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Laser fusion driver using stimulated Brillouin scattering phase conjugate mirrors by a self-density modulation

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Abstract

A new concept of laser fusion driver is proposed, which uses a beam combination technique with stimulated Brillouin scattering phase conjugate mirror (SBS-PCM). It is constructed systematically with a cross-type amplifier as a basic unit. In the first part of this paper, we introduce the cross-type laser amplifier using SBS-PCM, with several advantages by experimental results. These advantages are the ideal properties for practical laser fusion driver, such as the perfect isolation of leak beam, the compensation of thermally induced birefringence through the amplifiers, the easy maintenance and alignment insensitiveness, and the freely-scale-up energy. Next, some successful results for the phase control of SBS-PCM are presented, which is one of the main problems in the current beam combination laser using SBS-PCM. Particularly, a new technique for controlling the phase of SBS-PCM, "self-density modulation," is introduced, which is the simplest ever among those reported. With the advantages of the cross-type amplifier using SBS-PCM and the novel method for controlling the phase of SBS-PCM, the proposed beam combination laser system is presented as the most promising one, which can contribute to the realization of high energy laser that can operate with high repetition rate over 10 Hz, even in the case of huge output energy over MJ.

Keywords: Beam combination; Stimulated Brillouin scattering

1. INTRODUCTION

For practical laser fusion energy generation, it is necessary to operate a magajoul (MJ) laser system with a repetition rate over 10 Hz (Hogan *et al.*, 1995). Moreover, many laboratories are engaged in high energy density and warm dense matter research. Lasers along with intense particle beams are the main tolls to induce high energy density states in matter. This kind of basic research toward fusion energy would greatly benefit from an increased repetition rate of the experiments (Neumayer *et al.*, 2005; Schaumann *et al.*, 2005; Hoffmann *et al.*, 2005; Hora *et al.*, 2005; Jungwirt, 2005). Toward high energy and high power laser, many technique approaches have been taken in various ways, such as diode-pumped laser with gas cooling, electron–beam-pumped gas laser, large-sized ceramic laser, and beam combination laser (Ueda & Takuma, 1987; Kong *et al.*, 1997; Lu *et al.*, 2002). Among these, especially the beam combination technique with stimulated Brillouin scattering phase conjugate mirror (SBS-PCM) has been expected to be the best candidate for practical fusion driver (Kong *et al.*, 1997, 2005*d*, 2005e; Kappe *et al.*, 2007; Meister *et al.*, 2007). The laser system using a beam combination technique does not need a large gain medium because the laser beam is divided into several beams and recombined after separate amplification. Hence, it can be operated at a repetition rate exceeding 10 Hz regardless of the output energy, and can be easily adaptable to modern laser technology, the proposed beam combination laser system using SBS-PCM can be unlimitedly scaled up by increasing the number of separate amplifiers (Kong *et al.*, 1997, 1999). Furthermore, SBS-PCM produces a phase conjugated wave, and it can be utilized to compensate many kinds of induced optical distortions through the amplification (Zel'dovich *et al.*, 1972; Rockwell, 1988). Despite the merits of beam combination laser using SBS-PCM, it is necessary to control the phase of each reflected beam by SBS-PCMs, achieving a single beam with fixed phase in recombination. But the phase of the reflected beam by SBS-PCM shows an inherently random characteristic in general (Rockwell, 1988; Boyd *et al.*, 1990), since SBS

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starts from an acoustic noise in a SBS medium. For this reason, there have been many works done to control or lock the phases of SBS waves, and some successful works have been achieved in phase locking of SBS-PCM (Rockwell & Giuliano, 1986; Loree *et al.*, 1987), but there are still limits in the practical applications. Recently, a new phase control technique, which is the simplest ever, has been demonstrated, and its following researches have shown encouraging results (Kong *et al.*, 2005*a*; Lee *et al.*, 2005). This new method is called "Phase control of SBS-PCM by self-generated density modulation" or simply "self-phase-locking," it has only one concave mirror and no optical coupling with the other beams, wherein each beam is focused at separate focal points without using any backward Stokes seed beams. This method for controlling the phase of SBS-PCM is inspiring the realization of high energy laser that can operate with high repetition rate over 10 Hz, even with the lasers of huge output energy.

In this paper, we introduce the structure of a cross-type amplifier with SBS-PCM, in the concept of the presented laser fusion driver, using a beam combination technique with SBS-PCMs, and demonstrate its advantages (i.e., freely-scalable energy, perfect-isolated leak beam, compensating the thermally-induced optical distortion, and misalignment-insensitiveness) with experimental results, parts by parts. In addition, we present the recent results on phase-control of SBS-PCM, and finally propose a novel laser amplifier system of cross-type amplifier structure with phase-controlled SBS-PCM as the most expected, and the most promising for laser fusion driver.

2. THE CROSS-TYPE AMPLIFIER WITH SYMMETRIC SBS-PCMS

Kong *et al.* (1997, 1999, 2001, 2005*b*) proposed a "cross-type double-pass laser amplifier with symmetric SBS-PCMs," and a high power laser amplifier system, with the beam combination laser system based on the cross-type double-pass amplifier, here the cross-type double-pass amplifier is the basic unit of the scalable and structures laser fusion driver. Figures 1 and 2 presents the conceptual layout of the new laser fusion driver using SBS-PCMs and the structure of its basic unit, "cross-type double-pass laser amplifier with symmetric SBS-PCMs," respectively. In this paper, noteworthy advantages of the cross-type amplifier with SBS-PCMs are examined one by one, such as the perfect isolation of leak beam using the threshold of SBS-PCM, the compensation for thermally-induced birefringence, and the alignment-free property. Other important topics on laser amplifier using SBS-PCM are also introduced, such as the wave form preservation in reflections by SBS-PCM.

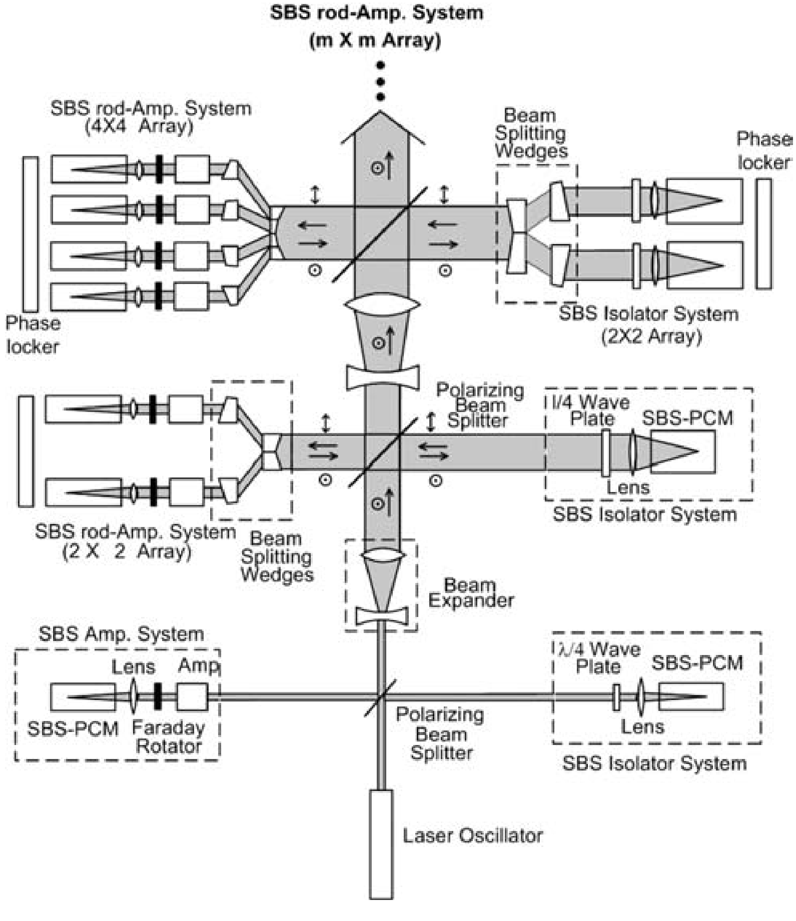

Fig. 1. A beam combination laser using SBS-PCMs with self phase locking.

