Coherent beam combination of adaptive fiber laser array with tilt-tip and phase-locking control

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We present an experimental study on tilt-tip (TT) and phase-locking (PL) control in a coherent beam combination (CBC) system of adaptive fiber laser array. The TT control is performed using the adaptive fiber-optics collimator (AFOC), and the PL control is realized by the phase modulator (PM). Cascaded and simultaneous controls of TT and PL using stochastic parallel gradient descent (SPGD) algorithm are investigated in this paper. Two-fiber-laser-, four-fiber-laser-, and six-fiber-laser-arrays are employed to study the TT and PL control. In the cascaded control system, only one high-speed CMOS camera is used to collect beam data and a computer is used as the controller. In a simultaneous control system one high-speed CMOS camera and one photonic detector (PD) are employed, and a computer and a control circuit based on field programmable gate array (FPGA) are used as the controllers. Experimental results reveal that both cascaded and simultaneous controls of TT using AFOC and PL using PM in fiber laser array are feasible and effective. Cascaded control is more effective in static control situation and simultaneous control can be applied to the dynamic control system directly. The control signals of simultaneous PL and TT disturb each other obviously and TT and PL control may compete with each other, so the control effect is limited.

Keywords: coherent beam combining, tilt-tip control, phase-locking control, adaptive fiber-optics collimator

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1. Introduction

Coherent beam combination (CBC) of fiber laser array is a promising way to achieve high energy density and high beam quality fiber laser output.[1–8] In a CBC system of fiber laser array, several fiber lasers are densely packaged together. Each laser is phase-locked (PL) by the phase modulator (PM) to make the phase differences between them invariable and the fringes of interference patterns stable. The PL control has been widely studied in many CBC systems. However, the tilt-tip (TT) errors of fiber laser wavefronts also play an important role in CBC system, which have seldom been considered.[1,9–12] The TT errors are usually produced by the limited accuracy of assembling, vibration of mechanism, atmosphere perturbation, etc. It has been demonstrated that the laser beam quality degrades seriously with TT errors, even though all the laser beamlets are well phase-locked.[13–15] Therefore TT control in CBC system should be taken into consideration in order to ensure the effect of CBC.

There are three common devices for TT control, i.e., liquid crystal spatial light modulator,[16] fast steering mirror,[17] and adaptive fiber-optics collimator (AFOC).[13–15] The AFOC is an optical passive device which can not only collimate the output laser beam, but also steer the beam direction via controlling the piezoelectric actuators around the fiber tip. The AFOC has significant advantages, such as precise control, small inertia, high resonance-frequency, and convenience of package compared with other TT control devices. In this paper we will employ the AFOC for the TT control in CBC system.

We present a series of experimental investigations on TT control and PL control in a CBC system using stochastic parallel gradient descent (SPGD) algorithm. Cascaded control and simultaneous control of TT and PL are studied to investigate how to perform TT control and PL control properly and effectively in a CBC system. Simultaneous and cascaded controls of 4-laser array are performed to compare the advantages and disadvantages of the two control strategies. It is revealed that the cascaded controls of TT and PL are more effective in static correction situations, simultaneous TT and PL controls can be used in the case of dynamic correction easily, but the TT and PL controls compete with each other to some extent.

2. Experimental setup

Two experimental setups have been built to investigate the cascaded and simultaneous controls of TT and PL control in CBC system. As shown in Fig. 1, in the cascaded control system, the seed laser is split into 8 channels by a 1×8 fiber beam splitter BS0 after preamplification through A0. The seed laser is operated at 1064 nm employing single cladding fiber with a core diameter of 6 μm and cladding diameter of 125 μm. The output laser power from the single channel is about

