



Coherent beam combining of two all-PM thulium-doped fiber chirped pulse amplifiers

Bo Ren¹ · Hongxiang Chang¹ · Can Li¹ · Tao Wang¹ · Kaikai Jin¹ · Jiayi Zhang¹ · Kun Guo¹ · Rongtao Su^{1,2,3} · Jinyong Leng^{1,2,3} · Pu Zhou¹

Received: 20 February 2024 / Accepted: 29 April 2024
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Abstract

In this paper, we report a coherent beam combining (CBC) system that involves two thulium-doped all-polarization maintaining (PM) fiber chirped pulse amplifiers. Through phase-locking the two channels via a fiber stretcher by using the stochastic parallel gradient descent (SPGD) algorithm, a maximum average power of 265 W is obtained, with a CBC efficiency of 81% and a residual phase error of $\lambda/17$. After de-chirping by a pair of diffraction gratings, the duration of the combined laser pulse is compressed to 690 fs. Taking into account the compression efficiency of 90% and the main peak energy proportion of 91%, the corresponding peak power is calculated to be 4 MW. The laser noise characteristics before and after CBC are examined, and the results indicate that the CBC would degrade the low frequency relative intensity noise (RIN), of which the integration is 1.74% in [100 Hz, 2 MHz] at the maximum combined output power. In addition, the effects of the nonlinear spectrum broadening during chirped pulse amplification on the CBC efficiency are also investigated, showing that a higher extent of pulse stretching is effective in alleviating the spectrum broadening and realizing a higher output power with decent combining efficiency.

Keywords Coherent beam combining · Thulium-doped fiber laser · High-average power · Chirped pulse amplifier

1 Introduction

Over the last decade, the high-power ultrafast laser with an operation wavelength extending to the 2.0 μm range has been attracting increasing research interests, mostly driven by its applications in various fields such as remote sensing, material processing, medical care, and mid-infrared broadband supercontinuum generation [1–6]. Specifically, the thulium-doped fiber (TDF) chirped pulse amplifier (CPA) has been recognized as a promising candidate for generating high

average power ultrafast lasers at 2.0 μm , thanks to the merits of fiber lasers in terms of high conversion efficiency, efficient heat dissipation and excellent beam quality [7–11]. With the recent emergence of large mode area (LMA) thulium-doped photonic crystal fiber, 2 μm ultrafast laser with up to 1-kW average power has been realized from TDF-CPA system [12]. Whereas owing to the tailored structure of the LMA fiber, previous demonstrations concerning high power ultrafast TDF amplifiers were mostly implemented with free-space coupled configuration, leading to a compromise of the compactness and the robustness of the laser system [13–16]. Moreover, due to the spectral phase distortions and thermal lens effect induced by the remarkable water vapor absorption lines at ~ 1900 nm, the amplified laser is prone to be deteriorated by strong beam deformation and nonlinear phase accumulation [17]. As such, an all polarization maintaining (PM) fiberized TDF amplifier is highly preferred for realizing a high quality and reliable operation of the laser source.

It should be noted that in an all-fiber laser amplifier, the active and passive fibers with relatively small diameter for fusion splicing and long transmission length for connection would cause significant nonlinear effects, hindering the scale

✉ Can Li
lc0616@163.com

✉ Pu Zhou
zhoup203@163.com

¹ College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China

² Nanhu Laser Laboratory, National University of Defense Technology, Changsha 410073, China

³ Hunan Provincial Key Laboratory of High Energy Laser Technology, National University of Defense Technology, Changsha 410073, China

of the output power [18, 19]. At present, the maximum output average power from the all-PM fiber CPA in the 2.0 μm range is 314 W [20], which is much lower than that from the free-space coupled counterparts. To further enhance the laser power, an alternative scheme is the coherent beam combining (CBC), which partitions the laser signal into multiple parallel amplification channels and subsequently coherently combines them into a single output beam with a power scaling factor being nearly the number of channels employed, thereby effectively mitigating the impact of nonlinearities and thermal effects of a single fiber amplifier [21–23]. A precondition for high efficiency CBC is the phase-locking between channels, which is usually realized by real-time controlling of phase modulators via active phase control algorithms such as multi-frequency dithering and stochastic parallel gradient descent (SPGD) algorithm [24–27]. Currently, significant progress has been achieved in the 1.0 μm range [28–32], and the highest average power of 10 kW [28] and single pulse energy of 32 mJ [31] were respectively obtained from coherently combined multiple fiber CPA channels. Regarding the 2.0 μm range, there are also efforts concerning the CBC [33–35], the correspondingly realized maximum pulse energy is up to 1.65 mJ [36] in femtosecond fiber lasers. Nevertheless, the employment of free-space coupled amplification channels in those demonstrations renders the system fragile and cumbersome, as well as difficult to extend the combining channels. More compact CBC of ultrafast lasers at 2.0 μm based on the all-fiber amplification channels has not yet been reported.

In this work, we experimentally demonstrated a two-channel CBC system based on all-PM TDF-CPA. The phase locking was realized through incorporating into one of the channels a high-speed fiber stretcher that was controlled by the SPGD algorithm, while an optical delay line inserted into the other channel was manually adjusted to guarantee the coherent interference between combined beams. A maximum combined average power of 265 W was obtained with the de-chirped pulse duration of 690 fs.

