Passive coherent beam combining of four Yb-doped fiber amplifier chains with injection-locked seed source

Yifeng Yang,[1] Man Hu,[1] Bing He,[1,2] Jun Zhou,[1,3] Houkang Liu,[1] Shoujun Dai,[1] Yunrong Wei,[1] and Qihong Lou[1]

[1]*Shanghai Key Laboratory of All Solid-State Laser and Applied Techniques, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*

[2]*email: bryanho@siom.ac.cn*

[3]*email: junzhousd@siom.ac.cn*

Received November 13, 2012; revised December 30, 2012; accepted February 7, 2013; posted February 8, 2013 (Doc. ID 179842); published March 11, 2013

An injection-locked fiber laser is introduced to the passive fiber laser coherent beam combination with all-optical feedback loop. A coherent beam combining system with two-dimensional four Yb-doped fiber amplifier chains is established, and the injection-locked fiber laser works as a switchable seed source. The 1064 nm output laser of the injection-locked fiber laser is extinguished automatically as the feedback injection power is high enough, and the injection-locked fiber laser acts as an amplifier for the feedback laser with 7.4 dB gains. We find that the phase-locked far-field interference pattern of our system with seed laser extinguished is stable, and the visibility is up to 91.5%, which is slightly higher than the prevalent method with auxiliary seed laser (88.2%).

OCIS codes: 140.3298, 140.3520.

Coherent beam combining (CBC) of fiber lasers and amplifiers has attracted increasing attentions due to its capability to scale fiber lasers to high power levels [1–3] and overcome the limits set by the nonlinear optical process of single fibers [4–6]. Passive CBC with an all-optical feedback loop is simple in design and operation, which has experienced a continuous improvement in recent years [7,8]. An auxiliary seed laser is necessary in passive CBC, which feeds the amplifier chains continuously, saturates the gain to safe levels, which prevents accidental pulses from growing to dangerous levels [9,10]. In order to improve the visibility of the far-field interference pattern when the phase locking is achieved, the seed laser needs to be turned off. However, the amplifiers may be damaged by self-oscillations without the seed laser. As a result, the protection of the amplifier chains and the improvement of the visibility of the far-field pattern becomes a dilemma. Recently, the theory and application of laser injection locking have been emphasized [11–13]. Thanks to its power ratio tunable feature, the injection-locked fiber laser can be used in a passive CBC system to solve this problem [14].

In this Letter, we will demonstrate passive CBC of four Yb-doped fiber (YDF) amplifier chains with an injection-locked seed laser. An injection-locked YDF laser is set up, and a passive CBC system with two-dimensional four YDF amplifier chains is established to verify the function and stability of it. The phase-locked far-field pattern is stable, and the visibility of it is up to 91.5% (the total CBC output power is 20 W), which is slightly higher than the passive CBC system with an auxiliary seed laser.

The schematic diagram of the injection-locked fiber laser proposed in this Letter is shown in Fig. 1. Its main structure is a ring cavity laser consisting of a 2×2 coupler (50:50), a 976/1064 nm WDM for 976 nm pump laser injection, a 2.5 m single-mode (SM), polarization maintained (PM) 6/125 μm YDF, a PM isolator and a fiber Bragg grating (FBG). The reflectivity of the FBG is > -30 dB–1064 nm laser. Feedback laser is injected into the fiber laser from the end of FBG. The output laser emits from one leg of the 2×2 coupler. The PM isolator plays an important role in the polarization selection. The degree of polarization of the output laser is 99.0%. The performance of the injection-locked fiber laser is studied without any feedback injection (under free running). The central wavelength of the output laser is 1063.9 nm, with a 0.13 nm FWHM. Figure 2 shows the relationship between the output power and the pump power. The slope efficiency of the injection-locked fiber laser is 20.5%.

