VILNIUS UNIVERSITY
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Nerijus Slavinskis

SHORT PULSE Q-SWITCHED LONGITUDINALLY DIODE PUMPED SOLID STATE MINILASERS: GENERATION, CHARACTERIZATION AND APPLICATION

Summary of doctoral thesis
Technology sciences, material engineering (08 T)
Laser technology (T 165)

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VILNIAUS UNIVERSITETAS
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Nerijus Slavinskis

TRUMPŲ IMPULSŲ KOKYBĖS MODULIACIJOS IŠILGAI DIODAIS KAUPINAMI KIETOJO KŪNO MINILAZERIAI: GENERAVIMAS, CHARAKTERIZAVIMAS IR PANAUDOJIMAS

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Contents

Introduction

From the first laser invention (1960, T. Maiman) there happened a lot of technical changes, which enabled development of a variety of lasers types (over 15000), from different state of materials, active elements and better pump sources [1]. Nevertheless, solid state lasers all this time continuously developed and are popular up to these days [2-6]. Recently, laser diodes (LD) have also been highly developed [7], LD of various wavelengths and high average power have been created, and today for several engineering reasons are well suitable for pumping solid state lasers [8]. All these benefits enable creating simple, compact, robust and cheap laser sources suitable for different types of applications. These are the guidance parameters for manufacturers of diagnostics and technological equipment for selecting laser sources for their own products [9, 10]. Lasers with passive Q-switching are very attractive, they can be very simple and robust, and well suitable for several applications [11-13]. Microchip lasers are among this type of lasers, but nevertheless these lasers can generate short pulses (< 100 ps), the energy of these pulses is very low. So, passively Q-switched solid state lasers which can generate pulses of several mJ are of interest. But these lasers also have several drawbacks, especially when CW pumping is used: difficult to control pulse repetition rate, no synchronization with external event and very high timing jitter of the generated pulses [14]. Thus, the problem of timing jitter reduction possibilities is very relevant. From the engineering point of view the active Q-switching is a solution of this problem, however these lasers are more complex, require tricky electronics and are not very robust.

For successful development and optimization of parameters of this type of laser systems, convenient techniques enabling one to take into account the characteristics of specific solid-state media, saturable absorbers, pumping systems and resonators are required [11–13,15, 16]. The simplified models usually leave aside a number of essential parameters, such as relaxation times of the excited lasing levels, fluctuations of the spontaneous photons in the lasing mode determined by the spontaneous and amplified spontaneous emission, etc. A detailed theoretical model for the description of generation dynamics of LD longitudinally pumped solid-state lasers with active and/or passive Q-switching using traveling wave approach [17] is presented. The distribution of generated laser pulse intensity and other laser parameters along the resonator is very inhomogeneous. The results presented in this thesis have been obtained for the case of Nd:YAG gain medium and Cr^{4+}:YAG passive Q-switch.

Considering that the duration of generated pulses even in microchip lasers is longer, a very relevant problem is how to achieve shorter pulses using effective pulse compression methods. It is well known that using stimulated Brillouin scattering in liquids it is possible to achieve the pulse duration shorter than 100 ps, but only after appropriate pulse processing [18, 19]. In this thesis a new method and a possibility how to achieve the pulse duration shorter than 60 ps with 3 times increased stability of the pulse duration and amplitude are shown.

Besides, this thesis demonstrates a suitability of created minilasers for Z-scan, paper cleaning and laser induced breakdown spectroscopy (LIBS) experiments.

Main objectives:

- To develop a mathematical traveling wave model of generated pulses of actively and passively Q-switched longitudinally diode pumped solid state lasers, perform numerical modelling and show advantages of this model compared with the usually used point laser model.
- To estimate causes of timing jitter of indicated types of lasers and to measure timing jitter values of generated pulses of created experimental minilasers when pulsed pumping is used, to perform timing jitter numerical modeling and suggest its reduction possibilities.
- To demonstrate practical application possibilities of created minilasers, for this purpose making effective pulse compression by stimulated Brillouin scattering and measuring nonlinear refractive indexes of optical materials by the Z-scan method, and also to show that parameters of generated pulses satisfy the requirements for portable laser cleaning and LIBS diagnostic systems.

Main tasks:

- To investigate physical mechanisms of energy interchange in the longitudinally diode pumped Q-switched solid state mini-lasers.

- To develop a mathematical opposite traveling wave model of generated pulses and performing numerical modelling to observe the dependence generated pulse parameters of arrangement of laser elements inside the resonator.
- Using numerical and physical experiments to investigate, in the regime of the high pulse repetition rate, timing jitter of generated pulses and investigate its reduction possibilities using controlled pumping.
- To investigate the possibilities of effective compression of short pulses (~ 1 ns) of created minilasers using different interaction schemes of pulsed beams in electrostrictive media.
- To demonstrate suitability of created minilasers for small nonlinear refractive index measurements by the Z-scan method in Kerr media.
- To demonstrate that created mini-lasers could be successfully used for laser cleaning of contaminated surfaces and for material elemental analysis by the LIBS method.

Novelty of this work:

By the numerical experiments for the first time it has been shown that, using a comprehensive traveling wave model, parameters of generated pulses depend on arrangement of active media, active and passive Q-switches in the linear resonator, i.e. time dynamics of generation process and energy efficiency could be very different depending on arrangement of these elements in the resonator.

Generation of single longitudinal mode short pulses by Q-switched solid state minilasers leads to creation of a new method of nanosecond pulse compression, when a compressed picosecond pulse in media with electrostriction nonlinearity is generated not from the spontaneous Brillouin scattering noise level, but from the counter-propagated seed signal of the same carrier frequency.