2 Experimental setup

The experimental setup of the coherently combined system based on two channels of all-PM TDF-CPA is illustrated in Fig. 1. The seed laser was a commercial mode-locked TDF oscillator with a central wavelength of 1957 nm and a 3-dB bandwidth of 46.5 nm (Fig. 2a). In addition, it emitted 180 mW positively chirped pulses with a repetition frequency of 80 MHz and a duration of 3.68 ps, as respectively shown in Fig. 2b and c. The pulse duration was temporally stretched to around 800 ps by using two stages of stretchers to manage the nonlinear effects. Each pulse stretcher consists of a circulator and a PM chirped fiber Bragg grating (CFBG) with

a reflectivity of 15% and a positive second-order dispersion of $+34.159 \text{ ps}^2$. Meanwhile, in order to compensate for the insertion loss ($\sim 10 \text{ dB}$) caused by the CFBG, a pre-amplifier constructed with a 4-m-long PM thulium-doped single-mode fiber (TSF) with a core/cladding diameter of $9/125 \mu\text{m}$ was employed to booster the signal power to $\sim 300 \text{ mW}$, with the core-pumping by a high-power 1550 nm fiber laser through a wavelength division multiplexer (WDM). Figure 2d shows the measured laser spectrum after the pre-amplification, and it is observed that the 3-dB bandwidth was narrowed to 25.5 nm, as a result of the limited reflection bandwidth of the CFBG. After passing through an isolator and a 5:5 splitter, the laser signal was divided and respectively launched into two separate amplification channels that have similar configuration. Both channels include two stages of amplification with the same length of the active fiber and pigtailed to ensure commensurate accumulation of the nonlinear phase shift. In the first amplification stage, a 2.5-m-long double-clad PM-TDF with a core/cladding diameter of $10/130 \mu\text{m}$, a core numerical aperture (NA) of 0.15, and an absorption coefficient of 4.7 dB/m at 793 nm was utilized to enhance the signal power to 6 W, which was realized by the pumping of a 793 nm multi-mode laser diode via a combiner. Between the amplification stages, an isolator was employed to block the back-scattered light. The main amplifier was constructed with four commercial 793 nm laser diodes that deliver a total maximum power of 400 W, a $(6+1) \times 1$ pump/signal combiner, and a 5-m-long commercial PM-LMA-TDF which has a core/cladding diameter of $25/400 \mu\text{m}$, a core NA of 0.09, and an absorption coefficient of 2.4 dB/m at 793 nm. Moreover, the PM-LMA-TDF was coiled in a runway type and temperature controlled by an aluminum heat sink, which was coordinately water-cooled with a temperature of $\sim 12^\circ\text{C}$. Subsequently, the amplified laser of the two channels were respectively emitted from a fiber collimator that incorporated with a cladding power stripper, and then passed through a dichroic mirror to separate from the residual pump.

To realize CBC of the two amplification channels, a fiber stretcher with a total length of 10 m and a stretch accuracy of $0.2 \mu\text{m}/\text{V}$ was incorporated into channel2 for real time phase locking between the channels. In addition, an electronically controlled fiber optical delay line (ODL) was inserted into channel1 to compensate for the optical path difference with a compensation range of 3 cm and an accuracy of 100 μm , enabling the realization of high fringe contrast for the coherent interference of the combined beams. The laser beams were orthogonally coincided at a polarization beam combiner (PBC1), prior to which half wave plates (HWPs) were utilized to adjust the polarization directions and guarantee orthogonal polarization overlapping. The combined beam was then passed through another HWP and PBC2 for diagnosing the combining efficiency. In principle, coherent polarization combining of two orthogonally polarized beams

