第 33 卷第 11 期
2021 年 11 月

强 激 光 与 粒 子 束
HIGH POWER LASER AND PARTICLE BEAMS

Vol. 33，No. 11
Nov.，2021

·Feature Issue on Novel Laser Technology•Overview·

Phase conjugation lasers based on stimulated Brillouin scattering with high-power and high-energy

Akinyimika Adewale[1,2,3]， Wang Yulei[1,2]， Bai Zhenxu[1,2]， Li Yunfei[1,2]， Lu Zhiwei[1,2]

（1. *Center for Advanced Laser Technology*, *Hebei University of Technology*, *Tianjin* 300401, *China*;
2. *Hebei Key Laboratory of Advanced Laser Technology and Equipment*, *Hebei University of Technology*, *Tianjin* 300401, *China*;
3. *Department of Physics*, *Federal University of Technology Akure*, *P. M. B* 704 *Akure*, *Nigeria*）

Abstract: Stimulated Brillouin scattering (SBS) is a third-order nonlinear process, which is phased conjugation reflected in the SBS phase conjugation mirror (SBS-PCM). Therefore, it is a very useful tool for the compensation of wavefront distortion induced by strongly thermally stressed active material, especially in high-power and high-energy lasers. To maximize the effectiveness of SBS-PCM, many research efforts have been poured in both theoretically and experimentally in the past decades. Several researchers have studied the liquid medium that is the best fit for SBS-PCM in high power laser systems; some have investigated the geometry (such as two-cell structure, choice of the optimum parameters, and the addition of a rotating wedge) of the system that will give the most appropriate desired characteristics; while some researched the impurities of the selected liquid. This work presents a review of the factors determining the performance of SBS-PCM, the applications of SBS-PCM in high power lasers, and recent scientific achievements in the SBS-PCM high power laser systems. This work is proposed as a reference and guiding manual for SBS-PCM-related experiments and research.

Key words: stimulated Brillouin scattering; phase conjugation mirror; energy reflectivity; optical breakdown; repetition rate

CLC number: TN242 **Document code:** A **doi**: 10.11884/HPLPB202133.210313

With the increase in laser output power or pulse energy, a great amount of scientific and industrial applications, for example, laboratory astrophysics[1-9], high energy density physics[10-17], fluid and plasma physics[18], material processing[19-21], basic research of inertial fusion[22-23], require lasers delivering high-quality optical beams whose divergence must not exceed the diffraction limit during beam propagation. However, beam quality keeps deteriorating with increasing pump power and repetition rate because of the continuous increase of heat accumulation at the strong pumping. Stimulated Brillouin scattering (SBS) has been hotly pursued for its unique ability to restore an aberrated beam to the original undistorted state in real-time since its discovery in 1972 by Zel'dovich *et al*[24]. SBS phase conjugation mirrors (SBS-PCMs) have been successfully used to compensate beam distortion[25-28] and control the phase conjugation-fidelity[29-33] caused by an optical phenomenon. Hence, it has improved the performance of high-power lasers[26-27, 34-46]. As a result of the SBS-PCM employed in high-power lasers, it can be used in systems requiring high beam quality such as space communication, laser fusion, and LiDAR[46-48].

To obtain the best SBS-PCM performance in high-power lasers, the SBS medium with a high optical breakdown threshold (OBT) and low absorption coefficient (AC) such as heavy fluorocarbon liquids must be adequately selected[49-52]. Among various gain media such as solids, gaseous, plasma media and vortex beam[29, 45-46, 49-56], liquid materials have obtained more popularity over other materials in SBS-PCM, due to their low cost, broad Brillouin linewidth, and easy design of liquid SBS cells with nearly no restriction in volume (in both length and cross-section)[49, 57-59]. However, particles in the selected medium

* **Received date:** 2021-07-24; **Revised date:** 2021-11-02
Foundation item: National Natural Science Foundation of China (62075056)
Biography: Akinyimika Adewale: walestev2012@gmail.com.
Corresponding author: Wang Yulei, wyl@hebut.edu.cn.

easily absorb electromagnetic radiation and increase thermal accumulation thereby resulting in optical breakdown[26-27, 51, 52]. Hence, the selected liquid material required quality purification. Besides, the structural design and composition of the system, such as the choice of lens focal length[25-26, 51, 60-61], incorporation of a rotating wedge[25, 51, 62-63], and two-cell structure[45, 60] , are other key factors that also influence the SBS characteristics of an SBS-PCM system. To obtain the best SBS-PCM system, the components of the system must be optimized.

Normally, a certain fraction of the pump energy is used to overcome the threshold energy of the SBS medium which varies for different media. Except when the pump energy is greater than the threshold energy of the medium used in the SBS experiment, no Stokes wave will be generated[64-65]. Owing to this property of the medium and the energy needed to generate an acoustic wave, the spatial frequency of the Stokes wave is lower than that of the original pump wave (the frequency of the Stokes wave is down-shifted). This paper also reports some scientific works that reduce this phenomenon to the barest minimum using different approaches including self-generated density modulation and prepulse. Although many scientists and engineers have successfully used phase conjugation mirrors to compensate for phase distortion, the thermal-induced birefringence of the active medium by a photo-elastic effect causes an inevitable depolarization loss. This paper also reviews some scientific works that benefited the reduction of this undesirable effect.

In high average power lasers, SBS-PCMs with liquid medium produce both high beam quality and high average power, compensating for both static and dynamic wavefront distortions induced by thermal effects[46, 54, 66-67]. However, at high pump energy and high repetition rate operation, heat accumulation at the focal point is always a challenge associated with SBS-PCM. Beam quality, energy reflectivity, phase fidelity, and other SBS parameters[68-70] are affected by the heat accumulation at the focus point which always causes thermal defocusing. To improve the current scientific achievement in the attempt to develop a laser system that simultaneously achieves high repetition rate, high energy reflectivity, and high beam quality, this paper additionally provides a review of some research works in these areas.

The fact that there have been some reviews on SBS, recent advances in laser technology call for a review of more recent works in the growing field of SBS-PCMs, as well as suggesting ideas for experimental designs and practical applications to optimize the performance of the system. This paper reviews the working principles and applications of SBS-PCM, the achievement of some recent SBS-PCM systems under different operating conditions, the SBS-PCM media suitable for high power lasers, experimental methods, and design of SBS-PCM devices. This review intends to provide a guide for the selection of SBS-PCM media, media purification, and experimental and geometric design that enables a highly stable and efficient SBS-PCM system in applications.

1　Phase conjugation by SBS

Stimulated Brillouin scattering involves the interaction between incident light, scattered light, and acoustic phonons induced by electrostriction. This is the physical compression of a medium owing to the large electric fields. Many high-power phase conjugation resonators use SBS[71-72]. SBS is a cubic power ($\chi3$) nonlinearity, $\chi3$ ($\omega_L = \omega_s + \omega_Q$) is the optical phenomenon generated as a result of the interaction of intense laser light with elastic acoustic waves in materials such as solid, liquid, gas or plasma[71]. ω_L is the incident light, ω_s is the Stokes energy and ω_Q is the phonon energy. Fig.1 is the energy level profile of this optical phenomenon.

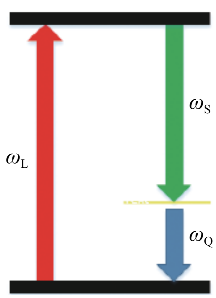

Fig. 1　Nonlinear SBS energy level diagram; ω_Q is the phonon frequency, ω_S is the Stokes frequency, and ω_L is the frequency of the incident electromagnetic wave[73]

Zel'dovich *et al.*, 1972 experimentally discovered phase conjugation in high-pressure methane gas. A focused strongly aberrated light into a nonlinear medium generates a non-uniform SBS, that is, an acoustic wave. Under normal operating conditions, the phase conjugation component of the Stokes wave can receive a linear gain e^{15} times larger than any other component[74].

In an SBS-PCM system, a high peak power pulsed laser is required instead of a continuous wave laser because: (1) the SBS threshold is often high, that is, SBS depends upon power over a short time; (2) SBS-PCM behaves like a saturable absorber; and (3) the Stokes frequency shift causes each mode to "lock" a mode of lower frequency.

2 Factors influencing the performance of SBS-PCM

Many scientific works have proven that beam quality deteriorates heavily with the higher operating power condition of the SBS-PCM. In addition to improving the load and operating power conditions, many scientists have investigated the factors that might be responsible for the side effects associated with the SBS-PCM system under high power operating conditions and mentioned that the liquid medium, the level of impurities, and the geometry of the system (focal length of the focusing lens, structure of the system, and introduction of a rotating wedge) influence the characteristics of the reflected energy and the performance of the SMS-PCM system. This section reviews a few of these studies related to SBS-PCM using a liquid medium. At high energy and high power, the AC, the gain coefficient (GC), and the OBT are the major factors affecting the fidelity and reflectivity of liquid SBS medium[51, 56, 72-77].

