Phase control of a stimulated Brillouin scattering phase conjugate mirror by a self-generated density modulation

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We report that the phase of a backward wave by stimulated Brillouin scattering (SBS) can be controlled by a self-generated density modulation without any backward Stokes seed beam, which is generated due to electrostriction induced by electromagnetic standing wave through the interferences between the main beam and the low intensity counter-propagating beam. The density modulation ignites the position of the Brillouin grating so that the phase of the backward SBS can be controlled. We obtained 96% success with the phase error less than a quarter wave under a proper scheme of the self-seeding methods. This phase control technique is so simple, scalable, and very efficient that it can be applied to many beam combination systems for a high power laser system with a high repetition rate over 10 Hz. © *2005 American Institute of Physics*.
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For achieving a high repetition rate in a high power laser, 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.[1–9] In particular, the beam combination method seems to be one of the most practical techniques for this application.[2–8] 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. Kong *et al.* proposed a promising beam combination laser system using stimulated Brillouin scattering-phase conjugate mirrors (SBS-PCMs) whose output energy can be unlimitedly scaled up by increasing the number of separate amplifiers.[2,3] In addition, the SBS-PCM produces a phase conjugate wave to compensate for many kinds of optical aberrations in the system, induced during amplification.[10] 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.[6,7] Kong *et al.* showed that for the relative phase difference larger than $\lambda/4$ 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.[2]

There have been several works to control or lock the phases of the laser beams for the beam combination with the SBS-PCM and some of them are very successful.[4–8] By overlapping the laser beams at one focal point, the phases are almost locked. However, since all the beams must be focused at one point, the energy scaling is limited and the alignment is also difficult. The backseeding of the Stokes beam overcomes the above-mentioned drawbacks, but the phase conjugation is incomplete if the injected Stokes beam is not completely correlated.[11] This letter proposes and demonstrates a phase control 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.[12] Because the SBS is the stimulated process among three waves—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 electromagnetic standing wave, which arises from the interference between the pump and its counter-propagating beam. The experimental setup is shown schematically in Fig. 1(a). A

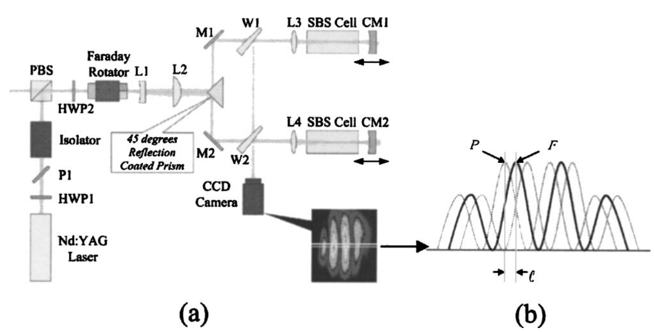

FIG. 1. (a) Experimental setup for the phase locking of two laser beams: M1 and M2, mirrors; W1 and W2, wedges; L1 and L2, cylindrical lenses: L3 and L4, focusing lenses, CM1 and CM2, concave mirrors; HWP1 and HWP2, half wave-plates; P1, polarizer; PBS, polarizing beam splitter. (b) Measurement of the relative phase difference δ between two beams. The fluctuation of the relative phase difference is expressed as $2\pi\ell/T$, where T is a spatial period of the interference pattern.

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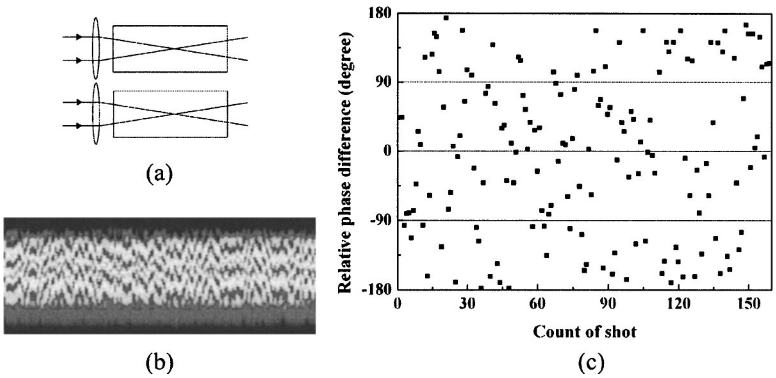

FIG. 2. (a) Schematic of the unlocked case. (b) Intensity profile of horizontal lines selected from 160 interference patterns. (c) Relative phase difference between two beams for 160 laser pulses.

