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Development of a stimulated Brillouin scattering phase conjugate mirror for high average power laser

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14. ABSTRACT
The purpose of this research is to develop an SBS-PCM for high input average power more than 100 W. To achieve this goal, the researchers tried to find the proper SBS media for high input average power. Theresearchers have tested several kinds of liquids (HT110 and HT270), solid (metallic inclusion free fused silica), and gas (highly pressurized N¬2 gas) media to make an SBS cell. For the liquids, the researchers used purified HT110 and purified HT270. The researchers measured the SBS reflectivity and the SBS reflected beam patterns of HT110 and HT270 by using Kumgang laser operating at 1 kHz repetition rate. The SBS reflectivity of HT110 and HT270 at the input energy of 50 mJ@1kHz were 64% and 43%, respectively. The SBS reflected beam patterns of HT270 were better than those of HT110, because of the high boiling point and high viscosity of HT270. However, the SBS reflected beam patterns of HT270 were still unstable because of convection even without boiling.
For the solid, the researchers used metallic inclusion free fused silica (Suprasil 311 made by Heraeus). The authors measured the SBS reflectivity and SBS reflected beam patterns of Suprasil 311 by using Kumgang laser operating at 1 kHz repetition rate. The SBS reflectivity at the input energy of 50 mJ@1kHz (input laser beam intensity 25 GW/cm2) was 35%. The SBS reflected beam patterns were stable and good, but OBD was observed at the input energy of 35mJ@10Hz (input laser beam intensity 53 GW/cm2), while the OBD threshold of Suprasil 311 is known as 55 GW/cm2.
For the gas, the researchers tested highly pressurized N¬2 gas. The authors measured the SBS reflectivity and SBS reflected beam patterns using Spectra-physics laser (GCR-100) operating at 10 Hz. The SBS reflectivity at the input energy of 240 mJ (363 GW/cm2) and the N2 pressure of 100 bar was 67%. Up to 50 bar of the N2 pressure, the OBD occurred severely. The higher the N2 pressure is, the lower the OBD occurrence probability is. However, the OBD still occurred when the input laser beam intensity of 300 GW/cm2 at the N2 pressure of 100 bar, while the OBD threshold of N2 gas at 1 bar is known as 6000 GW/cm¬2.
From these results, the researchers conclude that the SBS media has boiling/melting effect of the liquid/solid media and the OBD so that it is difficult to apply it to the high power laser system.

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1. Introduction

A high average power laser with high output energy and a high repetition rate has various applications in the field of the academic research, the industrial applications, laser weapons, and the inertial fusion energy. Especially, the laser inertial fusion energy is expected as one of the most-promising energy sources which can resolve the energy problem and the global warming caused by fossil fuel. To achieve a laser inertial fusion energy, we need the laser fusion driver module which can produce the energy more than 25 kJ per pulse and operates over 10 Hz repetition rate. However, the current laser module technology allows it less than 1 kJ operating at 10 Hz repetition rate.

It is difficult to achieve high average power with high energy and a high repetition rate for a bulk laser due to the thermal effects and the parasitic oscillation. To increase the output energy, it is necessary to increase the size of a laser gain medium. However, the large gain medium is hard to cool down. The Larger the gain medium becomes, the worse the beam quality of the output laser beam becomes, because of the wavefront distortion by thermal effects such as thermal lensing and thermal birefringence. Also, the larger the gain medium is, the less efficiency the amplifier has, due to the parasitic oscillation inside the gain medium. Therefore, it is impractical to increase the laser gain medium as we want to obtain high output energy. So, it is necessary to combine 25 laser modules using small gain medium coherently to get 25 kJ.

To combine the laser beams coherently, the wavefront distortion of each laser beam should be less than $\lambda/4$ and the relative phase fluctuation between the laser beams should be less than $\lambda/20$. There are three methods to compensate the wavefront distortion of the laser beam caused by the amplifier.

The first method is using a spatial filter. By using pinhole at the focal plane of the lens, we can cut off the high spatial frequency component of the laser beam. This method is hard to use for the high-power laser, because the pinhole material in the spatial filter can be damaged easily by high-power laser beam.

The second method is an adaptive optics system. The adaptive optics system is composed of many complicated optics, so that it is hard to combine many beams using this method. Also, the wavefront compensation by adaptive optics system is imperfect.

The third method is using a phase conjugate mirror (PCM). PCM is passive optics. To get a phase conjugate mirror, there are two typical ways, degenerate 4-wave mixing (DFWM) and stimulated Brillouin scattering (SBS). The DFWM has complex structure, therefore it becomes difficult to combine many beams. The SBS-PCM has the simplest structure and enables to combine many beams. However, it is considered that the coherent beam combining (CBC) using SBS-PCM is impossible because the reflected beam from a conventional SBS-PCM has inherently random phase. We proposed a self-phase-control SBS-PCM (SPC-SBS-PCM) in 2003 to lock the phase of SBS reflected beam. Using this SPC-SBS-PCM, we successfully demonstrated a coherent 4-beam combination at the low average power of 1 W with the low repetition rate of 10 Hz in 2010. It was necessary to prove the CBC using SPC-SBS-PCM at the high-power regime. The authors constructed the Kumgang laser system (4×0.1J@10kHz/10ns), and tried to develop SBS-PCM for high-power laser. However, there have been several issues such as severe thermal problem in the SBS medium and the optical breakdown (OBD) when we use SBS-PCM for the high-power laser.

