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High pulse-shape fidelity realized in stimulated Brillouin scattering generator with Stokes seed injection*

Yang Jun(杨 珺), Lü Zhi-Wei(吕志伟)†,
He Wei-Ming(何伟明), and Lü Yue-Lan(吕月兰)

Institute of Opto-Electronics, Harbin Institute of Technology, Harbin 150001, *China*

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In order to realize high pulse-shape fidelity of stimulated Brillouin scattering, a generator with Stokes seed injection is suggested and investigated. Theoretical and experimental researches show that the SBS duration becomes longer with the increase of the seed intensity, and the best pulse-shape fidelity of above 90% is experimentally obtained.

Keywords: stimulated Brillouin scattering, pulse-shape fidelity, pulse shape, seed injection
PACC: 4265C, 4265F

1. Introduction

Although phase-conjugation fidelity of stimulated Brillouin scattering (SBS) has been widely investigated, little attention has been paid to the pulse-shape fidelity. An important feature of traditional SBS phase conjugate mirror (PCM) is its shorter output pulse duration and its steeper leading edge in comparison with the input pulse. However, some of its potential applications in Inertial Confinement Fusion (ICF) laser drivers require that it should keep the SBS pulse shapes identical with the pump pulses, or at least that these two pulse shapes have stable correlation,[1,2] which is rather difficult to realize. Two reasons are responsible for the difficulty: the threshold nature of the SBS process and the nonlinearity of amplification under saturation. Additionally, it takes a finite time for the acoustic wave to establish in the SBS medium, which influences the SBS pulse shape. The most efficient means to make the deformation lowest is injecting a weak Stokes seed into the SBS generator.

In this paper, a novel SBS PCM scheme with high pulse-shape fidelity is suggested: inject a Stokes seed into the single-cell SBS generator, and the SBS process is initiated by this Stokes seed. In this process, the acoustic wave driven by the interference of the pump and the injected seed has shorter response time and better phase-conjugate phonon mode than that from spontaneous noise. It can reduce the SBS threshold and the conjugate acoustic wave does not need a long establishing time. So the SBS pulse deformation is minimized. Using a special definition of pulse-shape fidelity, pulse-shape fidelity is simulated in theory. Experimental results prove that the injection of Stokes seed improves the pulse-shape fidelity in a single-cell system.

2. Theory

2.1. Mathematic model

The weak Stokes seed with high beam quality is generated by another SBS cell with the same SBS medium. Stokes seed and the pump wave are counter-propagating. The focused pump field should be fully contained in the seed field.

Theoretical treatment of optical phase conjugation by SBS is based on the Maxwell wave equation and Navier–Stokes equation.[3,4] Omitting the transverse variation of waves and applying the usual slowly-varying-amplitude approximation, the transient SBS

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†E-mail: zhiweilu@yeah.net

equations can be written as[5,6]

$$\frac{\partial E_{\rm L}}{\partial z}-\frac{n}{c}\frac{\partial E_{\rm L}}{\partial t}=-{\rm i}g_{\rm L}\rho E_{\rm S}+\frac{\alpha}{2}E_{\rm L}, \tag{1a}$$

$$\frac{\partial E_{\rm S}}{\partial z}+\frac{n}{c}\frac{\partial E_{\rm S}}{\partial t}={\rm i}g_{\rm S}\rho^{*}E_{\rm L}-\frac{\alpha}{2}E_{\rm S}, \tag{1b}$$

$$\frac{\partial \rho}{\partial t}+\Gamma\rho={\rm i}g_{a}E_{\rm L}E_{\rm S}^{*}. \tag{1c}$$

Here $E_{\rm L}$, $E_{\rm S}$ and ρ are amplitudes of the pump, Stokes and acoustic phonon, respectively. $g_{\rm L}$, $g_{\rm S}$ and $g_{\rm a}$ are SBS coupling coefficients associated with the Brillouin medium. α is the absorption coefficient. Γ=$1/2\tau_{\rm P}$ denotes the spontaneous Brillouin linewidth where $\tau_{\rm P}$ gives the phonon lifetime.

