Demonstration of 2.5 J, 10 Hz, nanosecond laser beam combination system based on non-collinear Brillouin amplification

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Abstract: We demonstrated a four-beam combined laser system based on Brillouin amplification with a nanosecond output of 2.5 J at a 10 Hz repetition rate. We used simulations and experiments to assess factors affecting the energy extraction efficiency of non-collinear Brillouin amplification. Our results indicate that higher efficiency can be achieved by adding pump beams to the Brillouin amplification process, which enhances optical field intensity and interaction strength. To the best of our knowledge, this is the first demonstration of a multi-beam combination system based on Brillouin amplification with an output of joule level energy, high peak power and nanosecond pulses in 10Hz repetitive operation.

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1. Introduction

Laser systems with high energy and high peak power in repetitive operations are critical to current and future industrial and scientific applications, such as material processing [1–4], particle acceleration [5], and the pump sources for petawatt lasers and X-ray generators [6,7]. At present, it is challenging and expensive to develop the traditional high-energy, high-power laser amplification technologies with the onset of the severe thermal effects associated with, particularly as repetition rates increase. Coherent beam combination (CBC) is a potential pathway for further multiplying output energy and power with high beam quality in repetition operations. H.J. Kong et al., from Korea Advanced Institute of Science and Technology, realized an output of 0.4 J/10 ns/10 kHz–4 kW [8,9] using CBC. Recently, beam combination methods based on non-linear amplification effects have attracted significant attention, and many works have been conducted. R.P. Mildren et al. from Macquarie University [10] reported the utility of Raman amplification for combining four beams in diamond, where the output peak power exceeded 8.8 kW with a repetition rate of 1 kHz and the combing efficiency was approximately 69%. The R. Kirkwood group from the Lawrence Livermore National Laboratory [11,12], proposed a stimulated Brillouin scattering (SBS) beam combination based on a National Ignition Facility (NIF) with Plasma as the combiner optics. A 4.2 kJ nine-beam combined laser system, operating in single-pulse mode, with the combing efficiency of 52%, was reported. However, subject to the combination method and material, there is still no satisfactory solution for obtaining repetitive nanosecond pulses that are simultaneously high-power and high-energy.
Brillouin amplification beam combination (BABC) was proposed in 2002 by Z.W. Lu [13] from the Harbin Institute of Technology. Liquid materials were required in this method. BABC has significant specific advantages for achieving repetitive high-power short laser pulses. The first is the simple optical layout and flexible and compact system structure of BABC, which make the combined pulse parameters more controllable. Compared with CBC methods, BABC does not require a precise phase control device, because the energy transferring from pumps to Stokes happens spontaneously with beams overlapping. This allows the non-collinear structure for the BABC method. The adoption of a non-collinear structure eliminates the polarization beam splitting optics, which predigests optical layouts for a further step. Because more pump beams can easily join in the amplification process under this structure, higher pulse energy can be achieved and beam quality can be shaped to some extent. The second advantage of BABC is the choice of the liquid media that guarantees the output of high pulse intensity on the repetition rate. The energy capacity of liquid Brillouin media is not limited by its size. Liquid media can easily recover from damage and heat dissipation can be effectively realized by circulation. FC-72 is thermally and chemically stable and has a high damage threshold, which allows nanosecond pulses with high energy and intensity over several GW·cm$^{-2}$ to operate repetitively at room temperature. Additionally, a high Brillouin gain coefficient and low absorption coefficient make it the ideal media for BABC [14]. The third advantage of BABC is its low cost, which promotes the development and application of BABC laser systems in relevant industrial fields. Laser combination systems based on BABC methods are economical and have undemanding realization conditions, require unsophisticated facilities, and widely-used Brillouin media. Over the past few years, several studies [15,16] were conducted to verify the feasibility of the BABC method. However, none of the works realized a Brillouin amplification beam combination process with extra energy and power gains in a non-collinear structure in the experiment.

