Research Article
Vol. 59, No. 33 / 20 November 2020 / Applied Optics 10289

applied optics

Simplified system for relative phase control between two input beams for coherent polarization beam combination

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Received 11 August 2020; revised 17 October 2020; accepted 18 October 2020; posted 20 October 2020 (Doc. ID 405132); published 13 November 2020

We devised a simplified system for coherent polarization beam combination (CPBC), in which two beams with orthogonal polarizations are combined with a polarizing beam splitter (PBS). In a CPBC system, control of the relative phase between two beams is important to obtain an output beam with stable polarization. Herein, the beam leaked from PBS is used to control the relative phase, realizing a robust system. We experimentally demonstrate that the proposed system can be operated with high efficiency and without quality deterioration.

https://doi.org/10.1364/AO.405132

1. INTRODUCTION

Lasers with high power and high quality are required in diverse fields. For example, the waist size in laser processing must be reduced by a single transverse mode oscillation to enable microfabrication, whereas laser light with low-intensity and low-frequency noise is necessary for gravitational wave detection. Because the power of a single high-quality laser is limited, coherent addition is a solution when laser beams must simultaneously provide high quality and high power. This method combines multiple beams into a single one and makes it possible to emit power exceeding the upper limit of the single laser. Coherent addition can be achieved via several methods, such as addition using a beam splitter [1], arranging beams using a fiber array and superimposing far-field images [2,3], and mode synthesis using an optical cavity and multiple oscillating beams [4]. Among them, a combination using a polarizing beam splitter (PBS), called coherent polarization beam combination (CPBC) [5–8], is superior, as the arbitrary power ratios can be coupled. When adding three or more beams, it is possible to add them one by one to the main path of one axis, simplifying the configuration of the optical system.

In CPBC, the polarization state of the combined beam depends on the relative phase between the incident beams. Thus, it is critical to control the relative phase when a single polarization is necessary for the output beam. There are two methods to control the relative phase. One is passive phase control [9]. In this method, the relative phase is automatically controlled by laser oscillation in optical cavities. However, this method has a complicated structure, and alignment and stabilization are difficult to achieve. The other is active phase control. Some active phase control methods apply machine learning [10,11]. An advantage of machine learning phase control is a reduced number of detection ports to realize a control signal when many beams are combined. However, machine learning systems have limited control bandwidth. When a low-noise beam is required, wideband and high-speed analog control is necessary in the active phase control. A dithering method [7,8,12] and a heterodyne method [5,6] are often used in such applications. Both methods require phase modulation of the input beams as well as separation and detection of the output beam. Since these operations may introduce complexity and beam degradation through auxiliary optical and electrical systems, herein we report a simplified control method without phase modulation or picking up the output beam. In our method, leaked light from PBS in the CPBC replaces these operations. Our method is optimized for a few input beams. So if more beams are combined, a more complicated system is needed because the number of control systems is increased.

2. THEORY

The CPBC system uses two input beams: one p polarized and one s polarized. They are defined as $E_1 \exp[i(\omega t + \phi)]$ (p polarized) and $E_2 \exp(i\omega t)$ (s polarized). E_1 and E_2 are the real amplitude, ω is the angular frequency, and ϕ is the relative phase between the two input beams. Since the emitted beams travel in the same direction, information on the wavenumber is omitted. Then, the Jones vector of the output beam can be written as

$$\begin{pmatrix} E_1 e^{i\phi} \\ E_2 \end{pmatrix}. \tag{1}$$

Equation (1) shows that the polarization state of the output beam depends on the relative phase between the input beams. Therefore, to control the polarization state of the output beam, the relative phase difference between the input beams must be controlled.

Figure 1 shows a schematic view of the proposed control system for the relative phase between the two input beams. The leaked light from PBS is used as a control signal in this method. The two input beams are linearly polarized, but their polarization planes are slightly misaligned from the polarization plane of PBS. Then the small orthogonal components included in the two input beams are emitted as leaked light. Assuming that the mainly p-polarized input beam is $E_1 = (E_P, E_{PS})^T e^{i\phi}$ and the mainly s-polarized input beam is $E_2 = (E_{SP}, E_S)^T$, the Jones vector of leaked light $\boldsymbol{e}_{\text{leak}}$ is given as

$$\boldsymbol{e}_{\text{leak}} = \begin{pmatrix} E_{SP} \\ E_{PS} e^{i\phi} \end{pmatrix}. \tag{2}$$