Let $g_{\rm L}\approx g_{\rm S}=g_2$, $g_a=g_1$, the solution of Eq.(1c) is

$$\rho(z,t)={\rm i}g_1\int_0^t E_{\rm L}E_{\rm S}^{*}\exp[-\Gamma(t-\tau)]{\rm d}\tau, \tag{2}$$

here $E_{\rm L}$ and $E_{\rm S}^{*}$ are the interference driving terms.

Substituting Eq.(2) into Eqs.(1a) and (1b), considering the variation of the cross-section σ and using the transform $g=2g_1g_2/\Gamma$, we have

$$\left(\frac{\partial}{\partial z}-\frac{n}{c}\frac{\partial}{\partial t}\right)E_{\rm L}$$
$$=\frac{g\Gamma}{2\sigma}E_{\rm S}\int_0^t E_{\rm S}^{*}E_{\rm L}\exp\left[-\Gamma\left(t-\tau\right)\right]{\rm d}\tau+\frac{1}{2}\alpha E_{\rm L}, \tag{3a}$$

$$\left(\frac{\partial}{\partial z}+\frac{n}{c}\frac{\partial}{\partial t}\right)E_{\rm S}$$
$$=\frac{g\Gamma}{2\sigma}E_{\rm L}\int_0^t E_{\rm L}^{*}E_{\rm S}\exp\left[-\Gamma\left(t-\tau\right)\right]{\rm d}\tau-\frac{1}{2}\alpha E_{\rm S}. \tag{3b}$$

By implicit finite difference in time and backward difference in space, Eqs.(3) are discretized and numerically simulated. Boundary conditions are $E_{\rm S0}(z=0,t)=E_{\rm S0}$ and $E_{\rm LJ}(z=L,t)=E_{\rm LJ}(t)$. Pump and Stokes power is given as $P_{\rm L}=|E_{\rm L}|^2$ and $P_{\rm S}=|E_{\rm S}|^2$, thus forming a complete mathematical model.

2.2. Simulated results

There have been few reports on pulse-shape fidelity to date, and there is no existing method to scale it in mathematics, so here a pulse-shape fidelity F is defined as the pulse-shape fidelity criterion which is the energy ratio of peak-power-normalized output Stokes pulse to that of pump pulse:

$$F=\frac{\int\tilde{E}_{\rm S}'(z,t){\rm d}t}{\int\tilde{E}_{\rm L}'(z,t){\rm d}t}=\frac{\int\dfrac{\tilde{E}_{\rm S}(z,t)}{|E_{\rm S}(z)|}{\rm d}t}{\int\dfrac{\tilde{E}_{\rm L}(z,t)}{|E_{\rm L}(z)|}{\rm d}t}$$
$$=\frac{|E_{\rm L}(z)|}{|Es(z)|}\cdot\frac{\int\tilde{E}_{\rm S}(z,t){\rm d}t}{\int\tilde{E}_{\rm L}(z,t){\rm d}t},$$

where $\tilde{E}_{\rm L}'$ and $\tilde{E}_{\rm S}'$ are the normalized pump wave and Stokes wave, respectively.

CCl_4 is used as SBS medium and the following parameters are applied in numerical simulations: L=50cm, $\tau_{\rm P}$=0.6ns, n=1.5, g=4cm/GW and α=0cm^{-1}. The wavelength of the incident pump pulse is 1μm with 2ns FWHM, and has a Gaussian intensity profile with peak power 1MW.

