All-fiber 50 W coherently combined passive laser array

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We experimentally demonstrate 50 W of spontaneously phase-locked two-laser array in an all-fiber and all-passive configuration using large-mode-area (LMA) polarization-maintaining fiber laser cavities and an LMA fiber coupler. We show that both laser cavity length difference and fiber nonlinearity play an important role in achieving efficient and stable coherent beam combining. In addition, we compare the difference in coherent combining efficiency by using fibers with different mode-field diameters and discuss the underlying phase-locking mechanism and its power scalability. © 2009 Optical Society of America

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Coherent beam combining of multiple fiber lasers has received increasing attention for power upscaling and brightness improvement. Common passive coherent beam combining techniques include evanescent coupling [1–3], all-fiber interferometric combining [4–8], passive phasing [9,10], and the self-Fourier cavity method [11]. In free space, coherent combining of multiple fiber arrays of up to several hundred watts of output power has been reported [1,9]. Although the all-fiber beam combining approach is generally preferred for reliable, compact, rugged, and efficient high-power laser systems, its progress is by far lagging behind. There are some major limitations for this all-fiber path. First, the combined output power has been relatively low at around 2 to 3 W, and a high combining efficiency of 99% has been achieved only at even lower power level of tens of milliwatts. Second, active polarization control has been required to achieve efficient beam combining. This greatly limits the practicality of this method. Third, the combined output is often not stably continuous wave, and sometimes multiple beams are coherently combined only intermittently [2]. Fourth, its underlying mechanism is complex and is yet to be fully understood. There lacks a good consensus on the role that nonlinear phase plays in the coherent beam combining [2,12,13].

Recently, efficient all-fiber and all-passive coherent beam combining of two lasers up to 11.5 W and four lasers up to 12.2 W has been successfully demonstrated [14]. In this Letter, we show further power scalability using large-mode-area (LMA) fibers and LMA fiber coupling. We achieve to our best knowledge a record power of 50.1 W by coherently combining two fiber lasers in an all-fiber configuration without using any active controls. The laser array configuration is schematically shown in Fig. 1. Each laser cavity consists of a high-reflector (HR) grating, polarization-maintaining (PM) Yb-doped double-clad fiber (DCF), and a length of PM passive fiber. Each laser cavity is end-pumped using 975 nm multimode (MM) pump diodes from the HR end via a tapered pump combiner. For beam combining, the outputs of two fiber laser cavities are launched into two input ports of a fiber coupler—a 2×2 single-mode (SM) coupler with a 50:50 coupling ratio. One output port of the coupler is flat cleaved to provide a 3.4% broadband reflection, and the other port is angle cleaved to create sufficient loss discrimination between two output ports. For evaluating the coherent beam combining performance, we introduce a figure-of-merit parameter—coherent efficiency η defined by

$$\eta = \frac{P_1}{P_1 + P_2} 100\,\% , \tag{1}$$

where P_1 and P_2 are output powers from the flat and angle-cleaved ports, respectively.

First, we experimentally studied the effect of the laser cavity length difference on the coherent beam combining performance. In our configuration, we used a SM PM Yb DCF fiber, which has an NA of 0.11, a V number of 2.2 at 1060 nm, a mode-field diameter (MFD) of 7.6 μm at 1060 nm, a Yb cladding absorption of 2.0 dB/m at the 975 nm wavelength, and a PM beat length of 2.3 mm at 1060 nm. The HR grating has a center wavelength of 1083.0 nm with a 3 dB bandwidth of 1.2 nm and a reflectivity of >99%. The length of the Yb fiber in each cavity is 10.2 m.

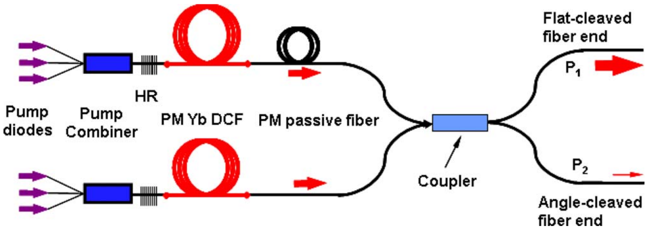

Fig. 1. (Color online) Schematic of all-fiber passive coherent array combining two lasers.