Practical value of this work:

The proposed timing jitter reduction method in a passively Q-switched laser using sharp triggered start up and release of modulated diode pumping can be easily realised experimentally. It allows one substantially to expand application possibilities of simple and robust passive Q-switch lasers.

Showed that given short (~ 1 ns) pulses of a diode pumped Q-switched Nd:YAG minilaser and using easily available CCl_4 liquid it is experimentally possible to achieve pulses shorter than ~ 60 ps with 50 % energy efficiency whose duration and amplitude stability and timing jitter parameters are 3-4 times better, while duration of compressed Stokes pulses are almost two times shorter than in a standard stimulated Brillouin scattering compression experiments.

Created short pulse minilasers, especially with the effective pulse compression, easily meet the criteria for Z-scan, portable laser cleaning and LIBS diagnostic systems. Thus, it is hope for expansion of these lasers applications in the processes of diagnostics and technology.

Statements to be defended:

1. The developed traveling wave model takes into account the arrangement of passive and active Q-switches in the resonator, besides, shapes of the counter propagating pulses are different, whereas their modulation in time, particularly when fast opening of the active Q-switch is used, has a lower inherent period than the round-trip time of the resonator.
2. The modulation of the continuous diode pumping of the passively Q-switched solid state minilasers, with the adequately highly powered rectangular pulses with their sharp triggered start up and release, stabilizes the period of the repetitive pulses approximately by two orders, reducing their timing jitter.
3. The effective compression of short pulses can be implemented in a new way, when in media with electrostriction nonlinearity compressed picosecond pulses are generated not from the spontaneous Brillouin scattering noise level, but from the counter-propagated seed signal of the same carrier frequency and duration.
4. Using the Z-scan method for the small nonlinear refractive index measurements a good compatibility of the measured values is obtained only when spatial and temporal properties of used focused pulsed beams are properly (through corresponding coefficients calculated from experimental data) included in the stage of the processing experimental data.

Approbation:

The results presented in this thesis were presented at 11th International Conference MMA (Jūrmala, 2006, Latvia); 37th and 38th Lithuanian National Physical Conference (Vilnius, 2007, 2009); LACONA VII, International Conference on Lasers in the Conservation of Artworks (Madrid, 2007, Spain); International Conference „Northern Optics 2009“ (Vilnius, 2009); XVIII Lithuanian and Belarus Conference „Lasers and optical nonlinearity“ (Vilnius, 2009), VIII International Conference „Laser physics and optical technologies“(September 27-30 2010, Minsk, Belarus).

Author's publications related to the thesis

Publications in the international ISI WEB of Science journals:

S1. V. Švedas, A. S. Dement'ev, E. Murauskas, **N. Slavinskis**, Cleaning of contaminated paper with the subnanosecond Nd:YAG laser pulses, Lithuanian J. Phys., **47**(2), p. 221-228 (2007).

S2. A. S. Dement'ev, R. Čiegis, I. Laukaitytė, **N. Slavinskis**, Numerical analysis of laser diode longitudinally pumped solid-state laser generation dynamics using traveling wave model, MMA, **15**(1), p. 23-38 (2010).

S3. A. S. Dement'ev, I. Diomin, E. Murauskas, **N. Slavinskis**, Compression of pulses during their amplification in the field of a focused counterpropagating pump pulse of the same frequency and width in media with electrostriction nonlinearity, Quantum Electronics, **41**(2), p. 153-159 (2011).

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S5. J. Marczak, M. Strzelec, R. Ostrowski, A. Rycyk, A. Sarzynski, W. Skrzeczanowski, A. Koss, R. Szambelan, R. Salimbeni, S. Siano, J. Kolar, M. Strilic, Z. Marton, I. Santa, I. Kisapati, Z. Gugolya, Z. Kantor, S. Barcikowski, P. Engel, M. Pires, J. Guedes, A. Hipolito, S. Santos, A. S. Dementev, V. Svedas, E. Murauskas, **N. Slavinskis**, K. Jasiunas, M. Trtica, „Advanced laser renovation of old paintings, paper, parchment and metal objects“, In: Lasers in the Conservation

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P10. A. S. Dementjev, E. Murauskas, K. Račkaitis, **N. Slavinskis**, Short pulse laser diode pumped solid-state *Q*-switched Nd minilasers: modeling, experiments and applications, Northern Optics 2009, 26-28 August 2009, Vilnius, Lithuania, Program and Book of Abstracts, p. 45.

P11. A. S. Dementjev, E. Murauskas, K. Račkaitis, **N. Slavinskis**, Measurements of Self- and Cross-Phase Modulation Coefficients of the Crystals using a modified Z-scan technique, Northern Optics 2009, 26-28 August 2009, Vilnius, Lithuania, Program and Book of Abstracts, p. 89.

P12. A. S. Dementjev, **N. Slavinskis**, R. Čiegis, I. Laukaitytė, Numerical modeling of short pulse generation by laser diode pumped solid-state *Q*-switched lasers using a traveling wave model, Northern Optics 2009, 26-28 August 2009, Vilnius, Lithuania, Program and Book of Abstracts, p. 90.

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Author's contributions:

The author made contributions in all experiments, created computer-assisted measurement stands for laser beam characterization, pulse compression, Z-scan and paper cleaning experiments. He planned, prepared and performed the majority of these experiments; contributed to the software creation of the numerical modeling and performed all numerical modeling. The author also performed processing of results obtained by experiments and numerical modeling, contributed to the conclusion formulations and preparation of the reports and publications.

Contribution of co-authors:

Prof. habil. dr. A. Dementjev[1] formulated tasks of implemented research, contributed to the creation of mathematical models and to the preparation of the methods for the experiments, to the processing of the results and preparation of publications.

