Coherent Beam Combination Technique Using SBS-PCM for High Repetition Rate Lasers

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Abstract: In this paper, the coherent beam combination technique using SBS-PCM for high repetition rate laser will be demonstrated. It is a novel concept capable of achieving to achieve a high-energy and high-repetition rate laser. The phase conjugation mirror and the beam combination laser will be introduced and the self-phase-controlling technique for the coherent beam combination will be shown. Next, a practical demonstration of the coherent beam combination laser using SBS-PCM will be presented. With the wave-front dividing scheme, the relative phases are measured under λ/26 when the amplifier is operating. The coherent beam combination laser using SBS-PCMs has various advantages to achieve the inertial fusion energy. In the conclusion, the 100J/10Hz laser fusion energy driver module which can currently available to achieve is suggested.

1. Introduction

The fusion energy is expected as one of the renewable energy sources. Especially, the inertial fusion energy is easy to maintenance, scale-up its scale, and has low damage caused by high energy neutrons and protons. On the other hands, magnetic fusion energy is hard to scale-up because of the turbulent flow of the plasma, and hard to maintenance. Moreover, it is hard to develop the material which can resist high-energy plasma. In these points, inertial fusion energy is respected as a promised renewable energy sources.

However, there is a problem to achieve the inertial fusion energy. To achieve the inertial fusion energy, it needs the pulsed laser which has 5MJ of output energy, 10Hz of repetition rates, and 10ns of pulse width. Though, there are no lasers which can operate in 10Hz in the world. The problem is the cooling of the laser material. To yield high energy, the size of the laser material should be increased. When the size of the laser material is increased, it is hard to cooling the laser material. Therefore, the repetition rate of the laser should be decreased. To overcome this problem, scientists has researched various methods, such as a laser diode pumping, a high thermal conductivity laser materials, and a cryogenic Yb:YAG[1-5]. These methods have a limitation on increasing output energy. Because of the parasitic oscillation, the output energy from one amplifier has a limitation.

On the other hands, Kong et al. proposed the beam combination laser using stimulated Brillouin scattering phase conjugation mirrors(SBS-PCMs) [6]. A beam combined laser utilizes small-sized amplifiers and combines the beams coherently. Thus it can increase the output energy without problems caused by cooling and parasitic oscillations. Especially the beam combined laser using SBS-PCMs is a promising technique to achieve the high-repetition rate and high-energy laser.[7-15] The phase conjugate property of the SBS-PCM is essential to combine the beam. In this paper, the SBS-PCM and the beam combination laser using SBS-PCMs will be introduced.

2. Phase conjugation mirror(PCM)

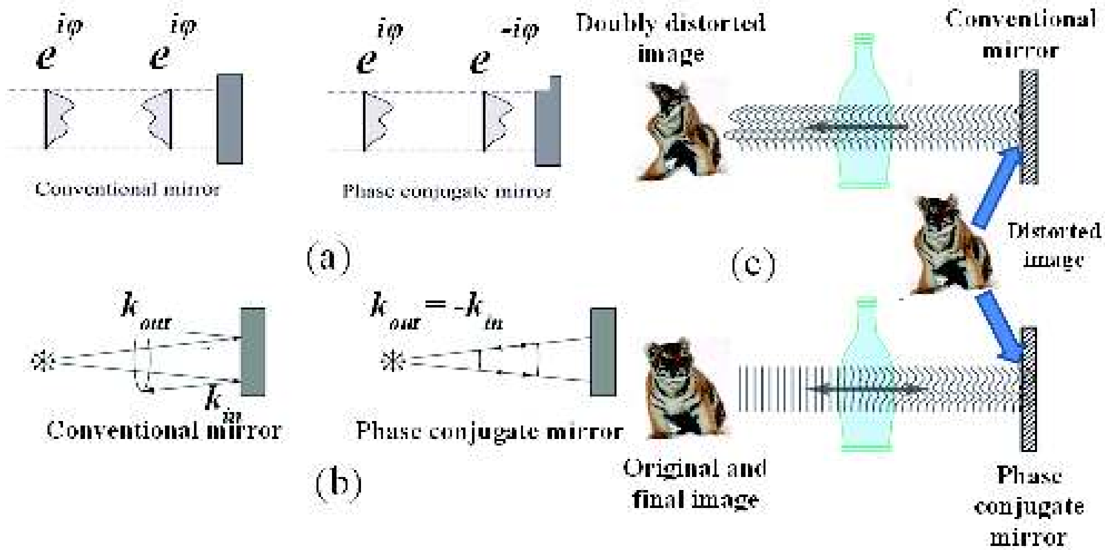


Figure 1. comparison of the conventional mirror and the phase conjugation mirror(PCM). (a) a phase property of the wave. (b) for the point source. (c) for the wave-front.

