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Pulse Compression of a Ti:Sapphire Laser by Stimulated Brillouin Scattering in Liquid Media

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Abstract: Studies of pulse shortening of a Ti:sapphire laser by the backward stimulated Brillouin scattering (SBS) are reported. Energy-conversion efficiency and the effect on pulse-compression characteristics in different liquid media are discussed based on a coupled equation model describing dynamics of SBS. Energy-conversion efficiencies of 37.5 percent in water and 61.4 percent in methanol were obtained experimentally. In case of water medium a compression ratio of 4 was obtained, but in case of methanol, the effect on the pulse compression was not significant due to increase in energy efficiency and use of a shorter cell length than the required. The theoretical simulation qualitatively agrees well with the experimental results.

Keywords: Ti:sapphire laser, Stimulated Brillouin scattering, Pulse compression, Injection seeding

1. Introduction

Typically, Titanium-doped sapphire (Ti:sapphire) generates tunable laser beam with a duration of few nanosecond (ns), and it has also been applied very much for the generation and amplification of ultrafast laser pulses in terms of few femtosecond. The methods of ultrashort light pulse generation described so far use modelocking technique [1] or pulse-chirp technique [2]. Nevertheless, some applications like fluorescence life time measurements, LIDAR Thomson scattering diagnostics of large plasma devices [3] do not require such extremely short pulses, and sub-ns laser pulses are competent enough. In such cases a high power laser pulse-compression by the stimulated Brillouin scattering technique is an effective means of pulse shortening since high compression efficiency is achievable and it involves a very simplified construction [4–6]. Many researchers have reported studies of pulse compression of different lasers using SBS gaseous and liquid media but the output is limited for a fixed-wavelength laser [7–12].

In this paper we report experimental and theoretical analyses of a pulse compression of a Ti:sapphire laser by the SBS process using different liquid media. A spectrally narrowed Ti:sapphire laser using a cw injection-seeding was developed with 8-12 ns FWHM pulses with an energy of 40 mJ/pulse by employing an oscillator-amplifier configuration for the investigation. The aim of this study is to understand the requirements for obtaining efficient pulse compression of Ti:sapphire laser by SBS process. The wavelength of Ti:sapphire laser is suitable for LIDAR Thomson scattering experiments. In **Section 2** experimental studies of pulse compression of the cw diode laser injection-seeded Ti:sapphire laser using different SBS liquid media; such as water, methanol, toluene has been described and corresponding results are discussed **Section 2.2**. In **Section 3**, the dynamics of the SBS process are described for different liquid media based on a coupled wave equation model.

2. Experiment of SBS by Ti:Sapphire Laser

In this work, a home-made Ti:sapphire laser was used with an oscillator-amplifier design. For successful pulse compression by SBS in a conventional long-cell design, a few hundreds of mJ of input energy is necessary to overcome SBS threshold condition. But in this experiment, since the equipment capacity was limited to an output of only few tens of mJ of the Ti:sapphire laser , an alternative arrangement was implemented with a short-cell design instead of using a conventional long-cell design [4–6]. Moreover, one necessary requirement of compression by SBS is the narrow linewidth operation of the input laser. In case of larger bandwidth the gain by SBS is reduced and in turn the threshold intensity for the Stokes initiation is increased [5]. Therefore spectral narrowing of the Ti:sapphire laser was achieved

