Effects of fill factor of fiber combiner on the all-fiber coherent combining

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A new approach for an all-fiber coherent beam combining by active phasing a fiber combiner is presented, and effect of fill factor of the fiber combiner on the all-fiber coherent combining is also numerical analyzed. Experimental results show that the power in the bucket (PIB) increases more than a factor of 2.35. The results validate the feasibility of coherent combining using a fiber combiner. The PIBs with different fill factors are calculated and the results show that the coherent combining is reduced with the increasing fill factor.

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Fiber laser has been attracting much attention, mainly because of its ability to provide good beam quality, high efficiency, compactness, and high reliability[1−3]. At present, a commercial single mode fiber (SMF) laser with 10-kW output power has been developed by IPG[1]. However, due to the fiber damage and nonlinearity in a single diffraction-limited fiber laser chain that operates in fundamental mode, further scaling the output power to a higher level is a challenging task. Coherent beam combining (CBC) technology is an effective solution to not only scale the output power but also maintain high beam quality[4−7]. The main configurations for CBC can include two categories: the free-space configuration and the all-fiber configuration. In free-space configuration, kilowatt level output power together with high beam quality has been reported[4,5]. However, beam combining in all-fiber configuration, which is a desirable path for reliable, compact, rugged, and efficient high power laser systems[6−8], is by far lagged. Fiber combiner is also a popular alternative to scale the output power in all-fiber form. And a laser system with 50-kW output power has become commercially available by IPG in 2010[9]. Nevertheless, the brightness is not increased and the M^2 factor of the output beam is 32.7, far from the near-diffraction-limited beam[10]. In many laser application fields, especially for the long-distance delivering, a laser with poor beam quality will become quickly inadequate, even if it has sufficient power. How to scale power while simultaneously preserving brightness by a fiber combiner is a challenge for us. In this letter, we will demonstrate an all-fiber and all-active coherent combing using a fiber combiner. This approach is assisted with active phase control and beam cleanup technology. In addition, the effect of fill factor on the coherent combining is also discussed.

For a better understanding, we firstly compare two schemes of beam combining with tapered fused bundles (TFBs) when input lasers are combined incoherently and coherently as shown in Fig. 1. Figure 2 illustrates the end face of a 7×1 TFB tip with full fusion degree. The claddings are fused and merged into unity one, leaving the seven cores alone. The simulated outputs results are shown in Fig. 3. Figure 1(a) shows that N laser sources are launched into respective SMFs, and the output is combined incoherently (Fig. 2(a)). The total output power scales with the number of lasers without brightness improvement. However, if one laser source is split into N SMFs, as shown in Fig. 1(b), all the fiber elements operate with the same wavelength and the relative phases of the elements are controlled. The coherent combining output is satisfied. Both output power and brightness are up-

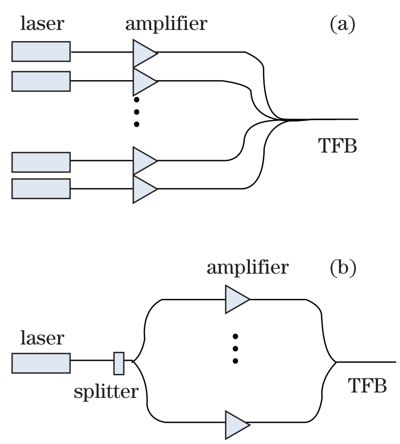

Fig. 1. Two schemes of beam combining with TFB (a) incoherently and (b) coherently.

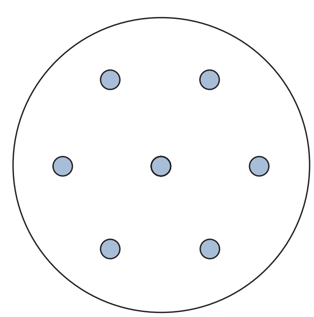

Fig. 2. End-view image of 7×1 TFB with full fusion degree.

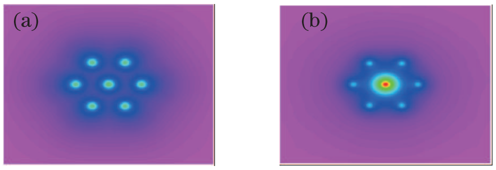

Fig. 3. Simulated outputs of a 7×1 TFB launched (a) incoherently and (b) coherently.

scaled proportionally to the number of lasers (Fig. 2(b)). It is possible to achieve coherent combining in all-fiber via an appropriately designed fiber combiner.

