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科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Investigations of spectrally tunable, nanosecond laser pulse compression characteristics by SBS technique

研究課題名（英文）Investigations of spectrally tunable, nanosecond laser pulse compression characteristics by SBS technique

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交付決定額（研究期間全体）：（直接経費）　　3,000,000円

研究成果の概要（和文）：この研究の目的は、誘導ブリルアン散乱(SBS)によりパルス圧縮特性を調査、広範囲に調整可能なns幅、数mJのTi:Saレーザーパルス圧縮方法を開発することでした。SBSに基づくns光パルス用のコンプレッサが設計および構築した。FC72およびFC40 SBS液体を使用し、720～850nm領域で18～30ns幅、5～13mJのTi:Saパルスの圧縮実験が実行した。キャビティ内エタロンを設定で、圧縮されたパルス幅は11.2から7.0nsに減少し、効率は42から55%に向上した。また、SHG（第二高調波発生）ユニットを構築し、より広いスペクトル領域でのSH変換効率と圧縮パルスの発生安定性を調査した。

研究成果の学術的意義や社会的意義
Single WL pulse compression by SBS has been done previously, but to the best of my knowledge, it has not been applied to wavelength-tunable laser pulses. By establishing such a compression method, one can compress and use ns pulses in different areas such as resonance Raman spectroscopy, LIDAR, etc.

研究成果の概要（英文）：The goal of this research was to investigate pulse compression characteristics and develop a pulse compression method for a broadly tunable, ns duration, few mJ energy Ti:Sapphire laser pulses by stimulated Brillouin scattering (SBS) technique.
A compact pulse compressor for ns optical pulses based on SBS was designed and built. Pulse compression experiments of 18-30ns duration, 5-13mJ energy Ti:Sapphire laser pulses in 720-850nm region were performed using FC72 and FC40 SBS liquids. Using an intracavity etalon, the compressed pulse width decreased from 11.2ns to 7.0ns, and the efficiency improved from 42% to 55%. The short coherence length of the pump pulses has been identified as the main reason for low energy conversion efficiency. To increase the conversion efficiency, narrowband pulses must be used. We have also built an SHG (second harmonic generation) unit and investigated the SH conversion efficiency and generation stability of the compressed pulses in a broader spectral region.

研究分野：High-power lasers

キーワード：誘導ブリルアン散乱　SBS　パルス圧縮　compact SBS cell　tubable ns pulses

１．研究開始当初の背景

There are many pulse compression techniques to increase the peak power of the laser pulses. In the ultrafast regime, techniques using prism- or grating pairs are applied to compress optical pulses. However, these methods cannot be applied to nanoseconds (ns) duration pulses. Pulse compression from several ns to sub-ns can be done by utilizing only nonlinear light-matter interactions such as degenerate four-wave mixing, stimulated Raman scattering, or stimulated Brillouin scattering (SBS).

SBS pulse compression in liquids has been investigated for many years. So far, different SBS liquids and compression geometries, such as single-, double-cell, counter-propagating pulses, etc., have been utilized. Analysis of the available literature indicates that more than 50 times pulse compression factors and energy efficiencies as high as 95 % can be achieved. Most investigations, however, were performed at discrete wavelengths (1064 nm, 532 nm, etc.) using quite long (1 – 3 m) SBS amplifier cells. The primary goal in previous investigations was compressing Joule class, 5 – 20 ns duration optical pulses as short as possible (~ 100 ps) for application in the inertial confinement fusion reactions as an ignitor-shock spike.

２．研究の目的

In our investigations, we have set a goal to study pulse compression characteristics of low energy (tenths of mJ), tunable, varying duration ns pulses. Such pulse compression systems could have applications, for instance, in material processing, in LIDAR (Light Detection and Ranging) for spatial (depth) resolution, in OPCPA (optical parametric chirped pulse amplification) for a pump pulse compression, or in remote resonance Raman spectroscopy (RRS) for increasing the S/N resolution. Spectrally tunable, nanosecond Ti:Sapphire laser operating in gain-switching mode is one such candidate. To increase the peak power of the pulses, minimize the pulse duration spread versus the wavelength, and achieve a good S/N ratio, two strategies can be applied: increasing the pump power or compressing the ns pulses to sub-ns duration. Due to the limitations of power upscaling, pulse compression seems to be the most viable option.

Recently, we have proposed a variable-length, compact SBS amplifier cell for ns pulse compression applications. In this report, we describe the pulse compressor system with the new SBS amplifier cell and present results of our ongoing investigations on pulse compression characteristics in terms of pulse compression factor and energy conversion efficiency.