Figure 3 illustrates the experimental apparatus for the passive CBC of four YDF amplifier chains with an injection-locked seed source. The essential components of the ring-geometry resonator include an array of four SM/PM fiber amplifier chains, which contain cascaded 1 and 30 W YDF amplifiers, a beam splicing system consisting of an array of collimators and reflectors, a beam splitter (BS1) that removes about 8% of the output beam for the subsequent optical structure, a Fourier transform lens that projects the collimated array onto a feedback fiber (FF), a second beam splitter (BS2) that removes about 10% of the light behind the transform lens to the CCD camera (Spiricon SP620U) to observe the far-field interference pattern, and a 1–4 fused fiber splitter, which recouples the light from the FF back to the amplifier chains. The FF, which is placed at the focal point of the transform lens, is a SM/PM 6/125 μm fiber. The feedback laser is amplified by a two-stage preamplifier chain, and

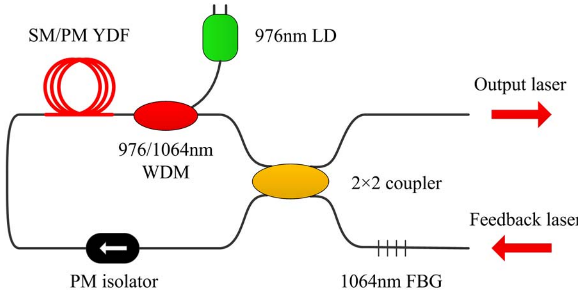

Fig. 1. (Color online) Schematic diagram of the injection-locked fiber laser.

0146-9592/13/060854-03$15.00/0

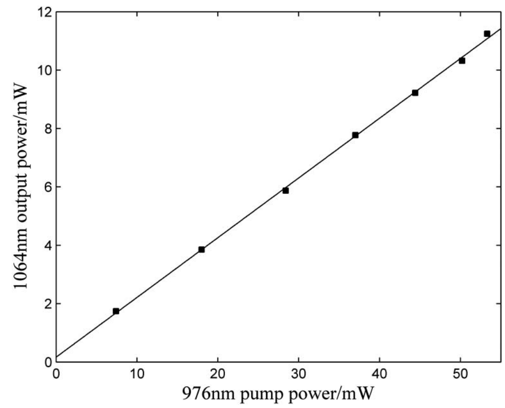

Fig. 2. 1064 nm output power of the injection-locked fiber laser versus the 976 nm pump power.

injected into the injection-locked fiber laser from the end of the FBG. The isolators are placed behind all of the amplifiers and used for preventing the return light. The output light of the injection-locked fiber laser gets into a 2×2 coupler (50:50), half of the power is coupled into the amplifier chains array, and the other half emits from the flat-cleaved (FC) fiber end. Thus, the spectrum of the FC end output laser represents the output spectrum of the injection-locked fiber laser. The unused leg of the coupler is angle cleaved (AC). The device in the solid box of Fig. 3 is a comparative experiment, which is a 1064 nm LD auxiliary seed laser coupling into the all-optical feedback loop by a 2×2 coupler (50:50).

The injection-locked fiber laser in our system works as follows. The injection-locked fiber laser under free running supplies a stable seed laser for the system to start the oscillation process. The feedback laser collected from the FF is injected into the injection-locked fiber laser. As the feedback power is high enough, the seed laser is extinguished. If the feedback loop is interrupted by accident, the seed laser comes up immediately to prevent the amplifier chains damaging by the self-oscillations.

To investigate the working mechanism of our system, phase locking is achieved with separate total output

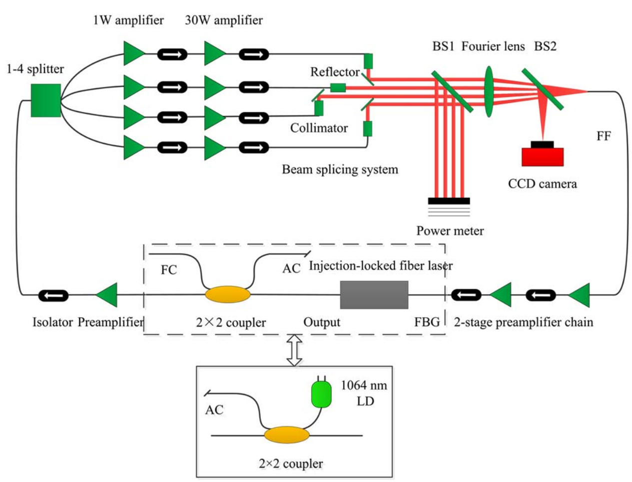

Fig. 3. (Color online) Experimental apparatus of the passive CBC of four YDF amplifier chains with an injection-locked fiber laser seed source. The device in the solid box is the contrast experiment with an auxiliary 1064 nm seed laser.