In this paper, we report a four-beam combination laser system based on non-collinear Brillouin amplification, achieving pulses of 2.5 J/10 ns/10 Hz with a beam intensity of 500 MW·cm$^{-2}$ and the combining efficiency of 72%. Simulations for non-collinear Brillouin amplification have been implemented to choose the appropriate media parameter, the cross angle of the laser beam layout, and the interacting optical field intensity. The SBS combination system produced nanosecond joule-level pulses with high beam intensity in repetitive operations, which promises the realization of scaling the energy to tens or even hundreds of joules by adding more pump beams into the beam combination system.

2. Theoretical analysis and experiment design

To simplify the optical layout, reduce system loss, and easily separate the Stokes beam from the pumps, the non-collinear geometry illustrated in Fig. 1 was used for the Brillouin amplification laser combination system. An axially directed Stokes seed beam propagated through the SBS media, which was crossed by several pump beams at a polar angle of $\theta$ (also refers to cross angle) and a different azimuthal angel. Each seed-pump pair was simultaneously resonant for Brillouin amplification. The non-collinear structure, however, produced problems of frequency mismatch [16], and decreased the interaction volume [17] between the Stokes and pump beams, which severely affected the amplifier gain and the energy transferring efficiency. Therefore, based on the traditional SBS coupling equation [18,19], Brillouin amplification under non-collinear conditions has been simulated. The SBS gain factor and energy transferring efficiency have been considered numerically in detail.
According to reference [19], the SBS gain factor $g$ can be deduced from the SBS coupling equation, which is described as follows:

$$g = g(0) \frac{(\Gamma_B \gamma_b / 2)^2}{(\Omega_B - \Omega)^2 + (\Gamma_B / 2)^2}, \quad (1)$$

$$g(0) = \frac{\omega^2 \gamma_b^2}{c^2 n_0 \rho_0 \Gamma_B}. \quad (2)$$

Where $\Gamma_B$ is the Brillouin linewidth, $\Omega_B$ is the Brillouin frequency of the amplification media, and $\Omega$ is the frequency of the driven acoustic wave. $g(0)$ is the line-center gain factor relative to the laser frequency $\omega$. The dependence of the gain coefficient on the cross angle $\theta$ can be given by the angular bandwidth formula, which can be simplified into the formula as follows:

$$g(\theta, \Omega_B') = g(0) \frac{\Omega_B'^2 \gamma_b^2 \cos^4(\theta / 2)}{\Omega_B'^2 \gamma_b^2 \cos^4(\theta / 2) + [\Omega_B + \Omega_B \cos(\theta / 2)]^2 [\Omega_B - \Omega_B \cos(\theta / 2)]^2} \quad (3)$$

where $\Omega_B'$ is the Brillouin frequency of the SBS generation media. If we use the same media in the Stokes generation cell and the SBS combiner, then according to the formula, the central frequency of the spectrum is $\Omega_B' \cos(\theta/2)$, and the FWHM value is $\Gamma_B' \cos^2(\theta/2)$. With the media parameters given in Table 1, the relationship between the Brillouin gain factor of a certain medium and the non-collinear cross angle is depicted in Fig. 2. As shown in the illustration, the larger the Brillouin linewidth $\Gamma_B$ of the media, the wider is the spectrum, which means a larger cross angle will be allowed in the media to maintain a relatively high interaction gain coefficient. Corresponding to Fig. 2, the offset angle for FC-72 to maintain the gain factor exceeding 90% of the maximum value is only less than 31.5° because FC-72 has the narrowest Brillouin linewidth. The critical offset angles increase further for FC-77, FC-3283, and FC-40, because the Brillouin linewidth grows in the same turn. The critical offset angle point has a definite relationship with $\Gamma_B$ according to Eq. (3). When the cross angle is smaller than the 90%-max critical point, the Brillouin coefficient decreases slowly as the angle increases. To guarantee a high Brillouin coefficient in beam combination experiments, the cross angle should be set in this range. After the 90% critical point, the gain coefficient drops rapidly to zero. However, it is also shown that the medium with a wider linewidth has a lower gain coefficient. Therefore, to choose the appropriate medium, comprehensive factors must be considered in energy transferring efficiency simulations.
Table 1. SBS media parameters used in the simulation

