Coherent Tiled 4 Beam Combination by Phase Controlled Stimulated Brillouin Scattering Phase Conjugation Mirrors Toward the Practical Laser Fusion Driver

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Abstract. The coherent beam combination using phase controlled stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) is one of the promising techniques for practical laser fusion drivers. Its ability has been demonstrated experimentally through this work. The phase fluctuations of the tilted beams are less than $\lambda/25$ even when amplifiers are inserted and operated in the beam combining system, which means that this new technique can be applied to combine the currently available lasers, such as 100 J/ns/10 Hz for a real laser driver module whose output energy is greater than 5 kJ/ns/10 Hz.

1. Introduction

Inertial fusion energy (IFE) needs a laser driver that generates several MJs/ns output and has a repetition rate of ~10 Hz [1]. For the uniform implosion of the laser fusion target, 200 laser beam lines are required. Therefore, one beam line of the laser driver should have more than 5 kJ/ns/10 Hz output [1]. Current laser technologies do not allow this kind of laser module having a high repetition rate because of a thermal problem with the laser medium. The National Ignition Facility (NIF) is the biggest laser facility in the world and produces 4.2 MJ/2 ns, but it operates only at several shots per day [2]. Other major laser facilities focusing on a high repetition rate operation generate much less energy per pulse [3].

A coherent beam combination of small lasers operating at a high repetition rate over 10 Hz can fundamentally solve the thermal problems since it only uses a small laser medium. The coherent beam combination can be achieved using phase controlled stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) [4, 5, 6, 7]. H. J. Kong et al. proposed "the self phase control technique" for the SBS-PCM, which had previously been thought to be impossible [4, 8]. The authors showed this new technique is able to lock/control the phases of SBS waves of each of the PCMs independently with a simple optical composition [4, 8]. They showed that, in principle, this new idea is able to increase the output energy unlimitedly by increasing the number of the combined beams of small output energy lasers with a high repetition rate.

This experimental work shows that beam combination using the self phase controlled SBS-PCM gives good phase fluctuation between the beams. The results obtained from the tiled 4 beam combination and the amplitude dividing 4 beam combination will be presented in section 2 and 3, respectably. In the tiled 4 beam combination, relative phases are fairly stabilized even when amplifiers are inserted and operated in the combining system.

2. Tiled 4 Beam Combination

In the tiled beam combination, the beam is split and recombined spatially. This method has advantages in increasing the output energy since sub beams do not interfere with each other in the recombination process.

Without amplification, it has been reported already that the tiled 4 beam combination shows good results [9]. With amplification, its results have been published only recently and this section is largely dependent on this paper [10].

2.1. Experimental Setup

FIG. 1. shows the experimental setup for the phase stabilization in the tiled 4 beam combination. An Nd: YAG laser beam is used as an input beam. The laser operates at 10 Hz with an injection seeder and active Q-switcher to generate a single longitudinal pulse with a pulse width of 8 ns. The input beam is expanded four times by a Galilean beam expander composed of plano-convex lenses with focal lengths of f =−50 mm and f =200 mm. The 4 beam aperture is placed after the expander. The aperture is a 2 by 2 array of circular hard apertures. Each hole has a diameter of 6 mm and the holes are separated by a 1.5 mm gap. Since the beam is p-polarized, it passes through the first polarizing beam splitter (PBS1).

Prisms (P1, P2, and P3) divide the beam spatially to make 4 sub beams. Each separated sub beam is amplified by passing through an amplifier. The active element of the amplifier is a Nd:YAG rod with a diameter of 8 mm and a length of 100 mm. It is pumped by one Xe flash lamp and cooled by water. Faraday rotators (FR1, FR2, FR3, and FR4) rotate the polarization of the sub beams after they have passed through the amplifiers. They have two purposes: first, they minimize the effect of thermal depolarization of the amplifiers [11], and second, they rotate the polarization of the beams to s-polarization so that the amplified sub beams are reflected by PBS1. The SBS-PCM is placed at the end of each beam line. The SBS-PCM is composed of a SBS cell and a concave mirror. The self-phase controlled SBS-PCM [4, 8] can effectively control the phase of the reflected wave. The cells are filled with a liquid SBS material of HT-70.