2.1 SBS-PCM media

Hasi *et al*., 2008 reported some SBS media and studied the relationships between SBS characteristics of perfluoro-compound (PFC) and perfluoropolyether (PFPE), and analyzed their chemical structures in detail. The SBS thresholds, the OBTs, the ACs, and the Brillouin frequency shifts of some media such as FC-43, FC-87, HT-55, and DET were measured. Furthermore, the Brillouin linewidth, phonon lifetime, and the GC of each medium were calculated. The results showed low ACs and high OBTs which were good SBS properties for media suitable for high power lasers[75].

Because of the unavailability of FC-75, it is necessary to find a substitute for it, and to obtain a better energy extraction efficiency and beam quality. Kmetik et al. 2000 reported high energy optical phase conjugation through SBS in FC-72, FC-75, and FC-77. These media were filtered with a millipore membrane of 25 nm pore size. The pulses energy of 73 J in near-IR-1 μm laser were phase conjugated without an optical breakdown using an SBS-PCM. This paper also reviewed the importance of ultra-filtration in building efficient, safe, stable, and convenient SBS-PCM in the near-IR region[37].

Guo *et al*., 2012 designed an experiment to accurately measure the OBTs and ACs of PFCs and PFPEs media, studied some SBS characteristics, and suggested suitable media for high peak power SBS systems. The experiment is similar to Fig.2. Their findings show that though there are differences between these media, PFCs media generally have small AC and high OBT, and that FC-72 has the highest OBT among the PFCs. For the PFPE family, OBT decreases and AC increases, as the average molecular weight (AMW) increases. The media with AMW lower than 1000 (e.g., DET, HT-70, HT-135, and DO_3) have small AC and high OBT which are suitable for high power SBS-PCM systems. On the other hand, media with AMW greater than 1000 (such as HS-260, HT-270, and HT-230) have high AC and low OBT. This implies that for PFPE series SBS media, the larger the AMW, the more the AC and the less the OBT. A new PFPE medium could be obtained by mixing HT-230, HS-260, and HT-270 in careful ratio with different AMW. The measured energy reflectivity of PFCs are very close; and due to the small GC of FC-70, its reflectivity is relatively low. There are large differences in the energy reflectivity of PFPEs. At pump energy greater than 200 mJ, optical breakdown occurs and reflectivity decreases[50]. Wang *et al*., 2010 measured the reflectivity of acetone, CCl_4, FC-72, and HT-230 at varying input energy and operating system of 10 Hz. FC-72 has the highest reflectivity of all the media studied. Its reflectivity is 70.5% at 100 mJ and about 78.8% at 300 mJ[51]. Being the medium with the highest breakdown threshold, about 66.3% reflectivity was still reported at 450 mJ. This reveals that FC-72 is a good medium for high-power SBS because of its high GC, low AC, and large breakdown energy.

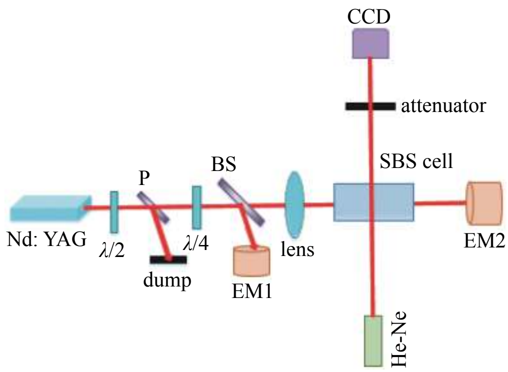

Fig. 2 Experimental set-up for measuring SBS medium properties (e.g., OBT)[48]

These media did not only increase the list of SBS media suitable for high power laser systems but also modify the performance of the SBS system, thereby improving the foundation for the application of SBS-PCM in high-power laser systems. The long list of PFCs and PFPEs provides a wide choice of media in practical applications. For example, the medium with small GC is selected if a flat-top waveform beam with a high energy transmissivity is preferred[78]; on the other hand, when there is a need to generate Stokes light with a high energy reflectivity, a high GC medium is used[79].

2.2 Purification of the SBS media

After the discovery of FC-72 as a gain medium with the highest OBT which makes it a good choice for high power laser systems, Wang *et al*., 2010 studied the reflectivity of the FC-72 at different levels of purity and reported different amounts of energy reflectivity at different levels of impurities. The reflectivity increased greatly after cleaning the liquid with 0.22 μm aperture millipore membrane filters. The experimental result shows that for unfiltered medium, there is evidence of breakdown at 160 mJ input energy and there is a rapid reduction in reflectivity with an increase of energy. At 300 mJ, it is only 50.3%. For a filtered medium with an aperture of 0.65 μm, 0.45 μm, and 0.22 μm, breakdown energies are 220 mJ, 270 mJ, and 350 mJ, respectively and, notable increase in reflectivity of 62.8%, 70.8%, and 78.4% at 300 mJ[51]. Wang *et al*. 2010, also cleaned the SBS medium with a filter of 0.22 μm aperture and reflectivity was evidently increased from 71.2% to 80%[60]. Xiongxin *et al*., 2017 used an ultra-filtration technology to filter FC-770, and obtained 98% energy reflectivity without optical breakdown under repetition rate of 200 Hz and at pump energy ranging from 500 mJ to 1100 mJ. The good stability of the reflected energy shows that ultrafiltration and good cleaning are useful methods of reducing thermal effect and improve the stability of SBS-PCM[27]. Kang *et al*., 2018 used an ultraclean closed-type single SBS-PCM cell to reduce the micro-particles of the SBS-PCM medium to 40 nm which significantly improved the thermal load ability of the closed-type SBS-PCM system. The system reported 92% energy reflectivity and no optical breakdown or serious thermal effects at 500 Hz pulse-repetition frequency (PRF) at about 120 mJ input or pump energy[26].

2.3 Geometry of the system

As proven by some researchers, the geometry of the system which includes the choice of lens focal length, the introduction of a rotating wedge, and the use of circulating two-cell structure are also some of the factors determining the performance of SBS-PCM. As reported by Gvger *et al*., 2020, lens focal length had a great impact on load capacity. 50 cm focal length was proven to be the most appropriate lens at 1 J input energy and 10 Hz repetition laser system. The experiment was conducted with lenses of a different focal length of 10 cm, 15 cm, 20 cm, and 30 cm while other parameters like SBS-PCM medium, the repetition rate of 10 Hz, input energy among others remain constant. It was reported that 30 cm focal length gave the highest reflectivity of 66.3% at 100 mJ and 83.1% at 450 mJ while optical breakdown occurs at 500 mJ[53]. Wang *et al*., 2010 also studied the effect of lens focal length on the reflectivity of an SBS-PCM system. It obtained reflectivity of 63.0%, 67.3%, and 70.4% for focal lengths of 7.5 cm, 20 cm, and 30 cm respectively at the input energy of 1 J and repetition rate of 10 Hz[60]. However, the result reported by Wang *et al*, 2019 was a little contradicting. At 50 mJ input energy, the reflected energy was about 30 mJ for 10 cm focal length while that of 15 cm focal length was about 13 mJ at the same input energy and high repetition rate. This result shows that the reflected power under the experimental structure with a focal length of 15 cm is much lower than that of a focal length of 10 cm, indicating that a short focusing lens can obtain higher SBS reflection energy[60-61], the changing trend is consistent with the trend under low repetition frequency.

Wang *et al*., 2010 introduced a rotating wedge into an SBS-PCM system to scatter the focal spot in the pool which made the focal point rotate with respect to the rotation of the wedge and discovered that the thermal gradient and the optical breakdown that, were induced due to absorption around the focus point were reduced. Hence the SBS reflectivity and stability were both improved[51]. Under the experimental conditions of 50 mJ at 1 kHz, Wang *et al*., 2019 used the rotating wedge method in addition to other methods and reported a high energy conversion efficiency and a good beam pattern. With the rotating wedge method, an energy reflectivity of about 78% was reported[25]. Wang *et al.*, 2010 also used a rotating wedge to improve the load ability of the SBS-PCM and for the compensation of phase aberration[80].

To optimize the influence of the rotating wedge on energy reflectivity, Wang et al., 2019[25]and Li et al., 2008[62]designed the wedge SBS-PCM (shown in dge SBS-PCM (shown in Fig.3(a)) and came up with some ideas that (1) the laser focus points should not overlap, (2) to spread the focal points, in other words, the thermal effect of the laser across a large area, R should be greater than 3 mm ($R \geqslant 3$ mm) and, (3) D should also be greater than 2 mm, shown in Fig.3 (b). In such a way, the thermal effect of the system can be effectively mitigated[62]. Where R is the distance between the center position of the focal point after a deflection and the center position of the focal point without deflection, and is also the radius of focus rotation after a deflection. R_f is the radius of the laser focus, and D is the distance between the focal points of two adjacent pulses.

