Coherent combining of tunable erbium-doped fiber lasers by a single-mode fiber feedback loop

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Received January 6, 2009

We experimentally demonstrate the coherent combining of two tunable erbium-doped fiber lasers by using a single-mode fiber feedback loop configuration. A single-mode fiber is arranged in the feedback loop to filter the far-field pattern, and the energy of desired in-phase mode is collected and injected into the resonators of two component fiber lasers. The coherently combined laser is tunable over a wide spectrum ranging from 1536 to 1569 nm, which means that the combining scheme is compatible with wavelength tuning. The effects and necessity of whether adopting polarization controlling measures or not in component lasers are investigated in detail. The results indicate that adding polarization controlling can improve the array's coherence, whereas it will decrease the output power and efficiency simultaneously.

OCIS codes: 140.3510, 140.3600, 140.3290, 030.1640, 070.6110.

doi: 10.3788/COL20090711.1018.

Coherent beam combining of multiple individual lasers, each with moderate power and good beam quality, can not only increase the overall output power and maintain their quality, but also circumvent the untamed problems which a single laser always suffers from while operating at high power levels, such as beam distortion, instability, nonlinearity, heat dissipation, etc. In recent years, much attention has been paid to coherent combining of fiber lasers and amplifiers due to their inherent advantages of compactness, high efficiency, good beam quality, and convenient heat management, and various schemes have been proposed to achieve efficient coherent combining of them[1−15]. The active phase controlling methods involve complicated phase detection and correction for each element of the array[1−3]. The passive self-adjusting process in a compound cavity needs tight optical coupling to obtain mutual coherence, and the lasing frequencies can self-adjust to adapt to the changes in optical path lengths caused by unavoidable mechanical and thermal effects[4−15]. If the coherent array owns multiple emitting ports, additional spatial filtering measures have to be adopted to make all elements operate in a fixed phase relation[4−9].

Passive coherent combining has also been demonstrated to be compatible with widely tunable fiber lasers by adding a diffraction grating or a tunable filter in the common part of their compound cavity[10,11]. However, all these reported tunable lasers only extract from a single port, and the ultimate output power is still limited owing to the material damage of a single fiber. Therefore, studying the properties of coherent combining of tunable fiber lasers with multiple output ports is significant and worthwhile. In this letter, we report the demonstration of coherent combining of two tunable erbium-doped fiber (EDF) lasers. A single-mode fiber (SMF) is specially utilized to collect the energy of desired in-phase mode and inject it back into the resonators of two component lasers, and a closed phase adjusting loop is formed to keep all emitters output in phase, i.e., a SMF feedback loop with intracavity filtering is constructed[8]. Moreover, the array's tunable and coherent output properties are experimentally investigated, and the effects and necessity of component lasers' polarization optimization on these properties are also discussed in detail.

The experimental setup is schematically shown in Fig. 1. The linear laser resonators are formed by a tunable fiber Bragg grating (FBG) and the 4% Fresnel reflection at the perpendicularly cleaved facet of output fiber collimator (FC). Two fiber lasers share the tunable FBG by a 50:50 polarization insensitive fiber coupler (PIFC). The rest port of the PIFC is connected with a feedback filtering fiber. The gain fibers are single-mode EDFs (Fibercore, DF1500F-980), and their lengths are 11.5 and 10 m, respectively. A pigtailed laser diode (LD) emitting at 980 nm with the output power ranging from 0 to 184 mW is utilized to pump two lasers simultaneously through a 50:50 fiber coupler. Two polarization controllers (PCs) are employed to optimize the polarization states of component lasers. An ordinary beam splitter with 4% reflection is placed at the output ports of FCs, and a small fraction of output power is reflected and sent to a positive lens L_1. This lens performs a Fourier transform from its front focal plane where a single-mode feedback fiber (SMFF, Corning SMF-28) is set to filter the spatial frequency spectrum. To realize efficient spatial filtering, the mode-field diameter of SMFF needs to be smaller than the central lobe size of the in-phase mode. In our configuration, the spacing of two output parallel beams d is nearly 5 mm, and the focal length of L_1 is chosen to be 10 cm, thus the lobe size of spatial mode can be calculated as $\Phi = \lambda f_1/d \approx 31$ μm, which is obviously larger than the mode-field diameter of SMFF (nearly 11 μm) and the filtering condition is satisfied. Moreover, a self-made erbium-doped fiber amplifier (EDFA) is inserted into the feedback loop to amplify the collected power to obtain enough feedback injection energy. Another positive lens L_2 with a focal length of 40 cm is employed to converge the output parallel beams, and a power meter (PM),

