Characteristics of perfluorinated amine media for stimulated Brillouin scattering in hundreds of picoseconds pulse compression at 532 nm

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The characteristics of stimulated Brillouin scattering (SBS) in perfluorinated amine media and the experimental structure used in hundreds of picoseconds pulse compression at 532 nm are demonstrated. A two-stage SBS pulse compression structure is adopted for this work. The compact double-cell SBS compression structure and the scattering media FC-70 are chosen to compress the incident light from 9.5 to about 1 ns in the first stage. Then, the light is used as the pumping source for the second pulse compression. In the second stage, using a single-cell SBS structure in a pulse compression system, perfluorinated amine media with different phonon lifetimes, such as FC-3283, FC-40, FC-43, and FC-70, are chosen to run the comparative experimental study. The narrowest compressed pulse times obtained are 294, 274, 277, and 194 ps; they respectively correspond to the above listed media. The average width of the compressed pulse width is 320 ps for FC-3283, with a fluctuation range of 87 ps. For FC-40, the average pulse width is 320 ps, with a fluctuation range of 72 ps. And for FC-43, the average pulse width is 335 ps, with a fluctuation range of 88 ps. However, the average pulse width is only 280 ps for FC-70, with a fluctuation range of 57 ps. The highest energy reflectivity is more than 80% for all of the media. The experimental results show that a two-stage SBS pulse compression system has lower pump energy requirements, thus making it easier to achieve a compressed pulse waveform. The results also show that the shorter the phonon lifetime of the medium, the narrower the obtained compressed pulse width.

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Inertial confinement fusion (ICF) has drawn the attention of governments and academies because of its potential for solving the energy crisis and supporting national security. In 2007, Betti *et al.*[1] proposed a shock ignition scheme for ICF, which pointed out that an igniter shockwave would be launched if a laser pulse of hundreds of picoseconds with energy of about 100 kJ could be generated. The shock ignition scheme has had a great influence on the laser ignition dream that researchers have been striving for nearly 40 years. However, one of the key technologies to achieve the shock ignition is the generation of a driving laser pulse. The driving laser pulse requires a width of about 200 ps, energy of several kilojoules, and a pulse peak power of 10 TW, which presents a new challenge for the amplification technology of a high-power laser.

Stimulated Brillouin scattering (SBS) pulse compression technology is a simple and practical method of high-power laser pulse width compression. Not only does it have a high pulse compression ratio and high-energy conversion efficiency, but it also capable of eliminating the wavefront aberrations of the laser pulse to improve the beam quality. Hence, by using SBS pulse compression technology, Stokes pulses with a width of hundreds of picosecond, a peak power of terawatts, and energy of several kilojoules can be obtained. This is the most direct and cost-effective method in shock ignition research right now. Although many people have studied SBS pulse compression technology, they mainly focused on low-energy nanoseconds pulses[2–6]. Only several teams have achieved the order of magnitude of a laser in picoseconds. However, the picosecond pulses have some defects, such as low conversion efficiency, low load capacity, poor stability, a short incident wavelength, repeated compression, and excessively complex experimental devices[7–9]. In 2009, Yoshida *et al.*[10] used FC-40 as the SBS medium in a compact two-cell SBS system and compressed an incident light from 13 ns to 160 ps. The maximum energy reflectivity was about 80%, which is the highest pulse compression ratio that has been achieved in a lab so far. The result is satisfactory, but the requirement of 1 J of pump energy to produce the seeds is very detrimental to the subsequent amplification process. Therefore, looking for a kind of structure that only requires a low pumping energy is very necessary.

Our preliminary research shows that, besides the pump parameters and the structure parameters, medium parameters also have a great influence on SBS pulse compression efficiency, especially the medium phonon lifetime[11]. Along with the further development of the research on SBS, different kinds of fluorocarbon SBS media are being successively presented. However, they are studied mostly in direct applications, or by contrast in couples. They are all on the 1064 nm wavelength; few researchers dedicate time to a variety of media for comprehensive comparison research under the condition of a 532 nm wavelength.