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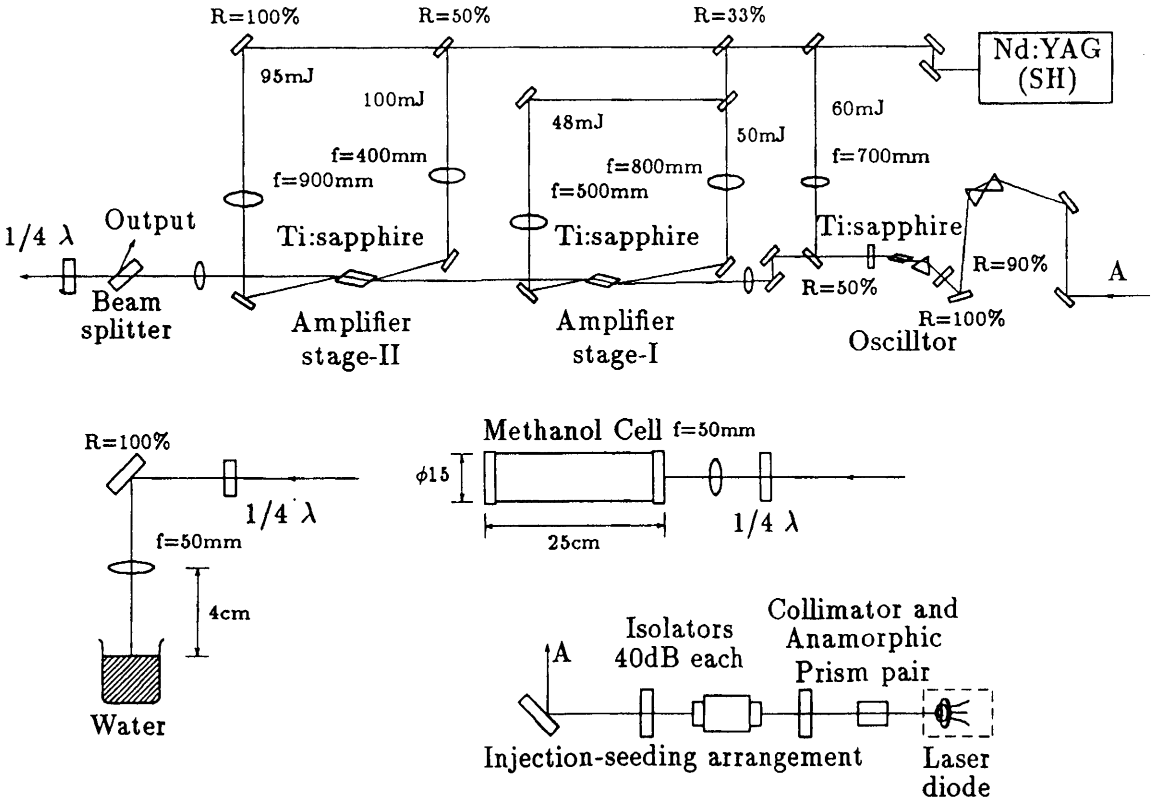


Fig.1 Experimental setup for SBS by injection-seeded Ti:sapphire laser for different liquid medium.

by using a cw single-mode diode laser injection-seeding technique [13].

2.1 Experimental setup

A line diagram of experimental setup is shown in Fig. 1. A Q-switched, frequency-doubled Nd:YAG laser (Spectra-Physics GCR-3) was used for pumping of oscillator and amplifier stages of the Ti:sapphire laser with a total input energy of 360 mJ at a repetition rate of 10 Hz. The Ti:sapphire laser oscillator was a 60 mm length straight cavity configuration with a prism as a coarse tuning element. A single-mode laser diode (Spectra Diode Laboratories SDL-5411-G1) was used as a cw injection laser at a wavelength of 807 nm. The output from laser diode was directed into the Ti:sapphire laser oscillator through a collimating optics and two optical isolators of 40 dB each to protect the laser diode. The injection-seeded oscillator output was passed through a two-stage amplifier with a single-pass design and an amplified output was obtained.

The amplified output was directed into an SBS medium passing through the polarizing beam splitter and a $\lambda/4$ wave plate. The $\lambda/4$ wave plate and the polarizing beam splitter combination was used to change the polarizing direction of the Stokes pulse with respect to the oscillator output by $\pi/2$ and to split it off at the beam splitter for measurement of Stokes pulse as well as to avoid re-entry of the short pulse Stokes output to the amplifier stage which may cause damage to the Ti:sapphire crystal. In case of a water medium, a beaker was used and an optimum operational characteristics were achieved with a focusing lens of 50 mm kept at a distance such that the focusing could be achieved at 10 mm below the water surface. In case of methanol, a short-cell was used with a focusing lens of 50 mm and similar focusing condition was maintained.

The input and output pulse width characteristics were measured using Tektronix 7104 oscilloscope having sample rating speed of 1 GS/s. The input energy was controlled with neutral density filter and input and output energy measurements were performed using a Scientech-372 energy meter.

