

Coherent Beam Combining of Two Tm-doped Fiber MOPAs with Output Power of 50 W

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Abstract— Thulium-doped fiber lasers operating at $\sim 2\ \mu\text{m}$ band have significant application prospects in fields such as eye-safe lidar, remote sensing, medical care and nonlinear frequency conversion. However, due to thermal damage, mode instability and nonlinear effects, the output power level of single Tm-doped fiber laser was limited, which confined the development of Tm-doped fiber laser. Coherent beam combining (CBC) is an effective method to improve power level of fiber lasers. In this paper, we demonstrated CBC of two Tm-doped fiber master oscillator power amplifiers (MOPAs) with total output power reaching 50 W. The output powers of the both MOPAs can reach $\sim 25\ \text{W}$ when the pump power of each MOPA was $\sim 55\ \text{W}$. Single frequency dithering technique was used to implement active phase locking in feedback loop of the CBC system. When the feedback loop was implemented, phase noises below 700 Hz in the system were compensated effectively, and the far field intensity patterns were highly stable compared with the fluctuating patterns obtained when the feedback loop did not work. The fringe contrast was increased from ~ 0.34 in open loop to ~ 0.90 in closed-loop. These results indicate that the system we presented is a promising way to increase the output power of Tm-doped fiber lasers. Since the output power of the system is pump-limited, it's reasonable to believe that higher output power at $\sim 2\ \mu\text{m}$ could be obtained via CBC, if more channels are combined together and/or the power of each channel is further scaled up.

1. INTRODUCTION

In recent years, thulium-doped fiber lasers (Tm-doped fiber lasers, TFLs) operating at $\sim 2\ \mu\text{m}$ have attracted researchers' interests. With many unique advantages [1, 2], such as eye-safe, higher nonlinear threshold and wide tunable range, lasers operating at $\sim 2\ \mu\text{m}$ have significant application prospects in eye-safe lidar, remote sensing, medical care, nonlinear frequency conversion and other fields [3].

However, the output power of single mode Tm-doped fiber laser is limited due to thermal effect, mode instability, nonlinear effect and the brightness of pump source [4], which confines the development of Tm-doped fiber in various application prospects. Coherent beam combining (CBC) of fiber lasers can increase the output power while simultaneously maintain good beam quality. There have existed several approaches for CBC, including passive phasing techniques (such as self-organized laser array [5–8], self-imaging resonator technique [9], self-Fourier laser cavity [10]), and active phasing techniques based on stochastic parallel gradient descent (SPGD) algorithm [11], multi-dithering technique [12] and single frequency dithering technique [13]. Although the configuration of passive CBC system is simple and there is no need of feedback loops to control and compensate phase noises, the number of combined lasers is limited due to the decrease of combination efficiency [14].

In the previous studies on CBC of Tm-doped fiber lasers, the output power was below several tens of watts. In 2013, 20 W passive CBC of two TFLs was reported [15], which is the highest power level of TFLs' CBC as far as we know.

In this paper, we demonstrated CBC with the output power of 50 W from two Tm-doped fiber master oscillator power amplifiers (MOPAs), which significantly increased the output power of TFL at $\sim 2\ \mu\text{m}$. The CBC was realized by active phase locking using single frequency dithering technique [13] in feedback loop.

2. EXPERIMENTAL SETUP

The experimental setup of the CBC of two Tm-doped fiber MOPAs is shown in Fig. 1.

Two MOPAs consisted of seed laser (SL), pre-amplifiers (PA and amplifiers (Amplifier 1, Amplifier 2). A single frequency fiber laser, whose center wavelength was 1971.5 nm, served as the seed laser. The output power of seed laser was 7.5 mW. Then the output power of seed laser was pre-amplified to 316 mW via PA, which consisted of a 1550 nm fiber laser, a 1550/2000 nm wavelength division multiplexer and 2.5 m single cladding Tm-doped fiber (6/125 μm). The output laser of PA was divided into two parts by a 10/90 coupler. The 10% part (29.6 mW) served as signal

