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Shortening of Free-running XeCl Laser Pulses by Stimulated Brillouin Scattering

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Abstract

A stimulated Brillouin scattering mirror has been used to "temporally tune" from nanoseconds to subnanoseconds the width of laser pulses generated by a free running XeCl oscillator, equipped with a super-Gaussian reflectivity unstable resonator. Pulse shortening techniques by stimulated Brillouin scattering (SBS) and by truncated SBS have been investigated. A maximum pulse shortening of about fifty has been achieved by truncated SBS.

1 Introduction

Owing to their broad bandwidth and high gain, excimer lasers are good candidates for sustaining very short pulses. Short duration, high power excimer laser systems are attractive for many applications including nonlinear optics, solid state physics, photochemistry and the generation of high-current electron bunches from a metal photocathode [1].

Short excimer laser pulses have been generally obtained by amplification of frequency converted short dye-laser pulses in subsequent excimer amplifiers and pulses as short as 60 fs have been obtained [2]. However, the systems required to obtain such results are quite complex and need several lasers that must work together properly [3]. To simplify the shortening system, several techniques to generate short pulses directly with an excimer laser have been developped. These techniques use saturable absorbers [4], fast electro-optic modulators [5,6] and surface plasma switches [7]. Moreover, pulse shortening by stimulated Raman scattering combined with the use of a saturable absorber dye jet has been reported on Ref. 8, and laser pulses as short as 43 ps have been generated [9] by truncated Brillouin backscattering (TRUBS) at 248 nm with a KrF oscillator-amplifier laser system. In such experiment the oscillator was tuned using a grazing-incidence grating and a Littrow grating in order to produce laser pulses with a linewidth of $< 1cm^{-1}$. The $70\mu J$ oscillator beam was then passed into the amplifier before being focused into the Brillouin cell. More recently stimulated Brillouin scattering was also obtained by using a broad-band (30 cm^{-1}) KrF laser system [10]. An oscillator-amplifier laser system without dispersive elements was used to obtain high-energy, good optical-quality laser beams and laser pulses about 200 ps long have been produced by TRUBS.

In this paper a stimulated Brillouin scattering mirror has been used to "temporally tune" from nanoseconds to subnanoseconds the width of laser pulses generated by a free-running XeCl oscillator equipped with a super-Gaussian reflectivity unstable resonator. On the performance of the super-Gaussian unstable resonator will be reported first. Then, the techniques to get pulse shortening both by stimulated Brillouin Scattering (SBS) and by TRUBS will be described.

2 Experimental apparatus and results

Our study is aimed to produce Brillouin backscattered radiation by broad-band pumping using a single discharge laser chamber. High quality laser emission is one of the most critical parameters for obtaining high intensity focusing in a nonlinear medium and this requirement can be met through a suitable design of the laser resonator. In this experimental work an unstable resonator with a super-Gaussian [11] reflectivity mirror as output coupler has been applied to a conventional UV-preionized discharge excited XeCl laser [12] to get a good mode control of the oscillating radiation. In particular, a flat output mirror with the intensity reflectivity profile having the analytical form

$$R(r) = Ro \exp[-2(r/Wm)^n]$$

has been used, where $Ro = 0.45$ is the peak reflectivity, $Wm = 1.5$ mm is the mirror's spot size, $n = 8$ is the order of super-Gaussianity, and r is the radial coordinate. The unstable resonator with magnification factor $M = 3.9$, was made of an aluminized convex mirror Mc with -1.5 m radius of curvature, and of the super-Gaussian reflectivity flat mirror (VR), placed 80 cm away from Mc (Fig. 1). By applying such resonator to the XeCl laser chamber, sealed with Brewster angle windows and filled with a standard gas mixture at a total pressure of 385 kPa, a linearly polarized output beam of 15 mJ and 14 ns duration has been obtained. A typical laser pulse time evolution is shown on Fig. 2a.

The normalized laser beam intensity profile on the output coupler was represented by the curve

$$I(r) \simeq [1 - R(r)] \exp[-2(r/w)^n]$$

where the output beam spot size $w = Wm(M^n - 1)^{1/n} \simeq 5.9mm$, as it turns out from a geometrical optics analysis.