To compare the temporal profiles of traditional SBS with those induced by injected Stokes seed, the reported noise initiation model[7,8] was adopted to calculate the pulse shapes of traditional SBS. And pulse profiles output from this seeded SBS model with different seed intensities were simulated. Results at f=5cm are shown in Fig.1. For the no-seed case, the SBS is developed from thermal noise after the pump pulse intensity exceeds the threshold, the SBS has a steep leading edge, and the pulse duration is compressed. However, when the Stokes seed is injected, the leading edge is no longer so steep, with increasing of the seed intensity from 10^{-12}MW/cm^2 to 10^{-6}MW/cm^2, the pulse duration becomes longer and almost the same as the pump pulse. Obviously, the injected Stokes seed improves SBS pulse shapes.

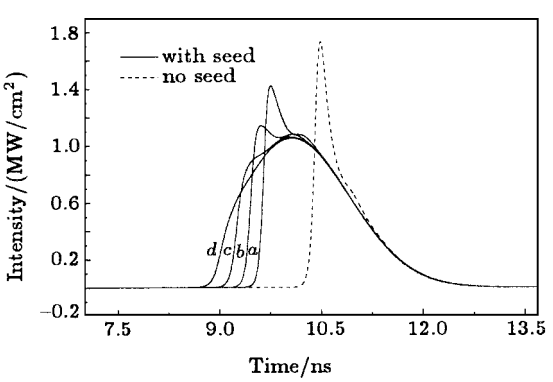


Fig.1. Pulse shapes of SBS for two cases of no seed and injected seed with seed intensity 10^{-12} (a), 10^{-10} (b), 10^{-8} (c), 10^{-6} (d) MW/cm^2.

Figure 2 illustrates the dependence of pulse duration and its shape fidelity on focal length when seed

intensities are 10^{-3}MW/cm^2 and 10^{-6}MW/cm^2. It shows that the pulse duration becomes shorter with the increasing of the focal length; accordingly, the fidelity falls down. It is concluded that the focal length should be as small as possible and the seed intensity be large enough to keep good shape fidelity.

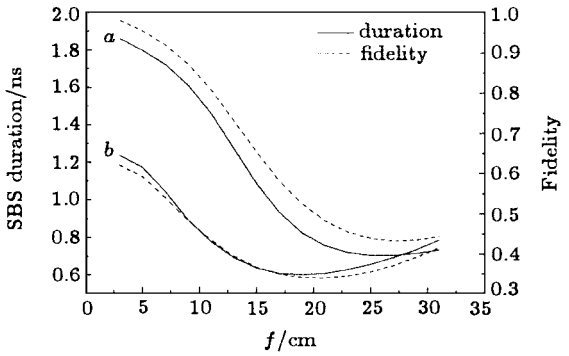


Fig.2. Dependence of SBS duration and fidelity on focal length for seed intensities 10^{-3} (a) and 10^{-6} (b) MW/cm^2.

The dependence of SBS pulse duration and pulse shape fidelity on the injected seed intensity for different focal lengths is shown in Fig.3. When increasing seed intensity, pulse duration becomes longer, tending to the pump duration, i.e. the pulse shape fidelity should be close to 1. This can be explained as that the injected Stokes seed reduces the SBS threshold, so the amplification process takes place at the end of the leading edge of the pump pulse, and the pulse shape of Stokes follows that of the pump. Moreover, the fidelity falls down with increasing focal length, which is in accord with results of Fig.2. This may be explained as follows: with the increasing of Rayleigh length for longer focal length, the effective interaction length increases, which is beneficial to the amplification of leading edge, and leads to steeper leading edge.

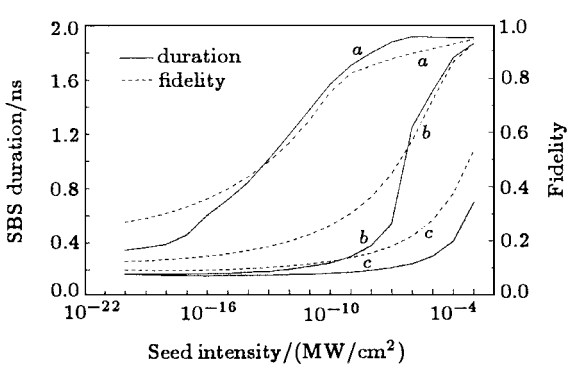


Fig.3. Dependence of SBS pulse duration and fidelity on seed intensity for focal length f=5cm (a), f=10cm (b), f=15cm (c).

