R. Wallenstein, "Low-noise 62 W CW intracavity-doubled TEM00 Nd:YVO4 green laser pumped at 888 nm," Opt. Lett. 32, 802-804 (2007).
[2] R. Cieslak and W. Clarkson, "Internal resonantly enhanced frequency doubling of continuous-wave fiber lasers," Opt. Lett. 36, 1896-1898 (2011).
[3] T. Sudmeyer, Y. Imai, H. Masuda, N. Eguchi, M. Saito, and S. Kubota, "Efficient 2nd and 4th harmonic generation of a single-frequency, continuous-wave fiber amplifier," Opt. Express 16, 1546-1551 (2008).
[4] T. Meier, B. Willke, and K. Danzmann, "Continuous-wave single-frequency 532 nm laser source emitting 130 W into the fundamental transversal mode," Opt. Lett. 35, 3742-3744 (2010).

Temporally resolved build-up and decay of mode instabilities in high power fiber amplifiers

Nicoletta Haarlammert[1], Oliver de Vries[1], Andreas Liem[1], Andrea Kliner[2], Thomas Schreiber[1], Ramona Eberhardt[1] and Andreas Tünnermann[1,2]

1 Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany
2 Friedrich-Schiller-University Jena, Institute of Applied Physics, Max-Wien-Platz 1, 07743 Jena, Germany

Abstract. : State-of-the-art high power Yb-doped large mode area fibers have been developed to a performance level able to reach the so-called mode instability threshold. In this contribution we will discuss the experimaental results regarding the temporal evolution (build-up and decay) of this effect to come closer to a comprehensive understanding of its driving mechanisms. With a pulsed pump source emitting pulses in the ms range, we investigated the temporal behavior of the build-up and degradation time for mode instability in a high power fiber amplifier. To the best of our knowledge these are the first systematic, time resolved investigations on that topic.

Introduction

Until a couple of years ago it was of common belief that active fibers can emit diffraction limited beams independent of their output power. But state-of-the-art high power Yb-doped large mode area fibers have been developed to a performance level able to reach the so-called mode instability threshold. At present, the term 'mode instability' stands for a sudden change in mode quality at a certain power level caused by an energy transfer from the fundamental transverse mode to higher order modes [1].

Recently, a debate arose about what physical mechanism(s) can cause the mode instabilities after all. Starting from optically induced long-period gratings via Kerr effect [2] right up to index modulations provoked by population inversion or thermal dynamics [3,4] the underlying force for all potential candidates seems a periodic change in refractive index of any kind whatsoever. But still there are a lot of open questions unsettled, for instance, the tangible influence of operation conditions, center wavelength, and bandwidth. On the experimental side there are some sporadic reports as well as systematic investigations already in existence [1,5], but some aspects still need enlightenment. Here we want to discuss the experimaental results regarding the temporal evolution of this effect. With a pulsed pump source emitting pulses in the ms range, we investigated the temporal behavior of the build up and degradation time for mode instability in a high power fiber amplifier. To the best of our knowledge these are the first systematic, time resolved investigations on that topic.

Experimental setup and results

The experimental setup is based on a high power fiber amplifier system comprising an Yb-doped double-clad photonic crystal fiber (core diameter = 42 µm, pump core diameter = 500 µm surrounded by an air cladding). A low-noise cw-signal of ~10 W at a center wavelength of 1070 nm was seeded into the laser core, while the 976 nm pump light was injected in counter propagating direction. The amplified signal was separated from the pump light with a dichroitic mirror. For cw pump powers up to around 800 W (resulting in an output power of around 500 W) the amplifier was single-mode but switched to unstable mode operation for higher pump powers. The detected averaged beam profiles for stable and unstable mode operation are illustrated in the insets of Fig. 1b. The beam profile below the instability threshold was near Gaussian.

For the following experiments, the pump source was used in a pulsed regime. This ensures that the laser dynamics in the fiber are shifting in the µs range and are much shorter than the relatively long rise time of the pump source (~1 ms) so that the amplifier system directly followed the pump source dynamic. A typical duty cycle, where the pump was periodically switched on for 20 ms and switched off for 80 ms, is shown in Fig. 1a.