The sub beams are reflected at the PBS1 after the double-pass amplifications. The half wave plate (HWP2) adjusts the polarization a little, and a high amount of the recombined beam is reflected by PBS2 (the output beam). The transmitted beam form PBS2 is utilized for measuring the relative phase.

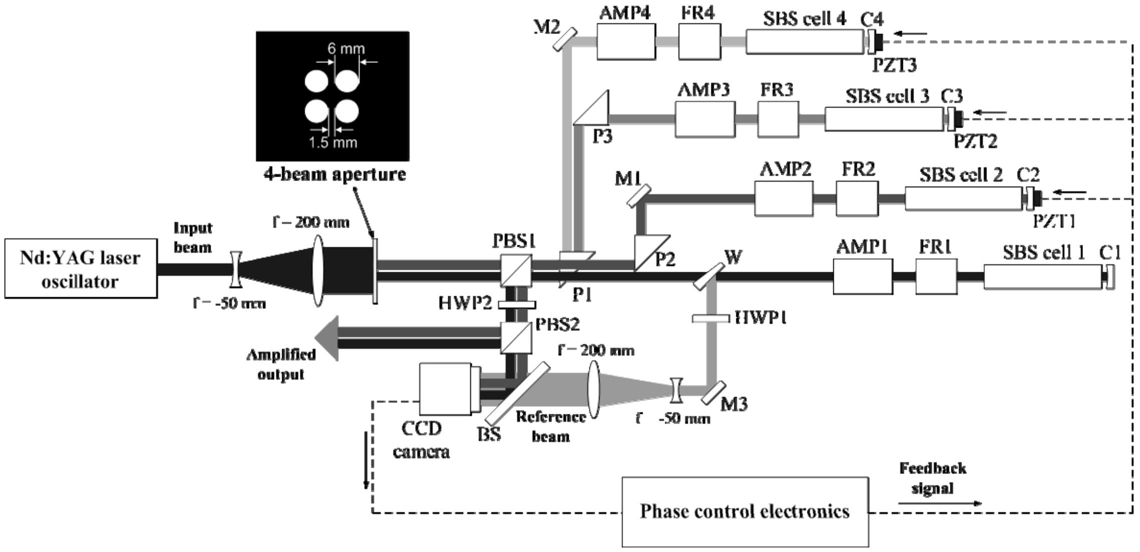
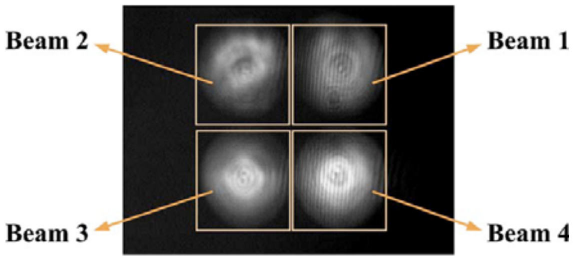


FIG. 1. Experimental setup for the phase stabilization in the tiled 4 beam combination: PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plates; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

(a) Four-beam combined output profile



(b) Interference pattern

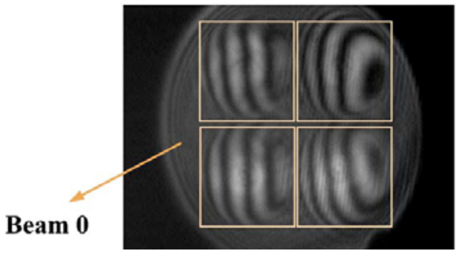


FIG. 2. (a) Four-beam combined output profile, and (b) interference pattern between the reference beam (Beam 0) and the recombined 4 beams (Beam 1, Beam 2, Beam 3, and Beam 4) for measurement of phase fluctuation.