Figure 1 shows the comparison of the phase conjugation mirror(PCM) and the conventional mirror. Figure 1(a) shows the phase conjugation. In conventional mirror, the reflected wave of the $e^{i\phi}$ wave has same phase ϕ with the incident wave. On the other hands, In the PCM, the reflected wave of the $e^{i\phi}$ wave has the phase $-\phi$, so the wave is change to $e^{-i\phi}$ wave.

Figure 1(b) shows the optical path of the reflected wave in the conventional mirror case and the PCM case. The reflected wave from the conventional mirror is diverged, but the reflected wave from the PCM is converged to the point source.

Figure 1(c) shows the wave-front of the reflected waves in the conventional mirror case and the PCM case. If the plane wave-front passes through the phase plate(in the figure, glass bottle), the plane wave-front will be distorted. If this distorted wave-front is reflected by the conventional mirror and passes through the phase plate again, the wave-front will greatly distorted. However, in the PCM case, the wave-front will be compensated after the wave passes through the phase plate again. This property can help the wave-front compensation in the beam combination laser system.

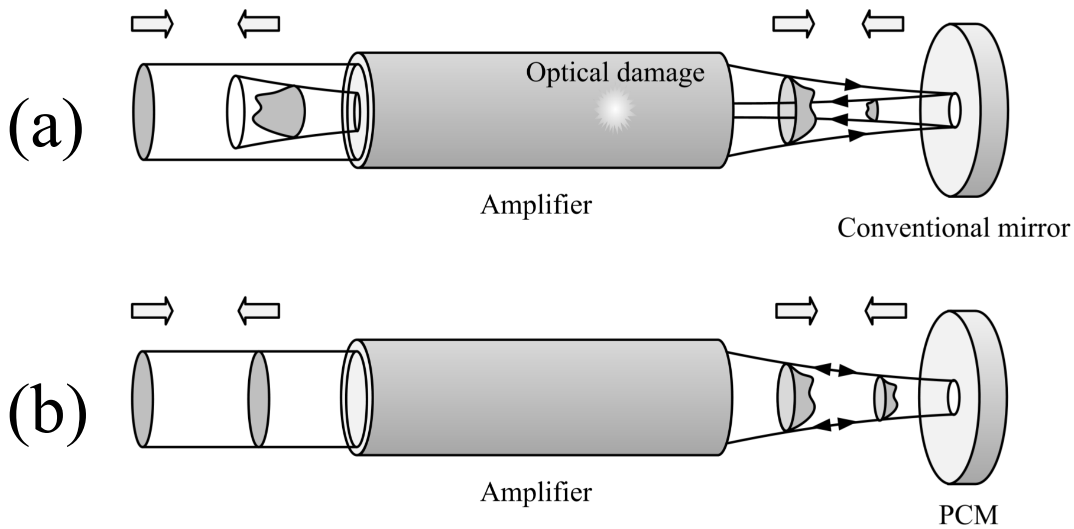


Figure 2. amplifier using the Conventional mirror and the PCM.(a) for the conventional mirror. Damage is induced in amplifier, and the output beam quality is low. (b) for the PCM. the output beam quality is excellent, and the thermal-lensing effect is compensated.

Figure 2 shows the methods that improve the beam quality using PCM. In general, the inner of the laser medium is high temperature and the outer of the laser medium has low temperature. Thus, the laser medium operates as a convex lens. For the laser using conventional laser, the beam is focused in the laser medium like figure 2(a). It causes the damage of the laser medium and low beam quality. Besides, for the laser using PCM, the thermal lensing will be compensated and the high beam quality can be achieved.