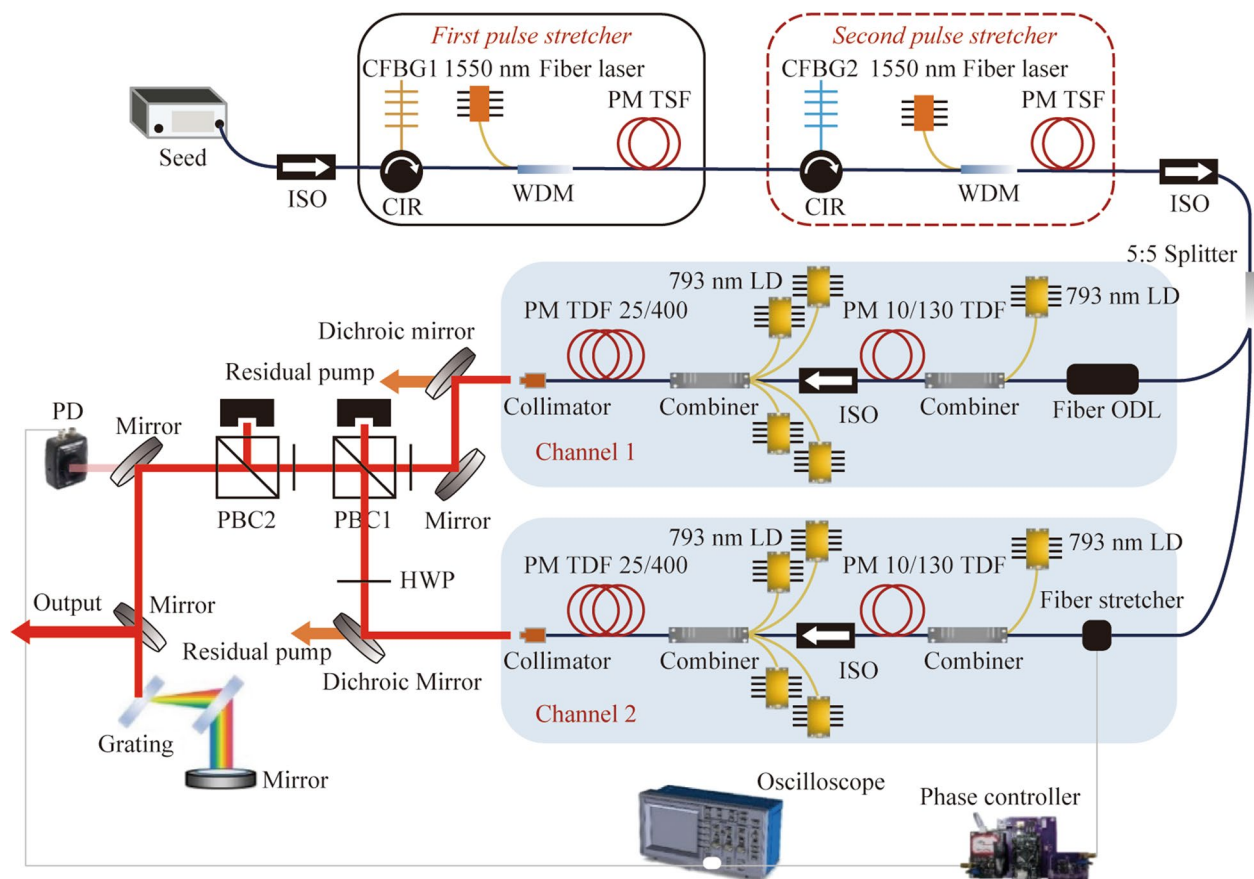


Fig. 1 Experimental setup of the CBC system based on two channels of all-PM TDF-CPA. ISO: isolator, CFBG: chirped fiber Bragg grating, CIR: circulator, WDM: wavelength division multiplex, LD: laser diode, ODL: optical delay line, PBC: polarization beam combiner, HWP: half wave plate, PD: photoelectric detector

would generate a single linearly polarized beam with high polarization extinction ratio (PER). After that, a reflective mirror was used to reflect the combined beam to a folded Treacy grating compressor, which was constructed by utilizing a transmission diffraction grating pair with line density of 800 l/mm for pulse de-chirping. Moreover, the transmitted laser signal from the mirror was detected by a photodetector, which cooperated with an oscilloscope and a phase controller for real-time controlling the fiber stretcher based on the SPGD algorithm.

3 Results and discussion

The efficiency and output power of the CBC were recorded and depicted in Fig. 3a. When the main amplifiers were unpumped, the transmitted power through PBC2 was 1.6 W with phase locking. By calculating the ratio of the transmitted output power to the input power through PBC2, the corresponding combining efficiency was ~86%. Compared with previous demonstrations, the relative lower combining

efficiency was mainly attributed to the limited compensation accuracy of the ODL. With increasing the pump power of the main amplifier, the combining efficiency was tardily decreased to 81%, and a pump power limited output power of 265 W was obtained. Figure 3b and c show respectively the normalized temporal intensity fluctuations of the combined laser with open and closed loop at the combined output power of 1.6 and 265 W. It is noted that at each of the measured power level, the ODL in channel1 was manually adjusted to maintain a highest possible contrast of the intensity fluctuation under the open loop regime, as the thermal effect in the main amplifier would induce drifting of the optical delay and weaken the interference effect. It can be seen from the figure that in the open loop regime, the contrast of the intensity fluctuations with zero and maximum pumping of the main amplifiers are roughly commensurate, indicating that the coherence of the laser changed hardly after the power scaling. Whereas in the condition of closed loop as shown in Fig. 3c, the intensity fluctuations minimized significantly and its characteristic parameters can be leveraged to estimate the residual phase error of the CBC system [37],

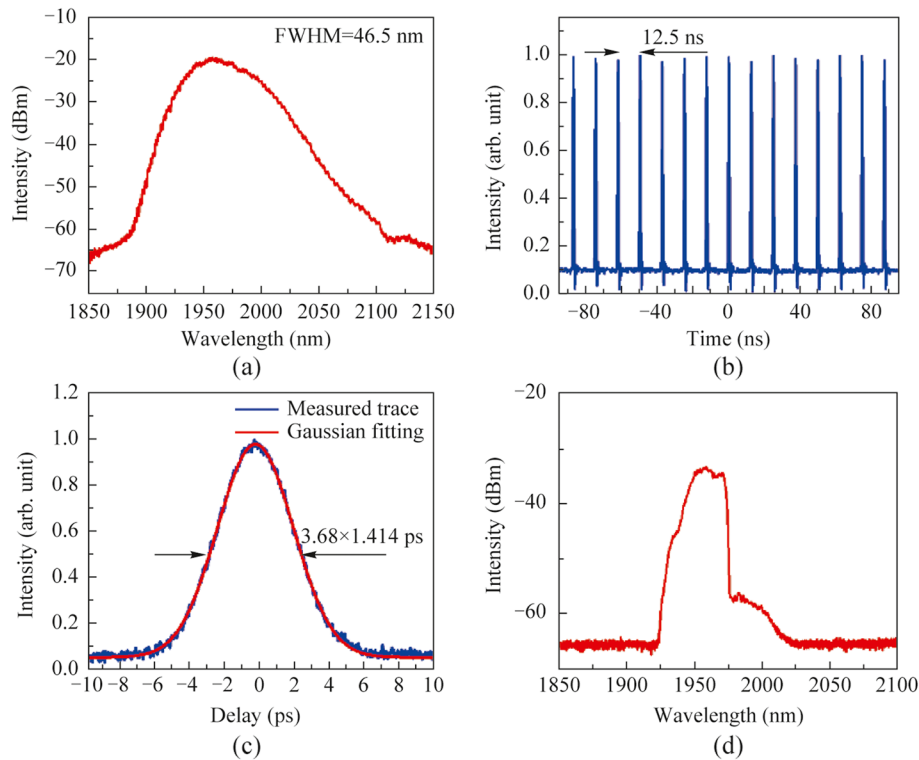


Fig. 2 **a** Optical spectrum, **b** pulse train and **c** pulse duration of the seed laser; **d** spectrum of the laser signal after the pre-amplification with core-pumping

the residual phase error at the maximum output power of 265 W was calculated to be $\sim \lambda/17$. Moreover, occasionally dropping of the combined intensity (more than 50%) is observed from Fig. 3c, and it is primarily attributed to the restricted voltage range of the phase controller and the slow response of the fiber stretcher. Regarding the output beam profiles, the randomly varied profile of the combined beam with open loop immediately changed into a stable Gaussian shape upon closing the controlling loop at the maximum combined power of 265 W, as shown in Fig. 3d.