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The passive fibers are also SM and PM. We varied the length difference between two laser cavities from 0 to 6 m by using different lengths of passive fibers. In each case, we measured output powers from both output ports at different power levels of up to 700 mW of total launched power, or 350 mW from each laser, and calculated the corresponding coherent efficiency. We observed different coherent combining characteristics in these cases as depicted in Fig. 2. When the total launched power is less than 100 mW or when the laser power is a little over the lasing threshold, the coherent combining efficiency remains high at about 99.4% irrespective of the laser cavity length difference. However, when the total launched power is greater than 100 mW, the coherent efficiency remains high at >99% in the power range measured for cases with the cavity length difference in the range of 3–6 m. In these cases, the combined output power is stable with a variation standard deviation of less than 0.3% for several minutes. But for two cases with cavity length differences of 0 and 1 m, the coherent efficiency decreases, and the output power becomes less stable. The coherent efficiency drops to around 90% when the cavity difference is 0 m.

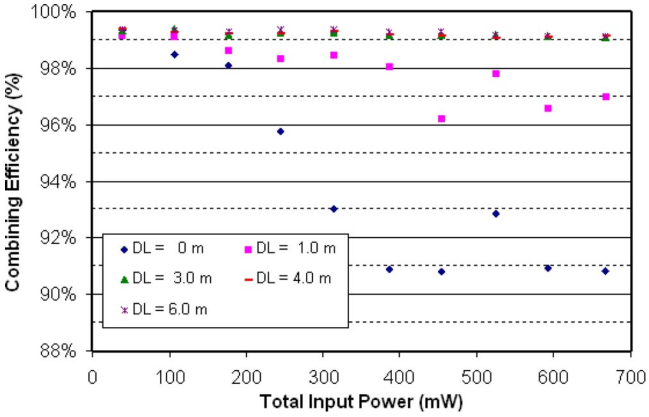

Fig. 2. (Color online) Coherent combining efficiency with various laser cavity length differences (DL, length difference).

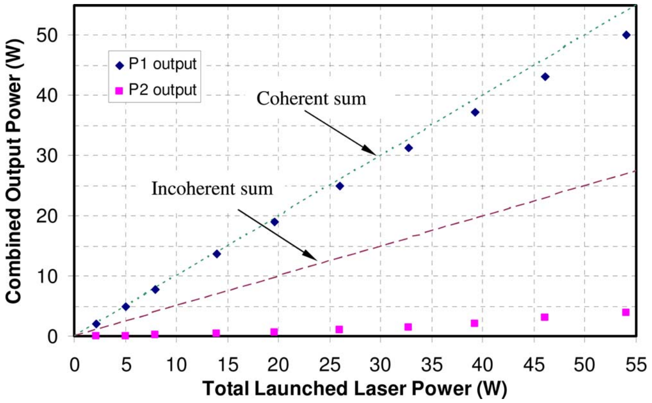

Fig. 3. (Color online) Output powers from two output ports of a coherently combined two-laser array (diamonds, power from the flat-cleaved port; squares, power from the angle-cleaved port; coherent sum, array with 100% coherent combination; incoherent sum, array with 100% incoherent combination).

To study the power scalability, we set up a two-laser coherent array using LMA fibers and an LMA output coupler. The LMA Yb-doped DCF fiber has an NA of 0.07, a V number of 2.3 at 1060 nm, and an MFD of 12.3 μm at 1060 nm. The fiber's Yb cladding absorption at 975 nm is 4.5 dB/m, and its PM beat length is 3.4 mm at 1060 nm. The passive fiber has fiber waveguide characteristics, which are similar to those of the Yb fiber. In the coherent array configuration, the length of the Yb fiber is 5.0 m for each laser cavity, and the cavity length difference is 2 m. Both HR gratings have a center wavelength of 1080.2 nm with 3 dB bandwidth of 1.6 nm and a reflectivity of >99%. For high-power beam combining, we fabricated LMA 2×2 3 dB couplers with the fiber that has an 11 μm core diameter and a 0.07 NA by using a Vytran GPX 3400 glass processing system. The split ratio of the coupler is 50:50. The excess losses of both ports are 0.05 and 0.07 dB, respectively. To characterize the combining efficiency, we first measured the output power of each laser before combining up to 27.0 W of laser output power (pump power limited) and then measured the combined output powers P_1 and P_2 from the flat- and angle-cleaved ports, respectively. The combined output powers from both ports are shown in Fig. 3. When two lasers are 100% coherently combined, all launched laser power emerges from the P_1 port. On the other hand, when two lasers are 100% incoherently combined, power evenly emerges from both P_1 and P_2 ports. In this case, the output power from either port is one half of total launched power. In this all-fiber passive laser array, we achieved 50.1 W of coherently combined output power from the P_1 port with a total launched power of 54.0 W—a combining efficiency of 92.8%. To gain further insight into the coherent combining characteristics, we performed additional experiments to compare the coherent efficiency by using a different Yb DCF fiber, which has a smaller 6 μm core diameter. A comparison of optical characteristics of these two fibers is shown in Table 1, and a comparison of the coherent efficiency for arrays using these two fibers is depicted in Fig. 4. The laser array with LMA fibers coupled with shortening the fiber length significantly improves the combining efficiency at high

