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Investigation on efficiency of non-collinear serial laser beam combination based on Brillouin amplification

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Abstract

A non-collinear laser beam combination based on Brillouin amplification is proposed. The influence of non-collinear Brillouin amplification on the combination efficiency is analyzed and discussed theoretically. It is shown that an efficiency of 80% can be achieved with the angle between the Stokes and the pump limited to a range of 10°. The theoretical prediction is tested in experiment of non-collinear amplification of one Stokes and one pump. A two-beam combination scheme is designed and a high combination efficiency of 80% is also obtained in this experiment. According to these results, a 20-beam combination scheme is designed to achieve 13.2-J output energy. A very simple construction for a multiple beams combination is designed.

Keywords: Beam combination; Phase conjugation; Stimulated Brillouin scattering

INTRODUCTION

Solid state lasers of high repetition rate, high power, and large energy may be widely applied in the domains of military, scientific research, and industry, such as inertial confinement fusion (Hoffmann *et al.*, 2005; Miley *et al.*, 2005), space optical communication and material processing (Thareja & Sharma, 2006; Veiko *et al.*, 2006). However, because of the limitation of crystal growth technology, heat distortion, and damage threshold, the output of a single-laser apparatus is restricted.

The laser beam combination is a technology that combines several laser beams with low power and energy to produce a high energy and high power laser output (Kong *et al.*, 2005*a*). Existing methods usually use a nonlinear optics phase conjugation approach to combine solid-state pulse lasers. Stimulated Brillouin scattering (SBS) is a very important way in these methods (Kong *et al.*, 1997; Shuangyi *et al.*, 2007). The SBS parallel beam combination is composed of the overlap coupling beam combination (Basov *et al.*, 1980), the back-seeding beam combination (Loree *et al.*, 1987), and the self-phase control beam combination (Kong *et al.*, 2005*b*; Lee *et al.*, 2005). The overlap coupling beam combination and the back-seeding beam combination are limited by the low load of the system and the poor backward reflectivity because several laser pulses are focused into one medium cell. In order to overcome these disadvantages, Kong *et al.* (2005*c*) proposed the self-phase control SBS parallel beam combination. In this new scheme, each laser pulse has an independent medium cell to realize phase conjugation, so that the system load is separated into many cells and is a simple optical arrangement (Kong *et al.*, 2008). Their study indicated that the piston error between pump beams was the key factor of the beam combination (Kong *et al.*, 2007).

The serial laser beam combination based on Brillouin amplification uses several pump beams to amplify one seed pulse so that the phase is matched during the amplifying process. In this beam combination technology, the pump pulses and the seed pulse must be collinear to achieve the highest Brillouin amplifying efficiency. However, with increasing the number of pump beams, the beam combination structure becomes more and more complex because of a great amount of usage of polarizer and wave plates that are necessary to beam input and output in this system. Thus, in this article, we propose a non-collinear scheme to simplify the structure of the beam combination setup. Unlike the collinear scheme, there is an angle between the Stokes beam and the pump beam for the non-collinear scheme in the SBS cell. The pump pulse and the Stokes pulse can be injected into the amplification cell directly, and the amplified Stokes pulse is also output from the cell directly. So the polarizer and wave plates are not needed in the non-collinear scheme. Removing the wave plates and

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polarizer has significantly simplified the non-collinear scheme. With the non-collinear scheme, the key problem to be solved is achievement of high efficiency of the beam combination. In this article, the amplifying efficiency of the non-collinear scheme is investigated and discussed.

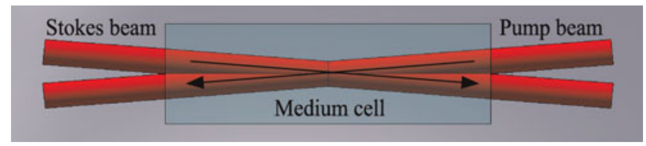

Fig. 1. (Color online) Model of non-collinear Brillouin amplification.

