High efficiency tandem Ho:YAG single-crystal fiber laser delivering >100 W output power

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Abstract We report on a high-efficiency, high-power tandem Ho:YAG single-crystal fiber (SCF) laser in-band pumped by a Tm-doped fiber laser (TDFL) at 1907 nm. In addition to the uniform heat distribution resulting from the large surface-to-volume ratio of this fiber-like thin crystal rod, the long gain region provided by the tandem layout of two SCFs enables high lasing efficiency and power handling capability. More than 100 W output power is achieved at 2.1 µm, corresponding to a slope efficiency of 70.5% and an optical-to-optical efficiency of 67.6%. To the best of our knowledge, this is the highest output power and efficiency ever reported from the SCF lasers in the 2-µm spectral range.

Key words: Ho:YAG, high-efficiency, single-crystal fiber (SCF), power handing capability

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1. INTRODUCTION

High-power solid-state lasers in the 2-μm spectral range have been widely applied in various fields, including remote sensing, lidar, laser surgery and therapy, laser welding of transparent plastics, and pumping mid-infrared optical parametric oscillators (OPOs) for mid-IR frequency conversion [1-4]. Tm^{3+}-doped, Ho^{3+}-doped gain media provide the main approach to directly generate 2-μm high-power laser [5-6]. Compared to the Tm^{3+} ions, the large emission cross section of Ho^{3+} ions doped crystals makes it more ideal to achieve high power of 2-μm laser, for instance, yttrium aluminum garnet ($Y_3Al_5O_{12}$, YAG) crystals doped with Ho^{3+} ions have a gain cross section 7 times larger than Tm:YAG [7-8].

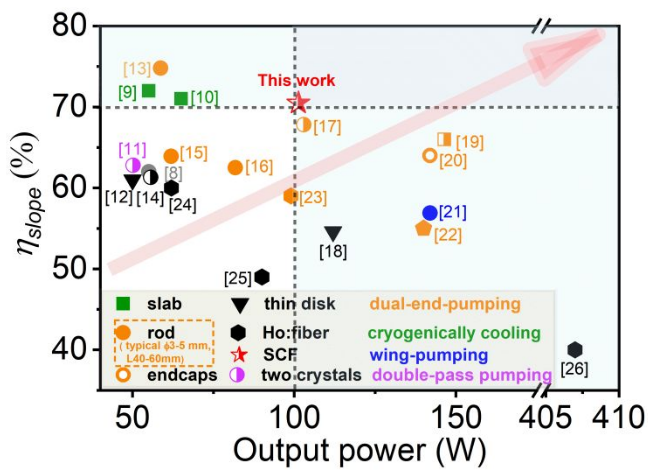

Fig. 1. Overview of 2-μm continuous-wave (CW) Ho:YAG and Ho:fiber lasers [8-26].

Fig. 1 presents an overview of CW Ho-lasers in the 2-μm spectral range [8-26], containing Ho:YAG bulk, thin-disk, slab and Ho:fiber laser systems, illustrating the significant advances in terms of high power and efficiency that have been achieved in recent years. Currently, YAG is still the preferred host material for high-power laser operation due to its high thermal conductivity, mechanical robustness, ease-of-preparation, and excellent chemical properties [27]. Nevertheless, further power scaling of Ho:YAG lasers remains challenging and need to be combined with different strategies for high power generation, e.g., high doping concentrations of Ho^{3+} ions [13], the cryogenically cooling system [9-10], single gain medium or dual gain media in conjunction with dual-end-pumping schemes [13,15-17,19-20,22-23], the wing pumping system [21], and gain media with end caps [20] or in special structures (i.e., the slab [9-10,19] or thin-disk geometry [12,18]). By comparison, current concepts for power scaling of 2 μm laser sources are inclined to use Tm- [28] or Ho-doped silica fibers [23-26] due to their simple thermal management, high brightness and compact structure, however, nonlinear effects, optical damage, photon darkening and transverse mode instability (TMI) [29-30] in fiber lasers seriously limit further power scaling.

Alternatively, the optical fiber structure in combination with the crystal properties of YAG offers an effective approach for achieving high average/peak power. Theoretically, the critical power supported by YAG single-crystalline fibers is six times higher than that of traditional silica fibers [31-32]. Note that, the concept of SCF is somewhat misleading but already established, referring to fiber-like thin-crystal rods with a large surface-to-volume-ratio and characterized by a diameter of less than 1 mm and a length of few centimeters. Some reports in the 1-μm spectral region, e.g., 250 W CW laser from a compact resonant cavity [33] and an average power of 290 W with 829 fs pulses in a two-stage amplifier [34] based on Yb-doped YAG SCFs and so on [35-36], all these demonstrations indicate that SCFs are ideal gain media for high average/peak power laser oscillators/amplifiers.