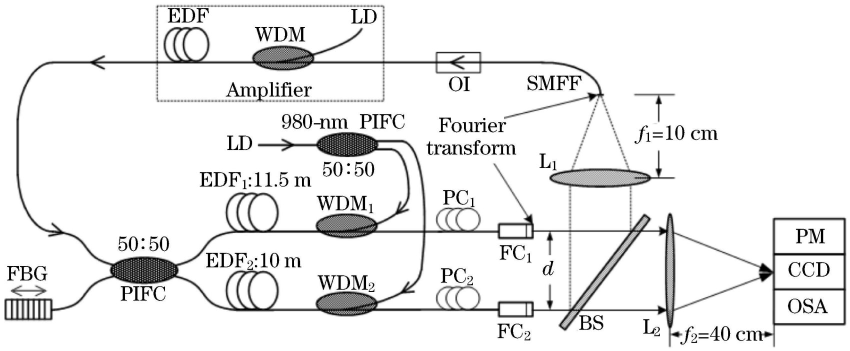

Fig. 1. Experimental setup for coherent combining of two tunable fiber lasers by a SMF feedback loop. WDM: wavelength division multiplexer; OI: optical isolator; BS: beam splitter with 4% reflection; L_1, L_2: two positive lenses with focal lengths f_1 = 10 cm and f_2 = 40 cm.

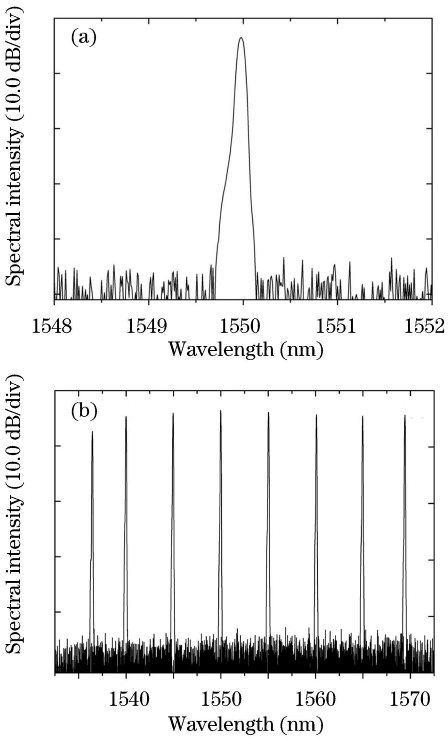

Fig. 2. Optical spectra of the tunable fiber laser array operating at (a) nearly 1550 nm and (b) 1536−1569 nm.

an infrared charge-coupled device (CCD), and an optical spectrum analyzer (OSA) are placed at its back focal plane to study its tunable and coherent output properties.

The array's output optical spectra and power are investigated by the OSA (Agilent, 86142A) and PM (ILX Lightwave, FPM8210H), respectively. The typical optical spectra of the tunable fiber laser array are shown in Fig. 2. The measured 3-dB bandwidth shown in Fig. 2(a) is 0.06 nm, which is evidently smaller than the tunable FBG's 3-dB bandwidth of 0.25 nm, thus efficient resonance and lasing have occurred in the compound cavity. The combined laser is tunable on a wide spectrum range of about 33 nm from 1536 to 1569 nm, as shown in Fig. 2(b). The tuning range is included in the gain bandwidth of our EDF ranging from 1525 to 1570 nm, and the shrinkage is owing to the limited tunable range of FBG and relatively long EDFs of the lasers. In the tuning range of 1540−1569 nm, no evident decrease in the output power of combined laser is observed, except that the lasing at 1550 nm is slightly stronger than those at other wavelengths, and the signal to ASE (amplified spontaneous emission) noise ratio stays above 40 dB over this tuning range.

The output power evolutions of the combined fiber laser with carrying out polarization optimization in component lasers or not at different pump powers are illustrated in Fig. 3. When the pump power is varied from 8.9 to 184.2 mW, the combined output without PCs almost linearly increases from 2.0 to 46.3 mW, and the slope efficiency is 25.2%. After two PCs are introduced into the two arms of individual lasers respectively, the combined output power linearly increases from 1.8 to 41.5 mW and its slope efficiency decreases to 22.6%. The decrease in output power and efficiency can be attributed to the insertion loss and spliced loss of introducing PCs, which increase the total cavity loss of the compound cavity.