Figure 4a shows the optical spectra of the single amplification channels and the CBC at the maximum output power of 265 W. Thanks to the larger extent of pulse stretching, the spectral broadening induced by the nonlinear effect was trivial and the laser spectra roughly preserved that of the seed before splitting. The B-integral of the two amplification channels were respectively calculated as 0.94 and 1.09, indicating that the laser pulse was basically amplified in a quasi-linear manner and the slight difference in profile of the output spectra of the two channels, while the coherently combined spectrum basically mimicked the broader version. The corresponding pulse autocorrelation traces after compression are depicted in Fig. 4b. It is noted that in order to realize a shorter

compressed pulse, the high-order dispersion of CFBG2 in Fig. 1 was coordinately adjusted via an engineered temperature profile to compensate for the accumulated nonlinear phase. With a superior compression efficiency of 90%, the Lorentz fitted pulse width was 690 fs with a main peak energy proportion of 91%, corresponding to a single pulse energy of 3 μ J and a peak power of 4 MW.

Unlike conventional CBC of narrow linewidth laser with long coherence length, the ultrafast laser generally involves nonlinear amplification and significant spectral broadening, rendering it more challenging to realize a high combining efficiency. In subsequent experiments, the impact of spectrum broadening during chirped pulse amplification and the controlling accuracy of the optical path difference on the CBC efficiency was further investigated. By removing the second pulse stretcher in Fig. 1, the pulse duration of the seed laser was stretched to only ~ 400 ps. As shown in Fig. 5a, with the increase of the pump power, the combining efficiency significantly diminished to 65% at a combined output power of 172 W. As shown in Fig. 5b, the spectra of the amplification channels and the CBC with closed loop were broadened significantly compared with that of the seed laser. In addition, the amplified output power of the two channels were respectively 124 and 143 W, corresponding

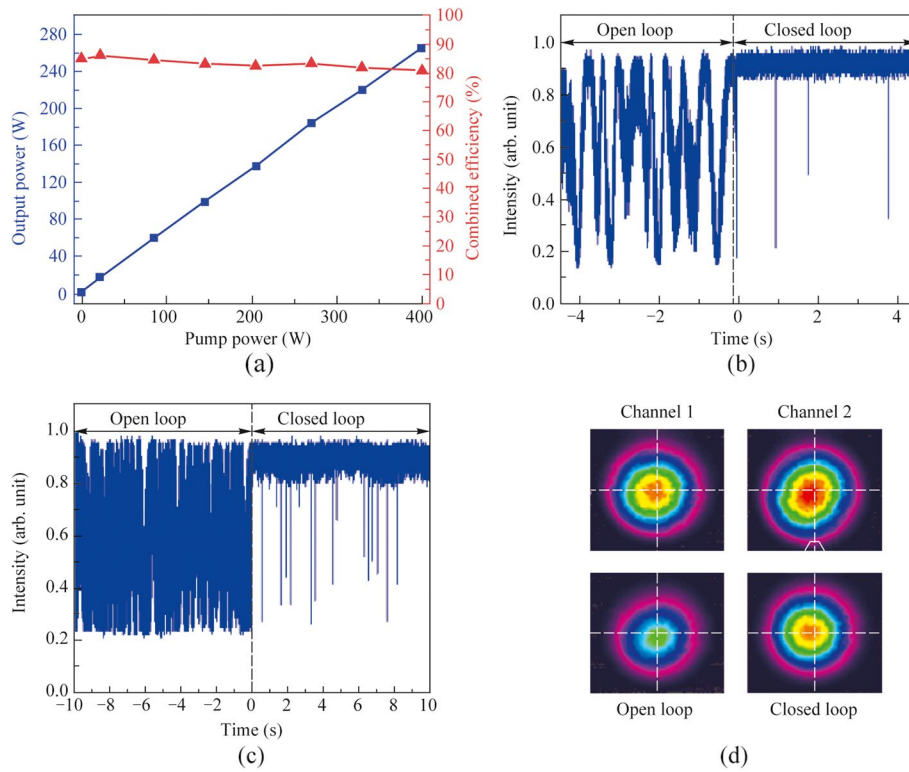


Fig. 3 Output characteristics of the CBC system: **a** output power and combining efficiency versus the pump power of the main amplifiers; normalized temporal intensity fluctuations of the combined laser before and after phase locking (i.e., open loop and closed loop) at the output power of **b** 1.6 W and **c** 265 W, respectively; **d** beam profiles of respectively the output of the two amplification channels, and that of the CBC with the open and closed loop under the operation power of 265 W

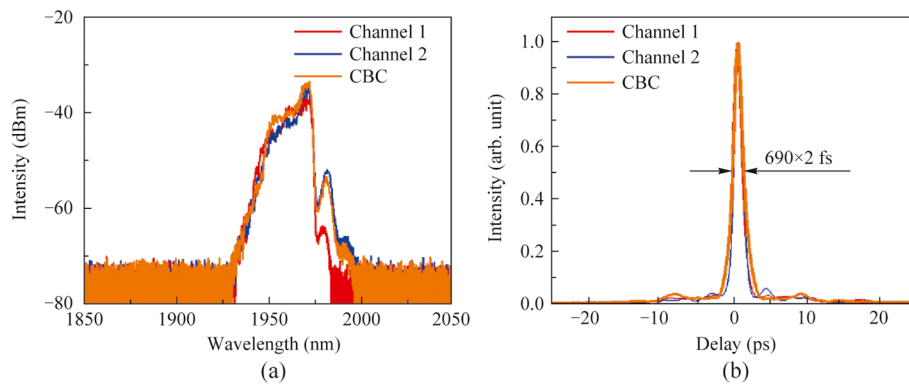


Fig. 4 Output characteristics of the single amplification channels and the CBC at the output power of 265 W: **a** spectra; **b** pulse autocorrelation traces after compression

to a calculated nonlinear phase shift accumulation of 1.64 and 1.84 rad, indicating a considerably enhanced nonlinear effects during the amplification process.