The object of this research project is to develop the SPC-SBS-PCM useful for high average input power more than 100 W. For this purpose, the authors have tested purified liquids, metallic inclusion free fused silica, and the high-pressurized N_2 gas for the media of the SPC-SBS-PCM. By using

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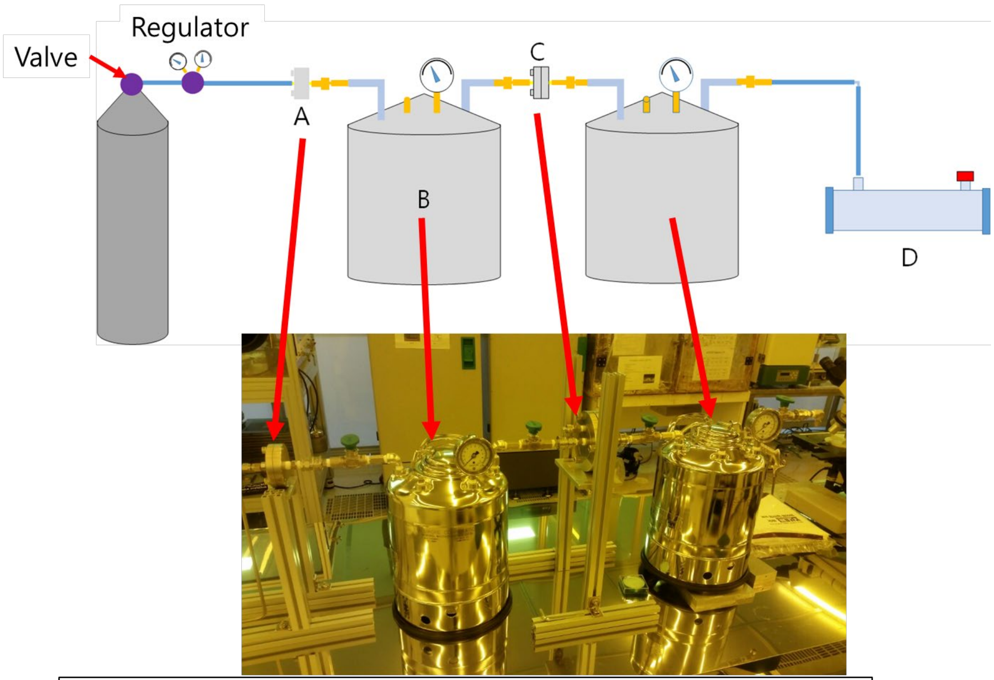
Spectra-physics laser (250mJ@10Hz/11ns) and Kumgang laser system (0.1J@1kHz/10ns), the authors measured the SBS reflectivity and the SBS reflected beam patterns to find a proper SBS media for high power laser. In this report, the authors will present the result of the measurement of the SBS reflectivity and the SBS reflected beam patterns of the SBS-PCM using the various liquids, the solid(metallic inclusion free fused silica), and the gas (high pressurized N_2 gas up to 100 bar) as SBS media.

2. Research on the liquid and solid media

The authors used three media, Galden HT110 (liquid), Galden HT270 (liquid), and the metallic inclusion free fused silica, Suprasil 311(solid) as the SBS media. Galden HT110 and Galden HT270 are purified by open-loop SBS liquid purification system using the pressurized N_2 gas. Figure 1 shows the SBS liquid purification system.



A: membrane filter (pore size 250 nm) B: pressure vessel
C, membrane filter (pore size 25nm) D: SBS cell

Figure 1. Open-loop purification system using pressurized N_2 gas for SBS liquid medium.

Table 1 shows the properties of three media, HT110, HT270, and the Suprasil 311. The absorption coefficient of the Suprasil 311 is 300 times lower than HT110, and the thermal conductivity of the Suprasil 311 is 20 times lower than HT110 and HT270. These imply that the maximum input power of Suprasil 311 can be 6,000 times higher than HT110 liquid. On the other hand, the optical breakdown threshold of the Suprasil 311 is about 5 times higher than that of HT110 and HT270. It is expected that the optical breakdown can limit the input average power of the Suprasil 311.

Table 1. Physical properties of three SBS media.

Properties	HT110	HT270	Suprasil 311
Kinematic viscosity (centiStroke)@25ºC	0.77	11.70	-
Density (g/cm^3)	1.68	1.85	2.2
Boiling point / softening point (°C)	110	270	1650
Refractive index	1.28	1.283	1.45
Absorption coefficient (cm^{-1})	**~3×10^{-4}**	**~3×10^{-4}**	**~ 10^{-6}**
Thermal conductivity (W/m·K)	**0.065**	**0.065**	**1.38**
Optical breakdown threshold (GW/cm^2)	>100	>100	55 (for 10 ns pulse & λ=1064 nm)
Phonon lifetime (ns)	0.6	0.1	4~6
Brillouin gain coefficient (cm/GW)	4.7	2.3	3.4

