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All-fiber passive Coherent Arrays Combining Four High Power Fiber Lasers

Baishi Wang(1), Eric Mies(1†), Monica Minden(2††), Anthony Sanchez(3)
(1) Vytran, LLC, 1400 Campus Drive, Morganville, NJ 07751,
(2) HRL Laboratories, LLC, 3011 Malibu Canyon Road, CA 90265
(3) AFRL/DELO 3550 Aberdeen Avenue, SE, Kirtland AFB, NM 87117

† Now with P.O. Box 509, Marlboro, NJ 07746, †† Cold Canyon Associates LLC, CA 91302

Fiber lasers have been increasingly used for marking, metal cutting and welding, and other industrial applications because of their high wall-plug efficiency and excellent output beam quality. The output power of CW fiber lasers in the kW level from a single fiber has been demonstrated [1,2]. Further power and brightness scaling of these laser systems requires coherent combining of multiple lasers. In free space, coherent combining of multiple fiber arrays of up to several hundred watts of output power has been reported [3,4]. All-fiber coherent laser systems are preferred for reliable, compact, rugged, and efficient high power laser systems. All-fiber monolithic coherent beam combining has been demonstrated in low power [5,6,7,8] and recently at higher powers without any active control [9,10].

In this paper, we experimentally demonstrate all-fiber and all-passive coherent beam combining of two, three, and four high power lasers without using any active control and describe the power scaling characteristics of these arrays. A schematic of a coherent array combining four lasers is shown in Fig. 1. The coherent array consists of four fiber laser cavities with polarization-maintaining (PM) fibers and three couplers. Each laser cavity has a high-reflector (HR) grating, PM Yb-doped double-clad fiber (DCF), and a length of PM passive fiber. In our configuration, PM Yb DCF fiber is single-mode (SM) and it has NA of 0.11, V number of 2.2 at 1060 nm, mode-field diameter (MFD) of 7.6 µm at 1060 nm, Yb cladding absorption of 2.0 dB/m at the 975 nm wavelength, and 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. The laser cavity is end-pumped using 975-nm multi-mode (MM) pump diodes from the HR end via a tapered pump combiner. Each laser output is launched into one input port of the 2x2 SM fiber coupler (C_1 or C_2) with a 50:50 coupling ratio. One output port of each coupler is flat cleaved and the other port angle cleaved to suppress the reflection. Two flat-cleaved ports are then spliced to two input ports of the third coupler (C_0). One output of the third coupler is flat-cleaved to provide a 3.4% broadband reflection and the other angle-cleaved.

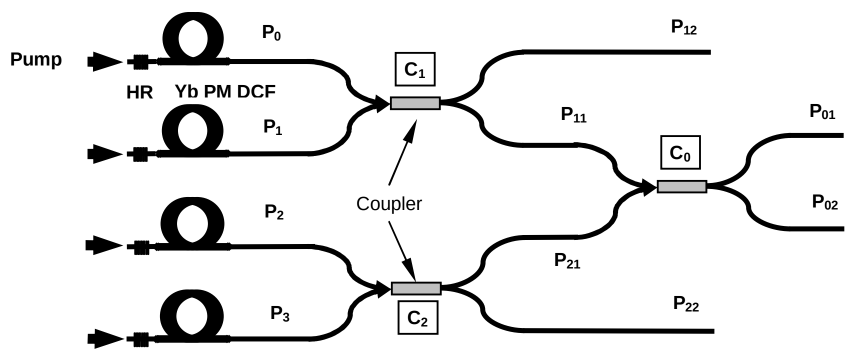

Fig. 1 Schematic of all-fiber passive coherent arrays combining four lasers

In addition to a four-laser array, we set up two-laser and three-laser coherent arrays. For the two-laser array, we used one coupler (C_1) with one output port (P_{11}) flat-cleaved and the other port (P_{12}) angle-cleaved. For the three-laser array, we used a second coupler (C_0) and spliced the P_{11} and P_2 ports to the input ports of the second coupler. One output of this coupler was flat-cleaved and the other angle-cleaved. Differential cavity length difference was introduced in all coherent arrays. For evaluating the coherent beam combining performance, we introduce a figure-of-merit parameter -- coherent combining efficiency, which is defined as

$$\eta = \frac{P_0}{\sum_{i}^{n-1} P_i} \cdot 100\% \tag{1}$$

where P_i is the output from I^{th} port and P_0 is the power from the coherent port, or the flat-cleaved port. We measured the output power at different output power levels by increasing the power from all four lasers. The output from each cavity was characterized to insure same output power at each power level. Combined output power from the flat-cleaved port and the power sum from other three angle-cleaved ports are shown in Fig. 2. In addition, we characterized the output powers from different ports for both the two-laser and three-laser arrays. Coherent combining efficiency results for the tested two-laser, three-laser, and the four-laser arrays are depicted in Fig. 3. In all array cases, the measurement was made up to 25 W of total input power, which is pump limited. For two-laser, three-laser, and four-laser arrays, the combining efficiencies are 99.1%, 98.2%, 95.6% at 2 W, 93.9%, 96.6%, 93.0% at 10 W, and 86.2%, 89.5%, 87.1% at 25 W of total input power, respectively. The results show both power and number scalability of these coherent arrays.

