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Great improvement of phase controlling of the entirely independent stimulated Brillouin scattering phase conjugate mirrors by balancing the pump energies

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For developing a beam combination laser with the stimulated Brillouin scattering-phase conjugate mirrors (SBS-PCMs), the phase control of the backward SBS waves is essentially required. We proposed a new effective and practical technique in previous works, in which entirely independent SBS-PCMs are used, so that there is no limit of the number of the beams for the beam combination laser. In this letter, we show that in the proposed technique, the phase of the SBS wave significantly depends on the pump energy and it can be stabilized—although the independently separate SBS-PCMs are used—provided that the pump energies are balanced under the density modulation. In this experimental work, the standard deviation of the relative phase difference between the SBS waves has been reduced less than $\lambda/30$ by the amplitude dividing method to provide the pump beams with the nearly same energies. © *2005 American Institute of Physics*.

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The beam combination is a promising technique for developing a high-power/energy laser with a high repetition rate because it can eliminate several constraints, such as the high thermal load and the crystal-growth volume, which the current laser technology should overcome. In particular, the beam combination laser with the stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) has many advantages, such as the compensation of distortion generated during amplification and the easy alignment because the SBS-PCM produces a phase conjugate wave.[1–12] However, it is essential to make the phases of the simulated Brillouin scattering (SBS) waves fixed to achieve a single recombined beam with a uniform phase because the phase of the SBS wave is naturally random.[1–12] In previous methods,[4–11] one beam should be always coupled with another beam for making the phases of the beams the same. Consequently, the number of the beams for a beam combination laser is practically limited. On the other hand, in the authors' proposed method,[2,3,12] the phase control of the SBS waves is done by use of entirely independent SBS-PCMs without coupling among the incident beams, implying that it is possible to increase the number of the beams freely. Therefore, the energy scaling of the beam combination laser is not limited and the phase conjugation is not disturbed. However, the degree of the phase control was not enough to pursue the development of the beam combination laser because large fluctuations existed. In this letter, we show that the phase fluctuation significantly arises from the pump energy fluctuation under the density modulation, and the degree of the phase control can be greatly improved by balancing the pump energy although the independent SBS-PCMs are used. We have achieved the standard deviation—of the relative phase difference between SBS waves—that is reduced less than $\lambda/30$.

For the case of the wave-front dividing,[2,12] the divided subpump beams get the fluctuating energies for every shot due to the beam pointing effect of the laser source, which seems to generate the fluctuation of the relative phase difference between the SBS waves, because SBS depends on the pump energy. This problem can be improved by employing the amplitude dividing method, by which the subpump beams are able to have the nearly same energy.

We measured the relative phase difference $\Phi=\phi_1-\phi_2$ between two Stokes beams for the case of the amplitude dividing, where ϕ_1 and ϕ_1 denote the phases of two Stokes beams, respectively. The experimental setup is shown schematically in Fig. 1. A Q-switched 1064 nm Nd:YAG oscillator with a bandwidth of ~120 MHz and ~2% energy stability is used for the pump. The pulse width is 7–8 ns and the repetition rate is 10 Hz. The output from an oscillator is divided into two subbeams by a beam splitter (BS). Both beams then pass through separate wedges (W1 and W2) and are backward focused into each SBS-PCM by a concave mirror with $R=50$ cm and >99% reflectivity at the laser wavelength. The focused leading edge of the pump pulse encounters a part of the unfocused pump pulse, so that the weak density modulation by the electromagnetic standing wave is created in the focal area, and it plays a key role in fixing the phase of the initial acoustic noise.[12] The partial reflection mirrors (PM1 and PM2) are used to vary the energy of the subpump-beams. The degree of the fluctuation of the relative

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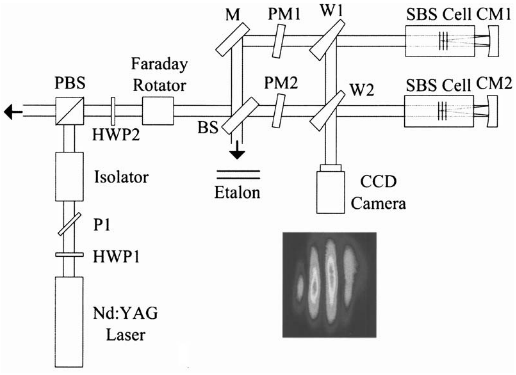

FIG. 1. Experimental setup for measuring the relative phase difference; HWP1 and HWP2, half wave plates; BS, beam splitter; M, mirror; PM1 and PM2, partial reflection mirrors; W1 and W2, wedges; P1, polarizer; PBS, polarization beam splitter; CM1 and CM2, concave mirrors.

phase difference between the SBS waves is quantitatively analyzed by measuring the movement of the peaks in the interference pattern which is captured by a charge coupled device (CCD) camera.[12] We have used Fluorinert FC-75 as an SBS medium.[13] The length of a SBS cell was 50 cm.

