PHOTONICS Research

Experimental demonstration of transverse mode instability enhancement by a counter-pumped scheme in a 2 kW all-fiberized laser

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Transverse mode instability (TMI) has become the major limitation for power scaling of fiber lasers with nearly diffraction-limited beam quality. Compared with a co-pumped fiber laser, a counter-pumped fiber laser reveals TMI threshold enhancement through a semi-analytical model calculation. We demonstrated a 2 kW high-power counter-pumped all-fiberized laser without observation of TMI. Compared with the co-pumped scheme, the TMI threshold is enhanced at least 50% in counter-pumped scheme, moreover, stimulated Raman scattering and four-wave mixing are suppressed simultaneously.

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1. INTRODUCTION

High-power fiber laser systems have experienced significant development with an increasing average power in the 21st century. Fiber lasers have been replacing gas lasers and solid-state lasers in industrial markets including cutting, welding, and drilling, due to good heat management, high conversion efficiency and excellent beam quality. However, a novel nonlinear effect, transverse mode instability (TMI), emerges in high-power fiber laser systems and degrades the beam quality with a sharp threshold [1]. Numerical, semi-analytical, and analytical models have been proposed to realize the TMI effect [2–5]. A thermal effect is responsible for onset of the TMI effect in most of these models. Fiber design seems to be a useful way to mitigate the TMI effect in the long term [6], while passive strategies, such as shifting pump wavelength and decreasing pump absorption, have been recently shown to be effective ways [7,8]. Nonetheless, other detrimental effects, including stimulated Raman scattering (SRS), four-wave mixing (FWM), and amplified spontaneous emission (ASE), will be induced in these systems, because of fiber lengthening to ensure pump power depletion. For suppressing these nonlinear effects simultaneously, utilizing a counter-pumped scheme in high-power fiber laser systems can be a robust way.

Gain saturation has been proposed to increase TMI threshold [9,10]. Different degrees of saturation break the symmetry between co-pumped and counter-pumped schemes. TMI thresholds of Yb-doped fiber (YDF) lasers have been computed in different pumping configurations, but no more detailed experiments followed [9,10]. A model including photodarkening effect indicated that a counter-propagating configuration had a higher TMI threshold. TMI thresholds of different pump configurations were compared to simulation results, but the experimental results were limited by fiber destruction [11].

In this paper, we have computed TMI thresholds in co-pumped and counter-pumped schemes by a semi-analytical model. Moreover, we investigated TMI in different pumped schemes with our experimental setup. With a home-made counter-pumped multimode power combiner (MPC), we demonstrated a 2 kW all-fiberized laser without observation of TMI. In addition, SRS and FWM are simultaneously suppressed in the counter-pumped scheme.

2. EXPERIMENTAL SETUP AND RESULTS

To investigate TMI in fiber lasers with the co-pumped and counter-pumped schemes, we established two fiber laser systems based on a master oscillator power amplifier (MOPA) configuration. Except for the different pumping scheme, parameters of the fiber lasers are identical. The experimental setup is shown in Fig. 1. For the master oscillator, pump power from a 50 W diode laser (DL) is injected into the cavity via a $(2+1) \times 1$ MPC. The laser cavity contains a high reflector (HR), 10/130 μm (core/cladding diameter) YDF and output coupler (OC). To realize a narrow-linewidth multi-longitudinal mode oscillator, a 4 m length of YDF is employed, as its nominal absorption coefficient at 976 nm is around 5 dB/m. A house-made cladding power stripper (CPS) is integrated to remove unwanted cladding power. A mode field adaptor (MFA) is connected to minimize the insertion loss and ensure good beam quality. In the co-pumped power amplifier, one $(6+1) \times 1$ MPC is applied to inject pump power from the DLs, which can reach 2.3 kW, and the wavelength centers at around 976 nm. Numerical apertures (NAs) of the 20/400 μm YDF core and inner cladding are 0.065 and 0.46, respectively. LP_{01} and LP_{11} modes can be transmitted in this kind of fiber. Nominal cladding absorption of YDF is around 1.2 dB/m at 976 nm, and a 13 m long fiber is employed to ensure pump power depletion. A house-made CPS, capable of handling cladding power of 500 W, and quartz block head (QBH) are integrated for signal power delivery. For the counter-pumped scheme fiber laser shown in Fig. 1, the setup of the power amplifier is reversed and an extra CPS is added after the counter-pumped MPC to remove leaking signal power as well as reflecting signal power.