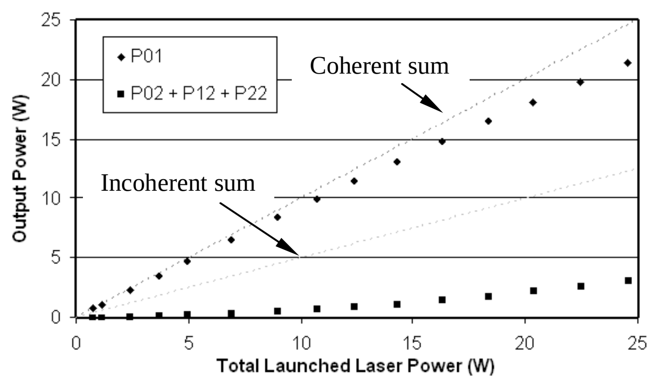

Fig. 2 Output powers of the four-laser coherent array

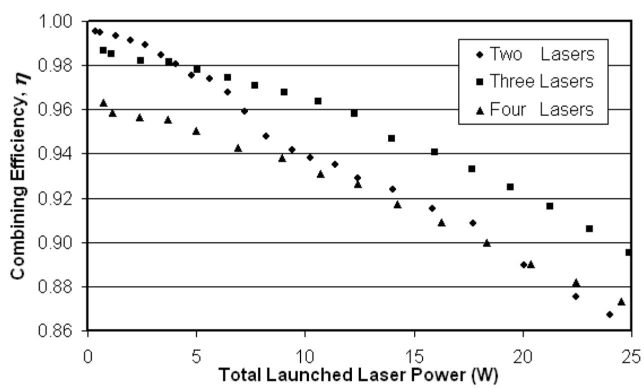

Fig. 3 Efficiency comparison of two-laser, three-laser and four-laser arrays

To further study power scalability of the coherent arrays, we assembled a two-laser array using LMA fibers and an LMA 50x50 output coupler fabricated in-house. The LMA Yb-doped DCF fiber has NA of 0.07, core diameter of 11 µ, and MFD of 12.3 m 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 length of the Yb fiber is 5.0 m for each laser cavity. Both HR gratings have a center wavelength of 1080.2 nm with 3 dB bandwidth of 1.6 nm and a reflectivity of 99%. To characterize the combining efficiency, we first measured the output power of each laser before combining up to 88.8 W of total laser input power and then measured the combined output from two output ports. The output powers from both ports are shown in Fig. 4. In this configuration, we reached 75.5 W of coherently combined output power from the flat-cleaved port. The output power from the angle-cleaved port is 13.3 W. This corresponds to a combining efficiency of 85% at this power level. For comparison, the combining efficiencies are 95.2%

and 90.9% at 31.2 W and 60.2 W input powers, respectively. Compared to the laser arrays using regular SM fibers, the combining efficiency was significantly improved by using 11-µm LMA fibers. Further power scaling is possible by using fibers with larger mode-field diameter.

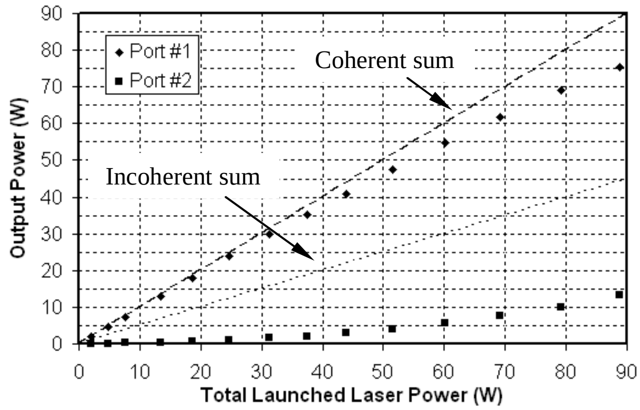

Fig. 4 Power scaling of two-laser array with LMA fiber lasers

We have presented all-fiber passive coherent arrays combining up to four high power Yb fiber lasers. For power scaling, we demonstrated coherent beam combination of two lasers up to record 75 W of combined output power using LMA fibers and coupler. Significant combining efficiency improvement was shown by using LMA fibers. In addition, we have showed roll-off of coherent combining efficiencies at high power. Kerr n_2 induced nonlinearity plays an important role in high power arrays when each laser is operated in the saturation region. Furthermore, we demonstrated number scalability by comparing coherent combining of two-laser, three-laser, and four-laser arrays. Further scaling seems possible by using LMA fibers and multiple numbers of fiber lasers.

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