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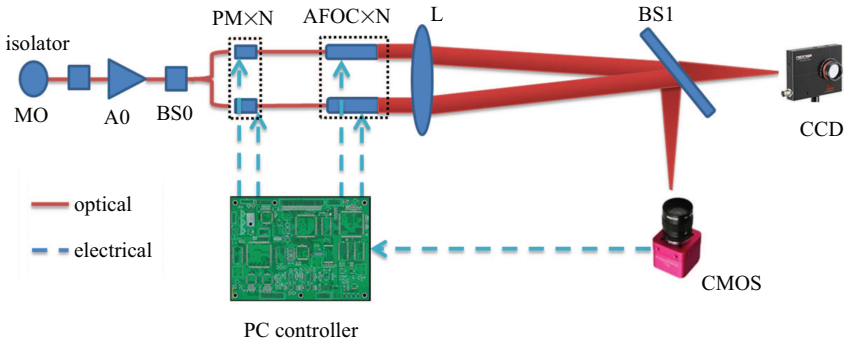


Fig. 1. (color online) Experimental setup of cascaded control system. MO: master oscillator; A0: amplifier; BS0, BS1: beam splitters; PM: phase modulator; PC: personal computer.

6 mW∼7 mW. N ($N = 2, 4, 6$) channels of fiber laser are employed in different experiments. Each channel laser goes through the phase modulator (PM) and then fuses to the AFOC. The diameter of the output laser beam from AFOC is about 2 cm. A convex lens is set behind the AFOC array to obtain the far field laser beams. The combined laser beam is split into two beams by BS1. The transmitted beam is collected by a CCD camera to observe the control effect. A high-speed CMOS camera collects the reflected laser beam and passes the data to a computer. In front of the camera an object lens of a microscope is employed to magnify the laser interference pattern for the convenience of data-collection. The computer serves as an algorithm controller, which controls the PM and AFOC through a program. Cascaded TT and PL controls of 2-laser array and 4-laser array are studied in the system introduced above. In this paper, the AFOC used to perform the TT control in CBC system are made jointly by the Institute of Optics and Electronics in Chinese Academy of Sciences and our institute.

In the TT control each channel needs two control signals (x-direction and y-direction angles),[15] so $2N$ control signals are required in CBC of N lasers. In the PL control each channel needs one control signal (piston phase). Therefore $3N$ control signals are required in the cascaded TT and PL control of the N-laser array CBC system. In the experiment of cascaded control only one computer is used as controller, so a $3N$ channels digital-to-analog (DA) conversion card is needed to export the control voltage signals. A 6-laser array has not been studied in the cascaded control system since the DA cards can only provide conversion of 16-channel voltage control signals for the time-being, which is not enough for the TT and PL control of 6-laser array. However, this problem did not happen in the simultaneous control system.

The simultaneous control system is similar to the cascaded one, except that a photonic detector (PD) is added to collect the laser beam reflected from BS2, and the interference pattern data in PD are passed to a control circuit based on a field programmable gate array (FPGA), which is used as an algorithm controller to perform the PL control on the PM as shown in Fig. 2. Two objective lenses of a microscope are set in front of the CMOS camera and PD to magnify the laser pattern so as to collect data easily. Because of the addition of a control circuit based on FPGA for PL control, only a $2N$-channel DA card is needed for the TT control in the simultaneous control system of N-laser array. Therefore 6-laser array is employed in the simultaneous control system to investigate the effects of fiber laser number on TT control and PL control. In the experimental setup shown in Fig. 2, simultaneous TT and PL control of 4-laser array and 6-laser array are investigated. The 2-laser array is not studied for its laser number is too small and the experiment can only provide less useful information than those of 4-laser and 6-laser arrays.