３．研究の方法

SBS is an inelastic interaction between light and sound. It can be described by the 3rd order term of the polarization induced in the medium by the applied optical field. It is associated with the nonlinear $\chi^{(3)}$ coefficient of the electric susceptibility of the material. SBS is a fully understood and mathematically described physical phenomenon, so here we will not go beyond qualitative explanations.

There are many applications of the SBS phenomenon, for instance, phase conjugation, optical limiting, coherent beam combination, pulse compression, etc. In the following, we will briefly describe the SBS pulse compression process. Fig. 1 illustrates the principle of the SBS pulse compression process. A pump pulse is focused into the SBS cell producing a backward scattering Stokes pulse at the focus. The rising edge of the Stokes pulse sweeps through and depletes the counter-propagating pump pulse, converting the energy from the pump pulse into a temporally compressed Stokes pulse during the interaction.

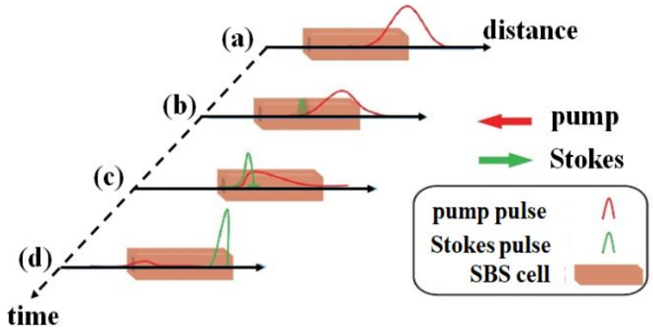


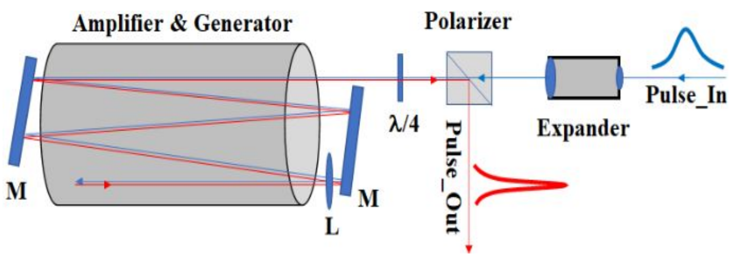
Fig. 1. Illustration of the SBS pulse compression process: (a), (b), (c), and (d) points on the time scale are representative moments for the pump pulse (red) entering the SBS cell, generating a counterpropagating Stokes wave (green), amplifying it by depleting the pump pulse, and exiting the SBS cell, respectively.

Fluorocarbons (FC72, FC70, FC40, etc.) are widely used SBS media due to their broad Brillouin linewidth, acceptable gain coefficients, thermal and chemical stability, transparency in the 400 – 1100 nm spectral region, fast phonon lifetimes, etc. In the present experiments, FC72 and FC40 liquids with ~ 1.2 ns and 0.2 ns phonon lifetimes, ~ 6 cm/GW and ~ 3.8 cm/GW SBS gain coefficients, and ~ 270 MHz and ~ 1292 MHz Brillouin bandwidths were used, respectively.

４．研究成果

The SBS pulse compressor schematics with the variable-length (folded), compact SBS amplifier is presented in Fig. 2.

Fig. 2. Schematic diagram of the pulse compression system using the variable length SBS cell for SBS interaction length optimization.



Linearly polarized pump pulse (blue) passes the polarizer, λ/4 plate, SBS cell with 50 cm length, and is tightly focused into the SBS cell using the lens L (f = 50 cm). The generated SBS wave (red) propagates back, is amplified in the same SBS cell, and is extracted from the polarizer. By changing the angles of two mirrors (M) relative to the amplifier cell windows, one can control the round-trip numbers of the laser pulse in the cell to optimize the interaction length (temporal overlap) between the pump and generated pulses in the amplifier.

To reduce the linewidth of the optical pulses, we have inserted a Fabry-Perrot etalon inside the laser resonator. In this way, the pulse bandwidth at 820 nm was reduced from

50 pm to about 5 pm (from 22.3 GHz to 2.23 GHz). In Fig. 3, a snapshot of the experimental setup is presented.

Fig. 3. Experimental setup of the pulse compression system.

A Ti:Sapphire laser operating in the gain-switching mode with the following parameters: 15 Hz rep. rate, 10~30 mJ/pulse energy, 15~30 ns FWHM pulse duration, 680–1000 nm spectral tuning range, ~ 50 pm (~ 0.72 cm^{-1}) linewidth, M^2 ~ 1.6, was used. FC-72 fluorocarbon liquid was used as an SBS liquid.

