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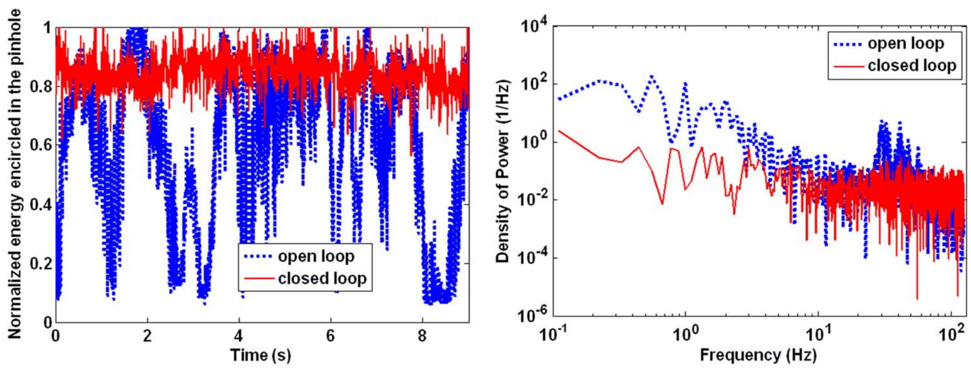

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Passive Coherent Polarization Beam Combination of a Four-Fiber Amplifier Array

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Abstract: We present what we believe to be a new architecture for coherent beam combination of a fiber amplifier array. Four polarization-maintained fiber amplifiers are passively coherent polarization beam combined by using an optical feedback in a ring cavity. Experimental results verify that the architecture is robust and effective. The combining efficiency of the whole system can be as high as 91%, and the phase noise can be suppressed effectively. We believe that the configuration presented in this paper is a promising approach for high-power laser combination without degrading the beam quality of the coherently combined beam.

Index Terms: Fiber amplifier array, coherent beam combination, passive phasing, polarization beam combination.

1. Introduction

Coherent beam combination (CBC) of fiber lasers/amplifiers has attracted intensive attention due to its advantageous aspect of brightness scaling [1]–[16]. Generally speaking, CBC can be classified into two categories, CBC of fiber amplifiers seeded by a common oscillator with active phasing technique [1]–[5] and passive phasing of a fiber laser/amplifier array without external control phase differences among the amplifier chains [7]–[16]. However, in order to further boost the coherent output power by CBC configuration, the power enhancement of the individual amplifier chain should be considered significantly. In active phasing technique, the line-width of the seed laser should be narrow to ensure the temporal coherence. Power scaling of each fiber amplifier chain is challenging due to the intrinsic stimulated Brillouin scattering (SBS) effect. As for passive phasing configuration, a potential important feature had been confirmed that the spatial coherence property is maintained even when temporal coherence is degraded with the laser wavelength spreading over a range of several tens of nanometers [11], which can effectively suppress the SBS effect [13]. Passive phasing had been accomplished by many techniques, for example, by use of self-Fourier laser cavity [6], evanescent coupling [7], and self-organization mechanism in fiber laser arrays [8]–[10]. As one of the passive phasing techniques, fiber amplifier array with an optical feedback had been presented and may be a promising solution to high power operation [11]–[16]. In addition, in most of the previous demonstrations that employed active phasing or passive phasing, all the emitters are tiled into an array, which causes a part of power collected into the side-lobes in the far-field pattern [17]–[19], thus inevitably degrading the beam quality and power concentration of the combined laser. Therefore,

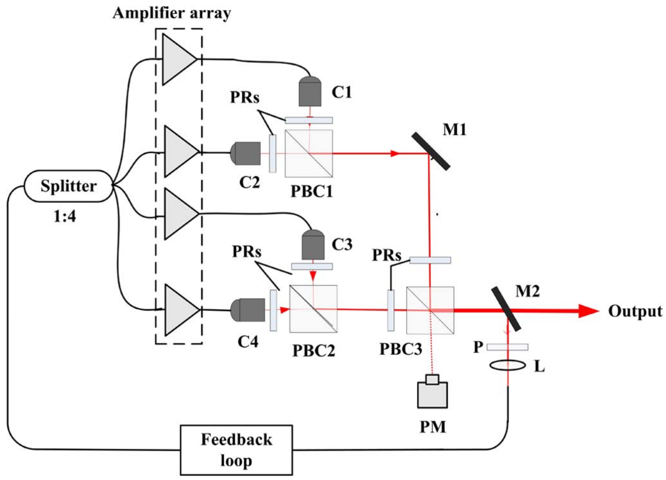

Fig. 1. The schematic of the new four-channel architecture. C1–C4, collimators; PRs, polarization rotators; PBC1-PBC3, polarization beam combiners; PM, power meter; M1, all- reflectance mirror; M2 high-transmittance beam splitter; P, linear polarizer, L, positive lens.

there is a requirement to provide a new CBC architecture for promising high power operation without degenerating the beam quality of the combined beam; at the same time, the side-lobes in common CBC architectures can be avoided.