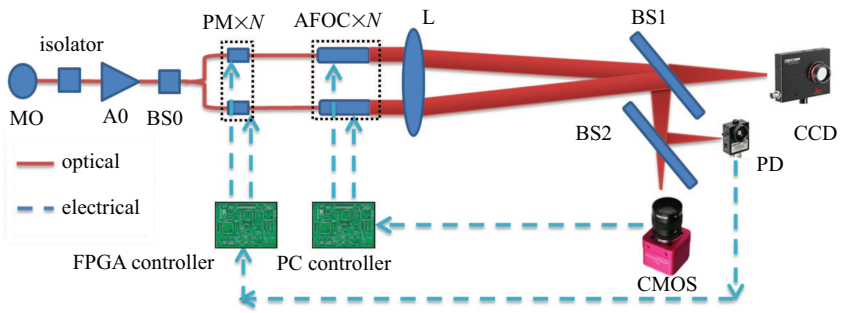


Fig. 2. (color online) Experimental setup of simultaneous control system. MO: master oscillator; A0: amplifier; BS0, BS1, BS2: beam splitters; PM: phase modulator; PD: photonic detector; PC: personal computer; FPGA: field programmable gate array.

3. Experimental results

3.1. Control algorithm

There are several demonstrations about CBC PL control strategies.[2–4,18–20] The SPGD technique[4,20] needs only one detector, and the control system is less complicated, which is employed in our experiments to perform the TT and PL control. The control methods of TT and PL are similar to each other except for the different values of control coefficients δ and γ. The metric function used in both TT and PL control is power-in-the-bucket (PIB), but the diameters of the bucket are different in TT control and PL control. The steps of SPGD algorithm are as follows.

(i) Generate a group of stochastic voltage perturbations $\delta \boldsymbol{u}^{(k)}$, which obey the Bernuolli probability distribution with zero mean, M is the control channel number, δ is the amplitude of perturbations $\delta \boldsymbol{u}^{(k)}$, and k is the iteration number.

(ii) Apply the signals $\boldsymbol{u}^{(k)} + \delta \boldsymbol{u}^{(k)}$ and $\boldsymbol{u}^{(k)} - \delta \boldsymbol{u}^{(k)}$ separately to the AFOCs or PMs, where $\boldsymbol{u}^{(k)}$ are the initial voltage signals, leading to the corresponding metric functions $J_+^{(k)}$ and $J_-^{(k)}$ via the camera or PD.

(iii) Update the voltage signals on the AFOCs or PMs:

$$\boldsymbol{u}^{(k+1)} = \boldsymbol{u}^{(k)} + \gamma \delta \boldsymbol{u}^{(k)} \left(J_+^{(k)} - J_-^{(k)} \right), \tag{1}$$

where γ is the gain coefficient.

(iv) Go to step (i) and continue the process, until the control procedure is stopped manually.

In the TT controls of the cascaded and simultaneous systems, the laser beam position on the detector is varied a lot, because the TT error compensation of each beamlet changes its optical axis. The PD effective detecting area with a pinhole is rather small and not enough in the TT control. A high-speed CMOS camera is chosen to serve as a detector for its larger detecting area than the PD. The camera used in this paper has 1024×1024 pixels with full frame and the highest full frame rate is about 150 Hz, which is comparatively low when applied to the TT control system. So the exposure time of the camera is set to be 0.02 ms, and 128×128 pixels are chosen to be active for an all-around consideration in the TT control of both cascaded and simultaneous systems. The stored PIB, which is different from the feedback PIB used in the TT control procedure, is calculated via the data from the 3×3 pixels in the center of the 128×128 pixels. Finally, the iteration rates of TT control using the SPGD algorithm in both systems are both about 58 Hz, which is adequate for the compensation of low frequency TT errors.

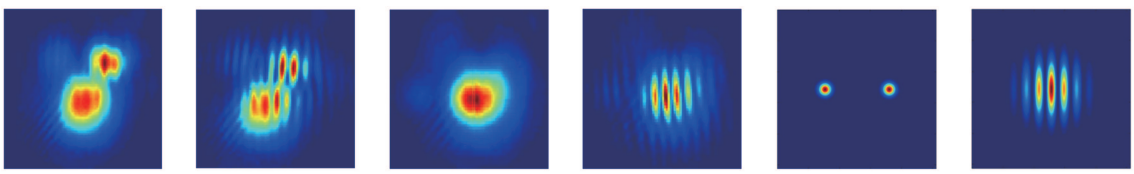
In the PL controls of both cascaded and simultaneous control systems, only 3×3 pixels from the high-speed camera are used to calculate the PIB. The iteration rate is about 3.7 kHz when the camera is employed in the PL control. The PL iteration rate is more than 1 MHz [21] when a control circuit based on FPGA and a PD with a pinhole are employed in the simultaneous control system.