A quarter-wave plate (QWP) is inserted for the leaked light. Then the beam is split by the second PBS. Afterwards, each beam is measured with a photodetector. The difference between the measured signals is used as the control signal. The Jones matrix of a QWP whose optical axis is tilted by an angle θ from the p-polarization axis is

$$\begin{aligned} M_{\text{QWP}}(\theta) &\equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \\ &= \begin{pmatrix} \cos^2\theta + i\sin^2\theta & (1-i)\cos\theta\sin\theta \\ (1-i)\cos\theta\sin\theta & \sin^2\theta + i\cos^2\theta \end{pmatrix}. \end{aligned} \tag{3}$$

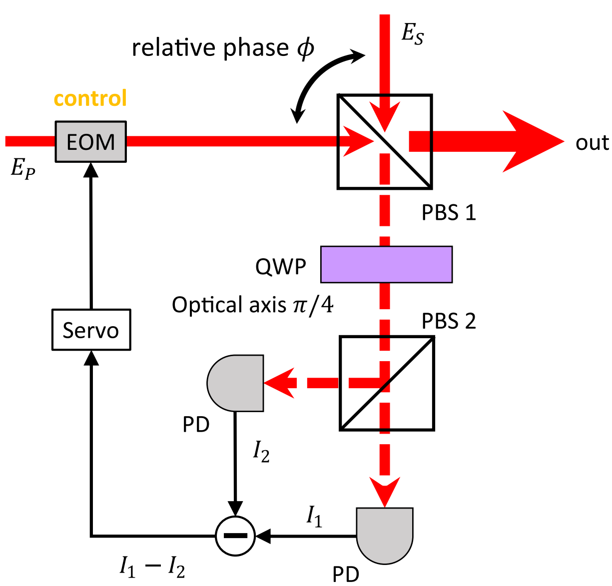

Fig. 1. External view of the proposed system. Two beams with orthogonal polarizations are combined by PBS 1. Leaked light is sent to PBS 2 through the quarter-wave plate (QWP) and the detector detects the two emitted light beams. Differential output controls the relative phase through the servo circuit.

The Jones vector after passing through QWP is $M_{\text{QWP}}(\theta) \cdot \boldsymbol{e}_{\text{leak}}$, and its p-polarized and s-polarized components are defined as E'_p and E'_s, respectively. Since the signals at the photodetectors are given by $I_1 = |E'_p|^2$ and $I_2 = |E'_s|^2$, the differential signal $I_1 - I_2$ is calculated as

$$\begin{aligned} I_1 - I_2 &= (E_{SP}^2 - E_{PS}^2)\cos^2 2\theta \\ &\quad + 2E_{SP}E_{PS}\sin 2\theta(\cos 2\theta\cos\phi + \sin\phi). \end{aligned} \tag{4}$$

If the angle of QWP is adjusted to $\theta = \pi/4$, the difference signal $I_1 - I_2$ is proportional to $\sin\phi$. Thus, by performing feedback control using this signal, the relative phase can be controlled as zero.

3. EXPERIMENT

An experiment was performed to verify the relative phase control using the devised method. Additionally, its performance was evaluated. We measured the coupling efficiency of coherent addition, the intensity noise of the output beam, and the transverse mode quality.

A. Setup

Figure 2 shows the experimental setup. We used a Nd:YAG laser (CW) with a wavelength of 1064 nm as a seed laser. The output beam was split into two and amplified by fiber-laser amplifiers to 10 W and 40 W, respectively. The 40-W beam was converted into the p-polarized beam, while the 10-W beam was converted into the s-polarized beam using half-wave plate (HWP) 1a and 1b and PBS 1a and 1b. They were used as incident beams for CPBC. However, they do not exhibit complete linear polarization because the leaked beam from PBS 2 is important to control the relative phase. Hence, it is necessary to insert HWP just before PBS 2 to generate the leaked beam from PBS 2 when beams from PBS 1a and PBS 1b are complete linear polarization. The two mirrors after PBS 1b were used to align two beams through PBS 2. The output beam was extracted as the p-polarized light by HWP 2 and PBS 4. The leaked beam from PBS 2 was used to acquire the control signal as described in Section 2. The relative phase control was performed by applying the amplified and filtered error signal to a fiber stretcher inserted between the seed laser and the 40-W fiber amplifier. Another fiber stretcher inserted between the seed laser and the 10-W fiber amplifier was used to compensate for the optical path length difference with the path of the 40-W fiber amplifier.