2.2 Experimental Results and Discussion

2.2.1 Spectral Narrowing by CW Injection-Seeding

Figure 2 shows output spectra of Ti:sapphire laser with and without injection-seeding. The indicated value of the laser power was measured inside the cavity. Without injection-seeding the spectral output extended from 801 to 813 nm. Subsequently, as the injection power was increased, the broad-band emission was quenched

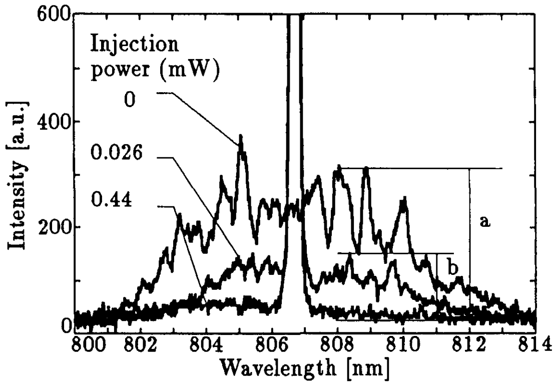


Fig.2 Spectra of cw injection-seeded Ti:sapphire laser output. Locking efficiency is defined as $\phi = 1 - b/a$.

and spectral narrowing was achieved. In Fig. 2 the spectral width of the injection-seeded laser is wider than the actual due to a low resolution of the spectrometer. In order to evaluate the degree of injection-seeding, a parameter, locking efficiency ϕ was considered. The locking efficiency ϕ can be defined as the ratio of the energy in the injected mode to the total lasing energy. Further, in case of homogeneously broadened spectra, this calculation can be simplified as follows,

$$\phi = 1 - \frac{b}{a}, \qquad (1)$$

where a is the height of any mode other than the injected mode in the free-running condition, and b is the height of the same mode during injection-seeding.

Figure 3 shows the locking efficiency ϕ as a function of the injection power. The locking efficiency ϕ increased from 0 to approximately 1 indicating complete injection-seeding with only 440 μW of injection power.

A Fabry-Perot interferometer (Burleigh RC-140) was

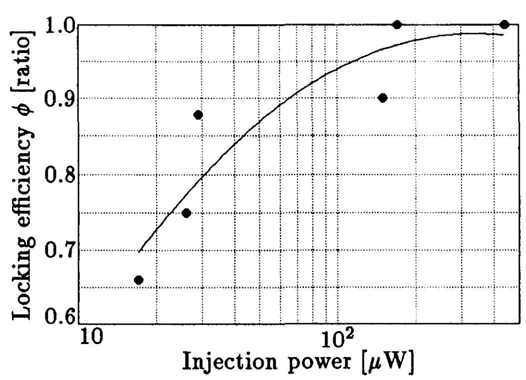


Fig.3 Locking efficiency ϕ with respect to injection power.

used to measure the linewidth of the injection-seeded laser. The Fabry-Perot interferometer was set for a free-spectral range (FSR) of 0.07 cm^{-1} with a resolution of $\approx$ 0.0015 cm^{-1}. Without injection-seeding no visible fringe pattern was obtained, but with injection-seeding well defined fringe pattern with a bandwidth of 0.01 cm^{-1}, matching with the injection laser was obtained. The injection-seeded output of 5.5 mJ/pulse from the oscillator was passed through the amplifier stages and an output energy of 40 mJ/pulse was obtained.

2.3 SBS in Different Liquid Media

In the next stage, the amplified Ti:sapphire laser output was focused into the water medium. The SBS scheme can be characterised by two parameters, namely an energy conversion efficiency and a pulse-compression ratio. The energy conversion efficiency can be defined as the ratio of the output energy of the Stokes pulse to the input laser energy. The pulse-compression ratio is defined as the ratio of the input laser pulse width at FWHM to the output Stokes pulse width at FWHM.

Figure 4 shows output characteristics of the Stokes pulse along with pulse width measurements with respect to different input energy. The solid circles in Fig. 4 represent experimental measured output characteristics and the solid line represents estimated output characteristics using theoretical simulation as described in **Section 3** based on experimental conditions. Experimental conversion efficiency was measured as 37.5% at an input energy of 40 mJ. The solid square shows the FWHM pulse-width measurements of the Stokes pulse. The chain dotted line in Fig. 4 represents theoretical