However, there have been relatively few studies on high-power SCF lasers in the 2-μm spectral range to date. Most recently, we have reported on the wing-pumped Tm:YAG SCF laser delivering 63 W output power at 2.01-μm [37]. In terms of lasers based on Ho:YAG SCFs, the Ho:YAG SCF fabricated by laser heated pedestal growth (LHPG) method was reported for the first time at 2.09-μm, and a quasi-CW output power of 23.5 W was achieved under pulsed pumping (10 Hz repetition rate, 50% duty cycle), while an output power roll-off at 10 W was observed due to thermal issues under CW pumping [38]. The CW output power of 35.2 W was achieved from an oscillator based on the YAG SCF doped with 0.6 at.% Ho^{3+} ions grown by the micro-pulling-down (μ-PD) method [39], while the corresponding slope efficiency was less than 45%, and the thermal effect was obvious at ~30W laser power. Thus, the unique geometry structure of SCFs with large surface-to-volume-ratio and the latest progress of SCF oscillators in the 2-μm spectral region motivated us to study the power scaling capability of CW SCF lasers, aiming to obtain high power lasers.

In this paper, the CW laser performance of the tandem Ho:YAG SCF was investigated in a compact resonator with a 1907 nm TDFL as the pump source. Benefiting from the high brightness of the in-band pumping scheme and the tandem-set SCFs with fiber-like-geometry structure, a maximum output power of 101.3 W with a slope efficiency of 70.5% was achieved at the pump power of 153 W. To the best of our knowledge, this is the highest power and efficiency of Ho:YAG SCF lasers, which proves the power scalability of SCF lasers and paves the way towards SCF ultrafast amplifiers emitting at 2 μm directly.

2. Experimental details

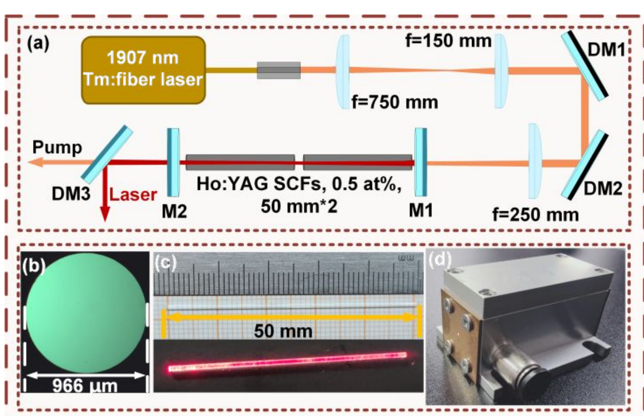

Fig. 2. Experimental setup of the tandem Ho:YAG SCF laser.

The experimental setup of the tandem Ho:YAG SCF laser with a physical cavity length of ~105 mm is depicted in Fig. 2. A 1907-nm Tm-doped fiber laser with a good beam quality of M^2 ~ 1.1 was used as the pump source. The pump beam passed through a telescope system, and then was focused into the latter part of the first SCF with a spot diameter of ~520 μm. Two series-arranged 0.5 at% Ho^{3+} doped YAG SCFs (966 μm in diameter and 50 mm in length) were employed as gain media, as shown in Figs. 2 (b) and (c), which were mechanically fabricated by cutting and grounding the Czochralski-grown Ho:YAG crystals. All the entire lateral surfaces and end facets of the SCFs have been optically polished, and all end facets of SCFs were anti-reflection (AR) coated at 1.9-μm and 2.1-μm, which can avoid parasitic laser oscillations and etalon effects. Fig. 2(b) displays the photograph of the end facet of the Ho:YAG SCF. The transmission losses of Ho:YAG SCFs were measured to be less than 3 dBm^{-1} at 632.8 nm. The mirror M1 was flat with high reflectivity at 2.1-μm and high transmission at 1.9-μm. The flat mirrors M2 with different transmissions (T_{OC} = 30%, 50%, 70% and 90%) for laser wavelength were used as output couplers (OCs). A dichroic mirror (DM3) was used to separate the laser and pump beams. To mitigate the thermal load, all SCFs were mounted on a specially designed water-cooled aluminum heat sink with both ends glue-sealed, which were directly water-cooled to 8 ℃, as shown in Fig. 2 (d).