B. Coupling Efficiency

We calculated the coupling efficiency by measuring the power of the output beams. The addition efficiency μ was calculated as $\mu = P_{\text{out}}/(P_{\text{inP}} + P_{\text{inS}})$. Here, P_{inP} is the beam power from the 40-W fiber amplifier immediately before PBS and is used to perform coherent addition, P_{inS} is the beam power from the 10-W fiber amplifier, and P_{out} is the power of the output beam extracted as the p-polarized beam after HWP and PBS. Using the maximum power of the two fiber amplifiers yields $P_{\text{inP}} = 37.8$ W, $P_{\text{inS}} = 8.46$ W, and $P_{\text{out}} = 45.3$ W. Then we calculated the coupling efficiency as $\mu = 0.979$.

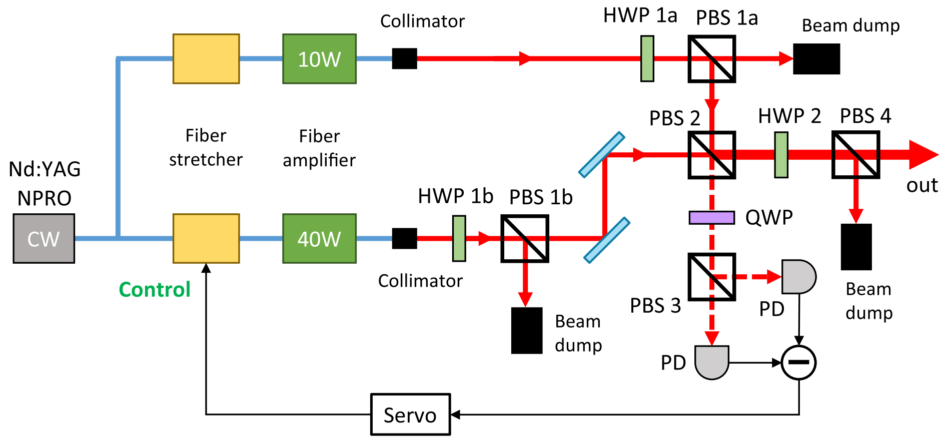

Fig. 2. Experimental setup. CW light beams (1064 nm) from the Nd:YAG laser pass through optical fibers and are amplified to 10 W or 40 W by fiber amplifiers. Afterwards, the light beams emitted in free space are converted into p-polarized light and s-polarized light, and combined by PBS 2. The added light is converted into p-polarized light by HWP 2 and PBS 4. The control signal is obtained by the devised method using the leaked light from PBS 2. Phase control is performed by the fiber stretcher inserted between the Nd:YAG laser and the 40-W fiber amplifier.

To verify whether the output beam was linearly polarized before passing through HWP and PBS, QWP was inserted between HWP and PBS, and the power change was measured. Converting this result into the relative phase difference ϕ between the incident beams gives $|\phi| < 0.1\pi$.

C. Intensity Noise

The intensity noise was measured as a quality evaluation of the CPBC output beam in the devised method. The output beam in Fig. 2 was reflected by a 99.99% reflectance mirror, and the transmitted beam was measured by a photodetector. This signal was sent to a spectrum analyzer and the relative intensity noise (RIN) was measured. The RIN values of the beam from the 10-W fiber amplifier, from the 40-W fiber amplifier, and after coherent addition were measured.

Figure 3 shows the result of the RIN measurements. These dotted, broken, and solid lines show the RIN values of the beams from the 10-W fiber amplifier, 40-W fiber amplifier, and after coherent addition, respectively. Several new peaks appeared compared to that before CPBC. Their sharpness indicates that these peaks may originate from resonances of the optical system or electrical circuits. For example, the peak at 1.6 kHz coincides with the resonance frequency of the fiber stretcher. The effect of these peaks can be improved by identifying and subsequently removing the cause.

In this coherent addition, the power ratio between the two input beams was about 4:1. Thus, the intensity noise of the higher power beam from the 40-W fiber amplifier dominates mainly the intensity noise after coherent addition. In Fig. 3, the spectrum after coherent addition overlapped mainly with the spectrum of the beam from the 40-W fiber amplifier. Therefore, significant noise sources, which may deteriorate the beam quality, are not present, except for the peak occurrence.