It is noted that the unlike the free-space coherent combining, as shown in the Fig. 1(b), in the fiber combiner, the several single mode beams from the TFB tip will be combined coherently along the multi-mode fiber (MMF) and the coherent output beam is in the form of multimode pattern, which does not have well defined phase and amplitude distributions[11]. Therefore, in order to increase the brightness, beam cleanup technique based on the stochastic parallel gradient descent (SPGD) algorithm[12,13] is a technique to transform a multimode beam into a near-diffraction limited Gaussian beam, which have been validated in our previous works[14,15].

The all-fiber active coherent combining system via a fiber combiner is schemed in Fig. 4. In the experiment, we have taken a 2×1 fiber combiner for an example. The seed source is a commercial 1 064-nm SMF laser. The laser is split into two input SMFs (Corning HI1 060 Flex, 5.9 μm MFD, 0.14 NA@1 064 nm) and then coherent combined in the output MMF (Corning, 25/125, 0.22 NA@1 064 nm). The two SMFs are tapered to an appropriate diameter, which is less than the diameter of the MMF core. It ensures both SMF lasers can be accepted by the MMF. After collimating, expanding, the output beam is divided into two beams. One is received by a pin-hole detector to control the phase modulator (PM). The reason is that due to the piston phase aberrations between the two arms of the combiner induced by environmental disturbances, i.e., temperature changes or stress, the far-field intensity distribution is changed erratically and slowly. Therefore, the PM, which is controlled by the PM controller with a multi-dithering algorithm[16,17], is added in one arm to realize a fixed phase difference and to achieve a stable output. The location of the pinhole is carefully adjusted to ensure the maximum output signal of the detector, in which case the maximum power of the interference pattern will be encircled in the pinhole. The optical power detected by the photoelectric detector is defined as the evaluation function J[14,15]. Another beam is incident on a phase only liquid crystal spatial light modulator (LC-SLM, BNS Company, 256×256 pixels, 24×24 (μm), and 8 bit). The beam reflected from the LC-SLM is focused to form a focal spot on the surface of a CCD (AVT Company, 1 032×768 pixels, 4.65×4.65 (μm), and 8 bit). The CCD is used to capture the far field intensity distribution. According to the images from the CCD, the PC carries out the SPGD algorithm to adjust the phase distribution of the LC-SLM iteratively to obtain an expected output.

The experimental results are shown in Fig. 5. From Fig. 5(a), it can be seen that when in open-loop, the beam cleanup process is not implemented and the far-field distribution density of the multimode output beam is low, and the beam is diverged widely so that the beam quality is degenerated seriously. When the loop is closed, a clear and stable spot is obtained and most of the power is included in the main lobe, which denotes a remarkable increase in energy encircled in the main lobe as shown in Fig. 5(b). Figure 5(c) demonstrates that the quality evaluation function curve after 800 iterations is 3.7. Comparing with the original value 1.02, the quality evaluation function is increased by more than a factor of 3. The PIB also been calculated. We have chosen the diffraction-limited bucket as the far-field bucket. The values of PIB before and after cleanup are 0.304 and 0.715, respectively. Therefore, the PIB is increased by a factor of 2.35.

The taper fiber bundle tip is formed by tapering and fusing N fibers together. The array distribution of the TFB tip is determined by the taper ration and taper length. As shown in Fig. 6, suppose that each fiber laser beam has a Gaussian single mode field distribution. The beam waist of each laser is ω_0. Fiber lasers are arranged in the array with the nearest neighbor separated by a distance of d. The fill factor is defined as $v = (d - 2\omega_0)/\omega_0$ to describe the compactness of the TFB. The smaller v corresponds to a tighter array. The effect of fill factor on the coherent combining of fiber combiner is analyzed through numerical simulation of the 7×1 combiner. When the fill factor varies from 0 to 3, the cross section of the respective far-field in x direction is presented in Fig. 7. With the increasing v, the peak power is reduced, and the fraction of the side lobes power increase. The relationship between the PIB values and v is presented in Fig. 8 directly. It is concluded that