3. Experiments

3.1. Experimental setup

The schematic of our experimental setup is shown in Fig.4. A Q-switched Nd:YAG laser oscillator produces single longitudinal quasi-Gaussian pulses with duration 12–13ns, wavelength 1.06μm and linear polarization at 1Hz repetition rate. A large part of the output from the Nd:YAG amplifier transmits through the reflector R and is focused into a two-cell pulse compressing conjugate mirror (C_1 and C_2). The produced backward pulse is reflected by polarizer P_2 and coupled by M_3 and M_4 into the SBS cell C of length 50cm, working as the pump beam. With the aid of polarizer P_3, the beam reflected by R is coupled into a two-stage SBS system consisting of C_3 and C_4, and the produced conjugate beam is directed into the SBS cell C, working as the Stokes seed beam. Pump and seed beams are adjusted to meet at the focus. P_2 extracts the output SBS. All SBS cells are filled with CCl_4. Energy-detectors ED1 (ED200) and ED2 (ED200) detect the energy of pump beam and output Stokes beam, respectively, while energy of the Stokes seed is detected by ED3 (ED200). Pulse shapes are detected by high-current tube and recorded by digital oscilloscope TDS684A.

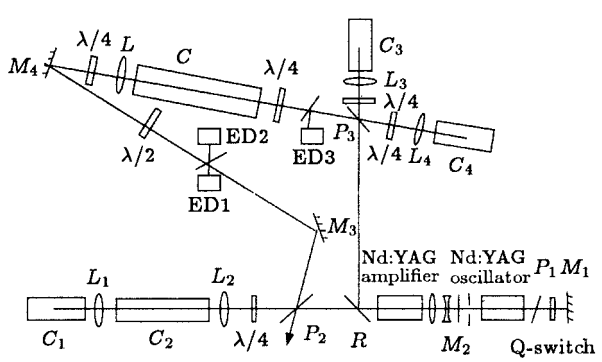


Fig.4. Schematic of experimental setup.

3.2. Experimental results and discussions

Figure 5 shows typical profiles of pump and SBS without seed injection at f=10cm and f=5cm. It shows that Stokes duration is compressed.

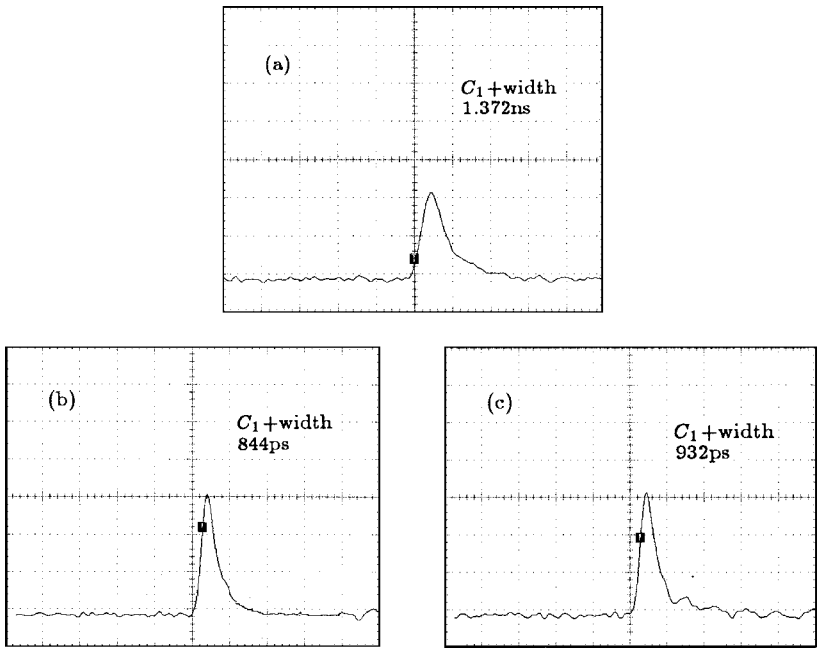


Fig.5. Temporal profiles of pump (a) and SBS with different focal lengths (b) f=10cm, (c) f=5cm).