<table>
<thead>
<tr>
<th>Medium</th>
<th>$g_0$ (cm/GW)</th>
<th>$\tau_p$ (ns)</th>
<th>$\Gamma_{a}$ (MHz)</th>
<th>$\Omega_{a}$ (MHz)</th>
<th>$\tau_s$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC-72</td>
<td>6.5</td>
<td>1.2</td>
<td>270</td>
<td>1100</td>
<td>0.9</td>
</tr>
<tr>
<td>FC-40</td>
<td>3.8</td>
<td>0.2</td>
<td>1292</td>
<td>1386</td>
<td>0.7</td>
</tr>
<tr>
<td>FC-3283</td>
<td>4.5</td>
<td>0.6</td>
<td>554</td>
<td>1281</td>
<td>0.8</td>
</tr>
<tr>
<td>FC-77</td>
<td>5.1</td>
<td>0.7</td>
<td>486</td>
<td>1360</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Fig. 2. The relationship of the SBS gain coefficient $g_\theta$ ($\Omega_{a} = \Omega_{a}$) on the non-collinear offset angle $\theta$, the dashed line refers to the cross angle at which the gain coefficient decreases to the 90% of the maximum value.

Another parameter directly affected by the non-collinear structure is the interaction volume. Because of the rod laser amplifiers utilized in the combination system, the laser beams can be regarded as transparent cylinders that intersect with one another at a cross angle of $\theta$ in the interaction region. The interaction length $L_e$ is defined as the ratio of the interaction volume to the laser beam size, and can be calculated by the formulas mentioned in [17].

Fig. 3. (a) $L_e$ changes with the cross angle at different beam diameter with the cell length fixed, (b) the relationship between $L_e$ and $\theta$ at different cell length with fixed beam diameter, where $d$ is the diameter of laser beam and $L$ is the length of the Brillouin amplification cell.

The simulation for the effects of cross angle on effective interaction length is shown in Fig. 3. It is clear from the curves that the effective interaction length continuously drops with increasing cross angle. Then, we strengthen the analysis based on two important parameters.
that affect interaction volume. One is the cross section of the laser beam, which can be characterized by diameter $d$. The fixed length of the Brillouin Cell is chosen as $L = 10$ cm. Our results indicate that as the diameter increases, the interaction length decreases, as illustrated in Fig. 3(a). The second important parameter is the length $L$ of the Brillouin cell. Figure 3(b) illustrates the dependence of the interaction length on the beam cross angle when the beam diameter is fixed. Interaction length decreases rapidly with increasing cross angle, and when the cross angle goes beyond 8°, the effective interaction length decreases rapidly and tends to approximate the value of beam diameter. The effective interaction length declines with $\theta$ much more sharply than with the gain coefficient.

![Image](Fig. 4. The energy extraction efficiency changes with cross angle under different optic field intensity is illustrated, (a) lower intensity, Stokes: 25 MW·cm$^{-2}$, pump: 75 MW·cm$^{-2}$ (b) higher intensity, Stokes: 175 MW·cm$^{-2}$, pump: 225 MW·cm$^{-2}$)

By inserting the expressions for gain coefficient $g$ and interaction length $L_e$ into the SBS coupling equation, we can numerically calculate the dependence of the energy extraction efficiency on the cross angle $\theta$ in certain Brillouin media. The definition of the energy extraction efficiency is given by,

$$\eta_E = \frac{E_{sout} - E_{sin}}{E_{pin}}.$$  \hspace{1cm} (4)