In this Letter, the characteristics of hundreds of picoseconds pulse compression using the perfluorinated amine SBS media is studied. A two-stage SBS pulse compression structure is adopted for this work. In the first stage, the compact double-cell SBS compression structure and FC-70 are chosen to compress the incident light of 9.5 down to about 1 ns. Then, the light is used as the pumping source for the second pulse compression. In the second stage, with a single-cell SBS pulse compression structure, perfluorinated amine media that have different phonon lifetimes, such as FC-3283, FC-40, FC-43, and FC-70, are used to run the comparative experimental study. The narrowest compressed pulse times that are obtained are 294, 274, and 277, and 194 ps; they respectively correspond to the above listed media. The highest energy reflectivity was more than 80% for all of them. The experimental results show that, through the two-stage SBS pulse compression system, a low pump power can achieve a narrow pulse compressed waveform. And, the shorter the phonon lifetime of the medium, the narrower the obtained compressed pulse width.

An excellent SBS medium for generating hundreds of picoseconds pulses must fulfill three requirements: it must have low absorption, a high energy load, and a short phonon lifetime[12]. According to the above three principles, we select the FC-3283, the FC-40, the FC-43, and the FC-70 perfluorinated amine media to launch the comparative experimental study. All of the above belong to the medium series of perfluorinated amine compounds (perfluorinated amine, compounds in which all the hydrogen connected to the carbon atoms are replaced by fluorine in amine molecules)[13].

The general formula for the perfluorinated amine molecules is $(C_nF_{2n+1})_3N$. For example, the FC-3283 is Perfluoro-tri-n-propyl amine $(C_3F_7)_3N$; FC-40 consists of Perfluoro-tributyl amine $(C_4F_9)_3N$ and a $(C_4F_9)_2NCF_3$ mixture of perfluorinated mixed amine; FC-43 is Perfluoro-tributyl amine $(C_4F_9)_3N$; FC-70 is Fluorizated-tripentyl amine $(C_5F_{11})_3N$. Their molecular structures are shown in Fig. 1. As the molecular structures indicate, the molecular structures of the four kinds of media are similar. Only the C-F chain is different, and they have many similarities in their physical and chemical properties. Therefore, the comprehensive comparison among the above similar media has an important reference significance to find the medium with the best SBS characteristics.

Our team has done considerable research on the correlation between the molecular structure and its property of SBS in a fluorine carbon medium. Firstly, the perfluorinated amines are composed of the chemical bonds C C, C-F, C-N, and X-H, which absorbs near-infrared light, so their absorption coefficient is low. Secondly, the radius of the fluorine atom is the smallest (Van der Waals

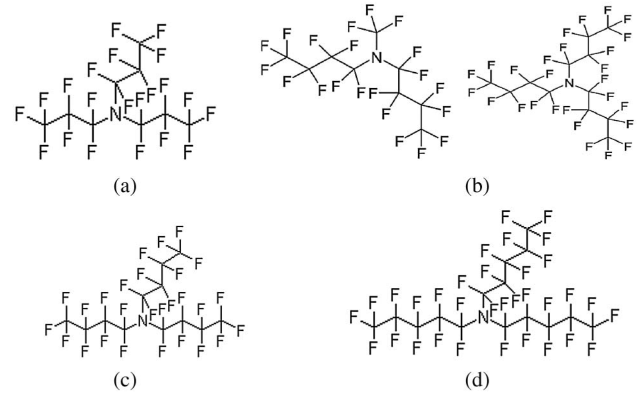

Fig. 1. Molecular structure of the perfluorinated amines: (a) FC-3283, (b) FC-40, (c) FC-43, and (d) FC-70.

radius is 0.135 nm), and they can protect the C C bonds efficiently[14], so the optical breakdown threshold (OBT) is high. Finally, according to expression of the phonon lifetimes[15] (λ is the incident light wavelength, η is the kinematic viscosity of medium), it can been seen that the shortest phonon lifetime is always accompanied by a bigger kinematic viscosity. For different perfluorinated amines, the difference of kinematic viscosity is larger (several times or dozens of times), although their physical parameters, such as the refractive index and the density, have small variation (only a few percent). Thus, by choosing the highest kinematic viscosity, the medium with the shortest phonon lifetime can be found. In general, the greater the average molecular weight, the greater the force between the molecules, the greater the kinematic viscosity, and the shorter the phonon lifetime, as listed in Table 1. Of all four kinds of perfluorinated amine media, FC-43 and FC-70 were found out by our team, and were used as SBS media for the first time[16]. The absorption coefficient and the OBT are measured directly[17]. The phonon lifetime, gain coefficient, and Brillouin shift are calculated according to the equations given by[15]. As shown in Table 1, the kinematic viscosity of FC-70 reaches 14.0 cSt, and its phonon lifetime is only 8 ps, which is the shortest recorded in the current available literature.