Dr. E. Murauskas[1] collectively created actively and passively Q-switched minilasers, carried out measurements of timing jitter of created minilasers, pulse compression, Z-scan and paper cleaning experimental research.

Dr. V. Švedas[1] collectively carried out experiments of paper cleaning and spectral research. He interpreted obtained results and contributed to the publication preparation.

PhD I. Demin[1] collectively performed pulse compression experiments.

Prof. habil. dr. R. Čiegis[2] and **dr. I. Laukaitytė**[2] created a numerical algorithm of the travelling wave model and contributed to the processing of obtained results and publication preparation.

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Thesis summary

The thesis consists of 5 chapters: introduction, two chapters with original results, main results and conclusions, and a list of the used references. The material of the thesis is presented in 143 pages, including 52 figures and 4 tables and 186 references were used.

In the **Introduction**, the relevance of the investigation is motivated and the objectives, main tasks, innovations of this work, propositions to defend and approbation of results are presented.

In **chapter 2**, the laser generation dynamics using a traveling wave model, timing jitter reduction possibilities and laser beam characterization are described. In **subchapter 2.1** a detailed theoretical model [S2] for the description of generation dynamics of diode laser longitudinally pumped solid-state lasers (SSL) with active and/or passive Q-switching using traveling wave approach is described (Fig. 1). This technological development of SSL requires a detailed modeling of such end–pumped SSL taking into account more parameters of active laser medium, pump sources and resonator architecture. In this model the Stark splitting of the lasing levels into sublevels, the finite lifetimes of excited levels, excited state absorption in active elements (AE) and saturated absorber (SA) and many other parameters of AE, SA and pump sources were taken into account (Fig. 2).

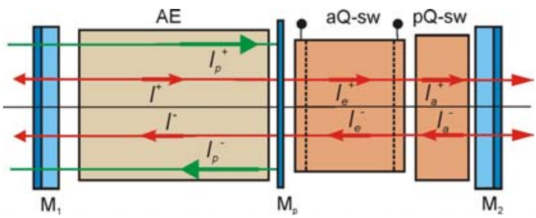

Fig. 1. Scheme of an actively and (or) passively Q-switched solid state laser.

When describing the generation dynamics of Q-switched lasers, two approximate approaches are most often used: considering the laser as a lengthy system within the intensity traveling wave model (TWM) and the laser as a dimensionless system within the point laser model (PLM). For validation of the latter model, the technique of spatial averaging of TWM equations in partial derivatives over the resonator length is often used [15, 20], however forward and backward traveling waves do not exist in these simplified methods. Thus, only the usage of TWM can provide the knowledge about intracavity dynamics during the pulse generation time.

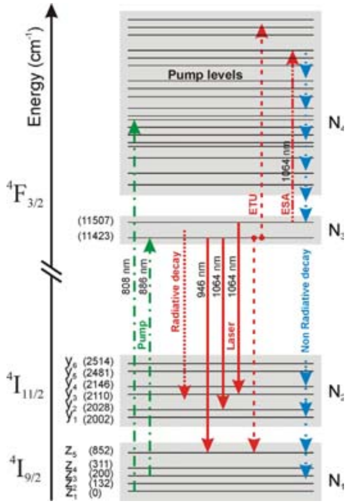

Fig. 2. A detailed view of the Nd:YAG energy levels and transitions included in the traveling wave model.

In this thesis the results which show the principal difference between results obtained using the laser TWM and PLM are presented. It is obvious that the results of TWM may depend on the optical element sequence inside the resonator, exactly on active and passive Q-switches (Fig. 3 shows the positive-traveling, toward the output coupler, laser pulses generated). The situation is different for PLM in which we cannot distinguish different element sequences because of the averaging procedure along the resonator.

Using this TWM it is shown that for outgoing pulses through the front (output) and rear mirrors not only amplitudes of pulses but also their shapes may be different. For rather fast Q-switching of active Q-switching (AQS), the shapes of generated pulses have temporal modulation with the period shorter than the resonator round-trip time. This modulation is caused by strong and fast modulation of pulse amplitudes inside the resonator. This modulation can be smoothed using lower AQS switching rate or additionally using passive Q-switching (PQS) with rather high enough initial transmittance.

The developed model allows us to control temporal and spatial changes of investigated variables in different planes along the resonator and at different predetermined times, e.g. before, in time and after giant pulse generation.

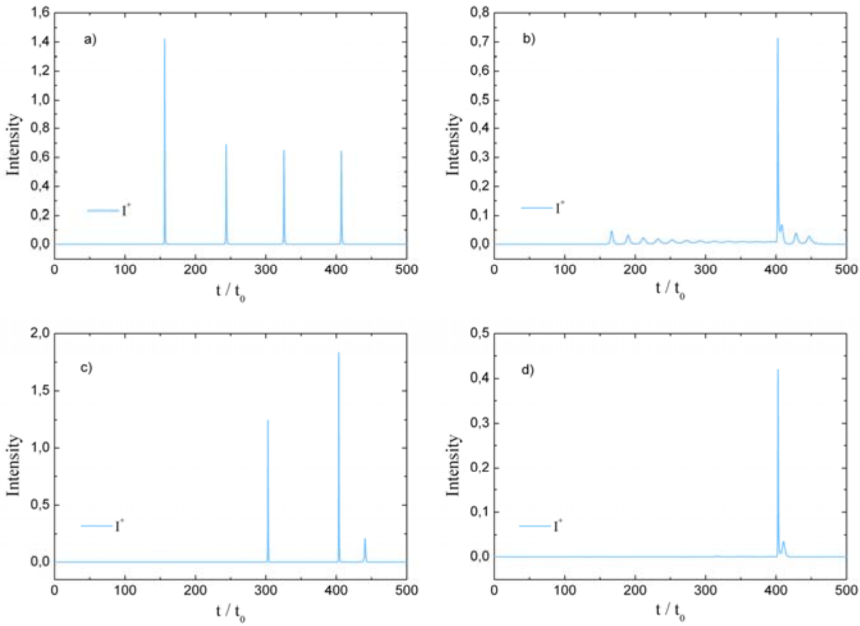

Fig. 3. Generation dynamics using a) passive, b) active, c) active-passive, d) passive-active Q-switching.