3. Results and discussion

Fig. 3 (a) shows the output power as a function of the incident pump power with different transmissions of T_{OC}=30%, 50%, 70% and 90%. The most efficient operation was achieved with the T_{OC}=70% output coupler, a maximum output power of 101.3 W was achieved at the incident pump power of 153 W (~97.7% pump absorption ratio under lasing conditions), corresponding to a slope efficiency of 70.5% and an optical conversion efficiency of 67.6% at the maximum output power. Compared to the reported complex Ho(0.8 at%):YAG dual-crystal folded cavity and each crystal double-ended pumped by Tm:YLF lasers [17], a more compact scheme (single-end pumped dual-SCFs) was utilized to achieve higher slope efficiency (>70%) in this work. The CW output power of 65 W was obtained with the output coupler of T_{OC} =30%, and the slope efficiency was decreased to 69%, which may be caused by the high-power density and the thermal effect at the low OC transmission. Output powers and slope efficiencies with high-transmission OCs (T_{OC}=50%, 70% and 90%) are higher compared to our previous report [39], which is attributed to the longer gain region, the spatial uniform distribution of pump intensity, and the large overlap between the pump and laser beams in the directly water-cooled tandem SCFs, thus resulting in high slope efficiencies of ＞70% and hundred-watt-level output powers.

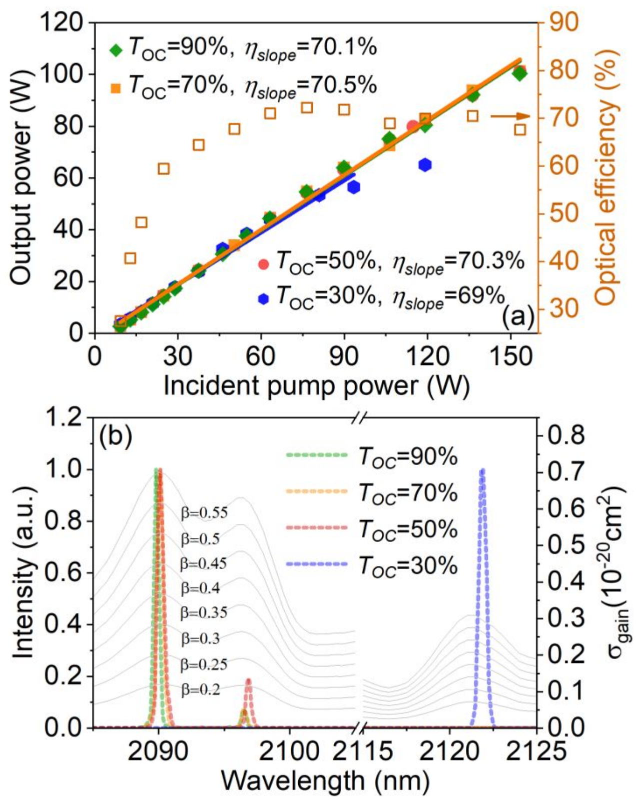

Fig. 3. (a) CW laser output powers and (b) the corresponding optical spectra of the Ho:YAG tandem SCF laser with different OC transmissions (T_{OC} = 30%, 50%,70% and 90%).

The measured optical spectra of the tandem Ho:YAG SCF laser with different OCs are depicted in Fig. 3(b). and the gain spectra of Ho:YAG [40] are also shown for an easy comparison. Two emission peaks for high transmission OCs maybe caused by the same gain cross-sections. The wavelength of the laser emission operated from ~2090 nm to ~2121 nm with decreasing transmittance of the OC, and such a wavelength red shift of ~31 nm is a typical feature of the quasi-three-level system due to the stronger reabsorption effect as lower population inversion with the low transmission of the OC [39].

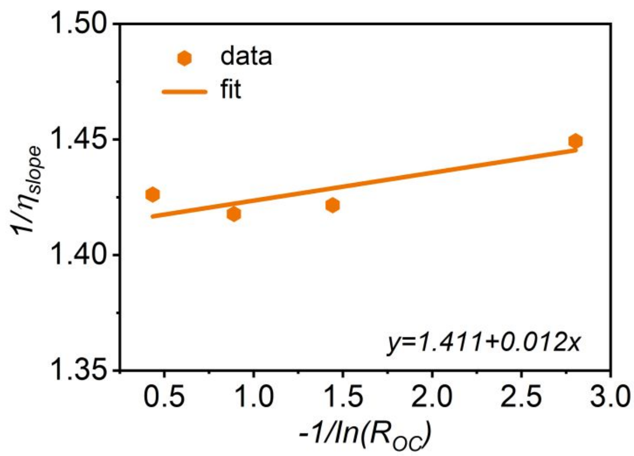

Fig. 4. Caird plot for the tandem Ho:YAG SCF laser: inverse slope efficiency with respect to the inverse output-coupling loss.