One of the four sub beams is used as a reference beam. For this purpose, a small amount of the sub beam 1 is reflected at the wedged window (W). To make interference between this reference beam and a part of the recombined output, the reference beam has to have p-polarization and be enlarged. HWP1 rotates the polarization of the reference beam and a beam expander expands it. The reference beam and the transmitted output from the PBS2 meet at the beam splitter (BS) and the charge coupled device (CCD) records the interference image.
FIG. 2. (a) shows the 4 beam combined output beam pattern. The apparent unequal intensity between the beams is artificial. FIG. 2. (b) shows the interference pattern between the interference beam and the recombined output. From the interference pattern, we can measure the fluctuations of the phase between the interference beam and the 4 sub beams. Although self-phase controlled SBS-PCMs are used, slowly varying long-term phase drifts due to the thermal effect remain. By measuring the phase, we can actively compensate for these phase drifts by moving the concave mirrors behind the SBS cells. This is done by three piezoelectric transducers (PZTs) attached behind the concave mirrors.

2.2. Experimental Results

Let Φ01, Φ02, Φ03, and Φ04 be the phase differences of the 4 beams (beam 1, beam 2, beam 3, and beam 4) relative to the reference beam, beam 0, respectively. To measure the fluctuations of the relative phases (ΔΦ01, ΔΦ02, ΔΦ03, and ΔΦ04), the combined beam is interfered with by the reference beam. Without amplification, the combined output energy after the reflection by the SBS-PCM is 9.9 ± 0.5 mJ when the input energy is 32.2 ± 0.3 mJ. In this case, ΔΦ01, ΔΦ02, ΔΦ03, and ΔΦ04 are stabilized with a standard deviation of λ/116, λ/38.9, λ/31.5, and λ/39.5, respectively, during 2,500 shots (250 s). Since ΔΦ01 is the relative phase between beam 1 and a part of beam 1, it is stabilized very well.