In the cascaded control experiment, first the camera captures a full frame picture and the combined beam's optical mass center is calculated. Then 128×128 pixels around the center are chosen for the TT control. After the TT control the parameters of the camera are changed and only 3×3 pixels in the center of the previous region are active for the PL control, and then the PL control is started. In the simultaneous control system, the camera captures the first picture and then the pixels for the TT control are chosen. Then the TT control via computer and the PL control via FPGA controller are implemented independently and simultaneously.

3.2. Cascaded CBC system

First, the cascaded TT control and the PL control of 2-laser array and 4-laser array are investigated. Figure 3 shows the 10-s long exposure intensity distribution of the 2-laser array CBC system. The PL control improves the fringe contrast from nearly 0 to about 0.67 before the TT control and 0.74 after the TT control. It can be concluded from Figs. 3(a) and 3(c) that the TT control makes the separate laser beams overlap each other well. Figures 3(e) and 3(f) show the simulated ideal laser intensity distributions in near field and far field. Figures 3(a), 3(d), and 3(f) indicate that both the TT and PL controls are effective.

Figure 4 shows the normalized PIB curves corresponding to the different control stages of the 2-laser array experiment. In this paper, the PIB is normalized via being divided by the maximum PIB in each experiment. Comparing part (a) with part (c) in Fig. 4 it can be concluded that the TT control increases mean PIB from 0.22 to 0.69 when PL control is off. The PL control improves the mean PIB from 0.22 to 0.28 in the absence of the TT control. After the TT control, the PL control increases the mean PIB from 0.69 to 0.98.



(a) (b) (c) (d) (e) (f)

Fig. 3. (color online) Long exposure intensity distributions in cascaded control experiment of 2-laser array: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control; (e) simulated ideal laser beam intensity distribution in near field; (f) simulated ideal laser beam intensity distribution in far field.

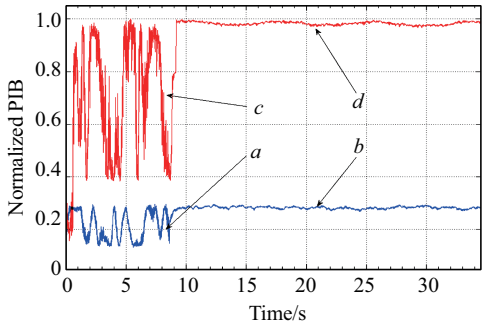


Fig. 4. (color online) PIB curves in cascaded experiment of 2-laser array: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control.

The 4-laser array cascaded TT and PL control are performed in the same experimental setup. The fiber lasers are arranged as a diamond pattern in near field as shown in Fig. 5(e). The simulated ideal far field laser intensity distribution is shown in Fig. 5(f). Figures 5(a)–5(d) show the long exposure intensity distributions in different control stages. The PL control improves the fringe contrast from 0.13 to about 0.73 before the TT control. After the TT control the PL control increases the fringe contrast from 0.15 to 0.88 as indicated in Figs. 3(c)–3(d). From Figs. 3(a), 3(d), and 3(f) it can be concluded that the TT control and PL control compensate for the TT errors and piston phase differences well.

The normalized PIB curves of 4-laser array are shown in Fig. 6. In open loop (in the absences of TT and PL control) the mean PIB is 0.32, after the TT and PL control the mean PIB increases to 0.99. The TT control improves the PIB from 0.32 to 0.73 in the absence of PL control. The PL control increases the PIB from 0.32 to 0.41 before the TT control and 0.73 to 0.99 after the TT control.