In this paper, we present a new architecture that fulfills those requirements. Coherent polarization beam combination (CPBC) technique [20]–[23] is incorporated into the traditional passive phasing array with an optical feedback. Different from our previous publications [22], [23], due to employing the passive self-organized phase locking technique based on an optical feedback, the complex active phase control circuit and the expensive phase modulators are left out in the configuration. The scheme is validated by CPBC of four polarization-maintained all-fiber amplifiers into a coaxially output beam. Experimental results show that the new configuration we developed is effective and has great potential for high power operation.

2. Principle and Experimental Setup

For simplicity, we use a four-channel system to illustrate the process of the new architecture. The schematic of four-channel new architecture is shown in Fig. 1. The laser beams from the splitter are amplified by four polarization maintained fiber amplifiers and sent to free space via four collimators. By rotating the polarization rotators (PRs), they can be combined in the polarization beam combiners (PBCs). After the final PBC, the combined laser power is sampled by a beam splitter (M2). A small fraction of sampled power is injected into a linear polarizer (P) and then focused by a positive lens (L). The focused beam is collected by a single mode fiber as the feedback loop.

When the phase difference between two orthogonally polarized beams is irrelevant and injected into a PBC, the polarization state of the combined beam is not pure linear-polarized, as it is a mixture of the two injected polarization states, thus restricting the further extendibility of the polarization combination system due to the fact that the combined power will disperse in the next PBC, as shown in Fig. 2(a). However, when the phase difference between the two orthogonal polarizations is locked and set to $\delta = n\pi$, where n is an integer and δ is the phase difference between two beams, the polarization of the combined beam is pure linear-polarized [see Fig. 2(b)], which can be completely transmitted through the next PBC by rotating the polarization direction of the combined beam; thus, it can be combined again with a linearly polarized beam, so multi-channel beams can be coherently combined through phase-locking. In this case, the energy coupled into each oscillator can be at maximum state if the laser beams are phase locked; thus, each cavity loss

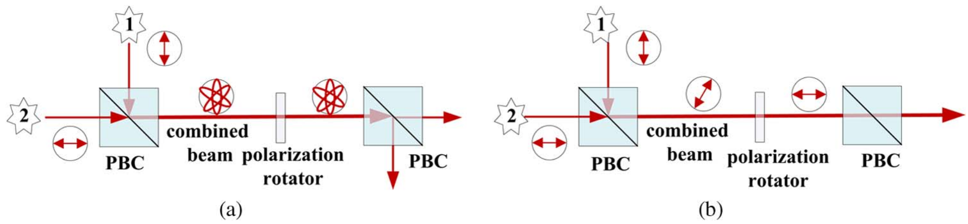

Fig. 2. The schematic of polarization combining process for (a) phase undefined and (b) phase locked.

can be at minimum state, and the relative phases among different oscillators can be locked by self-organized process.

From the analysis above, we suggest that passive phasing technique based on a ring laser cavity consisting of a fiber amplifier array can be employed in the multi-channel CPBC system. Before the self-organized process established, the combined power through the polarizer (P) fluctuates randomly due to the fact that the phase differences among the injected beams are fluctuant, owing to the thermal and mechanical effects, thus some of the power leaks into the power meter (PM). By polarization controlling and cavity-design, when a ring cavity where a single-mode fiber encircles the combined output power of the multiple-channel beamlets and feeds it back to the amplifier array, the self-organized process will establish and the longitudinal modes with lowest loss can be selected in the cavity. As a result, the phase relationships among different beams self-adjust to preserve minimum intra-cavity loss, so that the phase differences among all the channels can be locked to be nπ (n is an integer). It is to be noted that, in Ref. [11]–[16], the single mode feedback fiber has a core that approximately matches the central peak of the array's far field, thus providing the spatial filtering mechanism needed for phase locking. Also, the single mode feedback fiber should be adjusted carefully due to that fact that it plays an important role for phase locking effect and the far-field intensity distribution is so sensitive to the position of the fiber, thus degrading the stability of the system. Different from Ref. [11]–[16], as for the architecture we presented, assuming perfect alignment of the setup, the spatial frequency spectrum of each beam profile remains the same; thus, filtering is not indispensable for phase locking.