The output beam has been firstly collimated, by a 1.7 m focal-length lens (Lc), and then the 15-mm diameter collimated beam has been focused by a 9.3 m lens to estimate its divergence. It has been found that 85% of the total energy was contained in a far-field full angle $\vartheta = 0.2$ mrad. This value is four times the diffraction limited value $\vartheta d = 0.05$ mrad expected from a 15-mm-diameter plane wave. Then, it has been shown that high-mode-volume, good-optical quality laser beams can be extracted from a high-gain, short-pulse XeCl laser with a super-Gaussian reflectivity unstable resonator.

The output laser beam has been then sent by means of the flat aluminized mirror M_1 to the stimulated Brillouin scattering (SBS) mirror, made of a 10 cm focal length lens (L) and of the liquid cell (C) to be shortened. Methanol has been used as Brillouin medium, since it is characterized by a relatively high gain coefficient (g=0.013 cm/MW). A quarter-wave plate and a polarizing beamsplitter cube (P_{BS}) have been used to couple out the Brillouin backscattered radiation. The experimental set up is shown in Fig. 1. GENTEC pyroelectric detectors have been used to measure laser beam energies and a fast photodiode (HAMAMATSU R1328U-02) and a TEKTRONIX Transient Digitizer SCD 5000 have been used to monitor laser pulse durations.

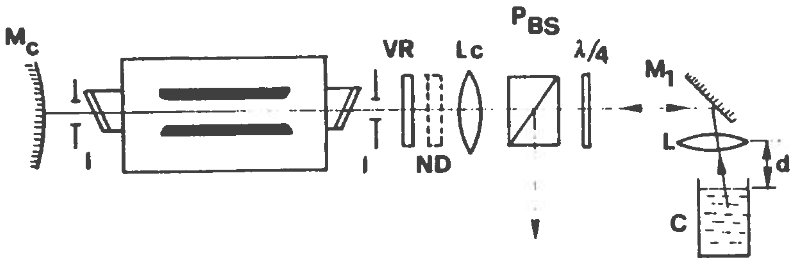

Fig. 1 Experimental set up. Mc: convex mirror; VR: super-Gaussian reflectivity output mirror; I: spatial apertures; ND: neutral density filters; Lc: collimating lens; P_{BS}: prism polarizer; M_1: high-reflectivity flat mirror; L: SBS mirror lens of 10 cm-focal length; C: liquid cell; d: distance between L and the liquid surface.

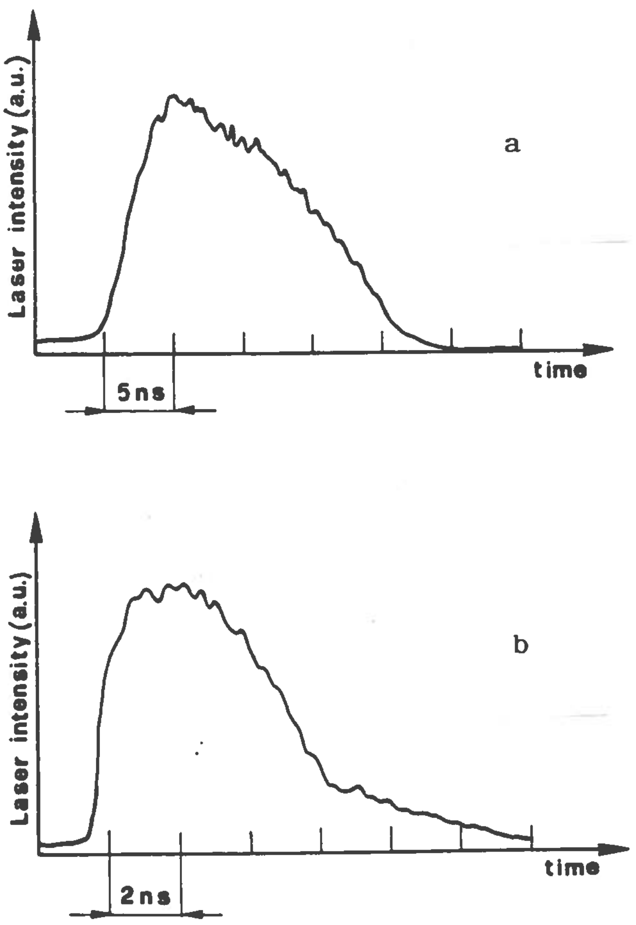

Fig. 2 Time evolution a) of the pump laser pulse; b) of the Brillouin backscattered radiation obtained by focusing a 9 mJ, 14 ns-long pump pulse in methanol.