Experimental results describing the characteristics of the pulse compression are presented in Fig. 4. At 800 nm, the pulse FWHM before entering the SBS compression system was ~ 18 ns. When the effective length of the SBS cell was ~ 1 m (2 passes), the pulse width was compressed to 13.8 ns with energy efficiency of ~ 55 %. When the effective length of the SBS cell was ~ 1.5 m (3 passes), the pulse width decreased to 11.2 ns with energy efficiency of ~ 42 %. At ~ 2 m (4 passes) SBS cell length, the pulse duration was 8.7 ns with ~ 30 % energy conversion efficiency.

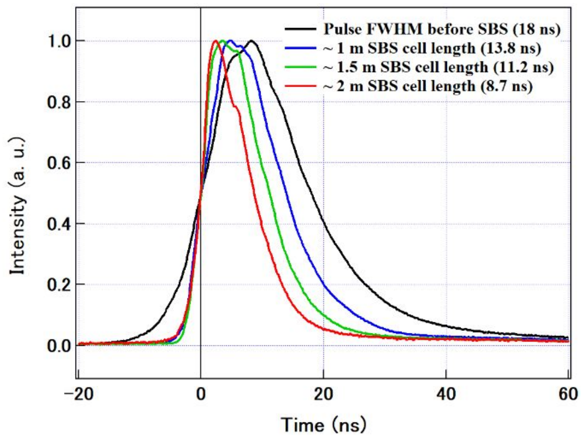


Fig. 4. Pulse compression characteristics of the SBS compressor at 800 nm.

In Fig. 5, the pulse FWHM dependence on the wavelength for two SBS liquids and L_S ~ 1.5 m effective interaction length in comparison with the same dependence, but without a compressor, is presented. As expected, due to the shorter phonon lifetime (0.2 ns vs. 1.2 ns), the compressed pulse FWHM in FC40 vs. FC72 was more efficient. The SBS energy conversion efficiency at around 770 - 800 nm range, on the other hand, was still low, ~ 0.55 (~ 0.7, if linear optical losses of the system are taken into consideration) for both FC72 and FC40 SBS liquids. Compared with the case without inserting the etalon and the same effective length of the SBS cell (L_S ~ 1.5 m or 3 passes), the pulse width decreased from 11. 2 ns to 7.0 ns, and the energy efficiency improved from ~ 42 % to ~ 55 %. To mitigate this problem, other SBS liquids such as galden perfluoropolyether (PFPE) compounds HT230 and HT270 (HT stands for Heat Transfer) which have 0.1 ns phonon lifetime, and 3.16 and 8.4 GHz Brillouin linewidths, respectively, could be used.

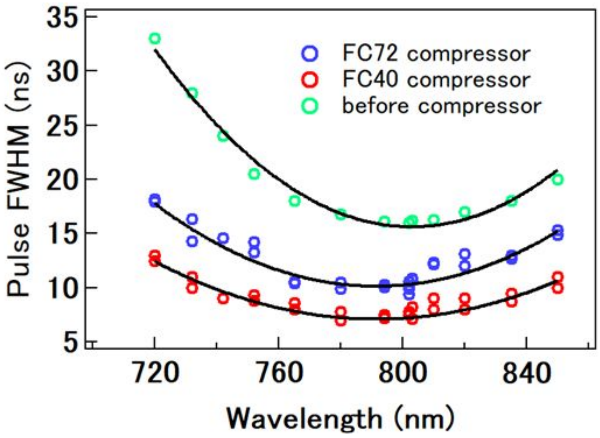


Fig. 5. Pulse FWHM dependence on the wavelength for FC40 and FC72 SBS liquids (L_S ~ 1.5 m) in comparison with the pulse FWHM before the compressor.

We have also built an SHG unit and investigated the SH conversion efficiency and stability of the compressed pulses in a broader spectral region. The compressed pulses were directed to the broadband coated BBO crustal where the second harmonics (SH) was generated. Using a dichroic mirror, the SH was separated from the fundamental frequency and measured by a power meter. The pulse-to-pulse stability of the SH was good. Although the FWHM of the SH pulses reduced, the SH pulse energies of the compressed pulses significantly dropped. Estimation shows that the peak intensities of the resulting pulses are also reduced to the ~ 90% level of the non-compressed pulses.

