

5.2 kW single-mode output power from a Yb 20/400 fiber with reduced thermo-optic coefficient

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ABSTRACT

We report the performance of an LMA Yb-doped fiber, designed for increasing the transverse mode instability threshold and minimizing nonlinear effects in multi-kilowatt class fiber lasers, by reducing the thermo-optic coefficient of the fiber core, compared with that of standard aluminophosphosilicate Yb-doped fibers. A TMI-free 5.2 kW single-mode output power from a Yb 20/400 fiber with a 17.5 μm mode-field diameter was achieved in a broad bandwidth, co-pumped amplifier with 78% optical-to-optical efficiency, while a 4 kW signal output was attained in a 26 GHz linewidth amplifier. Negligible photodarkening loss was observed during 150 hour laser operation at 2 kW.

1. INTRODUCTION

Ytterbium-doped fiber lasers have become an essential component in high-power laser systems used in applications requiring excellent beam quality, high electrical-to-optical efficiency, compact size, and low weight. Advancements in fiber design, laser architecture and laser diode technology led to a steady increase in the output power of fiber lasers over the past few decades. Transverse mode instability (TMI)¹ and nonlinear effects, namely stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), are the main limitations for further scaling the output power of kilowatt-class, diffraction limited fiber lasers. SBS limits the ability to decrease the linewidth of fiber lasers required for coherent beam combination, while SRS is the limiting nonlinear effect in broad-bandwidth lasers used for material processing and industrial applications. Efforts to decrease SBS and SRS by increasing the cladding absorption of the fiber to reduce its length, or by increasing the mode field diameter (MFD), have resulted in a reduced TMI threshold. We recently introduced new Yb doped fibers² designed with a large effective area for minimizing nonlinearities, while maintaining a high TMI threshold by increasing the high-order mode (HOM) bend loss of the fibers. A diffraction-limited output signal power of 5 kW was demonstrated in a Yb 22/400 fiber with a 20- μm MFD co-pumped amplifier, limited by available pump-power. An alternative approach for reducing nonlinearities and minimizing the thermal load impact in the refractive index modulation leading to TMI, is to use different materials that reduce the thermo-optic coefficient (TOC) of the Yb-doped fiber³⁻⁸. Here, we demonstrate the latter approach for multi-kilowatt fiber laser operation of a Yb-doped fiber designed with an estimated fiber core TOC $1 \times 10^{-6} \text{K}^{-1}$ lower than that of standard aluminophosphosilicate (APS) Yb-doped fibers.

2. EXPERIMENT

The decreased-TOC Yb 20/400 fiber had an MFD=17.5 μm , cladding absorption of 0.38 dB/m at 915 nm, and a 13 dB absorption length of 7.5 meters at 976 nm. The fiber was evaluated in a co-pumped amplifier (Figure 1), where up to 6.7 kW pump power from 976 nm, wavelength-locked diodes was coupled using a commercial (7+1)x1 pump-signal combiner (PSC) in a tree-architecture⁹. The output fiber was a 2-meter,

0.06 NA, 25/400 μm passive fiber spliced to the gain fiber. A cladding light stripper (CLS) was used to remove unabsorbed pump, before an AR-coated, angled end cap, while a photodiode (Pt) was used to detect TMI.

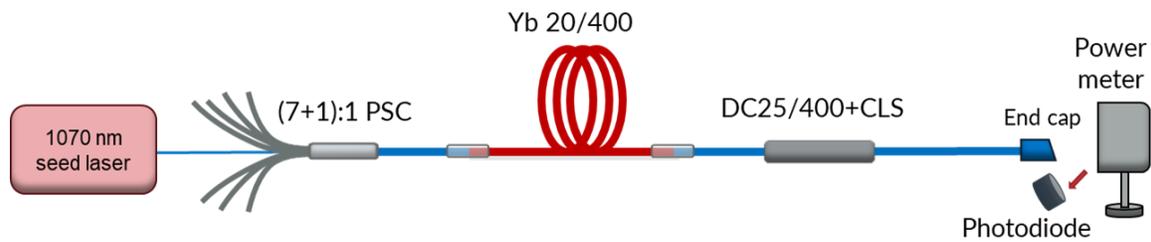


Figure 1. Schematic of the co-pump amplifier test setup.

A TMI-free 5.2 kW signal power with 78% optical efficiency (Figure 2a) was obtained using a 20 W broadband laser at 1070 nm as a seed source. We evaluated long-term operation of the fiber laser at 2 kW, where no signal power decay was observed in the decreased-TOC Yb 20/400 fiber in 150 hours (Figure 2b), demonstrating that this fiber is compatible with low-photodarkening material designs¹⁰, allowing for reliable long-term operation.

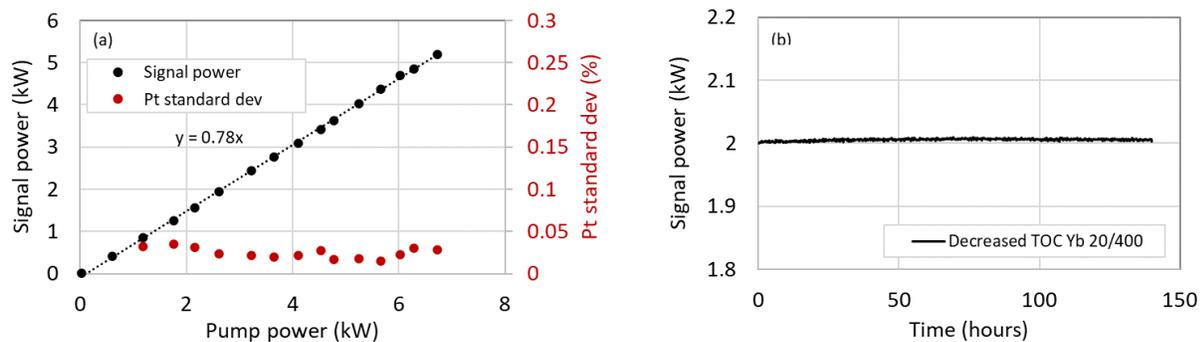


Figure 2: (a) Left: Signal power vs. pump power of the decreased-TOC Yb 20/400 co-pumped amplifier, and the photodiode (Pt) standard deviation vs. pump power showing TMI free operation (b) Right: Long term operation to test for photodarkening.