Our fiber lasers in the co-pumped and counter-pumped schemes can reach nearly 2 kW with maximal pump power. To investigate the TMI effect, we focus on the beam quality. For the co-pumped scheme, the beam quality degrades at a critical output power, about 1.3 kW, while in counter-pumped scheme, the beam quality maintains in single mode regime, as shown in Fig. 2. Because of available pump power limitation, the TMI threshold of the counter-pumped fiber laser is expected to be larger than 2 kW. In Fig. 3, the spectrum of the

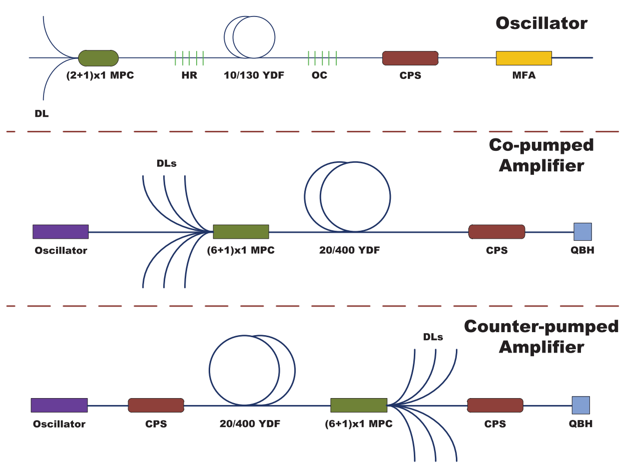

Fig. 1. Experimental setup.

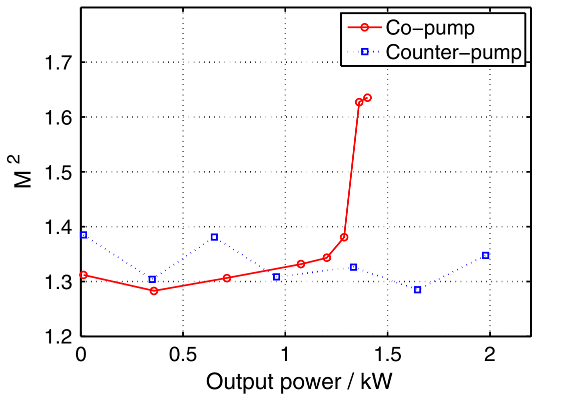

Fig. 2. M^2 factor variation of the co-pumped and counter-pumped schemes as a function of the output power.

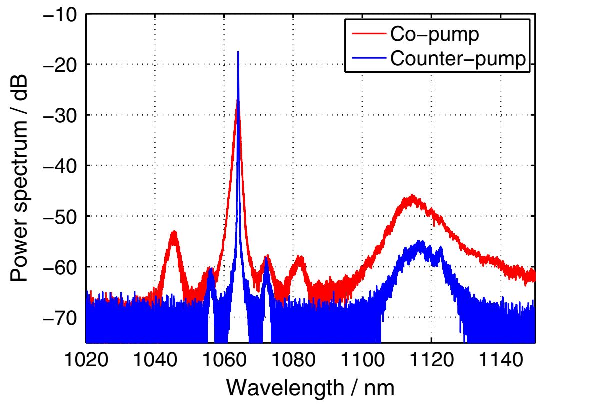

Fig. 3. Spectra of the co-pumped and counter-pumped schemes with output power of nearly 2 kW.

counter-pumped scheme seems to suppress SRS and FWM, and the SRS peak is suppressed at approximately 20 dB compared to the co-pumped scheme. The output power reaches nearly 2 kW, the 3 dB bandwidth is 0.12 nm in the counter-pumped scheme while it is 0.68 nm in co-pumped scheme, and the laser wavelength centers at 1064 nm. Obviously, compared to that of the co-pumped scheme, the counter-pumped scheme can enhance TMI threshold at least 50% and suppress SRS and FWM simultaneously in our experiment. No ASE is observed in either of these amplifiers.