In **Chapter 2**, **subchapter 2.2** the problems of generated pulse timing jitter and its lowering possibilities are described. The PQS lasers due to their robustness and reliability in exploitation have recently become very attractive for various applications. Besides, in these lasers it is easy enough to generate single longitudinal mode pulses. However, these lasers have several drawbacks which limit the application possibilities, especially when CW pumping is used: difficult to control pulse repetition rate, no synchronization with external event and very high timing jitter of the generated pulses [14]. The principal reason for timing jitter in all lasers is quantum noises of spontaneous emission. However, quantum noises determining timing jitter is a physical limit which cannot be reached so simply. Thus, it is believed that the main reason for timing jitter however is pump instabilities determined by technical noises [21]. Performed calculations using expanded PLM had shown than when CW pumping instability is 1%, the instability of pulse period is 2.4%. By increasing the repetition rate, relative (standard deviation of timing jitter divided by pulse period) pulse timing jitter decreases (Fig. 4). One of the timing jitter lowering possibilities, suggested earlier, is to

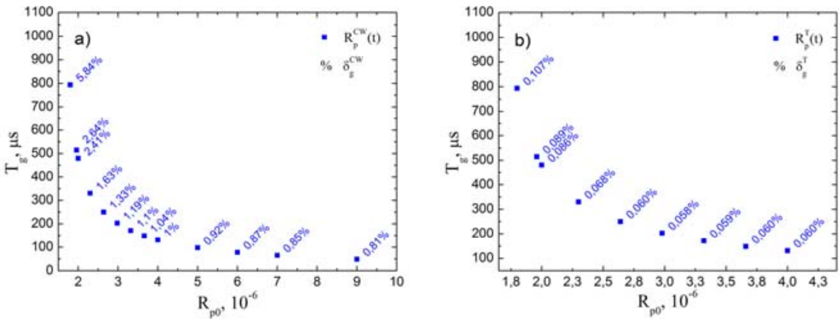

Fig. 4. Standard deviation of timing jitter of generated pulse dependence on pumping average intensities in the case of different pumping methods: CW (a) and modulated (20 % modulation depth) with triggered pump cancellation after generation of laser pulse (b).

use rectangular modulated pump pulses [22]. Performed calculations confirmed this possibility, though not so much (as higher than one order) as it was stated (up to six orders [22]). Modulated pumping allows stabilising timing jitter in the appropriate range of pumping intensities. By increasing the depth of modulation the timing jitter became stable at the lower average pump intensities. The dynamics of pulse generation and population of higher laser level dependence on the depth of modulation can be seen in Fig. 5. The lowest timing jitter (0.026%) was observed when the depth of modulation

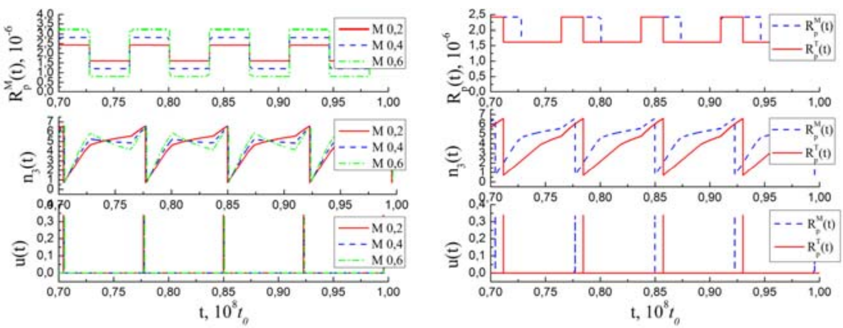

Fig. 5. Comparison of pulse generation dynamics in steady state in the case of different modulation depths (left) and when modulated pumping (20 %) with and without pump cancelling is used (right).

was 100% at the pulse repetition rate of about 2 kHz. The other timing jitter reduction possibility is to use composite pumping, i.e. firstly to pump at low intensity and then steeply increase the pumping intensity. Using this pumping method in the numerical simulations the lowest obtained timing jitter is 0.0165%. In this thesis the new pumping method is suggested – to fully cancel or switch to a lower pumping level after the pulse is generated (Fig. 5). It is shown that using this new method it is always (for various pulse repetition rates and modulation depths) possible to achieve lower timing jitter than without pump cancelling. So, using depth of modulation of 100% the timing jitter was reduced to 0.018%, i.e. it is close to the case of composite pumping when high relative (high/low pumping) intensities were used.

During research of this thesis two lasers with pulsed pumping were constructed experimentally: with PQS and with AQS. The timing jitters of both lasers were measured using the fast digital storage oscilloscope at repetition rates of 200 Hz, and measurements were done from an additional external synchronization pulse by measuring the pulse generation time at 50% amplitude levels of both (sync. and generated pulse) pulses (Fig. 6). So, in the first case standard deviation of timing jitter of generated pulses was about 180 ns, in the second - about 50 ps.

