Experimental investigation of a seven-element hexagonal fiber coherent array

Xinyan Fan(范馨燕)[1*], Jingjiao Liu (刘京郊)[1], Jinsheng Liu (刘金生)[1], and Jingli Wu (武敬力)[2]

[1]*National key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001, China*

[2]*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*

[*]*E-mail: fanshong_02@yahoo.com.cn*

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The phase noises of a 10-m polarization-maintaining (PM) fiber and a 10-W PM fiber amplifier are experimentally measured. The results indicate that the 10-m PM fiber with similar phase noise could be used to investigate the architecture of master oscillator power amplifier coherent combination. A seven-element hexagonal fiber coherent array is developed to investigate the far-field distribution and phase controlling technique of a coherently combining fiber laser array. A hexagonal prism is designed as the combining and splitting component to achieve a fill factor of 0.66. The hill climbing method is employed to detect and lock the element phase.

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Coherent combining of multiple fiber lasers is becoming a viable alternative for high power and high brightness laser source. Various coherent combining techniques have been investigated in low power configurations[1−6]. Active phasing and passive phasing implementations are two main approaches. Active phasing implementations mostly employ the master oscillator power amplifier (MOPA) architectures[1−3] with additional phase locking electronics. Passive phasing implementations generally include interferometric resonator[5], self-Fourier resonator[6], self-imaging resonator[7,8], and fiber couplers[9]. For MOPA coherent combining architecture, fill factor of approaching unity and phase locking technique are the two most challenging tasks. The two-dimensional (2D) array could contain more elements than a linear array with the same area. However, most of researchers studied the linear fiber amplifier arrays of two or three elements[2,3]. At present, many researches have brought up various techniques of phase sensing and locking electronics, including heterodyne detection[1,2], hill climbing method[3], and self-synchronous phase locking[4]. In this letter, the phases noises induced by a 10-m polarization-maintaining (PM) fiber and a 10-W fiber amplifier are measured. With this information, we establish a 2D hexagonal array of seven elements with a high fill factor of 0.66.

The phase noise of fiber amplifier has been measured in previous work[9]. However, the phase noise of PM fiber itself has not been investigated. We are interested in the phase noise difference between two processes, the PM fiber transmitting and amplifying the master oscillator (MO) signal. Theoretically, phase noise can also be generated after the MO signal is transmitted through the PM fiber with no pumping or amplification due to variable refractive index and environmental perturbation, such as temperature variations, mechanical resonances, acoustic noise, and seismic noise. For the PM fiber amplifier, as the injected MO signal power is amplified, potential heating effect and nonlinear effect may worsen the phase noise. Therefore, the phase noise of fiber amplifier may be different from the laser signal transmitted through PM fiber.

The phase noise measurement configuration is shown in Fig. 1. The MO is a single frequency non-planar ring oscillator (NPRO) with diode-pumped Nd:YVO_4 which is operated at 1064 nm and outputs power of 0 − 1000 mW. The laser beam frequency linewidth is less than 5 kHz. The MO is coupled into a 1×2 PM coupler, and then split into a reference arm and a signal arm. Separate experiments were done with the signal arm of the passive or active fiber arm to measure the phase noise. The passive fiber arm is a 10-m PANDA PM fiber of 6.6-μm core diameter manufactured by Nufern. The active fiber arm is a Nufern single frequency PM fiber amplifier with 10-W output power. After collimation, the reference arm and the signal arm coaxially interfere with each other. A sample of the interference beam is used to measure the phase noise with a photo-detector. The photo-detector is an AsGaIn PIN photodiode of 1.5-ns response time.

Figure 2 shows the phase noise spectral distribution of the passive and active fibers obtained by applying Fourier transforms to the steady-state phase noise. It can be seen in Fig. 2 that, for the 10-m PM fiber and the 10-W PM fiber amplifier, the majority of the phase noises are both centralized at the frequency of several kilohertz.

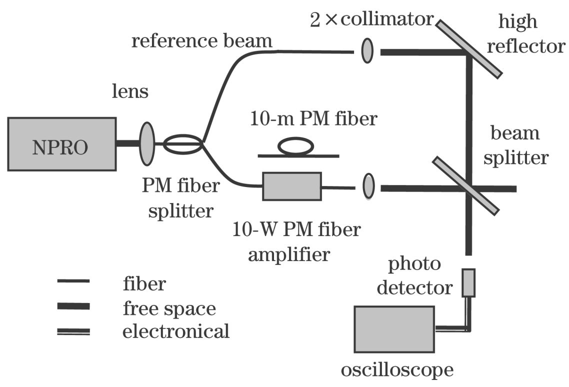

Fig. 1. Schematic of the phase noise measurement configuration.