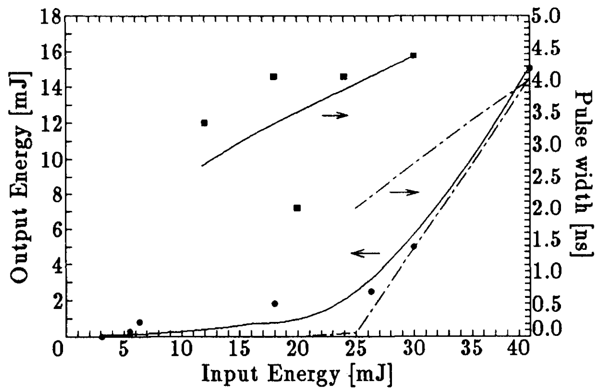
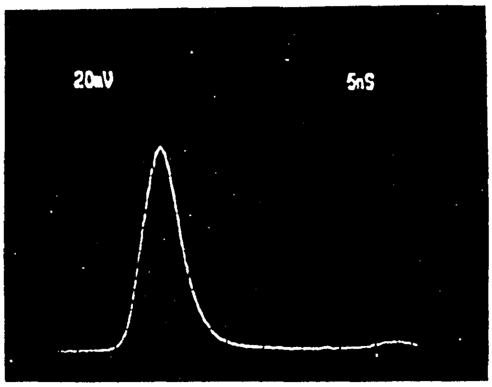
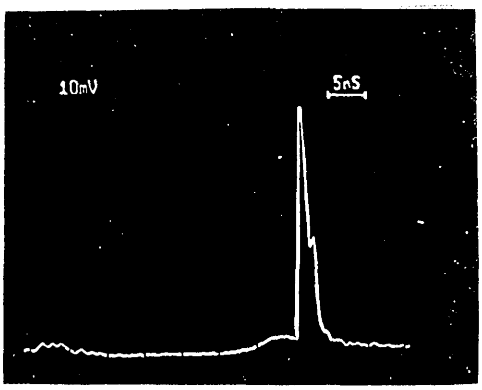


Fig.4 Output characteristics and FWHM pulse-width measurements of SBS Stokes pulse of Ti:sapphire laser in water medium. Ti:sapphire laser beam was focused in the beaker of water with a focusing lens of 50 mm and the focal plane was 10 mm below the water surface.



(a)



(b)

Fig.5 Pulse shape characteristics of (a) Ti:sapphire laser , (b) SBS Stokes pulse near threshold condition when Ti:sapphire laser beam was focused in the beaker of water with a focusing lens of 50 mm and the focal plane was 10 mm below the water surface.

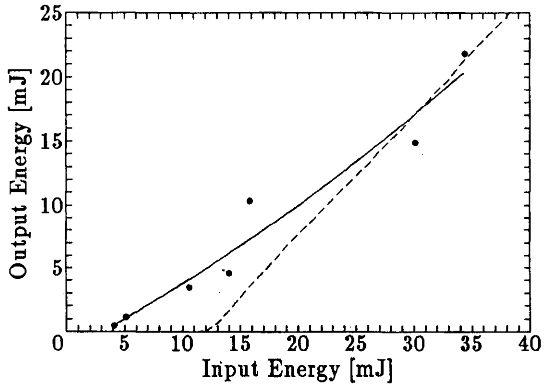


Fig.6 Output characteristics of SBS Stokes pulse of Ti:sapphire laser in methanol medium. Ti:sapphire laser beam was focused in the cell of methanol with a focusing lens of 50 mm and the focal plane was 10 mm below the methanol surface.

simulation of pulse width of Stokes pulse and as input energy is increasing the effect on pulse compression is decreasing.

Figure 5 (a), and (b) shows pulse shape measurements of Ti:sapphire laser and SBS Stokes pulse respectively. As shown in Fig. 5 (a), the pulse width of Ti:sapphire laser was measured as $\approx$ 8 ns FWHM. Figure 5 (b) shows the Stokes pulse near threshold operation and pulse width was measured as 2 ns with a pulse-compression ratio of $\approx$ 4. With increase in input energy, no significant effect on pulse compression was observed. Figure 4 shows that experimental trend is qualitatively in agreement with the theoretical simulation.

Figure 6 shows output characteristics of SBS stokes pulse when methanol is used as an SBS medium. The solid circles in Fig. 6 represent experimental measurements and the solid line represents theoretical estimation. In case of methanol, the threshold level for Stokes initiation was less than that corresponding to the water medium and the conversion efficiency was measured as 61.4% at an input energy of 34 mJ. In case of SBS in methanol, a pulse-compression ratio of only 1.2 could be achieved at 34 mJ. The measured results were in qualitative agreement with theoretically calculated output characteristics. As discussed in **Section 3**, the incomplete compression of the pump pulse could be explained on the bases that the length of the focusing was much shorter than the input pulse. In addition, the input power was sufficient enough that the Stokes pulse had left an intense acoustic wave in the medium, which acted as a high reflectivity Brillouin mirror and reflected the remainder of the input pulse without any compression.