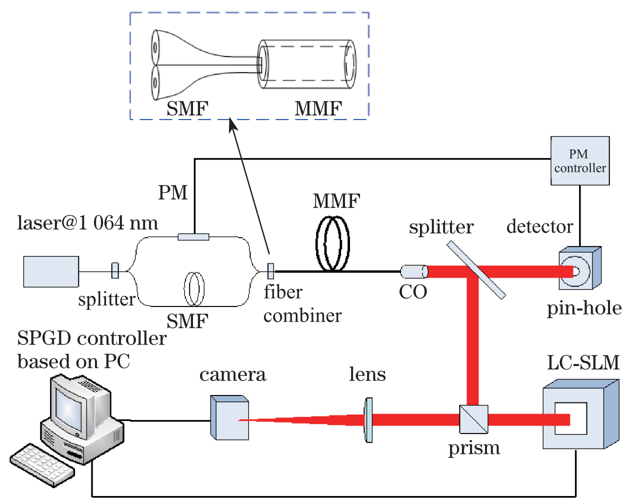

Fig. 4. Schematic of the experimental system.

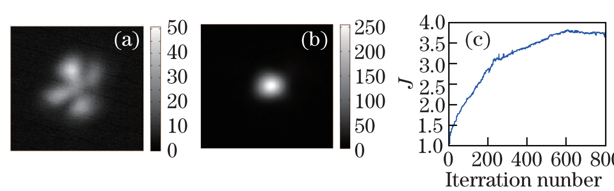

Fig. 5. Experimental results. Captured image of far-field intensity distribution (a) before and (b) after cleanup; (c) evaluation function curve.

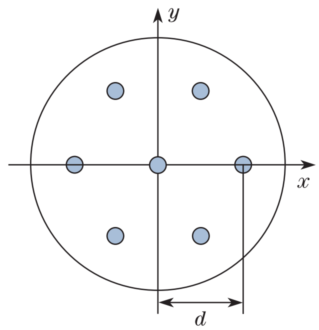

Fig. 6. Array distribution of the TFB tip.

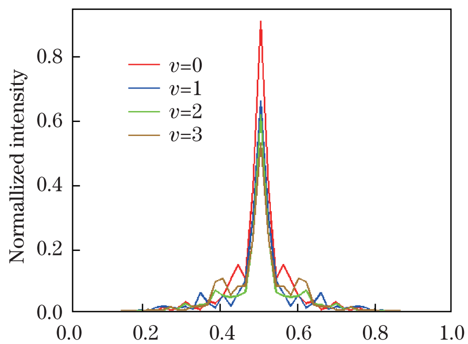

Fig. 7. Intensity distribution of the respective far-field with different v in the x direction.

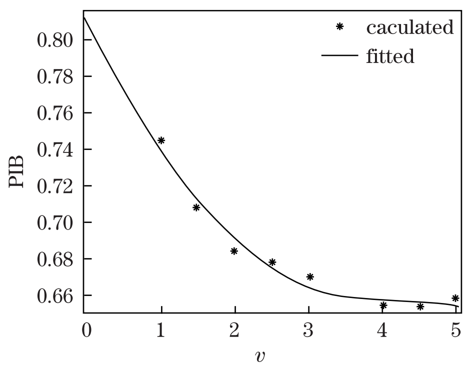

Fig. 8. Relationship between the PIB values and fill factor v.

the beam quality is reduced with the increasing v. The results are consistent with that of the free-space coherent combining laser arrays.

In conclusion, a new all-fiber coherent combining configuration is presented. Using active control and beam cleanup technology, a high power output maintaining good brightness is realized by the fiber combiner. Meanwhile, the effect of the fill factor of the fiber combiner on the coherent combining is studied numerically. Results show that a fiber combiner with a smaller fill factor is more efficient for the all-fiber coherent combing. In order to decrease fill factor, the fiber cladding, which does not carry power, should be reduced. Hydrofluoric acid is an effective way to etch away the fiber cladding, and therefore the taper ration can be minimized. This conclusion offers a guide for designing and manufacturing the fiber combiner used for coherent combining.

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