Principle of the Phase Controlling of the SBS Wave and its Application to the Beam Combination Laser for the Laser Fusion Driver

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The phase control of the stimulate Brillouin scattering (SBS) wave by a standing wave is the most important technique for the realization of the beam combination laser system. In this work, a theoretical model has been developed for explaining the principle of the phase controlling. The phase fluctuation of the SBS wave has been numerically calculated using this theoretical model. Consequently, it predicts the phase of the SBS wave will be stabilized as the fluctuation of the pump energy decreases and the pump energy increases. Furthermore, the change of the relative phase difference between the SBS waves can be easily calculated by this model in the beam combination laser system.

Key Words: Stimulated Brillouin scattering, Phase control, Phase conjugate mirror, Beam combination laser

1. Introduction

Stimulated Brillouin scattering (SBS) is a well-known nonlinear process generating a phase conjugate wave. In general, the SBS wave has a random phase because it is initially generated by a thermal noise.[1-2] The phase control of the SBS wave becomes an important issue because of its application to the beam combination,[3-10] which is one of the promising methods for achievement of the laser fusion driver. In our laboratory, a phase control technique using self-generated density modulation was proposed by H. J. Kong *et al.* recently.[3-4] This phase control technique is completely different from previously developed methods, such as beam overlapping,[5-6] back-seeding,[7] and Brillouin enhanced four wave mixing (BEFWM).[8] With beam overlapping or BEFWM, it is almost impossible to combine many beams, because the optical compositions are too complicated and focusing many beams to one point causes a serious optical breakdown in the SBS medium. And the back-seeding destructs the phase conjugation. However, with this proposed technique, it is possible to control each beam phase independently quite easily without any destruction of the phase conjugation by the simplest optical composition using only one concave mirror, called the feedback mirror. Therefore, the laser energy is unlimitedly scaled-up without any structural limitations.

The experimental results of our previous papers show the well-controlled phase between two SBS waves with ~λ/50 fluctuation by standard deviation.[3-4] However, there are not sufficient theoretical explanations about the principle of our SBS phase control technique in those papers. Therefore, in this paper, the theoretical model of SBS phase control by a standing wave has been developed. And the phase fluctuation of the SBS wave has been numerically calculated with this theoretical model.

2. Phase control of SBS wave by a standing wave

In the SBS medium, the pump wave and the Stokes wave are described by

$$s_p = A\sin(\omega_p t - k_p z + \varphi_p) \quad , \qquad \text{(pump wave)} \quad (1)$$

$$s_B = B\sin(\omega_B t + k_B z + \varphi_B)\,, \qquad \text{(Stokes wave)} \quad (2)$$

where φ_p and φ_B denote the initial phase of the pump and the Stokes wave, respectively.

$$\begin{aligned}\rho \sim \left|S_p + S_B\right| &= A^2\sin^2(\omega_p t - k_p z + \varphi_p) \\ &+ B^2\sin^2(\omega_B t + k_B z + \varphi_B) \quad \text{(DC)} \\ &+ AB\cos\left[(\omega_p + \omega_B)t - (k_p - k_B)z + (\varphi_p + \varphi_B)\right] \\ &\qquad \text{(Fast oscillation)} \\ &+ AB\cos\left[(\omega_p - \omega_B)t - (k_p + k_B)z + (\varphi_p - \varphi_B)\right] \\ &\qquad \text{(Acoustic wave)}\end{aligned} \quad (3)$$

Then, the density modulation through the electro-striction can be represented as

$$\rho = \rho_0\cos(\Omega t - k_a z + \varphi_a) \quad (4)$$

Since DC component and fast oscillating component can not drive the acoustic wave, these terms of Eq. (3) can be dropped. If the acoustic wave is considered as
the phase relations of $\Omega = \omega_p - \omega_B$, $k_a = k_p + k_B$, and $\varphi_a = \varphi_p$

$$\begin{aligned}\rho &= \rho_0\cos[\Omega(t - t_0) - k_a(z - z_0)] \\ &= \rho_0\cos[\Omega t - k_a z - \Omega t_0 + k_a z_0]\end{aligned} \quad (5)$$