Typical profiles of SBS induced by Stokes seed with different focal lengths are shown in Fig.6 and Fig.7. The variation of seed intensity was realized by attenuating seed energy with various attenuators. In the experiments, the energy of pump beam was 22mJ, while seed energy changed from 2.6mJ to 6×10^{-5}mJ. Seed intensity was calculated from the measured energies and the spot sizes, and varied from 10^{-11}MW/cm^2 to 10^{-6}MW/cm^2 approximately. It can be seen that injected Stokes seed weakens the effect of pulse compression, the SBS durations are longer than those of traditional SBS. The focal length also has an effect on SBS pulse duration: a longer one gives shorter duration. It is too laborious to calculate F for every measured point, so SBS duration is adopted to evaluate the shape fidelity in the experiments. Only values of some pulse-shape fidelity of the best pulse shapes are calculated. For example, the pulse-shape fidelity of pulses in Fig.6(d) is about 90%; and 87% in Fig.7(d). Compared with the 48% of Fig.5(c) and 40% of Fig.5(b), this suggests that seed injection improves the pulse shape fidelity.

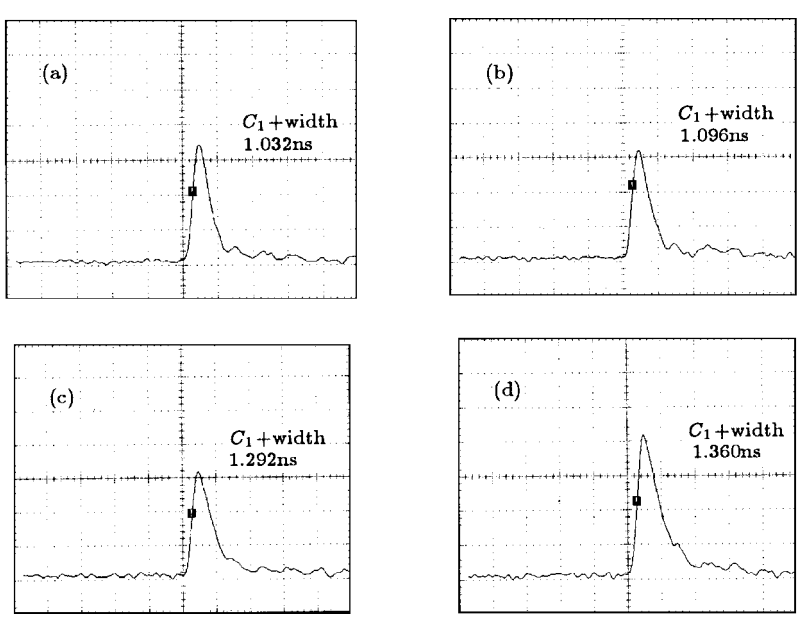


Fig.6. Dependence of SBS pulse shape on seed intensity. f=5cm (seed intensity: (a) 1.0×10^{-11}, (b) 1.0×10^{-9}, (c) 1.0×10^{-8}, (d) 1.0×10^{-6}MW/cm^2).