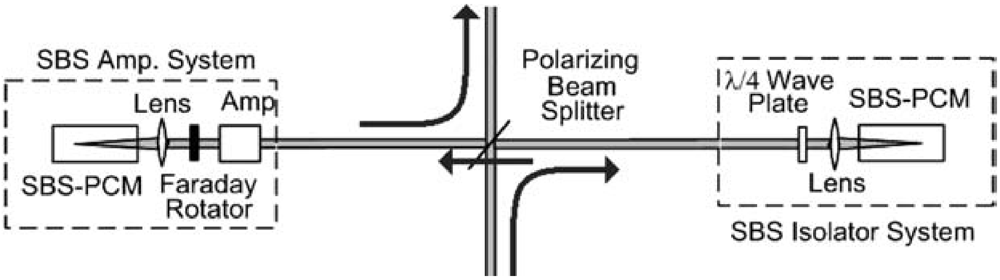

Fig. 2. A cross-type amplifier using SBS-PCM as a basic unit of a beam combination laser.

2.1. Cross-type isolator using threshold nature of SBS

In the proposed laser beam combination, each amplification stage is cross-shaped, which is composed of two parts, the amplifier and the isolator as shown in Figure 2. The cross-type amplifier using SBS-PCM implies several advantages, its function as a perfect isolator by SBS-PCM, the SBS-PCM located on the right side works as an ideal isolator (Kong *et al.*, 1998, 2001). Figure 3a presents the experimental setup for testing the isolation using SBS-PCM, here an amplifier on the left side is omitted and the mirror, M1, is in place for the experiment. In Figure 3b, it is demonstrated that the optical isolator using the SBS-PCM can completely cut-off the leak beam, as well as the backward propagating beam, due to amplified spontaneous emission (ASE) from post stages, SBS-PCM located on the right arm works as the optical isolator. It gives the perfect isolation of master oscillator from the leak beam, under the condition that the optical path length, *L*, between the SBS-PCM, and the post stage is long enough compared to the pulse length (i.e., the temporal duration of pulse times the speed of light). When the energy of the leak beam is lower than the threshold of SBS, the leak beam cannot be reflected by the SBS-PCM, and consequently, it isolates the oscillator from the leak beam. Figure 4 shows the typical reflectivity of SBS-PCM in various medium such as FC-75, acetone, and CCl_4, we can easily verify the important characteristics of SBS: threshold nature, nonlinear reflectivity, and dependence on the pumping-mode.

2.2. Alignment-free characteristic in cross-type amplifiers with SBS-PCM

Figure 5 compares the application of SBS-PCM in a conventional master oscillator power amplifier (MOPA) system and the suggested cross-type amplifier system with two SBS-PCMs. In Section 2.1, the principle of the isolator using SBS-PCM is explained, but the additional arm using SBS-PCM implies another function, it is the alignment-free characteristic of this system, one advantage of the cross-type amplifier system with SBS-PCM is shown in Figure 6, although other systems such as Figures 6b and 6c give changes to the beam pointing due to the misalignment of PBS, the suggested system of Figure 6a does not give any change to the beam pointing, it means that the beam pointing for the output has the same level as the input (i.e., of master oscillator). The special property of the cross-type amplifier system guarantees insensitivity to the misalignment and tilting of any other optical components except for the oscillator itself, since the

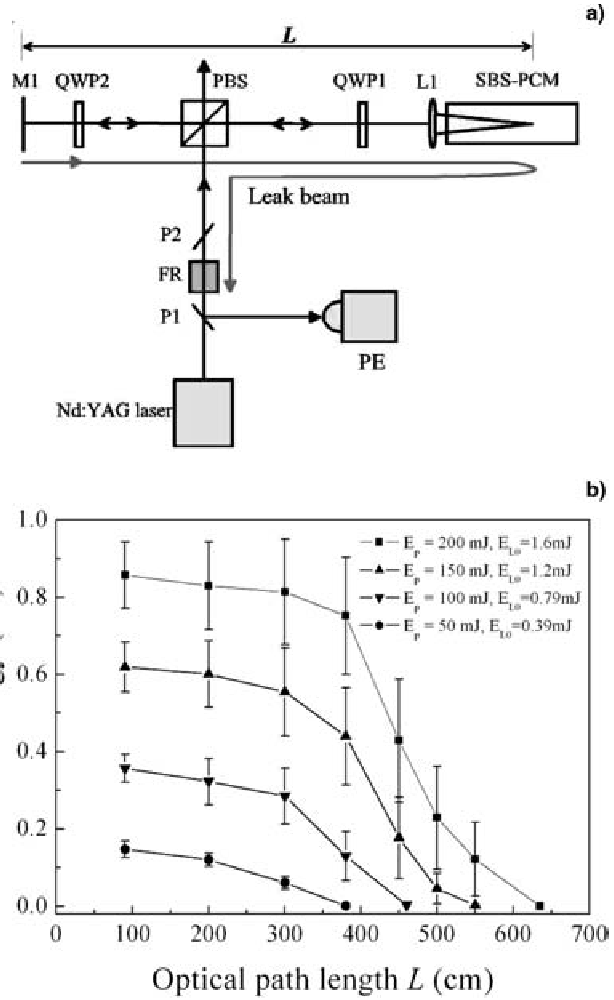

Fig. 3. (**a**) Schematic of the experimental set up: P1 & P2, polarizer; FR, Faraday rotator; PE, pyro-electric energy meter; QWP1 & QWP2, quarter-wave-plate; L1, lens; PBS, polarizing beam splitter; M1, conventional mirror. (**b**) Leak beam energy dependence on the optical path length *L*. It demonstrates that the optical isolator can completely cut off the leak beam from the post stage. The energy of the leak beam reduces to zero as *L* is increased.

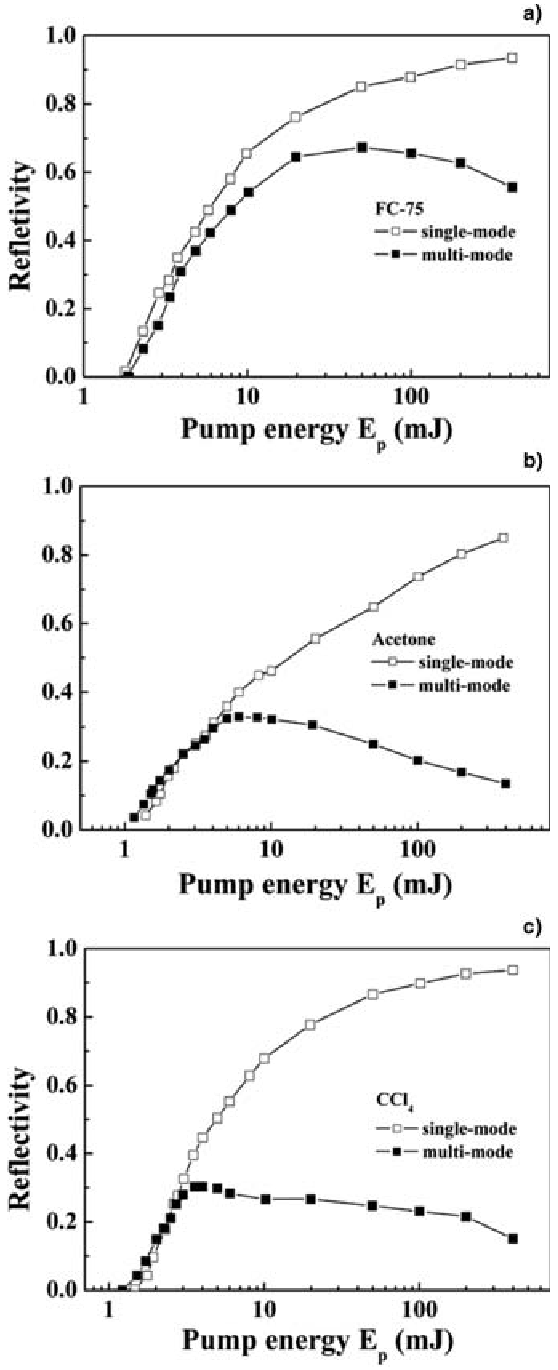

Fig. 4. SBS reflectivity vs. pump energy for (**a**) FC-75, (**b**) acetone, and (**c**) CCl_4, as the active medium and for laser radiation in the single-mode and the multi-mode cases.

beam reflected by SBS-PCM follows the exact same path as the incoming beam by its phase-conjugate characteristic.