1064 nm Nd:YAG oscillator with a bandwidth of ~120 MHz was used for the pump. The pulse width was 7–8 ns and the repetition rate was 10 Hz. The output from an oscillator passes through a 2× cylindrical telescope and is divided into two beams by a prism, which has high reflection coating for 45° incident angle. Both beams then pass through separate wedges and are focused into each SBS-PCM. The wedge reflects a part of the backward Stokes beam, which is overlapped with that of the other Stokes beam onto a CCD camera to get an interference pattern of them. For controlling the phase by the self-generated the density modulation, 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. The leading edge reflected by the uncoated concave mirrors is so weak that the density modulation induced by the standing wave due to electrostriction is also weak and does not disturb the acoustic wave generated by coupling the pump and the Stokes beam. We used Fluorinert FC-75 as a SBS medium.[13] The length of a SBS cell was 50 cm.

The diagnostics for the phase control of the Stokes beams is straightforward. The interference pattern acquired by the CCD camera yields the relative phase difference $\delta = \Phi_1 - \Phi_2$ between the laser beams incident on the CCD, where Φ_1 and Φ_2 denote the phases of two laser beams, respectively. Therefore, we can quantitatively analyze the degree of the phase controlling by measuring the movement of the peaks. In every interference pattern, one horizontal line is selected as shown in Fig. 1(b). A peak position P is then determined from the selected line. Since the relative phase difference δ between two beams fluctuates, the peak position P also moves to the left or right with respect to some fixed point F. When ℓ is the distance between F and P, the relative phase difference δ can be expressed as $2\pi\ell/T$, where T is a spatial period of the interference pattern.

Figure 2 shows the experimental schematic and results for the unlocked case when the focal length of the focused lenses was 25 cm and energy of each incident beam was ~9 mJ. Each point in Fig. 2(c) represents one of 160 laser pulses. As naturally expected, δ has random values and the standard deviation is ~0.295λ. This indicates that the phases of two backward beams are independent and are not fixed. Figure 2(b) shows the intensity profile of the 160 horizontal lines selected from each interference pattern. The profile also represents the random fluctuation. Figure 3(a) shows the first experimental schematic for controlling 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. 3(c). The energy of each incident beam was 13 mJ and 203 laser pulses were examined. The standard deviation is ~0.165λ. Moreover, 88% of the data points is contained within the range of ±0.25λ(±90°). This result gives a demonstration that the self-generated density modulation can make the phase of the backward SBS wave fixed. In addition, we observed that the phase of the SBS wave was varied by the precise movement of the concave mirror where a PZT was attached. As the mirror position was changed by PZT, the interference pattern moved slowly into one direction although the fluctuations existed. This implies that we can control the phase of the SBS waves freely and get rid of the intensity spikes of the beam combination laser by making the relative phase be zero. 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

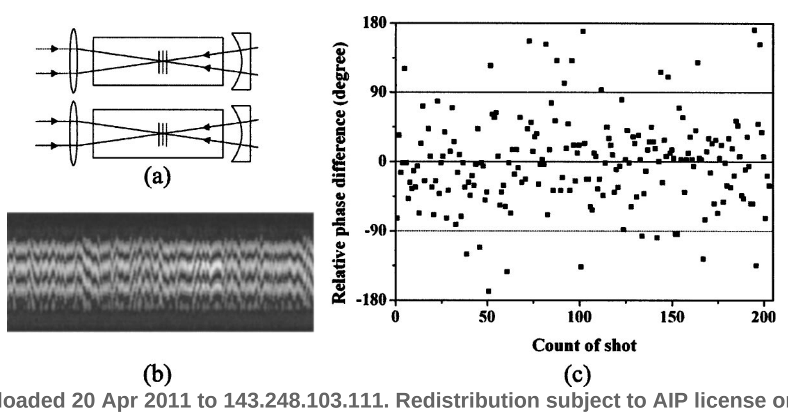

FIG. 3. (a) Weak density modulation by a concentric type. (b) Intensity profile of horizontal lines selected from 203 interference patterns. (c) Relative phase difference between two beams for 203 laser pulses.