Additionally, according to the analysis in Ref. [38], the spectral broadening could decrease the coherence length and thus the combining efficiency under a certain optical path difference, and can be calculated as [38]:

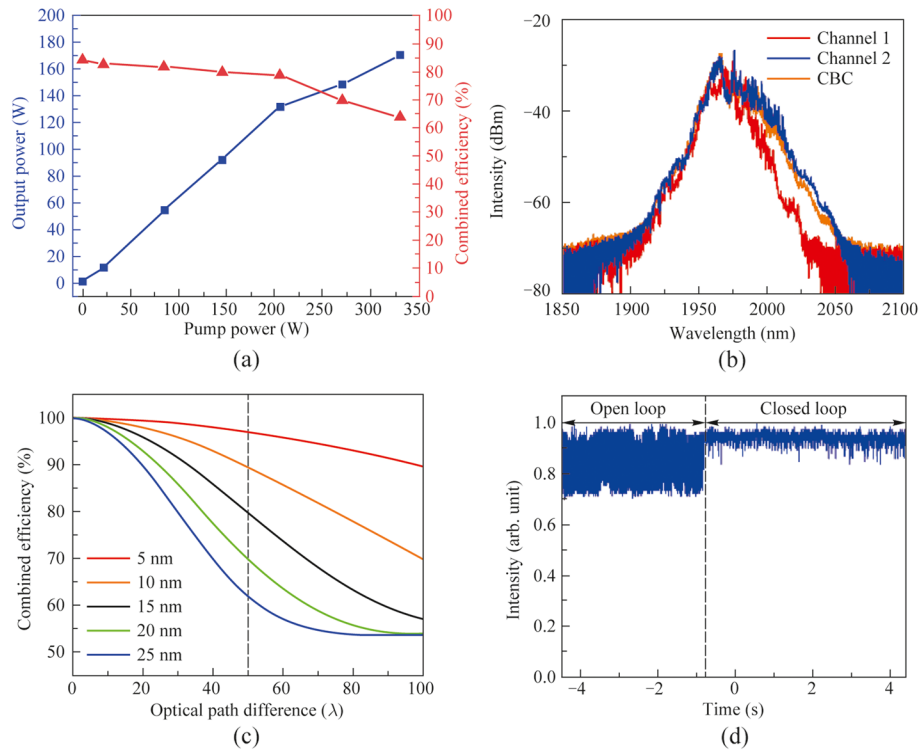


Fig. 5 Output characteristics of the CBC system with single pulse stretcher: **a** output power and combining efficiency versus the pump power of the main amplifiers; **b** output spectra of the two amplification channels and the CBC with closed loop at the output power of 172 W; **c** the calculated combining efficiency versus the optical path difference under different 3 dB bandwidth of the spectrum; **d** normalized temporal intensity fluctuations of the combined laser before and after phase locking (i.e., open loop and closed loop) at the output power of 172 W

$$\eta = \frac{1}{2} + \frac{1}{2} \sqrt{\frac{P_1^2 + P_2^2 + 2P_1P_2 \left\{ 2 \exp \left[-\frac{1}{8 \ln 2} \left(\frac{\Delta\omega}{c_0} \Delta l \right)^2 \right] \cos^2 \left(\frac{\omega_0}{c_0} \Delta l \right) - 1 \right\}}{P_1 + P_2}}, \tag{1}$$

where η is the combining efficiency, P_1 and P_2 are respectively the peak power of the two channels, $\Delta\omega$ is the full width at half maximum of the pulse spectrum, ω_0 is the central angular frequency of the spectrum, c_0 is the speed of light in vacuum, and Δl is the optical path difference. It should be noted that Eq. (1) is based on the assumption that other factors that affect the combining efficiency have been completely eliminated or compensated. Figure 5c demonstrates the calculated combining efficiency versus the optical path difference under different 3-dB bandwidth of the spectrum. It is observed that the impact of optical path difference drifting between the two channels on the combining efficiency would become increasingly significant with the broadening of the laser spectrum. Considering an ODL accuracy of 100 μm (approximately 50λ), the system combining efficiency would diminish from 97% to nearly 60% with the 3-dB bandwidth of the spectrum broadened from

5 to 25 nm, agreeing well with the experimental results. Figure 5d shows the normalized temporal intensity fluctuations of the combined laser before and after phase-locking (i.e., open loop and closed loop) at the output power of 172 W. It is observed that the spectral broadening induced weakening of the interference effect between the main amplifiers is remarkable as shown in the open loop trace, and the corresponding residual phase error with phase-locking was calculated to be $\lambda/13$. Therefore, except for improving the controlling accuracy of the optical path, another intuitive scheme to increase the combining efficiency is to manage the nonlinear effects in the fiber amplifier to mitigate the spectral broadening or distortion of the amplified laser.

To further characterize the noise properties of the CBC system, the relative intensity noise (RIN) at the maximum combined power of 265 W was examined from 100 Hz to 2 MHz by using a signal analyzer, a 12.5 GHz photodetector,

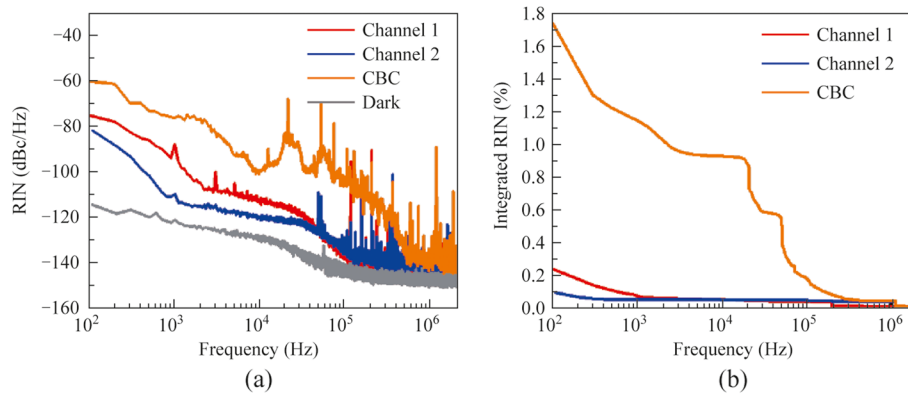


Fig. 6 Noise characteristics of the single amplification channels and the CBC at the output power of 265 W: **a** relative intensity noise spectra; **b** integrated relative intensity noise