2.3. Compensation of thermal birefringence in cross-type amplifiers with SBS-PCM

Diminishing the thermal load and the related thermal effects is one of the traditional and important topics in the high

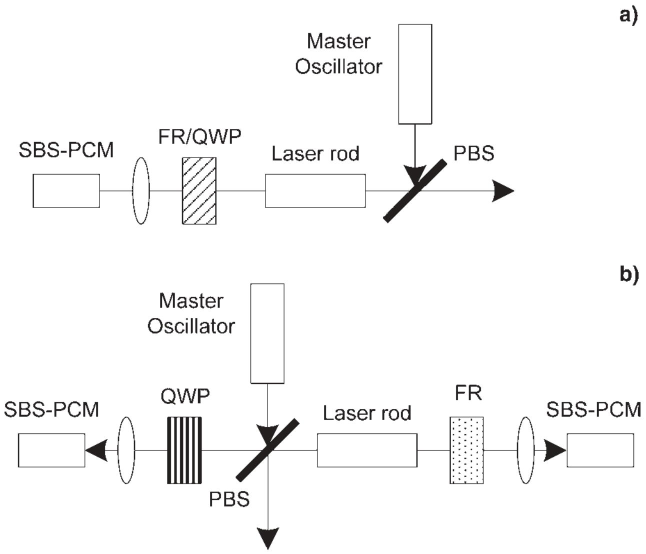

Fig. 5. The schematic diagram of (**a**) conventional MOPA and (**b**) the suggested cross-type amplifier system.

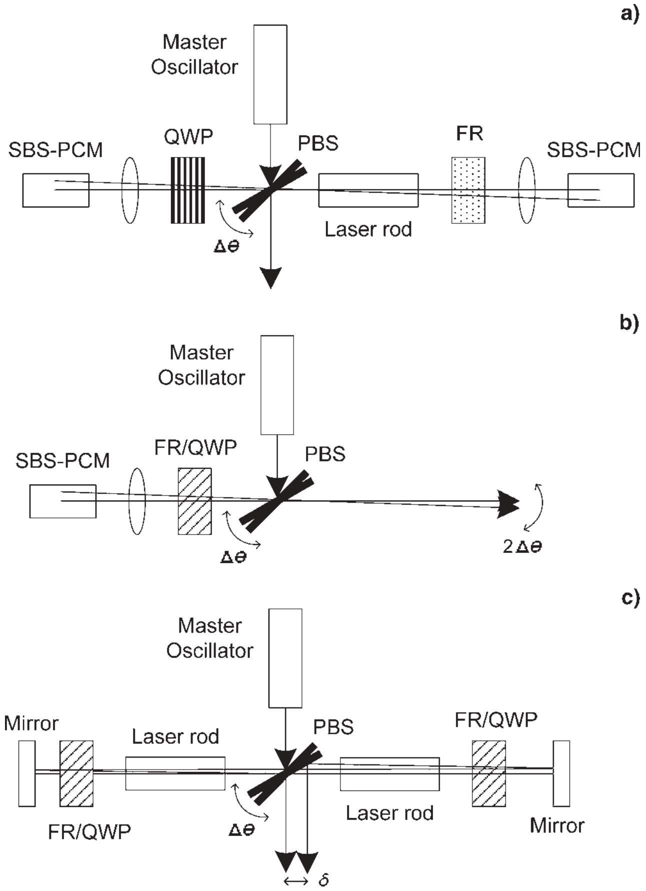

Fig. 6. Change of the beam pointing due to the tilting PBS: (**a**) gives no change in cross-type amplifier with symmetric SBS-PCMs; (**b**) gives tilting in the conventional application of SBS-PCM; (**c**) gives displacement in the combination of conventional mirrors.

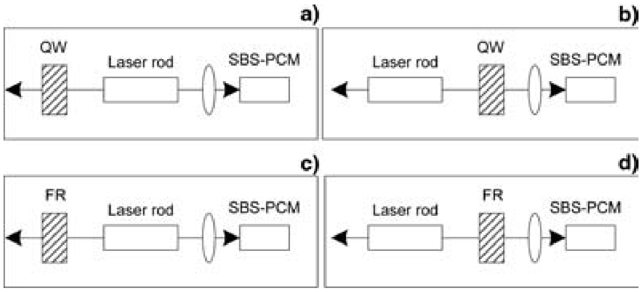

Fig. 7. Four possible optical schemes for rotating the polarization of the backward beam by 90-degree with respect to the input beam.

energy laser field, and particularly, the compensation of thermally-induced birefringence (TIB) is the interesting subject. Here, we introduce noteworthy results for the compensation of TIB in the cross-type amplifier system with SBS-PCM. As shown in Figure 2, the amplifying part of cross-type amplifier with SBS-PCM consists of three components, amplifier rod, polarization rotator (i.e., FR, Faraday rotator or QWP, Quarter-wave-plate), and SBS-PCM (SBS-cell and focusing optics), they can be seen on the left arm of the cross-type amplifier with SBS-PCM. The total system has four available optical configurations, as shown in Figure 7. Among these schemes, the setup of Figure 7d gives a 90-degree-rotated output in the polarization state, with respect to the polarization of input beam. The related experimental results are shown in Figure 8, which shows the good compensation of TIB in the setup of Figure 7d through the depolarization ratio, experimental results for depolarization ratio in the schemes of Figures 7d and 7b are shown in Figures 8a and 8b, here the low and constant depolarization ratio in FR, using setup means the good compensation of thermally-induced birefringence.

Comparing with a similar situation (Han & Kong, 1995), theoretical explanation to this phenomenon can be given by Jones matrices. Assuming the input polarization state as $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$, Faraday rotator as $F = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}$, quarter-wave-plate as $Q = \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix}$, the glass rod as $G = \begin{bmatrix} e^{i\phi_r} & 0 \\ 0 & e^{i\phi_\theta} \end{bmatrix}$ in polar

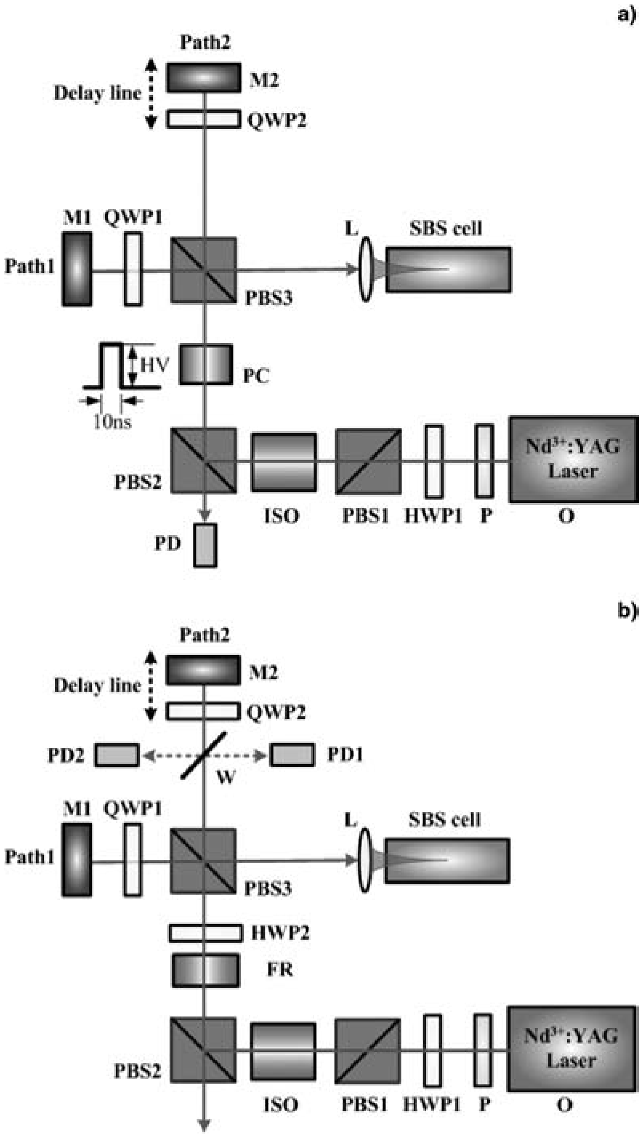

Fig. 9. A cross-type amplifier using SBS-PCM as a basic unit of a beam combination laser. (**a**) Proposed system for preserving a temporal SBS pulse shape; (**b**) experimental setup for this experiment: O, Nd3+:YAG laser oscillator; *P*, linear polarizer; HWPs, half-wave-plates; PBSs, polarizing beam splitters; ISO, Faraday isolator; FR, Faraday rotator; QWPs, quarter-wave plates; PC, Pockels cell; Ms, full mirrors; W, wedge; L, convex lens $f = 15$ cm; PDs, photodiodes; SBS cell (FC-75, 30 cm long).