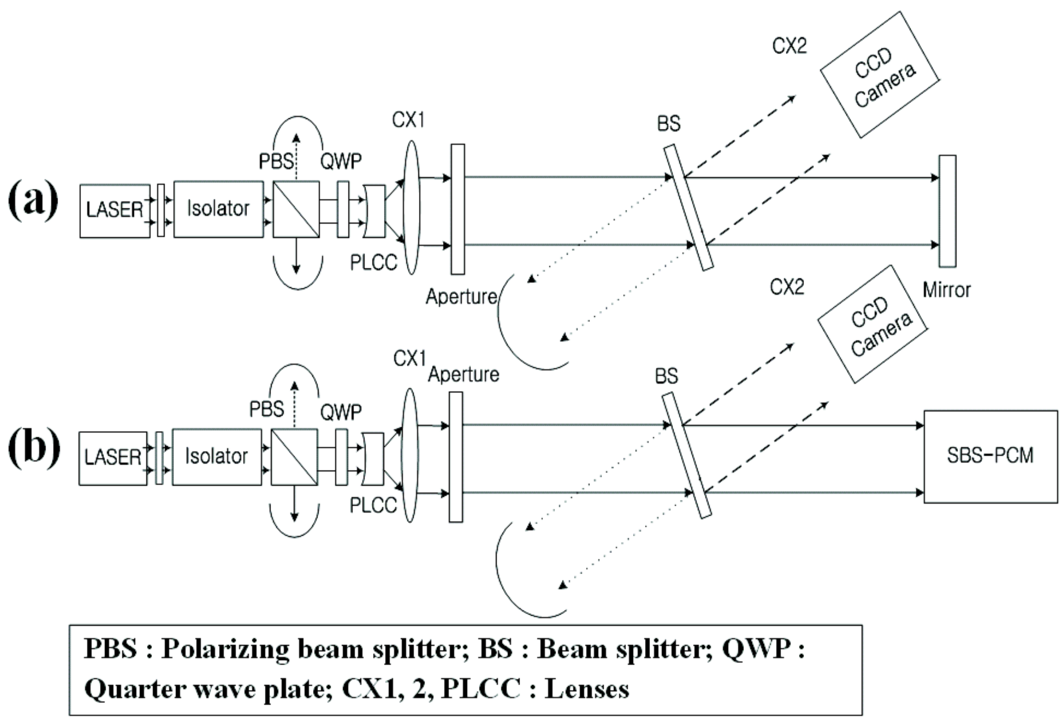


Figure 3. the experimental setup of the wave-front compensation by phase conjugation mirror.

Figure 3 shows the experimental setup of the wave-front compensation by phase conjugation mirror. in figure 3(a), the beam passes through the rose-shape aperture. The beam is reflected by the conventional lens, and captured by CCD camera. The distance between the aperture and mirror is 1 m, and the distance between the mirror and the CCD camera is 1 m. In figure 3(b), the beam is reflected by the PCM instead of the conventional mirror. Figure 4 shows the comparison of the reflected beam from the conventional mirror and the PCM. The reflected beam from the conventional mirror shows the diffracted beam pattern, but the reflected beam from the PCM is compensated.

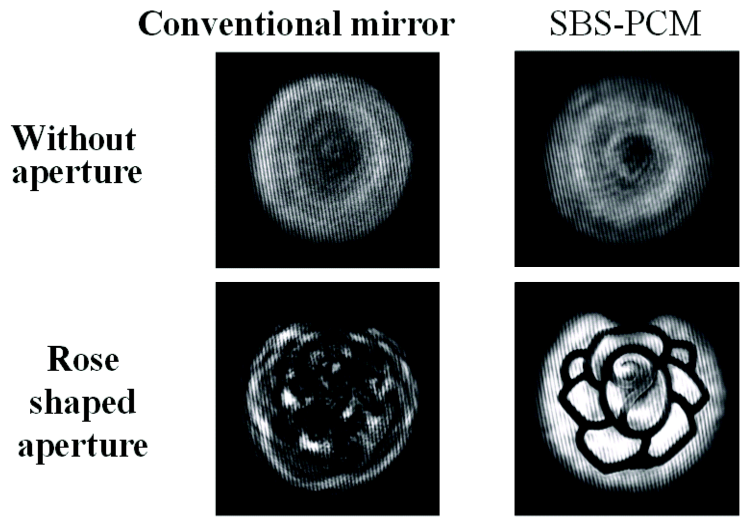


Figure 4. the reflected beams by conventional mirror and SBS-PCM. for conventional mirror, the image is greatly distorted.

3. Beam combination laser using SBS-PCM

It is noticed that the large size of the laser medium is needed to make a high-energy laser. Especially, the pulse laser which has pulse width of less than 10ns should increase the diameter of the laser medium. However, there is no method to cooling the inner of the solid directly. Therefore, the solid laser has the limitation of the output energy due to its structure and the thermal conductivity of the laser medium.

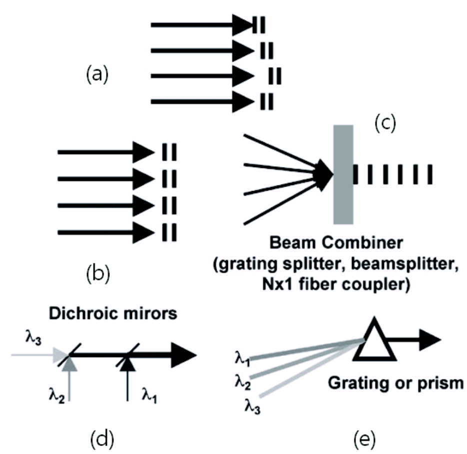


Figure 5. The methods of the beam combination; (a) side-by-side beam combining. (b) coherent beam combining by the tiled aperture. (c) coherent beam combining by the filled aperture. (d) wavelength beam combining by serial implementations. (e) wavelength beam combining by parallel implementations.

