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Efficient All-fiber Passive Coherent Combining of Fiber Lasers

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Abstract

We experimentally demonstrate efficient all-fiber coherent combining of multiple single-mode polarization maintaining (PM) fiber arrays without using any active controls. We explore the influencing factors for reliably achieving spontaneously self-organized beam combination for two PM-cavity fiber lasers at power levels up to 20 Watts. We showed that cavity length difference facilitates efficient and stable combining of multiple lasers at high power output. However, at low power levels just over the lasing threshold, the lasers are coherently combined efficiently irrespective of the cavity length difference. The underlying mechanism of passive coherent combining is discussed. We also report our initial result of passively combining four fiber lasers.

Introduction

Coherent beam combining of multiple lasers has received increasing attention for laser power up-scaling and brightness improvement. Coherent combining of multiple fiber arrays in free space up to several hundred watts of output power has been reported [1, 2]. Common coherent beam combining techniques include passive phasing of fiber lasers [2, 3], all-fiber interferometric combining of multiple fiber lasers [4-8], evanescent coupling of fibers [1, 9, 10], and self-Fourier cavity method [11]. Among these, all-fiber approach is generally preferred for reliable, compact, rugged, and efficient high power laser systems.

However, the progress in all-fiber coherent beam combining is lagging. There are some major limitations for this approach. First, the combined output power is relatively low around 2-3 Watts, and a high combining efficiency of 99% has been achieved only at even lower power level. Second, active polarization is required to achieve a good efficiency. This further limits the practicality of this method. Third, the combined output is usually not so stable, and sometimes multiple beams are coherently combined only intermittently. Fourth, its underlying mechanism is complex and is yet to be fully understood. For example, it lacks a good consensus on the role of nonlinear phase played in coherent beam combining [9, 12, 13].

In this paper, we attempt to broaden the understanding of the conditions required for reliably achieving highly-efficient coherent beam combination in completely passive, all-fiber PM fiber laser arrays, with the goal of extending the power scaling capabilities of such systems. We experimentally explore both 2-laser and 4-laser arrays under varying cavity configurations and power levels, up to and including 20 watts of combined power. We will present the results of these findings and discuss the underlying theory for the observed performance.

All-fiber Coherent PM Fiber Laser Arrays and Beam Combining

The configuration of PM all-fiber coherent arrays combining two fiber lasers is schematically shown in Fig. 1. Each PM laser cavity includes an HR grating and single-mode polarization-maintaining Yb-doped double-clad fiber (DCF). The HR grating has a center wavelength of 1083 nm and reflectivity of > 99%. The Yb DCF fiber has an LP_{11} mode cutoff of 950 nm and a 7.5-µm mode-field diameter at 1060 nm. Its Yb cladding absorption at 975 nm is 2 dB/m and its PM beat length is 2.3 mm at 1060 nm. Each laser cavity is end-pumped using a 975-nm pump diode from the HR end via a tapered pump combiner.

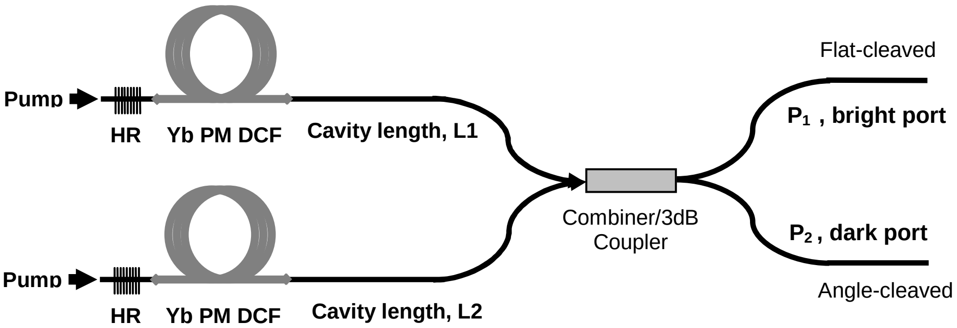

Fig. 1. Schematic of PM coherent arrays combining two fiber lasers

For passive beam combining, the outputs of two PM fiber laser cavities are launched into the input ports of a beam combiner -- a 2x2 single-mode (SM) coupler with a 50/50 coupling ratio in this case. One output port of the coupler is flat-cleaved to provide a 3.4% broadband reflection and other port angle-cleaved to provide a return loss of > 55 dB. We call the flat-cleaved port the “bright port” and the other the “dark port”. When input beams are 100% coherently combined, all input power emerges from the “bright port” and no power comes out from the “dark port”. We use coherent contrast ξ defined by equation (1) as a figure-of-merit for evaluating the coherent beam combining property. P_1 and P_2 are the measured output power from these two ports. The coherent contrast ξ varies from 0 to $+\infty$ with 0 being the case of incoherent combining and $+\infty$ being the perfect coherent combining. We further define the coherent combining efficiency as P_1/P_0 with P_0 being the total launched laser power.