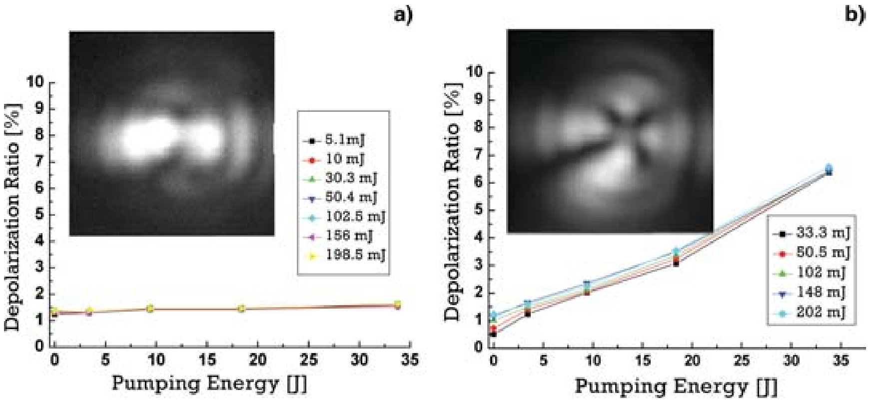

Fig. 8. Experimental results for depolarization ratio for (**a**) the scheme of 7d and 7b the scheme of 7b, with respect to the electrical pumping energy on flashlamp. The different energies in the box represent input energies for amplifiers.

coordinates, and the rotation operator as $R = \begin{vmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{vmatrix}$, then the output polarization state $\begin{bmatrix} E_x \\ E_y \end{bmatrix}$ becomes as following, after double-pass amplification. In the setup of Figure 7a, the output polarization is represented by:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = QRGR^{-1}1RGR^{-1}Q\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$
$$= -\frac{i}{2}\begin{bmatrix} (\cos\theta - i\sin\theta)^2\ (e^{2i\phi_r} - e^{2i\phi_\theta}) \\ (e^{2i\phi_r} + e^{2i\phi_\theta}) \end{bmatrix},$$

in Figure 7b, similarly:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = RGR^{-1}Q1QRGR^{-1}\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$
$$= -\frac{i}{2}\begin{bmatrix} 8\sin\theta\cos\theta(e^{i\phi_r} - e^{i\phi_\theta})^2\,(\cos^2\theta e^{i\phi_r} + \sin^2\theta e^{i\phi_\theta}) \\ -(e^{i\phi_r} + e^{i\phi_\theta})^2 + (e^{i\phi_r} - e^{i\phi_\theta})^2\cos 4\theta \end{bmatrix}.$$

in Figure 7c in the same manner:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = FRGR^{-1}1RGR^{-1}F\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$
$$= -\frac{i}{2}\begin{bmatrix} \cos 2\theta\ (e^{2i\phi_r} - e^{2i\phi_\theta}) \\ -(e^{2i\phi_r} + e^{2i\phi_\theta}) + (e^{2i\phi_r} - e^{2i\phi_\theta})\sin 2\theta \end{bmatrix},$$

in Figure 7d, similarly:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = RGR^{-1}F1FRGR^{-1}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = -2e^{i\phi_r + i\phi_\theta}\begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

As shown above, the setup of Figure 7d gives the perfect 90-degree-rotated output, compensating the thermally-induced birefringence.

2.4. Pre-pulse technique for the preservation of wave form

In the system using a series of amplifiers with SBS-PCM for achieving the high energy output, there are some problems prior to its high energy application. The pulse deformation in SBS process is an important one among them, in general, temporal-pulse-shape deformation takes place when the pulse is reflected from the SBS medium, and it is well known that the reflected SBS wave shows a steep rising edge. If SBS cells are employed in series, the rising edge of the pulse shape becomes steeper every time it is reflected. This deformation is able to make optical breakdown in the optical components, and thereupon, able to cause the low reflectivity and low fidelity of the phase conjugated wave in the medium. It is known that the wave form deformation is caused by the coherent coupling between the incoming wave and the propagation of the acoustic

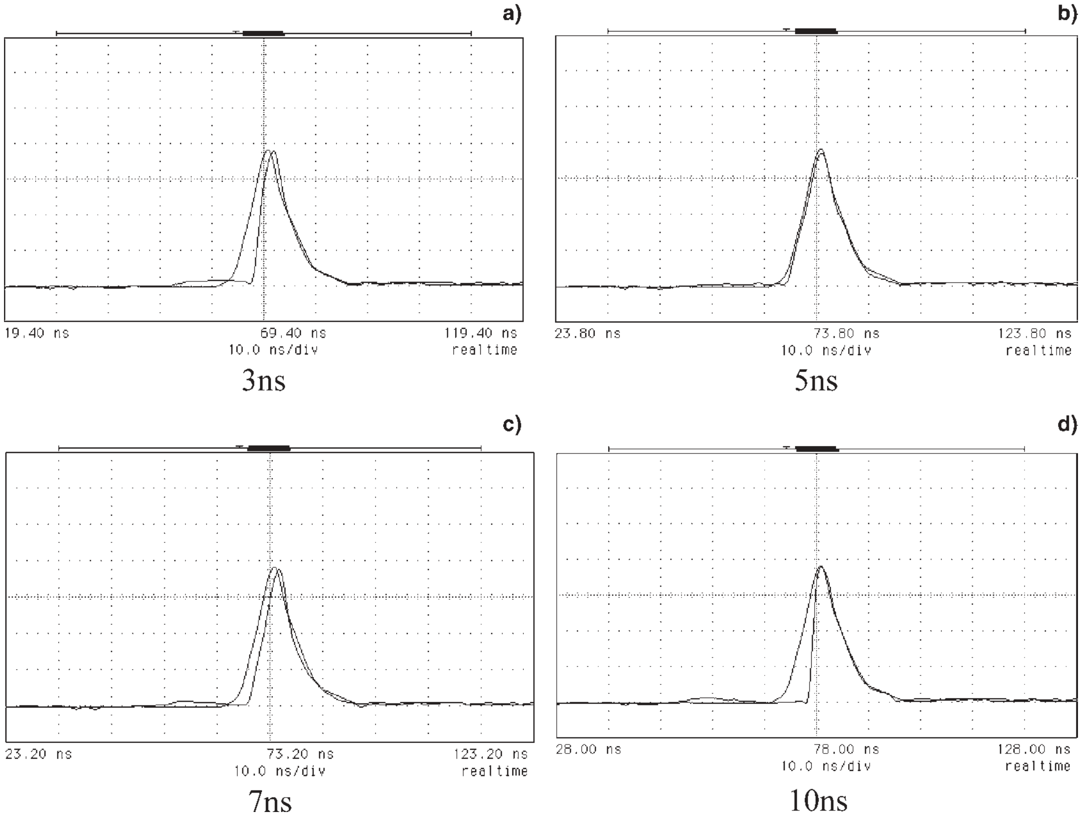

Fig. 10. Wave forms of the incident wave and the reflected wave for delay times of (**a**) 3 ns, (**b**) 5 ns, (**c**) 7 ns, and (**d**) 10 ns, when the energies of main pulse and pre-pulse are 10 mJ and 5 mJ, respectively.