Wang *et al*., 2010, designed a circulating two-cell structure (shown in Fig.4(a)) using FC-72 as the SBS medium and experimentally studied its advantages over a traditional SBS-PCM structure using the same medium. Maximizing the focusing lens and the collimation lens to obtain maximum efficiency, lens focal lengths of 30 cm and 150 cm were selected respectively. Compa-ring the result with one-cell structure, the circulating two-cell structure achieved higher energy load, good stability, and 84.7% reflectivity[60]. Jaberi *et al*., 2017 reported the effects of longitudinal modes structure on SBS energy reflectivity and temporal waveform of the reflected pulse for a single and two-cell SBS-PCMs (shown in Fig.4(b)). The results show that when the laser oscillator operates in a multi-mode regime, the two-cell PCM has better performance in terms of energy reflectivity and waveform correction. However, 80% highest energy reflectivity was recorded when the laser operates in a double-mode structure[45].

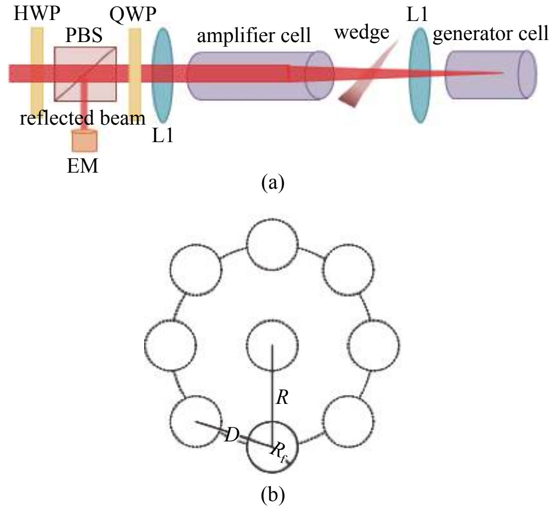

Fig. 3 (a) SBS-PCM system with a rotating wedge[25] and (b) laser spot at focus plane[62]

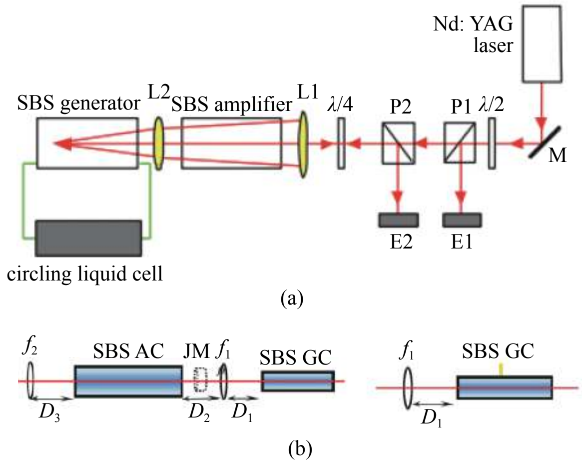

Fig. 4 (a) Experimental setup of the circulating two-cell structure[60], (b) two SBS cell structure (right) and single cell setup (left)[45]

3 Wavefront correction and fidelity

The waveform of the normal SBS wave generated in the SBS process usually shows a steep rising edge because, during the creation of the acoustic wave, the pump wave loses the front path of its energy to generate the acoustic Brillouin grating. Hence, the reflected wave is deformed[65]. The quest to successfully control the phase conjugation-fidelity of SBS with high pump energy more accurately and conveniently has given birth to much research because high reflectivity and good phase conjugation fidelity are required for high energy pump beams such as in beam combination systems. SBS-PCM has also been used with double-pass amplification to mitigate this undesirable effect and provides output beam of high quality[29, 34, 43-46, 81]. It should also be noted that the beam distortion will also increase greatly with constant amplification of the laser beam energy. This section reports some scientific progress in eliminating this problem.

Kong *et al*., 2005 stated that it was possible to control the phase of a reflected wave of an SBS using a self-generated density modulation that did not require any backward Stokes seed beam and, each beam was focused at different focal points (shown in Fig.5). Hence, the system provided undisturbed phase conjugation and unlimited energy scaling. The interference between the main beam and the low-intensity counter-propagating beam produced an electromagnetic standing wave which induced the periodic self-generated density modulation at the focal area. The position of the acoustic wave was ignited by the density modulation so that the phase of the reflected wave of the SBS could be controlled. Under a proper scheme of the self-seeding methods and with the phase error less than λ/4, 96% success was obtained. Due to the scalability, simplicity, and

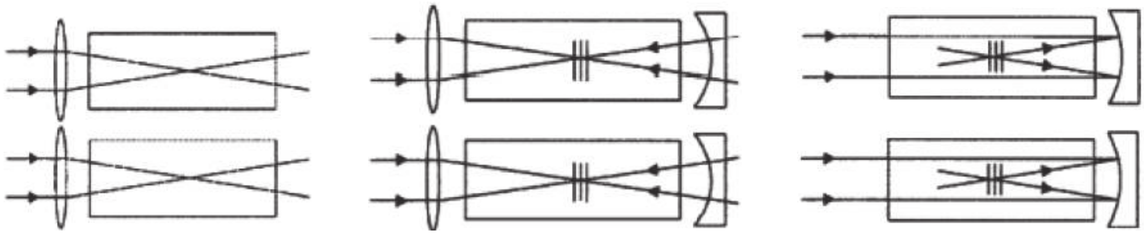

Fig. 5 (a) Diagram of the unlocked case, (b) a concentric type produces weak density modulation and (c) backward focusing produces weak density modulation[82]

efficiency of the system, it can be applied to many beam combination systems for a high-power laser with a high repetition rate (higher than 10 Hz) such as a laser fusion driver. Moreover, due to the pumping energy fluctuation, 100% success of the phase-locking has not been achieved. If the curvature/reflectivity of the concave mirror is optimized and the output energy of the pump laser is stabilized, it is possible to obtain 100% phase control. The medium used was FC- 75[82].

Some other scientists have experimentally proved that it is feasible to recover the high spatial frequency of optical images with the use of a prepulse[28, 64-65] in an SBS. Beak *et al*., 2008 proposed and used a prepulse method (shown in Fig.6) and obtained an increase in the amplitude of 41% compared to the normal SBS scheme at a spatial frequency of 0.027 mm^{-1}. The system uses three pulses: prepulse, main pulse, and phase-conjugation pulse. The prepulse is used to create the acoustic grating and the acoustic grating scattered the main pulse to produce the phase-conjugation waves. Thus, the high spatial frequency of the main pulse is recovered. One important fact to note is that the beams involved in the prepulse scheme are independent of the polarization state. The acoustic grating can only be generated by the prepulse. Brillouin-enhanced four-wave mixing (BEFWM) technique was also studied and the same 41% increase was measured at the same spatial frequency[64]. The waveform of the reflected wave depends on both the prepulse energy and the time delay[65, 83] between the main pulse and the prepulse. Under the experimental condition of 10 Hz repetition rate and a time delay of 5 ns, the prepulse energy of 5 mJ was found to give the best result for FC-75. It is supposed that the prepulse energy should be equal to or greater than the threshold energy of the SBS medium which is different for several kinds of media. This method can easily be applied to an SBS system employed in an optical image system, and it can also be conveniently applied to develop a multistage system employing serially connected many SBS cells for high-power laser applications.

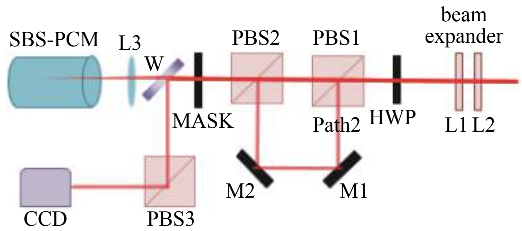

Fig. 6 A sample experimental setup for a prepulse system. PBS: polarizing beam splitter; HWP: half-wave plate; L1: planoconcave lens; L2 and L3: planoconvex lens; M: mirrors; W: wedge; SBS-PCM (FC75, 30 cm long) [64]

Using a single cell SBS generator, Wang *et al*., 2009 experimented with high energy SBS and achieved maximum energy of 3.42 J. The research further studied the fidelity of the system and discovered that for low pump energy, the fidelity of more than 0.9 high value was achieved but a significant fluctuation in the reflected beam was noticeable when the pump energy was greater than 1.5 J. This influenced the fidelity and it gradually decreased to 0.5 at the pump energy of 3.42 J. At high pump energy, both fidelity and reflectivity exhibit the same property of great fluctuation and the fidelity becomes more unstable as the saturation state of reflectivity increases. At a saturated reflectivity regime, optical breakdown occurs at high input energy that greatly exceeds the SBS threshold, which is responsible for the fidelity instability. The SBS medium used is FC-72[84]. At the pulse energy of 500 mJ and 10 Hz operating frequency, studying the strength of SBS-PCM in compensating for the wave-front aberrations in a high-power laser, Wang *et al*., 2009 obtained a mean wave-front fluctuation of 0.5λ (with a phase differences of 0.2λ) which increased to 8.6λ after transmitting through a random phase plate (RPP) and this was reduced to 0.9λ when SBS-PCM was used instead of a high reflection mirror. This shows that the SBS-PCM compensates for the wave-front distortion induced by the RPP. It was measured that the reflectivity becomes stable at about 70% and instability changed from ± 4.1% to ± 0.9%. Though the compensated wavefront distortion was not 100%, 0.6λ mean value was obtained (with a phase difference of 0.3λ), which was close to the value of the original wavefront distribution. The results show that when there are no other nonlinear effects such as optical breakdown, the reflectivity of the SBS-PCM is very high and stable[80].