$$\xi = 10 \cdot \log_{10}(P_1 / P_2) \qquad \text{(dB)} \qquad (1)$$

First, we experimentally studied the coherent beam combining characteristics by varying the physical length difference between two laser cavities. The Yb fiber length in each cavity is 10.22 m. We measured the output power from the “bright port” and the “dark port” at different power levels up 700 mW of total power, or 350 mW from each laser. In each case, we varied the length difference from 0 m up to 6 m. The cavity length difference was introduced by splicing a different length of passive fiber between the Yb fiber and one input leg of the coupler. The results of coherent contrasts determined from measured output power versus the cavity length difference are shown in Fig. 2.

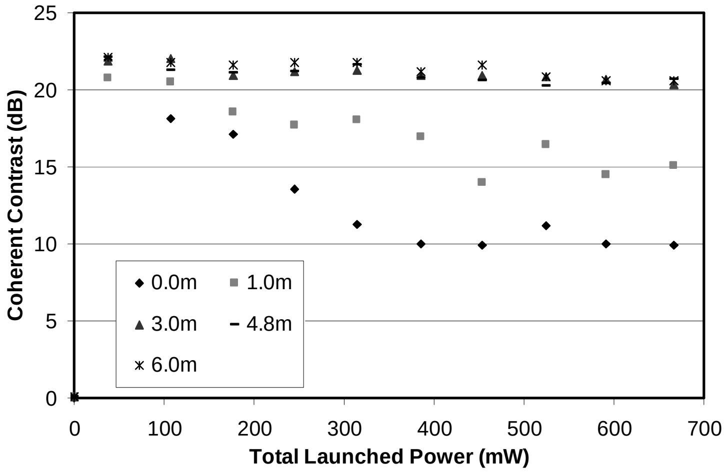

Fig. 2. Coherent contrast using PM two-laser arrays with various cavity length differences

From the results, we observed that the PM two-laser coherent fiber array can spontaneously self-organize into in-phase states without any active control. For the length difference of > 3m up to 6 m, two lasers were efficiently combining with a coherent contrast of > 20 dB and a combining efficiency of > 99% in the power range tested. The output contrast is 22 dB (or 99.4% combining efficiency) at the power level around or less than 100 mW. In addition, the combined output power is pretty stable with a short-term variation (1σ) less than 0.3%. On the other hand, when the cavity length difference is small, the coherent contrast becomes worse at power level of > 100 mW and the output power becomes less stable. However at very low power levels of < 100 mW, or specifically at the power region a little over the lasing threshold the coherent contrast remains high about 22 dB irrespective of the laser cavity length difference.

Next, we increased the launched power of each laser cavity using the same PM laser array. Still, the laser array is all -fiber and all passive without using any active control devices. The cavity length difference is 3 m. We first characterized the output power of each laser before combining up to 14 Watts (pump power limited). We then spliced each laser to the input leg of a 50/50 SM coupler. One output port of the coupler is flat-cleaved and the other angle-cleaved. Measured power outputs from both bright and dark ports, P_1 and P_2, are shown in Fig. 3.

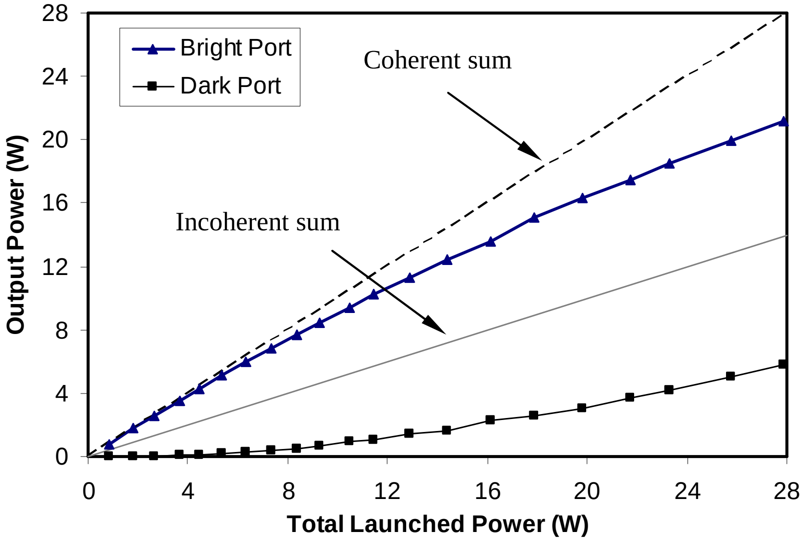

Fig. 3. Coherent combining of two PM fiber lasers up to > 20 Watts of combined power

