Long-term stabilized two-beam combination laser amplifier with stimulated Brillouin scattering mirrors

Hong Jin Kong, Jin Woo Yoon, Jae Sung Shin,a) and Du Hyun Beak

Department of Physics, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

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The beam combination method is the promising technique for constructing a very high energy laser with a high repetition rate over 10 Hz such as a real fusion driver. In our previous works, the phase control technique essential for realizing this system was proposed and demonstrated experimentally. However, these previous works were done without amplifiers. In this work, we employed amplifiers to test the real beam combination system and obtained a well stabilized phase controlling with $\lambda/51$ fluctuation by standard deviation during 5000 laser shots (500 s) at 204 mJ total output energy.


Laser fusion energy (LFE) is well known as one of the most promising inexhaustible sources of practically clean energy for mankind. A typical laser fusion driver requires pulse energies of order of megajoules and repetition rates around 10 Hz. However, the present high energy solid state laser drivers, such as NIF and GekkoXII, can operate only several shots per day as it takes several hours to cool down the large size active media. The beam combination method can play a decisive role in overcoming this cooling problem by combining separately amplified sub-beams of smaller energies. In our laboratory, Kong et al. proposed a promising beam combination laser system using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs). Figure 1 shows the conceptual scheme of this beam combination system with the amplitude dividing part employing polarizing beam splitters. This beam combination system is composed of series of cross type amplification stages. This cross type system is relatively insensitive to the optical misalignment, thus, the energy scaling is a straightforward matter. Each amplification stage is composed of the SBS isolator system in the right side and the array amplification system in the left side. The leaked back reflection can be completely cut off by the SBS isolators, and the beam energy is separately amplified in the array of amplifiers. This separate amplification does not need a large size active media. Therefore, it can operate with a repetition rate exceeding 10 Hz regardless of the output energy and is easily adaptable to the modern laser technology.

In the beam combination system, the SBS-PCMs were used as the reflectors instead of the ordinary mirrors because the thermal distortion in the active media could be compensated by the phase conjugate waves generated in the SBS-PCMs. Yet, with the conventional SBS-PCMs, the SBS waves have random initial phases as they are generated by thermal noises. Hence, the phase difference between the beams, reflected from each SBS cell is random for every laser shot, and it is the main obstruction for the beam combination system. For this reason, the phase control of the SBS wave was necessary for the beam combination system and the phase control method with the self-generated density modulation was proposed by Kong et al. recently. This phase control technique is completely different from previously developed methods, such as beam overlapping, backseeding, and four-wave mixing. The backseeding method destructs the phase conjugation and the overlapping method and the four-wave mixing method cannot be applied to the many-beam combination due to the optical breakdown and the complicated setup, respectively. On the other hand, in this proposed technique, it is possible to control each beam phase independently quite easily by the simplest optical composition using only one concave mirror, called the feedback mirror, without any limitations in the number of beams and the destruction of the phase conjugation. Therefore, the structural limitation for the energy scaling is entirely removed using this phase control technique. In our previous works, the experiments were performed to demonstrate the principle of the phase controlling, and the well-

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a)Author to whom correspondence should be addressed. Electronic mail: jsshin@kaist.ac.kr.
controlled phase was obtained by measuring the interference pattern of two reflected SBS beams during the several hundreds shots of 10 Hz operation. Meanwhile, the long-term phase fluctuation induced by the thermal convection of the liquid SBS medium was observed as the laser shot was increased. This slowly varying fluctuation could be easily compensated by the active control of the feedback mirror position using an additional lead zirconate titanate (PZT) shifter. With these techniques, the stabilized relative phase has been obtained with 1/110 fluctuation by standard deviation for a quite long period of time in combining two SBS waves with 10 mJ input energy.

In this work, as the next major step, we have constructed a two-beam combination system with a double-pass amplification, as illustrated in Fig. 2. The oscillator used in this system is a linearly polarized single longitudinal mode Q-switched Nd:YAG (yttrium aluminum garnet) laser (Spectra-Physics, Model #GCR-150), operating with a 10 Hz repetition rate and at 1064 nm wavelength. This laser pulse has a quasi-Gaussian shape with the beam diameter of 8 mm and the pulse width of 7 ns [full width at half maximum (FWHM)]. At first, the beam from the oscillator, rotated by 45° is incident on the polarizing beam splitter (PBS). The incident beam has a stable energy fluctuation with a 0.7% standard deviation. This beam is divided by PBS into two sub-beams of s and p polarizations with nearly equal energies. Each perpendicularly polarized sub-beam is double-pass amplified by passing through the flashlamp-pumped Nd:YAG rod amplifier twice with the help of the SBS-PCM. Each amplifier has an Nd:YAG rod with 100 mm length and 8 mm diameter as a laser medium and a Xenon flashlamp at 450 Torr pressure as a pumping source. The electrical pump energy of each flashlamp is 13.5 J/pulse. After the double-pass amplification, the sub-beams are recombined again at PBS and the recombined beam enters the output part. The Faraday rotators, placed in each divided line, change the output beam direction by rotating the polarization vertically through the double pass. These Faraday rotators can also compensate the thermally induced birefringence in the amplifiers.