Firstly, the laser beam has been focused in the middle of the liquid cell to investigate how the energy and the temporal evolution of the Brillouin backscattered radiation is affected by the pumping beam energy. Care was taken to focus the pump beam at an angle into the liquid, to avoid the collection of the light reflected by the liquid surface, and by the lens surfaces.

It must be observed that the output laser beam energy reduces to about 9 mJ after passing through the optical component between VR and L. By focusing the 9 mJ, 14 ns long pump pulse in the Brillouin medium, backscattered pulses of 0.6 mJ and 5 ns long have been extracted through P_{BS} therefore a temporal shortening of 65% has been obtained. Fig. 2b shows a typical time evolution of the backscattered pulses. The pulse duration of the Brillouin backscattered radiation is mainly determined by the temporal evolution of the pump pulse and by the time required by the Brillouin medium to reach threshold and reflect the incident pump radiation [13]. The fast-rising leading edge of the pulse shown in Fig. 2b is characteristic of the rapid transient onset of SBS reflection. It must be observed that the risetime of the SBS pulse is less than 1 ns, whereas the pump pulse risetime was $\sim$ 5 ns long.

It is believed that the quite low SBS mirror reflectivity ($\sim$ 8%) obtained under our experimental conditions is due to the large bandwidth ($\sim$ 790 GHz) of the pumping radiation [14] and to the not very high optical quality ($\vartheta/\vartheta d \simeq 4$) of the pump beam which affects both the pump intensity distribution at the focus, and the interaction length, considered equal to the confocal parameter in a focused geometry.

By placing neutral density filters (ND) between VR and Lc to reduce the pump beam energy, shorter backscattered pulses can be extracted through P_{BS}. In fact, the time needed to the Brillouin medium to reach threshold increases as the pump energy decreases. The experimental results obtained under our experimental conditions by varying E_p from 9 mJ to 2 mJ are summarized in Table 1. One observes from Table 1 that backscattered pulses 3ns long have been extracted by focusing a 2 mJ-pump beam but, a SBS mirror reflectivity of 3% has been measured. It is important to point out that shorter pulses could be obtained at lower E_p values, but the pulse length of the backscattered radiation exhibited some fluctuations as E_p was closer to the threshold value required to have SBS in methanol.

To investigate how the SBS mirror reflectivity depends on the optical quality and then on the focusing properties of the pump beam, the divergence of the laser radiation provided by our laser system has been improved.

A faster establishment of a diffraction limited mode and so a better control of the oscillating laser radiation, can be obtained with an unstable resonator applied to a high gain short pulse excimer laser, by reducing the active mode volume cross section [15,16], as well known.

Table 1

Pulse shortening by pump energy variation. Ep, pump energy; Eo and Δto, energy and time length of the backscattered radiation; R, SBS mirror reflectivity

E_p(mJ)	Eo(mJ)	Δto(ns)	R(%)
9.0	0.6	5	8
6.5	0.3	4	6
2.0	0.05	3	3

In fact, by placing a spatial aperture (I) of 4 mm diameter in front to each window of our laser chamber, an output laser beam of 1 mJ and with a divergence 1.5 larger than the diffraction limit has been provided by our XeCl laser. In particular, the divergence of the 6 mm diameter collimated output beam was $\vartheta = 0.18$ mrad, whereas the time evolution of the laser beam was similar to that of Fig. 2a.

By focusing in the Brillouin medium 0.7 mJ of energy of this last laser beam, backscattered pulses of 0.06 mJ and 4.5 ns long have been extracted through P_{BS}. The SBS mirror reflectivity has been estimated to be $\sim 11\%$ in these last experimental conditions. A further reduction of E_P to about 0.4 mJ has allowed us to get backscattered pulses of 0.02 mJ and of 3 ns duration; the SBS mirror reflectivity was $\sim 6\%$. By comparing these last experimental results with those reported in Table 1 one observes that at pump energies much lower than 2 mJ, SBS mirror reflectivities higher than 3% have been obtained by improving the focusing characteristics of the pump radiation. However, when the pump beam energy was lower than 0.4 mJ the pulse length and energy of the backscattered radiation were quite unstable. Then, backscattered pulses shorter than 3 ns could not be produced by SBS with our experimental set up.