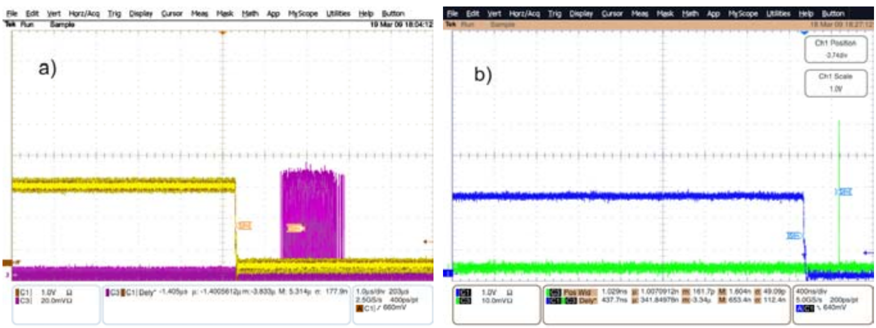

Fig. 6. Oscillograms presenting timing jitter of experimental minilasers with passive Q-switching (a, 1 μs/div) and active Q-switching with negative feedback (b, 400 ns/div).

In **subchapter 2.3** the beam characterization by the moving knife edge method is described. It is shown how the beam parameters (beam widths in directions of principal ellipse axes and ellipse orientation angle in the laboratory coordinate system of the general astigmatic beam) defined by the second order moment method can be determined from the measurement data when the laser beam is scanned in three different directions. This new method was used for measurements of beam propagation ratios of created lasers and pump sources.

All three subchapters of **Chapter 3** are dedicated to the laser applications. In **subchapter 3.1** the results of studying the compression of short (with a width close to the relaxation time of hypersonic waves) signal pulses during their amplification in the field of focused counter propagating pump of the same carrier frequency and width in media with electrostriction nonlinearity are presented. In standard (from the level of spontaneous-scattering noise) stimulated Brillouin scattering (SBS) experiments using focused ~ 0.9 ns pump pulses of a miniature Nd:YAG laser the compressed Stokes pulses with $\tau_S > 100$ ps can be easily observed. However, compressed pulses with duration lower than 100 ps and better stability under these standard experimental conditions were sometimes observed. The hypothesis was formulated that the compressed pulses were generated not from the level of spontaneous-scattering noise but from the seed signal which is a back scattered pump by the cell surfaces. So, for verification of this hypothesis the experimental scheme presented in Fig. 7 was set up.

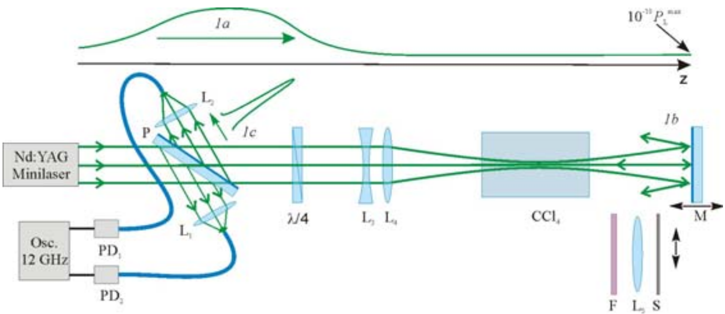

Fig. 7. Schematic of the experimental setup: diode-pumped solid-state miniature Nd:YAG laser; (1a) spatial shape (length) of the pump pulse power; (1b) pump radiation reflected by a plane mirror; (1c) compressed pulse; ($L_{1,2}$) lenses focusing the pump and compressed pulses into an optical fibre; (P) dielectric polarizer; ($\lambda/4$) quarter-wave plate; ($L_{3,4}$) lenses of the system focusing pump radiation; cell with an electrostriction (SBS) medium; (M) reflecting mirror; ($PD_{1,2}$) fast photodiodes; (Osc.) broadband digital oscilloscope; (F) neutral filters; (L_5) collimating lens; (S) screen.

Here the seed signal (1b) was pump radiation (1a) reflected by a plane mirror (M) which can be displaced along the beam propagation direction. One of the purposes of this experiment was to measure the time jitter for compressed pulses with respect to the laser pump pulses calculated at the 50% level on the pulse leading edges (shown by arrows in Fig. 9). Our hypothesis is confirmed by Fig. 9 which shows what happens when the counter propagating seed pulse is involved (the jitter decreased from 39 to 12 ps).

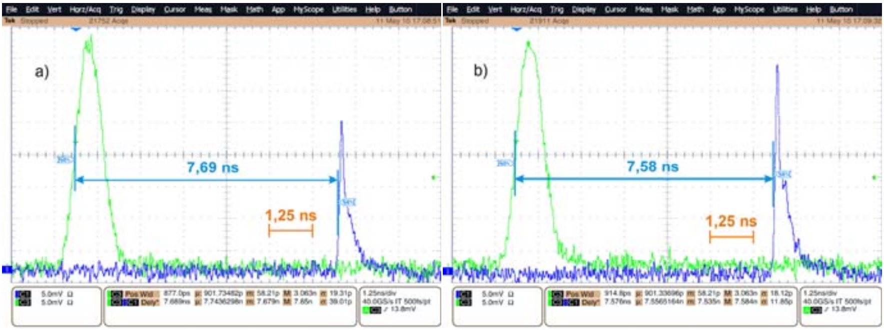

Fig. 9. Oscillograms of the pump pulses (on the left) and compressed pulses (on the right): (a) in the conventional SBS compression regime from the noise level and (b) in the presence of a seed pulse due to the transmitted-pump reflection by an additional mirror.