THEORETICAL SIMULATION

The geometry of non-collinear Brillouin amplification is shown in Figure 1, the angle between the Stokes beam and the pump beam is β. In this experiment, the pulse is a cylindrical beam so the intersection volume of the two beams is defined as the overlap volume *V*. The effective interaction length L_{eff} is defined by the result of *V* divided by the cross section area *S*. The beam diameter is given by *d*. So the effective interaction length L_{eff} in the medium cell is defined as

$$L_{eff} = V/S = \begin{cases} \frac{4}{3\pi}\frac{d}{\cos\alpha\sin\alpha} & (L_m \le L) \\ (V1+V2+V3+V4)/S & (L_m > L) \end{cases}, \quad (1)$$

where

$$S = \pi d^2/4,\ V1 = \frac{d^3}{3\sin\alpha\cos\alpha}$$

$$V2 = \left(\frac{\pi}{4\cos\alpha} - \frac{\arcsin(L\sin\alpha/d)}{2\cos\alpha}\right)d^2L$$

$$V3 = \frac{\sin^2\alpha}{6\cos\alpha}\sqrt{\left[\left(\frac{d}{\sin\alpha}\right)^2 - L^2\right]^3}$$

$$V4 = -\frac{d^2}{2\cos\alpha}\sqrt{\left(\frac{d}{\sin\alpha}\right)^2 - L^2},\ \alpha = \beta/2$$

L is the length of the medium cell, and L_m is the length of the intersection domain. In the one-dimension transient condition, the non-collinear Brillouin amplification process is seen as a wave vector mismatch process. The wave vector direction is the pulse propagation direction. Thus the mismatch angle is just the angle of the two beams. Finally the numerical model of the non-collinear amplification is shown below (Shuangyi *et al.*, 2007)

$$\left(\frac{n}{c}\frac{\partial}{\partial t} - \frac{\partial}{\partial z}\right)E_P = \frac{g\Gamma}{2}E_S\int_0^t E_S^* E_P \exp(-\Gamma(t-\tau))d\tau + \frac{1}{2}\alpha E_P \quad (2a)$$

$$\left(\frac{\partial}{\partial z} + \frac{n}{c}\frac{\partial}{\partial t}\right)E_S = \frac{g\Gamma}{2}E_P\int_0^t E_P^* E_S \exp(-\Gamma(t-\tau))d\tau - \frac{1}{2}\alpha E_S \quad (2b)$$

$$g = g_{\max}\frac{(\Gamma/\upsilon_a)^2}{(\Gamma/\upsilon_a)^2 + 4[(4\pi/\lambda)(1-(\cos(\beta/2)))]^2} \quad (2c)$$

$$L_{eff} = V/S = \begin{cases} \frac{4}{3\pi}\frac{d}{\cos\alpha\sin\alpha} & (L_m \le L) \\ (V1+V2+V3+V4)/S & (L_m > L) \end{cases} \quad (2d)$$

Where $g_{\max}$ is the medium gain coefficient. E_P and E_S are the pump and Stokes fields, respectively.

Using this model, the non-collinear Brillouin amplification process is simulated. FC-72 is chosen as the SBS medium and its parameters are given by: gain coefficient $g_{\max} = 6.0$ cm/GW, absorption coefficient $\alpha = 10^{-5}\text{cm}^{-1}$, medium refractive index $n = 1.25$, the Gaussian laser pulse widths are both 10 ns (full width at half maximum). As shown by Figure 1, the change of the angle will change the intersection area in the medium cell greatly, and therefore the effective interaction length changes too. Assuming that the cell length is 20 cm, the result according to Eq. (2) is shown in Figure 2. The angle impacts greatly on the effective interaction length. When the angle is nearly 90 mrad, the effective length reduces to half of the cell length. In other words, the cell length becomes short. But the change of the gain coefficient can be ignored. In conclusion, it is the effective interaction length that impacts the energy amplifying efficiency, but not the gain coefficient for this scheme. Fortunately, short cell length is good in the strong signal Brillouin amplification process. So the scheme is efficient in achieving high efficiency of amplification when the angle is limited within 200 mrad.

ANALYSIS AND DISCUSSION

According to the analysis above, the change of angle between the pump and the Stokes will directly influence the efficiency.