The experimental setup is shown in Fig. 2. The laser pumping source is p-polarized light produced by a single-mode injection seeded by a Q-switched Continuum Nd:YAG laser with a line width of 50 MHz at a fundamental wavelength of 532 nm. The first SBS pulse compression system consists of two SBS cells (amplifier cell $L_1 =$ 80 cm; generator cell $L_2 = 60$ cm) and two convex lenses (focal lengths $f_1 = 150$ cm and $f_2 = 40$ cm). Convex lens f_1 is placed in front of amplifier cell 1 (its focal point is not in amplifier cell 1, because its strength does not match with the SBS threshold), which can increase the pump power intensity in the amplifier cell so that the Stokes light can be amplified effectively. Polarizer P and a quarter-wave plate were operated as optical isolators to prevent the backward Stokes from returning to the laser oscillator, and for protecting against optical damage. The

Table 1. Physicochemical properties and SBS parameters of the perfluorinated amines

Medium	FC-3283	FC-40	FC-43	FC-70
Refractive index	1.281	1.290	1.291	1.303
Average molecular weight	521	650	670	820
Density (g/cm^3)	1.83	1.87	1.86	1.94
Kinematic viscosity (cSt)	0.75	1.7	2.5	14.0
Boiling point (°C)	128	155	174	215
Absorption coefficient (cm^{-1})	0.0009	0.0011	0.0012	0.0012
OBT (GW/cm^2)	179	173	178	180
Phonon lifetime (ps)	148	64	43	8
SBS gain coefficient (cm/GW)	4.0	1.8	1.3	0.2
Brillouin shift (MHz)	2159	2151	2159	2133
Medium velocity (m/s)	448	444	445	436

laser pulse width of the Nd:YAG laser output is about 9.5 ns after the first two-cell SBS pulse compression system laser with a pulse width of about 1 ns is obtained, and it is used as the second-level pulse compression pump. The second pulse compression system is composed of a focal lens ($f_3 = 25$ cm) and generator cell 3 ($L_3 = 60$ cm). The input laser energy was adjusted by rotating the half-wave plate.

The s-polarized light from the first stage is turned into p-polarized light by the half-wave plate. Then, it is turned into circularly polarized light through the quarter-wave plate. The polarized light is focused on generator cell 2 by lens f_2 to generate the backwards Stokes light. The backwards Stokes light is coupled with the pumping light in amplifier cell 1 and effectively amplified. Through the quarter-wave plate, the above light becomes s-polarized light, and then is reflected by the polarizer P_1. The polarized light focused in generator cell 3 by lens f_3 to generate the seed light. The seed light after quarter-wave plate is turned into the s-polarized light, and then is reflected by the polarizer P_2.

The detection system is composed of a PIN photodiode, a digital oscilloscope, and an energy meter (MIN-E1000). The energies of the input laser and the compressed laser were detected by a PE50BB-DIF-V2 (OPHIR) energy meter. The pulse shapes were detected by a PIN photodiode with an 18.5 ps rise time (New Focus, 1454), and were recorded by a digital oscilloscope (DPO71254C) with a bandwidth of 12.5 GHz, a sample rate of 100 Gs/s, a rise time of 32 ps. The properties of the first double-cell pulse compression system have been studied before[18]. In this Letter, we mainly research the properties of the second single-cell pulse compression system, and acquire the pattern of how the SBS picosecond pulse compression is influenced by the phonon lifetime of the gain medium.