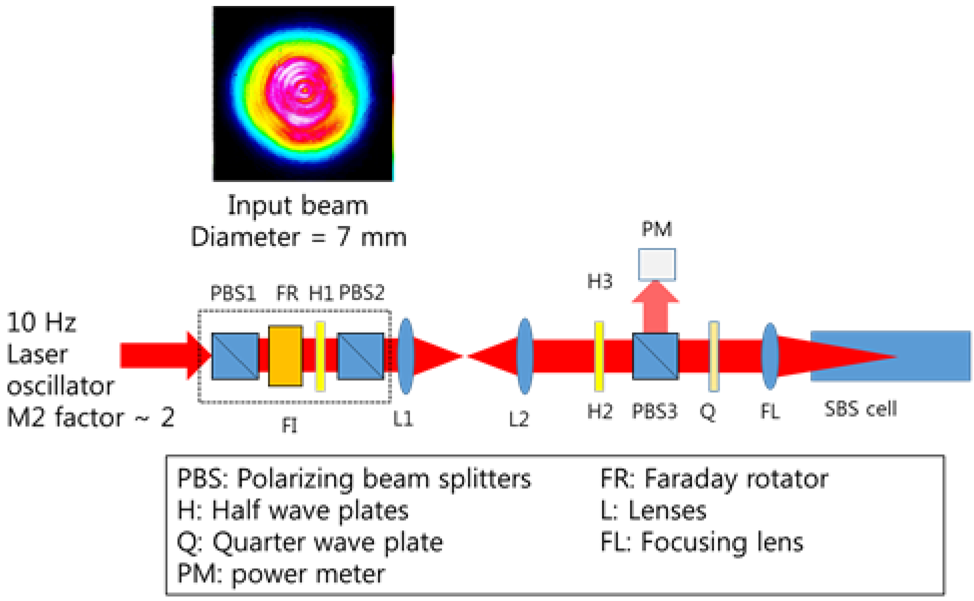


Figure 2. Schematic diagram of the measurement of SBS reflection by using Spectra-physics laser operating at 10 Hz.

At first, the laser oscillator operating at 10 Hz (Made by Spectra-Physics) is used to test the reflectivity of the liquid media, and Suprasil 311. Figure 2 shows the schematic diagram of the measurement of SBS reflection by using Spectra-physics laser operating at 10 Hz. The beam produced by Oscillator passes through the Faraday isolator (FI). L1 and L2 collimates the laser beam. A pair of a half wave plate (H2) and a polarizing beam splitter (PBS3) controls the input energy to the SBS-cell. A quarter wave plate (Q) changes the polarization of the input beam from the P-polarization to the circular polarization, and the polarization of the SBS reflected beam from the circular polarization to the S-polarization. PBS3 reflects SBS reflected beam from the SBS-cell. A pair of a half wave plate (H3) and a polarizing beam splitter (PBS4) splits the SBS reflected beam. We measure the reflected power by a power meter (PM).

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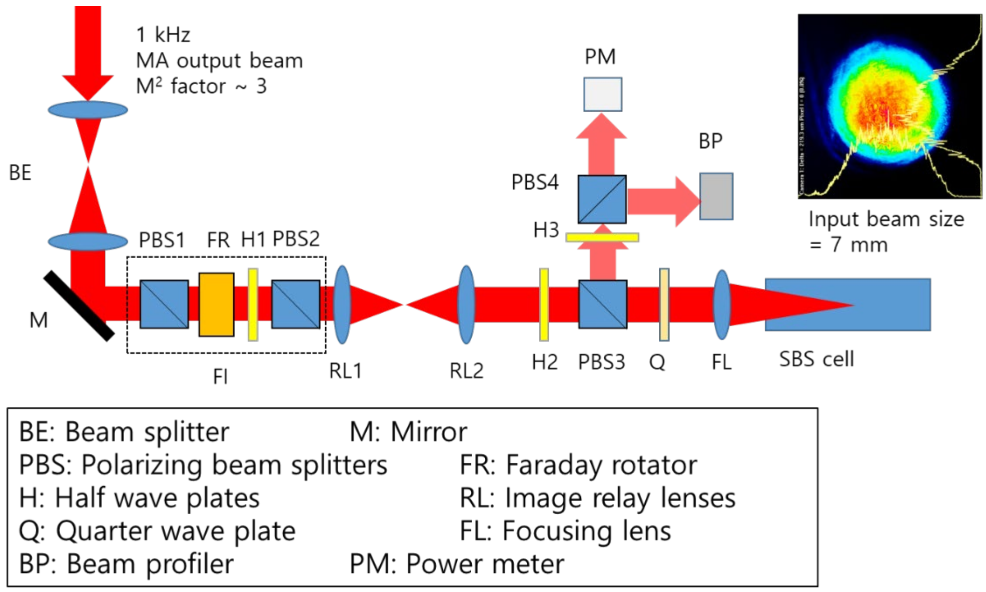

Figure 3. Schematic diagram of the measurement of SBS reflection by using Kumgang laser operating at 1 kHz.

After the test at 10 Hz repetition rate operation, we tested liquid media and Suprasil 311 at 1 kHz repetition rate operation using Kumgang laser system. Figure 3 shows the schematic diagram of the measurement of SBS reflection by using Kumgang laser operating at 1 kHz. The input beam from the Kumgang laser main amplifier (MA) is expanded by BE and passes through an isolator which consists of a polarizing beam splitter (PBS1), Faraday rotator (FR), a half wave plate (H1), and a polarizing beam splitter (PBS2) of a half wave plate (HWP1). A pair of lenses (RL1 and RL2) relays the beam. A pair of a half wave plate (H2) and a polarizing beam splitter (PBS3) controls the input power of the SBS cell. A quarter wave plate (Q) changes the polarization of the input beam from the P-polarization to the circular polarization, and the polarization of the SBS reflected beam from the circular polarization to the S-polarization. PBS3 reflects the beam from the SBS cell and a pair of a half wave plate (H3) and a polarizing beam splitter (PBS4) splits the SBS reflected beam. A beam profiler (BP) and a power meter (PM) measures the reflected beam pattern and the reflected power, respectively.