and a 2.5 MHz low-pass filter was used to avoid the detector from being saturated by the signal at the repetition frequencies. The measured RIN spectra are shown in Fig. 6a, in which the RIN of the single amplification channels are about the same level at frequencies higher than 50 kHz and reaches to a noise plateau of -140 dBc/Hz at the frequency of 2 MHz. Whereas at frequencies < 50 kHz, the RIN of channel 2 is lower than that of channel 1, mostly owing to the variations of pump power and thermal effects between the channels. Moreover, the RIN spectrum of the combined laser exhibited an overall increase of ~ 20 dB at frequencies < 300 kHz, primarily attributed to the remainder phase noise of the CBC system and the electronic noise of the controlling loop [28]. Additionally, the integrated RIN of channel 1, channel 2, and the CBC at the maximum output power were respectively 0.24%, 0.09%, and 1.74%, as shown in Fig. 6b.

4 Conclusion

In conclusion, we have experimentally demonstrated a CBC system based on two thulium-doped all-PM fiber chirped pulse amplifiers. By actively controlling the relative phase with a fiber stretcher based on the SPGD algorithm, the coherent combining efficiency was $\sim 81\%$ with an estimated residual phase error of $\lambda/17$ at the maximum output power of 265 W. After being compressed by a pair of diffraction gratings, the duration of the combined laser pulse was measured to be 690 fs. Taking into account the compression efficiency of 90% and a main peak energy proportion of 91%, the corresponding peak power was calculated to be 4 MW. An examination of the noise characteristics manifested that the CBC would degrade the laser RIN, which was estimated to be 1.74% with an integration frequency range from 100 Hz to 2 MHz at the maximum

output power. Additionally, the impact of nonlinear effects induced spectrum broadening during chirped pulse amplification on the loss of CBC efficiency was further investigated, and the results indicated that a higher extent of pulse stretching is effective in alleviating the nonlinear spectrum broadening and maintaining a preferable combining efficiency at higher output power. It is anticipated that higher power and energy femtosecond laser output can be realized through increasing the number of amplification channels and optimizing the controlling loop.

Acknowledgements This work was supported in part by the National Key Research and Development Program of China (No. 2022YFB3606000), and in part by State Key Laboratory of Pulsed Power Laser Technology (No. SKL2020ZR02).

Authors' contributions BR and CL conceived the idea. BR, HC, TW, KJ, JZ, and KG carried out experiments. BR, CL, and PZ helped analyze the data, and revised the manuscript. CL, RS, JL, and PZ provided the experimental equipment. CL and PZ supervised the entire project. All authors read and approved the final manuscript.

Availability of data and materials The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Declarations

Competing interests The authors declare that they have no competing interests.