Table 1. Fiber Parameter Comparison of Two Different PM Yb DCF Fibers

	11 μm PM Yb DCF	6 μm PM Yb DCF	Unit
Yb cladding absorption at 915 nm	4.5	2.0	dB/m
Core NA	0.07	0.11	
MFD at 1060 nm	12.3	7.6	μm
V number at 1060 nm	2.3	2.2	
Cladding diameter	125	125	μm
Cladding NA	0.46	0.45	
Coating diameter	245	250	μm
Birefringence	3.1×10^{-4}	4.6×10^{-4}	
Vendor	Nufern	OFS	

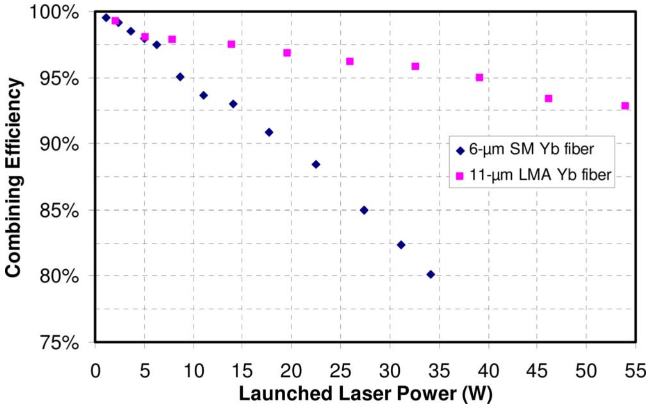

Fig. 4. (Color online) Comparison of coherent combining efficiency with two different Yb gain fibers.

power. At the condition with a total launched power of 34 W, the combining efficiency of the array with the LMA fibers is 95.5% compared to 80.1% for the array with smaller core fibers. Interestingly, the coherent efficiency is similar for both fiber arrays when the total launched power is less than 5 W. This possibly attributes to the n_2 induced fiber nonlinearity. At high power, the presence of the n_2 induced nonlinearity leads to self-phase modulation, which partially disrupts the formation of the spontaneous phase locking of the longitudinal modes.

We successfully demonstrated for the first time to our knowledge a phase-locked two-laser array with 50 W of coherently combined output power in an all-fiber and all-passive configuration without using any active controls. The use of PM fibers is important to preserve the polarization state of the propagating beams. At high power, differential laser cavity length, which facilitates the formation of in-phase longitudinal modes owing to the Vernier effect, is critical for achieving efficient and stable coherent beam combining. When the cavity length difference is small, coherent combining is still possible but with reduced combining efficiency and output power stability. However, at low power or at the power level just above the lasing threshold, near perfect coherent beam combining has been achieved with >99% efficiency regardless of the cavity length difference. We believe this phenomenon possibly attributes to the dynamic phase change induced by the Kramers–Kronig effect, as the lasers are not so saturated. However, in the high-power region, the Kramers–Kronig induced phase change is less pronounced, because the lasers are more saturated and their gain changes become small. As a result, the laser array loses coherence quickly for laser arrays with the same cavity length, as it becomes more difficult for the laser array to find common in-phase longitudinal modes. The linear cold-cavity resonator analysis [13] does not account for these phenomena we observed both in low-power and at high-power regions. We believe that by optimizing the laser array configuration and manipulating the fiber nonlinearity and by better understanding the coherent locking mechanism, we should be able to achieve further upscaling both in combined power and in the number of combined lasers in all-fiber and all-passive configurations.

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