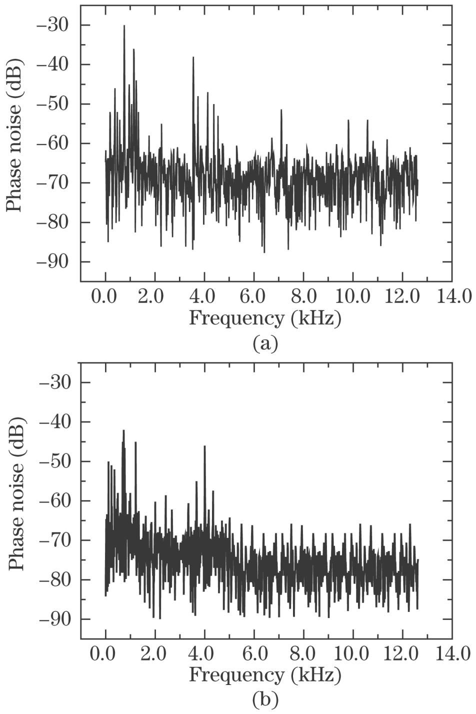

Fig. 2. Phase noises of (a) 10-W PM fiber amplifier and (b) 10-m PM fiber transmitting the MO signal.

The phase noise is mainly caused by temperature variations, mechanical resonances, and acoustics noise in a laboratory environment. These effects are identical for the 10-m PM fiber and the amplifier. The primary difference between the 10-W fiber amplifier and the 10-m PM fiber is in the frequency range higher than 5 kHz, however, the amplitude is smaller than that in the frequency range of 0 − 5 kHz. The reason is that the fiber amplifier suffers more serious thermal effect and nonlinear effect[10]. Anyway the dominant noise sources that need to be corrected are between zero and several kilohertz. Based on the similar phase noise characteristic, the PM fiber could be used as the element to develop the coherent combining array of a MOPA architecture. The work will be the foundation of the MOPA coherent combining array. The results also indicate that the bandwidth of the phase locking electronics should be designed in the range of several kilohertz, and the bandwidth of phase modulator of $\sim$ 10 kHz is required for a laboratory environment.

With the phase noise measurement results, we develop a seven-element hexagonal fiber array with a 10-m PM fiber transmitting the MO signal. The coherent array configuration is shown in Fig. 3. The MO and PM fiber are the same, as shown in Fig. 1. The 1×8 PM fiber coupler is composed of one 1×2 coupler and two 1×4 couplers. The MO is split into one reference arm and seven signal arms. The seven signal arms are 10-m PM fibers just transmitting the MO signals without amplification. After collimation, the signal arms individually pass through lithium niobate phase modulator. A hexagonal prism is employed as a combining component to transform the seven signal arms as a seven-element array with a fill factor. A sample of laser beam from each signal arm interferes with the one from the reference arm to measure the relative phase of that arm to the reference arm. Similarly, a hexagonal prism is used to split the seven laser beams to incident to the individual photo-detector. The combining and splitting principle of the hexagonal prism is shown in Fig. 4. The phase controlling electronics detect and adjust the phase of each signal arm with a control voltage to the phase modulator. The principle of hill climbing phase measurement is shown in Fig. 5. A Fourier transform lens is used to image the far-field pattern in the focal plane where a charge-coupled device (CCD) camera is set.

Regarding the hexagonal array and precise position requirement, we design a hexagonal prism which is shown in Fig. 4. The hexagonal prism is cut into six 45° inclined

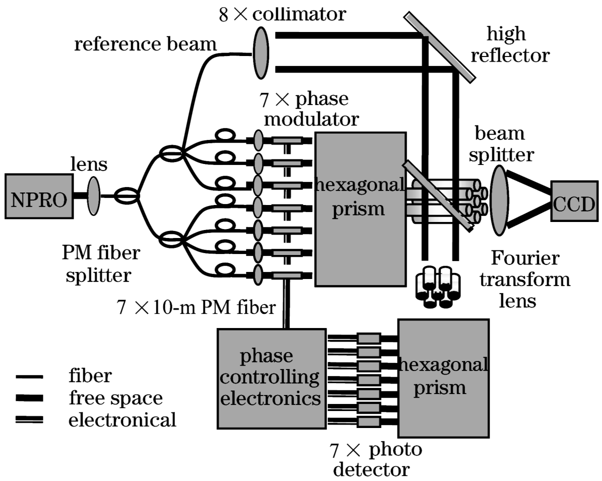

Fig. 3. Schematic of coherent combining of the seven-element fiber array.