$- \varphi_B$ are obtained.
Now, let us assume that the acoustic wave is generated at t_0

$$\varphi_a = -\Omega t_0 + k_a z_0 \quad (6)$$

and z_0. Then, the acoustic wave can be rewritten as
Then, the initial phase of the acoustic wave is given by
In conventional case of the SBS generation, t_0 and z_0 are not

be determined because the Stokes wave is ignited by a random

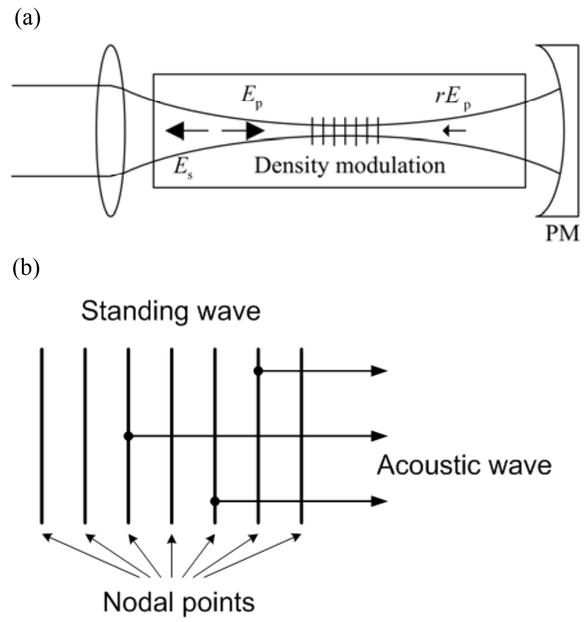

Fig.1 (a) Concept of phase control of the SBS wave by a standing wave. and PM is a concave mirror with the coefficient of reflection r. E_p and E_S denote the pump wave and the SBS wave, respectively. (b) Ignition of the initial position of the acoustic wave by the density modulation.

noise. If it is possible to determine t_0 and z_0, the acoustic wave will follow Eq. (5) and the phase can be locked.

2.1 Determination of z_0

Figure 1(a) shows the concept of phase control of the SBS wave by a standing wave. PM is a concave mirror with the coefficient of reflection r, and E_p and E_S are the pump wave and the SBS wave, respectively. The weak density modulation is generated at the focal point of the lens by an electro-magnetic standing wave, which arises from the interference between E_p and counter-propagating rE_p. One of the nodal points of the standing wave acts as an ignition position of the Brillouin grating for the SBS process, as shown in Fig. 1(b). There are many candidates of nodal points for the ignition position z_0. However, the phase difference between them is an integer multiple of 2π, neglecting the Brillouin shift (order of GHz). Therefore, the phase of SBS wave would be no more random and it would be fixed.

2.2 Determination of t_0

We have assumed that the critical time $t_c = (t_0)$, at which the SBS wave is initiated, is determined by the following equation,

$$E_{th} = \int_0^{t_c} P(t)dt \tag{7}$$

where E_{th} and $P(t)$ are the SBS threshold energy and the pump power. According to Eq. (7), the critical time t_c is determined by the pump power and can be represented as a function of the total pump pulse energy E_0, which is given by

$$E_0 = \int_0^{\infty} P(t)dt \tag{8}$$

2.3 Numerical calculation of the phase fluctuation

Since the critical time t_c varies with the total energy E_0, the change of initial phase $\Delta\varphi_0$ can be represented by the energy fluctuation ΔE_0 as

$$\Delta\varphi_0 = -\Omega\Delta t_c = -\Omega\frac{\Delta t_c}{\Delta E_0}\frac{\Delta E_0}{E_0}E_0 \tag{9}$$

assuming that z_0 is fixed.