powers. The four laser beams from the collimators are tiled side by side by the reflectors into a 2×2 array whose fill factor is 0.85. Set the total output power to be 4 W (1 W for each amplifier chain), the power transformed to the input plane of the FF is 288 mW, of which 30.2 μW (about 0.01%) is collected by the FF as the phase locking is achieved. Figure 4(a) shows the output spectrum of the FC end when the pump power of the injection-locked fiber laser is 28.4 mW, which shows the 1063.9 nm seed laser and the 1067.9 nm feedback laser are both propagating in the all-optical feedback loop. The extinguishing of the seed laser occurs when the pump power decreases to 18 mW, and at this time, there is only 1067.9 nm laser propagating in the loop, as shown in Fig. 4(b). The 2.1 mW feedback laser is amplified by the injection-locked fiber laser to 4.4 mW with 7.4 dB gains. Increasing the total output power to 20 W (5 W for each amplifier chain), the power on the input plane of the FF is 1.44 W, and similar to the previous case, about 0.01% (142.1 μW) is collected by the FF. When the pump power is larger than 28.4 mW, the seed laser can coexist with the feedback laser in the loop. Figure 4(c) shows the output spectrum with 44.4 mW pump power, including the 1063.9 nm seed laser and the 1068.2 nm feedback laser. Decreasing the pump power to 28.4 mW, we find that the seed laser is extinguished. The output is only a 1068.2 nm laser, as shown in Fig. 4(d). The 3.1 mW feedback laser is amplified to 6.5 mW with ~7.4 dB gains by the injection-locked fiber laser. The results obtained from the two situations show that the injection-locked fiber laser in the passive CBC system has a pump power upper bound to extinguish the seed laser. The pump power upper bound is directly proportional to the total output power of the passive CBC system. Furthermore, when the seed laser is extinguished, the injection-locked fiber laser acts as an amplifier for the feedback laser with 7.4 dB gains.

Experimental and calculated far-field intensity distributions with and without phase locking of four laser beams at the total output power of 20 W are shown in Fig. 5. Figure 5(a) shows the far-field interference pattern of the four independent beams when the system is in an open loop, which is constantly moving at irregular paces and directions. The calculated far-field intensity distribution of the four phase-locked beams is shown in Fig. 5(b).

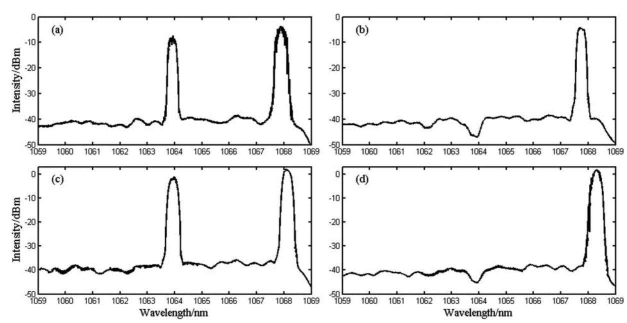

Fig. 4. Spectrum of the output laser of injection-locked fiber laser with different CBC total output powers and pump powers. (a) Output power = 4 W, pump power = 28.4 mW. (b) Output power = 4 W, pump power = 18 mW. (c) Output power = 20 W, pump power = 44 mW. (d) Output power = 20 W, pump power = 28.4 mW.

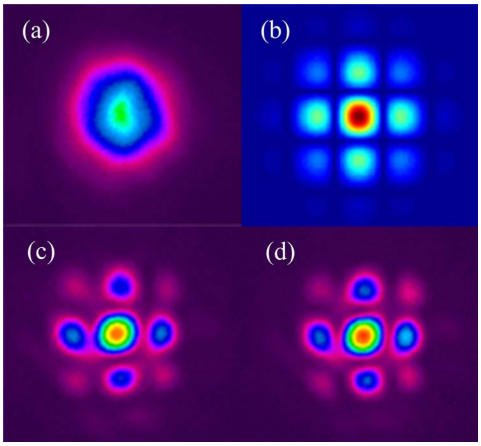

Fig. 5. (Color online) Far-field interference pattern of four independent beams (the total CBC output power is 20 W): (a) far-field pattern in an open loop, (b) calculated far-field phase-locked pattern, (c) far-field phase-locked pattern of the passive CBC with an auxiliary seed laser, and (d) far-field phase-locked pattern with the seed laser of the injection-locked fiber laser is extinguished.