In order to analyze the behavior at the mode instability threshold a small fraction (< 0.01%) of the high-power signal was focused and detected with an InGaAs photo diode connected to an oscilloscope. Since the beam was larger than the detector only a spatial fraction was detected resulting in a constant signal for stable mode operation and a strongly modulated signal for unstable mode operation. One example time trace of the detected signal above the mode-instability threshold is shown in Fig. 1b. The example demonstrates that mode instability did not set in instantaneously with switching on the pump power. Temporally the amplifier showed stable fundamental-mode operation, but switched to unstable mode operation with a delay of some ms.

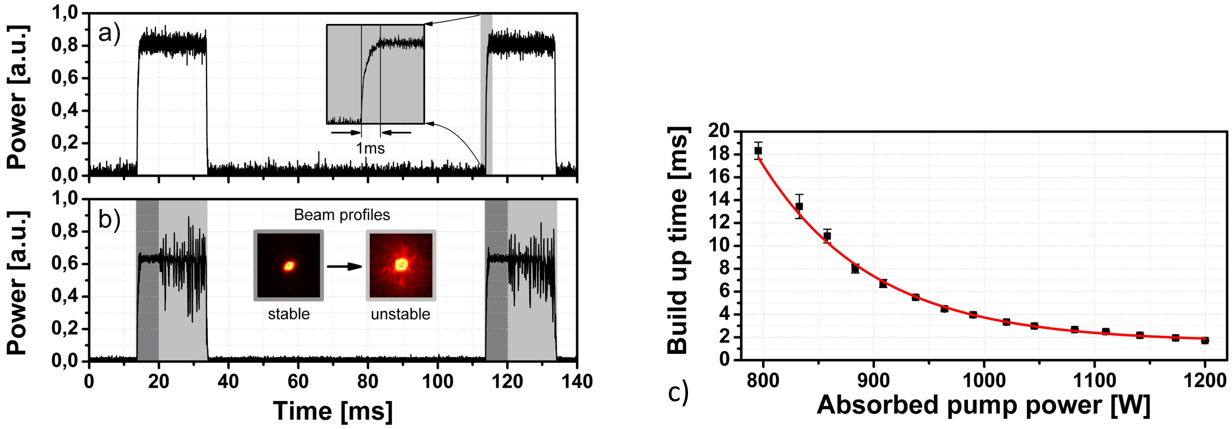

Fig. 1.: Example to illustrate a) the pulsed pump scheme and b) the detected signal above the mode instability threshold. Temporally, the amplifier showed stable fundamental-mode operation (dark gray shaded areas), but switched to unstable mode operation with a delay of some ms (light gray shaded areas).c) Mode instability build up time in dependence on the absorbed pump power.

Both regimes (stable/unstable) showed clear qualitative differences in the presented detection setup. To distinguish carefully the standard derivation of the time signal was used. In this way, we defined and measured the build-up time of the modulation instability.

In Fig. 1c the build-up time is plotted in dependence on the pump peak power (mode instability threshold at ~800 W). A duty cycle with 20 ms pulse duration and 120 ms off-time was chosen for this experiment. Each data point in the graph was averaged over 120 pulses and the depicted error bars were calculated from the standard derivation. An exponential decrease of the build-up time in dependence on the absorbed pump power was found and an exponential fit indicated that the build-up time converged to 1.6 ms. Assuming thermal effects as mechanism responsible for mode instability a non-zero minimal build-up time is expected because a thermal gradient inside the fiber will not build up instantaneously. However, the measured build-up time of 1.6 ms was influenced by technical limitations: the pulse rise time of the pump diode was about 1 ms. Thus, the actual build-up time is shorter than the measured one and can be estimated to be <1 ms.

Another investigations show the temporally resolved decay behaviour and dependence of the build-up time and decay by applying pre- and post-pump power directly before/after the main pump pulse. In this way, the relation to transient thermal effects has been proven by "pre- and post-heating" as well as the mode instability decay is probed and will be discussed during the presentation.

In conclusion we have investigated, for the first time to our knowledge, the time scales for build-up and decay of mode instability in an Yb-doped high power fiber amplifier and its dependence on pump power and duty-cycle. The method of pulsed pumping has been used and reveals important experimental information on the mechanism of mode-instabilities in fiber lasers.