Shorter and reproducible laser pulses could be instead obtained by truncated stimulated Brillouin scattering. In fact, if the laser beam is focused at the liquid-air interface, and the intensity at the surface is high enough to cause optical breakdown after the onset of SBS, an abrupt termination of the backscattered pulse can be obtained by the sudden onset of avalanche ionizations [9]. Backscattered pulses as short as 300 ps and of about $15 \mu J$ have been produced by TRUBS either with the 9 mJ, 15 mm-diameter pump beam, or with the 0.7 mJ, 6 mm diameter pump beam (Fig. 3). Therefore a maximum pulse shortening of about fifty has been achieved. It is believed

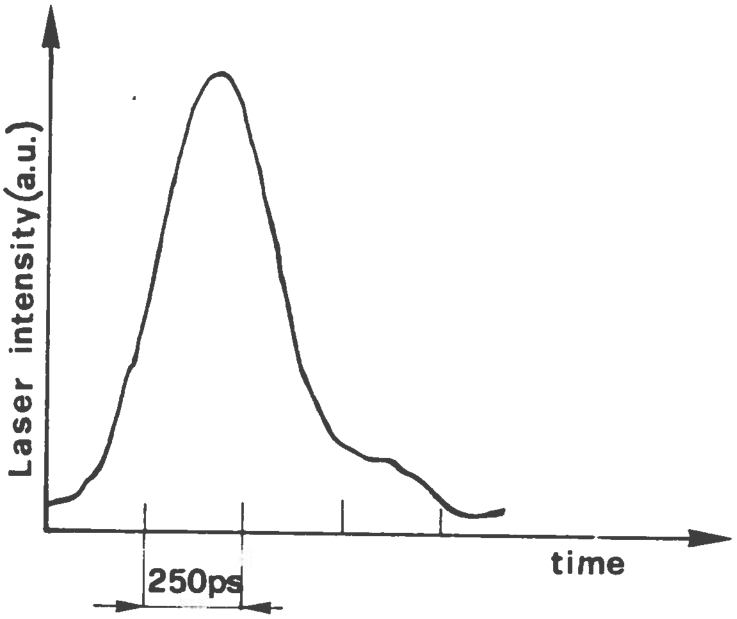

Fig. 3 Time evolution of the backscattered radiation produced by TRUBS. The FWHM pulse duration is 327 ps.

that shorter backscattered pulses could be produced by TRUBS by using an SBS mirror lens of shorter focal length [5].

It must be observed that breakdown at or near the surface occurred over a range of several microns under our experimental conditions. Therefore, by varying carefully the separation d between the lens and the liquid surfaces, the onset time of breakdown could be changed and this allowed us to tune easily the duration of the backscattered radiation from 3ns to 300ps. Fig. 4 shows typical backscattered pulse time evolutions obtained by focusing the 9 mJ pump beam at the liquid-air interface and by "varying" d. The output beam energy E_0 extracted through P_{BS} is also given on Fig. 4 for each pulse, respectively. As one expects E_0 decreases as the pulse length gets shorter for the faster onset of optical breakdown. It has been observed that the energy and pulse length of the backscattered radiation were quite stable at each distance d.

It can be seen form Fig. 4 that backscattered pulses of $\sim$ 0.5 mJ and $\sim$ 3 ns long have been also obtained by TRUBS. By comparing such experimental result with those reported on Table 1 it turns out that it is more efficient to get pulse shortening by TRUBS than by decreasing E_P.

Optical breakdown over a range of several microns has been observed also by focusing the 0.7 mJ pump beam at the liquid-air interface, and experimental results similar to those reported on Fig. 4 have been obtained.