4 Other applications and scientific works on SBS-PCM

Jaberi *et al*., 2015 analyzed the spectral of a double-pass amplifier with a two-cell SBS mirror and compared the result to that of a conventional mirror. Both numerical simulations and experimental results revealed that SBS-PCM Stokes had unique spectral behaviour, with the beating between Fourier components of the input field clearly reduced. The theoretical work shows that lower pumping energy produced a more effective result when using the SBS-PCM to filter the Fourier components. The result agreed with the experimental work which shows that low energy Fourier components and high frequency produce a better output field filtration when using the SBS-PCM[85]. Therefore, when SBS-PCM is used as a turning mirror in a double pass pulse amplifier, it produces a short duration profile highly free from beating. More so, amplifiers with phase conjugating beam combiner and reflector provide a temporal pulse compression and compensation of spatial aberrations, which makes it an attractive approach for high energy laser drivers.

Tsubakimoto *et al*., 2016 developed a high-average-power green laser system based on the second harmonic conversion of a laser diode-pumped master oscillator Nd:YAG power amplifier. The system used an SBS-PCM as a high-reflectivity-mirror to double-pass the scheme. This compressed the pulse duration, reduced the thermal phase distortion, removed the continuous-wave (CW) noise and amplified spontaneous emission (ASE), and improved the beam quality. As such, the SBS-PCM helped to improve the harmonic conversion efficiency by a factor of 2. The SBS-PCM reflectivity for 10 Hz input was higher than that of the high-average-power laser, and for an input pulse energy of 45 mJ (average power of 127 W), the maximum reflectivity observed was 44%. 670 W with a pulse width of 7.9 ns was the fundamental beam output power. 335 W with a 4.8 ns pulse width was the second harmonic beam output power and, with the use of LiB_3O_5 (LBO) crystal, 80 mJ pulse energy was produced[38].

Qiu *et al*., 2016 developed a high beam quality and high repetition rate Nd:YAG nanosecond laser operated at joule-level of input energy. It should be noted that the beam distortion associated with high power laser would be more pronounced with constant amplification of the laser beam energy. High-quality laser beam output was achieved through the use of a PCM that compensated for the phase distortion associated with the high-power laser system. The thermal disturbance of the optical components and the laser amplifier caused deformation, wavefront aberration, and non-uniformity which could be repaired by the SBS phase conjugation and achieve an amplified homogenous beam output of high quality close to the diffraction limit. The system achieved a gain of 1.53 J output energy from 8.19 μJ single pulse energy injected by a single longitudinal mode seed operated at 200 Hz repetition frequency. 7.41 ns pulse width, 9 mm diameter, 1.2% energy stability (RMS), far-field beam spot of 1.32 times the value of the diffraction limit, and less than 13 μrad far-field beam spot angular shift were the characteristics of the output laser[39].

For the past few decades, overcoming the power limit of available lasers has been a challenge in laser technology. As such, scientists and engineers have been making great efforts to discover a means of employing both rotating wedge and self-phase locking in the SBS-PCM system. However, in 2016, a coherent four-beam combination system (shown in Fig.7) that utilized the self-phase locking of an SBS-PCM with a system of a rotating wedge was developed[40]. This optical configuration enabled a coherent beam combination of kW-level high-power lasers. Its usefulness and phase-locking strength on the beam-combination laser were practically demonstrated. The measured relative phases between the beams were less than $\lambda/24.7$. The design of the system allows for scalability and can also be applied to a MOPA based coherent beam combination laser system. Hence, a dream (ultra-high-power) laser is feasible.

Although PCMs have been proven effective in compensating for phase distortion, the thermally induced birefringence of the active medium by a photo-elastic effect causes an inevitable depolarization loss. Using Jones matrix calculations, the depolarization loss in a double-pass Nd:YAG rod amplifier with an SBS-PCM was studied[29]. Moreover, leak beam patterns and the depolarization ratios for four possible optical schemes (composed of a quarter-wave plate or a Faraday rotator) were theoretically and experimentally obtained. The experimental setup is shown in Fig.8. From the experimental findings, the increase of the depolarization ratio of the AMP-FR scheme to the electrical input energy is the lowest and that of the QWP-AMP scheme has the highest value, while the depolarization ratio of the other schemes increases as the electrical input energy increases. The results of the two methods (theoretical and experimental) reveale that a Faraday rotator located after the amplifier

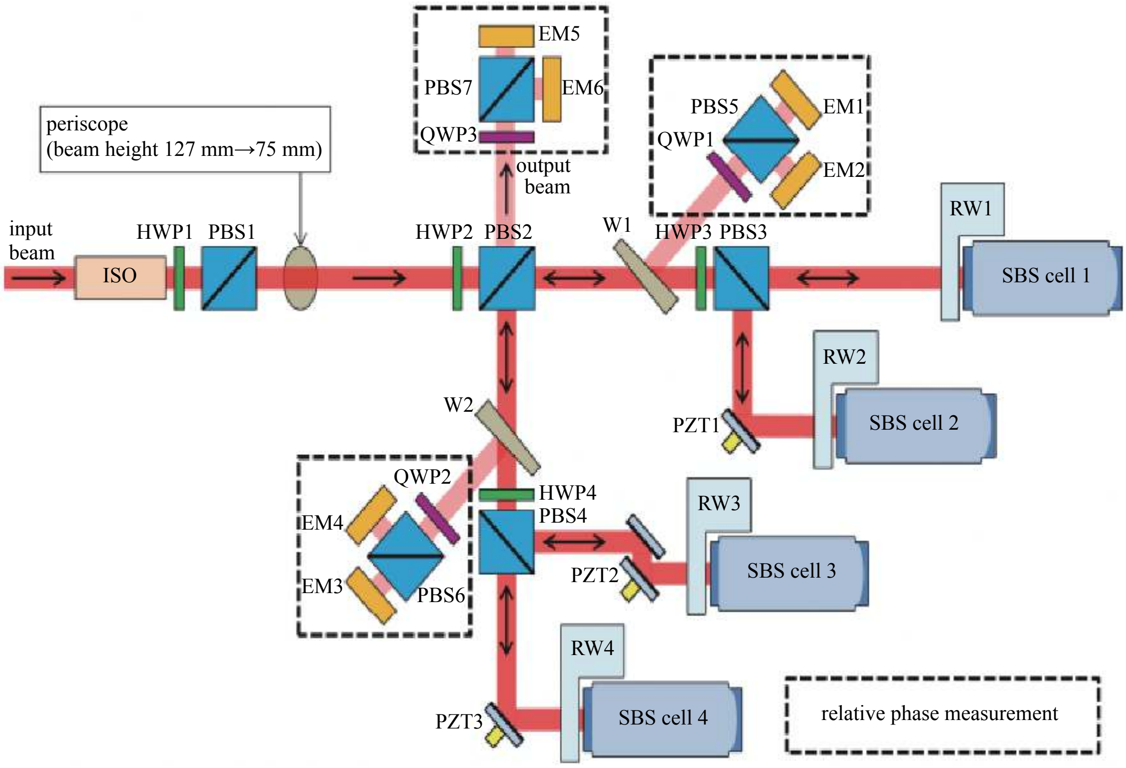

Fig. 7 A typical experimental setup of a four-beam combination system using the RW-SSP. ISO: optical isolator; PZT: 45 degree mirror attached piezoelectric transducer; RW: rotating wedge device; QWP: quarter wave plate; EM: energy meter[40]

is an effective way of abating the depolarization.