The SBS-PCM used in this experiment is composed of a SBS cell and a concave mirror as depicted in Fig. 2. A heavy fluorocarbon liquid FC-75 (3M Company) was used as an SBS medium because of its excellent reflectivity and high fidelity. The length of the SBS cell is 300 mm and a high reflectivity (>99%) coated concave mirror with a 150 mm radius of curvature was used for focusing the pump beam.

The recombined beam has two cross-polarized components, not interfering with each other, but after passing through the 45° polarizer, it has an interference term as in the following equation:

\[
E_{\text{int}} = E_1 + E_2 + 2\sqrt{E_1 E_2} \cos \Delta \Phi,
\]

where \(E_{\text{int}}\) is the measured interfered output energy, \(E_1\) and \(E_2\) are the measured energies at the output part of polarizer from the SBS cell 1 and SBS-cell 2, respectively, and \(\Delta \Phi\) is the phase difference between two SBS waves. Measuring \(E_{\text{int}}, E_1,\) and \(E_2\), the phase difference \(\Delta \Phi\) is easily calculated using the upper formula.

Figure 3(a) presents the experimental results of the interfered energy fluctuations and the calculated phase difference between two SBS beams during 5000 laser shots (500 s) when the incident beam energy of each separate amplifier was 50 mJ and the total input energy was 100 mJ. After the double-pass amplification, the output beam energy measured before the polarizer was 204 mJ which corresponded to 2.04 net gain. The standard deviation of energy fluctuation of \(E_1\) and \(E_2\) was 1.60% and 1.55%, respectively. The obtained phase difference was composed of the long-term and short-term fluctuations. The slowly varying long-term phase fluctuation was caused by a thermal convection of the liquid SBS medium and could be easily compensated by adjusting the concave mirror position by PZT control. Measuring the interfered energy, the computer was used to determine the necessary mirror shift to maximize the interfered energy. Figure 3(b) illustrates the experimental results of the interfered energy fluctuations and the phase difference between two SBS beams during 5000 laser shots (500 s) using PZT control. The stabilized output energy with 5.55% fluctuation by standard deviation, corresponding to \(\lambda/51\) phase fluctuation, was obtained with this active PZT control.
method. However, some abrupt phase jumps were observed as shown in Fig. 3(b) and the maximum phase jump was measured to \( \lambda / 5.7 \). The removal of these abrupt phase jumps is the next work to be resolved for the amplitude dividing scheme, while it is not a problem for the wave-front dividing beam combination scheme where the phase fluctuation within \( \pm \lambda / 4 (\pm 90^\circ) \) is tolerable as shown in Fig. 3(b) with the filled range.\(^7\)\(^8\)

In conclusion, it was demonstrated that the two-beam combination system, which includes amplifiers for developing a high power/high energy system with a high repetition rate, can really work. The phases of SBS waves were well-controlled using the self-generated density modulation, and the thermally induced long-term phase fluctuation could be suppressed using the active control of the feedback mirror position. As a result, the stabilized phase controlling with \( \lambda / 51 \) fluctuation by standard deviation was obtained during 5000 laser shots (500 s) with 204 mJ total output energy and 10 Hz repetition rate. Infrequently, abrupt phase jumps were observed in this system, but this phenomenon will be solved in the future work. In the high energy operation of 75 J pulse energy and 13 ns pulse duration (FWHM), any optical breakdown was not observed with the use of SBS material, FC-75.\(^28\) Therefore, this material can be used for a laser input around 75 J, and the output energy over 100 J can be obtained with the double-pass amplification in each separate amplification line. Besides the piston error, there was another problem for realization of the multistage beam combination laser, the optical breakdown generated from the fast rising edge of the reflected SBS wave. We found that it is possible to preserve the temporal waveform of the reflected SBS wave using the prepulse technique.\(^8,13,29\) From the results of these investigations, it is expected that much higher output energies with high repetition rates can be easily obtained by combining many beams amplified by \( \sim 100 \) J amplifiers operating at \( \sim 10 \) Hz and, thus, becoming well suited for the laser fusion drivers.

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\(^{2}\) W. J. Hogan, Energy from Inertial Fusion (IAEA, Vienna, 1995), Chap. 3.