In the experiment, the energies of the Stokes pulse and the pump pulse are both 52 mJ, and the width of the pulse is 6 ns.

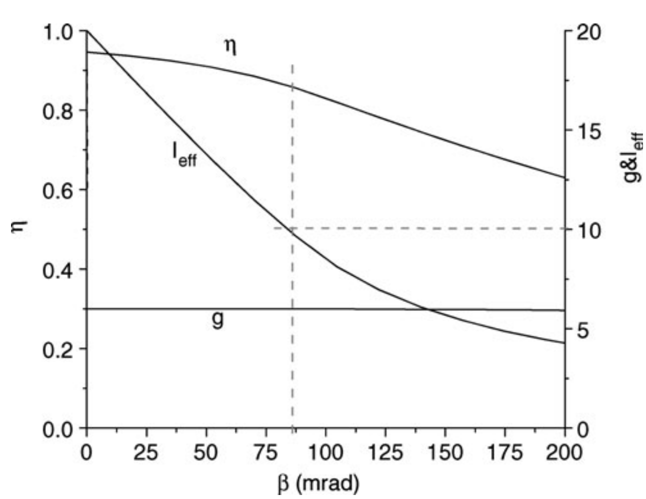

Fig. 2. Influence of cross-angle various on Brillouin amplification.

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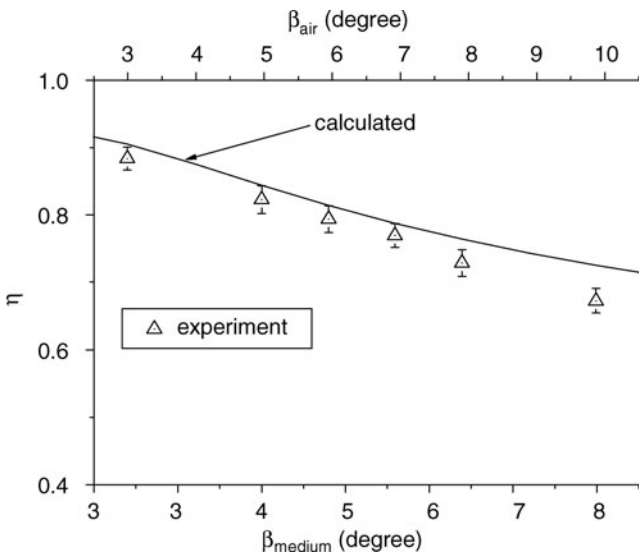

Fig. 3. Influence of various cross-angle on the Brillouin amplification.

Results of Brillouin amplification in different cross-angles can be obtained by adjusting the optical path gradually. The incident angle is defined as β_{air} and the refractive angle is defined as β_{medium}. Results from the experiment are shown in Figure 3. In the figure, the abscissa above represents the cross-angle between the pump beam and the Stokes beam outside the medium cell, while the abscissa below represents the cross-angle in medium cell. The influence of the two angles on the efficiencies is investigated by experiment, and the results are shown in Figure 3. As shown in the figure, on the condition of β_{air} varying from 3° to 10° energy extraction efficiency decreases along with the increasing of β_{air}. These experimental results are consistent with theoretical results.

As discussed above, non-collinear Brillouin amplification is efficient. With the simplest optical arrangement, two non-collinear laser beams are of great significance to the beam combination. On the one hand, the research can be helpful to seek the feasibility of Stokes beam amplification by multiple pump beams. On the other hand, it can also provide technical support on design of serial laser beam combination.

Based on research of signal pump beam amplification, experimental setup of the two-beam combination is shown in Figure 4. A Nd:YAG laser with pulse duration of $\sim$10 ns is split into three laser beams. One of them is used to the Stocks beam; the others are used as pump beams to combine into one.

The pump beam is divided by beam splitter into two beams: a reflected beam is reflected by mirror M5 and a transmitted beam is reflected by mirrors M3 and M4. The two pump beams are both reflected into the medium cell to amplify the Stokes beam together and the energies of the two beams are combined to one Stokes seed. The cross-angles between pump beams and the Stokes beam are both 5° (approximately 87 mrad). Length of the medium cell is 20 cm and the medium material is FC-72. Experimental results are shown in Figure 5.