D. Transverse Mode

We measured the transverse mode of the combined beam to evaluate the quality of coherent addition in the proposed

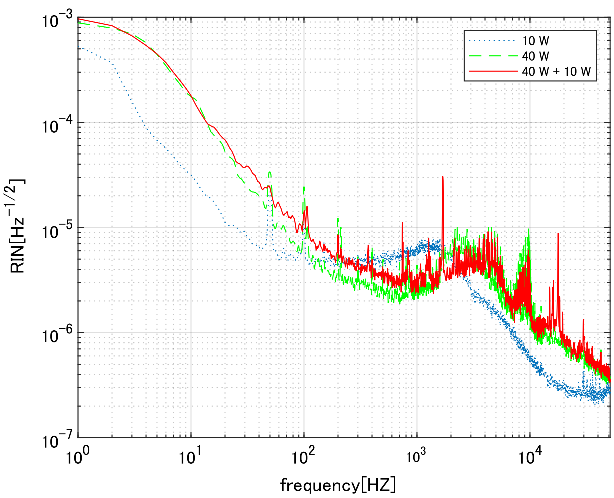

Fig. 3. Relative intensity noise (RIN). Dotted line is the RIN of the beam from the 10-W fiber amplifier. Dashed line is the RIN of the beam from the 40-W fiber amplifier. Solid line is the RIN of the beam after coherent addition of the 10-W beam and 40-W beam. RIN after coherent addition (solid line) and RIN of 40-W beam (dashed line) have almost the same spectrum.

method. As a measurement of the intensity noise, the transmitted light beam from the high-reflectance mirror was measured. In this measurement, this beam was guided to a triangular optical resonator. The beam exiting the resonator was measured by a photodetector while changing the resonator length using the piezo actuators of the resonator. The information of the transverse mode was extracted by analyzing and measuring the acquired signal [13] from the transverse mode of the beam from the 10-W fiber amplifier, from the 40-W fiber amplifier, and after coherent addition.

Figure 4 shows the quality of the transverse mode. In TEM_{lm} mode analysis, the modes where $g = l + m$ is constant are degenerate. However, the mode degeneracy can be solved depending on whether l is even or odd since a triangular optical resonator is used in this measurement. In Fig. 4, the horizontal

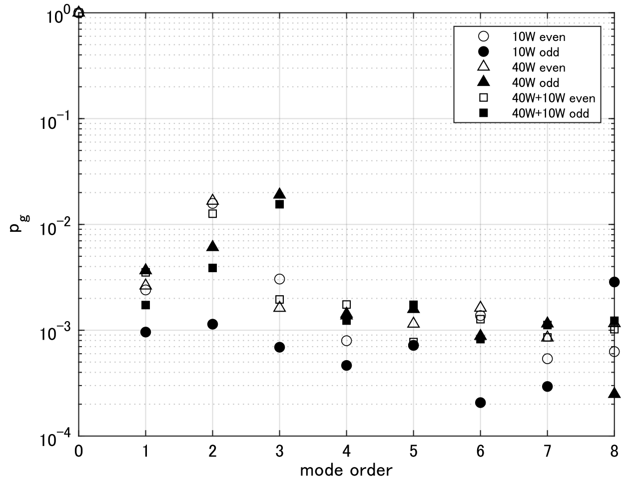

Fig. 4. Transverse mode analysis. Transverse mode analysis of the 10-W laser beam (circle), 40-W laser beam (triangle), and laser beam after coherent addition (square) are shown. Higher-order modes included in each beam are shown in relative proportions when each fundamental mode is one. Mode order is $g = l + m$ when the transverse mode is TEM_{lm}. Open and filled markers indicate that l is odd and even numbers, respectively.

axis represents the mode order according to $g = l + m$, and the vertical axis represents the ratio of each mode normalized by the fundamental mode. The circle, triangle, and square labels show the transverse mode quality of the beam from the 10-W fiber amplifier, the beam from the 40-W fiber amplifier, and the combined beam, respectively. Additionally, open markers indicate l is an even number and filled markers indicate an odd number. The ratio of the transverse mode is calculated up to the eighth mode.

From the results in Fig. 4, the ratio of the fundamental mode included in each beam was calculated. The ratios from the 10-W fiber amplifier, 40-W fiber amplifier, and combined beam were 0.963, 0.942, and 0.951, respectively. Hence, coherent addition is advantageous because adding a beam with a better transverse mode increases the transverse mode quality of the output beam compared to that of the input beam. Therefore, coherent addition with the devised method can be performed without transverse mode quality deterioration. When the transverse mode quality of the 10-W laser beam is worse than that of the 40-W laser beam, the transverse mode quality of the combined output beam is poorer than that of the 40-W input laser beam, but the rate of deterioration is small. If the above result is the opposite, i.e.,, if the ratio of the fundamental mode from the 10-W fiber amplifier is 0.942 and that from the 40-W fiber amplifier is 0.963, the ratio of the combined beam will theoretically be 0.959. Therefore, deterioration is negligible, and the input beam with the better transverse mode is dominant in the output beam.