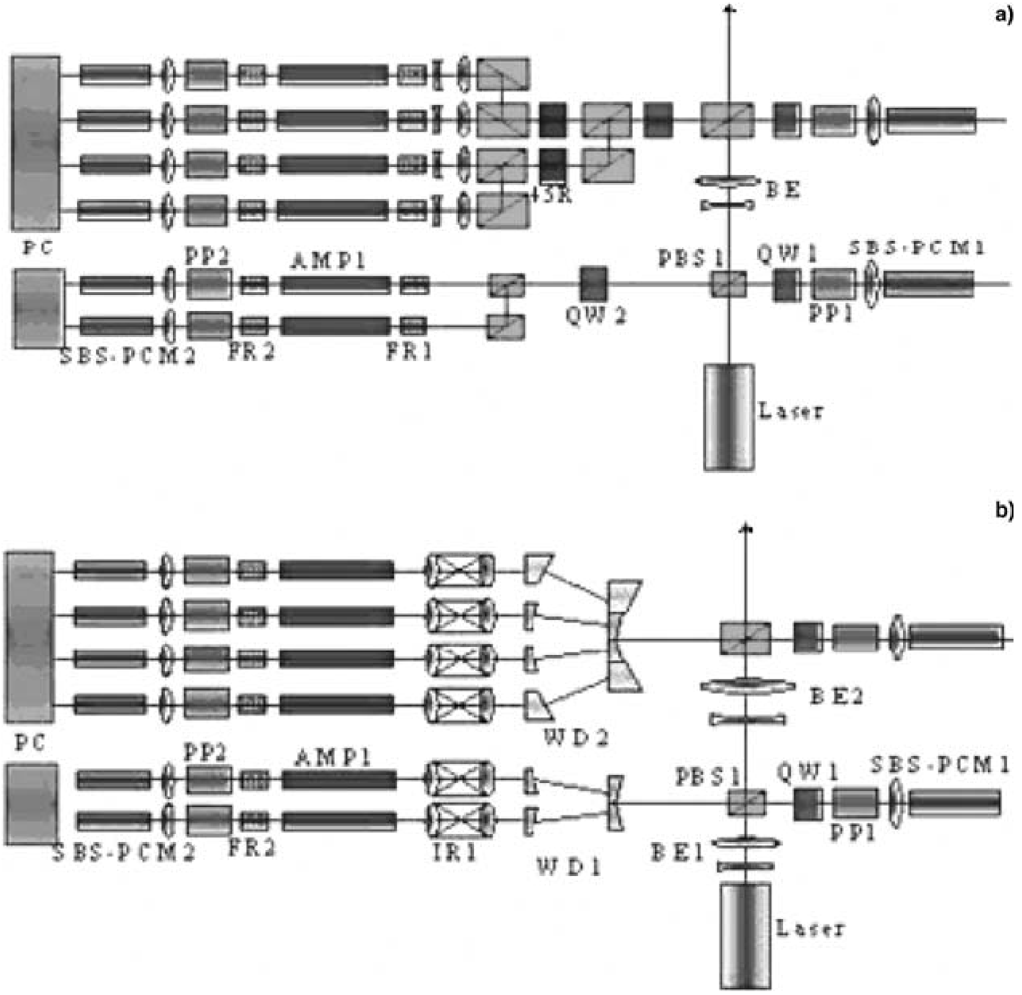

Fig. 11. A beam combination laser (**a**) amplitude dividing scheme and (**b**) wave front-dividing scheme: PC, phase controller; PP1 & PP2, Pre-pulse rs; AMP1 & AMP2, amplifiers; FR1 & FR2, faraday rotators; IR1 & IR2, image relays; WD1 & WD2, wave-front dividers; BE1 & BE2, beam expanders; PBS1, polarizing beam expanders; QW1 & QW2, quarter-wave-plates; 45R, 45-degree rotator.

Brillouin grating (Hon, 1980), it can be minimized by reducing the interaction length, Rayleigh length. Here we introduce the recent information about the deformation, that the deformation is also due to the effect of losing the front part of the pumping energy to create the acoustic Brillouin grating for SBS process, so it can be compensated by the pre-pulse technique (Kong *et al.*, 2005*c*).

Within the frame work of Kong and coworkers, it will be possible to keep the temporal wave form, if the acoustic grating is generated from the pre-pulse before the main pulse enters the interaction region of SBS, the main pulse need not lose its front-part energy by acoustic-grating generation. Through careful experiments, Kong and coworkers have found that the temporal wave form can be kept by the pre-pulse technique, free from the wave form deformation. Figure 9a presents the optical layout of the proposed system for wave form preservation using pre-pulse technique. Figure 9b is the corresponding setup, as a substitute for the proposed system of Figure 9a. From Kong *et al.* (2005*c*), the corresponding experimental setup of **Q1** Figure 9b was used in the first experiment for wave form preservation, and thereafter the proposed system has been used for the wave form preservation. The proposed system has two arms (i.e., pre-pulse arm and main pulse arm) to optimize delay time with Pockels cell (PC), and PC is replaced with half-wave-plate (HWP), and Faraday rotator (FR) in the corresponding experimental setup, these components function as an energy divider by controlling the polarization of the input beam, a small part of the energy is divided by an incomplete-90-degree rotation, and the small part of the energy becomes the pre-pulse. In Figure 10, the comparisons between the wave forms of the incident wave and the reflected waves are presented for delay times of (a) 3 ns, (b) 5 ns, (c) 7 ns, and (d) 10 ns, when the energies of the main pulse and pre-pulse are 10 mJ and 5 mJ, respectively. It is shown clearly that the pre-pulse technique is quite useful to preserve the pulse shape in detail (Beak *et al.*, 2006).

Table 1. *Wavefront dividing and amplitude dividing in the phase locking of SBS-PCM*

	Wavefront dividing	Amplitude dividing
Spatial profile	Depending on the phase difference	Good
Temporal profile	Good	Depending on the phase difference
Requirement on phase difference	$<\lambda/4$	$<\lambda/100$
Image relaying	Necessary	Unnecessary
Polarization rotator with lager aperture	Unnecessary	Necessary

3. PHASE CONTROLLING IN BEAM COMBINATION LASER WITH SBS-PCM

As previously stated, beam combination laser amplifier pursues the high-energy/power system with a high repetition rate by beam dividing and recombining, for eliminating several constraints of the conventional high energy laser such as the high thermal load and the crystal-volume-growth limit. But it gives return-demerits which are caused by the dividing and recombining process. Particularly, it is important to control the phase of each beam reflected by SBS-PCM to achieve the single beam with a fixed phase in recombination, in general, the phase of the reflected beam by SBS-PCM shows inherently random character, since SBS starts from a noise in the medium, for reference, with the relative phase difference larger than $\lambda/4$ between the neighboring beams, the recombined laser beam in wave front dividing has an interfering spatial profile with many undesirable spikes, which can damage the optical components in the next amplifying stages (Kong *et al.*, 1997). For this reason, we will focus on the phase controlling in the beam combination laser using SBS-PCM. First, we start by introducing a very successful method for the phase controlling of SBS-PCM, “Self-phase-locking scheme” (Kong *et al.*, 2005*a*). Prior to it, Figure 11 briefly introduces the two major methods in the beam combination using SBS-PCM, which are the amplitude dividing and the wave front dividing. Next, Table 1 summarizes their strong and weak points.

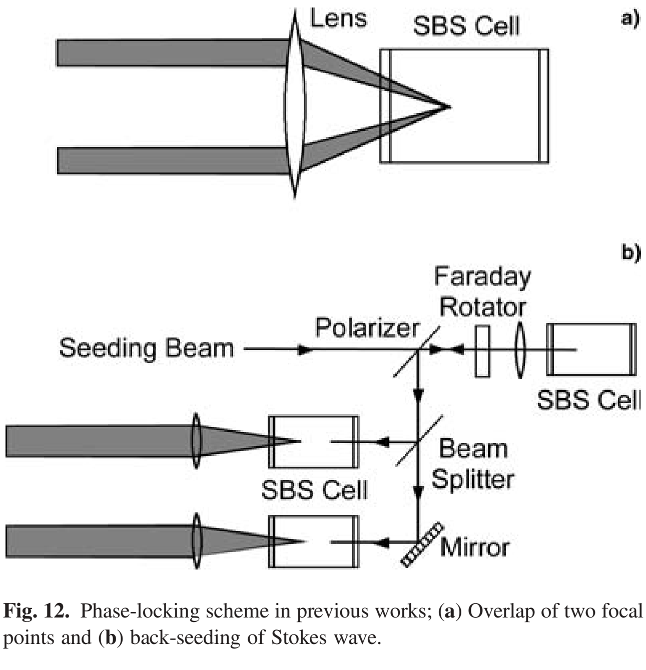

Fig. 12. Phase-locking scheme in previous works; (**a**) Overlap of two focal points and (**b**) back-seeding of Stokes wave.

3.1. Phase locking scheme by a self-generated density modulation

In the history of phase locking with SBS-PCM, we can meet some successful pioneer works (Rockwell & Giuliano, 1986; Loree *et al.*, 1987), but they have shown some problems in practical applications, in the method of overlapping the laser beams at one common focal point, the phases are almost locked, however, the energy scaling is limited and the alignment is difficult, in the method of back-seeding beam, those obstacles can be overcome, but the phase conjugation is incomplete if the injected Stokes beam is not completely correlated, they are simply sketched in Figure 12. Recently, Kong and coworkers have proposed and demonstrated a new phase control technique on SBS-PCM, “Phase locking by self-generated density modulation” or simply “Self-phase-locking” in which each beam is focused at separate focal points without using any backward-Stokes-seed beams, these characteristics guarantee that the energy scaling is not limited, and the phase conjugation is not disturbed by seeding beam.