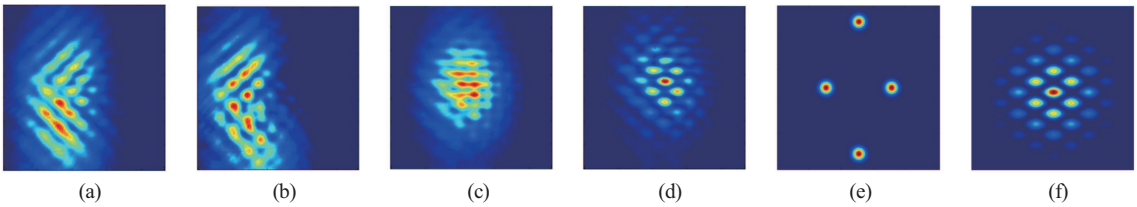


Fig. 5. (color online) Long exposure intensity distributions in cascaded control experiment of 4-laser array: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control; (e) simulated ideal laser pattern in near field; (f) simulated ideal laser pattern in far field.

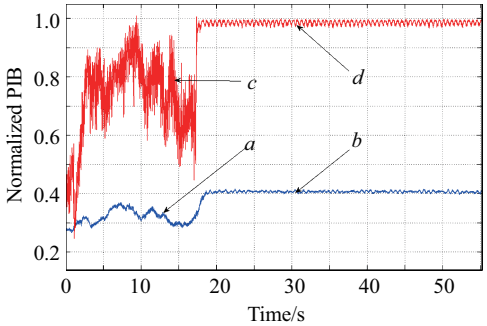


Fig. 6. (color online) PIB curves in cascaded experiment of 4-laser array: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control.

In the cascaded controls of TT and PL, the TT control can compensate for the TT errors effectively and make the laser beams superpose on each other well. In the 2-laser array the TT control makes the two separate laser beams superpose on each other well in about 1 s. It takes about 2 s–3 s to make the partially overlapped laser beams superpose on each other well in the 4-laser array. It indicates that the increase in control channel slows down the convergence speed of TT control. The PIB curves are clean and steady, which means the cascaded controls of TT and PL are effective. However, this method can only be used in the quasi-static case where the TT error perturbation frequency is low. That is because it needs 1 s–2 s to set the camera parameters (change the affected pixels from 128×128 to 3×3) when starting the PL control after the TT control. Another main limitation to the control bandwidth of this strategy is that the iteration rate of the TT control is only 58 Hz.

3.3. Simultaneous CBC system

Simultaneous TT and PL controls of 4- and 6-laser arrays are investigated. Figures 7(a)–7(d) show the far field laser intensity distributions in different control cases in the 4-laser experiment, and figures 7(e)–7(f) depict the simulated ideal results in near field and far field. The TT control makes the partially overlapped beams superpose together well. The PL control compensates the piston phase differences between fiber lasers effectively, and the interference pattern is steady and clear. The simultaneous TT and PL control improve the fringe contrast from 0.29 in open loop to 0.88 in closed loop.

The normalized PIB curves of simultaneous control of 4-laser array are shown in Fig. 8. The mean PIB in open loop is 0.25, and the PIB increases to 0.28 when only PL control is on. The TT control improves the mean PIB to 0.46 when the PL control is off. When the TT and PL control are performed simultaneously, the mean PIB reaches to about 0.92, which means that the simultaneous control can achieve an obvious CBC effect.

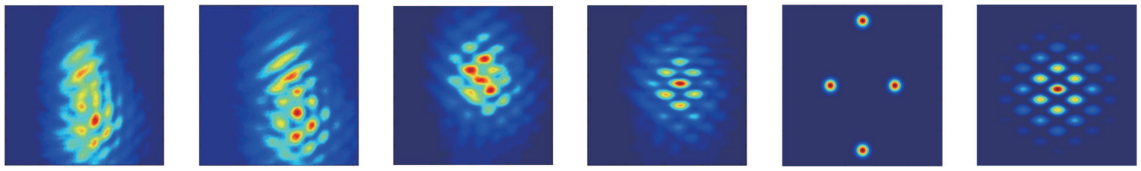


Fig. 7. (color online) Long exposure intensity distributions in simultaneous control experiment: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control; (e) simulated ideal laser pattern in near field; (f) simulated ideal laser pattern in far field.