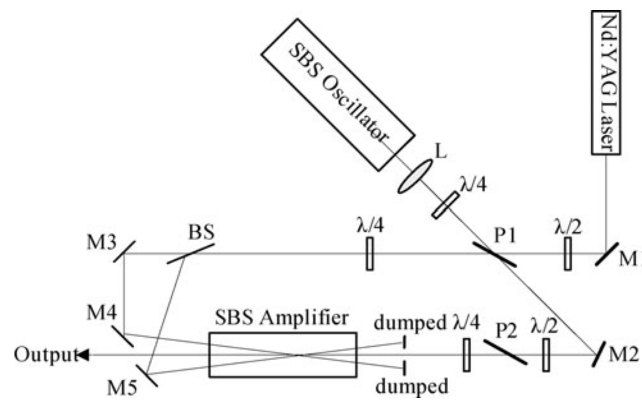

Fig. 4. Experimental setup of two-beam combination.

In order to characterize the efficiency of beam combination, two efficiencies are defined as (1) efficiency of beam combination $\eta_1 = E_{SA}/(E_S + E_P)$, and (2) depleted ratio of pump energy $\eta_2 = (E_P - E_{PR})/E_P$. Where E_{SA} and E_{PR} are the energy of the amplified Stokes beam and the residual energy of the pump beam after amplifying, respectively. E_S and E_P are the energies of the Stokes and the pump, respectively.

In Figure 5, η_{21} and η_{22} represents the depleted ratio of the two pump beams, respectively. As is shown in this figure, total energy extraction efficiency increases with the increasing of Stokes energy, and the efficiency of beam combination also increases. When the two pump beams are 47.1 mJ and 41.5 mJ, respectively, and Stokes beam is up to 88.0 mJ, a beam combination efficiency of 80.7% is achieved. Furthermore, a higher efficiency of beam combination is achieved with a higher energy of the Stokes beam, which results in a stabilization of the efficiency. The result demonstrates the efficiency of a non-collinear beam combination and is useful to the multi-beam combination with a strong Stokes seed (Ostermeyer *et al.*, 2008).

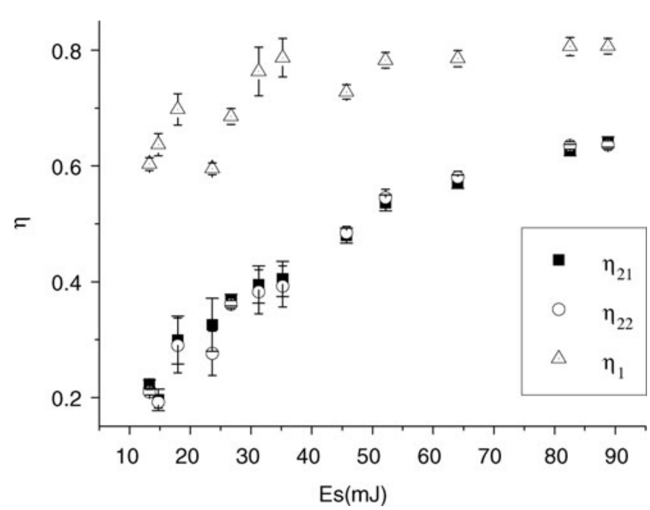

Fig. 5. Experimental results of two-beam combination based on non-collinear Brillouin amplification.

DESIGN AND DISCUSSION OF MULTI-BEAM COMBINATION

According to the discussion above, we know that the non-collinear beam combination has a higher efficiency compared with the linear beam combination. This provides a method for more effective and simpler laser beam combination scheme. In this section, a 20-beam combination is designed and the layout is shown in Figure 6. Here, the length of the medium cell is 10 cm, diameters of pump beam P1–P3, P4–P7, P8–P13, P14–P19 are 3 cm, 4 cm, 5 cm, and 6 cm, respectively. Using a non-collinear scheme, the 20-beam combination could be no larger than $150 \times 150\ \mathrm{cm}^2$. In order to get an effective combination, a regulation can be observed that the total gain of the system is near but not more than the Brillouin threshold. The output energy of 13.2 J will be expected by this 20-beam combination scheme with the energy of 818 mJ for every pump pulse. The efficiency of this beam combination is approximately 81%.