Figure 5(c) shows the far-field pattern of the four phase-locked beams with an auxiliary 1064 nm seed laser, which is the comparative experiment. The visibility of the pattern is 88.2%. We define the visibility by the formula $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, in which $I_{\max}$ and $I_{\min}$ are the maximum intensity and the adjacent minimum intensity of the primary maximum on the intensity distribution pattern, respectively. Figure 5(d) shows the far-field interference pattern with the seed laser of injection-locked fiber laser is extinguished. The pattern is stable and robust, and the visibility of it is up to 91.5%. As evident, there is a good agreement between the experimental and calculated results of phase-locked far-field interference pattern, and the performance of the passive CBC system with the injection-locked seed source is better than the system with the auxiliary seed.

In conclusion, we have proposed and demonstrated passive CBC of four YDF amplifier chains with an injection-locked seed laser. The phase locking of four laser beams is achieved. The 1063.9 nm seed laser of the injection-locked fiber laser is extinguished when the pump power is lower than the upper bound. As the seed laser is extinguished, the far-field phase-locked intensity distribution of the four beams is stable and robust, and the visibility is 91.5%, which is slightly better than the system using an auxiliary seed laser (88.2%). The setup is equivalent to a standard scheme in terms of output power and beam profiles but with high security and has a more compact form.

This work is partly supported by the National Science and Technology Major Project (No. 2010ZX04013), the National High Technology Research and Development Programs of China (863 Program) (No. 2011AA030201), and the National Natural Science Foundation of China (No. 60908011).

References

1. N. R. Van Zandt, R. J. Bartell, S. Basu, J. E. McCrae, and S. T. Fiorino, Opt. Eng. **51**, 104301 (2012).
2. E. J. Bochove and S. A. Shakir, IEEE J. Quantum Electron. **15**, 320 (2009).
3. B. He, Q. Lou, W. Wang, J. Zhou, Y. Zheng, J. Dong, Y. Wei, and W. Chen, Appl. Phys. Lett. **92**, 251115 (2008).
4. H. Liu, B. He, J. Zhou, J. Dong, Y. Wei, and Q. Lou, Opt. Lett. **37**, 3885 (2012).
5. H. Liu, Y. Xue, Z. Li, B. He, J. Zhou, Y. Ding, M. Jiao, C. Liu, Y. Qi, Y. Wei, J. Dong, and Q. Lou, Chin. Phys. Lett. **29**, 044204 (2012).
6. S. J. Augst, T. Y. Fan, and A. Sanchez, Opt. Lett. **29**, 474 (2004).
7. J. Lhermite, A. Desfarges-Berthelemot, V. Kermene, and A. Barthelemy, Opt. Lett. **32**, 1842 (2007).
8. Y. Xue, B. He, J. Zhou, Z. Li, Y. Fan, Y. Qi, C. Liu, Z. Yuan, H. Zhang, and Q. Lou, Chin. Phys. Lett. **28**, 054212 (2011).
9. B. He, Q. Lou, J. Zhou, J. Dong, Y. Wei, D. Xue, Y. Qi, Z. Su, L. Li, and F. Zhang, Opt. Express **14**, 2721 (2006).
10. S. A. Shakir, B. Culver, B. Nelson, Y. Starcher, G. M. Bates, and J. J. W. Hedrick, Proc. SPIE **7070**, 70700N (2008).
11. S. Pan, Z. Tang, D. Zhu, D. Ben, and J. Yao, Opt. Lett. **36**, 4722 (2011).
12. P. Zhou, Y. Ma, H. Ma, and Z. Liu, Opt. Lett. **35**, 950 (2010).
13. M. Katsuragawa and T. Onose, Opt. Lett. **30**, 2421 (2005).
14. Z. Li, J. Zhou, B. He, H. Liu, C. Liu, Y. Wei, J. Dong, and Q. Lou, Chin. Phys. Lett. **29**, 074203 (2012).