3. SEMI-ANALYTICAL MODEL

Based on coupled mode theory, the TMI model can be depicted as mode coupling between the fundamental mode (FM) and the first higher order mode (HOM). Gain saturation, including signal power saturation and pump power saturation, is considered and leads to different TMI thresholds in different pumped schemes. Therefore, the power equations that describe mode coupling and power amplifying are given as

$$\frac{\partial P_1}{\partial z} = -\chi'(\Omega) g P_1 P_2 + \Gamma_1 g P_1, \tag{1a}$$

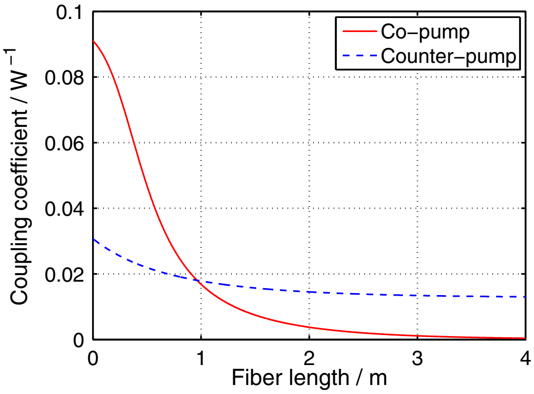

Fig. 4. Coupling coefficients of the co-pumped and counter-pumped schemes along the 50/400 fiber. The reader can refer to Smith and Smith's model for the fiber amplifier parameters [9].

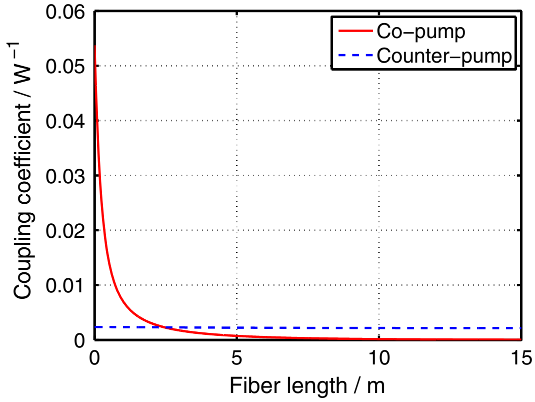

Fig. 5. Coupling coefficients of the co-pumped and counter-pumped schemes along the 20/400 fiber.

$$\frac{\partial P_2}{\partial z} = \chi'(\Omega) g P_1 P_2 + \Gamma_2 g P_2, \tag{1b}$$

$$\chi'(\Omega) = \chi(\Omega) \frac{1 + I_p/\Gamma_p I_p^{\text{sat}}}{1 + I_p/\Gamma_p I_p^{\text{sat}} + I_s/I_s^{\text{sat}}}, \tag{2}$$

$$\chi(\Omega) = 2k_0 \mathrm{Im}\Bigg(4n_0^2\varepsilon_0^2c^2 \sum_{v}\sum_{m=1}^{\infty} \frac{\alpha n_2}{\pi(\alpha\beta_m^2 - j\Omega)} \frac{R_v(\beta_m, r)}{N(\beta_m)} \times \int_{r=0}^{r_b}\int_{\phi=0}^{2\pi}\int_{r'=0}^{r_{Yb}}\int_{\phi'=0}^{2\pi} R_v(\beta_m, r')\Phi(\phi - \phi') \times \psi_1'\psi_2'\psi_1\psi_2 r' r \mathrm{d}r' \mathrm{d}\phi' \mathrm{d}r \mathrm{d}\phi\Bigg). \tag{3}$$