Figure 9 shows the laser interference patterns in a 6-laser array experiment. Since there are only 6 AFOCs that can be used in experiment, the near field lasers are arranged as figure 9(e) shows. Figures 9(e) and 9(f) show the simulated 6-laser array patterns in near field and far field. It can be concluded from Figs. 9(a)–9(d) that the TT control and PL control are effective to a certain extent. The laser beams are controlled to almost overlap each other. The contrast fringes of interference patterns improve from 0.27 in open loop to 0.69 in closed loop.

The normalized PIB curves of 6-laser array experiment are shown in Fig. 10. The simultaneous TT and PL control make the mean PIB improved from 0.14 in open loop to 0.83 in closed loop. The TT control increases the PIB from 0.14 to 0.64 even though the PL control is off. The PL control improves the PIB from 0.14 to 0.16 in the absence of TT control and from 0.64 to 0.83 in the presence of TT control.

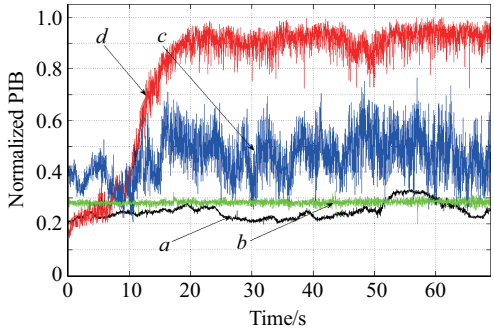


Fig. 8. (color online) PIB curves in simultaneous experiment of 4-laser array: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control.

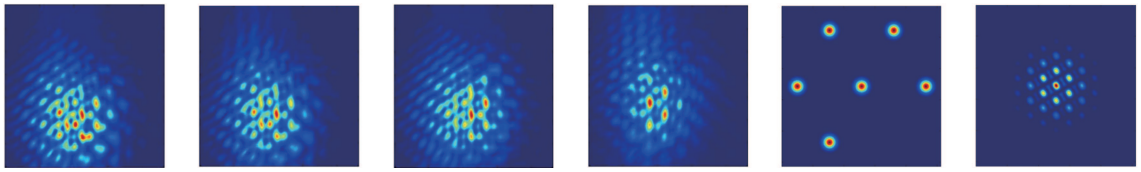


Fig. 9. (color online) Long exposure intensity distributions in simultaneous control experiment: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control; (e) simulated ideal laser pattern in near field; (f) simulated ideal laser pattern in far field.

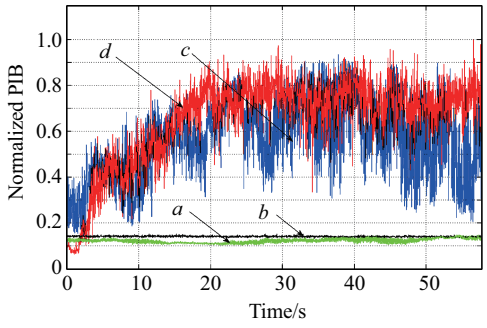


Fig. 10. (color online) PIB curves in simultaneous experiment of 6-laser array: (a) open loop; (b) PL control only; (c) TT control only; (d) both TT control and PL control.