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References

1. Yao, C., Jia, Z., Li, Z., Jia, S., Zhao, Z., Zhang, L., Feng, Y., Qin, G., Ohishi, Y., Qin, W.: High-power mid-infrared supercontinuum laser source using fluorotellurite fiber. *Optica* **5**(10), 1264–1270 (2018)
2. Jackson, S.D.: Towards high-power mid-infrared emission from a fibre laser. *Nat. Photonics* **6**(7), 423–431 (2012)
3. Toor, F., Jackson, S., Shang, X., Arafin, S., Yang, H.: Mid-infrared lasers for medical applications: introduction to the feature issue. *Biomed. Opt. Express* **9**(12), 6255–6257 (2018)
4. Kalaycioglu, H., Elahi, P., Akcaalan, O., Ilday, F.O.: High-repetition-rate ultrafast fiber lasers for material processing. *IEEE J. Sel. Top. Quantum Electron.* **24**(3), 1–12 (2018)
5. Zhou, J., Pan, W., Qi, W., Cao, X., Cheng, Z., Feng, Y.: Ultrafast Raman fiber laser: a review and prospect. *PhotonIX* **3**(1), 18 (2022)
6. Wang, M., Wu, H., Ouyang, D., Liu, M., Chen, Y., Zhao, J., Liu, X., Ruan, S.: High power noise-like pulse at 2 μm and its applications in mid-IR Raman light and flat supercontinuum. *Infrared Phys. Technol.* **131**, 104635 (2023)
7. Liu, J., Liu, C., Shi, H., Wang, P.: High-power linearly-polarized picosecond thulium-doped all-fiber master-oscillator power-amplifier. *Opt. Express* **24**(13), 15005–15011 (2016)
8. Ren, Z., Fu, Q., Xu, L., Price, J.H.V., Alam, S.U., Richardson, D.J.: Compact, high repetition rate, 4.2 MW peak power, 1925 nm, thulium-doped fiber chirped-pulse amplification system with dissipative soliton seed laser. *Opt. Express* **27**(25), 36741–36749 (2019)
9. Lenski, M., Heuermann, T., Gebhardt, M., Wang, Z., Gaida, C., Jauregui, C., Limpert, J.: Inband-pumped, high-power thulium-doped fiber amplifiers for an ultrafast pulsed operation. *Opt. Express* **30**(24), 44270–44282 (2022)
10. Ren, C., Shen, Y., Zheng, Y., Mao, Y., Wang, F., Shen, D., Zhu, H.: Widely-tunable all-fiber Tm doped MOPA with > 1 kW of output power. *Opt. Express* **31**(14), 22733–22739 (2023)
11. Xing, Y.B., Liao, L., Bu, F., Wang, Y.B., Peng, J.G., Dai, N.L., Li, J.Y.: Fabrication of Tm-doped fibers for high power and 121 W output all-fiber Tm-doped fiber laser. *Chin. Phys. Lett.* **32**(3), 034204 (2015)
12. Gaida, C., Gebhardt, M., Heuermann, T., Stutzki, F., Jauregui, C., Limpert, J.: Ultrafast thulium fiber laser system emitting more than 1 kW of average power. *Opt. Lett.* **43**(23), 5853–5856 (2018)
13. Gaida, C., Gebhardt, M., Stutzki, F., Jauregui, C., Limpert, J., Tunnermann, A.: Thulium-doped fiber chirped-pulse amplification system with 2 GW of peak power. *Opt. Lett.* **41**(17), 4130–4133 (2016)
14. Wang, Z., Heuermann, T., Gebhardt, M., Gaida, C., Jauregui, C., Limpert, J., Dong, L., Zervas, M.N.: 108 W average power ultra-short pulses with GW-level peak power from a Tm-doped fiber CPA system. In: *Fiber Lasers XVII*, p. 112600K. Technology and Systems (2020)
15. Stutzki, F., Gaida, C., Gebhardt, M., Jansen, F., Jauregui, C., Limpert, J., Tunnermann, A.: Tm-based fiber-laser system with more than 200 MW peak power. *Opt. Lett.* **40**(1), 9–12 (2015)
16. Stutzki, F., Gaida, C., Gebhardt, M., Jansen, F., Wienke, A., Zeitner, U., Fuchs, F., Jauregui, C., Wandt, D., Kracht, D., Limpert, J., Tunnermann, A.: 152 W average power Tm-doped fiber CPA system. *Opt. Lett.* **39**(16), 4671–4674 (2014)
17. Gebhardt, M., Gaida, C., Stutzki, F., Hadrich, S., Jauregui, C., Limpert, J., Tunnermann, A.: Impact of atmospheric molecular absorption on the temporal and spatial evolution of ultra-short optical pulses. *Opt. Express* **23**(11), 13776–13787 (2015)
18. Qiao, T., Cheng, H., Wen, X., Wang, W., Lin, W., Zhou, Y., Guo, Y., Liu, Y., Yang, Z.: High-power 2 GHz fs pulsed all-fiber amplified laser system at 20 μm . *Opt. Lett.* **44**(24), 6001–6004 (2019)
19. Wang, T., Li, C., Ren, B., Guo, K., Wu, J., Leng, J., Zhou, P.: High-power femtosecond laser generation from an all-fiber linearly polarized chirped pulse amplifier. *High Power Laser Sci. Eng.* **11**, e25 (2023)
20. Ren, B., Li, C., Wang, T., Guo, K., Wu, J., Zhou, P.: Thulium-doped all-PM fiber chirped pulse amplifier delivering 314 W average power. *High Power Laser Sci. Eng.* **11**, e73 (2023)
21. Fsaifes, I., Daniault, L., Bellanger, S., Veinhard, M., Bourderionnet, J., Larat, C., Lallier, E., Durand, E., Brignon, A., Chanteloup, J.C.: Coherent beam combining of 61 femtosecond fiber amplifiers. *Opt. Express* **28**(14), 20152–20161 (2020)
22. Chang, Q., Hou, T., Long, J., Deng, Y., Chang, H., Ma, P., Su, R., Ma, Y., Zhou, P.: Experimental phase stabilization of a 397-channel laser beam array via image processing in dynamic noise environment. *J. Lightwave Technol.* **40**(19), 6542–6547 (2022)
23. Jiang, M., Wu, H., An, Y., Hou, T., Chang, Q., Huang, L., Li, J., Su, R., Zhou, P.: Fiber laser development enabled by machine learning: review and prospect. *PhotonIX* **3**(1), 16 (2022)
24. McNaught, S.J., Thielen, P.A., Adams, L.N., Ho, J.G., Johnson, A.M., Machan, J.P., Rothenberg, J.E., Chun-Ching, S., Shimabukuro, D.M., Wacks, M.P., Weber, M.E., Goodno, G.D.: Scalable coherent combining of kilowatt fiber amplifiers into a 2.4-kW beam. *IEEE J. Sel. Top. Quantum Electron.* **20**(5), 174–181 (2014)
25. Antier, M., Bourderionnet, J., Larat, C., Lallier, E., Lenormand, E., Primot, J., Brignon, A.: kHz closed loop interferometric technique for coherent fiber beam combining. *IEEE J. Sel. Top. Quantum Electron.* **20**(5), 182–187 (2014)
26. Yang, K., Zhu, G., Hao, Q., Huang, K., Laurat, J., Li, W., Zeng, H.: Coherent polarization beam combination by microcontroller-based phase-locking method. *IEEE Photonics Technol. Lett.* **28**(20), 2129–2132 (2016)
27. Chang, H., Chang, Q., Xi, J., Hou, T., Su, R., Ma, P., Wu, J., Li, C., Jiang, M., Ma, Y., Zhou, P.: First experimental demonstration of coherent beam combining of more than 100 beams. *Photon. Res.* **8**(12), 1943–1948 (2020)
28. Müller, M., Aleshire, C., Klenke, A., Haddad, E., Legare, F., Tunnermann, A., Limpert, J.: 10.4 kW coherently combined ultrafast fiber laser. *Opt. Lett.* **45**(11), 3083–3086 (2020)
29. Stark, H., Buldt, J., Müller, M., Klenke, A., Limpert, J.: 1 kW, 10 mJ, 120 fs coherently combined fiber CPA laser system. *Opt. Lett.* **46**(5), 969–972 (2021)
30. Yu, H.L., Zhang, Z.X., Wang, X.L., Su, R.T., Zhang, H.W., Ma, Y.X., Zhou, P., Chen, J.B.: High average power coherent femtosecond pulse combining system based on an all fiber active control method. *Laser Phys. Lett.* **15**(7), 075101 (2018)
31. Stark, H., Benner, M., Buldt, J., Klenke, A., Limpert, J.: Pulses of 32 mJ and 158 fs at 20-kHz repetition rate from a spatiotemporally combined fiber laser system. *Opt. Lett.* **48**(11), 3007–3010 (2023)
32. Peng, S., Wang, Z., Hu, F., Li, Z., Zhang, Q., Lu, P.: 260 fs, 403 W coherently combined fiber laser with precise high-order dispersion management. *Front Optoelectron.* **17**(1), 3 (2024)
33. Honzatko, P., Baravets, Y., Todorov, F., Peterka, P., Becker, M.: Coherently combined power of 20 W at 2000 nm from a pair of thulium-doped fiber lasers. *Laser Phys. Lett.* **10**(9), 095104 (2013)
34. Oermann, M.R., Carmody, N., Hemming, A., Rees, S., Simakov, N., Swain, R., Boyd, K., Davidson, A., Corena, L., Stepanov, D., Haub, J.: Coherent beam combination of four holmium amplifiers with phase control via a direct digital synthesizer chip. *Opt. Express* **26**(6), 6715–6723 (2018)