3. Theoretical Considerations of Pulse Compression by SBS

3.1 Theoretical Model

SBS is the coupling of two process where the input and scattered light waves interfere to produce an acoustic wave electrostrictively, and the input wave is reflected back by the acoustic wave to produce a compressed scattered light wave. To understand the effect of input laser energy on pulse compression and conversion efficiency with respect to different Brillouin liquid media, a computer model for a single-cell SBS process is developed [5,6]. Conceptually, pulse compression of a laser pulse, by SBS process, focused into a single cell filled with an SBS liquid or gas can be described as shown in Figure 7. In this case, SBS process can be described by equations derived from the Maxwell's equations for the electric fields and from the Navier-Stokes equation describing material response with input laser field (E_l), backscattered Stokes field (E_s) and acoustic fluctuation (Q). Finally, the resulting coupled rate equations can

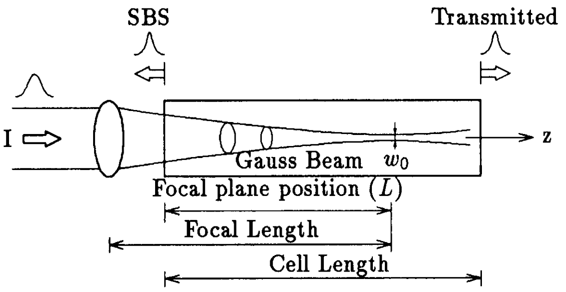


Fig.7 Configuration representing SBS process consists of single-cell filled with liquid medium into which the laser pulse is focused.

be expressed as follows with the assumptions that high-order scattering and optical losses are negligible.

$$\left(\frac{\partial}{\partial z}+\frac{n}{c}\frac{\partial}{\partial t}\right)E_l=\frac{-1}{2}gQE_s \tag{2}$$

$$\left(\frac{\partial}{\partial z}-\frac{n}{c}\frac{\partial}{\partial t}\right)E_s=\frac{-1}{2}gQ^*E_l \tag{3}$$

$$\left(\frac{\partial}{\partial t}+\frac{1}{2\tau}\right)Q=\frac{1}{2\tau}E_lE_s^*+w \tag{4}$$

where z is the distance measured in the direction of propagation, t is time, c/n is the speed of light in the medium, w is the spontaneous noise source, τ is the phonon lifetime representing damping time of the acoustic wave which can be calculated as $\tau = 1/(2\pi\Delta\nu_B)$, where $\Delta\nu_B$ is Brillouin linewidth, and g is the Brillouin gain coefficient and can be calculated for different Brillouin media as follows [12,14],

$$g=\frac{g_o}{1+\Delta\nu_l/\Delta\nu_B} \tag{5}$$

where g_o is the steady-state line-center gain factor for SBS value, $\Delta\nu_l$ is spectral linewidth of the input laser, which is assumed to be same as that of the experimental value of 300 MHz. From eq. (5) it is explicit that the gain by SBS is reduced with increased laser bandwidth. Table 1 shows values of g_o, g, $\Delta\nu_B$ and τ used in this analysis for different liquid media, namely water, methanol, and toluene.

Table 1 Gain (g), Brillouin linewidth ($\Delta\nu_B$) and damping time (τ) for some Brillouin liquid media.

Liquid	g_o [cm/GW]	g [cm/GW]	$\Delta\nu_B$ [MHZ]	τ [ns]
Water	6.6	3.39	317	0.502
Methanol	13	5.91	250	0.637
Toluene	13	8.56	579	0.275

In this analysis due to focused geometry in the cell, changes in the irradiance can be considered by changing the cross-sectional area of the beam with respect to propagation distance consistent with ideal Gaussian beam focusing. The temporal pulse shape of the input laser field is assumed to be a quadratic sin profile. The input Stokes field is set to zero and the SBS interaction is started by seeding the phonon wave with spontaneous noise. Equations (1)-(3) were solved numerically using parameters listed in Table 2 for different Brillouin media, such as water, methanol, toluene.

3.2 Numerical Results and Discussion

In the first stage, numerical calculations with respect to different values of input energy for toluene, methanol and water media were performed. In this case for near-optimal compression, the cell length of 1.5 m was considered with L equal to 1.2 m, approximately one-half the temporal pulse width of the input laser (τ_l = 10 ns). Figure 8 shows Stokes output for different values of input energy and it explicitly illustrates that the threshold input energy requirements for the SBS is the lowest for

Table 2 Numerical values used in the theoretical simulation.