References

1. T. Eidam et al., "Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers," Opt. Express **19**, 13218–13224 (2011).
2. N. Andermahr et al., "Optically induced long-period fiber gratings for guided mode conversion in few-mode fibers," Opt. Express **18**, 4411–4416 (2010).
3. A. V. Smith et al., "Mode instability in high power fiber amplifiers," Opt. Express **19**, 10180–10192 (2011).
4. C. Jauregui et al., "Impact of modal interference on the beam quality of high-power fiber amplifiers," Opt. Express **19**, 3258–3271 (2011).
5. C. Jauregui et al., "Temperature-induced index gratings and their impact on mode instabilities in high-power fiber laser systems," Opt. Express **20**, 440– 451 (2012).

A 140 W Large Mode Area Double Clad Holmium Fibre Laser

Alexander Hemming[1], Shayne Bennetts[1], Nikita Simakov[1], John Haub[1] and Adrian Carter[2]

[1]*Electronic Warfare and Radar Division, Defence Science and Technology Organisation, PO Box 1500, Edinburgh, SA, 5111, Australia*
[2]*Nufern, 7 Airport Park Road, East Granby, Connecticut, 06026, USA*

alexander.hemming@dsto.defence.gov.au

The 2 μm wavelength band provides advantages in terms of eye-safety, atmospheric transmission, and reduced susceptibility to nonlinear effects. It is of interest for a broad range of applications in fields such as defence, medicine and remote sensing. Thulium fibre lasers operating in this spectral band have been demonstrated at output powers above 1 kW [1], as well as operating with narrow line-width output at powers up to 608 W [2]. However, further power scaling of such devices is limited by thermal constraints and the brightness of pump diodes. Resonantly pumped double clad holmium fibre lasers offer possible solutions to these power scaling issues. The ability of holmium fibre lasers to be pumped by an array of high brightness, efficient, medium power thulium fibre lasers in a tandem pumping architecture with a low quantum defect (pumping at 1950 nm, lasing at 2120 nm), offers a promising route to the further power scaling of 2 μm fibre laser sources.

We have demonstrated a 140 W resonantly pumped double clad holmium fibre laser. The laser uses a large mode area fibre consisting of a 40 μm 0.08 NA core and a 250 μm octagonal inner cladding. A 0.22 NA fluorine-doped glass cladding is used to provide low-loss guidance of the 1.95 μm thulium fibre laser pump power. The slope efficiency of the laser versus coupled power was 55% and the laser operated across a broad wavelength band, 2120-2140 nm, demonstrating the potential operation of these sources beyond 2.1 μm.

This demonstration shows the potential of this fibre laser architecture and demonstrates a path to further power scaling of 2 μm fibre lasers in an all-fibre format, with particular relevance to coherent and spectral beam combination for high power laser applications.

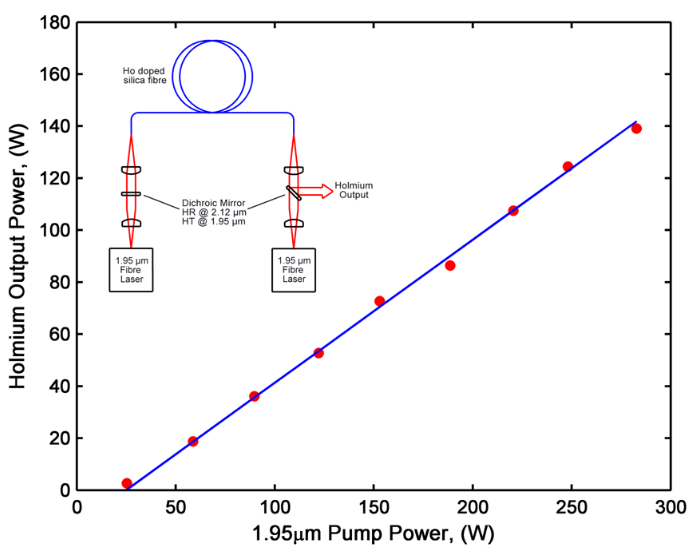

Fig. 1: Output power of holmium fibre laser vs input pump power. Inset: A schematic of the experiment.

[1] T. Ehrenreich et al.,"1-kW, All-glass Tm:fibre Laser", SPIE Photonics West, 2010
[2] G. D. Goodno et al., "Low-phase-noise, single-frequency, single-mode 608 W thulium fibre amplifier," Opt. Lett. 34, 1204-1206 (2009)