5 Recent scientific breakthroughs on high energy reflectivity, high beam quality, and pump width of SBS-PCM

5.1 Using a rotating off-centered lens at 1 kHz and 50 mJ

At high pump energy and high-repetition-rate operation, heat is always accumulated at the focal point of an SBS-PCM. To reduce this effect and increase energy reflectivity, Wang *et al*., 2019 proposed and used a rotating off-centered lens to reduce this negative effect at the focal spot of an SBS-PCM. The beam intensity pattern at the focal point was simulated theoretically. When compared with a rotating wedge and a conventional lens, the result of a rotating off-centered focusing lens showed reduced coma-aberration. The new method, a rotating off-centered focusing lens, operates very well at high input power while a non-rotating conventional method operates well at lower input power. As such, the SBS output parameters of the new method are much better than those of a non-rotating conventional method for high-repetition-rate operation. In the experimental conditions of 50 mJ at 1 kHz, the new method reported high reflected energy which means a better energy conversion efficiency and a good beam pattern[25].

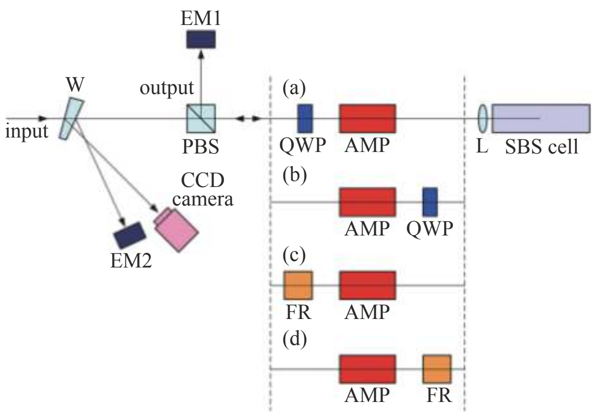

Fig. 8 Experimental setup for the measurement of the leak beam patterns and the depolarization ratio for the four possible optical schemes in a double-pass Nd:YAG rod amplifier with an SBS-PCM. W: wedged window; AMP: Nd:YAG rod amplifier; FR: Faraday rotator[59]

The rotating off-centered lens showed an energy reflectivity of 81.2% which was higher than that of a rotating wedge (about 78%). It was found that the rotating wedge and rotating off-centered lens resulted in the same energy loss for the following reasons. (1) According to the simulation result, large focusing beam size decreased the reflected energy due to the reduction of the power density at the focal point. (2) The less surface reflection loss in the rotating off-centered lens method was attributed to a fewer number of optical components. The relative standard deviation (RSD) profile showed the value of ~1.1%

when rotating off-centered lens was used while that of a rotating wedge was ~1.5% which was much larger than the previously mentioned method. Reduced coma-aberration of the focus beam pattern and the few optical components which improved the accuracy of optical alignment were responsible for the differences in the values obtained from the two methods. From the RSD values above, it was clear that the rotating off-centered lens method was more stable compared with the method of a rotating wedge.

Fig.9 is the reflected energy for input energy of 30 mJ and 50 mJ at 1 kHz repetition rate for about 15 min. Due to the fluctuations in the input power, the output power is also observed to exhibit some fluctuations. The SBS reflected power for rotating off-centered lens is 2.35 times compared with the case of using a normal focusing lens, and under the input energy of 50 mJ, the energy RSD value is decreased to 3.0% from 8.9%. Thus, for good reflected energy and RSDs, the rotating off-centered lens could be used instead of the rotating wedge that still employs a normal focusing lens. However, as the injection pump energy increases, the heat accumulation at the focal point also increases. Hence, the strength of the rotating off-centered lens reduces with an increase in pump energy.

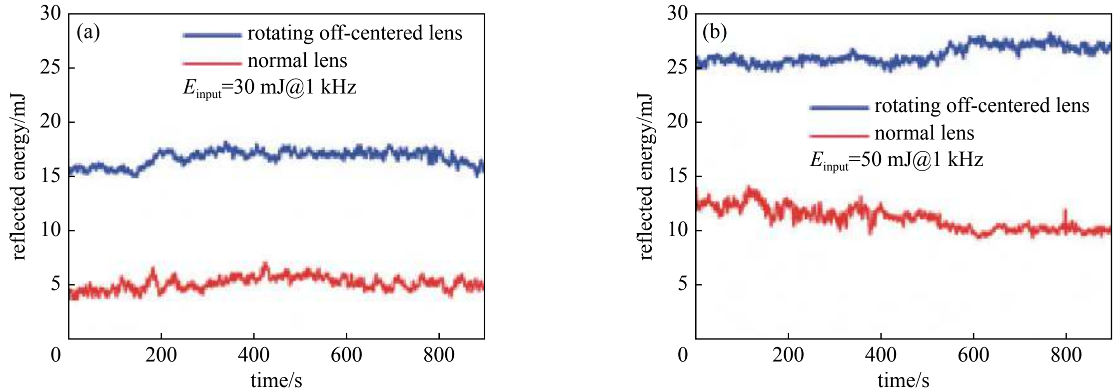

Fig. 9 Reflected energy with rotating off-centered lens and normal lens[25]

5.2 Using an ultraclean closed-type SBS-PCM at 500 Hz

In the quest to improve the reflectivity and the beam quality of the reflected beam of an SBS-PCM system, Kang *et al*., 2018 proposed and used an ultraclean closed-type single-cell SBS-PCM to achieve high pulse energy, high beam quality, and high average power laser system at high repetition rate. The micro-particles (impurities) of the SBS-PCM medium were reduced to 40 nm. This greatly improved the thermal load ability of the closed-type SBS-PCM. Without a scanning wedge plate, the paper achieved 92% high reflectivity and no optical breakdown or serious thermal effects at a 500 Hz pulse-repetition frequency (PRF). A single polarized output, about 1.1 J pulse energy, approximately beam quality (M^2) of 2, and 550 W output power were reported. Maximum output power pulse-width was compressed from 30 ns to around 10 ns and thermal phase distortion was compensated[26].

5.2.1 Influence of the closed-type SBS-PCM cleanliness on thermal effects at 500 Hz

When light falls on the SBS cell under high pulse repetition frequency (PRF), the impurity particles absorb a certain amount of light causing thermal distortion that results in an increase in SBS threshold and broadening of the focal waist. This reduces phase-conjugation fidelity and SBS energy stability. This section reports the impact of cleanliness on factors like pulse-waveform stability and beam cross-section (spatial distribution and intensity). A high-quality purification technique based on ultra-cleaning and ultra-filtration of the closed-type SBS-PCM is used to effectively suppress the thermal effect. If there are many small sizes particles in a closed-type SBS cell, under PRF operation, the phase-conjugation fidelity and pulse-waveform stability would be affected. This technique removes microparticles larger than 40 nm which increase the heat load capacity of the closed-type SBS-PCM. At pulse repetition rates up to 500 Hz, there are no optical breakdown or obvious thermal effects . Using this type of SBS-PCM, both high fidelity and stability can be obtained.

The transmitted and reflected beams of the normal SBS-PCM are distorted by the big size particles present in the SBS medium. It is observed that the heat flux of the medium caused dynamic changes in the distortion of the beam. This indicates that the stability of SBS reflected energy and the fidelity of the SBS phase conjugation reduced rapidly. The influence of the

SBS thermal effect is greatly reduced when the clean SBS-PCM is used at 500 Hz. Good phase-conjugation fidelity and energy stability are characteristic of the reflected beam.

5.2.2 Reflectivity of closed-type SBS-PCM at different repetition rates

Due to thermal effects in the SBS medium, SBS reflectivity decreases with an increase in PRF. Fig.10 shows the setup used to measure the reflectivity of the closed-type SBS-PCM for different repetition rates.

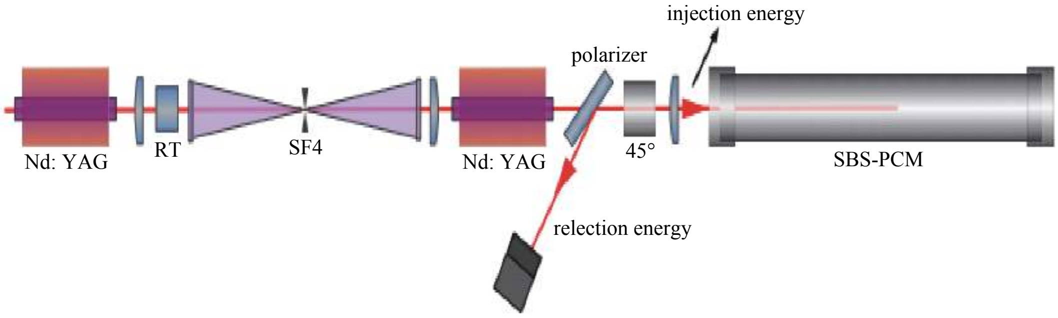

Fig. 10 Closed-type SBS-PCM used to measure reflectivity at varying repetition rates. RT: quartz rotator; SF: spatial filter[26]

The reflectivity of an SBS-PCM is the amount of energy it reflects based on the energy injected into the SBS cell. At a PRF of 200 Hz and an input pulse energy of 160 mJ, a maximum reflectivity of 94% was recorded. The threshold energy of the SBS was approximately 3.0 mJ. At a PRF of 500 Hz and an input pulse energy of 120 mJ, a maximum reflectivity of 92% was observed. This reduced input energy is due to the thermal stress limit of the laser crystal. The threshold energy remains unchanged. These results show that closed-type SBS-PCM minimized thermal degradation effects even at 500 Hz repetition rate.