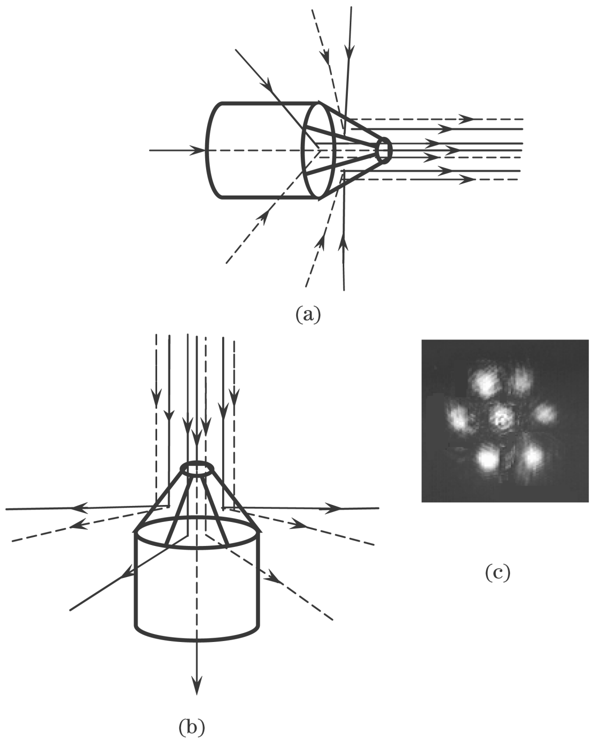

Fig. 4. Combining and splitting principle of the hexagonal prism and the obtained near-field pattern. (a) Hexagonal prism as a combining component; (b) hexagonal prism as a splitting component; (c) near-field pattern of the seven-element hexagonal array.

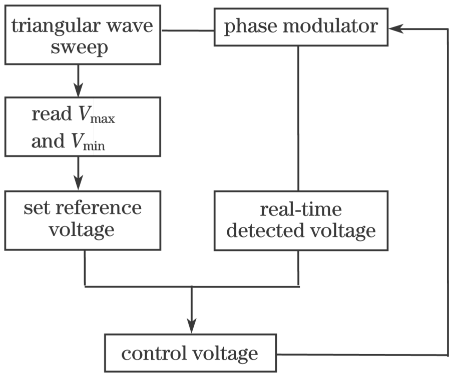

Fig. 5. Principle of hill climbing phase controlling electronics.

planes with 99.9% golden reflective coating and one central through hole. It combines beams as follows: six circular laser beams are incident with 45° incidence angle in the plane perpendicular to the paper and then reflected to horizontal direction, while the central laser beam exits from the central through hole, as shown in Fig. 4(a). Then the seven laser beams are transformed to an array of seven parallel beams. In the same way, when the seven parallel laser beams are incident to the hexagonal prism vertically, seven laser beams with different directions will be split, as shown in Fig. 4(b). The collimated laser beam diameter is 2.4 mm, and the spacing between the beams is 3.6 mm. The near-field distribution of seven laser beams is shown in Fig. 4(c). The coherent fiber array could lead to a fill factor of 0.66. Here, the fill factor is calculated by dividing the spot size of the element aperture by the distance of the elements, that is, $f = 2\omega_0/d$. In our experimental setup, the high fill factor is a unique advantage for the hexagonal prism as combining component. Furthermore, compared with traditional V-groove array[1] with precise accuracy requirement, the hexagonal prism has the advantage of high aligning accuracy when it is used as a combining component, because there is adequate space for separate element to align. As a splitting component it has the advantage of increased detecting precision. The array could scale to a multi-circle hexagonal array by adding another hexagonal prism with a larger central through hole, or to other structure by cutting the prism to other shapes of more than six reflecting surfaces.

The use of phase controlling electronics is another key technique in the MOPA architecture. We employed a hill climbing method commonly used in adaptive optics systems, as shown in Fig. 5. The concept of hill climbing phase detection is a technique automatically optimizing the control point by software control. A triangular wave is applied to the phase modulator periodically. The detected voltage is identical to the interference intensity of the two beams. After sweeping several periods, a maximal output value is created, representing the maximal intensity of the interference fringe. A reference voltage is set to be at 90% of the maximal voltage by software. The detected real-time voltage is compared with the reference voltage, resulting in a control voltage. A control voltage is feed back to the phase modulator for each signal arm to correct the phase of that arm. The feedback process is cyclic continuously until the interference intensity reaches the maximum. In this way, all of the output phases of the signal arm are exactly locked with the reference arm.