Beam combination laser can solve this problem. The beam combination methods are categorized by five methods. Figure 5 shows these five methods[16]. The methods are the side-by-side beam combining, the coherent beam combining with tiled aperture, the coherent beam combining with filled aperture, the wavelength beam combining using serial implementations and the wavelength beam combining using parallel implementations. These can be classified by the coherent beam combining and the wavelength beam combining. The wavelength beam combining and side-by-side beam combining can give the high energy, but when the coherent beam is needed, the coherent beam combining should be required.

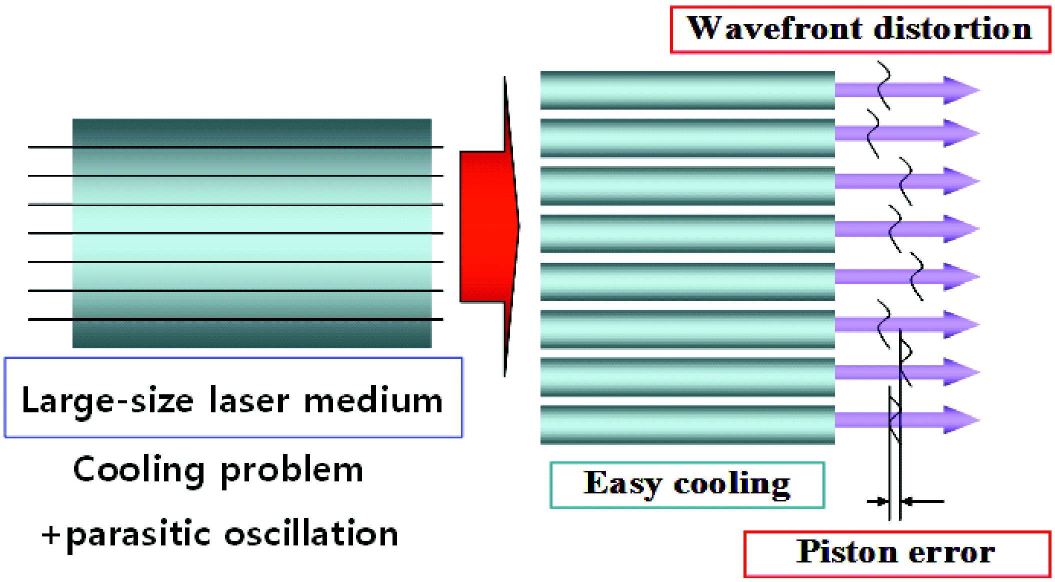


Figure 6. comparison of the large-size single amplifier and the beam combination laser.

Figure 6 shows how the beam combination solves the cooling problem of the laser medium. In the left of the figure 6, the size of the laser medium should be increased. However it is hard to cooling the laser medium immediately. In the right of the figure 6, the beam combination uses the small amplifiers. These small amplifiers are easy to cooling. The output energy is determined by the number of the amplifiers. However there are different wave-front distortions in each amplifier, so it is impossible to combine the laser beams coherently. The spatial filtering and the adaptive mirror can be used, but the spatial filtering cause the beam loss and the adaptive mirror shows the bad result of the beam cleaning. The PCM has advantages such as the good efficiency of the beam cleaning inexpensiveness, so it is good solution.

The PCM is achieved by degenerated four wave mixing(DFWM) using nonlinear crystal optics and the stimulated Brillouin scattering[17,18]. DFWM has the limitation of the input energy and it is complicated, but SBS needs simple system. Moreover, when the medium is damaged, it can be restored itself if the Fluoro-carbonate liquid is used as a SBS medium.

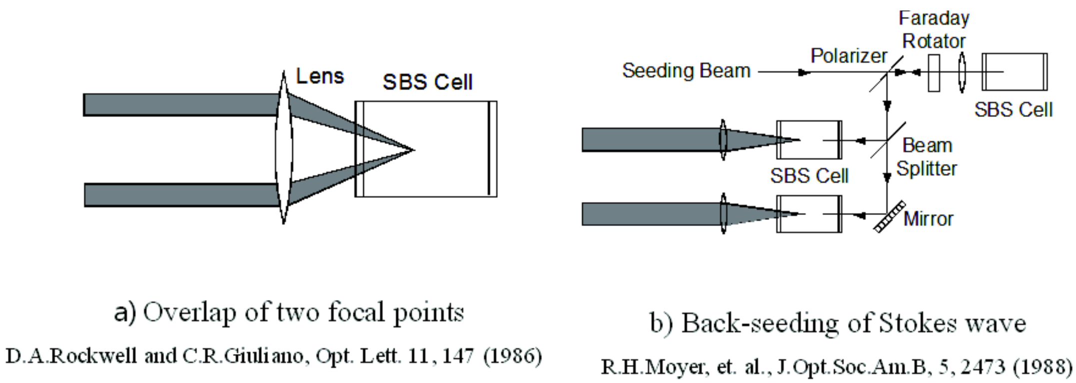


Figure 7. conventional SBS control method. (a) overap of two focal points. (b) back-seeding of stokes wave.