35. Wang, X., Zhou, P., Wang, X., Ma, Y., Su, R., Xiao, H., Si, L., Liu, Z.: 108 W coherent beam combining of two single-frequency Tm-doped fiber MOPAs. *Laser Phys. Lett.* **11**(10), 105101 (2014)
36. Heuermann, T., Wang, Z., Lenski, M., Gebhardt, M., Gaida, C., Abdelaal, M., Buldt, J., Muller, M., Klenke, A., Limpert, J.: Ultrafast Tm-doped fiber laser system delivering 1.65-mJ, sub-100-fs pulses at a 100-kHz repetition rate. *Opt. Lett.* **47**(12), 3095–3098 (2022)
37. Jolivet, V., Bourdon, P., Bennai, B., Lombard, L., Goular, D., Pourtal, E., Canat, G., Jaouen, Y., Moreau, B., Vasseur, O.: Beam shaping of single-mode and multimode fiber amplifier arrays for propagation through atmospheric turbulence. *IEEE J. Sel. Top. Quantum Electron.* **15**(2), 257–268 (2009)
38. Yu, H.L., Ma, P.F., Wang, X.L., Su, R.T., Zhou, P., Chen, J.B.: Influence of temporal–spectral effects on ultrafast fiber coherent polarization beam combining system. *Laser Phys. Lett.* **12**(10), 105301 (2015)



Bo Ren received the B.S. degree in optoelectronic information engineering from Changchun University of Science and Technology, Changchun, China, in 2014 and master degree in optical engineering from South China Normal University, Guangzhou, China, in 2018. He is currently working toward the Ph.D. degree at the National University of Defense Technology, Changsha, China. His current research interest focuses on ultrafast fiber lasers.



Hongxiang Chang received the B.S. degree in measurement and control technology and instrument from Central South University, Changsha, China, in 2018 and master degree in optical engineering from National University of Defense Technology, Changsha, China, in 2020. He is currently working toward the Ph.D. degree at the National University of Defense Technology, Changsha, China. His current research interest focuses on coherent beam combining.



Can Li received the Ph.D. degree in engineering in 2015 from South China University of Technology, Guangzhou, China. He was a Postdoctoral Fellow at the University of Hong Kong, Hong Kong, China, where he was engaged in developing new fiber laser technologies and their applications in bio-imaging from 2015 to 2019. He is currently an associate professor at the National University of Defense Technology, Changsha, China. His current research interests include high-power fiber lasers and amplifiers in the pulsed and continuous-wave regime.



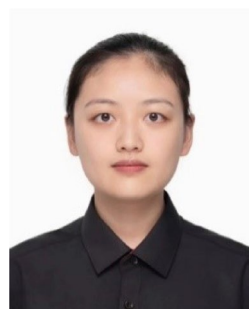
Tao Wang received the B.S. degree in optical engineering from Beijing Institute of Technology, Beijing, China, in 2017 and master degree from National University of Defense Technology, Changsha, China, in 2019. He is currently working toward the Ph.D. degree at the National University of Defense Technology, Changsha, China. His current research interest focuses on pulsed fiber lasers.



Kaikai Jin received the B.S. degree in optoelectronic information engineering from National University of Defense Technology, Changsha, China, in 2022. He is currently working toward the master degree at the National University of Defense Technology, Changsha, China. His current research interest focuses on coherent beam combining.



Jiayi Zhang received the B.S. degree in 2021 in optical engineering from Nanjing University of Science and Technology, Nanjing, China. She is currently working toward the Ph.D. degree at the National University of Defense Technology, Changsha, China. Her current research interests include coherent beam combination and ultrafast fiber lasers.



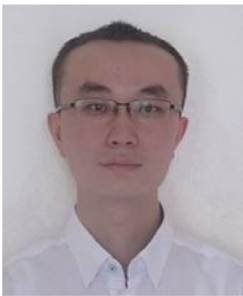
Kun Guo received the B.S. degree in optical information science and technology in 2020 and master degree in electronic and information from National University of Defense Technology, Changsha, China, in 2022. She is currently working toward the Ph.D. degree at the National University of Defense Technology, Changsha, China. Her current research interest focuses on ultrafast fiber lasers.



Rongtao Su received the B.S. degree, master degree and Ph.D. degree in optical engineering from National University of Defense Technology, Changsha, China, in 2008, 2010 and 2014, respectively. He is currently an associate professor at the National University of Defense Technology, Changsha, China. His current research interests include high-power fiber lasers and coherent combining of fiber lasers.



Jinyong Leng received the B.S. degree, master degree and Ph.D. degree in optical engineering from National University of Defense Technology, Changsha, China, in 2004, 2006 and 2011, respectively. He is currently an associate professor at the National University of Defense Technology, Changsha, China. His current research interests include high-power fiber lasers and coherent combining of fiber lasers.



Pu Zhou received the B.S. degree and Ph.D. degree in optical engineering from National University of Defense Technology, Changsha, China, in 2005 and 2009, respectively. He is currently a full professor at the College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha, China. His current research interests include fiber laser/amplifier technology, coherent combining of fiber lasers/amplifiers, and adaptive optics.