5.3 Using an ultra-filtration technology SBS-PCM at 200 Hz with joule-level energy

The characteristics of SBS-PCM working under joule-level pump energy and 200 Hz repetition rate were studied experimentally. The SBS medium used that worked in high-power conditions was FC-770. After exceeding the threshold value, the SBS-PCM pulse output energy linearly depends on the pulse input energy. As input energy increases to a certain value, reflectivity growth becomes slow till saturation. At 100 W pump power without a rotating wedge, 98% reflectivity was recorded without optical breakdown under 200 Hz and pump energy from 500 mJ to 1100 mJ because of the unique preparation process and ultra-filtration technology used for the SBS-PCM medium. The width of the incident and reflected pulse increases with pump energy. At 800 mJ pump energy, the seed pulse width is 40.3 ns and the reflected beam pulse width is 38.8 ns. At certain pump energy, reflected pulse width becomes approximately equal to incident pulse width. At about 800 mJ pump energy, the quality of the laser beam improved to 1.42 times after the double-pass amplification, and the near-field patterns were also reduced. The result shows good reflectivity stability which implies that ultra-filtration and good cleaning are successful ways of reducing thermal effect and improving the stability of SBS-PCM[27].

In Fig.11, a Faraday rotation, a half-wave plate, and a PBS are placed between AMP6 and L4. Faraday rotator is used to rotate pump beam polarization; half-wave plate for adjusting polarization direction of pump beam and PBS to split beam.

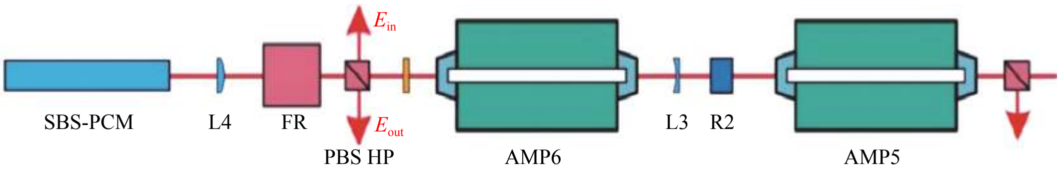

Fig. 11 Fraction of the light pathway for testing SBS reflectivity[27]

5.4 Using Fluorinert FC-75

The SBS reflectivity of an SBS-PCM cell using Fluorinert FC-75 as the SBS medium was measured. The SBS threshold energy of FC-75 was found to be about 5 mJ. A maximum SBS reflectivity of approximately 69 % was obtained at a 48 mJ incident energy[41]. The maximum input power to the SBS cell was 280 W at 25 kHz without degradation of the reflecting laser beam. Scientists also found that as incident energy increased, SBS reflectivity increased gradually[25-27, 41] and the reflecting point in the cell moved towards the cell entrance. As a result, optical breakdown did not occur because the focusable intensity during focus did not increase. They obtained an average output power of 500 W at 15 kHz. This system consisted of six 0.7 mm diameter YAG amplifiers. The amplified output pulse width decreased from 15 ns to 8 ns with 68 % reflectivity at a 100 mJ output energy. A typical spot size for the SBS-PCM return beam was about 1.5 to 2 times diffraction-limited. The near field pattern of reflected beam results is very smooth without the higher spatial components.

Table 1　Some scientific achievements in SBS-PCM reflectivity

max. reflectivity (%)	input energy/mJ	frequency/Hz	output Pulse width/ns	medium	year	reference
98	800	200	38.8	FC-770	2017	[27]
95.2	900	170	20	FC-770	2017	[52]
94	160	200	10	FC-770	2018	[26]
93	600	200	9.3	FC-770	2020	[46]
92	10	500	14	HT-270	2019	[61]
92	120	500	10	FC-770	2018	[26]
88	220	10000	8.5	HT-70	2014	[86]
84.7	600	10	–	FC-72	2010	[60]
81.2	50	1000	–	HT-270	2019	[25]
78.4	300	10	–	FC-72	2010	[51]
75	7.36	50	50	FC-75	2005	[63]
69	48	25000	8	FC-75	2011	[41]
60	130	1000	28	FC-75	2003	[87]
44	45	15000	–	FC-75	2016	[38]

6 Conclusion

This paper presents a review on the recent achievements in SBS-PCM systems operating under high pump power laser: the working principles, the applications of SBS-PCM, and the factors influencing the performance of an SBS-PCM system in a high-power laser. It has been found that (1) HT-270, FC-72, DET among others are good liquid media for high power laser due to their high optical breakdown energy, high GCs, and low ACs; (2) The lower the level of impurities in the medium, the better the performance of the liquid. For instance, an SBS liquid medium with an impurity level lower than 40 nm performed far better than that of 0.22 μm; (3) the design of the system, particularly the presence of a rotating wedge plate, helps to scatter the focal points in the cell, reducing the chance of optical breakdown and consequently improve the performance of the system. The summary of the breakthroughs ever reported in SBS-PCM reflectivity operating with high power laser is shown in Table 1.

During the creation of the acoustic wave, a certain amount of the pump energy is used to generate Stokes wave, hence the waveform of the Stokes wave produced in the SBS process is deformed. It is also reported that the SBS-PCM has excellently controlled the phase conjugation-fidelity of SBS with high pump energy more accurately and conveniently, producing high energy reflectivity and good phase conjugation fidelity. Hence it is applied in high energy pump beams such as in beam combination systems, high energy laser drivers, SBS systems employed in an optical image system, laser ranging for detecting space debris, etc. A dream laser (ultra-high-power lasers) is achievable. The design of the beam combination system that allows scalability makes it possible. Furthermore, this also finds application in a MOPA based coherent beam combination laser system.

Reference:

[1] González M, Stehlé C, Audit E, et al. Astrophysical radiative shocks: from modeling to laboratory experiments[J]. Laser and Particle Beams, 2006, 24(4): 535-540.

[2] Liu Jianxun, Ma Yanyun, Yang Xiaohu, et al. High-energy-density electron beam generation in ultra intense laser-plasma interaction[J]. Plasma Science and Technology, 2017, 19: 015001.

[3] Yang Yue, Zhao Zongqing, Zheng Jianhua, et al. Production of bright high-energy X-rays based on interaction of laser and near-critical-density plasma[J]. High Power Laser and Particle Beams, 2017, 29: 082003.

[4] Santos J J, Bailly-Grandvaux M, Ehret M, et al. Laser-driven strong magnetostatic fields with applications to charged beam transport and magnetized high energy-

density physics[J]. Physics of Plasmas, 2018, 25: 056705.

[5] Li Hanzhen, Yu Tongpu, Hu Lixiang, et al. Ultra-bright γ-ray flashes and dense attosecond positron bunches from two counter-propagating laser pulses irradiating a micro-wire target[J]. Optics Express, 2017, 25(18): 21583-21593.

[6] Magnusson J, Gonoskov A, Marklund M. Energy partitioning and electron momentum distributions in intense laser-solid interactions[J]. The European Physical Journal D, 2017, 71: 231.

[7] Kluge T, Rödel M, Metzkes-Ng J, et al. Observation of ultrafast solid-density plasma dynamics using femtosecond X-ray pulses from a free-electron laser[J]. Physical Review X, 2018, 8: 031068.

[8] Li Yanfei, Shaisultanov R, Chen Yueyue, et al. Polarized ultrashort brilliant multi-GeV γ rays via single-shot laser-electron interaction[J]. Physical Review Letters, 2020, 124: 014801.

[9] Xue Kun, Dou Zhenke, Wan Feng, et al. Generation of highly-polarized high-energy brilliant γ-rays via laser-plasma interaction[J]. Matter and Radiation at Extremes, 2020, 5: 054402.

[10] Hoffmann D H H, Blazevic A, Ni P, et al. Present and future perspectives for high energy density physics with intense heavy ion and laser beams[J]. Laser and Particle Beams, 2005, 23(1): 47-53.

[11] Hu Yanting, Zhao Jie, Zhang Hao, et al. Attosecond γ-ray vortex generation in near-critical-density plasma driven by twisted laser pulses[J]. Applied Physics Letters, 2021, 118: 054101.

[12] Weichman K, Robinson A P L, Murakami M, et al. Strong surface magnetic field generation in relativistic short pulse laser–plasma interaction with an applied seed magnetic field[J]. New Journal of Physics, 2020, 22: 113009.

[13] Rosmej O N, Gyrdymov M, Günther M M, et al. High-current laser-driven beams of relativistic electrons for high energy density research[J]. Plasma Physics and Controlled Fusion, 2020, 62: 115024.