However, when the SBS-PCM is using in the beam combination laser, the phase of the reflected beam is randomly changed because the SBS is randomly occur due to statistical noise[19]. These effects fluctuate during several times of the phonon lifetime; as a result the piston errors in its phase occur between each beam line. There are several ways to solve the piston error. Figure 7(a) shows the method proposed by D. A. Rockwell in 1986[20]. The method focuses all beams to one SBS-cell, can lock the phase. This method is not appropriate for practical use because the number of beams which can be focused is limited. Figure 7(b) shows the method proposed by R. H. Moyer et al in 1988[21]. The method involves the use of a Stokes beam as a back-seeding beam. However, this method is complicated and also is not appropriate for many beam combination. In this method, the back-seeding beam breaks the phase conjugation.

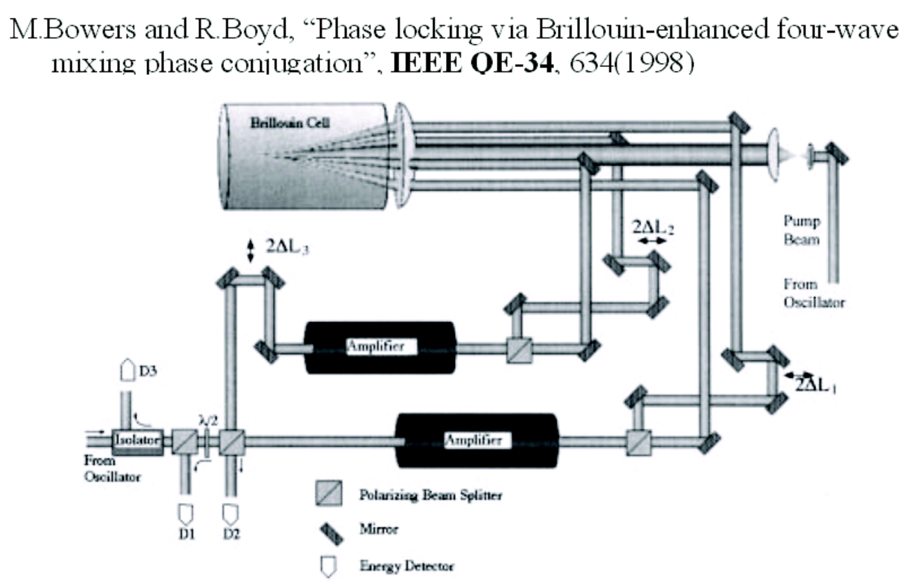


Figure 8. experimental setup of the Brillouin enhanced four-wave mixing(BEFWM)

In 1998, M. Bowers and R. Boyd proposed the Brillouin-enhanced four-wave mixing (BEFWM), shown in figure 8[22]. It requires highly complicated optics and is limited in the number of the beams to be combined.

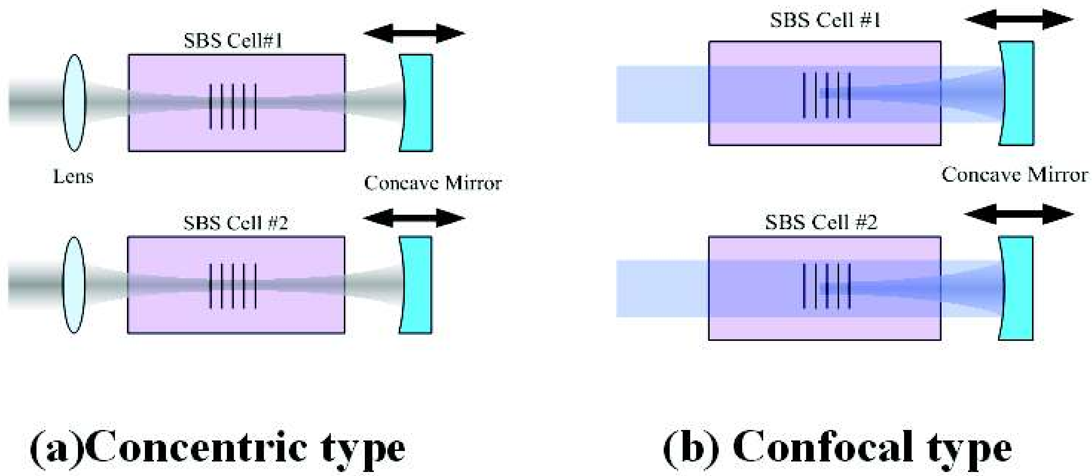


Figure 9. the self-phase controlling method. (a) concentric type. (b) confocal type.