It should be emphasised that here the main thing is not the decrease in the mean (measured) width of compressed pulses from 109 to 96 ps but much higher stability of their parameters. Fig. 10 shows the results of studying the dependence of the change in the energy efficiency of compression and the compressed pulse stability on the mirror

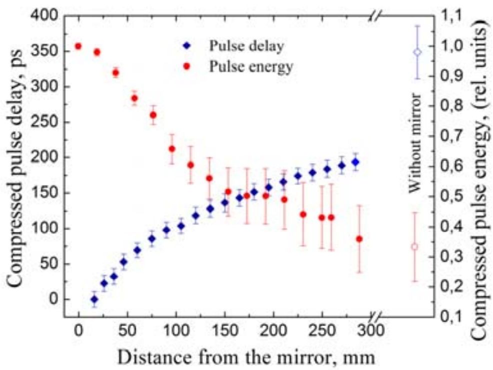

Fig. 10. Dependences of the delay and energy of compressed pulses on the distance from the mirror.

position. It can be seen that with an increase in the mirror-cell distance, as a result of the decrease in the amplitude and increase in the delay of seed signals, their gain as well as the energy stability decreased. It can also be seen that the time jitter of the compressed pulse occurrence barely changes when the mirror is displaced along the axis by a distance up to 30 cm but increases by a factor of more than 3 when the mirror is misaligned, screened, or absent. Another experimental setup was created for studying the compression of pulses with lower delay times of seed pulses. Fig. 11 shows that the optimal delays are close to zero, a situation where both pulses arrive at the beam waist inside the SBS-cell almost simultaneously. In this case, pulses with a measured minimum mean width of 66 ps and standard deviation of 4.4 ps were obtained (Fig. 11b). Taking into account the proximity of the measured widths to the measurement resolution limit, the real width of the thus compressed pulses can be estimated as 52 ps.

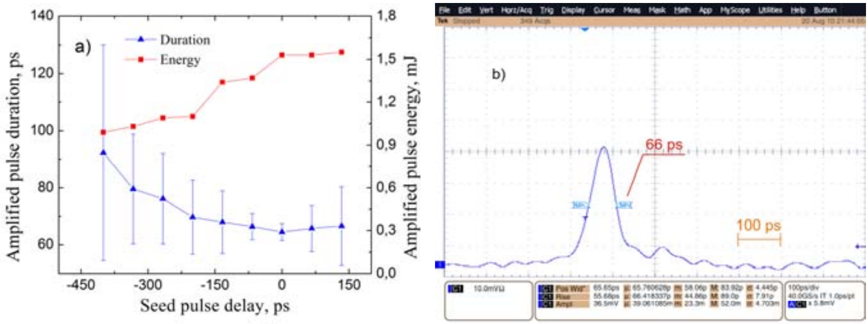

Fig. 11. Dependences of the width and energy of amplified pulses on the delay of the seed pulse with respect to the pump pulse (a) and obtained shortest pulse at optimal delays (b).

In **subchapter 3.2** the experimental results of the Z-scan measurements obtained using pulses with different pulse shapes (Fig. 12) for fused silica with small nonlinear index n_2 are presented. After introduction of this method a keen interest in the accuracy and reliability of the results obtained by means of this method has been shown, but the main attention was paid to the influence of the finite aperture size, the thickness of samples and similar problems. Although hundreds of papers on Z-scan measurements were published and lasers with different pulse shapes and durations were used, only the original paper [23] and a few others obviously indicate that the results must be temporally averaged properly when the non-rectangular pulses are used. In our Z-scan experiments short pulses with different pulse shapes were used (Fig. 12). The main motivation to use the pulses of the created actively Q-switched minilaser was possibility to generate single (SLM) and multi-longitudinal mode (MLM) pulses with the same spatial properties. This property allows us to perform Z-scan experiments in the same focusing geometry and to observe what the difference in the measured Z-scan signal is, and how to correctly extract the true values of the nonlinear index from measured data. The spatial properties of the beams were controlled by the modified moving knife-edge method and the CCD camera.

In general the nonlinear refractive index is determined by several physical mechanisms, acting in a broad range of time scales. In non-resonant interactions and for pulse durations of about 1 ns the main mechanisms that contribute to the nonlinear index of refraction in solid state materials (for example, in fused silica) are electronic and nuclear Kerr effects. These mechanisms are very fast, with typical time responses of about $\sim 10^{-15}$ s and $\sim 10^{-13}$ s, respectively. Vibrational (nuclear) contribution to the nonlinear index n_2 is significant enough (10 – 20 % in glasses). The contribution of the electrostrictive effect is also often considered. Besides, it is very important that the electrostrictive response time, which is roughly equal to the time required for an acoustic deformation to travel across the diameter of the optical beam in the medium, is more than ~ 10 ns under our experimental conditions. Thus, the

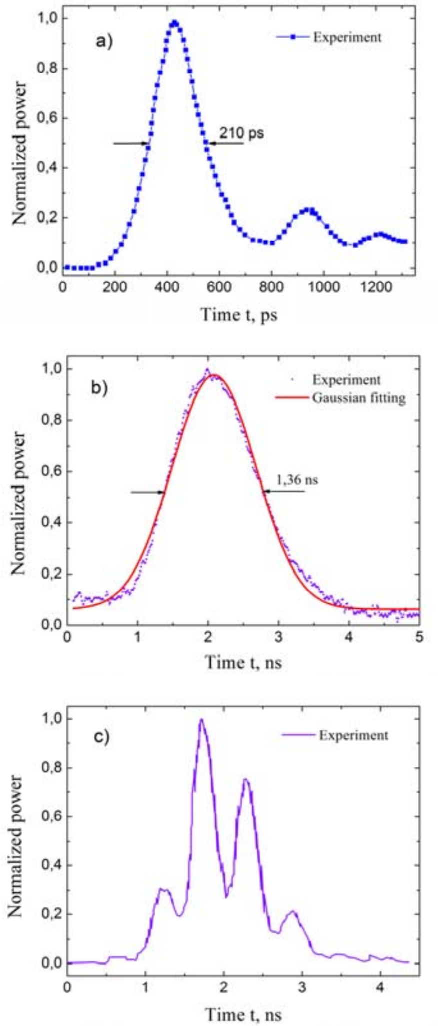

Fig. 12. Shapes of pulses used in Z-scan experiments: a) pulse shape of SBS-compressor; b) SLM pulse shape; c) typical MLM pulse shape.

electrostrictive response is very slow, and therefore its contribution is very low as compared to the electronic and nuclear Kerr effect and cannot strongly influence our measurement results with short pulses.