Figure 13 presents to us the new attempt toward the phase locking of SBS-PCM (Kong *et al.*, 2005*a*). Under wave front dividing configuration, the relative phase difference between the two beams is measured by the analysis of interference patterns, as the measuring standard for the phase locking. From Figures 14, 15, and 16, we can confirm that the self-phase-locking is an effective one for phase locking of SBS-PCM, and that the confocal-type setup (i.e., the setup of Fig. 16) gives the best result in successful phase locking of 96%, in the wave front dividing, we regard the relative phase difference less than $\lambda/4$ as the successful phase locking. With the reference to the successful phase locking in wave front dividing, Kong *et al.* (1997) have shown that, with the relative phase difference larger than $\lambda/4$ between the neighboring beams, the recombined laser beam has an interfering spatial profile with many undesirable spikes, which can damage the optical components in the next amplifying stages.

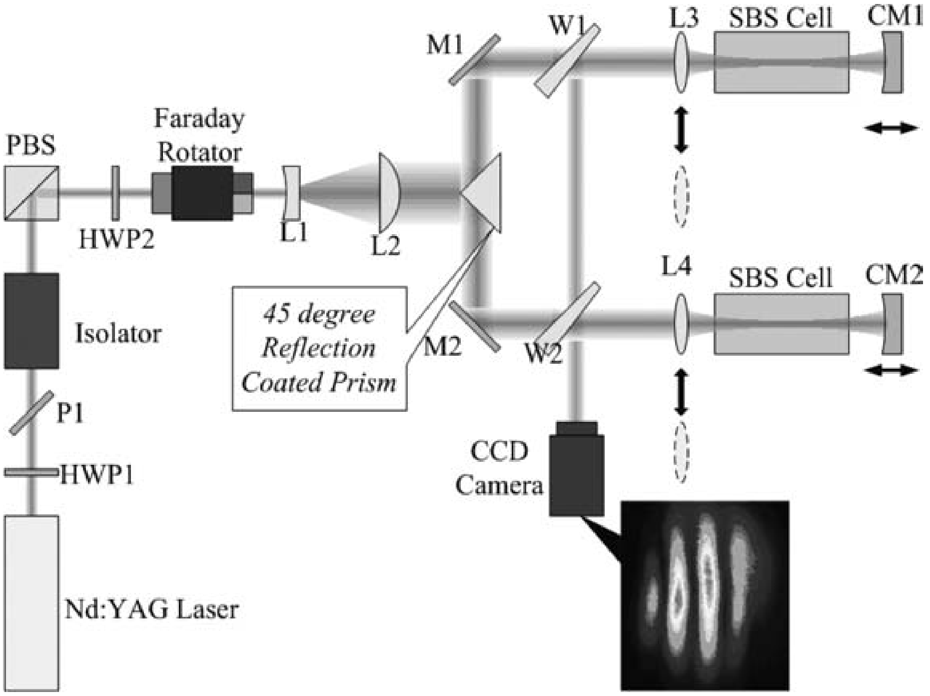

Fig. 13. Experimental setup for the phase locking of two laser beams with wave front dividing: M1 & M2, mirrors; W1 & W2, wedges; L1 & L2, cylindrical lenses; L3 & L4, focusing lenses; CM1 & CM2, concave mirrors; HWP1 & HWP2, half-wave-plates; P1, polarizer; PBS, polarizing beam splitter. Here, the relative phase difference between two beams is measured. And the relative phase difference is expressed as $2\pi L/T$, where T is a spatial period of the interference pattern.

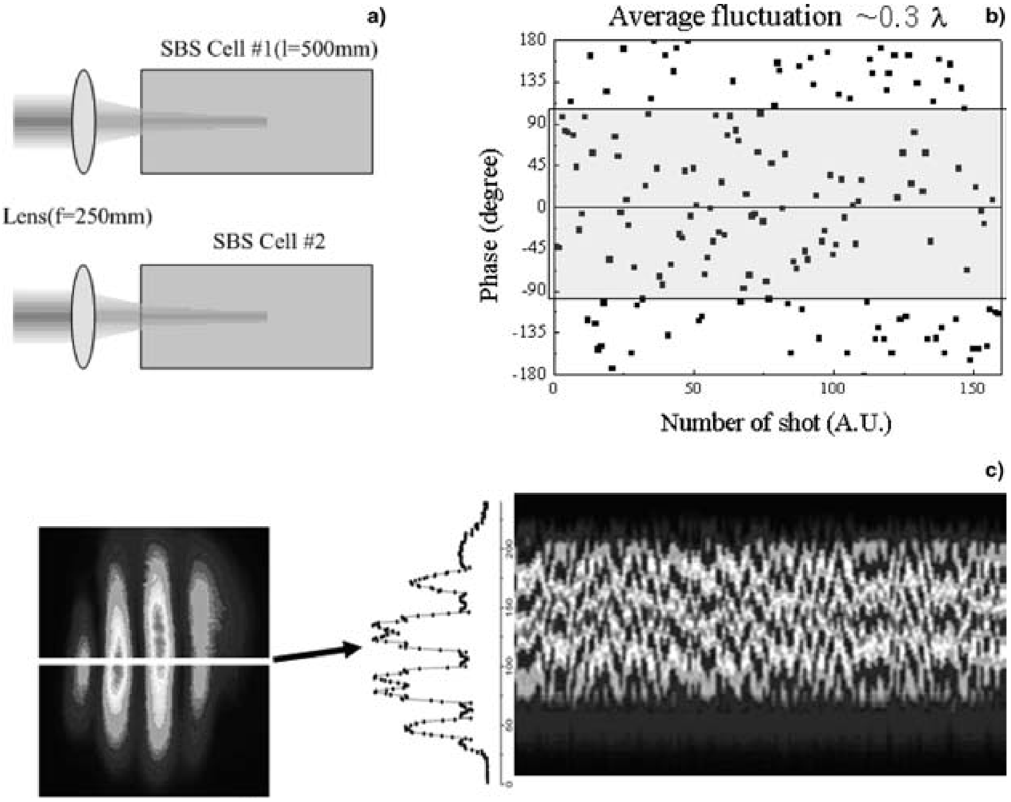

Fig. 14. (**a**) Schematic of the unlocked case. (**b**) Relative phase difference between two beams for 160 laser pulses. (**c**) Intensity profile of horizontal lines selected from 160 interference patterns.

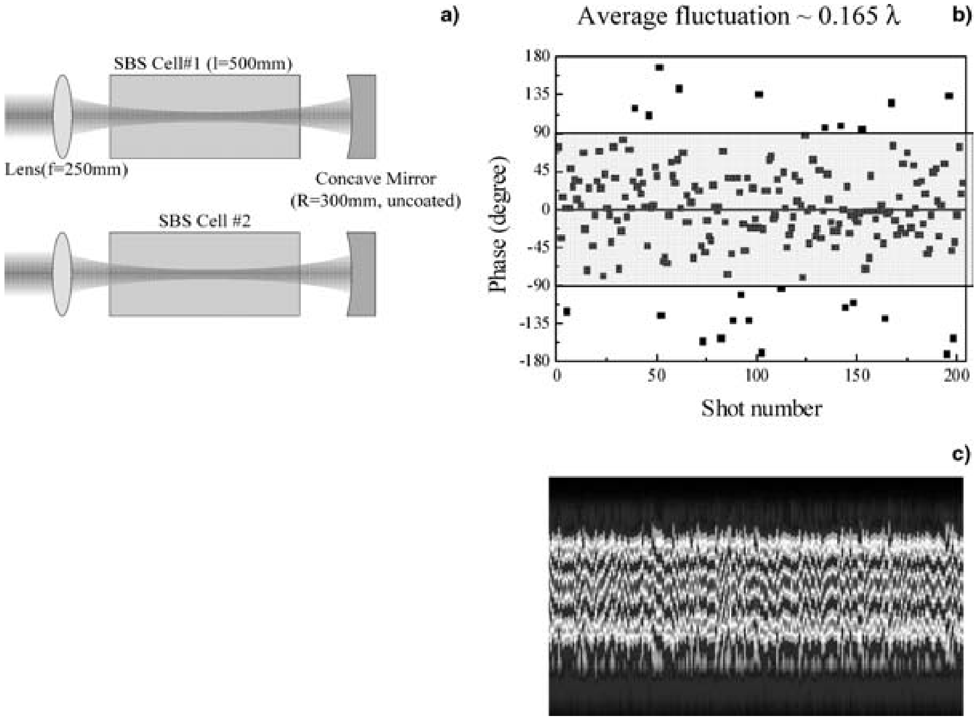

Fig. 15. (**a**) Weak density modulation by a concentric type. (**b**) Relative phase difference between two beams for 203 laser pulses. (**c**) Intensity profile of horizontal lines selected from 203 interference patterns.