The self-phase controlling method, proposed by H.J.Kong, is shown in figure 9. This self-phase controlling method uses a feedback mirror after the SBS cell; thus, the counter propagating beams from the feedback mirror and the incident beams create a standing wave. The standing wave generates density modulation in the SBS media by the electro-strictive force. This standing density modulation operates as a seed of the moving Bragg grating. The Bragg grating locks the phase of the SBS wave, allowing the SBS phase to be controlled. Phase-controlling of the SBS wave is possible via positioning of the feedback mirror. Figure 9(a) is called concentric type, and figure 9(b) is called confocal type.

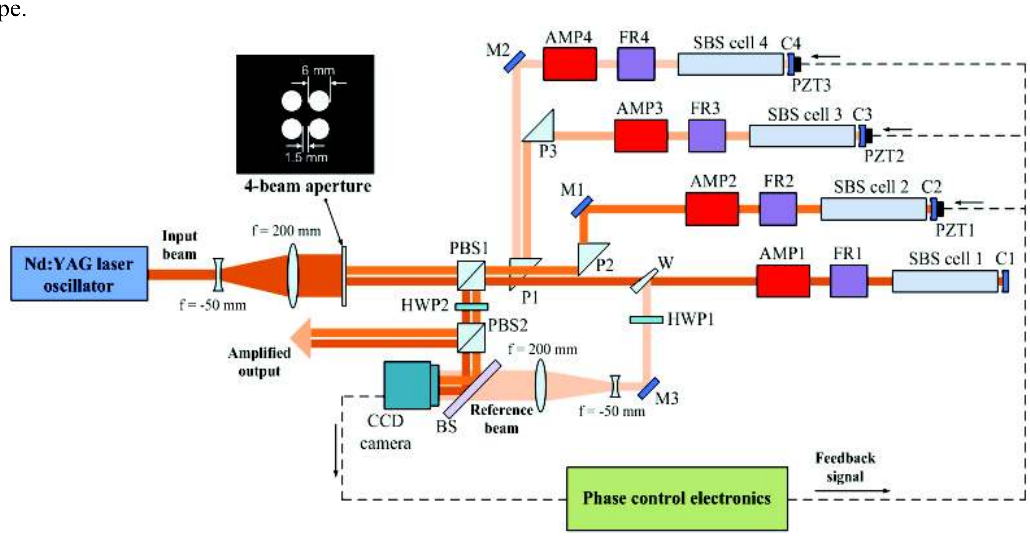
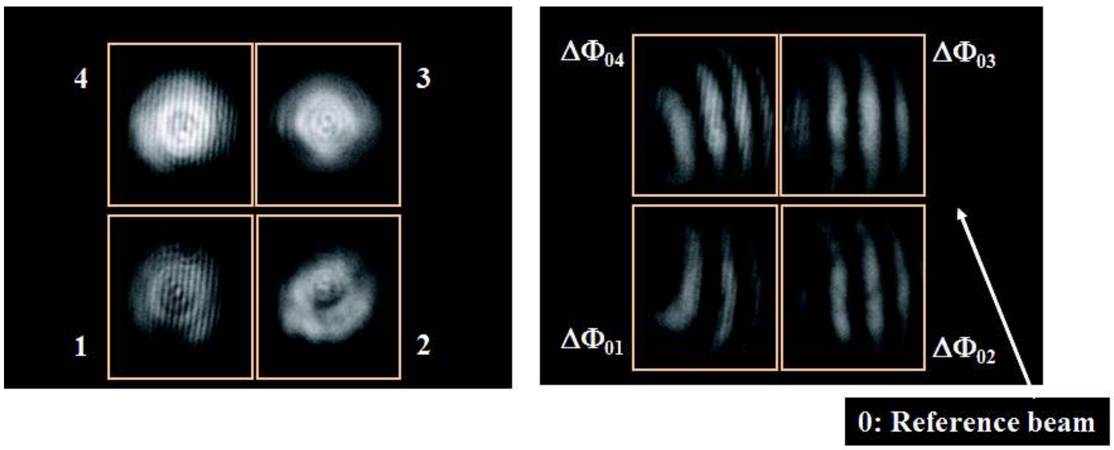


Figure 10. 4-beam combination laser system using confocal type SBS-PCMs. HWP, half wave plate; PBS, Polarized beam splitter; BS, beam splitter; P, Prism; M, mirror; AMP, amplifier; FR, Faraday rotator; C, concave mirror; PZT, piezoelectric translator; W, wedge.