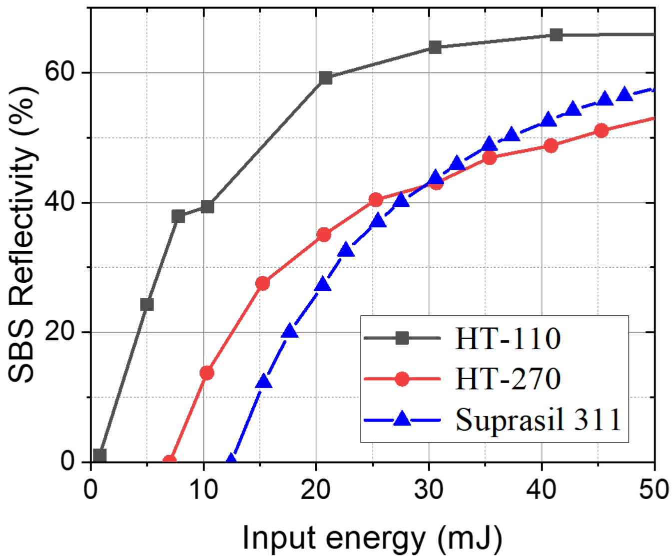

Figure 4. Input energy vs. SBS reflectivity for three media at the 10 Hz repetition rate operation.

Figure 4 shows the reflectivity of the SBS media HT110, HT270, and Suprasil 311 at the 10 Hz repetition rate operation. The reflectivity of the HT110, HT270, and the fused silica was 66%, 53%, and 58% for HT110, HT270, and the Suprasil 311, respectively.

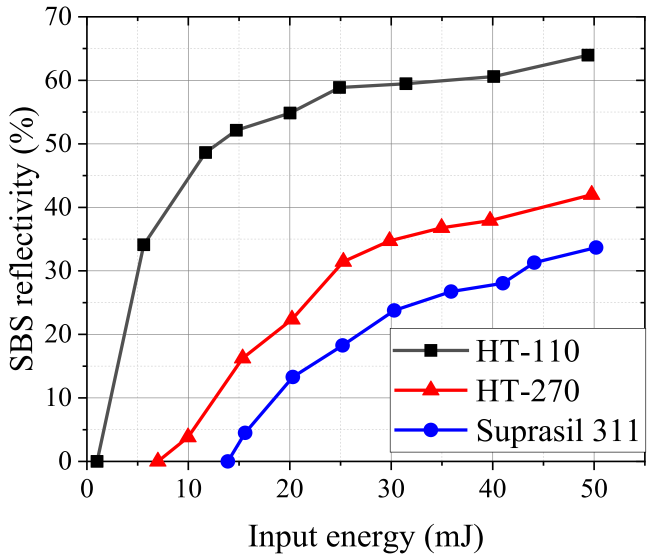

Figure 5. Input energy vs. SBS reflectivity for three media at the 1 kHz repetition rate operation.

Figure 5 shows the SBS reflectivity of HT110, HT270, and the Suprasil 311 at the 1 kHz repetition rate operation. At the input power of 50mJ@1kHz, the SBS reflectivity of the HT110, HT270, and Suprasil 311 was 64%, 43%, and 34%, respectively. Figure 6 shows the 7 SBS reflected beam patterns captured continuously at the input power of 50 W (50mJ@1kHz) for HT110, HT270 and Suprasil 311. Suprasil 311 shows the most stable beam patterns among three materials.

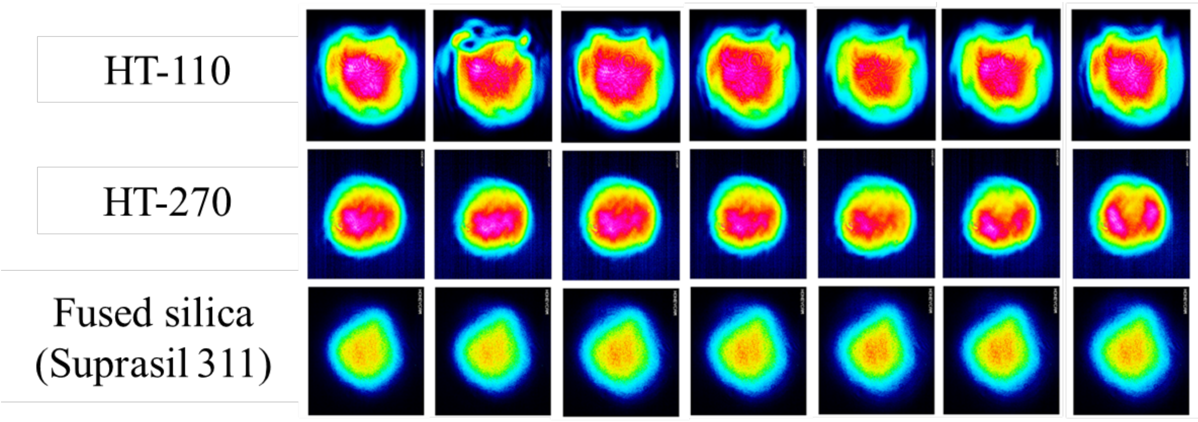

Figure 6. 7 reflected beam patterns in time for three SBS media.