The layout shown in Figure 6 is still a complex application, even though the non-collinear scheme is simple. Therefore, to design such an application requires a special geometry. The following is a proposed design for a multi-beam combination based on the non-collinear scheme. The geometry is shown in Figure 7. In this scheme, multiple pump beams are injected into the same medium cell simultaneously, and the Stokes seed is amplified by all the pumps. Two aspects of this scheme are useful to the multiple beams combination: one is that higher pump energy is achieved by multiple pump beams and not a pump beam injected into single cell, thus higher Stokes energy is obtained. The other is that this layout is more compact and simple. What is more, multiple pump beams interacting with the Stokes beam at the same time also lessen time delay. To get a more effective combination, every stage of the non-collinear beam combination should satisfy the regulation that the total gain of the system is near but not more than the Brillouin threshold.

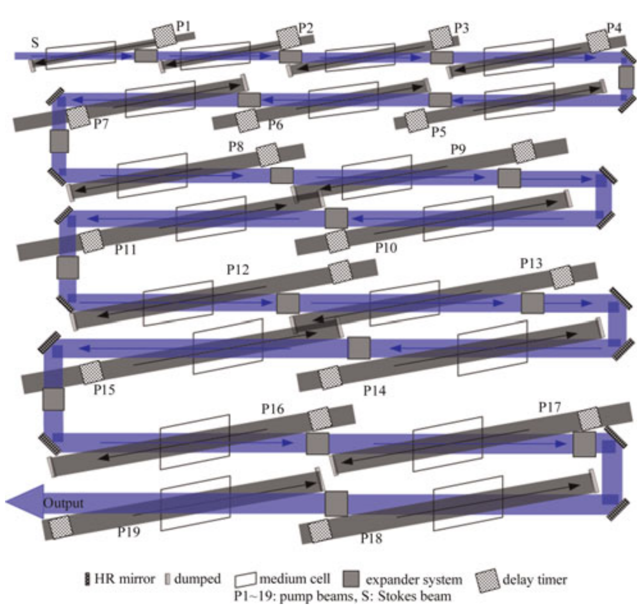

Fig. 6. (Color online) Layout of a twenty-beam combination with 10-cm-cell-length.

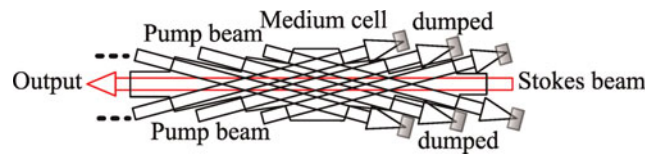

Fig. 7. (Color online) Scheme design of a serial beam combination based on multiple pump beams with non-collinear Brillouin amplification.

CONCLUSION

The non-collinear scheme of serial laser beam combination based on Brillouin amplification is presented. And the efficiency of beam combination is investigated. The results show that when the interaction length between the pump and the Stokes is long enough, a high efficiency can be achieved with the angle between the pump and the Stokes limited in 200 mrad.

The two-beam combination scheme is then studied. It is found that the energy extraction efficiency increased with the increasing of Stokes beam energy, and the combination efficiency increased too. A high beam combination efficiency of 80.7% was obtained in experiment with two pump energies of 47.1 mJ and 41.5 mJ and Stokes energy of 88.0 mJ. The experimental result is consistent with the theoretical analysis.

A 20-beam combination is designed with the parameters of a medium cell with length of 10 cm, laser beam cross-angle of 10°, pulse duration of 10 ns and the beam diameter of 1 cm. An output energy of 13.2 J will be expected, with an efficiency as high as 81%. The results show that the scheme of beam combination based on non-collinear construction is suitable to apply when the energy of a single laser beam is larger, since the larger size beam is needed in a high energy laser system. In order to simplify the complex construction of the twenty-beam combination, a special geometry is designed which is suitable in all the cases of a multiple-beam combination.

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