Here, P_i is optical power and Γ_i is the overlapping factor, where $i = 1, 2$ represent FM and HOM. $\chi'(\Omega)$ is a nonlinear coupling coefficient, while Ω is the offset frequency between FM and HOM. I_s and I_p are the optical intensities of the signal and pump, respectively. Superscript sat indicates the saturation power. k_0 is the wave vector of the signal, and β_m can be obtained by solving the equation due to the boundary condition, $\beta_m J_v'(\beta_m r_b) + J_v(\beta_m r_b) h_q/\kappa = 0$.

Gain saturation is proved to be effective in TMI enhancement. Moreover, the coupling coefficient along the fiber is decreased compared to that of no gain saturation. To investigate the difference between our semi-analytical model with the Smiths' model considering gain saturation [9], we apply its 50/400 fiber amplifier parameters in our model. The coupling coefficients in the co-pumped and counter-pumped schemes are shown in Fig. 4. The result is similar to Smith and Smith's results as well as Hansen and Laegsgaard's results [9,10].

4. DISCUSSION

When gain saturation is neglected, the coupling coefficient is identical along the fiber in different pumped fiber amplifiers. While gain saturation is considered, the coupling coefficient is decreased with a different degree, as shown in Fig. 5. The fiber amplifier parameters are presented in Table 1. For a 20/400 fiber amplifier in the co-pumped scheme, the coupling coefficient is relatively high in the front of YDF. However, the coupling coefficient is smoothing along the fiber due to a strong degree of gain saturation. As a result, the TMI threshold of the counter-pumped scheme is enhanced by a factor of more than 2 compared to that of the co-pumped scheme. Detailed data are shown in Table 2. More details about 400 μm cladding fibers with varying core diameter are investigated with the co-pumped, counter-pumped, and bi-pumped schemes. For the bi-pumped scheme, pump power is equal in two directions. In our experiment, the TMI threshold is enhanced at least 50% for the 20/400 fiber in the counter-pumped scheme. The difference between the measurement and simulation results occurs for two reasons. One is that the available pump power is limited in our experiment, and the other is that the thermal lens effect and transverse hole burning are neglected in our model. Overall, we still propose that the counter-pumped scheme can enhance the TMI threshold experimentally and theoretically in all-fiberized lasers.

Experiments of different pumping schemes are demonstrated, and most of them confirm similar results. Most recently, some of them showed that TMI thresholds were

Table 1. Parameters of Test Amplifier

d_{core}	20 μm	λ_s	1064 nm
n_{core}	1.4575	λ_p	976 nm
NA_{core}	0.065	h_q	1000 W/(m^{2}K)
NA_{clad}	0.46	τ	901 μs
N_{Yb}	6.52×10^{25} m^{-3}	η	1.2×10^{-5} K^{-1}
σ_{ap}	1.77×10^{-24} m^2	κ	1.38 W/(Km)
σ_{ep}	1.71×10^{-24} m^2	ρ	1.55×10^6 J/(Km^3)
σ_{as}	6.40×10^{-27} m^2	P_s	20 W
σ_{es}	3.98×10^{-25} m^2	R_N	10^{-10} Hz^{-1}

Table 2. TMI Threshold Comparison I: with Identical Cladding Diameter

Fiber	Length/m	Co-Pump/W	Counter-Pump/W	Bi-Pump/W	ER
20/400	15	1853	4716	3195	155%
30/400	8	1185	2356	1903	99%
50/400	5	658	1076	1091	64%