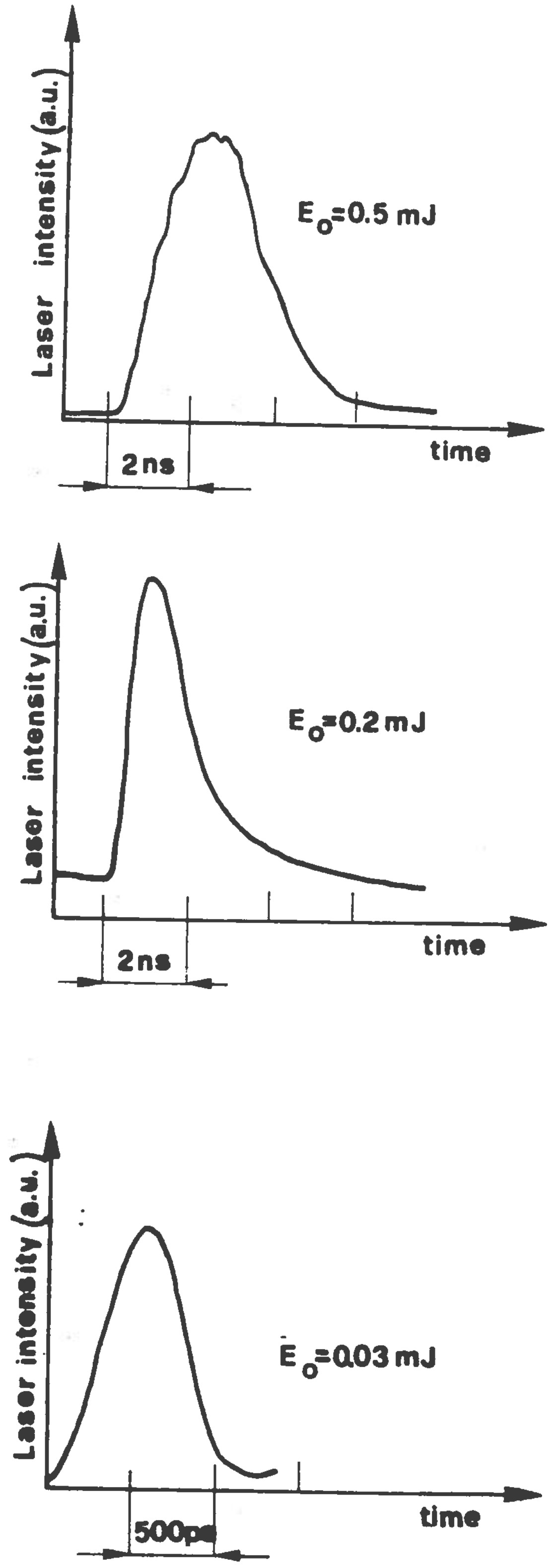

Fig. 4 Time evolution of the backscattered radiation produced by TRUBS with the 9 mJ pump beam by carefully varying the separation d between the lens and the liquid surfaces. E_0 is the output beam energy.

3 Conclusions

By applying a super-Gaussian reflectivity unstable resonator of magnification M=3.9 to a high gain short pulse XeCl laser, good optical quality laser beams, suitable for obtaining high intensity focusing in a nonlinear medium, have been extracted.

The pulse shortening techniques, both by SBS and by TRUBS have tested with such broad-band XeCl laser beams and it has been observed that reproducible laser pulses with a time width tunable from nanoseconds to subnanoseconds, can be efficiently obtained by TRUBS. Laser pulses as short as $\sim$ 300 ps have been produced by focusing a 14 ns long pump beam at the liquid-air interface with a 10 cm focal length lens. So a maximum pulse shortening of about fifty has been achieved. A peculiar property of such simple pulse shortening technique is the negligible frequency shift of the backscattered radiation, then the same single discharge laser chamber could be used either as pump laser source or as amplifier of the backscattered radiation [17]. Work is in progress in such direction. In fact, commercial discharge excited excimer lasers, similar to the one we have used, have a typical discharge cross section of about $(2 \times 2) cm^2$ and produce laser pulses about $15 \div 30$ ns long, and we have shown that by applying a super-Gaussian reflectivity unstable resonator to only a small portion of the laser active volume, good optical quality laser beams suitable for obtaining high intensity focusing in a nonlinear medium, can be produced. Moreover, it has been observed that the onset of Brillouin backscattered radiation occurs at the beginning of the pump pulse.

We believe that our experimental results can be of interest to the excimer lasers users to realize a simple short-pulse, UV-laser source.

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