Description	Numerical value
Focal length	Variable (mm)
Cell length	Variable (m)
Focal plane position (L)	Variable (mm)
Pulse width (τ_l)	10 ns
Laser input	Variable (mJ)
Spontaneous noise (w)	0.000001 + i0.000001

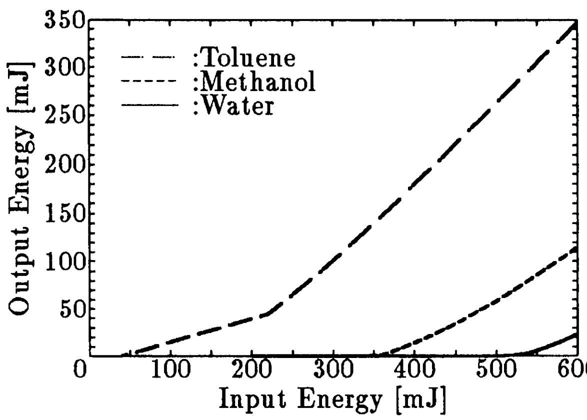


Fig.8 Numerical calculation of Stokes output versus input laser energy for toluene, methanol and water media. This calculations were made with L of 1.2 m at an approximately one-half of the input laser pulse width (τ_l = 10 ns).

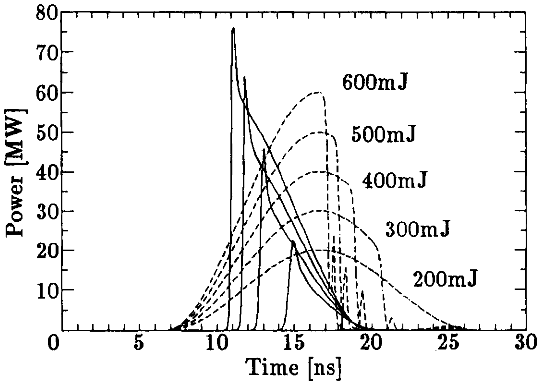


Fig.9 Numerical calculation of Stokes and transmitted-pulse temporal profiles with respect to laser input energy for SBS in toluene medium. This calculations were made with L of 1.2 m at an approximately one-half of the input laser pulse width (τ_l = 10 ns). Solid lines represent Stokes output and dotted lines show transmitted output.

toluene followed by methanol and finally water medium. In addition, the conversion efficiency for toluene is the highest ($\approx$ 58%) as compared to methanol ($\approx$ 19%) and water($\approx$ 4%) at an input of 600 mJ. Further, in all cases, with increase in input energy conversion efficiency also increases.

Subsequently, the effect on pulse compression was simulated for toluene, methanol and water media with respect to different values of input energy keeping other variables fixed. In all liquid media with increase in input energy, effective Stokes pulse compression could not be achieved in spite of improvement in the energy conversion efficiency. As a typical case, Fig. 9 shows temporal profiles of Stokes output and transmitted pulse for SBS in toluene medium. Solid lines show Stokes output and dotted lines show transmitted output. With a 200 mJ of input energy the pulse-compression ratio was $\approx$6.66 and it was decreased to $\approx$2.77 with an input energy of 600 mJ.

This effect can be explained based on the fact that even with the near-optimum focal length, the minimum compressed pulse width is also a function of the input energy. If the input is higher than the optimum, the Stokes pulse will initiate earlier and it can receive amplification only in the front of the input pulse. The apparent length of the compressor cell will become shorter than the optimum required, therefore the compressed pulse will emerge earlier than all the laser input pulse entered the cell. However, the compressed pulse will leave an intense acoustic wave in the medium, which acts as a high reflectivity Brillouin mirror that reflects the remainder of the pulse without compression [4,7].

4. Conclusion

Efficient compression of Ti:sapphire laser not only depends on the optimum focal length so that the condition $\tau_l \leq 2ln/c$ is obeyed, but also depends on the input energy. In case of experiment due to output energy limitations, and to avoid absorption and other scattering losses, the shorter cell was used. In water as an SBS medium, energy conversion efficiency of 37.5% and the pulse-compression ratio of 4 was obtained and in methanol as an SBS medium, energy conversion efficiency was improved to 61.4% but the pulse-compression ratio of only 1.2 could be obtained.

A theoretical model was developed which explained the characteristic requirements of the SBS pulse-compression technique. Theoretical simulation with a short cell design predicted similar trend as that of the experiment and could explain the cause for a low compression ratio.

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