Figure 2(a) shows the Fabry-Perot interferograms for the pump laser (left) and the SBS return from the SBS-PCM with the phase control technique (right). We have used the Fabry-Perot interferometer with the free spectral range of 5 GHz. The interfergrams show that the backward SBS wave is reflected only by the acoustic wave, but the Bragg scattering by the density modulation is not generated because there is no overlapping between two interferograms, considering that the Brillouin frequency shift is 1.34 GHz for FC-75.[13] Figure 2(b) shows the Fabry–Perot interferograms for the SBS return from the SBS-PCM with no phase control technique (left) and the SBS return from the SBS-PCM with the phase control technique (right). The results also demonstrate that the SBS wave is reflected only by the acoustic wave.

The experimental investigation carried out for the cases of $E_{p1} \cong 0.37E_{p2}$, $E_{p1} \cong 0.68E_{p2}$, $E_{p1} \cong E_{p2}$, $E_{p1} \cong 1.11E_{p2}$, and $E_{p1} \cong 1.45E_{p2}$ with $E_{p2} \cong 10$ mJ, where E_{p1} and E_{p2} denote the energies of two subpump beams, in order to investigate the pump energy dependency of the phase of the SBS wave. We have measured the relative phase difference Φ to establish the degree of the phase stabilization. Figure 3 shows the experimental results. Each point in Figs. 3(a)–3(e) represents one of 220 laser pulses. The standard deviations (SDs) of the relative phase difference for the cases of $E_{p1} \cong 0.37E_{p2}$, $E_{p1} \cong 0.68E_{p2}$, $E_{p1} \cong E_{p2}$, $E_{p1} \cong 1.11E_{p2}$, and $E_{p1} \cong 1.45E_{p2}$ are $\lambda/7.6$, $\lambda/16.5$, $\lambda/36$, $\lambda/23.8$, and $\lambda/10.6$, respectively. From these results, it can be noted that the relative phase difference Φ becomes more stabilized as E_{p1} approaches E_{p2}, and Φ is mostly stabilized for the case of $E_{p1} \cong E_{p2} \cong 10$ mJ. In Fig. 3, the right-hand side figures show the mosaic intensity profiles composed of 220 lines selected from each interference pattern. The intensity profile, as shown in Fig. 3(c), also represents that Φ is remarkably stabilized for the case of $E_{p1} \cong E_{p2} \cong 10$ mJ. These results show that the phase of the SBS wave depends on the pump energy under the self-generated density modulation.

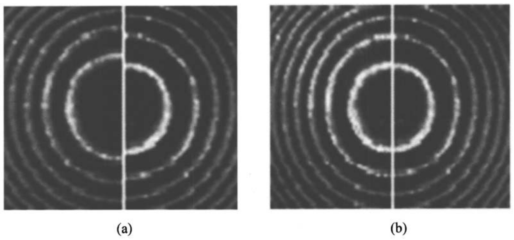
(a) (b)

FIG. 2. Fabry–Perot interferograms. (a) The spectra of the pump laser (left) and the SBS wave reflected from the SBS-PCM with the phase control technique (right). (b) The spectra of the SBS wave reflected from the SBS-PCM with no phase control technique (left) and that with the phase control technique (right). The free spectral range of the interferometer is 5 GHz.