Where $E_{sout}$ and $E_{sin}$ represent the energy of the combined output Stokes pulse and the input Stokes before laser combination respectively, and $E_{pin}$ is the total energy for all input pump beams. The calculation results are illustrated in Fig. 4. The curves have similar tendencies with respect to the relationship curves of the interaction length and cross angle. Contrasting Figs. 4(a) and 4(b), it is demonstrated that as the intensity of the optical field increases, the maximum efficiency value increases in the same Brillouin medium, and the efficiency remains high for a larger angle range. For FC-72, the maximum efficiency increases from 0.91 to 0.94, and the angles for efficiency values higher than 90% of the maximum enlarges from 3.8° to 12.6°. For FC-40, the maximum efficiency increases from 0.65 to 0.8, and the corresponding nonlinear cross angle is enlarged to 8.1°. A high intensity laser field requires a shorter interaction length to finish the energy transferring process, as we can deduce from the coupling equation, and the maximum efficiency is also increased. In addition, when the cross angle is smaller than 50°, FC-72 has a higher efficiency than FC-40. However, when the cross angle exceeds 50°, FC-40 surpasses FC-72. FC-72 has a larger Brillouin gain coefficient than FC-40, but FC-40 has a wider linewidth, which enables the gain coefficient to remain almost constant at a larger angle range. To take full advantage of the energy in the SBS amplification system to achieve high energy extraction efficiency, we choose FC-72 as the SBS medium for our combination system, with the cross angles of the pumps and Stokes less than 10° in the optical layout of the system.
3. Experiment

A four-beam combination system layout is illustrated in Fig. 5. The laser source generates approximately 120 mJ at 1064 nm at a repetition rate of 10 Hz, with a pulse duration of 7 ns (FWHM) in single-longitudinal mode. Double passing the booster Nd:YAG rod amplifier, the pulse energy of the seed is amplified to 400 mJ. Between the laser source and booster amplifier, an isolator is inserted to protect the laser source from the damage caused by the backward-propagating laser. A laser head output with linear polarization is directed to another isolator, and then amplitude-divided into four parts by sets of a half-wave plate and polarization beam splitter to generate the Stokes seeds and the pump beams.

The Stokes seed is generated by the first part of the divided beam injected into the SBS phase conjugate mirror. The FC-72 liquid is used in the Stokes generator as the SBS combiner cell, to achieve SBS amplification conditions. Stimulated Brillouin Scattering Phase-Conjugate Mirror (SBS-PCM) also compensates for the thermal distortion of the Stokes beam. To improve load capacity and prevent optical breakdown, the media were finely purified by a multistage 22 nm filter membrane. \( f \) is a focusing lens of 150 mm. The double-pass rod amplifier is used to boost the energy of the Stokes seed to over 600 mJ with a pulse duration of 6.3 ns and beam diameter of 8 mm, and the maximum intensity can reach up to 190 MW·cm\(^{-2}\). The pulse duration of the Stokes seed is compressed slightly during the SBS generation process. The other three parts of the divided beam are regarded as the pump seeds to be injected into the pump amplifiers. Each beam provides 900 mJ to pump the Stokes seed in the SBS combiner. The pulse duration is 6.7 ns and the beam diameter is 8 mm, and the maximum pulse intensity can be up to 270 MW·cm\(^{-2}\). In this part, three 0° high reflection mirrors of the double-pass pump amplifiers are used to detuning the sequence of the beams injection into the SBS beam combiner, and the Stokes arrived at the SBS combiner 1 ns earlier than the pump beams to depress other nonlinear effects and take full use of the system energy.