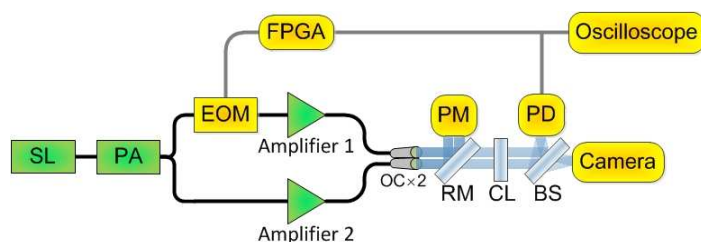


Figure 1: (Color online) Experimental setup of CBC of two Tm-doped fiber amplifiers in MOPA configuration. SL: seed laser; PA: pre-amplifier; EOM: electro-optical modulator; OC: optical collimator; RM: reflect mirror; PM: power meter; CL: convex lens; BS: beam splitter; PD: photodetector with pinhole; FPGA: field programmable gate array.

laser in one channel, which contained an electro-optical modulator (EOM) and Amplifier 1. And the 90% part (274 mW) served as signal laser in the other channel, which contained Amplifier 2. The bandwidth of EOM was 100 MHz at 2 μm . Two amplifiers (Amplifier 1 and Amplifier 2) were both made up of two 793 nm LDs, a $(6 + 1) \times 1$ signal pump combiner and 3.4 m double cladding Tm-doped fiber (25/250 μm). Thus, two MOPAs can output 25.0 W and 23.9 W via amplifiers, respectively.

And the output laser beams were collimated by two optical collimators (OC). A high reflectivity mirror (RM, $\sim 99\%$) and a power meter (PM) were used to measure the output power from two collimators. Only a small amount of power could be transmitted through reflect mirror, which was employed to detect the far field intensity patterns and control the feedback loop. Convex lens (CL) and beam splitter (BS) were used to obtain far field intensity patterns and cast them into camera and the pinhole of photodetector (PD). The camera recorded far field intensity patterns. And photodetector transformed optical intensity signal into electric signal to drive field programmable gate array (FPGA) and control electro-optical modulator (EOM). Field programmable gate array employed in our experiment was based on single frequency dithering technique to realize phase locking of two MOPAs. There existed optical isolators after each seed laser, pre-amplifiers and amplifiers in MOPAs to protect system.

3. RESULTS AND DISCUSSION

Based on experimental setup in Fig. 1, we measured the output power of two MOPAs separately via power meter. And experimental results were shown in Fig. 2. Output power of both MOPAs can reach to ~ 25 W when pump power was ~ 55 W. therefore, the combined output power can reach up to ~ 50 W.

An optical spectrum analyzer (OSA, 0.05 nm resolution) was used to measure the spectrum of output laser. As shown in Fig. 3, the spectrum of output laser centered at ~ 1971.5 nm.

After each MOPA's output power and their combined spectrum characteristics obtained, we confirmed that the output laser beams of these two MOPAs could be coherently combined and the output power would be ~ 50 W. In this experiment, coherent beam combining was realized by active

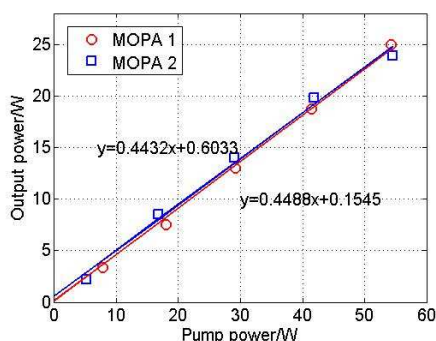


Figure 2: (Color online) Characteristics of each MOPA's output power.

