Yb-doped Fibers for kW-Class Fiber Lasers

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Abstract: We demonstrate a TMI-free 5.2 kW single-mode output from a fiber amplifier using Yb 20/400 fibers with reduced core thermo-optic coefficient. The TMI threshold is increased by 50% compared to that of commercial Yb-doped fibers. © 2024 The Author(s)

1. Introduction

Ytterbium-doped fiber lasers have been widely adopted in high-power laser systems used in applications requiring excellent beam quality, high electrical-to-optical efficiency, low maintenance, compact size, and low weight. Advancements in laser diode technology, laser architecture and fiber design 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.

TMI is observed as the sudden degradation of the beam quality of the fiber laser and is associated with the thermally induced transfer of energy between the fundamental mode (FM) and higher-order modes (HOM). Several passive and active approaches to increase the TMI threshold have been proposed [2]. Some of the passive strategies are aimed to reduce the thermal load on the gain fiber, while others to increase the bend loss of HOM by coiling methods [3,4], or advanced fiber designs [5,6].

We recently introduced new Yb doped fibers [6], designed with a large effective area for minimizing nonlinearities, while maintaining a high TMI threshold by increasing the 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. Higher signal power is attainable due to Raman OSNR of more than 50 dB at 5 kW. 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 fiber [7-11]. Here, we demonstrate the latter approach for multi-kilowatt fiber laser operation.

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, where up to 6.7 kW pump power from 976 nm, wavelength-locked diodes was coupled using a commercially available, OFS CoolMode™ (7+1):1 pump-signal combiner (PSC) in a tree-architecture [12]. The output fiber was a 2-meter, double-cladding (DC) 25/400 µm passive fiber spliced to the gain fiber (Fig. 1). 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.

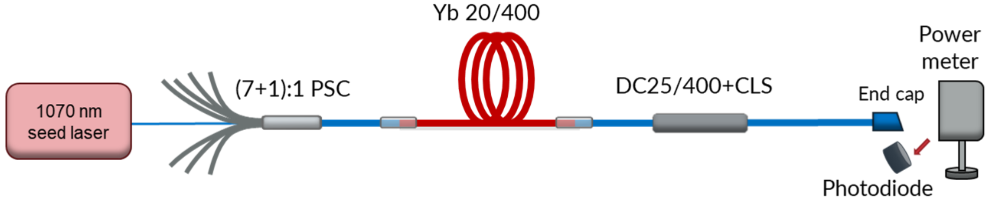

Fig. 1. Schematic of the co-pump amplifier test setup.

A TMI free 5.2 kW signal power with 78% optical efficiency (Fig. 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 (Fig. 2b), demonstrating that this fiber is compatible with low-photodarkening material designs [13], allowing for reliable long-term operation.

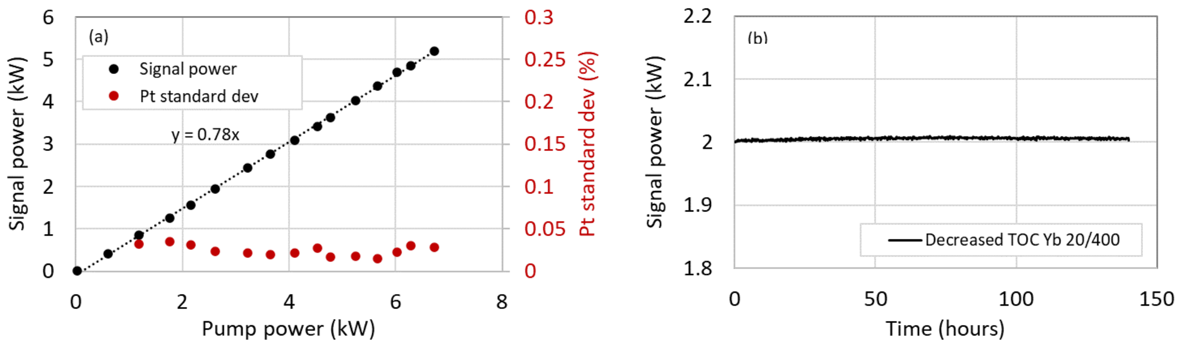

Fig. 2: (a) Left: Signal power vs. pump power of the decreased-TOC Yb 20/400 co-pumped amplifier, and the photodiode (Pt) standard deviation vs. pump power showing TMI free operation (b) Right: Long term operation to test for photodarkening.