Let us assume that the pump pulse $P(t)$ given by

$$P(t) = \frac{4E_0}{a^2\sqrt{\pi}}t^2\exp\left[-(t/a)^2\right] \tag{10}$$

Then, $\Delta\varphi_0$ can be calculated numerically for a heavy fluorocarbon liquid FC-75 (3M company) used in the experiments,[11] which has the acoustic wave frequency 1.34 GHz and the SBS threshold of about 2.5mJ for 10 ns pulse. Figure 2 shows the calculated critical time t_c and $\Delta\varphi_0$ as a function of the pump energy, when the energy stabilities $\Delta E_0/E_0$ of the pump beam are 1%, 2%, and 5%. $\Delta\varphi_0$ is inversely proportional to the pump energy for each stability case. In addition, $\Delta\varphi_0$ decreases as the energy fluctuation becomes small. Consequently, the phase of the SBS wave will be stabilized as the fluctuation of the pump energy decreases and

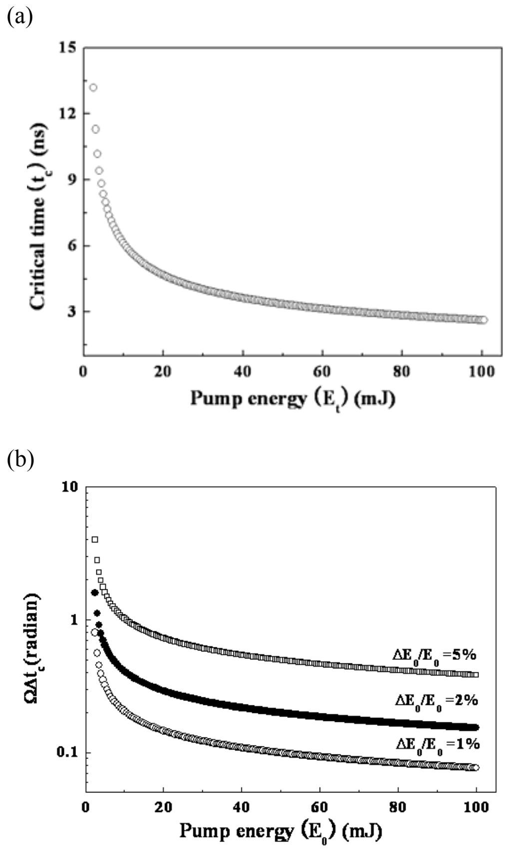

Fig.2 (a) Critical time t_c as a function of the pump energy. (b) Initial phase change $\Phi_0=\Omega\Delta t_c$ of the SBS depending on the pump energy stability ($\Delta E_0/E_0$ = 1%, 2%, 5%) as a function of the pump energy.

(a)

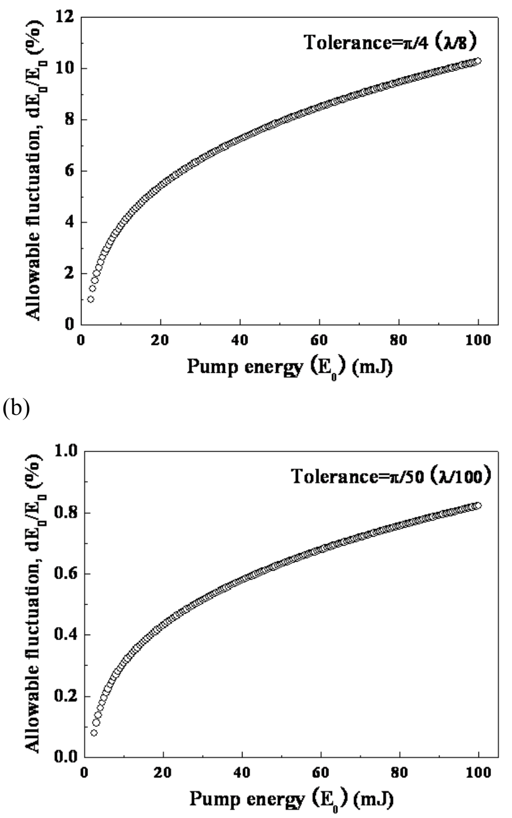

Fig.3 The tolerance of the pump energy stability $\Delta E_0/E_0$ for obtaining the phase stability (a) $\Delta\Phi_0=\pi/4(=\lambda/8)$ and (b) $\Delta\Phi_0=\pi/50(=\lambda/100)$.

the pump energy increases.

Figure 3 shows the tolerance of the pump energy stability for the phase stability of $\Delta\varphi_0 = \pi / 4(= \lambda / 8)$ and $\Delta\varphi_0 = \pi / 50(= \lambda / 100)$. For the pump energies of 5 mJ, 10 mJ, and 100 mJ, the allowable tolerance are 2.4%, 3.8%, and 10.3% in the case of $\lambda / 8$ phase stability, and 0.19%, 0.31%, and 0.82% in the case of $\lambda / 100$ phase stability. This result represents that the phase controlling becomes more effective and practical as the pump energy increases.