From the result, we can see that the PM laser array can be coherently combined even at a high power level using our all-fiber passive array configuration. The coherent contrast is 20 dB (or 99% combining efficiency) up to 2.5 W of combined power, and the coherent contrast is 15 dB (or 97% efficiency) up to 6.0 W. With further increase of the input power, two beams are still coherently combined though with decreasing coherent contrast and combining efficiency. The coherent contrasts are 10 dB (or 91% efficiency) and 6 dB (or 80% efficiency) respectively at 10.5 W and 20.2 W of combined output power.

Furthermore, we assembled 4-laser PM fiber arrays and studied their coherent beam combining characteristics. We still used 50/50 fiber couplers to concatenate four lasers to form laser arrays. The beam combining is also all-fiber and no active control devices were used. The bright port P_1 was flat-cleaved and all other ports were angle-cleaved. We measured the output power from P_1 and P_2 ports up to > 2 W of total input power. We will report results at higher power later. The coherent contrast result is shown in Fig. 4. The average coherent contrast is around 16 dB in the measured power range and the beam combining efficiency is 98%.

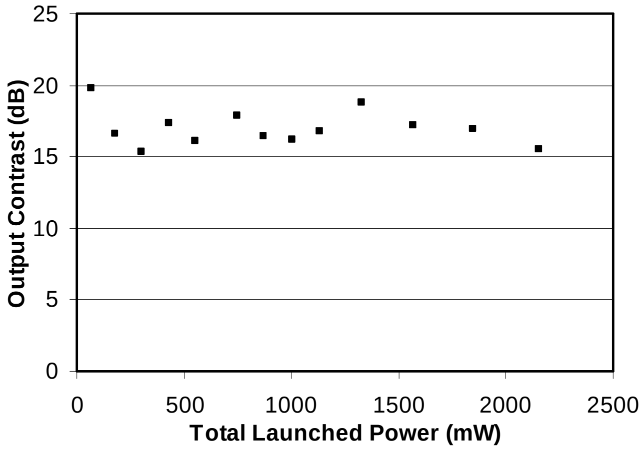

Fig. 4. Coherent contrast using PM four-fiber arrays

Discussion and Conclusions

1. We successfully demonstrated for the first time to our knowledge efficient all-fiber coherent combining of two PM fiber arrays up to > 20 Watts without any active control. The combining efficiencies are >99%, > 90%, and > 80%, respectively, up to 2.5 W, 10.5 W, and 20.2 W of combined output power. The highest combining efficiency achieved is 99.4% (or 22 dB coherent contrast) at the power level of < 100 mW and the combined output power is stable with variation of < 0.3% (1σ).
2. Our experimental study showed that differential laser cavity length is critical to achieve efficient and stable coherent beam combining at high output power. When the cavity length difference is small, the output coherent contrast degrades and the combined output power becomes less stable. Coherent contrast improves with the increase of the cavity length difference up to 3 meters beyond which the coherent contrast change is negligible up to 6 meters in our test cases.
3. However, at very low power range or specifically at the power level just above the lasing threshold, the laser arrays spontaneously reach in-phase states with an excellent coherent contrast of around 22 dB regardless of the cavity length difference. We believe this self-organization phenomenon attributes to dynamic phase change induced by the Kramers-Kronig effect as the lasers are not so saturated. But at the high power level the lasers become more saturated and the resulting gain change becomes less. Therefore, the Kramers-Kronig induced phase change is small. As a result, the laser array loses coherence quickly for laser arrays with the same cavity length as it is difficult to find common in-phase longitudinal modes. However, for laser arrays with a large enough cavity length difference, the lasers are coherently combined with better efficiency and stability because the length difference facilitates the formation of common in-phase longitudinal modes.
4. Coherent loss along with some degrees of power instability occurs at high power. We believe this is possibly due to the onset of nonlinear effects which lead to a decrease of the number of in-phase longitudinal modes. The linear cold-cavity resonator analysis does not seem to be sufficient for predicting the coherent beam combining behavior that we observed both at low power and at high power regions. A thorough understanding of its underlying mechanism should lead us to a "bright" path for advancing all-fiber passive coherent power scaling to over 100 Watts and beyond.
5. We also demonstrated all passive coherent combining of four PM fiber arrays without any active control. The combining efficiency is 98%. We will report results at a higher power level later.

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