Laser and Particle Beams (2005), *23*, 55–59. Printed in the USA.

DOI: 10.1017/S0263034605050111

Beam combined laser fusion driver with high power and high repetition rate using stimulated Brillouin scattering phase conjugation mirrors and self-phase-locking

HONG JIN KONG, SEONG KU LEE, AND DONG WON LEE
Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon, South Korea
(RECEIVED 27 August 2004; ACCEPTED 20 October 2004)

Abstract

For achieving practically useful laser fusion energy generation, it is necessary to have a M-J laser system with a repetition rate over 10 Hz. We believe that a beam combination method using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCM) is one of the most practical techniques for achieving the high repetition rate of the high power laser. In this paper, we present the recent results about the beam combination laser, such as SBS reflectivity depending on the mode structure, the cross type isolator, and the phase-locking technique. For the phase-locking technique, especially, the self-phase-locking is proposed and its result is discussed.

Keywords: Beam combination; Laser fusion driver; Phase locking; Stimulated Brillouin scattering

1. INTRODUCTION

For achieving a high repetition rate in a high power laser, which is required for a laser fusion driver, several methods have been widely investigated by many researchers such as a beam combination technique, a diode pumped laser system with gas cooling, an electron beam pumped gas laser, and a large sized ceramic Nd:YAG (Hogan *et al.*, 1995; Kong *et al.*, 1997, 1999; Loree *et al.*, 1987; Lu *et al.*, 2002; Rockwell & Giuliano, 1986). The beam combination method seems to be one of the most practical techniques for this application (Kong *et al.*, 1997, 1999; Loree *et al.*, 1987; Rockwell & Giuliano, 1986). The laser system using a beam combination technique, in which a laser beam is divided into several beams and recombined after separate amplification does not need a large gain medium. Hence, it can operate at a repetition rate exceeding 10 Hz regardless of the output energy and is easily adaptable to the modern laser technology. This technique is very important for high power laser in inertial fusion research, which are currently constructed or operated already (Danson *et al*., 2005; Neumayer *et al.*, 2005). Kong *et al*. (1997, 1999) proposed a promising beam combination laser system (see Fig. 1), using stimulated Brillouin scattering-phase conjugate mirrors (SBS-PCM) whose output energy can be unlimitedly scaled up by increasing the number of separate amplifiers. In addition, the SBS-PCM produces a phase conjugate wave to compensate many kinds of optical aberrations in the system, induced during amplification (Rockwell, 1988). In the beam combination laser using the SBS-PCMs, however, it is necessary to control the phase of each beam reflected by the SBS-PCM, in order to achieve the single recombined beam with a uniform phase, because the phase of the beam reflected by the SBS-PCM is naturally random (Boyd *et al*., 1990). In this paper, we present the experimental results about the beam combination laser, such as the SBS reflectivity depending on the mode structure, the cross type isolator, and the phase-locking technique. For the phase-locking technique, especially, the self-phase-locking is proposed and its result is discussed.

Address correspondence and reprint requests to: Hong Jin Kong, Korea Advanced Institute of Science and Technology, Department of Physics, Daejeon 305-701, South Korea. E-mail: hjkong@kaist.ac.kr

2. SBS REFLECTIVITY

We have investigated the characteristics of the SBS reflectivity by the multi-mode pump a with large number of longitudinal modes over a wide range of energy, in contrast to the single-mode pump case. The pump laser used was a Q-switched Nd^{+3}:YAG laser (GCR-150-10, Spectra Physics) with a single-longitudinal mode injection seeder. The laser line-width in the single-mode and the multi-mode cases were found to be $\sim$0.003 cm^{-1} (0.09 GHz) and