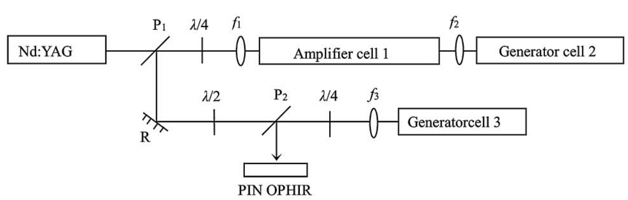

Fig. 2. Schematic of the experimental setup.

In the experiment, the input pulse has a pulse width of 9.5 ns at 532 nm, repeated at a rate of 1 Hz. The beam diameter is 9.5 mm with a divergence angle of 0.45 mrad. In the first stage, FC-70 is chosen as the SBS medium of the compact double-cell system. The perfluorinated amine media that have different phonon lifetimes, including FC-3283, FC-40, FC-43, and FC-70, are chosen to carry on the comparative experimental study in the second system. The waveforms of the output laser pulse and the one after the first stage of the pulse compression are shown in Fig. 3. The output laser pulse width is about 9.5 ± 0.5 ns, with energy of about 80 mJ. After the first pulse compression system, the width of the pulse waveform is about 1 ± 0.2 ns, with energy of about 30 mJ.

The compressed pulse widths of the four different media under different input energies in the second single-cell SBS system are shown in Fig. 4.

For all four kinds of media, the Stokes pulse width narrows rapidly with the incident energy at the beginning,

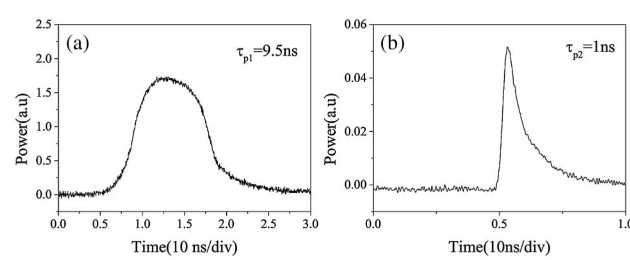

Fig. 3. (a) Laser pulse waveforms from the laser. (b) Laser pulse waveforms after the first pulse compression.

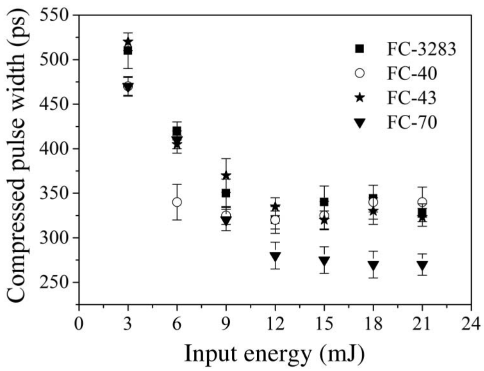

Fig. 4. The compressed pulse widths of the four different media under different input energies.

and then slowly with the energy rise. This is because the integrated gain of the system, the pulse compression efficiency, and the Brillouin amplification efficiency gradually enhance with the increase of the input energy. But when the incident light energy increases further, the SBS pulse compression reaches its limit, and the compressed pulse width of the SBS narrows slowly. As can be seen from the diagram, with the improvement in the incident light energy, the compressed pulse width of the FC-70 medium is narrower than that of FC-3283, FC-40, and FC-43. From Table 1, the phonon lifetime of FC-70 is shorter than the other three kinds of media. It proves that the shorter the phonon lifetime, the narrower the pulse width can be compressed.

In addition, to achieve a pulse width at level of 200 to 300 ps, the previous compact double-pool experiments require 300 mJ pump energy or higher[16]. In this experiment, due to the structure of the two-stage compression, only 80 mJ initial pump energy will be able to achieve this goal.