3. Research on the gas medium

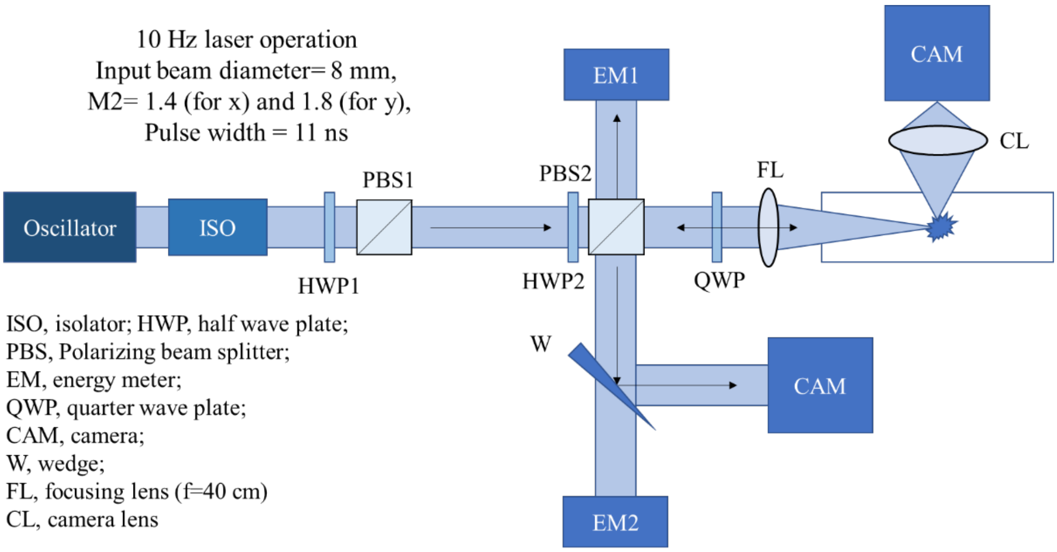

Figure 7. The schematic diagram of the experimental setup for the SBS-PCM using highly pressurized N_2 gas.

Figure 7 shows the experimental setup for the SBS-PCM using highly pressurized N_2 gas as an SBS medium. The oscillator produces an input laser beam at 10 Hz repetition rate. The input beam diameter is 8 mm, and the beam quality of the input beam is 1.4 and 1.8 for x and y, respectively. The input pulse width is 11 ns. The input pulse energy varies by a pair of a half-wave plate (HWP1) and a polarizing beam splitter (PBS1). Another pair of a half-wave plate (HWP2) and a polarizing beam splitter (PBS2) split the input beam to measure the input pulse energy by using an energy meter (EM1). The input beam passes through a quarter-wave plate (QWP) and a focusing lens. A camera with a camera lens takes a picture of the focal spot to observe the optical breakdown (OBD) for every shot. SBS reflected beam is reflected by PBS2 and split by a wedge(W). A camera takes the reflected beam pattern and an energy meter (EM2) measured the reflected energy. Figure 8 shows a picture of the SBS-PCM using highly pressurized N_2 gas.

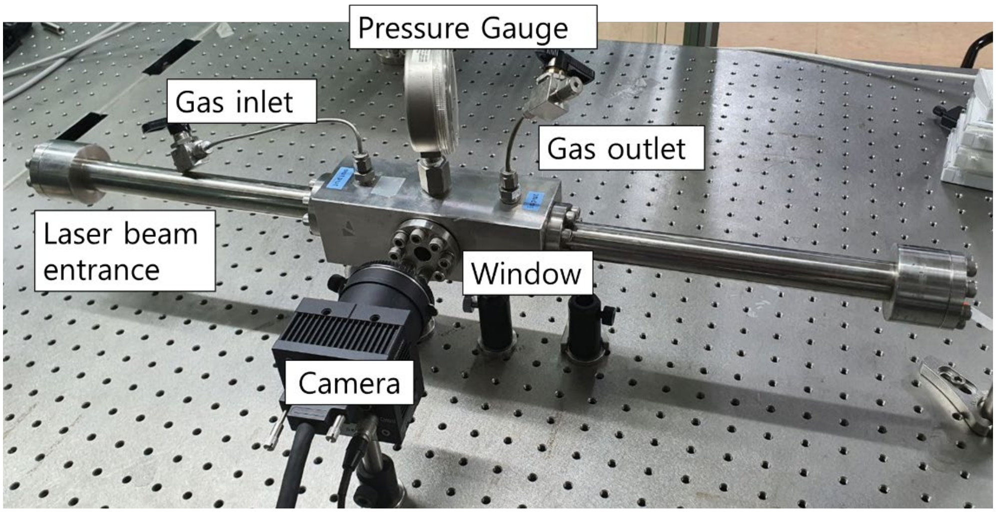

Figure 7. The SBS-PCM using highly pressurized N_2 gas.