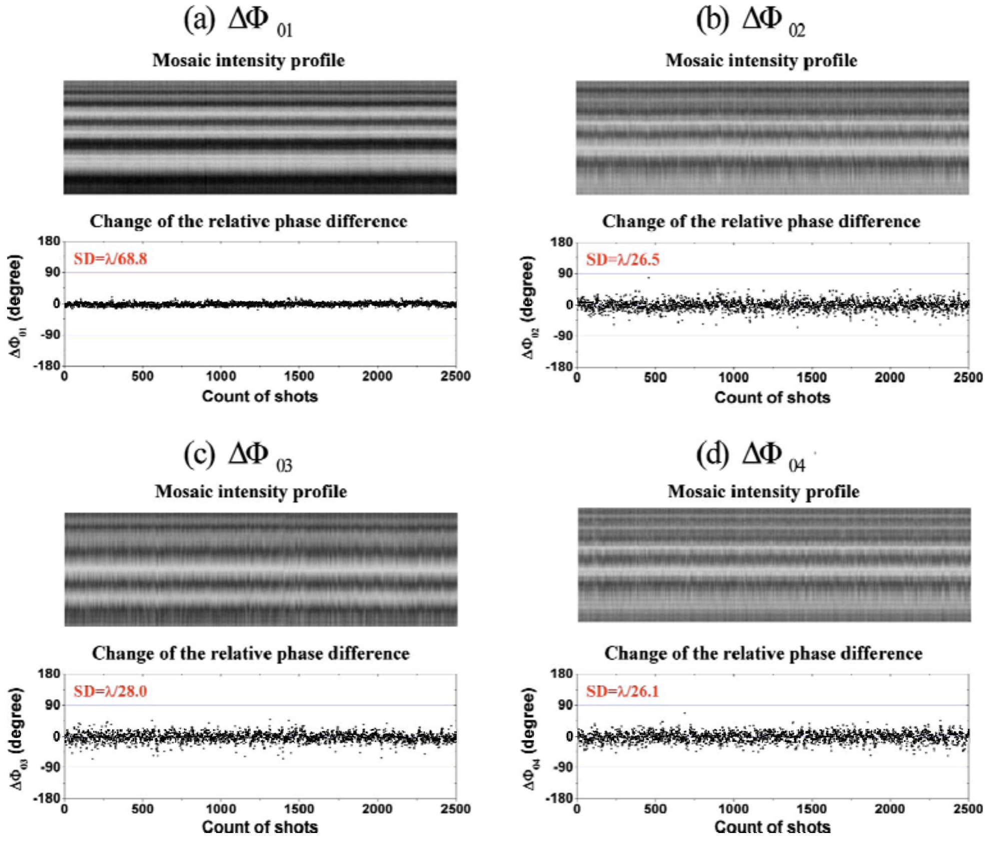


FIG. 3. Measured mosaic intensity profiles of the interference patterns and changes of phase differences between the reference beam and (a) beam 1,(b) beam 2, (c) beam 3, and (d) beam 4 during 2500 shots (250 s), with the operation of the amplifiers

FIG. 3. shows the mosaic intensity profiles from the interference pattern and calculated relative phases from the interference pattern of the 4 beams. When the amplifiers are operating, the combined output energy is 169 ± 6 mJ corresponding to a total gain of 5.3. In this case, ΔΦ01, ΔΦ02, ΔΦ03, and ΔΦ04 are stabilized with a standard deviation of λ/68.8, λ/26.5, λ/28.0, and λ/26.1, respectively, during 2,500 shots (250 s).

3. Amplitude Dividing 4 Beam Combination

In the amplitude dividing beam combination, the beam is split and recombined by beam splitters. This method has advantages in beam quality since splitting into sub beams does not induce diffraction. Furthermore, the recombined beam can have a Gaussian beam profile or a profile with a high fill factor.

Without amplification, it has already been reported that the amplitude dividing 4 beam combination shows good results [12]. The experimental setup for the amplitude dividing 4 beam combination with amplification will be given in section 3.1. The experimental results from the aforementioned paper [12] will be given in section 3.2.

3.1. Experimental Setup

FIG. 4. shows the experimental setup for the phase stabilization in the amplitude dividing 4 beam combination. An Nd: YAG laser beam is used as an input beam. The laser operates at 10 Hz with injection seeder and active Q-switcher to generate a single longitudinal pulse with a pulse width of 8 ns. The original beam is spatially filtered by a vacuum spatial filter

composed of a pinhole with a diameter of 0.3 mm and plano-convex lenses with focal lengths of f =1000 mm and f =700 mm. Since the beam is p-polarized, it passes through the first polarizing beam splitter (PBS1).

The first quarter wave plate (QWP1) and PBS2 divides an input beam into two beams. The half wave plates (HWP1 and HWP2) and the other PBSs (PBS3 and PBS4) divide these beams once again. Each separated sub beam passes through the Faraday rotator (FR), the amplifier (AMP), and the Faraday rotator again. The active element of the amplifier is a Nd:YAG rod with a diameter of 8 mm and a length of 150 mm. It is pumped by two Xe flash lamps and cooled by water. The second Faraday rotators (FR5, FR6, FR7, and FR8) rotate the polarization of the sub beams after the amplifiers. They minimize the effect of the thermal depolarization of the amplifiers [11]. The first Faraday rotators of the sub beam lines (FR1, FR2, FR3, and FR4) rotate the polarization of the sub beams once again. Therefore, the sub beams return to their initial polarization after double-passing the elements. The SBS-PCM is placed at the end of each beam line. The SBS-PCM is composed of a SBS cell and a concave mirror. The self-phase controlled SBS-PCM [4, 8] can effectively control the phase of the reflected wave. The cells are filled with a liquid SBS material of HT-70.