3.2. Phase locking experiment in the amplitude dividing

In Section 3.1, we looked around the brief history of phase locking with SBS-PCM: the successful pioneers, their limit on practical applications, and finally self-phase-locking proposed by Kong and coworkers. Recently, Kong and coworker reported a successful method for phase locking in SBS-PCM by “Phase locking by self-generated density modulation” (Kong *et al.*, 2005*a*), and it has proven the possibility and the usefulness of the simple phase locking

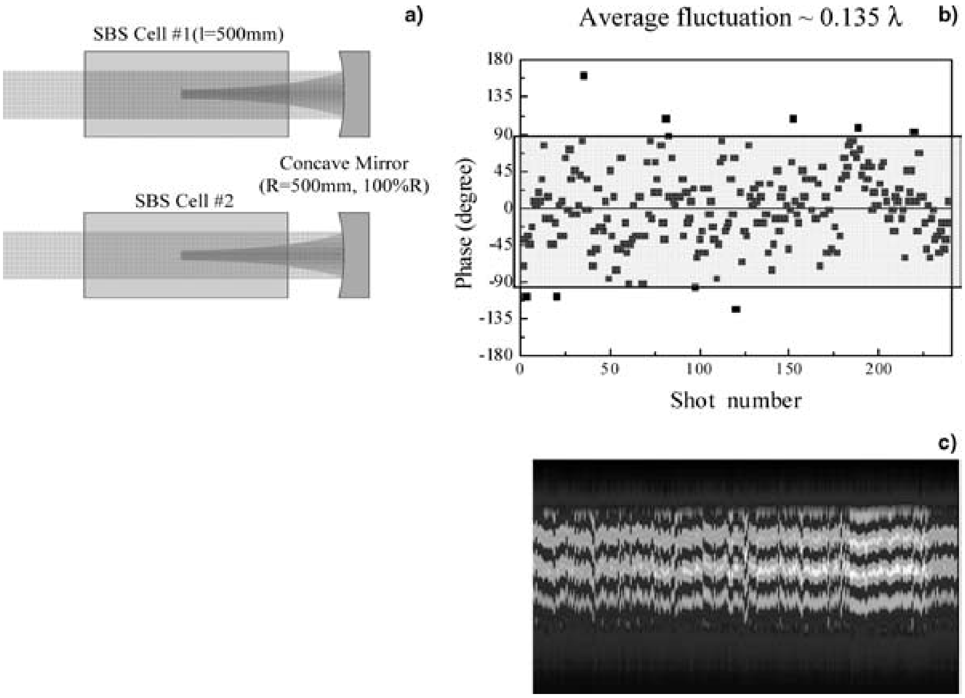

Fig. 16. (**a**) Weak density modulation by a confocal type. (**b**) Relative phase difference between two beams for 238 laser pulses. (**c**) Intensity profile of horizontal lines selected from 238 interference patterns.

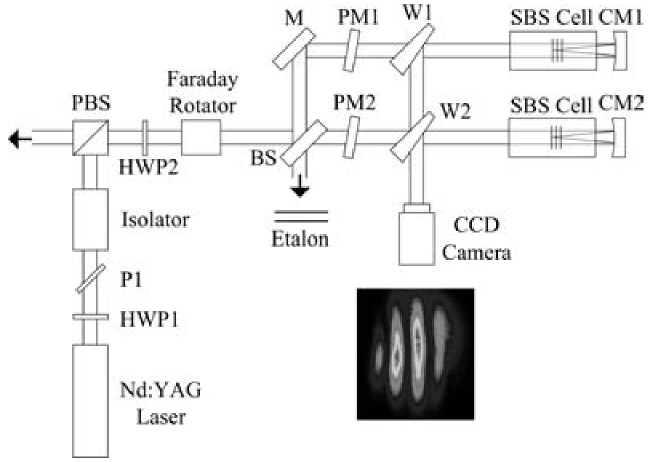

Fig. 17. Experimental setup for measuring the relative phase difference with amplitude-dividing; HWP1 & HWP2, half wave plates; BS, beam splitter; M, mirror; PM1 & PM2, partial reflection mirrors; W1 & W2, wedges; P1, polarizer; PBS, polarization beam splitter; CM1 & CM2, concave mirrors.

with SBS-PCM. Succeeding researches have been successful using the self-phase-locking in amplitude dividing (Kong *et al.*, 2005*b*; Lee *et al.*, 2005). In these researches, the amplitude dividing is used for phase locking with SBS-PCM, to progress the stability of phase locking by eliminating the energy fluctuation from beam pointing in the wave front dividing, the beam pointing from the oscillator is a problem, since the energy fluctuation due to beam pointing can disturb the phase locking in the self-generated density modulation, its qualitative description will be given briefly in Section 3.3, here it is noteworthy that the amplitude dividing is much better (i.e., smart and stable) than the wave front dividing in the view of phase locking with SBS-PCM.

Figure 17 presents the experimental setup for measuring the relative phase difference in the amplitude dividing, which corresponds to Figure 13. Figure 18 shows the relative phase difference with respect to the energies entering into two SBS cells of Figure 17, note that the energy fluctuation is clearly the one important origin of its random phase (i.e., disturbed phase locking of SBS-PCM).

3.3. Theoretical modeling on the stability of phase controlling

Based on the successful experiments on phase-locking of SBS-PCM, Kong *et al.* (2006*a*) suggested the theory about the phase-locking control of SBS-PCM using self-generated density modulation. Figure 19 describes the concept of the phase control by the self density modulation. According to this modeling, the weak periodic density modulation is generated at the focal point due to the electrostriction of standing wave, which arises from the interference between the main

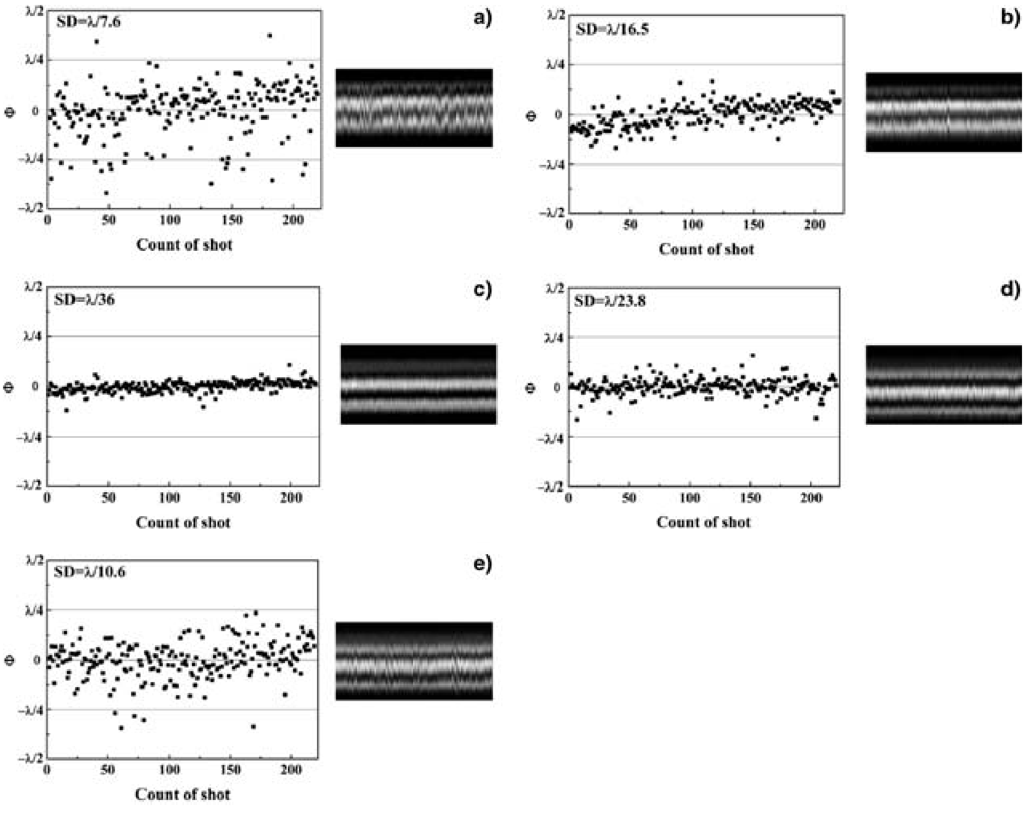

Fig. 18. The relative phase difference (left) and the mosaic intensity profile (right) selected from 220 interference patterns for the cases of (**a**) $E_{p1} = 0.37E_{p2}$, (**b**) $E_{p1} = 0.68E_{p2}$, (**c**) $E_{p1} = E_{p2}$, (**d**) $E_{p1} = 1.11E_{p2}$, and (**e**) $E_{p1} = 1.45E_{p2}$, with $E_{p2} = 10\ mJ$.