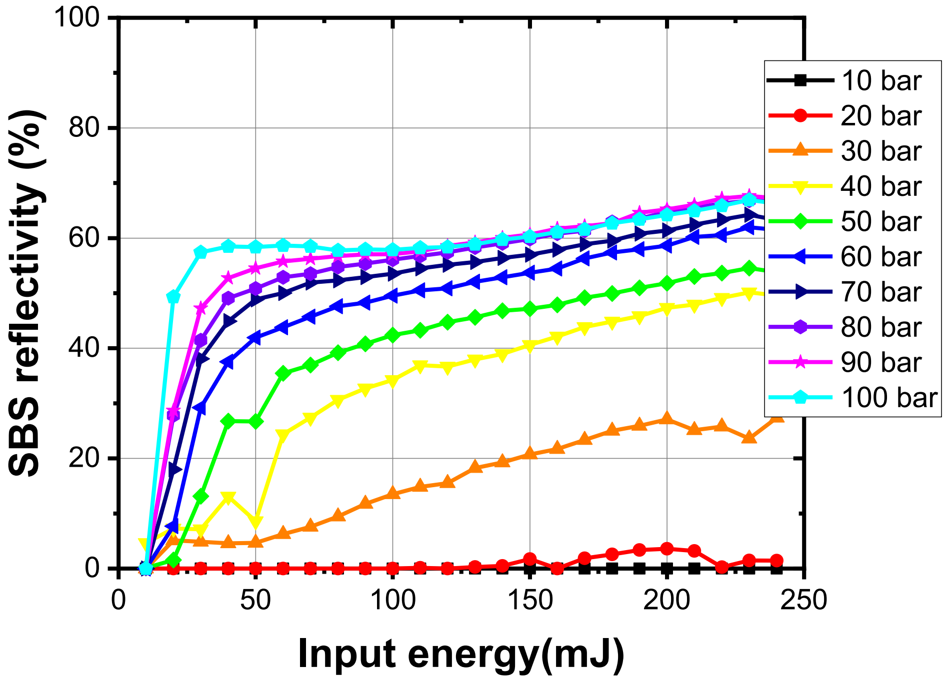

Figure 8. SBS reflectivity of the SBS-PCM using highly pressurized N2 gas for the input energy from 10 mJ to 240 mJ and the N2 pressure of 10 bar to 100 bar.

Figure 8 shows the SBS reflectivity of the SBS-PCM using highly pressurized N_2 gas for the input energy from 10 mJ to 240 mJ and the N_2 pressure of 10 bar to 100 bar. The SBS reflectivity is 67% at the 100 bar of the N_2 pressure and 240 mJ of the input energy. The higher the N_2 pressure is, the higher SBS reflectivity is.

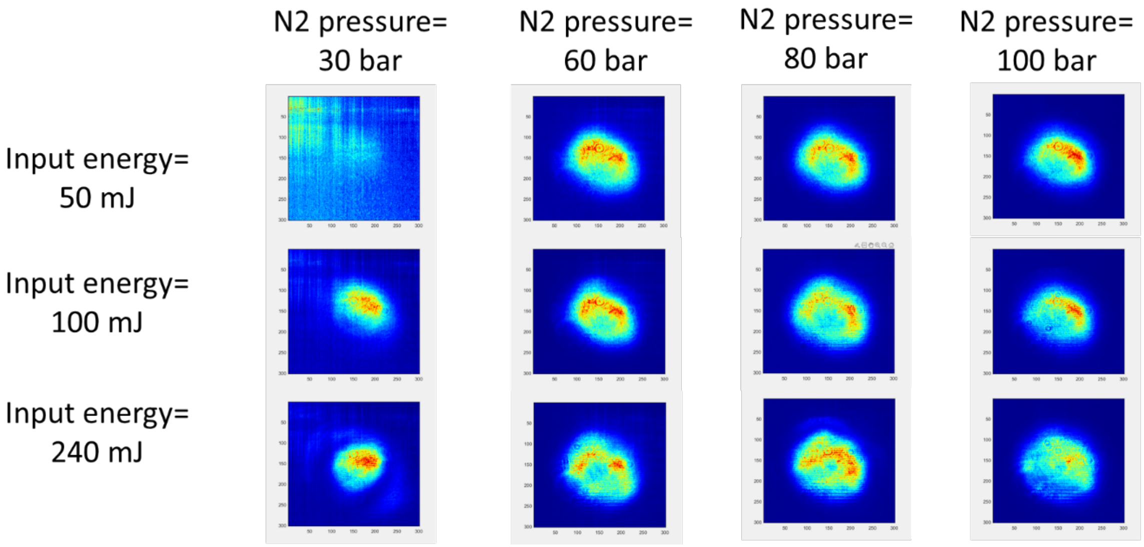

Figure 9. the SBS reflected beam pattern for 50, 100, and 240 mJ of the input energy and 30 bar, 60 bar, 80 bar, and 100 bar of the N2 pressure.

Figure 9 shows the SBS reflected beam pattern for 50, 100, and 240 mJ of the input energy and 30 bar, 60 bar, 80 bar, and 100 bar of the N_2 pressure. The SBS reflected beam pattern looks stable under the input energy of 100 mJ but it becomes unstable over the input energy of 100 mJ.

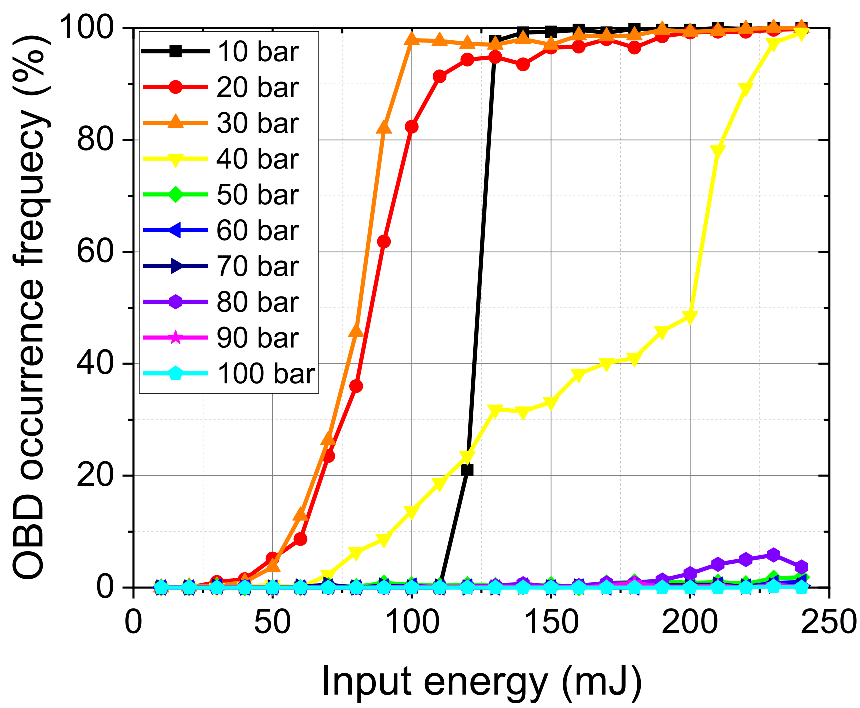

Figure 10. the optical breakdown probability for the SBS input energy from 10 mJ to 240 mJ and the N2 pressure from 10 bar to 100 bar.

