5 kW Single-Mode Output Power from Yb-doped Fibers with Increased Higher-Order Mode Loss

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ABSTRACT

We report results from a new Yb-doped gain fiber with increased higher-order-mode (HOM) loss, compared to conventional step-index fibers. The fiber had 20 µm mode-field diameter (MFD), high absorption, and high transverse-mode instability (TMI) threshold. TMI-free operation with 5 kW output power was demonstrated from a 9 m length of gain fiber, limited by pump power. The large MFD and high absorption allowed for a 7.5 m long amplifier with greater than 80% o-o efficiency and the Raman peak more than 50 dB below the signal. These results were also enabled by a new, small-size, 7+1:1 pump-signal combiner.
Keywords: High-power fiber lasers, narrow-linewidth fiber lasers, Transverse-mode instability.

1. INTRODUCTION

The combination of high efficiency, high power, excellent beam quality, and low weight make ytterbium-doped fiber lasers a critical component in high-power laser systems. For high power operation, nonlinear impairments such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) become limiting factors in further increases in output power beyond a certain limit.

There are several potential avenues to increasing nonlinear thresholds in high-power fiber lasers. For SBS, for example, one possibility is to use different materials that reduce the Brillouin gain[1]. While promising, lasers based on such fibers have yet to achieve power levels or efficiencies equivalent to more conventional Yb-doped fibers. Nonlinearities can also be reduced by using highly doped, short fibers or increasing the mode-field diameter (MFD), but these approaches lead to a corresponding increase in transverse modal instabilities (TMI), another limiting factor in power scaling of fiber lasers. Above the TMI threshold, a high-power fiber laser begins to oscillate unstably between the fundamental (LP_{01}) mode and higher-order modes (HOMs) (typically the LP_{11} mode), limiting further increases in output power[2]. Because modal instability is facilitated by quantum-defect heating of the fiber core[3], increasing the dopant concentration and pump absorption decreases the TMI threshold as the heat per unit length increases. High HOM losses allow for high TMI thresholds[4], but increasing the LP_{01} MFD generally decreases the HOM loss, and lowers the TMI threshold.

Given the balance required between the size of the mode-field diameter and TMI thresholds, achieving higher output power requires new fiber designs that increase the HOM loss. Increased HOM loss will allow higher TMI thresholds for shorter fibers with larger MFDs, thereby increasing the nonlinear threshold. Crucially the HOM loss must be maintained under high heat load, as the quantum-defect induced heating also impacts the fiber refractive index profile, increasing the core index relative to the cladding via the thermo-optic coefficient, and tending to reduce HOM loss under high power operation[4].

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Previously, we reported on a next-generation strategy to increase the HOM losses in Yb-doped gain fibers that were compatible with high-power laser systems[5]. This approach allowed for simultaneously increasing the MFD of the fundamental mode while also maintaining high TMI thresholds, even for higher-absorption fibers with increased heat load. Using this strategy, a 21 µm MFD gain fiber was demonstrated with an operating length of 6.5 m. High-power measurements demonstrated TMI-free, pump-power limited operation with 3.6 kW of signal power, as compared to TMI limited operation at 3.3 kW signal power from a conventional gain fiber with 19.5 µm MFD and 9 m operating length. Furthermore, in narrow-linewidth amplification experiments, 2.74 kW signal power was achieved with 6 GHz linewidth from the 21 µm MFD fiber, compared to 10 GHz linewidth at 2.68 kW signal power in the 19.5 µm MFD fiber. In this work, we demonstrate that gain fibers designed with this strategy are capable of TMI-free operation at signal powers as high as 5 kW. Furthermore, the large MFD and high absorption of these next-generation gain fibers allow for amplifiers with very low levels of Raman scattering at these signal powers, when pumped at 976 nm.

2. EXPERIMENT

The next-generation gain fiber was built into an amplifier for characterization, shown in Fig. 1. The cladding diameter of the gain fiber was 400 µm. The amplifier was forward pumped with a pump-signal combiner (PSC) spliced to the input of the gain fiber. For this experiment, a newly developed PSC with 7 input pump legs was utilized, compared to a more conventional PSC with 6 input pump legs. This new 7+1:1 PSC was in the same small form factor package as the 6+1:1 design. Forty-four, wavelength-locked, 976 nm pump diodes were spliced to the PSC using pump combiners in a tree architecture. With the additional pump leg, the newly upgraded test setup had up to 6 kW of pump power available for launching into the gain fiber. The output of the gain fiber was spliced to a 25 µm core, 400 µm cladding delivery fiber that was end terminated with an AR-coated, angled end-cap.

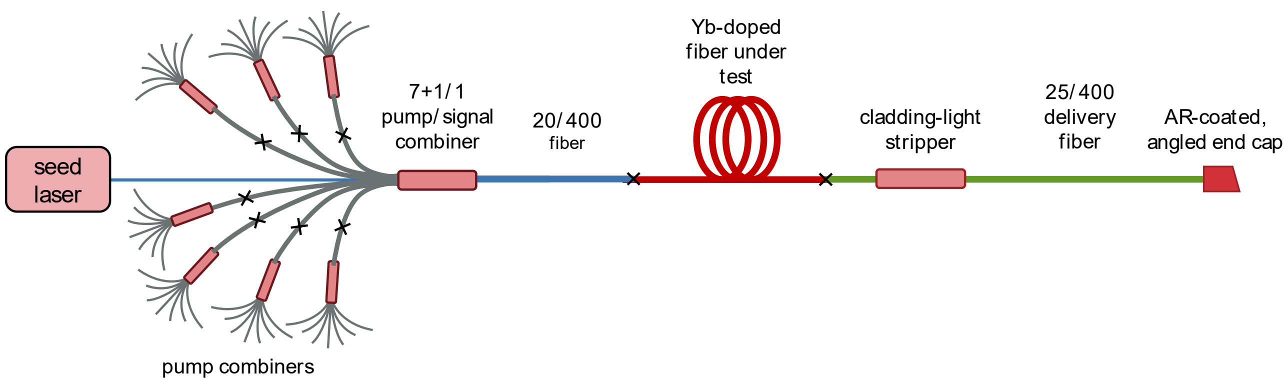

Figure 1. Schematic of amplifier test configuration.