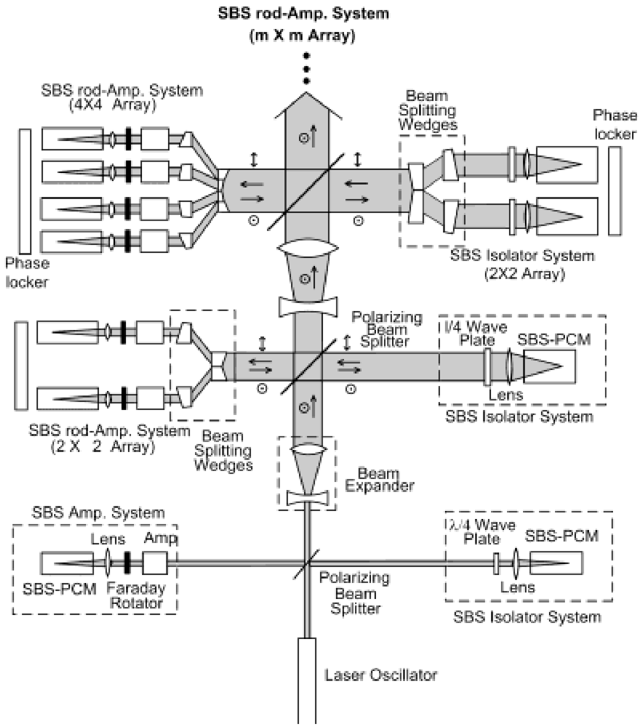

Fig. 1. A beam combination laser using SBS-PCMs and self-phase-locking.

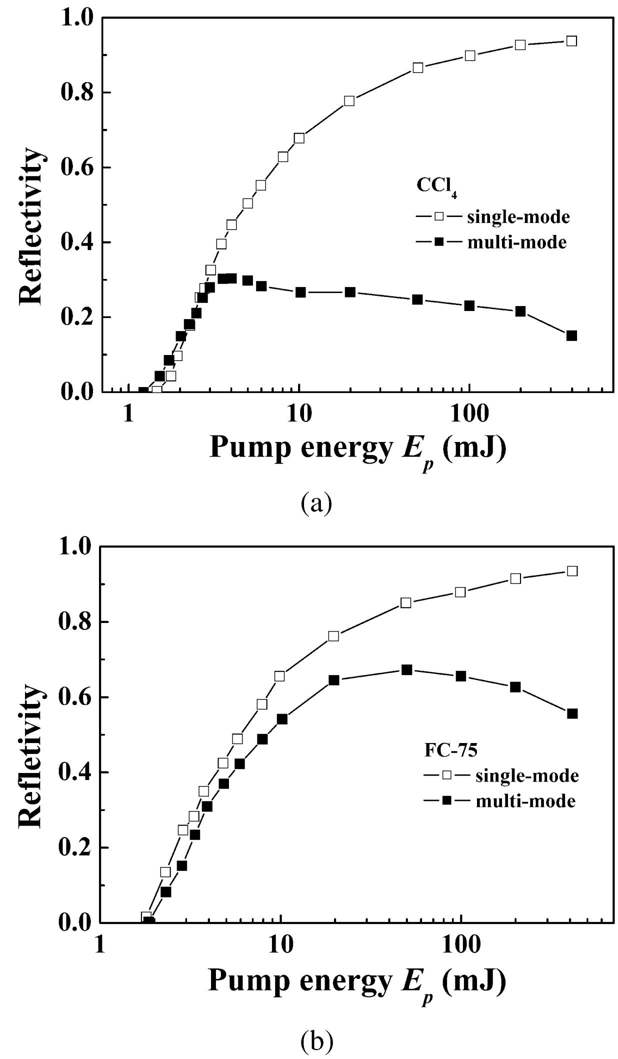

Fig. 2. SBS reflectivity vs. pump energy for (**a**) CCl_4 and (**b**) FC-75 as active medium and for laser radiation in the single-mode and multi-mode cases.