Figure 10 shows the optical breakdown probability for the SBS input energy from 10 mJ to 240 mJ and the N_2 pressure from 10 bar to 100 bar. The higher the input energy is, the lower the OBD occurrence probability is. The optical breakdown occurrence probability was lower than 6% when the N_2 pressure is more than 50 bar. However, there still the OBD occurs at the energy more than 200 mJ at the N_2 pressure of 100 bar. If the input energy increases more than 200 mJ, the OBD can occur. Therefore, the OBD will limit the input energy of the SBS-PCM.

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4. Analysis of the SBS media: liquid, solid, and gas

The authors measured the SBS reflectivity and the reflected beam patterns of the SBS-PCM using liquids, solid, and gas media. From them, the authors found two issues in the SBS-PCM for high average power input. First, when the high average power laser beam incidents to the SBS media, boiling/melting can occur in the liquid/solid media. These cause a low SBS reflectivity and unstable SBS reflected beam patterns. Second, the OBD occurs in the SBS media and it disturbs the SBS reflection for solid and gas media. Especially, the solid medium can be broken by the OBD.

Table 2. Boiling point, Absorption coefficient, and thermal conductivity of HT110 and HT270.

Parameters	HT110	HT270
Boiling point (BP, °C)	110	270
Absorption coefficient (cm^{-1})	~3×10^{-4}	~3×10^{-4}
Thermal conductivity (W/m·K)	0.065	0.065

The authors calculated the temperature increment when the high average power incidents to the liquid media. Table 2 shows the boiling point, the absorption coefficient, and the thermal conductivity of two liquid media. By using them, the maximum temperature at the focal point due to the input pulse energy is calculated. Figure 11 shows the calculation result. For the 1 kHz repetition rate operation, the temperature of HT110 and HT270 at the focal spot reaches the boiling point of HT110 and HT270 when the input energy is 32. 6 mJ and 93.9 mJ, respectively. When the input average power is 100 W, the temperature increment at the focal spot is 255 K for the liquid media. This result implies that the input average power limit of the liquid media is almost 100 W.

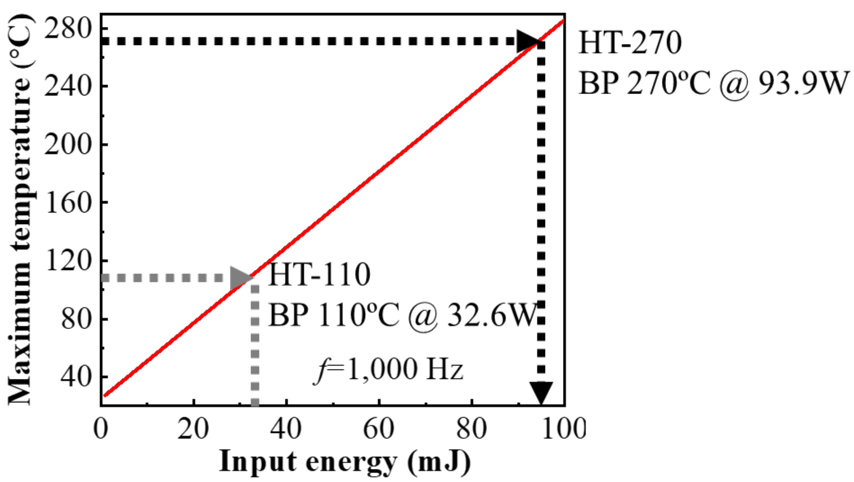

Figure 11. The maximum temperature at the focal spot in the SBS liquid media due to the input energy at the 1 kHz repetition rate operation.

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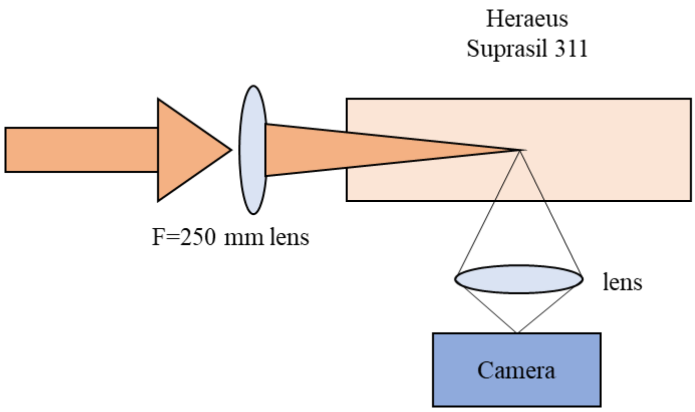

Figure 12. a schematic diagram of the measurement of fused silica (Suprasil 311) OBD threshold.