3. Application to the beam combination laser

The most significant application of the SBS phase control technique by a standing wave is the beam combination laser system.[3-4] Figure 4 shows two kinds of conceptual schemes of the beam combination systems, with wave-front division and amplitude division. In both cases, the main beam is divided into several sub-beams, amplified separately in the array amplification system, and finally recombined. This system can operate with a high repetition rate by overcoming the cooling problems, because the separate amplification does not require large size active media. Therefore, the beam combination method is the promising technique for construction of a very high energy laser with a high repetition rate over 10 Hz such as a real laser fusion driver. Futhermore, the SBS isolator system in each amplification stage can completely cut off the

(a)

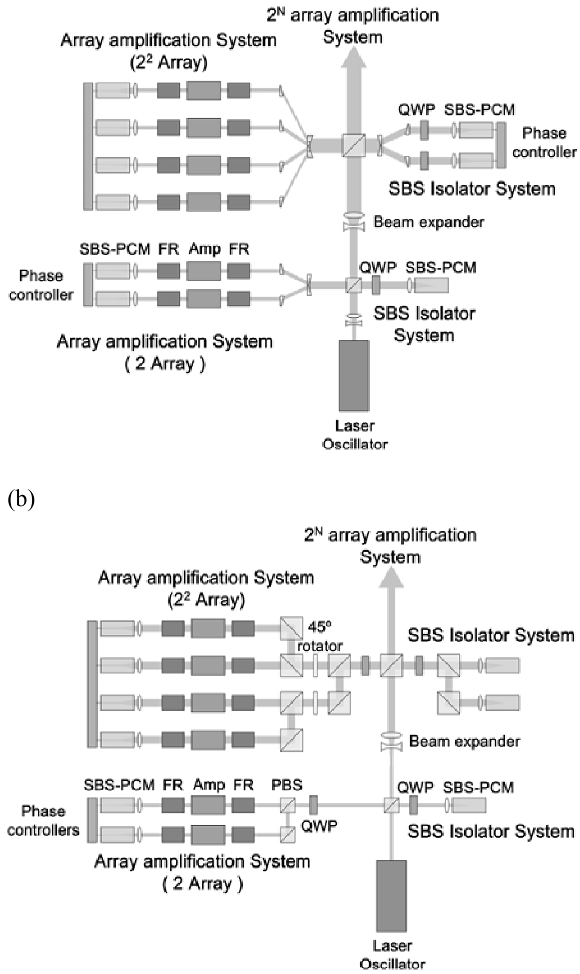

Fig.4 Conceptual scheme of the beam combination systems using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) with (a) wave-front division and (b) amplitude division (FR, Faraday rotator; AMP, amplifier; QWP, quarter wave plate; PBS, polarizing beam splitter).

leaked back reflection.

Our theoretical model can predict the change of the relative phase difference between the SBS waves with the phase control technique in the beam combination system. Let us consider that a laser beam is divided into two sub-beams with the energies of E_1 and E_2. Then, the change of the relative phase difference $\Phi = \varphi_1 - \varphi_2$ is represented by the energy fluctuation ΔE_1 and ΔE_2 of each sub-beam as

If E_1, E_2, ΔE_1, andΔE_2 are known parameters, $\Delta\Phi$ would be easily obtained from the numerical calculation of t_c .

4. Conclusions

In conclusion, a theoretical model has been developed for explaining the SBS phase control method by a standing wave. Theoretical analysis shows the phase of the SBS wave significantly depends on the pump energy, and the phase fluctuation is inversely proportional to the pump energy. Consequently, the numerical calculation shows the phase of the SBS wave will be stabilized as the fluctuation of the pump energy decreases and the pump energy increases. And the calculations of the energy stability tolerance represent that the phase controlling becomes more effective and practical as the pump energy increases. Furthermore, this theoretical model can predict the change of the relative phase difference between the SBS waves in the beam combination system. It is expected that this theoretical model will also contribute to predict the phase fluctuation and the energy fluctuation of the high power/energy many beam combination system in the future.

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