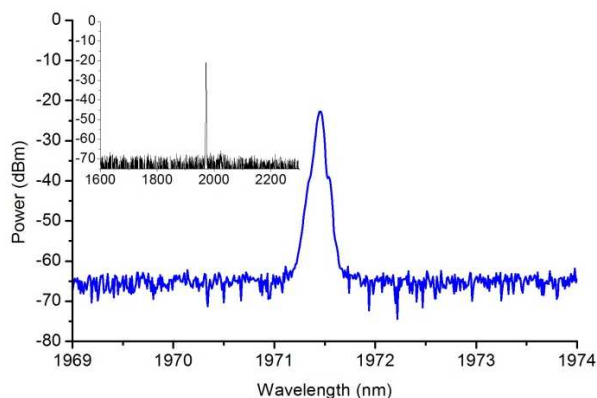


Figure 3: (Color online) Spectrum of output laser.

phase locking of two MOPAs using single frequency dithering technique. Field programmable gate array was employed to implement active phase locking by accepting signals from photodetector and controlling electro-optical modulator, which formed a feedback loop as shown in Fig. 1. Then we studied the changes of far field output patterns by switching the state of feedback control circuit. When system was in the open-loop state, the far field output patterns observed was like the one shown in Fig. 4(a), whose intensity was fluctuating all the time. While the patterns in closed-loop state was shown in Fig. 4(b), whose intensity concentrated in the center and was highly stable. The fringe contrast was increased from ~ 0.34 in open loop state to ~ 0.90 in closed-loop state. Thus, it can be concluded that the intensity of output coherently combined power could be increased and centered using active phase locking technique.

According to Fig. 5, phase noises below 700 Hz were compensated when system was in closed-loop state, which suggested that the output power in the center of laser beam increased significantly.

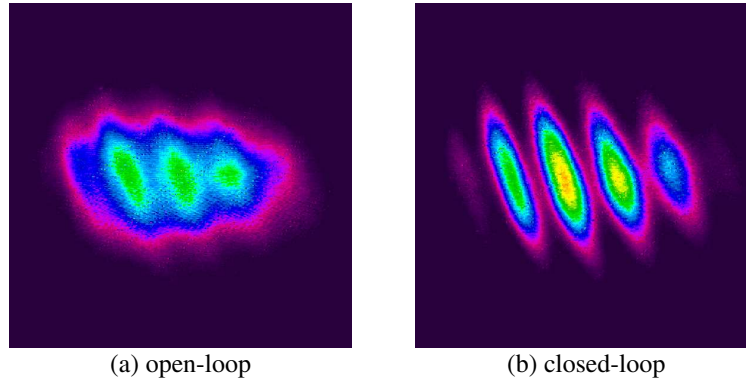


Figure 4: (Color online) Far field output patterns in (a) open and (b) closed state of feedback loop.

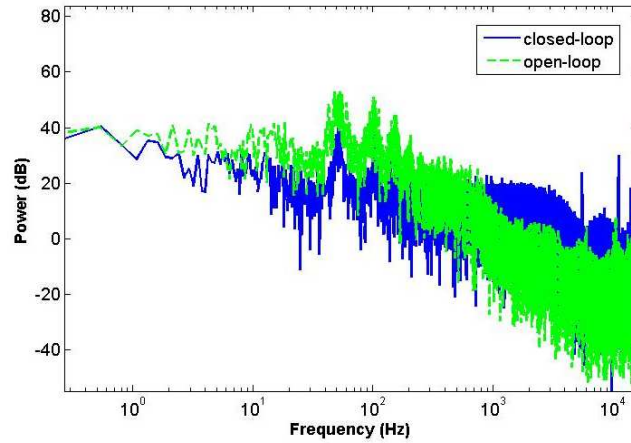


Figure 5: (Color online) Spectral density of output power. Green dotted line: open-loop; blue solid line: closed-loop.

4. CONCLUSIONS

In this paper, we presented CBC of 50 W at 1971.5 nm obtained from two Tm-doped fiber MOPAs using single frequency dithering technique for active phase locking. Phase noises below 700 Hz in the system were compensated effectively, and the fringe contrast was increased from ~ 0.34 to ~ 0.90 .

Since the output power of the system is pump-limited, it's reasonable to believe that higher output power of Tm-doped fiber lasers could be obtained in the CBC system we presented, if more channels are combined together and/or the power of each channel is further scaled up.

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