On the other hand, the Suprasil 311, metallic inclusion free fused silica made by Heraeus has small absorption coefficient of 10^{-6}/cm and high thermal conductivity of 1.38 W/(m K), so its temperature increment for 100 W is 0.04 K, which is 64 times smaller than the liquid media. However, the fused silica can be broken by the OBD. The authors measured the OBD threshold of the fused silica. Figure 12 shows a schematic diagram of the measurement of fused silica OBD threshold. When the input energy was 30 mJ and the focal spot size was 85 µm, the OBD occurred and the fused silica was broken. From this measurement, the OBD threshold of the Suprasil 311 is calculated as 53 GW/cm^2, which is similar value with known value of the fused silica OBD threshold 55 GW/cm^2.

Table 3 shows the comparison of the three types of SBS media, liquid, solid, and gas media.

Table 3. Comparison of liquid, solid, and gas media.

Medium	HT270	Fused silica	N_2 (100 bar)
Phase	Liquid	Solid	Gas
Advantages	Self-healing	Stable	Self-healing
Disadvantages	Convection, boiling, and OBD	Thermal shock and OBD (irreversible damage)	OBD
Absorption coefficient (/cm)	3×10^{-4}	1×10^{-6}	6.7×10^{-8}
Thermal conductivity (W/(m·K))	0.065	1.38	0.03
Temperature increment(K) for 100 W	255	0.04	0.12
OBD threshold (GW/cm^2)	>100	55	6,000 (at 1 bar)
Maximum input average power (by temperature)	94 W	3 kW	No limitation
Maximum input pulse energy (by OBD, τ = 10 ns), D_{focal} **90 µm**	64 mJ	35 mJ	3.8 J
Maximum input pulse energy (by OBD, τ = 10 ns), D_{focal} **1 mm**	7.9J	4.3J	471 J

5. Conclusion

The purpose of this research is to develop an SBS-PCM for high input average power more than 100 W. To achieve this goal, the authors tried to find the proper SBS media for high input average power. The authors have tested several kinds of liquids (HT110 and HT270), solid (metallic inclusion free fused silica), and gas (highly pressurized N_2 gas) media to make an SBS cell.
For the liquids, the authors used purified HT110 and purified HT270. The authors measured the SBS reflectivity and the SBS reflected beam patterns of HT110 and HT270 by using Kumgang laser operating at 1 kHz repetition rate. The SBS reflectivity of HT110 and HT270 at the input energy of 50 mJ@1kHz were 64% and 43%, respectively. The SBS reflected beam patterns of HT270 were better than those of HT110, because of the high boiling point and high viscosity of HT270. However, the SBS reflected beam patterns of HT270 were still unstable because of convection even without boiling.
For the solid, the authors used metallic inclusion free fused silica (Suprasil 311 made by Heraeus). The authors measured the SBS reflectivity and SBS reflected beam patterns of Suprasil 311 by using Kumgang laser operating at 1 kHz repetition rate. The SBS reflectivity at the input energy of 50 mJ@1kHz (input laser beam intensity 25 GW/cm^2) was 35%. The SBS reflected beam patterns were stable and good, but OBD was observed at the input energy of 35mJ@10Hz (input laser beam intensity 53 GW/cm^2), while the OBD threshold of Suprasil 311 is known as 55 GW/cm^2.
For the gas, the authors tested highly pressurized N_2 gas. The authors measured the SBS reflectivity and SBS reflected beam patterns using Spectra-physics laser (GCR-100) operating at 10 Hz. The SBS reflectivity at the input energy of 240 mJ (363 GW/cm^2) and the N_2 pressure of 100 bar was 67%. Up to 50 bar of the N_2 pressure, the OBD occurred severely. The higher the N_2 pressure is, the lower the OBD occurrence probability is. However, the OBD still occurred when the input laser beam intensity of 300 GW/cm^2 at the N_2 pressure of 100 bar, while the OBD threshold of N_2 gas at 1 bar is known as 6000 GW/cm^2.
From these results, the authors conclude that the SBS media has boiling/melting effect of the liquid/solid media and the OBD so that it is difficult to apply it to the high power laser system.

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6. Lists of papers and conference presentation

a) Paper published in peer-reviewed journal

1. H. Wang, S.Cha, Y. Wang, H. J. Kong, and Z. Lu, “SBS pulse compression using bulk fused silica by diode-pumped solid-state lasers at 1 kHz repetition rate”, JOLT, 128, 106258 (2020)

b) Conference presentation without papers

1. S.Cha, Stimulated Brillouin scattering phase conjugate mirror (SBS-PCM) using purified liquid medium for high average power laser, ALTA 2019, Jeju, Korea, 2019. 5
2. H. J. Kong, Coherent beam combination laser using solid medium self-phase-controlled stimulated Brillouin scattering phase conjugate mirrors, LCS 2019, Zakopane, Poland, 2019.9
3. S.Cha, Investigation of the stimulated Brillouin scattering phase conjugate mirror (SBS-PCM) using fused silica medium at high average input power, LCS 2019, Zakopane, Poland, 2019.9
4. H. J. Kong, Stimulated Brillouin scattering phase conjugate mirror (SBS-PCM) using the fused silica for the high average power laser, ALT 19, Czech Republic, 2019. 9.
5. S. Cha, Stimulated Brillouin scattering phase conjugate mirror (SBS-PCM) using purified liquid medium for high average input, ALT 19, Prague, Czech Republic, 2019.
6. S. Cha, O. Kim, H. J. Kong, Reflectivity measurement of the stimulated Brillouin scattering phase conjugate mirror using high-pressure N2 gas, 2021 OSK winter meeting, Korea, 2021.
7. S. Cha, O. Kim, H. J. Kong, Investigation of the reflection properties of stimulated Brillouin scattering phase conjugate mirror using highly pressurized N2 gas, Advanced Laser Technology and their Application (ALTA) 2021, Korea, 2021.

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