Table 3. TMI Threshold Comparison II: with Identical Core Diameter

Fiber	Length/m	Co-Pump/W	Counter-Pump/W	Bi-Pump/W	ER
30/250	3	634	1018	1003	60%
30/400	8	1185	2356	1903	99%
30/600	15	1933	4927	3326	155%

similar in different pumped schemes [12]. Smith and Smith proposed that a larger cladding fiber raised TMI threshold, while a smaller cladding fiber reduced the TMI threshold due to the degree of saturation [9]. However, in Table 2, while the cladding diameter is maintained, with larger core diameter, the TMI threshold enhancement ratio (ER) between the counter-pumped and co-pumped schemes is reduced. Furthermore, we make some calculations of different commercial fibers with identical core diameter while the cladding diameters are different, and the results are listed in Table 3. The amplifier parameters of all these fibers in Tables 2 and 3 can be referred to in Table 1 in addition to the diameters of core and cladding. In Table 3, the result shows that ER increases with the larger cladding.

SRS is suppressed in the counter-pumped scheme corresponding to Fig. 3. The reason for SRS suppression is the B-integral reduction of the counter-pumped scheme, compared to that of the co-pumped scheme. In Raman fiber lasers, the SRS effect is supposed to result in heat generation as well as a quantum defect effect. For high-power Raman fiber lasers, the TMI effect can be induced by SRS [13]. In our experiment, we have lengthened the guided fiber (GDF) connected to the end of the fiber amplifier. We found that the temperature of the GDF increases compared to that of the residual. The results showed that the TMI threshold was decreased while the peak of the SRS in spectrum was increased. Obviously, SRS effect is strengthened and the TMI effect can be induced along the GDF. Therefore, except for gain saturation, suppression of SRS in the counter-pumped scheme results in the enhancement of TMI threshold.

In addition to utilizing the counter-pumped scheme to enhance the TMI threshold, we attempted to enhance the TMI threshold in the co-pumped fiber laser. Our first attempt at enhancing the TMI threshold was through the content of the seed; the TMI threshold can be enhanced by the seed with lower HOM content. Through our model calculation, shown in Fig. 6, less HOM content leads to higher TMI threshold. However, with a seed of smaller M^2 value, the TMI threshold has no obvious enhancement in our experiment. The reason for this is that the M^2 analyzer cannot determine the content of the HOM, and amplifier can excite the HOM due to coiling and splicing. In the second attempt, we considered the power of the seed; higher power seed can enhance the TMI threshold since the degree of gain saturation is strengthened, as shown in Fig. 7. In our experiment, we varied the power of the oscillator from several watts to tens of watts, and no evident enhancement of TMI threshold was observed. The major limitation is available pump power of this oscillator, and more detailed experiments should be followed. Therefore, compared with these two attempts, the counter-pumped scheme seems to be an effective way to enhance the TMI threshold in passive strategies.

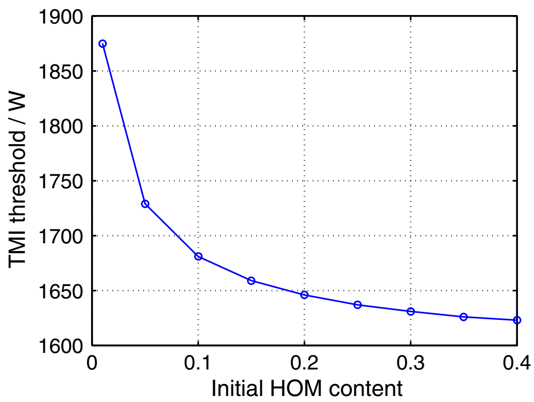

Fig. 6. TMI threshold of the co-pumped amplifier as a function of initial HOM content.

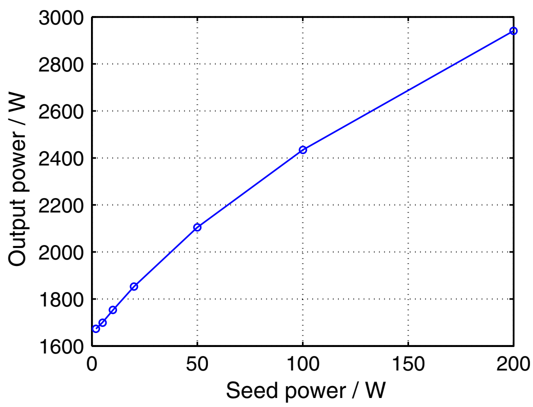

Fig. 7. Output power of the co-pumped amplifier as a function of seed power.