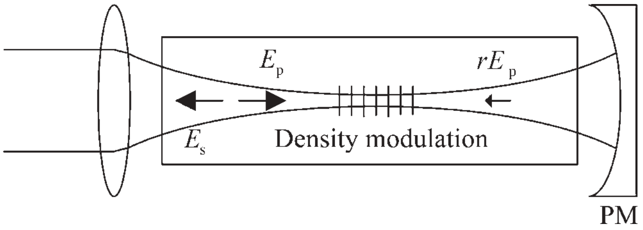

Fig. 19. Concept of phase control of the SBS wave by the self-generated density modulation. L is a focusing lens and PM is a partial reflectance concave mirror whose reflectivity is r. E_P and E_S denote the pump wave and the SBS wave, respectively.

beam, E_P, and its low-intensity counter-propagating beam, rE_P. Then an acoustic wave starts to travel in the direction of the pump beam from the position of standing wave, the theory presumes that the acoustic wave starts to travel when input energy exceeds the threshold of SBS, since the density modulation by the standing wave ignites the acoustic wave from the acoustic noise. From this point of view, we can lock the phase of SBS-PCM through fixing the starting position and starting time of the acoustic wave (Kong *et al.*, 2006*a*). Figure 20 shows that this simple model makes a good agreement qualitatively with the experimental results, and gives an impressive prediction that allowable energy stability increases as the energy of pump beam increases, it means that the self-phase-locking method becomes more effective and powerful in the high-power/energy application of SBS-PCM, the details of this study will be reported soon (Kong *et al.*, 2006*b*).

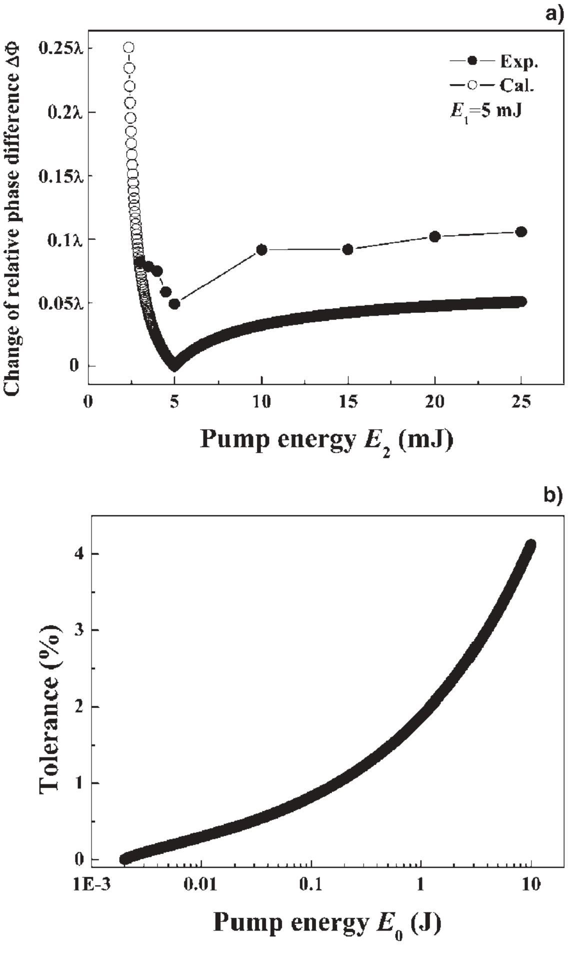

Fig. 20. (**a**) Changing aspects between the relative phase differences for the cases of the experiment and the calculation by the theoretical model as a function of pump energy. (**b**) The tolerance of the pump energy stability $\Delta E_0/E_0$ for obtaining the phase stability of $\Delta\phi_0 = 2\pi/100$ $(=\lambda/100)$.

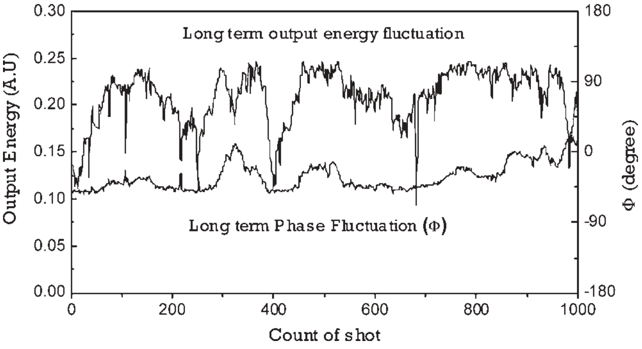

Fig. 21. General long-term-fluctuation of the output energy and the phase difference of the two beam combination system during 1000 s for the case of 10 mJ pump beam.

3.4. Long-term phase stabilization conclusion

Finally, we introduce the long-term fluctuation in beam combination laser using SBS-PCM (Kong *et al.*, 2006*a*; Yoon *et al.*, 2006). Its typical aspect is shown in Figure 21, although the self phase controll is successful, its phase shows a severe long-term fluctuation. Considering the pump-energy fluctuation of 1.9% from the oscillator, it is due to the density fluctuation by thermal convection of the liquid SBS medium, heated by pump laser. Solving it, Kong *et al.* (2006*c*) tried to control long-term phase locking of SBS-PCM with feedback-mirror control

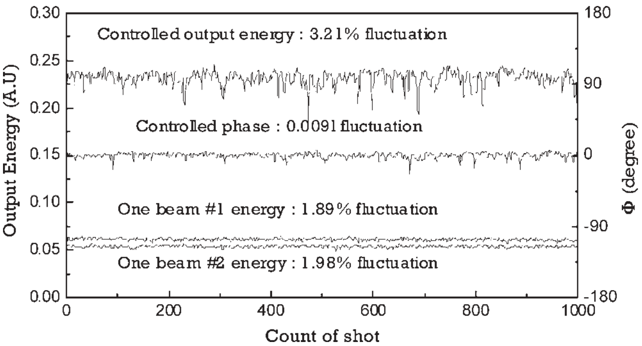

Fig. 22. Experimental results for the phase difference of two SBS beams through active control (10 mJ-two-pump beams).

Q2 by PZT, and as a result, achieve the energy-control level of 3.2% (i.e., corresponding to the phase control of 0.009 λ). It is noteworthy that the control of phase locking has progressed, comparing to the controlling of 0.028 λ in the case of self-phase-locking. Figure 22 presents the improved result by feedback control, the details of this study will be reported soon.

4. CONCLUSION

In this paper, we introduced the high energy/power amplifier system using SBS-PCM which is proposed as the most practical and most promising for laser fusion driver. It is constructed using cross-type amplifier with SBS-PCM as a basic unit. We started from the explanation on the cross-type amplifier with SBS-PCM and its several advantages (i.e., freely-scalable energy, perfect-isolated leak beam, compensating the thermally-induced optical distortion, and misalignment-insensitiveness) with experimental results. In the second part, the recent results on the phase control of SBS-PCM have been informed with the detail experiments. Particularly, a new phase-control technique, "self-density modulation," and its successful following works are introduced simply by each subsection. They are the phase control using amplitude dividing, theoretical modeling about the phase control of SBS-PCM, and long-term fluctuation in the phase control. The new phase control, "self-density modulation," is a powerful technique rather in the amplitude dividing, theoretical modeling gives the good agreement with experimental results, and the long-term fluctuation can be corrected by feedback-mirror control. In conclusion, the proposed beam combination laser system based on the cross-type amplifier using SBS-PCM with the novel methods for controlling the phase of SBS-PCM will contribute the realization of the high energy/power laser which can operate with high repetition rate over 10 Hz even in the case of huge output energy over MJ.

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