[14] Domański J, Badziak J. Generation of ion beams from high-Z target irradiated by laser pulse of ultra-relativistic intensity[J]. Acta Physica Polonica A, 2020, 138(4): 586-592.

[15] Liang Zhenfeng, Shen Baifei, Zhang Xiaomei, et al. High-repetition-rate few-attosecond high-quality electron beams generated from crystals driven by intense X-ray laser[J]. Matter and Radiation at Extremes, 2020, 5: 054401.

[16] Domański J, Badziak J. Properties of heavy ion beams produced by a PW sub-picosecond laser[J]. Journal of Instrumentation, 2020, 15: C05037.

[17] Frost M, Curry C B, Glenzer S H. Laser cutting apparatus for high energy density and diamond anvil cell science[J]. Journal of Instrumentation, 2020, 15: P05004.

[18] Kumar S, Park J, Nam S H, et al. Laser-induced plasma generated by a 532 nm pulsed laser in bulk water: unexpected line-intensity variation with water temperature and the possible underlying physics[J]. Plasma Science and Technology, 2020, 22: 074009.

[19] Savelyev M S, Agafonova N O, Vasilevsky P N, et al. Effects of pulsed and continuous-wave laser radiation on the fabrication of tissue-engineered composite structures[J]. Optical Engineering, 2020, 59: 061623.

[20] Zhu Chenguang, Zhao Dongmei, Wang Kedian, et al. Direct laser writing of graphene films from a polyether ether ketone precursor[J]. Journal of Materials Science, 2019, 54(5): 4192-4201.

[21] Luo Dan, Liu Ying, Li Xiangyu, et al. Quantitative analysis of C, Si, Mn, Ni, Cr and Cu in low-alloy steel under ambient conditions via laser-induced breakdown spectroscopy[J]. Plasma Science and Technology, 2018, 20: 075504.

[22] Bibeau C, Bayramian A, Beach R J, et al. Mercury and beyond: diode-pumped solid-state lasers for inertial fusion energy[J]. Comptes Rendus de l'Académie des Sciences-Series IV-Physics, 2000, 1(6): 745-749.

[23] Kawashima T, Kanabe T, Matsui H, et al. Design and performance of a diode-pumped Nd: silica-phosphate glass Zig-Zag slab laser amplifier for inertial fusion energy[J]. Japanese Journal of Applied Physics, 2001, 40(11R): 6415-6425.

[24] Zel'Dovich B Y, Popovichev V I, Ragulskii V V, et al. Connection between the wave fronts of the reflected and exciting light in stimulated Mandel' shtam–Brillouin scattering[J]. JETP Letters, 1972, 15: 109-112.

[25] Wang Hongli, Cha S, Kong Hongjin, et al. Rotating off-centered lens in SBS phase conjugation mirror for high-repetition-rate operation[J]. Optics Express, 2019, 27(7): 9895-9905.

[26] Kang Zhijun, Fan Zhongwei, Huang Yutao, et al. High-repetition-rate, high-pulse-energy, and high-beam-quality laser system using an ultraclean closed-type SBS-PCM[J]. Optics Express, 2018, 26(6): 6560-6571.

[27] Tang Xiongxin, Qiu Jisi, Fan Zhongwei, et al. Experimental study on SBS-PCM at 200 Hz repetition rate pumped with joule-level energy[J]. Optical Materials, 2017, 67: 64-69.

[28] Omatsu T, Kong H J, Park S, et al. The current trends in SBS and phase conjugation[J]. Laser and Particle Beams, 2012, 30(1): 117-174.

[29] Shin J S, Park S, Kong H J. Compensation of the thermally induced depolarization in a double-pass Nd: YAG rod amplifier with a stimulated Brillouin scattering phase conjugate mirror[J]. Optics Communications, 2010, 283(11): 2402-2405.

[30] Zhang Ying, Ke Xizheng, Chen Mingsha. Simulation experiment of wavefront distortion correction in stimulated Brillouin scattering[J]. Infrared and Laser Engineering, 2018, 47: 1122001.

[31] Raab V, Heuer A, Schultheiss J, et al. Transverse effects in phase conjugate laser mirrors based on stimulated Brillouin scattering[J]. Chaos, Solitons & Fractals, 1999, 10(4/5): 831-838.

[32] Lamb R A, Damzen M J. Phase locking of multiple stimulated Brillouin scattering by a phase-conjugate laser resonator[J]. Journal of the Optical Society of America B, 1996, 13(7): 1468-1472.

[33] Chen Xudong, Chang Chengcheng, Pu Jixiong. Stimulated Brillouin scattering phase conjugation of light beams carrying orbit angular momentum (Invited Paper)[J]. Chinese Optics Letters, 2017, 15: 030006.
[34] Qiu Jisi, Tang Xiongxin, Fan Zhongwei, et al. High repetition rate and high beam quality joule level Nd: YAG nanosecond laser for Thomson scattering diagnosis[J]. Acta Physica Sinica, 2016, 65: 154204.
[35] Fan Zhongwei, Qiu Jisi, Tang Xiongxin, et al. A 100 Hz 3.31 J all-solid-state high beam quality Nd: YAG laser for space debris detecting[J]. Acta Physica Sinica, 2017, 66: 054205.
[36] Zhu Xuehua, Wu Daohua, Wang Guanling, et al. High efficiency laser spatial beam smoothing based on stimulated Brillouin scattering[J]. Laser Physics, 2019, 29: 065402.
[37] Kmetik V, Yoshida H, Fujita H, et al. Very high energy SBS phase conjugation and pulse compression in fluorocarbon liquids[C]. Proc. SPIE: Advanced High-Power Lasers, 2000, 3889: 818-826.
[38] Tsubakimoto K, Yoshida H, Miyanaga N. High-average-power green laser using Nd: YAG amplifier with stimulated Brillouin scattering phase-conjugate pulse-cleaning mirror[J]. Optics Express, 2016, 24(12): 12557-12564.
[39] Qiu Jisi, Tang Xiongxin, Fan Zhongwei, et al. 200 Hz repetition frequency joule-level high beam quality Nd: YAG nanosecond laser[J]. Optics Communications, 2016, 368: 68-72.
[40] Park S, Cha S, Oh J, et al. Coherent beam combination using self-phase locked stimulated Brillouin scattering phase conjugate mirrors with a rotating wedge for high power laser generation[J]. Optics Express, 2016, 24(8): 8641-8646.
[41] Yoshida H, Tsubakimoto K, Fujita H, et al. Stimulated-Brillouin-scattering via phase-conjugation-mirror for high-average-power Nd: YAG laser systems[C]//Proceedings of 2011 Conference on Lasers and Electro-Optics Europe and 12th European Quantum Electronics Conference (CLEO EUROPE/EQEC). IEEE, 2011.
[42] Yoshida H, Nakatsuka M, Hatae T, et al. YAG laser perfomance improved by stimulated Brillouin scattering phase conjugation mirror in Thomson scattering diagnostics at JT-60[J]. Japanese Journal of Applied Physics, 2003, 42(2R): 439-442.
[43] Kornev A F, Makarov A M, Katsev Y V, et al. 2 Joule 10 Hz flashlamp-pumped 1047 nm Nd: YLF laser with near-diffraction-limited beam quality[C]//Proceedings of 2020 International Conference Laser Optics (ICLO). IEEE, 2020.
[44] Wang Jianlei, Zhao Kaiqi, Feng Tao, et al. 1.5 J high-beam-quality Nd: LuAG ceramic active mirror laser amplifier[J]. Chinese Optics Letters, 2020, 18: 021401.
[45] Jaberi M, Farahbod A H, Soleimani H R. Effect of pump mode structure on reflectance of SBS mirrors[J]. Optical and Quantum Electronics, 2017, 49: 53.
[46] Ding Jianyong, Yu Guangli, Fang Chunqi, et al. High beam quality of nanosecond Nd: YAG slab laser system with SBS-PCM[J]. Optics Communications, 2020, 475: 126273.
[47] Brignon A, Huignard J P. Phase conjugate laser optics[M]. Hoboken: John Wiley & Sons, 2004.
[48] Fisher R A. Optical phase conjugation[M]. New York: Academic Press, 1983.
[49] Hasi W L J, Lu Z W, Gong S, et al. Investigation of stimulated Brillouin scattering media perfluoro-compound and perfluoropolyether with a low absorption coefficient and high power-load ability[J]. Applied Optics, 2008, 47(7): 1010-1014.
[50] Guo X Y, Hasi W L J, Zhong Z M, et al. Research on the SBS mediums used in high peak power laser system and their selection principle[J]. Laser and Particle Beams, 2012, 30(4): 525-530.
[51] Wang Y L, Lu Z W, Li Y, et al. Investigation on high-power load ability of stimulated Brillouin scattering phase conjugating mirror[J]. Applied Physics B, 2010, 98(2/3): 391-395.
[52] Gao Yue, Wang Yanjie, Chan A, et al. High average power diode pumped solid state laser[J]. Laser Physics Letters, 2017, 14: 035803.
[53] Gyger F, Liu Junqiu, Yang Fan, et al. Observation of stimulated Brillouin scattering in silicon nitride integrated waveguides[J]. Physical Review Letters, 2020, 124: 013902.
[54] Garmire E. Perspectives on stimulated Brillouin scattering[J]. New Journal of Physics, 2017, 19: 011003.
[55] Garmire E. Stimulated Brillouin review: invented 50 years ago and applied today[J]. International Journal of Optics, 2018, 2018: 2459501.
[56] Neshev D, Velchev I, Majewski W A, et al. SBS pulse compression to 200 ps in a compact single-cell setup[J]. Applied Physics B, 1999, 68(4): 671-675.
[57] Dane C B, Neuman W A, Hackel L A. High-energy SBS pulse compression[J]. IEEE Journal of Quantum Electronics, 1994, 30(8): 1907-1915.
[58] Park H, Lim C, Yoshida H, et al. Measurement of stimulated Brillouin scattering characteristics in heavy fluorocarbon liquids and perfluoropolyether liquids[J]. Japanese Journal of Applied Physics, 2006, 45(6A): 5073-5075.
[59] Hasi Wuliji, Lü Zhiwei, He Weiming, et al. Study on Brillouin amplification in different liquid media[J]. Acta Physica Sinica, 2005, 54(2): 742-748.
[60] Wang Yulei, Lv Zhiwei, Guo Qi, et al. A new circulating two-cell structure for stimulated Brillouin scattering phase conjugation mirrors with 1-J load and 10-Hz repetition rate[J]. Chinese Optics Letters, 2010, 8(11): 1064-1066.
[61] Wang Hongli. Research on pulsed compression technologies of kHz sub-nanosecond laser based on stimulated Brillouin scattering[D]. Harbin: Harbin Institute of Technology, 2019.
[62] Li Yong. Investigation on compensate phase aberration of repetition laser by SBS-PCM[D]. Harbin: Harbin Institute of Technology, 2008.
[63] Yoshida H, Nakatsuka M. High-power phase-conjugating mirror based on stimulated Brillouin scattering in liquid and solid materials[C]//Proceedings of 2005 Pacific Rim Conference on Lasers & Electro-Optics. IEEE, 2005: 1166-1167.
[64] Beak D H, Yoon J W, Shin J S, et al. Restoration of high spatial frequency at the image formed by stimulated Brillouin scattering with a prepulse[J]. Applied Physics Letters, 2008, 93: 231113.