~0.33 cm^{-1} (10 GHz), respectively. Figure 2 shows the SBS reflectivity for both single and multi-mode cases in CCl_4 and Fluorinert FC-75 as a function of the pump energy. It is seen that for both liquids, the peak values exceeding 90% can be obtained with the single-mode pump. For the multi-mode pump, the SBS reflectivity is different for each of the liquids. In CCl_4, the peak reflectivity is 30% at most. FC-75 provides a peak reflectivity over 65% but the reflectivity decreases as the pump energy increases. The SBS reflectivity in CCl_4 is slightly higher for the multi-mode pump than for the single-mode pump near the SBS threshold of the single-mode case, although, in general, the single-mode pump has a higher SBS gain (Arecchi & Schulz-Dubois, 1972). However, for FC-75 the behavior is exactly opposite. Note that both CCl_4 and FC-75 have very similar SBS properties such as the SBS gain and Brillouin linewidth (see Table 1) (Erokhin *et al.*, 1986; Kmetik *et al.*, 1998; Sutherland *et al.*, 1996), which results in similar reflectivity for both liquids for the single-mode pump case. We interpret the SBS reflectivity for the multi-mode pump in terms of the temporal intensity spikes of the multi-mode pulse, which is absent in the single-mode pulse. This is because the intensity spikes, created by beating between a large number of longitudinal modes have enough power to induce the nonlinear effects and the optical breakdown. In our experiments, the multi-mode pulse is composed of 55 longitudinal modes. Thus, from the critical power p_c, as listed in Table 1, the multi-mode pulse can induce self-focusing in CCl_4 due to the high intensity spikes even at powers lower than the SBS threshold. Consequently, self-focusing results in lower SBS threshold and slightly higher reflectivity near the SBS threshold in the CCl_4 are shown in Fig. 2. We note that backward stimulated Raman scattering (SRS) was not observed in this low energy regime up to 10 mJ. On the other hand, the SBS reflectivity in the FC-75 is not affected by the self-focusing near the SBS threshold because the critical power for FC-75 is approximately 18 times larger than for CCl_4. Consequently, the SBS reflectivity for the multi-mode pump is lower than that for the single-mode pump near the SBS threshold. The self-focusing seems to be deleterious for SBS since it can enhance optical breakdown. It can be certified from the experimental results that the optical breakdown in CCl_4 starts at $E_p \sim 1.7$ mJ, while it began at ~6 mJ in FC-75, as listed in Table 1. We have observed that the breakdown appears around the focal spot near the breakdown threshold and it becomes severe

https://doi.org/10.1017/S0263034605050111 Published online by Cambridge University Press

Table 1. *Properties of the liquids, used for experiments at a wavelength of 1 μm.* Γ, *Brillouin line-width;* g_B, *steady state SBS gain;* n_2, *nonlinear refractive index;* P_c, *critical power for self-focusing (calculated);* E_b, *breakdown threshold energy (measured)*

Liquid	Γ (MHz)	g_B (cm/GW)	n_2 (10^{-22} m^2/V^2)	P_c (MW)	E_b (mJ)
FC-75	350	4.5–5	0.34	7.0	6
CCl_4	528	3.8	5.9	0.4	1.7

and results in a filament consisting of bright sparks, as the pump energy increases. This breakdown disturbs the creation of the acoustic phonon. Therefore, for the multi-mode pump, FC-75, which has relatively small n_2 provides higher SBS reflectivity than CCl_4 at high pump energies. On the other hand, for the single-mode pump, reflectivity of both the liquids was almost the same because no optical breakdown occurred up to a pump energy of 400 mJ.

3. CROSS TYPE ISOLATOR

In the proposed beam combination laser, each amplification stage is in the shape of a cross, which is composed of two parts, amplifier and isolator as shown in Fig. 1. The cross type amplifier has advantages: The beam pointing of the output is the same as that of an oscillator and a SBS-PCM located on the right side works as an isolator (Kong *et al*., 1998, 2001). In Fig. 3(a), an amplifier is omitted and a SBS-PCM is replaced with a mirror (M1) for the experiment. We have 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 ASE generated from the post stage provided that the optical path length L between the SBS-PCM and the post stage is long enough compared to the pulse length, which is the pulse width times the speed of light. The optical isolator is located in the right arm, which is composed of an SBS-PCM and a quarter wave plate (QWP1). If the output beam of the oscillator is strong enough, the SBS-PCM reflects the laser beam to the post stage. On the other hand, when the energy of the leak beam generated from the post stage is lower than the SBS threshold, the leak beam cannot be reflected by the SBS-PCM and it cannot enter the oscillator.