Figure 10 shows the 4-beam combination laser system using confocal type SBS-PCMs[23]. The laser beam source is Nd:YAG laser oscillator, and the polarization of the laser is P-polarization. The beam expander consists of lenses which focal lengths are -200 mm and –50 mm. The beam expander expands the size of the laser beam by four times. The expanded beam is divided into four sub-beams, beam 1, 2, 3 and 4 after passing through the four- beam circular aperture. The passes of the sub-beams are divided by prisms and mirrors. Each sub-beam pass through the amplifiers and the Faraday rotators, and the polarization of the sub-beams are π/4. The sub-beams are reflected by SBS-PCM, and pass through the amplifiers and Faraday rotators again. Thus the polarization of the sub-beams is S-polarization. The sub-beams are combined and reflected by PBS1, and HWP2 tilts the polarization of the combined beam. PBS2 splits the beam, so output beam is reflected by PBS2. A Wedge splits the beam 1, and the beam expander expands a part of the beam 1 by four times. This expanded beam is called a reference beam. A part of the combined output beam and the reference beam generates an interference pattern to measure the relative phases between the sub-beams. From the measured relative phase, phase controlling electronics controls piezoelectric translator to adjust relative phases between the sub-beams Figure 2 shows the combined beam and the interferogram between the reference beam and the combined beam.



J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

Figure 11. the image of the combined beam and the interferogram. (a) the image of the combined beam. (b) the interferogram between the reference beam and each sub-beams.

The image of the combined beam and the interferogram is shown in figure 11. 4-beams are successfully combined, as shown in figure 11(a). Figure 11(b) shows the interferogram between the reference beam and the each sub-beam. The relative phases are called ΔΦ01, ΔΦ02, ΔΦ03, ΔΦ04. For the 2500 shots, the phase fluctuation is measured in figure 12. The input energy of the beam is 32.2 ± 0.3 mJ, and the output energy of the amplified beam is 169 ± 6 mJ. The relative phases are less than λ/26. It can be regarded as one beam. Therefore, this self-phase controlling method can control the phase of SBS-wave, and the combined beam shows the property which is same to one beam. Especially, the M^2 factor of the output beam is near 1.0 because the output beam is a phase conjugation wave. This beam combination laser is easy to scale-up when the pulse energy input to SBS-PCM is more than 50mJ, the pulse width is more than 1ns and less than 10ns, and the seed pulse is single longitudinal mode.

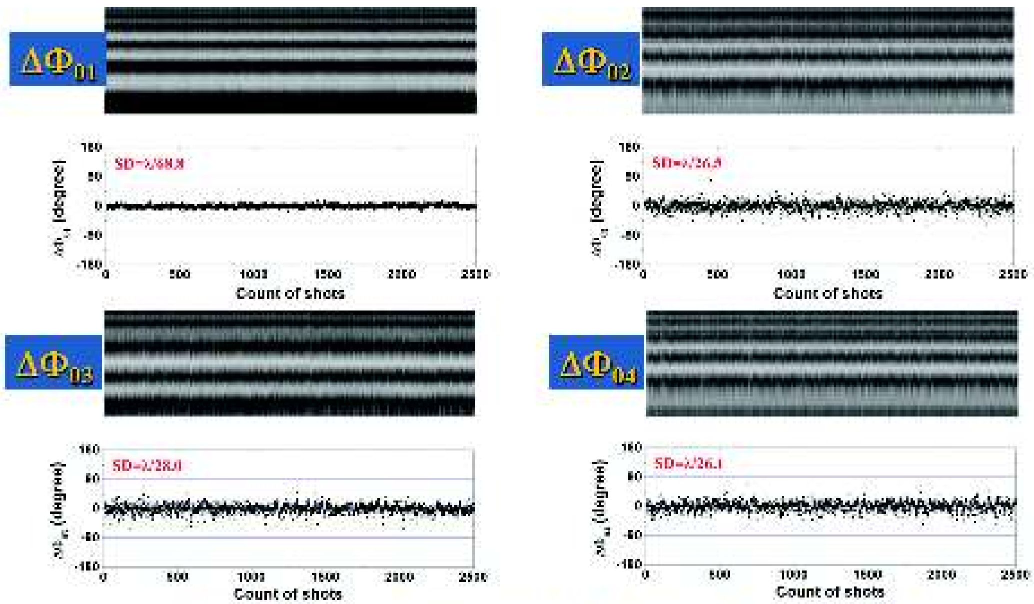


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Figure 12. the mosaic patterns and the relative phase distribution during 2500shots.

This beam combination laser using SBS-PCM has various advantages. Using the beam combined laser using SBS-PCMs, the laser beam can navigate itself to the target without the injection laser [24]. In the fusion reaction, the problem is target injection. The repetition rate of the target injection is 10Hz, and the target speed is 400m/s. the accuracy of target position is needed to 20μm. Because of the turbulent flow after the fusion reaction, it is impossible to inject the target with the accuracy of 20μm. Figure 13 shows the concept of the self-navigation technique. The glinting laser is scattered by target before the target is on the center. The scattered beam is amplified, and reflected by SBS-PCM. Then the beam is redirected to the target position when the glinting laser is scattered. Because the target is moving, so we need to compensate about 100μm, but the frequency of the amplified beam is converted to 3ω, so the amplified beam can be redirected accurately by adjust the prism. This methods can give the accuracy of 1μm when the turbulence in the air.