In this report, we have described the optical pulse compression principle based on the stimulated Brillouin scattering (SBS) phenomenon. A variable-length, folded SBS amplifier cell allowing compact cell design with reduced SBS liquid volume, has been proposed for ns pulse compression applications. An SBS pulse compressor was designed and built. Pulse compression experiments using ~ 18 ns duration, ~ 30 mJ energy Ti:Sapphire laser pulses at 780 nm, 800 nm, and 820 nm were performed. An etalon was inserted into the laser resonator to reduce the pulse bandwidth, and pulse compression experiments using ns laser pulses in 720 – 850 nm spectral region were performed using FC72 and FC40 SBS liquids. Compared with the case without the etalon and the same effective length of the SBS cell (L_S ~ 1.5 m or 3 passes), the pulse width decreased from 11. 2 ns to 7.0 ns, and the energy efficiency improved from ~ 42 % to ~ 55 %. Nevertheless, the energy conversion efficiency was not enough for practical applications. Our analysis showed that the main reason for the low energy conversion efficiency is still the short coherence length of the pump pulses (L_c ~ 13.5 cm, bandwidth ~ 2.23 GHz).

We have built also an SHG unit and investigated the SH conversion efficiency and stability of the compressed pulses in a broader spectral region. Although shorter SH pulses could be obtained, the peak powers for compressed pulses were on the ~ 90% level compared with the pulses before the compression. The main problem hindering the improvements of the pulse compression ratio and energy conversion efficiency has been identified to be the short coherence length of the available nanosecond Ti:Sapphire laser. Our experiments indicate that the proposed SBS cell and pulse compression technique can be applied to broadly tunable ns laser pulses having bandwidths compatible to the transform-limited ones.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　0件／うち国際共著　0件／うちオープンアクセス　3件）

１．著者名 H. Chosrowjan, S. Taniguchi, T. Somekawa	４．巻 33
２．論文標題 Investigations of Spectrally Tunable Nanosecond Laser Pulse Compression Characteristics by Stimulated Brillouin Scattering (SBS) Technique	５．発行年 2022年
３．雑誌名 ILT年報　https://www.ilt.or.jp/wp-content/uploads/2023/04/955ea86e3c49524ab7312481cd0cfb29.pdf	６．最初と最後の頁 27 - 30
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 H. Chosrowjan, S. Taniguchi, T. Somekawa	４．巻 34
２．論文標題 Investigations of Spectrally Tunable Nanosecond Laser Pulse Compression Characteristics by Stimulated Brillouin Scattering (SBS) Technique	５．発行年 2023年
３．雑誌名 ILT年報　https://www.ilt.or.jp/wp-content/uploads/2024/04/7c9e37470a4ade38332013e546ca7850.pdf	６．最初と最後の頁 27 - 31
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 H. Chosrowjan, S. Taniguchi, T. Somekawa	４．巻 35
２．論文標題 Tunable Nanosecond Ti:Sapphire Laser Pulse Compression Characteristics by the Stimulated Brillouin Scattering (SBS) Technique	５．発行年 2024年
３．雑誌名 ILT年報　(in press)	６．最初と最後の頁 -------
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 H. Chosrowjan, T. Somekawa, S. Taniguchi
２．発表標題 Investigations of spectrally tunable, nanosecond laser pulse compression characteristics by SBS technique
３．学会等名 第83回応用物理学会秋季学術講演会　　(21p-P04-5)
４．発表年 2022年

1．発表者名 H. Chosrowjan, T. Somekawa, S. Taniguchi
2．発表標題 Nanosecond pulse compression by SBS technique and investigations of its SHG characteristics
3．学会等名 第70回応用物理学会春季学術講演会　　(15a-PB01-3)
4．発表年 2023年

1．発表者名 H. Chosrowjan, T. Somekawa, S. Taniguchi
2．発表標題 Investigations of Tunable, Nanosecond Ti:Sapphire Laser Pulse Compression Characteristics by Stimulated Brillouin Scattering (SBS) Technique
3．学会等名 OPIC2023, ALPS2023, Advanced Lasers and Photon Sources 2023　　(ALPSp2-06))（国際学会）
4．発表年 2023年

1．発表者名 H. Chosrowjan
2．発表標題 Investigations of spectrally tunable, nanosecond laser pulse compression characteristics by SBS technique
3．学会等名 第69回応用物理学会春季学術講演会　　(24p-P05-5)
4．発表年 2022年

1．発表者名 H. Chosrowjan, T. Somekawa, S. Taniguchi
2．発表標題 Nanosecond Ti:Sapphire pulse compression characteristics by the SBS technique
3．学会等名 第84回応用物理学会秋季学術講演会　　(21p-P13-4)
4．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関