The beam splitter (BS1) splits about 8% of the returning beam from the combined beam from beam line 1 and beam line 2. The diagnostics system composed of QWP2, PBS5, and energy meters (EM1 and EM2) measures the relative phase between beam line 1 and beam line 2. A detailed explanation of the phase measurement is described in the previous work [12]. The relative phase between beam line 3 and beam line 4 is measured using exactly the same method. After passing through PBS2, all the beams are recombined. BS3 and anothor set of phase measuring optics measures the relative phase between the two sub-beams coming to PBS2. Once again, a detailed explanation could be found in the previous work [12]. Finally, QWP1 rotates the polarization of the recombined beam and PBS1 reflects the amplified output beam.

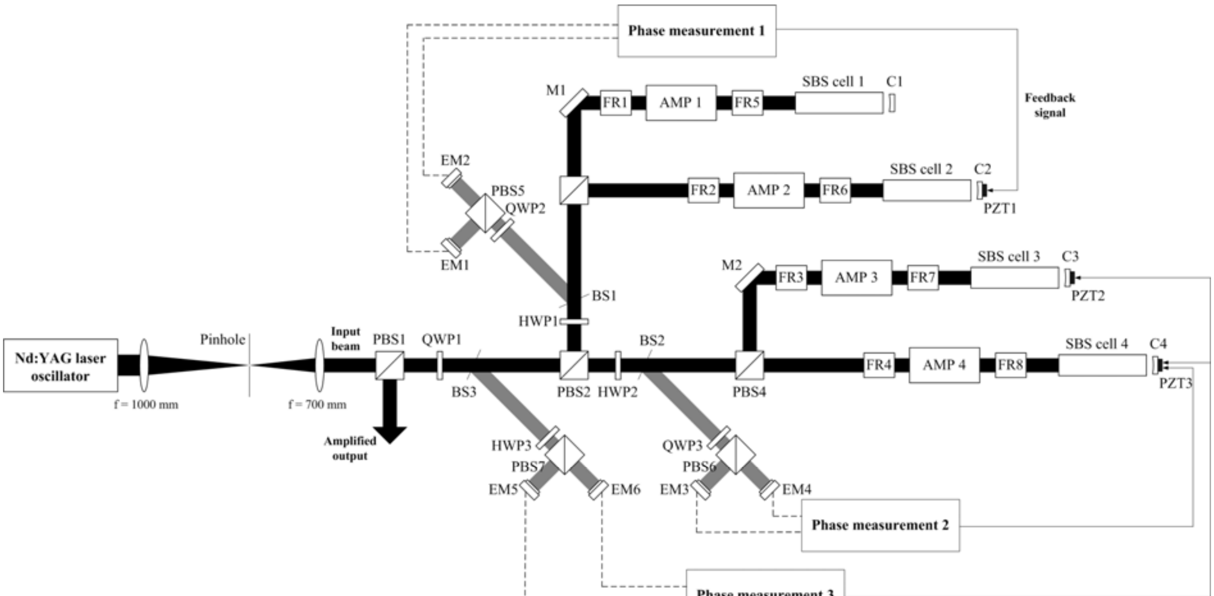


FIG. 4. Experimental setup for the phase stabilization in the amplitude dividing 4 beam combination: PBS1 through PBS7, polarizing beam splitters; QWP1, QWP2 & QWP3, quarter wave plates, HWP1, HWP2 & HWP3, half wave plates; BS1 & BS2, beam splitters; M1 & M2, 45 degree mirrors; FR1 through FR8, Faraday rotators; AMP1, AMP2, AMP3 & AMP4, amplifiers; C1, C2, C3 & C4, concave mirrors; EM1 through EM6, energy meters; PZT1, PZT2 & PZT3, piezoelectric translators.

Although self-phase controlled SBS-PCMs are used, slowly varying long-term phase drifts due to the thermal effect remain. By measuring the relative phase at three points, we can actively compensate for these phase drifts by moving the concave mirrors behind the SBS cells. It is done by three piezoelectric transducers (PZTs) attached behind the concave mirrors.

3.2. Experimental Results

In this section, experimental results of the amplitude dividing 4 beam combination without amplification will be presented. The experimental setup is exactly the same except an absence of the spatial filter, the Faraday rotators, and the amplifier [12].