E. Arbitrary Relative Phase Control

By inserting HWP after QWP in Fig. 1, arbitrary relative phase control becomes possible. The Jones matrix of HWP whose optical axis is tilted by an angle θ from the p-polarization axis is

$$M_{\mathrm{HWP}}(\theta) \equiv \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix}. \quad \textbf{(5)}$$

The Jones vector after passing through QWP (optical axis θ_1) and HWP (optical axis θ_2) is $M_{\mathrm{HWP}}(\theta_2) M_{\mathrm{QWP}}(\theta_1) \cdot \boldsymbol{e}_{\mathrm{leak}}$. As before, the difference signal $I_1 - I_2$ can be calculated as

$$\begin{aligned} I_1 - I_2 = {} & (E_{SP}^2 - E_{PS}^2) \cos 2\theta_1 \cos(2\theta_1 - 4\theta_2) \\ & + 2 E_{SP} E_{PS} [\sin 2\theta_1 \cos(2\theta_1 - 4\theta_2) \cos\phi \\ & - \sin(2\theta_1 - 4\theta_2) \sin\phi]. \end{aligned} \quad \textbf{(6)}$$

If the angle of QWP is adjusted to $\theta = \pi/4$ in Eq. (6), the difference signal $I_1 - I_2$ is proportional to $\sin(4\theta_2 - \phi)$ and can be controlled to zero by the feedback loop. Since θ_2 is the angle of the optical axis of HWP, the relative phase difference can be arbitrarily controlled as $\phi = 4\theta_2$ by adjusting the angle of HWP.

The arbitrary relative phase control in Section 2 is described in this section. HWP is inserted immediately after QWP in Fig. 2. As explained in Section 2, the optical axis of QWP is tilted by $\pi/4$ from the p-polarization axis. In this case, according to the angle θ_2 of the QWP, the relative difference ϕ between two input beams becomes $\phi = 4\theta_2$. By rotating HWP in the path of the output beam, the maximum and minimum values of the power of the output beam and the angle of HWP where the maximum power is reached can be measured. Then the relative phase difference can be estimated from these values. This measurement method cannot determine whether the relative phase difference ϕ is between zero and π or between $-\pi$ and zero. However, since the control signal polarity can be inverted by the servo amplifier, this is not an issue, even if the relative phase difference ϕ is between zero and π.

Figure 5 shows the change in the relative phase difference ϕ with the rotation of HWP angle θ_2. The relative phase can be controlled from 0.10π to 0.93π in the devised method. Therefore, nearly arbitrary relative phase control can be realized.

In this measurement, the input beams were not perfectly linearly polarized, and the alignment of PBS was imperfect. Because the leaked light from each incident beam depended on p-polarized light and s-polarized light, the relative phase difference ϕ did not reach zero or π due to the complicated

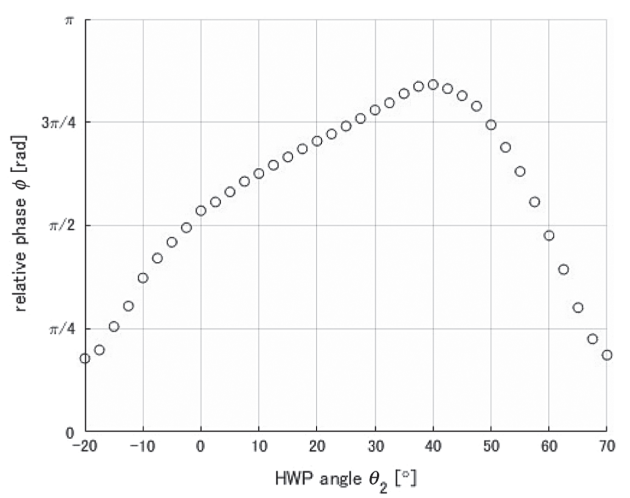

Fig. 5. Relative phase difference ϕ between the two input beams for the angle θ_2 of HWP.

polarization state of the leaked light from PBS. We infer that the relative phase difference ϕ does not change linearly for the same reason.

4. CONCLUSION

We developed a simplified relative phase control method using leaked light from a PBS for CPBC. In addition, we demonstrated the effectiveness of the proposed method. The achieved coupling efficiency was 0.979 when the relative phase difference between the two input beams was controlled to be zero. In addition, we confirmed that coherent addition by the devised method deteriorates neither the intensity noise quality nor the transverse mode quality. By extending the devised method (inserting HWP), almost arbitrary phase control from 0.10π to 0.93π (and from -0.93π to -0.10π) can be realized.

Disclosures. The authors declare no conflicts of interest.

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