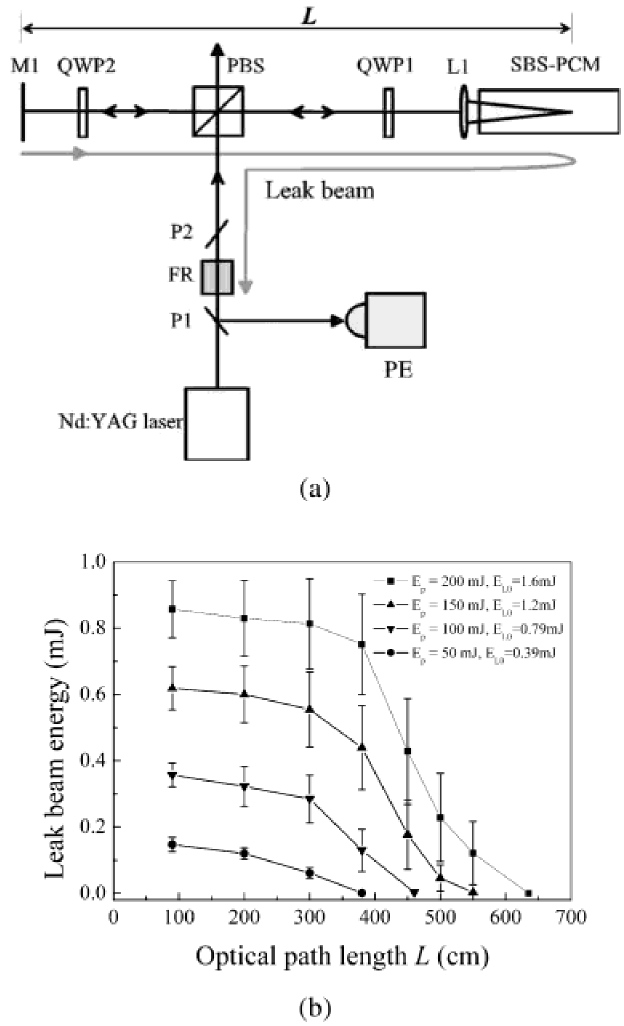

Fig. 3. (**a**) Schematic of the experimental set up: P1 & P2, polarizer; FR, Faraday rotator; PE, pyroelectric energy meter; QWP1 & QWP2, quarter wave plate; L1, lens; PBS, polarizing beam splitter; M1, ordinary mirror. (**b**) Leak beam energy dependence on the optical path length L. (b) also shows the experimental results, which demonstrates that the optical isolator can completely cut off the leak beam from the post stage. The energy E_L of the leak beam reduces to zero as L is increased. The energy E_{L0} of the leak beam injected from the post stage was 0.39, 0.79, 1.2, and 1.6 mJ when the energy of the pump beam was 50, 100, 150, and 200 mJ, respectively. In Fig. 3(b), the SBS reflectivity of the leak beams is more than 40 % when L=90cm even if the energy of the injected leak beams is lower than the SBS threshold ~2 mJ. This is because the acoustic wave due to the pump pulse still survives until the leak beam reaches the SBS-PCM and enhances the SBS of the leak beam.

4. SELF-PHASE-LOCKING

Kong *et al*. (1997, 1999) showed that for the relative phase difference larger than λ/4 between the neighboring beams, the recombined laser beam had an interfering spatial profile with many undesirable spikes, which can damage the optical components in the next stages. There have been several works done to control or lock the phases of the laser beams for the beam combination with the SBS-PCM (Loree *et al*., 1987; Rockwell & Giuliano, 1986). In this paper, we have proposed and demonstrated a new phase-locking technique, wherein each beam is focused at the separate focal points without using any backward Stokes seed beams and hence, the energy scaling is not limited and the phase conjugation is not disturbed.