Figure 5 shows the shortest compressed pulse waveforms of the four media. The shortest compression pulse of FC-3283 is 294 ps, 274 ps for FC-40, 277 ps for FC-43, and 194 ps for FC-70. At the same time, when the incident energy for each medium is 12 mJ, the distribution of 80 groups of the Stokes light pulse width have been counted. The average width of the compressed pulse is 320 ps for FC-3283, with a fluctuation range of 87 ps. For FC-40, the average pulse width is 320 ps, with a fluctuation range of 72 ps. For FC-43, the average pulse width is 335 ps, with a fluctuation range of 88 ps. However, the average pulse width is only 280 ps for FC-70, with a fluctuation range of 57 ps. From the above results, it can be seen that the compressed pulse width of FC-70 is not only the narrowest, but also has the minimum fluctuation range of the pulse width. Compared with the previous experimental results, the two-stage structure of the small-pulse fluctuation range is significantly smaller, and the compressed wave profile is more conducive to be further enlarged.

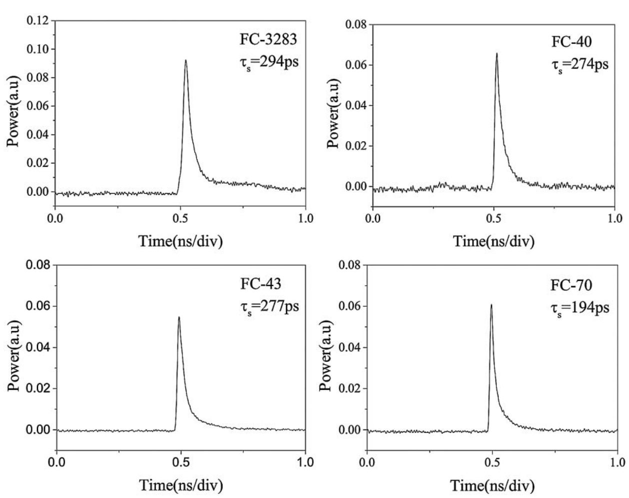

Fig. 5. The shortest compressed pulse of the four kinds of media.

The experimental curves of the SBS energy reflectivities of the four different media under different input energies are shown in Fig. 6. When the input energy is equal, the energy reflectivities of the four kinds of media tend to be close, and the highest energy reflectivity is more than 80% for all of them if the optical mirror surface scattering loss is taken into account. The energy reflectivity is not only related to the gain coefficient, but also to the absorption coefficient, the OBT, and other nonlinear effects. In addition, we found that in the experiment, optical breakdown is easier to achieve in the second pulse compression system than during the first stage. This may because the picosecond laser pulse has a higher peak power than the nanosecond laser.

In conclusion, a two-stage SBS pulse compression structure is adopted for hundreds of picoseconds pulse compression at 532 nm. With the compact double-cell SBS compression structure, FC-70 is chosen to compress an incident light of 9.5 ns down to about 1 ns in the first stage. Then, the light is used as the pumping source of the second pulse compression. In the second system, with a single-cell SBS pulse compression structure, perfluorinated amine media that have different phonon lifetimes, including FC-3283, FC-40, FC-43, and FC-70, have been tested for the comparative experimental study. The narrowest

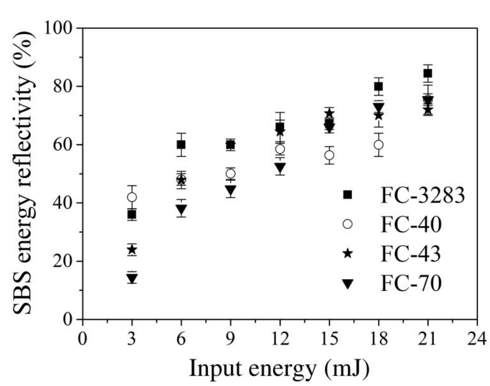

Fig. 6. The energy reflectivities of the four different media under different input energies.

compressed pulses, which respectively correspond to the above media, are 294, 274, 277, and 194 ps. With the specular scattering loss counted, the highest energy reflectivity is around 80%. The experimental results show that the compression efficiency and stability of FC-70 is better than the others, and FC-70 is very suitable to be chosen for generating hundreds of picoseconds pulses. To obtain a SBS hundreds of picoseconds pulse compressed waveform, the required energy of the two-level SBS pulse compression system is lower than that of single compression system; this is more conducive to generate further amplification of the necessary seed. The shorter the phonon lifetime of the medium, the narrower the compressed pulse width that can be obtained. This provides a shortcut for the acquisition of a hundreds of picoseconds laser pulse.

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