5. CONCLUSIONS

Passive strategies to enhance the TMI threshold are currently effective ways. Considering gain saturation, including signal and pump power saturation, the counter-pumped scheme can enhance the TMI threshold in our semi-analytical model. Generally, with larger cladding and smaller core, ER will be higher in the counter-pumped scheme. In our experiment, the counter-pumped scheme can be realized at 2 kW in a single-mode regime in an all-fiberized laser. The TMI threshold is enhanced at least 50%, which is limited by the available pump power. SRS and FWM are both suppressed in the counter-pumped scheme with narrower linewidth. It is preferred that the GDF connected to the end of amplifiers be shorter to avoid inducing SRS and TMI. Larger seed power and less initial HOM content injecting into the amplifiers can in theory enhance the TMI threshold. More detailed experiments should be performed. Furthermore, this 2 kW all-fiberized laser with the counter-pumped scheme is promising for power scaling in beam combination.

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REFERENCES

1. T. Eidam, C. Wirth, C. Jauregui, F. Stutzki, F. Jansen, H. J. Otto, O. Schmidt, T. Schreiber, J. Limpert, and A. Tunnermann, "Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers," Opt. Express **19**, 13218–13224 (2011).
2. C. Jauregui, T. Eidam, J. Limpert, and A. Tunnermann, "The impact of modal interference on the beam quality of high-power fiber amplifiers," Opt. Express **19**, 3258–3271 (2011).
3. A. V. Smith and J. J. Smith, "Mode instability in high power fiber amplifiers," Opt. Express **19**, 10180–10192 (2011).
4. K. R. Hansen, T. T. Alkeskjold, J. Broeng, and J. Laegsgaard, "Thermally induced mode coupling in rare-Earth doped fiber amplifiers," Opt. Lett. **37**, 2382–2384 (2012).
5. L. Dong, "Stimulated thermal Rayleigh scattering in optical fibers," Opt. Express **21**, 2642–2656 (2013).
6. C. Jauregui, J. Limpert, and A. Tunnermann, "High-power fibre lasers," Nat. Photonics **7**, 861–867 (2013).
7. C. Jauregui, H. J. Otto, F. Stutzki, F. Jansen, J. Limpert, and A. Tunnermann, "Passive mitigation strategies for mode instabilities in high-power fiber laser systems," Opt. Express **21**, 19375–19386 (2013).
8. R. Tao, P. Ma, X. Wang, P. Zhou, and Z. Liu, "1.3 kW monolithic linearly polarized single-mode master oscillator power amplifier and strategies for mitigating mode instabilities," Photon. Res. **3**, 86–93 (2015).
9. A. V. Smith and J. J. Smith, "Increasing mode instability thresholds of fiber amplifiers by gain saturation," Opt. Express **21**, 15168–15182 (2013).
10. K. R. Hansen and J. Laegsgaard, "Impact of gain saturation on the mode instability threshold in high-power fiber amplifiers," Opt. Express **22**, 11267–11278 (2014).
11. C. Jauregui, H.-J. Otto, S. Breitkopf, J. Limpert, and A. Tunnermann, "Optimizing high-power Yb-doped fiber amplifier systems in the presence of transverse mode instabilities," Opt. Express **24**, 7879–7892 (2016).
12. C. X. Yu, O. Shatrovoy, and T. Y. Fan, "All-glass fiber amplifier pumped by ultrahigh brightness pump," Proc. SPIE **9728**, 972806 (2016).
13. S. Naderi, I. Dajani, J. Grosek, and T. Madden, "Theoretical and numerical treatment of modal instability in high-power core and cladding-pumped Raman fiber amplifiers," Opt. Express **24**, 16550–16565 (2016).