The array's coherent output properties are researched by an infrared CCD (Electrophysics, 7290A) and relevant laser beam analyzer (LBA-PC, software version 4.22, Spiricon Inc.). The recorded far-field interference patterns of the two emitters are shown in Fig. 4. The large number of lobes (about 14) is due to the poor filling factor in the near field. The obvious interference patterns

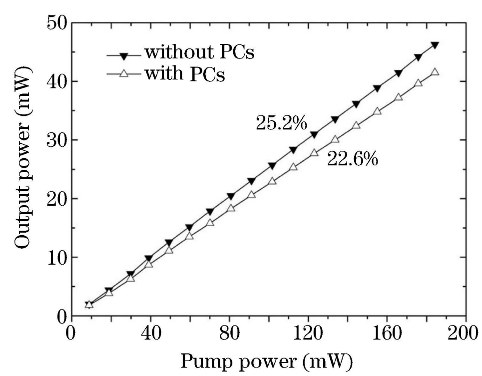

Fig. 3. Output power evolutions of the combined fiber laser without and with PCs at different pump powers.

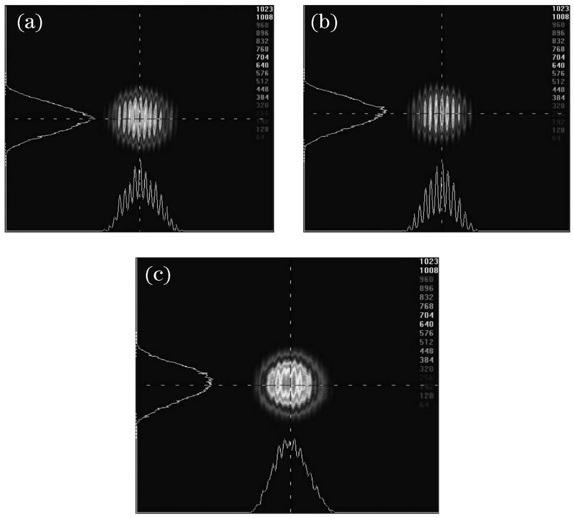

Fig. 4. Far-field interference patterns of the combined laser output (a) with SMFF but no PCs, (b) with both SMFF and PCs, (c) without SMFF.

shown in Figs. 4(a) and (b) indicate that the two output beams have been phase locked efficiently, whether the PCs are introduced or not. However, after introducing the PCs, its fringe visibility has been increased from 0.34 to 0.60, which means that the degree of coherence of the combined beams has been improved evidently. Considering the low adjusting precision of our three-loop mechanical PCs and reported experimental results in Ref. [8], the array's coherence has the potential to be further improved.

Although the array's coherence can be improved by taking polarization controlling measures or adopting polarization maintaining devices in component lasers, we do not believe that it is quite necessary to do this. On one hand, high precision polarization controlling elements are usually very expensive and they will decrease the ultimate output power of the array owing to their inherent loss, which has been explicitly illustrated in Fig. 3; on the other hand, the array's combined output with partial coherence is adequate in some application fields, especially at high power situations, where the crucial issues of coherent combining are concentrating as much energy as possible in the central lobe and keeping the far-field intensity distribution stable in a certain period of time. In general, if the purpose is to obtain a high-power and high-brightness laser source, constructing a partial-coherently combined array without polarization controlling may be more advisable; when a highly coherent laser source is needed, taking the polarization controlling measures is quite necessary.

Another important factor is that the SMFF spatial filtering is responsible for the stability of phase locking state. When the SMFF is removed from the back focal plane of L_1, the beam profile exhibits low-contrast and instable interference pattern due to the common FBG, which is typically shown in Fig. 4(c), and these poor visibility fringes move constantly with irregular pace and direction. The SMFF filtering technique is essentially the same as self-Fourier or self-imaging filtering techniques[4−6]; they all utilize a spatial filter to bring loss difference between desired in-phase mode and other unwanted supermodes. Actually, the spatial mode filtering technique presented here was firstly used to make a 40-element GaAlAs gain guided coupled stripe array operate in a single lobe[16], recently it has been employed to achieve passive phase locking of four fiber amplifiers and to control a multimode fiber amplifier's transverse mode[8,17], and it has also been introduced to realize efficient phase locking of two fiber ring lasers[9]. In this scheme, partial in-phase mode's energy is collected and fed back into component lasers through the SMFF, thereby the in-phase mode (i.e., a fixed phase relation or supermode) has the lowest loss, and it is selectively excited as the supermode of the array. Moreover, the shared FBG also provides some level of interaction between the two laser fields, and individual regenerative feedback may be also involved in each fiber laser if sufficient nonlinearity exists in them[18], thus the array's phase locking characteristics may be also affected by the nonlinear regenerative feedback from individual fiber laser in addition to the coupled feedback from the SMFF.