By evaluating the round-trip resonator loss of the tandem Ho:YAG SCF laser, the modified Caird analysis was used as a commonly adapted method to plot inverse of the slope efficiencies versus the inverse of the output coupler reflections. The losses and the intrinsic slope efficiency of the laser can be estimated by [41]:

$$1/\eta_s = 1/\eta_0(1+2\gamma/\gamma_{OC})$$

$$\gamma = -In(1-L)$$

$$\gamma_{OC} = -In(1 - T_{OC})$$

Where η_S is the measured slope efficiency, η_0 is the intrinsic slope efficiency, L is the internal loss per pass, and γ_{OC} is the output coupling loss, T_{OC} is the transmission of the output coupler. As shown in Fig. 4, the linear relationship between the experimentally measured points of the inverse slope efficiency ($1/\eta_S$) as a function of output coupler reflections [-1/In(R_{OC})] provides a straightforward way to determine the internal loss per pass (L) and intrinsic slope efficiency (η_0). The best fit value of the propagation loss was determined to be L/l = 0.0004 cm^{-1}, and the intrinsic slope efficiency was calculated to be ~70.9%, which is very nearly equal to the measured slope efficiency, indicating the great potential of the designed laser for further power scaling and future ultrashort-pulse SCF amplification experiments.

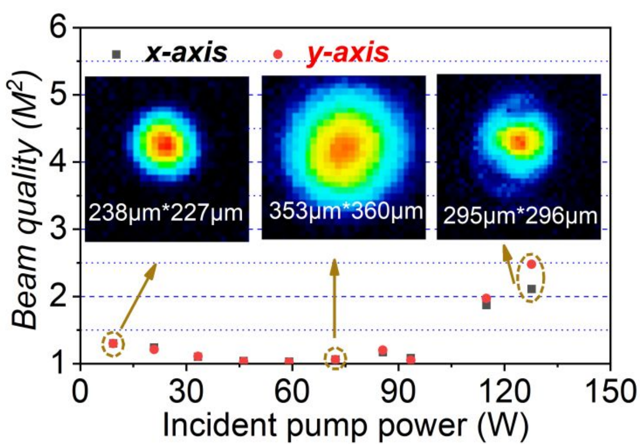

Fig. 5. The measured beam quality at different power levels, the insert is the corresponding near field beam profiles.

Beam propagation factors(M^2) of the tandem Ho:YAG SCF laser with T_{OC} =70% were recorded to assess the beam quality with a mid-infrared CCD camera (WinCamD-IR-BB, Dataray Inc.) at different pump powers. The similar trend of the beam propagation factors along the x- and y-axis indicates that tandem-set SCFs provide a uniform heat distribution in their transverse cross-section. As shown in Fig. 5, when the incident pump power was less than 100 W, the M^2 factors measured in both the x- and y- directions were around 1.1 by taking advantages of the large surface-to-volume ratio of the SCF and the direct water-cooling scheme. However, the excitation of higher-order transverse modes gradually degrades the beam quality at the pump power of ~130 W, resulting in M^2 factors along the x- and y- directions of 2.11 and 2.48, respectively. The beam quality along the y-axis deteriorates more seriously than the x-axis, which may be caused by unidirectional heat dissipation of the ∼ 1 mm protuberance of the SCF outside the module under high pump power levels. Further beam propagation factors optimization and power improvement can be realized by employing SCFs with diffusion-bonded undoped YAG end caps, or optimizing the directly water-cooled aluminum heat sink without protuberances of SCFs outside the module, thus mitigating thermal effects under high pump power levels.

4. Conclusion

In summary, we have experimentally investigated the laser performance of tandem-set Ho:YAG SCFs. The maximum output power of >100 W was obtained with a slope efficiency of >70 %, by taking advantage of the long gain region, the large surface-to-volume ratio, and the low propagation loss of SCFs. Compared to our previous work [39], we simply reduced the doping concentration of Ho^{3+} ions in YAG SCF and employed two directly water-cooled tandem SCFs as the gain medium to reduce the thermal effect and extend the gain length, thus resulting the high-power, high-efficiency laser output. Such a high-performance laser based on the tandem-set SCFs demonstrates an efficient way to realize high-power output and lay the foundation for expanding the output power of SCF lasers to multi-hundreds of watts in the near future. Furthermore, the tandem-set SCFs not only provide long gain region and simple thermal management due to their fiber-like geometry and crystal properties, but also suppress nonlinear effects and nonlinear phase accumulation effectively, thus paving the way for high average/peak power femtosecond pulse amplification.

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