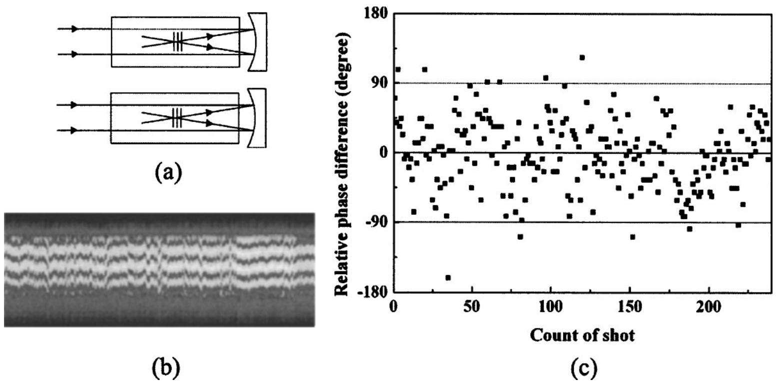

FIG. 4. (a) Weak density modulation by backward focusing. (b) Intensity profile of horizontal lines selected from 238 interference patterns. (c) Relative phase difference between two beams for 238 laser pulses.

beams among the large number of laser systems statistically, because our method corresponds to absolutely uncoupled beams. The optical path length between the focal point and the uncoated concave mirror is longer than 30 cm in this setup, considering the radius of curvature of the uncoated concave mirror (R=30 cm) and the refractive index of FC-75 (n=1.268). Thus, considering a round-trip, the SBS may be generated from the acoustic noise before the density modulation is induced because the density modulation is generated only after more than 2 ns after the pump laser pulse reaches the focal point. This may increase the fluctuation of the relative phase difference.

To reduce the fluctuation, we repeated the measurements for another scheme as shown in Fig. 4(a), where the pump beams were 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 $(I_{max}-I_{min})/(I_{max}+I_{min})$, 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 part of the unfocused pump pulse. The experimental result is shown in Fig. 4(c) when the incident energy was 8 mJ and 238 laser pulses were examined. The standard deviation is ~0.135λ. Furthermore, 96% of the data points are contained in the range of ±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. 4(b) also manifests the improved result.

In conclusion, we have investigated a method of the phase control of the SBS-PCM to develop the beam combination laser with a repetition rate higher than 10 Hz. It has been demonstrated that phase control can be achieved by inducing a periodic self-generated density modulation at the focal area by the electromagnetic standing wave. Moreover, it has been shown that the fluctuations of the relative phase difference are less than λ/4 for more than 96% of the laser pulses. We consider that the main reason that 100% success of the phase locking has not been achieved is due to the pumping energy fluctuation, because the ignition timing is dependent on the pumping energy according to a study which will be published shortly. We expect that 100% phase control is possible if we stabilize the output energy of the pump laser and optimize the reflectivity/curvature of the concave mirror. This phase controlling method can be applied to lock the phase of the SBS-PCM in the beam combination amplifying system to obtain a very high output power/energy laser system with high repetition rate over 10 Hz for example such a laser fusion driver.[2]

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[1]W. J. Hogan, *et al.*, *Energy from Inertial Fusion* (IAEA, Vienna, 1995), Chap. 3.
[2]H. J. Kong, J. Y. Lee, Y. S. Shin, J. O. Byun, H. S. Park, and H. Kim, Opt. Rev. **4**, 277 (1997).
[3]H. J. Kong, S. K. Lee, and D. W. Lee, Laser Part. Beams (to be published).
[4]D. A. Rockwell and C. R. Giuliano, Opt. Lett. **11**, 147 (1986).
[5]H. Becht, J. Opt. Soc. Am. B **15**, 1678 (1998).
[6]T. R. Loree, D. E. Watkins, T. M. Johnson, N. A. Kurnit, and R. A. Fisher, Opt. Lett. **12**, 178 (1987).
[7]R. H. Moyer, M. Valley, and M. C. Cimolino, J. Opt. Soc. Am. B **5**, 2473 (1988).
[8]M. W. Bowers and R. W. Boyd, IEEE J. Quantum Electron. **QE-34**, 634 (1998).
[9]J. Lu, J. Lu, T. Murai, K. Takaichi, T. Uematsu, J. Xu, K. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, Opt. Lett. **27**, 1120 (2002).
[10]D. A. Rockwell, IEEE J. Quantum Electron. **QE-24**, 1124 (1988).
[11]G. G. Kochemasov and V. D. Nikolaev, Sov. J. Quantum Electron. **9**, 1155 (1979).
[12]R. W. Boyd, K. Rzążewski, and P. Narum, Phys. Rev. A **42**, 5514 (1990).
[13]H. Yoshida, V. Kmetik, H. Fujita, M. Nakatsuka, T. Yamanaka, and K. Yoshida, Appl. Opt. **36**, 3739 (1997).