Using a fiber laser cavity with 20 W output power at 1070 nm as a seed source, 5 kW of signal power was obtained for 5.93 kW of launched pump power, corresponding to 84.3% optical to optical (o-o) efficiency with respect to launched pump power, as shown in Fig. 2a. For this experiment the length of the gain fiber was 9 m. The amplifier output was free from TMI, with the experiment limited by available pump power.

Next, the amplifier fiber was cut to 7.5 m length and remeasured. The length of 7.5 m corresponded to the measured length for 13 dB of absorption of the 976 nm, wavelength locked pumps, when operating at high power. In this configuration, the o-o efficiency of the amplifier was 80.7%

The optical spectra measured at maximum power for the two tested lengths are shown in Fig. 2b. For the 9 m fiber, the Raman peak was 40 dB below the signal peak at 5 kW of signal power. When the fiber was cut to 7.5 m, the Raman peak was below the noise floor of the measurement, more than 50 dB below the signal peak.

3. CONCLUSIONS

In conclusion, a 20 µm MFD next-generation gain fiber has been demonstrated to achieve TMI-free operation at 5 kW of signal power, in a fiber with a 13 dB pump absorption length of only 7.5 m. With a 9 m long amplifier, the Raman OSNR was 40 dB and the o-o efficiency of the amplifier was 84.3 %. With a 7.5 m length of gain fiber, the Raman OSNR was > 50 dB and the o-o efficiency was 80.7%. These results were also enabled by the development of a new 7+1:1 PSC which enabled coupling of additional pump power into the gain fiber. Narrow line-width amplifier experiments at these power levels are currently underway.

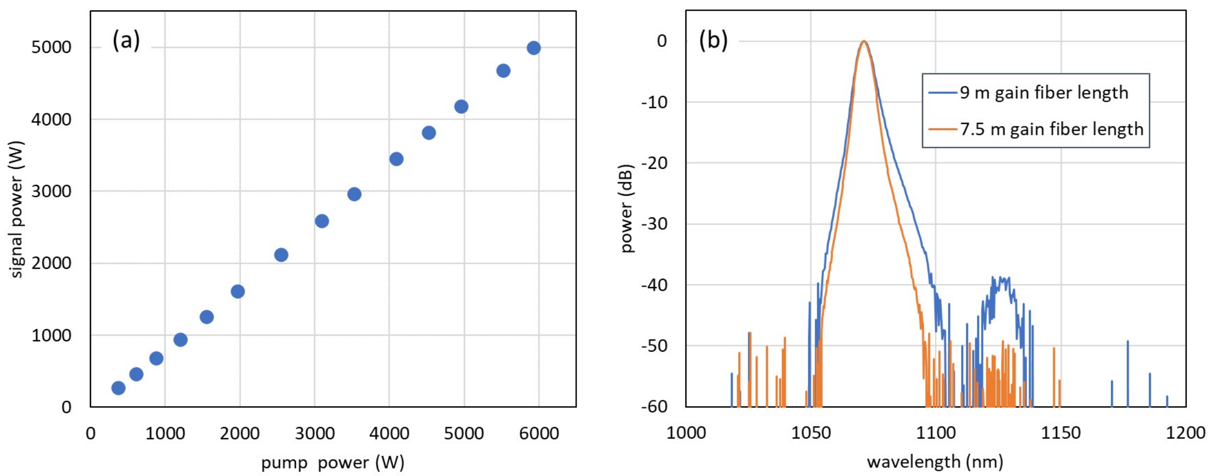

Figure 2. (a) Output power vs. pump power using broad-linewidth seed and 9 m fiber length. (b) Output spectra at maximum power for 9 m and 7.5 m gain fiber length. 7.5 m length corresponded to 13 dB of absorption of the 976 nm wavelength-locked diode pumps.

REFERENCES

[1] P. D. Dragic, M. Cavillon, A. Ballato, and J. Ballato, International Journal of Applied Glass Science 9, 278 – 287 (2018)

[2] C. Jauregui, T. Eidam, J. Limpert, and A. Tünnermann , Opt. Express 19 (4), 3258 (2011)

[3] Y. Fan, B. He, J. Zhou, J. Zheng, H . Liu, Y. Wei, J. Dong, and Q. Lou, Opt. Express 19 (16) 15162 (2011)

[4] C.X. Yu, O. Shatrovoy, T.Y. Fan, T.F. Taunay, Optics Letters 41(22) 5202 (2016)

[5] J.W. Nicholson, A. DeSantolo, R.S. Windeler, E. Monberg, V. Lukonin, J. Pincha, A. Hariharan, X. Xu1, G. Williams, Z. Goldberg, A. Rosales-Garcia, P. Kristensen, D. Knight, and D.J. DiGiovanni, Proc. SPIE 11981, Fiber Lasers XIX: Technology and Systems, 119810R (4 March 2022)