The SBS combiner is a Φ100 mm × 100 mm glass media cell filled with FC-72. The Stokes is injected into the cell from one side while the pumps from the other. To simplify the optical
layout and avoid extra separation of the amplified Stokes from several pumps, a non-collinear amplification structure is adopted. The cross angles between the Stokes and Pumps I–III are 6.1°, 6.5°, and 9.5°, respectively. The undepleted pump energy is absorbed by the dumps. The combined output beam is reflected into an energy detector. To measure the beam energy, we used the power meter (Ophir LaserStar Dual Channel) and the energy sensor (Ophir PE50BF-DIC-F RHOS). A photodiode (ALPHALAS Ultrashort photodetector UPD-40-UVIR-D) and oscilloscope (Tektronix DPO 71254) were employed to measure pulse duration.

4. Results and discussion

Table 2 shows the statistical results of the output energy for each beam prior to the SBS combination process, where \( E_{\text{ave}} \) represents the average pulse energy and \( E_{\text{std}} \) represents the standard deviation, \( E_{\text{max}} \) is the maximum energy value and \( E_{\text{min}} \) is the minimum value, and \( t_p \) is the average pulse duration. The Stokes energy is lower than the pump energy, and the reflection of SBS-PCM can barely reach 100% because of the low energy of the Stokes beam and intrinsic loss in the SBS media.

Table 2. Statistical results of the output energy and pulse duration of Stokes and pumps

<table>
<thead>
<tr>
<th>Laser</th>
<th>( E_{\text{ave}} ) (mJ)</th>
<th>( E_{\text{std}} ) (mJ)</th>
<th>( E_{\text{max}} ) (mJ)</th>
<th>( E_{\text{min}} ) (mJ)</th>
<th>( t_p ) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stokes</td>
<td>600.3</td>
<td>14.03</td>
<td>673.0</td>
<td>589.0</td>
<td>6.3</td>
</tr>
<tr>
<td>Pump1</td>
<td>897.9</td>
<td>8.775</td>
<td>916.0</td>
<td>870.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Pump2</td>
<td>903.4</td>
<td>7.151</td>
<td>921.0</td>
<td>880.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Pump3</td>
<td>866.1</td>
<td>13.04</td>
<td>887.0</td>
<td>786.0</td>
<td>6.7</td>
</tr>
</tbody>
</table>

The combined output energy of the four-beams is optimized by adjusting the encounter time and the position in the SBS combiner, by varying the positions of high reflection mirrors in the pump amplifiers part. The combined output pulse energy distribution at a repetition rate of 10 Hz is illustrated in Fig. 6. The combined laser beam energy was measured consecutively by an energy detector connected to the computer. The average pulse energy of the sampled pulses was 2.39 J, and the maximum pulse energy was 2.53 J. The system combing efficiency is 72%, which is the highest SBS combination efficiency reported to date. The definition of the system...
combining efficiency is the ratio of the system output energy and the total energy injected into the combination process, evaluating the energy usage of the laser combination system. When the ratio of the Stokes energy and the pumps energy is constant, the combining efficiency has a linear relationship with the energy extraction efficiency. In Fig. 6, the energy of 75% combined output pulses ranged from 2.35 J to 2.5 J. Among the other 25% of the combined output pulses, 22.5% pulses had energy values lower than 2.35 J and only 2.5% of the pulses had energy values exceeding 2.5 J. This lowered the average values and affected system output capacity. Optical breakdowns occurred more frequently with the increases in the number of laser shots injected into the SBS generator, because of the accumulation of localized heat loads along the beam path in the SBS combiner [20,21]. This degraded the reflectivity and fidelity of the SBS generator. The optical breakdowns led to the distortion of the Stokes beam profile. The Stokes became weak and divergent and could barely be fully amplified by the rod amplifier. Therefore, the intensity of the Stokes injected into the SBS combiner decreased, significantly reducing the combination efficiency. Although the medium was been carefully filtered, the thermal accumulation in the medium aggravated the optical breakdown.