The main parameter needed for the determination of γ_2 value is the power-weighted time-averaged on-axial nonlinear phase change at the beam waist $\langle \Delta\Psi_0(t) \rangle$, which in the Z-scan method is found by the fitting procedure of measured transmittance data to the formula of normalized transmittance. However, the obtained values depend significantly on the used fitting procedure (Fig. 13). It has been shown that the reasonable choice is to use the value of z_R found by independent measurement of M_σ^2.

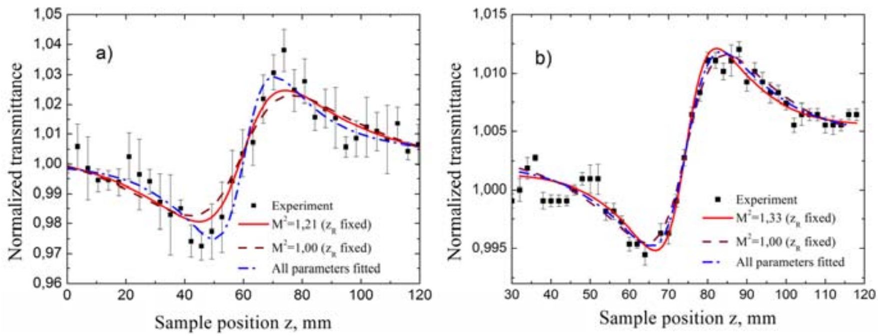

Fig. 13. Z-scan dependences of the normalized transmittance versus the sample position when different pulses were used: a) SBS-compressed pulses; b) SLM pulses.

The results of Z-scan measurements using SBS-compressed pulses are presented in Fig. 13a. The calculated value of the coefficient which takes into account the shape of the pulse is $\eta_{SBS}^{(1)} = 1.9$. The nonlinear refractive index calculated for this case was $\gamma_2 = 2.52 \cdot 10^{-16}$ cm^2W^{-1}. The same processing procedure was applied to the data obtained by using SLM pulses of the Nd:YAG minilaser (Fig. 13b) and the values of $\gamma_2 = 2.59 \cdot 10^{-16}$. Despite the fact that the shape of SLM pulse ($\eta_{SLM}^{(1)} = 1.56$) was close to theoretical Gaussian shape ($\eta_G^{(1)} = \sqrt{2}$), the approximation of the real SLM pulse profile by the Gaussian profile would lead to the value of γ_2 lower 1.29 times. The situation was more complicated when MLM pulses were used in the experiments. Due to interference of all existing modes in the resonator the temporal structure of the generated pulse shape is more complex (Fig. 12c). It can be seen from Fig. 14 that in this case the registered signal was higher 1.4 times. It means that the on-axis intensity and the induced by MLM laser pulses transmittance are also higher, although the lower pulse energies were used. However, applying the same processing procedure to the obtained data the value of $\gamma_2 = 2.55 \cdot 10^{-16}$ cm^{2}W^{-1} was calculated. Thus, good compatibility between the values of γ_2 for the same samples of fused silica is obtained only if the temporal shapes and spatial profiles of the used pulses are properly taken into account.

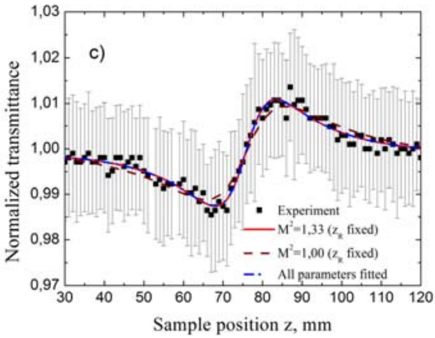

Fig. 14. Z-scan dependences of the normalized transmittance versus the sample position when MLM pulses were used.

In **subchapter 3.3** the application possibilities of created minilasers for contaminated paper cleaning and LIBS experiments are presented. From the restoration point of view, cleaning of the historical paper documents presents a labour consuming task due to delicate substrate material. Usually the paper surface is first cleaned by mechanical methods and tools such as erasers or scalpels, and then it is chemically treated with water and chemical solvents. The paper surface damage or irreversible changes of the substrate structure and the chemical composition often result from the sequence of these ordinary cleaning procedures. The use of pulsed laser radiation for cleaning and restoration of historical documents and artworks has recently been proposed. This technique allows avoiding negative effects found when using mechanical and chemical procedures to remove paper impurities. Moreover, the laser assures a non-contact well localized action, and also the computer control of the process.

The aim of this work was to treat the artificially contaminated paper by the short 0.15 ns pulse Nd:YAG laser radiation and to investigate laser caused modifications of the paper substrate by three Fourier Transform Infrared (FTIR) spectra sampling methods. In this thesis it is demonstrated that soft laser cleaning of the artificially contaminated paper recovers more than 80% of initial brightness and does not cause noticeable chemical modifications of the paper. The case of laser operating above the paper modification threshold led to the uplifting of the paper surface and thinning-out of cellulose fibres. The results of experimental studies have shown that the created short pulse minilaser with active (with negative feedback) Q-switch provides possibility to synchronize pulses of both such minilasers allowing one to perform LIBS technique with sequence of two pulses. Thus, created short pulse minilasers, especially with the effective pulse compression, easily meet the criteria for portable laser cleaning and LIBS diagnostic systems.