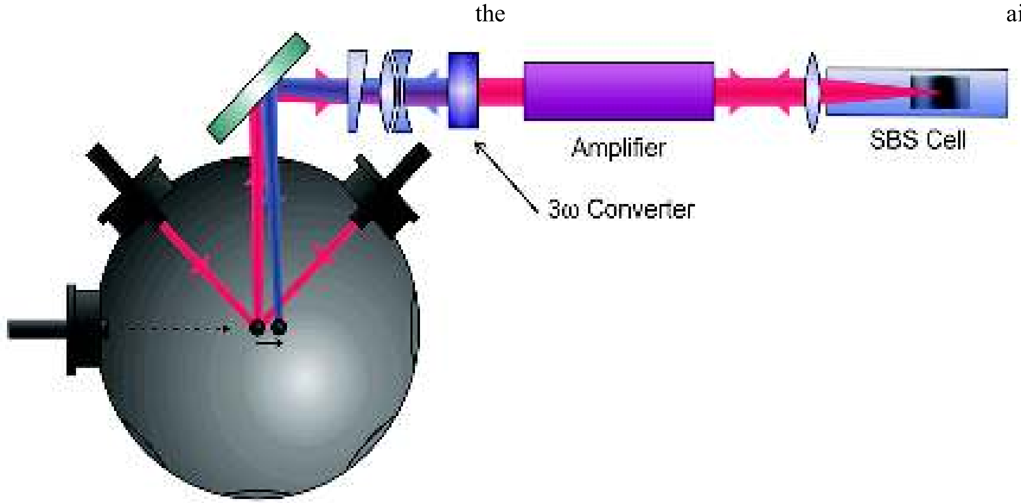

Figure 13. The self-navigation technique using SBS-PCM.

4. Conclusion

The beam combination laser using SBS-PCM is introduced in this paper. Its unlimited output energy and the high repetition rate can give various applications. Especially, this high-energy and high-repetition rate laser can be used in the high-speed laser processing, the large area laser processing using holograms, EUV generation for the EUV lithography, and With OPCPA(optical parametric chirped pulse amplification), the beam combination laser using SBS-PCM can make ~fs high energy/high power/high repetition rate laser. So, it is expected to a resource to make a compact particle accelerator and a proton/neutron generator. The proton generator can be used for the cancer treatment, and the neutron generator can be used for the non-destructive inspection.

The research on the key techniques of the coherent beam combination laser has been completed. From these techniques, we can make a 1J@10kHz module and the 100J@10Hz module. Especially, if the 100J@10Hz module shown in figure 14 is developed, we can scale-up the module to 2.5kJ@10Hz. This module is a basic beamline of the inertial fusion energy. Thus the beam combination laser using the SBS-PCM is the key to the future dream laser to achieve the inertial fusion energy.

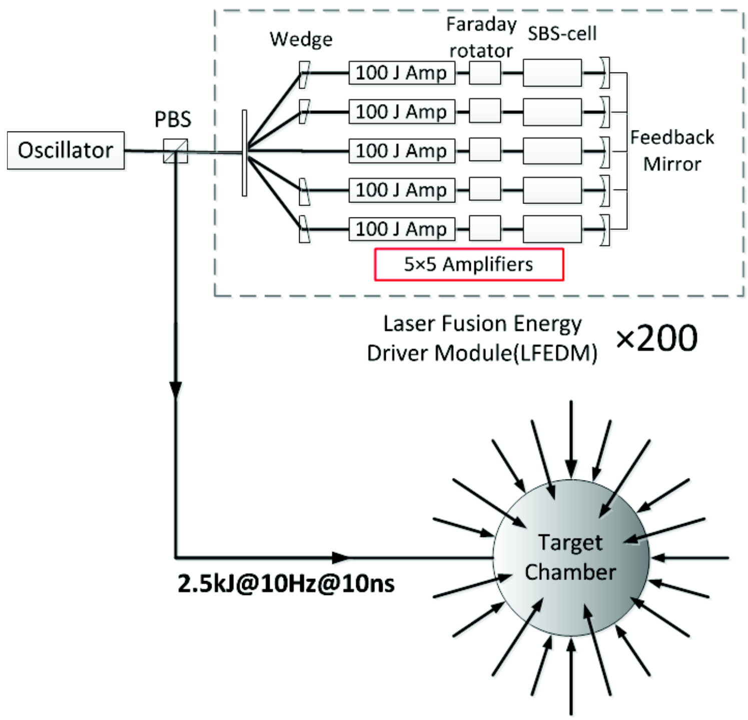

Figure 14. The sheme of the Laser Fusion Energy Driver Module(LFEDM).

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