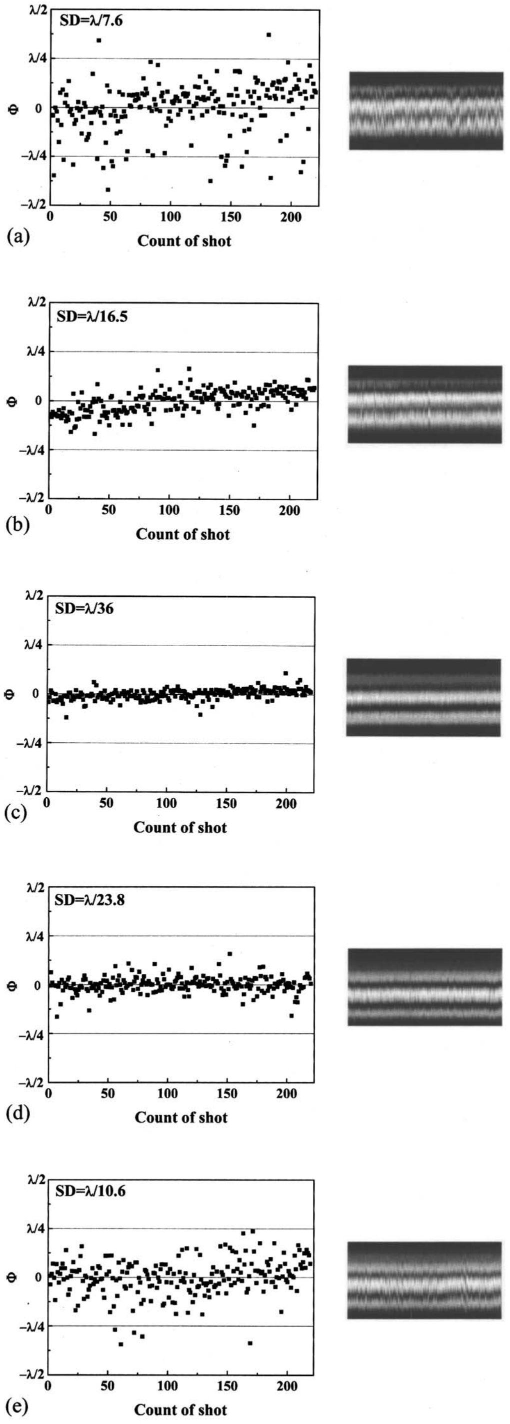

FIG. 3. The relative phase difference Φ (left) and the mosaic intensity profile (right) selected from 220 interference patterns for the cases of (a) $E_{p1} \cong 0.37E_{p2}$, (b) $E_{p1} \cong 0.68E_{p2}$, (c) $E_{p1} \cong E_{p2}$, (d) $E_{p1} \cong 1.11E_{p2}$, and (e) $E_{p1} \cong 1.45E_{p2}$ with $E_{p2} \cong 10$ mJ.

Let us assume that the main pump energy is given by $E_p = E_0 + \Delta E$, where E_0 is the average pump energy and ΔE is the variation in the pump energy caused by the energy fluctuation of the oscillator output. The energies of two divided pump beams can be written as $E_{p1} = r(E_0 + \Delta E)$ and $E_{p2} = (1 - r)(E_0 + \Delta E)$, where r is the division ratio of the BS. Thus, the energy change of two divided pump beams can be given by $\Delta E_{p1} = r\Delta E$ and $\Delta E_{p2} = (1 - r)\Delta E$. Because the value of ΔE changes randomly, the energies of two divided pump beams also change for every shot to shot, which can induce the fluctuation of the relative phase difference because the phase of the SBS wave depends on the pump energy for this phase controlling scheme. However, if r is equal to 0.5, the effect of the energy fluctuation of the main beam on the relative phase difference will vanish due to $E_{p1} = E_{p2}$. The experimental results also show that the relative phase difference Φ is mostly stabilized for the case of $r \sim 0.5$. Thus, balancing the pump energies can easily make the relative phase difference stabilize, even if the energy fluctuation of the oscillator output exists. In addition, compared with the wave-front dividing cases,[2,12] in which the division ratio r is fluctuated randomly due to the beam pointing effect of the oscillator, it is seen that the fluctuation of the relative phase difference for the amplitude dividing case is considerably reduced. Consequently, we have shown that it is possible to stabilize the relative phase difference between the SBS waves by inducing the self-generated density modulation, provided that the pump energies are balanced, and the phase of the SBS wave significantly depends on the pump energy under the self-generated density modulation.

In conclusion, we have demonstrated that the phase control technique using weak density modulation is very effective at stabilizing the phases of the SBS waves reflected by all independent SBS-PCMs. This is essentially required to develop the high-power/energy beam combination laser with the high repetition rate. We have shown that the phase of the SBS waves depends on the pump energy under the density modulation, and the relative phase difference between the SBS waves can be stabilized by balancing the pump energies. By employing amplitude dividing, the relative phase difference is remarkably stabilized to the SD of $\lambda/36$, although the independently separate SBS-PCMs are used. We expect that the degree of the phase control will show greater improvement if we stabilize the output energy of the pump laser. The phase control technique is expected to be very useful for developing the beam combination laser with the SBS-PCM and the high-power/energy laser.

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