Let Φ12 and Φ34 be the phase differences between the final sub beams (beam 1 and beam 2, beam 3 and beam 4, respectively). And let Φ13 be the phase differences between the combined beam of beam 1 and beam 2 and the combined beam of beam 3 and beam 4. To measure the fluctuations of the relative phases (ΔΦ12, ΔΦ34, and ΔΦ13), a total of six energy meters is used as explained above. The output energy is well-stabilized and the measured energy fluctuation is 6.16% by standard deviation.

Fig. 5. shows the measured phase differences between the beams during 2,000 shots (200 s). ΔΦ12, ΔΦ34, and ΔΦ13 are stabilized with a standard deviation of λ/34.3, λ/44.1, and λ/37.6, respectively, during 2,000 shots (200 s).

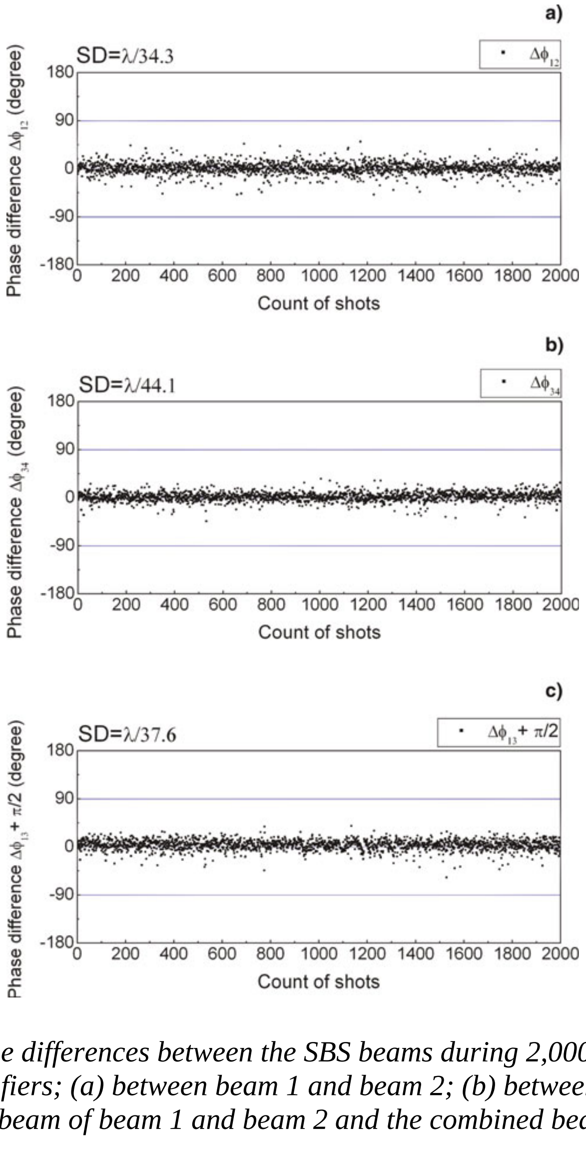


FIG. 5. Measured phase differences between the SBS beams during 2,000 shots (200 s), with the operation of the amplifiers; (a) between beam 1 and beam 2; (b) between beam 3 and beam 4; (c)between the combined beam of beam 1 and beam 2 and the combined beam of beam 3 and beam 4.

4. Concluding Remarks

The experimental results show that phase fluctuation with amplification is larger than that without amplification. The heat from the flash lamps causes a fluctuating optical path length due to the thermal effect, which gives additional phase fluctuation. Nevertheless, the relative phases of the amplified beams are well-stabilized within λ/25 with the tiled beam combination. For thie amplitude dividing 4 beam combination, the relative phases of the beams are well-stabilized within λ/34.

Based on these experimental demonstrations, it is expected that the beam combination technique can be applied to develop a practical laser fusion driver such as 2.5 kJ/ns/10 Hz by combining 25 J/ns/10 Hz level lasers that are currently available.

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