[65] Kong Hongjin, Beak D H, Lee D W, et al. Waveform preservation of the backscattered stimulated Brillouin scattering wave by using a prepulse injection[J]. Optics Letters, 2005, 30(24): 3401-3403.

[66] Rockwell D A. A review of phase-conjugate solid-state lasers[J]. IEEE Journal of Quantum Electronics, 1988, 24(6): 1124-1140.

[67] Wang V, Giuliano C R. Correction of phase aberrations via stimulated Brillouin scattering[J]. Optics Letters, 1978, 2(1): 4-6.

[68] Kir'yanov Y F, Kochemasov G G, Maslov N V, et al. Influence of thermal defocusing on the quality of phase conjugation of Gaussian beams by stimulated Brillouin scattering[J]. Quantum Electronics, 1998, 28(1): 58-61.

[69] Andreev N F, Khazanov E A, Pasmanik G A. Applications of Brillouin cells to high repetition rate solid-state lasers[J]. IEEE Journal of Quantum Electronics, 1992, 28(1): 330-341.

[70] Andreev N, Kulagin O P, Palashov O V, et al. SBS of repetitively pulsed radiation and possibility of increasing the pump average power[C]//Proceedings of SPIE 2633, Solid State Lasers for Application to Inertial Confinement Fusion (ICF). 1995: 476-493.

[71] Amnon Y. Phase conjugate optics and real-time holography[J]. IEEE Journal of Quantum Electronics., 1978, 14(9): 650-660.

[72] Bai Zhenxu, Yuan Hang, Liu Zhaohong, et al. Stimulated Brillouin scattering materials, experimental design and applications: a review[J]. Optical Materials, 2018, 75: 626-645.

[73] Damzen M J, Vlad V I, Babin V, et al. Stimulated Brillouin scattering: fundamentals and applications[M]. Bristol: IOP Publishing Ltd, 2003.

[74] Boyd R W. Nonlinear optics[M]. San Diego, CA: Academic Press, 2020.

[75] Hasi W L J, Lu Z W, Li Q et al. Research on the enhancement of power-load of two-cell SBS system by choosing different media or mixture medium[J]. Laser and Particle Beams, 2007, 25(2): 207-210.

[76] Schiemann S, Ubachs W, Hogervorst W. Efficient temporal compression of coherent nanosecond pulses in a compact SBS generator-amplifier setup[J]. IEEE Journal of Quantum Electronics, 1997, 33(3): 358-366.

[77] Yoshida H, Kmetik V, Fujita H, et al. Heavy fluorocarbon liquids for a phase-conjugated stimulated Brillouin scattering mirror[J]. Applied Optics, 1997, 36(16): 3739-3744.

[78] Lu Z W, Hasi W L J, Gong H P, et al. Generation of flat-top waveform by double optical limiting based on stimulated Brillouin scattering[J]. Optics Express, 2006, 14(12): 5497-5501.

[79] Boyd R W, Rzaewski K, Narum P. Noise initiation of stimulated Brillouin scattering[J]. Physical Review A, 1990, 42(9): 5514-5521.

[80] Wang Y L, Lu Z W, Li Y, et al. Investigation on high power phase compensation of strong aberrations via stimulated Brillouin scattering[J]. Applied Physics B, 2010, 99(1/2): 257-261.

[81] Hon D T. Applications of wavefront reversal by stimulated Brillouin scattering[J]. Optical Engineering, 1982, 21: 212252.

[82] Kong Hongjin, Lee S K, Lee D W, et al. Phase control of a stimulated Brillouin scattering phase conjugate mirror by a self-generated density modulation[J]. Applied Physics Letters, 2005, 86: 051111.

[83] Wang Yulei, Lu Zhiwei, Lin Dianyang, et al. The performance of stimulated Brillouin scattering pulse improved by a prepulse seed[C]//Proceedings of 2010 Academic Symposium on Optoelectronics and Microelectronics Technology and 10th Chinese-Russian Symposium on Laser Physics and Laser Technology Optoelectronics Technology (ASOT). IEEE, 2010: 157-159.

[84] Wang Y L, Lu Z W, He W M, et al. A new measurement of stimulated Brillouin scattering phase conjugation fidelity for high pump energies[J]. Laser and Particle Beams, 2009, 27(2): 297-302.

[85] Jaberi M, Farahbod A H, Soleimani H R. Spectral behavior of amplified back-scattered Stokes pulse in two-cell phase conjugating mirror[J]. Optics Communications, 2015, 335: 7-15.

[86] Kong Hongjin, Park S, Cha S, et al. Current status of the development of the Kumgang laser[J]. Optical Materials Express, 2014, 4(12): 2551-2558.

[87] Kiriyama H, Yamakawa K, Nagai T, et al. 360-W average power operation with a single-stage diode-pumped Nd: YAG amplifier at a 1-kHz repetition rate[J]. Optics Letters, 2003, 28(18): 1671-1673.

基于受激布里渊散射的高能高功率相位共轭激光

Akinyimika Adewale[1,2,3]， 王雨雷[1,2]， 白振旭[1,2]， 李云飞[1,2]， 吕志伟[1,2]

（1. 河北工业大学 先进激光技术中心，天津 300401； 2. 河北工业大学 河北省先进激光技术与装备重点实验室，天津 300401；
3. 阿库拉联邦理工大学 物理系，阿库拉 704，尼日利亚）

摘　要：受激布里渊散射是一种三阶非线性光学过程，具有完全背向散射的相位共轭特性，利用这种特性，可以补偿高能高功率激光系统中强泵浦而引起的相位畸变，从而实现高光束质量激光输出。过去几十年开展了大量理论和实验研究以提升受激布里渊散射相位共轭镜（SBS-PCM）的作用效果，一部分研究集中在研究适合高功率激光系统应用的液体介质和介质纯化，一部分集中在 SBS-PCM 的结构优化（包括双池结构、结构参数优化、旋转楔板结构等）。回顾了影响 SBS-PCM 作用效果的主要因素，以及 SBS-PCM 在高功率激光系统中的应用，总结了近年来的一些应用成果，为 SBS-PCM 的实验研究提供了参考。

关键词： 受激布里渊散射；相位共轭镜；能量反射率；光学击穿；重复频率