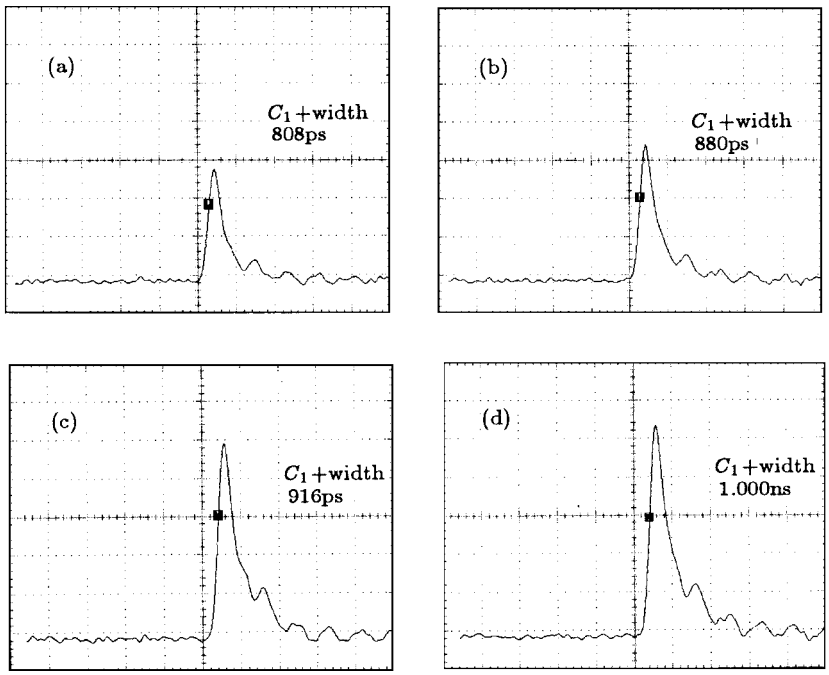


Fig.7. Dependence of SBS pulse shape on Stokes seed intensity. f=10cm (seed intensity: (a) 1.0×10^{-11}, (b) 1.0×10^{-10}, (c) 1.0×10^{-9}, (d) 1.0×10^{-8}MW/cm^2).

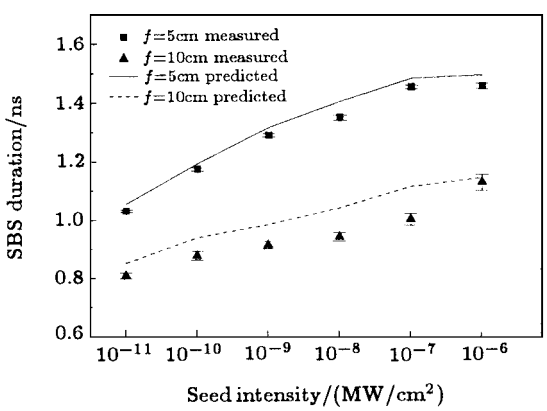


Fig.8. Dependence of SBS duration on Stokes seed intensity with different focal lengths.

The dependence of SBS duration on seed intensity is shown in Fig.8. Squares and triangles denote experimental results at f=5cm and f=10cm, respectively, while solid and dashed curves show their theoretical calculations. The mean duration of pump pulse was about 1.5ns. SBS duration becomes longer with increasing of the seed intensity, tending to that of the pump; but shorter focal length can give longer duration. Previous theoretical simulation agrees with these results. Theoretical and experimental trends are the same. However, the theoretical calculations are in better quantitative agreement with experimental points when focal length is 5cm, and in the 10cm case the experimental points are lower than the theoretical. Possible reasons are that various nonlinear optical effects have more influence on the SBS medium in the cell when the focal length is 10cm, and that peaks of SBS pulses impact on the accuracy of measurements. Here the highest pulse-shape fidelities are calculated as about 92% and 73% when focal lengths are 5cm and 10cm, respectively.

4. Conclusions

In conclusion, to overcome the pulse compression effect of the SBS process, a Stokes seed is injected into the SBS generator, the SBS grows from the injected Stokes seed and then has high pulse-shape fidelity. Theoretical and experimental results show that the Stokes seed injection improves pulse-shape fidelity of SBS to the pump beam. Though the pulse-shape fidelity is enhanced with the increasing of seed intensity, too intense a seed will bring instability. So our experiments were performed with low energy; simulation results prove that with energy of several hundred mJ, good pulse-shape fidelity can be maintained.

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