In the simultaneous controls of TT and PL in the 4-laser array, the TT can compensate for the TT errors effectively, making the partially overlapped laser beams superpose on each other well. Meanwhile the PL can make the interference patterns clear and steady, which means that the piston phase differences are well corrected. In the 6-laser array, the TT and PL control are less effective than the 4-laser array: the closed loop laser patterns in experiment (Fig. 9(d)) are not so clear as the simulated patterns (Fig. 9(f)), and the PIB curves are coarse and unshaped. There are some reasons for this result. First of all, the TT and PL controls may disturb each other to some extent, despite the fact that the iteration rate of PL control (1 MHz) is much faster than that of TT control (58 Hz). The small voltage perturbations of TT control on AFOC array using the SPGD algorithm can make the laser beam dither obviously on the PD pinhole, which may result in the PIB from PD changing largely and degrade the PL control effect. The PL control signals may also influence the control effect of TT. The perturbations to the PL control can be seen as high-frequency noises in the TT control, and the TT control signals can be considered as low-frequency noises in the PL control. Another important reason is that the TT control using a camera may cause the laser beams to move apart from the pinhole before PD, while the PL control using PD tends to keep the maximum spot of laser beams staying in the pinhole, so the images of laser beams in the camera and PD cannot actually be strictly

conjugated. This results in competition between both controls. The third reason is that even small residual TT errors and piston phase differences will result in obvious degradation of the laser interference patterns in 6-laser array CBC system. This reason may also be attributed to the result that the simultaneous control effect of 4-laser array is better than that of 6-laser array as shown in Figs. 7 and 9. In addition, the bracket of the AFOC array cannot be absolutely steady in the laboratory, and the movement of each AFOC couples with others. Therefore the increase in the number of AFOC may make the TT control more complicated and difficult, which results in the degradation of simultaneous control effect in 6-laser array compared with that in 4-laser array.

The improvement of simultaneous control system can be made by adding a frequency filter in each of the controls to weaken the interference between controls, or optimizing the parameters used in the SPGD algorithm to improve the control efficiency. In addition, the TT control in the 4-laser array takes about 15 s to compensate for the TT errors whereas the time for the 6-laser array needs more than 20 s. Therefore the increase in control number slows down the correction process and reduces the effect of control. However, the simultaneous controls of TT and PL can be used in the dynamic control case easily since the control procedure can be performed without the interruption as in the cascaded control case.

3.4. Summary

Some experimental results of cascaded and simultaneous control systems can be summarized by comparing the two control strategies. Firstly, both control strategies compensate for the TT errors and piston phase differences effectively. Secondly, the cascaded controls of TT and PL can avoid the interference between controls in the simultaneous system, which will degrade the whole control effects of TT and PL. So the convergence speed of TT in the cascaded control is faster than that in the simultaneous control. The PIB curves of both control strategies indicate that the cascaded control is more steady and effective. Thirdly, the TT control bandwidth of cascaded control system restricts its applications in the quasi-static case since it takes 1 s–2 s to change the camera parameters between TT and PL control. However, the simultaneous control system is not restricted by such issues, and it has been used in the dynamic control case directly. Meanwhile, the iteration rate of PL control in the simultaneous system using PD (1 MHz) is much faster than that in the system using the camera (3.7 kHz), so the PL control bandwidth in the simultaneous system is enough to compensate for the piston phase differences in most cases. The PL control bandwidth of cascaded system using the camera needs further improving. Last but not least, in the simultaneous system, the laser beam images cannot be strictly conjugated, so the TT control and PL control may compete with each other, which will degrade the control effect.

4. Conclusion

We presented two CBC systems of fiber laser array with the TT and PL controls using the SPGD algorithm. It can be concluded that the TT control using AFOC and PL control using PM in CBC of fiber laser array are feasible and effective, and the cascaded and simultaneous controls of TT and PL are both practical. However, the cascaded control system has better static correction effect but worse dynamic control properties. The simultaneous PL control and TT control disturb each other obviously and the control effect is limited, since the signals of each control act as noise in the other control procedure. In the simultaneous control system the images of laser beams cannot be ideally conjugated so the TT and PL controls may compete with each other and degrade the control effect of the system. In the future, the CBC of more TT and PL control channels and higher laser power using AFOC should be further investigated.

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