Main results and conclusions

- For the numerical analysis of the laser generation dynamics a more detailed traveling wave model has been developed. This model includes the level splitting due to the Stark effect, Boltzman factors of population densities, relaxation times from the excited lasing levels, direct pumping possibility and other parameters of active and passive elements including their distribution in the resonator.
- The developed software allows control of time and spatial distributions of forward and backward traveling waves of pump and laser intensities in the resonator, time and spatial changes of the level population densities in the active element and the saturable absorber. Performed calculations have shown that generation dynamics highly depend on the optical element sequence inside the resonator, the shapes of the pulses traveling in opposite directions are different and their temporal modulation when fast Q-switching is used has the period shorter than the resonator round-trip time.
- The CW pumping modulation of passively Q-switched lasers by triggered high enough power rectangular pulses with their steeply start up and automated cancellation after the laser pulse is generated allows one to synchronize pulse generation moments with external events and to reduce their timing jitter by two orders of magnitude. Such pumping modulation can be easily realized experimentally and allows one to significantly extend application possibilities of these simple and robust passively Q-switched lasers.
- The method of second order moments adapted for the data processing obtained by the moving knife method allows one to find beam widths of the general astigmatic beam in directions of principal ellipse axes and ellipse orientation angle in the laboratory coordinate system. This modified moving knife method can be successfully used for measurements of beam widths and propagation ratios defined by second order moments in the spectral ranges where multielement detectors like CCD do not exists.

- The effective short pulse compression is realized by the new method, when in the medium with electrostriction nonlinearity the picosecond pulse is generated not from the level of spontaneous-scattering noise, but from the seed signal of the same carrier frequency and duration, which is counter propagating to the focused pump pulse. This allows us using easily available CCl_4 liquid to compress short (~ 1 ns) pulses of the diode pumped Nd:YAG laser with 50 % energy efficiency up to pulses shorter than 60 ps, whose duration, amplitude stability and timing jitter parameters are 3-4 times better, while duration of compressed pulses is almost two times shorter than that of compressed Stokes pulses in standard stimulated Brillouin scattering experiments.
- Using Z-scan method for the small nonlinear refractive index measurements of a fused silica good compatibility between the measured values ($\gamma_2 \cong 2.6 \cdot 10^{-16}$ cm^2/W) is obtained only when during the processing of experimental data the temporal and spatial parameters of the used (compressed by stimulated Brillouin scattering, single and multiple mode pulses of minilaser) pulses are properly (through the coefficients appropriately calculated from experimental data) taken into account.
- Created short pulse actively Q-switched minilasers (with negative feedback) provide possibility to synchronize the pulses of such minilasers allowing one to perform perspective LIBS technique with sequence of two pulses. Thus, created short pulse minilasers, especially with the effective pulse compression, easily meet the criteria for Z-scan, portable laser cleaning and LIBS diagnostic systems. Thus, there is hope for expansion of these lasers in the processes of diagnostics and technology.

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Santrauka

Trumpų impulsų kokybės moduliacijos išilgai diodais kaupinami kietojo kūno minilazeriai: generavimas, charakterizavimas ir panaudojimas

Disertaciją sudaro 5 skyriai: įvadas, du originalūs skyriai su poskyriais, pagrindiniai rezultatai ir išvados bei cituojamos literatūros sąrašas. Disertacijos medžiaga pateikta 143 puslapiuose, įskaitant 52 paveikslus ir 4 lenteles, o jos rengimui panaudoti 186 literatūros šaltiniai.

Įvade yra trumpai pristatoma darbo motyvacija, darbo tikslai bei uždaviniai, darbo mokslinis naujumas, ginamieji teiginiai bei rezultatų aprobacija.

Antrasis skyrius yra sudarytas iš trijų poskyrių. Pirmame poskyryje yra pristatomas bėgančiųjų bangų modelis įskaitant daugiau lazerio aktyviosios terpės, kaupinimo šaltinio ir rezonatoriaus architektūros parametrų. Šio poskyrio gale yra pateikti rezultatai demonstruojantys šio modelio privalumus lyginant su paprastesniu taškiniu lazerio modeliu. Antrame poskyryje yra nagrinėjama generuojamų impulsų laikinio tirtėjimo problema lazeriuose su pasyviąja kokybės moduliacija. Išnagrinėti laikinio tirtėjimo mažinimo būdai, naudojant moduliuotą, kombinuotą, impulsinį kaupinimą, įskaitant naujai pasiūlytą būdą su kaupinimo trigeriniu paleidimu bei nutraukimu. Pateikti eksperimentiniai laikinio tirtėjimo matavimo rezultatai. Trečiajame poskyryje yra pateiktas naujas, antrųjų momentų principu pagrįstas, pluošto charakterizavimo judančiu peiliu metodas, kuris leidžia charakterizuoti bendrojo astigmatizmo pluoštus ir surasti jų sklidimo invariantus.

Trečiasis skyrius yra sudarytas iš trijų poskyrių. Pirmajame poskyryje yra nagrinėjamos lazerių impulsų spūdos galimybės tetrachlorido CCL_4 skystyje. Pademonstruota, kad naudojant to paties dažnio ir trukmės užkrato signalą kai jis sklinda priešpriešai fokusuotam kaupinimo impulsui galima gauti žymiai trumpesnius (< 60 ps) ir stabilesnius optinius impulsus. Antrame poskyryje yra aprašomas netiesinio lūžio rodiklio kvarciniame stikle matavimas Z-skenavimo metodu ir gautų duomenų apdorojimo procedūra įskaitant naudojamų impulsų erdvinę ir laikinę formą. Trečiajame poskyryje yra aprašomi eksperimentai, kuriuose sukurti minilazeriai taikomi popieriaus paviršiaus valymui bei LIPS diagnostikai.

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