To validate the feasibility of the principle above, we carry out a proof-of-concept experiment by passive CPBC of a four fiber amplifier-array by an optical feedback. Fig. 3 demonstrates the experimental setup of passive phasing the four-channel ring cavity. In each oscillator, the amplifier chain is an all fiber single mode and polarization-maintained amplifier made by ourselves. The active fiber employed is polarization-maintained Yb-doped fiber (YDF), which has a 6 μm core diameter and a 125 μm inner cladding diameter. After pumped by a 480 mW single-mode pigtailed laser diode (LD) with a 974 nm central wavelength, the average laser power in each channel can be boosted to be more than 130 mW. Behind each wavelength-division multiplexing (WDM), 4-m-long active fiber is employed and a section of passive fiber is spliced after the active fiber for output power delivery. In each oscillator, the passive fiber is fused to a 2.5 mm-radius collimator with embedded isolator (ISO) to prevent backscattering light and send the laser beam into free-space. In the experiment, we use the half wavelength plates (HWPs) as the PRs. By rotating the HWPs, the four laser beams can be combined by the PBCs. M1 is an all-reflectance mirror, and M2 is a high-transmittance beam splitter with 4% reflectivity. After M2, a small part of the power is reflected to a positive lens (L) with a focal length of 75 mm and focused to a single mode fiber. The power encircled by the polarization maintained feedback fiber is amplified by a pre-amplifier chain (pre-A) to adapt to the amplifier array and then feeds into the four amplifier array by a 1:4 splitter. In our experiment, a seed laser with central wavelength of 1064 nm is incorporated into the feedback loop by a polarization-maintained 50:50 coupler. The function of the seed laser is mainly contributed to feed the amplifier chains to specific power levels and helps to perform coaxial adjustment of the whole system safely before the passive phasing process established. To optimize the combining efficiency of the whole system, the seed laser should be turned off completely during operation of

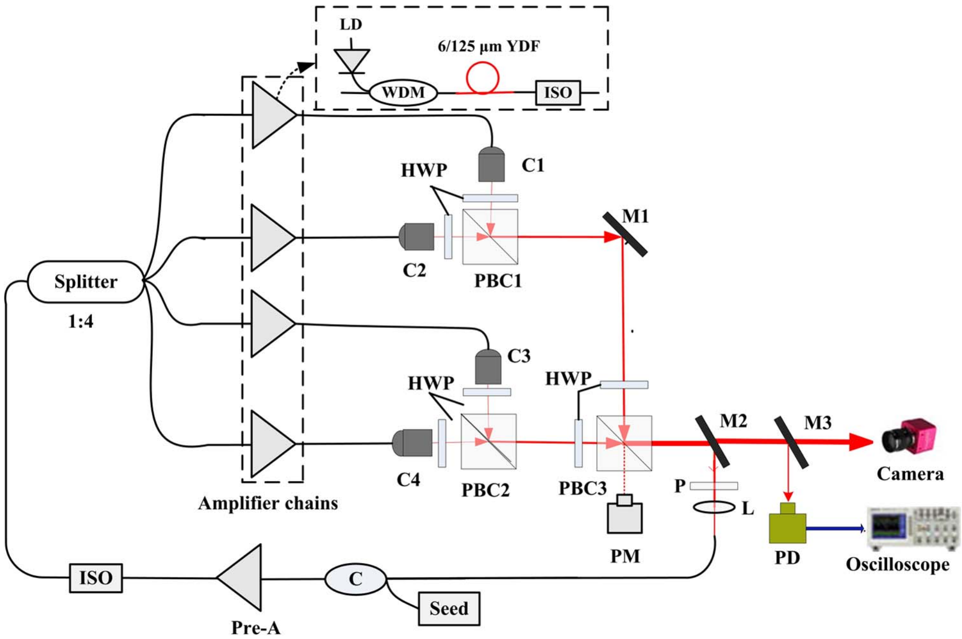

Fig. 3. The experimental setup of four-channel CPBC system by a ring cavity. Seed, seed laser; C, coupler; pre-A, pre-amplifier chain; ISO, isolator; LD, laser diode; WDM, wavelength-division multiplexing; C1-C4, collimators; HWP, half wavelength plate; PBC1-PBC3, polarization beam combiners; PM, power meter; M1, all- reflectance mirrors; M2 and M3, high- transmittance beam splitters; P, linear polarizer; L, positive lens; PD, photo detector.