The phase of the backward SBS wave is naturally random because SBS is generated from the acoustic noise (Boyd *et al*., 1990). Because the SBS is the stimulated process

https://doi.org/10.1017/S0263034605050111 Published online by Cambridge University Press

among the three waves, which are the acoustic wave, the SBS wave, and the pump wave, the phase of the SBS wave will be fixed if the phase of the acoustic wave is fixed. For fixing the acoustic noise, we have induced a weak periodic density modulation in the focal region inside the SBS-PCM by means of an electro-magnetic standing wave, which arises from the interference between the pump and its counter-propagating beam. In proposed technique (Fig. 5a), the pump pulse focused into the SBS-PCM is reflected partially by the uncoated concave mirror (~4% reflection), so that a standing wave is built up, especially at the focal area by the interference between the leading edge and the remaining part of the pump pulse. We used Fluorinert FC-75 as a SBS medium (Kmetik *et al*., 1998). The diagnostics for the phase locking is straightforward. Interference pattern of both Stokes beams were acquired by the CCD camera, which yields the relative phase difference $\delta = \Phi_1 - \Phi_2$ between the Stokes beams. Therefore, we can quantitatively analyze the degree of the phase locking by measuring the movement of the peaks. Figure 4 shows the experimental schematic and results for the unlocked case. As naturally expected, δ has random values and the standard deviation is $\sim 0.295\lambda$. This indicates that the phases of two backward beams are independent and are not fixed. Figure 4c shows the intensity profile of the 160 horizontal lines selected from each interference pattern. The profile also represents the random fluctuation. Figure 5 shows the experimental schematic for locking the phase of the SBS wave by generating the weak density modulation. The pump beam was reflected by the uncoated concave mirror with R = 300 mm and then injected into SBS-PCM. The relative phase difference δ is shown in Fig. 5b. The energy of each incident beam was 13 mJ and 203 laser pulses were examined. The standard deviation is $\sim 0.165\lambda$. Moreover, 88% of the data points is contained within the range of $\pm$ 0.25λ ($\pm$ 90°). This result gives a demonstration that the self-generated density modulation can make the phase of the backward SBS wave fixed. We note that this method can be applied to the beam combination laser composed of a large number of laser beams, although the experiment has been carried out for just two laser beams. This can be justified if we consider the two laser beams in the experiment as a set of arbitrary two laser beams among the large number of a laser system statistically, because our method corresponds to absolutely uncoupled beams.

To reduce the fluctuation, we repeated the measurements for the another scheme as shown in Fig 6a, where the pump beams was backward focused by a concave mirror with R = 50 cm and >99% reflectivity at the laser wavelength. In this case, the delay time to induce the density modulation is almost zero. However, the contrast of the standing wave which is expressed as $(I_{max} - I_{min})/(I_{max} + I_{min})$

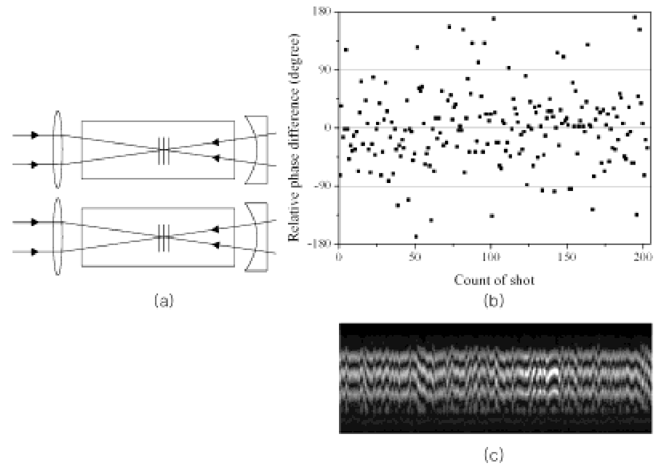

Fig. 5. (**a**) Weak density modulation by a concentric type. (**b**) Relative phase difference between two beams for 203 laser pulses. (**c**) Intensity profile of horizontal lines selected from 203 interference patterns.