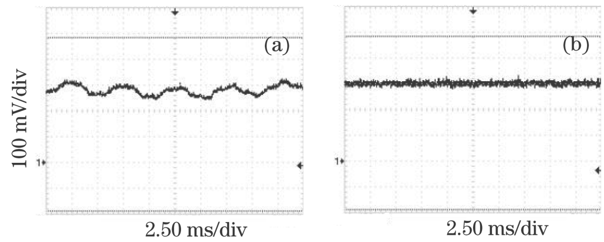

Fig. 6.Phase controlling results by hill climbing method. (a) Phase unlocked; (b) phase locked.

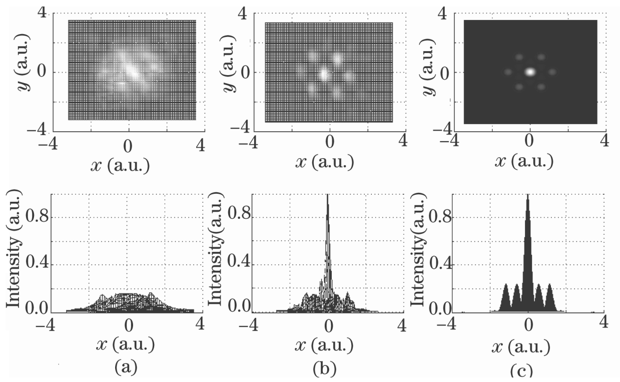

Fig. 7. Far-field intensity profiles of the seven-element hexagonal fiber array. (a) Experimental far-field intensity profile of incoherent combining; (b) experimental far-field intensity profile of coherent combining; (c) theoretical far-field intensity profile of coherent combining. The upper shows the plane profiles, and the lower shows the profiles along x axis.

Figure 6 shows the phase controlling results of two element fiber coherent combining. It can be seen that the phase noise in the frequency range of kilohertzs is corrected by a hill climbing electronic system. The electronics are designed to be operating at 10 kHz and the control precision is $\lambda/10$ which is verified by the experiment.

The experimental and theoretical results of the seven-element hexagonal fiber array are shown in Fig. 7. We measured the far-field intensity distributions of incoherent combining and coherent combining. The measured far-field peak intensity of coherent combining is nearly seven times of that of incoherent combining. Calculated from the gray values of the CCD photos, with a fill factor of 0.66, the energy contained in the central lobe of 0.40 and the Strehl ratio of 0.91 are obtained, while the theoretical energy contained in the central lobe for 0.66 fill factor is 0.51. The energy contained in the central lobe[2,11] and the Strehl ratio[12] are two key metrics for the far-field distribution of the coherent array. The energy contained in the central lobe is defined as the ratio of the energy in the central lobe to the whole energy. The Strehl ratio is defined as the ratio of the on-axis intensity of actual coherent combining beam to that of an ideal equal-power top-hat beam.

As a note, the fill factor of the seven-element hexagonal fiber array is as high as 0.6, which is an original advantage of our coherent combining system. The energy contained in the central lobe increases with the enlargement of fill factor[12]. The smaller fill factor must bring more side lobes and reduce the energy contained in the central lobe.

In conclusion, we have measured the phase noise of passive fiber and active one. The experimental results indicate that the PM fiber could be used in MOPA coherent array to investigate the far-field distribution of a seven-element hexagonal fiber array. A seven-element hexagonal fiber array with 10-m PM fiber of fill factor as high as 0.66 is developed. The MOPA coherent array architecture with hexagonal prism greatly improves the fill factor and detection precision. The combining and splitting component is quite useful for the fiber amplifier array to obtain high fill factor. We obtain the far-field distribution of 0.40 energy contained in the central lobe and 0.91 Strehl ratio. As a note, we employ a relatively simple phase controlling technique of hill climbing method to realize the coherent combining of seven hexagonal laser beams with high fill factor. Although we have measured the phase noise of the 10-m PM fiber and the 10-W PM fiber amplifier, which are centralized around several kilohertzs, the application of the phase controlling technique of hill climbing method in fiber amplifier array still needs further investigation.

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