In conclusion, we report the coherent combining of tunable fiber lasers with two emitting ports by using a SMF feedback loop. The coherent combining scheme is compatible with wavelength tuning, and it can also be performed by inserting a tunable filter in the feedback loop. The configuration may also adapt to coherent combining of multiple pulsed fiber lasers[8,19]. The effects and necessity of adopting polarization controlling measures or not in component lasers are particularly discussed, and we believe this issue chiefly depends on the actual application demands. Since the scheme is a typical side-by-side combining technique, compared with the tree or similar structures with only one output port[10−13], its thermal management and expandability are improved evidently. The array can be easily scaled up to more elements by connecting more individual fiber lasers with different cavity lengths to the common tunable FBG, and this technique presents an alternative method to make a widely tunable fiber laser source with high power.

This work was supported by the Hunan Provincial Innovation Foundation for Postgraduate and the Innovation Foundation of National University of Defense Technology, China (No. B070702).

References

1. J. Anderegg, S. Brosnan, E. Cheung, P. Epp, D. Hammons, H. Komine, M. Weber, and M. Wickham, Proc. SPIE **6102,** 61020U (2006).
2. T. M. Shay, V. Benham, J. T. Baker, C. B. Ward, A. D. Sanchez, M. A. Culpepper, S. D. Pilkington, L. J. Spring, L. D. J. Nelson, and L. C. A. Lu, Opt. Express **14,** 12015 (2006).
3. C. Bellanger, A. Brignon, J. Colineau, and J. P. Huignard, Opt. Lett. **33,** 2937 (2008).
4. L. Liu, Y. Zhou, F. Kong, Y. C. Chen, and K. K. Lee, Appl. Phys. Lett. **85,** 4837(2004).
5. B. He, Q. Lou, J. Zhou, Y. Zheng, D. Xue, J. Dong, Y. Wei, F. Zhang, Y. Qi, J. Zhu, J. Li, S. Li, and Z. Wang, Chin. Opt. Lett. **5,** 412 (2007).
6. C. J. Corcoran and F. Durville, Appl. Phys. Lett. **86,** 201118 (2005).
7. L. Li, A. Schülzgen, H. Li, V. L. Temyanko, J. V.

Moloney, and N. Peyghambarian, J. Opt. Soc. Am. B **24,** 1721 (2007).
8. J. Lhermite, A. Desfarges-Berthelemot, V. Kermene, and A. Barthelemy, Opt. Lett. **32,** 1842 (2007).
9. B. Lei, Y. Feng, L. Wei, and Z. Liu, J. Opt. A: Pure Appl. Opt. **11,** 015509 (2009).
10. D. Sabourdy, V. Kermène, A. Desfarges-Berthelemot, L. Lefort, A. Barthélémy, P. Even, and D. Pureur, Opt. Express **11,** 87 (2003).
11. S.-P. Chen, Y.-G. Li, K.-C. Lu, and S.-H. Zhou, J. Opt. A: Pure Appl. Opt. **9,** 642 (2007).
12. A. Shirakawa, T. Saitou, T. Sekiguchi, and K. Ueda, Opt. Express **10,** 1167 (2002).
13. H. Bruesselbach, D. C. Jones, M. S. Mangir, M. Minden, and J. L. Rogers, Opt. Lett. **30,** 1339 (2005).
14. P. Zhou, Z. Chen, X. Wang, X. Li, Z. Liu, X. Xu, J. Hou, and Z. Jiang, Chin. Opt. Lett. **6,** 523 (2008).
15. B. Lei and Y. Feng, Opt. Commun. **281,** 739 (2008).
16. L. Goldberg and J. F. Weller, Appl. Phys. Lett. **51,** 871 (1987).
17. B. M. Shalaby, V. Kermene, D. Pagnoux, and A. Barthelemy, J. Opt. A: Pure Appl. Opt. **10,** 115303 (2008).
18. C. J. Corcoran, F. Durville, and K. A. Pasch, IEEE J. Quantum Electron. **44,** 275 (2008).
19. D. Sabourdy, A. Desfarges-Berthelemot, V. Kermène, and A. Barthélémy, Electron. Lett. **40,** 1254 (2004).