![Fig. 7. Output waveform of the combined laser pulse.](image)

The time domain of the output laser beam is illustrated in Fig. 7. Compared with the Stokes and pump pulse durations listed in Table 2, the combined output pulse duration of 7 ns was extended. This was affected by the time delay between the interaction beams. Figures 8(a) and 8(b) show the spatial profile of Stokes before and after the beam combination respectively. The spatial beam profile was measured with a charge-coupled device camera produced by Andor (Apogee Alta KAF-16801). The diameter of the combined output beam profile was 9.5 mm with the intensity exceeding 500 MW·cm\(^{-2}\). The central area of the Stokes was enlarged after the beam combination, because the beam boundary was amplified by the non-collinear propagating pumps. It is foreseeable that a better output beam profile is within reach if we can increase the quantity and optimize the spatial distribution (viz. cross angle and overlap with Stokes) of the pump beams.
The dependency of the energy extraction efficiency on the number of pump beams and the intensity of the seed beam was studied. As shown in Fig. 9, efficiency increased with Stokes intensity regardless of how many pumps joined in the amplification process, in which three pumps had the same energy and optical intensity. The efficiency increased with the increase of the pump numbers. The superposition of the pump beams enhanced the optical intensity at the interaction volume with the Stokes seed, and the stronger acoustic fields were stimulated, which increased the energy extraction efficiency. Based on the SBS coupling equation set [19], the source term of the acoustic wave equation indicates that the intensity of the acoustic field has a positive correlation to the amplitude of the pumps and the Stokes field. The increase of the pump field amplitude enhances the intensity of the acoustic wave, and the stronger acoustic field promotes the energy transferring process, resulting in the improvement of the energy extraction efficiency. The mechanisms for the heat deposition and the thermal effects on system energy stability require further investigation in order to accurately analyze the effects of media heating on long-term operations.

We demonstrated a four-beam combination laser system based on Brillouin amplification, which did not exhibit a degradation of efficiency with increased Stokes intensity operating steadily at 10 Hz for a relatively long time. To arrange tens or even hundreds of pump beams.
into a compact structure, an amplification cavity accommodating multiple laser rods and multilayer optical path structures was considered and is under design. Since the SBS combination process is aimed at transferring the energy of multiple lower power pulses into one Stokes beam to achieve high power output, the utility of the small-size laser rods allows the system free from complicated and expensive cooling system and the damage caused by the thermal distortion. Moreover, the power load and the Stokes beam size are not limited by the beam combination media with FC-72. Contributing to the low-cost of the liquid media, a circulation system can be employed into the Brillouin amplification cell to rapidly dissipate waste heat, thereby guaranteeing system stability even for high operation repetition rates. Different from the solid-state SBS media, the combined output power is not limited by the size of the media, on the contrast, the shape of the SBS combiner can be designed according the requirement of the laser combination system. By enlarging the Stokes beam size, other self-stimulated nonlinear effects can be avoided with increasing pulse energy but decreasing combined output beam intensity. Therefore, we are confident in the realization of a 100 J/10 ns/10 Hz beam combination laser system based on Brillouin amplification.

5. Conclusion

In this paper, a concept for an SBS amplification combination system has been proposed to generate a laser beam output with a uniform phase and narrow frequency bandwidth. A four-beam combination system based on a non-collinear Brillouin amplification structure using FC-72 as the SBS medium was first reported and was theoretically designed and experimentally investigated. During the combination process, the system combining efficiency reaches 72%, while the maximum output energy exceeded 2.5 J. We systematically demonstrated the dependency of the combination efficiency on the cross angle, Brillouin media, and the optical intensity. We proved that an increased number of pump beams interacting with the Stokes together strengthen the combination efficiency. With the BABC method combining laser beams together, greater energy output can be achieved on the basis of the current single solid-state laser system output capability. Considering a Brillouin combination in FC-72 alleviates the constraints of phase control, thermal load risk, and other nonlinear effects, a system of 100 J/10 ns/10 Hz based on this principle can be expected in the near future.

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References