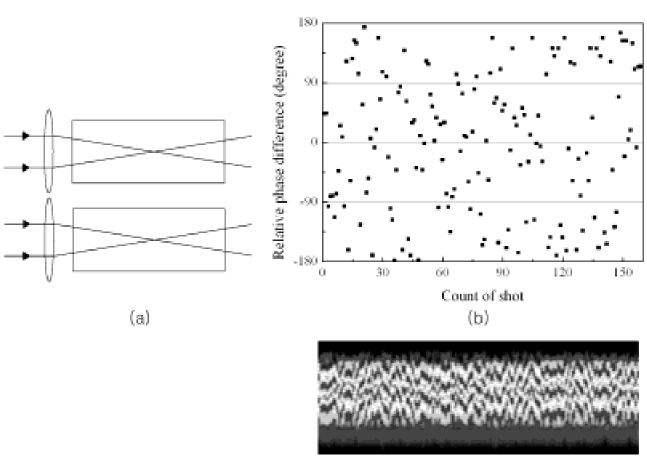

Fig. 4. (**a**) Schematic of the unlocked case. (**b**) Relative phase difference between two beams for 160 laser pulses. (**c**) Intensity profile of horizontal lines selected from 160 interference patterns.

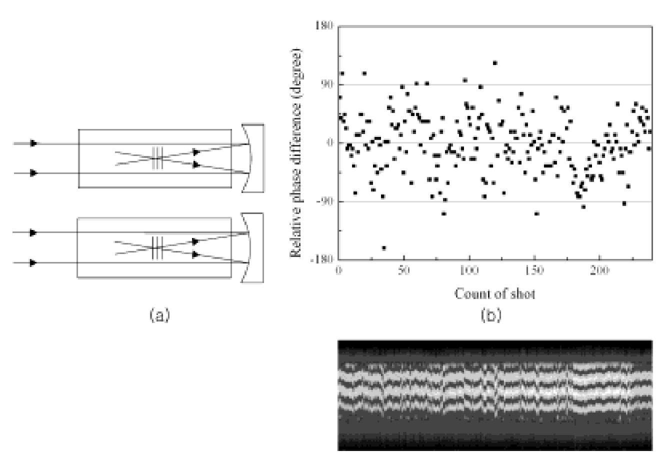

Fig. 6. (**a**) Weak density modulation by a confocal type. (**b**) Relative phase difference between two beams for 238 laser pulses. (**c**) Intensity profile of horizontal lines selected from 238 interference patterns.

https://doi.org/10.1017/S0263034605050111 Published online by Cambridge University Press

is so small that the density modulation is not quite distinct as compared to the previous scheme, because the focused leading edge of the pump pulse encounters a part of the unfocused pump pulse. The experimental result is shown in Fig. 6b when the incident energy was 8 mJ and 238 laser pulses were examined. The standard deviation is $\sim 0.135\lambda$. Furthermore, 96% of the data points are contained in the range of $\pm$ 0.25λ. Therefore, it has been shown that the degree of the phase controlling can be very much improved. The intensity profile of the horizontal lines in Fig. 6(c) also manifests the improved result.

5. CONCLUSION

We have investigated a beam combination technique with the SBS-PCMs for obtaining a very high output power/energy laser system with high repetition rate over 10 Hz, which is very important for high power laser in inertial fusion research. Through the measurement of the SBS reflectivity, it is seen that the single-mode pump provides a stable and high reflectivity whereas the SBS reflectivity by the multi-mode pump increases rapidly and then decreases slowly as the pump energy increases. This is because a multi-mode pulse has high intensity spikes created by mode beating, which have enough power to induce optical breakdown and nonlinear effects such as self-focusing. In addition, we have demonstrated that an optical isolator in a cross type amplifier can perfectly cut off the leak beam from the post stage if the optical path length between the SBS-PCM and the post stage is long enough compared to the pump pulse length. Finally, we have demonstrated that the phase control of the SBS-PCMs can be achieved by inducing a periodic self-generated density modulation at the focal area by the electromagnetic standing wave. We expect that this beam combination technique provides a promising one to develop the fusion driver with high output power and a repetition rate more than 10 Hz.