the phasing process due to that fact that, when the power of the seed laser exceeds some certain value, the ring feedback will be interrupted and the phase locking process will be invalid. In our experiment, we find that, when the ratio of the average feedback power to the seed power is less than 97%, the self-organized process will be influenced remarkably. A PM is also used to measure the leakage power of the PBC3 and optimize the coaxial adjusting of the ring. M3 is a beam splitter with 1% reflectivity, and a small fraction of power is collected by the photo-detector (PD) connected with a oscilloscope to display the phase locking process; the most of the power is injected into a camera with some attenuators to observe the intensity profiles of the combined beam. It is to be noted that the optimal polarization orientation can be selected to improve the system performance further by rotating the linear polarizer (P) behind the PBC3.

3. Results and Discussion

In the experiment, we observe the phasing process by controlling the power of the seed laser. By increase the power of the seed laser, the feedback loop is interrupted and the system is in open loop. As a result, both the power encircled by PM and the intensity profiles at the camera fluctuate along with time, which indicates that the combined output power is unsteady due to the fact that the phase differences among the oscillators continuously change owing to thermal and mechanical effects. When the seed laser turns off and the system is in the closed loop, the intensity profile and the combined output power are steady. By rotating the linear polarizer (P) behind PBC3 to optimize the system, the output power can be maximum and the leakage power in PBC3 is minimum. The two-dimensional and three-dimensional intensity profiles in the closed loop are shown in Fig. 4, and we have observed that the coherently combined beam quality is similar to one of the four amplified single mode beams and the beam quality is not degraded. The combined output power measured at the output port of M2 is 514 mW, and the leakage power in the PM is 50 mW. Due to the limited polarization extinction ratios (PERs) of the four combined beams, some fractional powers are leaked at the other port of PBC1 and PBC2. In the experiment, the leakage powers in PBC1 and

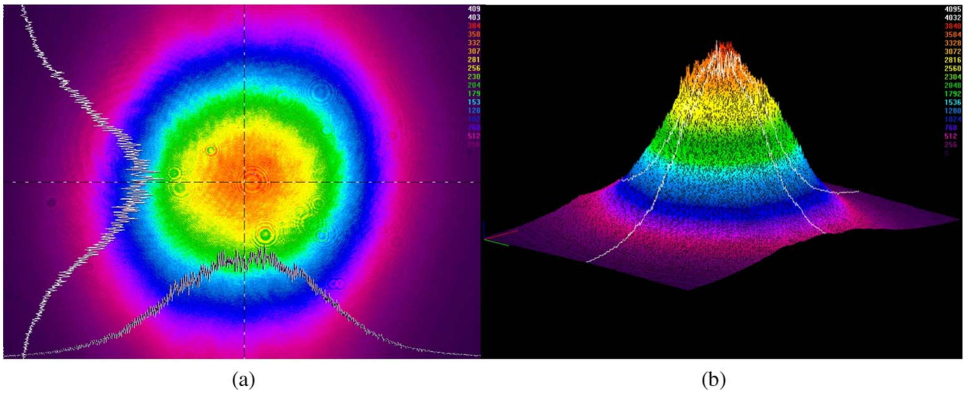

Fig. 4. Intensity profiles of coherently combined beam in closed loop for (a) two-dimensional image and (b) three-dimensional image.

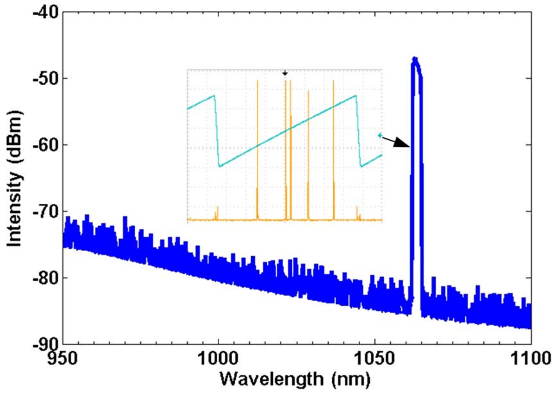

Fig. 5. The spectrum of the coherently polarization combined beam.