The TMI threshold of standard Yb-doped APS fibers tested in a co-pumped amplifier follows a logarithmic dependance that increases with the HOM bend loss of the fiber, and decreases as its cladding absorption increases, as shown in Figure 3. The TMI threshold of the decreased-TOC Yb 20/400 was increased by 50% compared with that of standard APS Yb-doped fibers with similar HOM bend loss, cladding absorption, and mode field diameter.

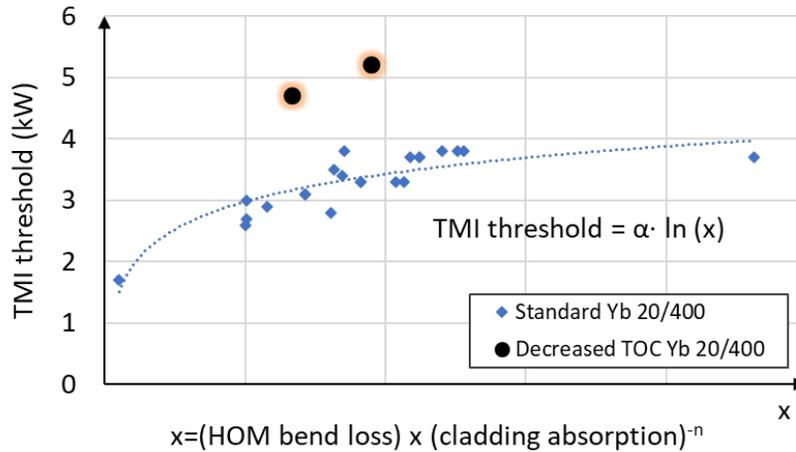


Figure 3: TMI threshold dependence on HOM bend loss and cladding absorption, comparing standard Yb 20/400 fibers with the decreased TOC Yb 20/400 fiber.

The decreased TOC Yb-doped fiber also exhibits low nonlinearity, particularly SBS³⁻⁸. We compared the SBS threshold in a 26 GHz-linewidth co-pumped amplifier, launching a depolarized seed source modulated using PRBS9. The standard Yb 20/400 was limited to 2.6 kW, while the SBS threshold increased to 4 kW using the decreased-TOC Yb 20/400 fiber. We then compared the performance with standard Yb-fibers with larger MFD¹¹. The decreased TOC 17.5- μm -MFD fiber shows lower SBS threshold compared with the standard 20- μm -MFD fiber (Figure 4). This shows that the MFD must still be increased to further increase the SBS threshold and reduce other nonlinearities, which is attainable by implementing advanced designs with high HOM bend loss^{2,11}. This provides a path to higher performance gain fibers, combining the benefit of low-TOC glass gain medium with high HOM suppression fiber designs for low-nonlinearity and TMI-free fiber laser operation at the multi-kilowatt level.

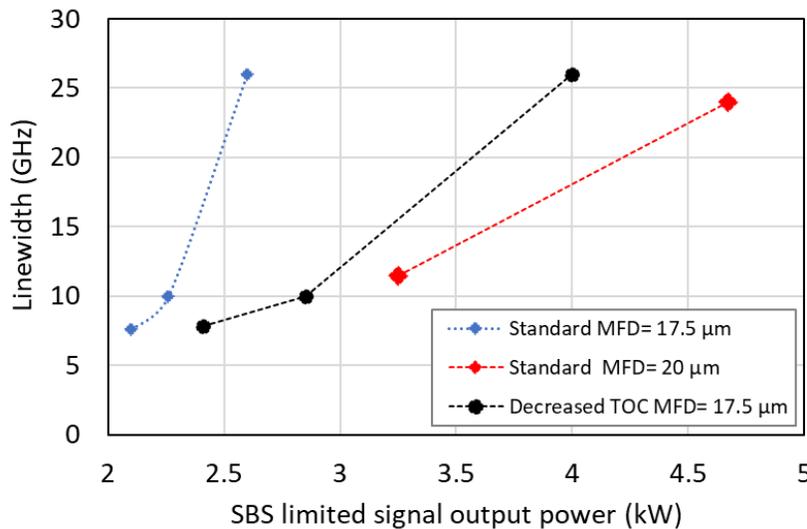


Figure 4: Linewidth vs output power comparing decreased TOC and standard Yb-doped fibers.

3. CONCLUSIONS

In conclusion, we presented the performance of an LMA Yb-doped fiber, designed for increasing the transverse mode instability threshold and minimizing nonlinear effects in fiber lasers, by reducing the thermo-optic coefficient of the fiber core. A TMI-free 5.2 kW signal was achieved in a broad-bandwidth, co-pumped amplifier, while a 4 kW signal output was attained in a 26 GHz-linewidth amplifier. The TMI threshold increased by 50% compared with standard aluminophosphosilicate fibers with similar HOM bend loss, mode field diameter and cladding absorption. Nonlinearities can limit further power scaling, but these can be mitigated by incorporating advanced designs for increasing the HOM bend loss in large effective area Yb-doped fibers. The combination of low-TOC glass gain medium with high-HOM suppression LMA fiber designs, provides a path for high-performance gain fibers, for low-nonlinearity and reliable fiber laser operation at the multi-kilowatt level.

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