ACKNOWLEDGMENT

This work was supported by the KISTEP, the RRC at Dankook University and the IAEA, Austria, contract No. 11636/R1.

REFERENCES

Arecchi, F.T. & Schulz-Dubois, E.O. (1972). In *Laser Handbook*, Vol. 2, p. 1119. Amsterdam: Elsevier North-Holland.

Boyd, R.W., Rążewksi, K. & Narum, P. (1990). Noise initiation of stimulated Brillouin scattering. *Phys. Rev. A* **42**, 5514–5521.

Danson, D.N. *et al*. (2005). Vulcan Petawatt: Design, operation, and interactions at 5×10^{20} Wcm^{-2}. *Laser Part. Beams* **23**, 87–94.

Erokhin, A.I., Kovalev, V.I. & Faizullov, F.S. (1986). Determination of the parameters of a nonlinear response of liquids in an acoustic resonance region by the method of nondegenerate four-wave interaction. *Sov. J. Quan. Electron.* **16**, 872–877.

Hogan, W.J. *et al*. (1995). *Energy from Inertial Fusion*, Chap. 3. Vienna: International Atomic Energy Agency.

Kmetik, V., Fiedorowicz, H., Andreev, A.A., Witte, K.J., Daido, H., Fujita, H., Nakatsuka, M. & Yamanaka, T. (1998). Reliable stimulated Brillouin scattering compression of Nd:YAG laser pulses with liquid fluorocarbon for long-time operation at 10 Hz. *Appl. Opt.* **37**, 7085–7090.

Kong, H.J., Lee, J.Y., Shin, Y.S., Byun, J.O., Park, H.S. & Kim, H. (1997). Beam recombination characteristics in array laser amplification using stimulated Brillouin scattering phase conjugation. *Opt. Rev.* **4**, 277–283.

Kong, H.J., Kang, Y.G., Ohkubo, A., Yoshida, H. & Nakatsuka, M. (1998). Complete isolation of the back reflection by using stimulated Brillouin scattering phase conjugation mirror. *Rev. Laser Engin.* **26**, 138–140.

Kong, H.J., Shin, Y.S. & Kim, H. (1999). Beam combination characteristics in an array laser using stimulated Brillouin scattering phase conjugation mirrors considering partial coherency between the beams. *Fus. Engin. Des.* **44**, 407–417.

Kong, H.J., Lee, S.K. & Kim, J.J. (2001). A cross type double pass laser amplifier with two symmetric phase conjugation mirrors using stimulated Brillouin scattering. *Chinese J. Lasers* **B10**, I5–I9.

Loree, T.R.D., Watkins, E., Johnson, T.M., Kurnit, N.A. & Fisher, R.A. (1987). Phase locking two beams by means of seeded Brillouin scattering. *Opt. Lett.* **12**, 178–180.

Lu, J., Murai, T., Takaichi, K., Uematsu, T., Xu, J., Ueda, K., Yagi, H., Yanagitani, T. & Kaminskii, A.A. (2002). W diode-pumped continuous-wave 1319-nm Nd:YAG ceramic laser. *Opt. Lett.* **27**, 1120–1122.

Neumayer, P. *et al*. (2005). Status of the PHELIX laser and first experiments. *Laser Part. Beams* **23**, In print.

Rockwell, D.A. & Giuliano, C.R. (1986). Coherent coupling of laser gain media using phase conjugation. *Opt. Lett.* **11**, 147–149.

Rockwell, D.A. (1988). A review of phase-conjugate solid state lasers. *IEEE J. Quan. Electron.* **QE-24**, 1124–1140.

Sutherland, R.L. (1996). *Handbook of Nonlinear Optics*, p. 457. New York: Marcel Dekker, Inc.

https://doi.org/10.1017/S0263034605050111 Published online by Cambridge University Press