PBC2 are measured to be only 0.71 mW and 0.48 mW, respectively. The combining efficiency (η) of the whole system is calculated to be 91% by the expression [24]

$$\eta = \frac{P_{M_2}}{P_{M_2} + P_{PM} + P_{P1} + P_{P2}} \quad (1)$$

where PM_2 is the output power measured at the output port of M2, P_{PM} is the leakage power measured by PM, P_{P1} is the leakage power in PBC1, and P_{P2} is the leakage power in PBC2.

In our present setup, the influence of limited PERs on efficiency loss is calculated to be within 0.2%. It is to be noted that, in high power operation, the limited PERs induced efficiency loss that would increase on account of the decrease of PERs of the combined amplifiers. Nevertheless, in power scaling of the system, the influence of beam quality degeneration of the amplifiers on the combining efficiency should also be considered carefully. Recently, we have investigated the change of PER and beam quality of a 332 W all fiber polarization-maintained amplifier, and the average PER and beam quality of the amplifier degrades little along with the power scaling to maximum power [25]; hence, we think the configuration we presented is promising in scaling the output power to higher power. In the system we presented, a drawback that should be noticed is that some leakage power is existed in each PBC; hence, necessary protection should be adopted in high power-level operation. In addition, the incorporated polarizing elements (PBCs and HWPs) add the complexity of the system comparing with the traditional passive CBC configurations.

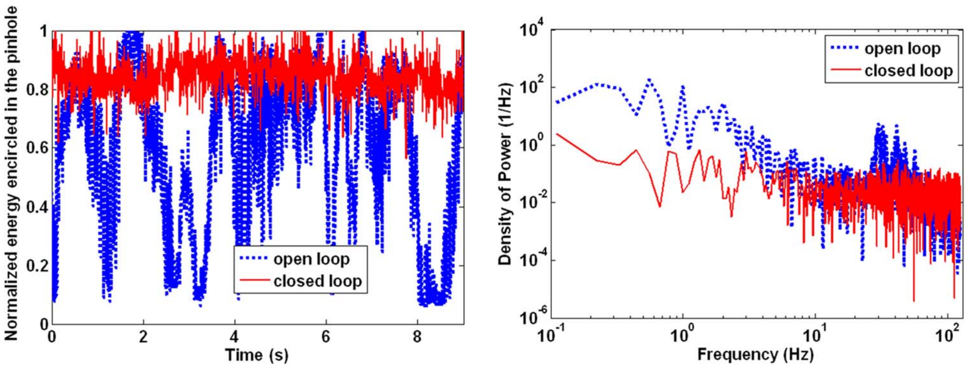

Fig. 6. Time series signals (a) and spectral density of power encircled in the PD (b) in open loop and closed loop.

The spectra of the coherently polarization combined beam are measured using an optical spectrum analyzer. In order to demonstrate the refined structure of the spectra, we also use an F-P scanner to measure the longitudinal modes of the coherently combined beam. The representative result is shown in Fig. 5. We see that, within one period of the F-P scanner, several longitudinal modes with lowest loss can be selected in the cavity, which is crucial for mitigating the influence of SBS effect and power scaling of the individual amplifier chain.

The fidelity of passive phasing of a four fiber amplifier array and the phase noise suppression process can be further studied by the time series signal and spectral density of energy collected by the PD, which is shown in Fig. 6. When the system is in open loop, the normalized power collected by the pinhole of the PD is fluctuant randomly; while the self-organized process established, the normalized power in the pinhole can be locked effectively [see Fig. 6(a)]. When the system is in closed loop, the phase noise below 150 Hz is also suppressed effectively [see Fig. 6(b)].

4. Conclusions

In summary, we have developed a new architecture for passive phasing and polarization beam combination of a fiber amplifier array by an optical feedback. The phase relationships among different channels are self-adjusted by a common ring cavity, so that no complex active control module is required. When the system is in closed loop, the combining efficiency of the whole system can be as high as 91% without degeneration of beam quality. Experimental results reveal that the architecture is effective and can be implemented steadily. The architecture we present combines the advantages of passive phasing and CPBC together, and we believe this passive phasing scheme is a promising approach for high-power laser scaling without degrading beam quality.

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