The TMI threshold of commercial Yb-doped 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 Fig. 3. The TMI threshold of the decreased TOC Yb 20/400 was increased by 50% compared with that of commercial Yb-doped fibers with similar HOM bend loss, cladding absorption, and mode field diameter.

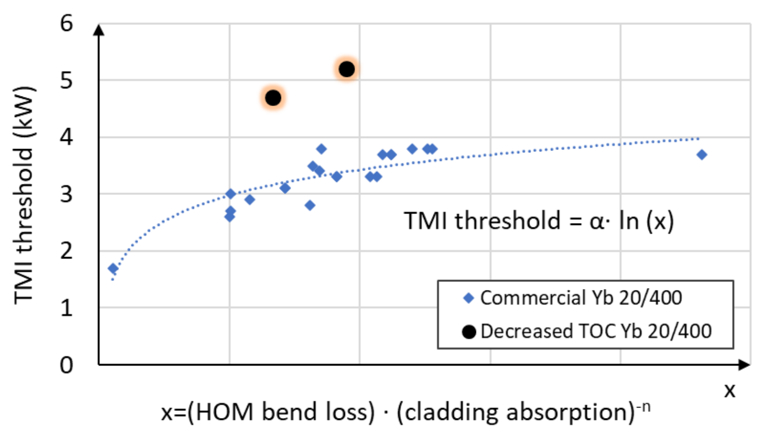

Fig.3: TMI threshold dependance on HOM bend loss and cladding absorption, comparing the commercial with the decreased TOC Yb 20/400 fibers.

The low TOC fiber also exhibits low nonlinearity, in particular SBS [7-11]. We compared the SBS threshold in a co-pumped amplifier, using a 26 GHz linewidth, depolarized seed source modulated using PRBS9. The commercial 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.

The optical spectrum was recorded when the broadband fiber laser at 1070 nm was used as the seed source. At 5 kW output power, the Raman peak was 38 dB below the signal peak (Fig. 4). SRS will hinder the ability to continue increasing the output power or the fiber length of the amplifier for applications that require higher total pump absorption or long delivery fibers. The combination of low TOC with increased HOM bend loss in larger effective area Yb-fiber designs, will provide the benefit of low nonlinearities and TMI free operation for long-term reliability fiber laser operation at the multi-kilowatt level.

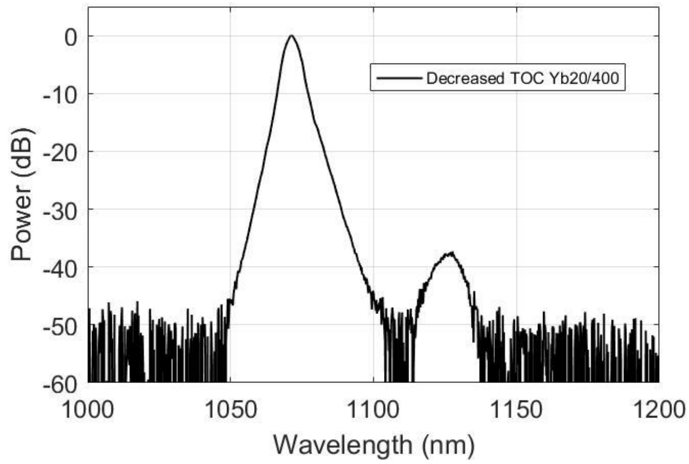

Fig.4: Optical spectrum at 5 kW signal power.

3. Conclusions

We presented the performance of Yb-doped fibers 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. A TMI-free, 5.2 kW signal was achieved in a broad bandwidth, co-pumped amplifier, increasing the TMI threshold by 50% compared to commercial fibers with similar HOM bend loss, mode field diameter, and cladding absorption. The fiber design is also beneficial for reducing nonlinear effects. We compared the SBS threshold in a 26 GHz linewidth co-pumped amplifier. The commercial 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. Negligible photodarkening loss was observed in 150 hour fiber laser operation at 2 kW. SRS can limit further power increase but can be mitigated by incorporating advanced designs for increasing the HOM bend loss with large effective areas in Yb-doped fibers.

4. References

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