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YEREVAN STATE UNIVERSITY

GRIGORYAN ARMINE PAPIN

THE STUDY OF THE PECULIARITIES OF SPECTRAL COMPRESSION AND SELF-COMPRESSION OF REGULAR AND RANDOMLY MODULATED PULSES

Dissertation on scientific degree of Doctor of Philosophy (Ph.D.) in Physics and Mathematics in specialty 01.04.21 Laser Physics

ABSTRACT

YEREVAN-2017

Ատենախոսության թեման հաստատվել է Երևանի պետական համալսարանում

Գիտական ղեկավար՝ ֆ.-մ.գ.դ., պրոֆեսոր Ռ.Ս. Հակոբյան

Պաշտոնական ընդդիմախոսներ՝ ֆ.-մ. գ. դ., պրոֆեսոր Յ.Հ. Ավետիսյան
ֆ.-մ. գ. դ. Ա.Մ.Իշխանյան

Առաջատար կազմակերպություն՝ Հայ-ռուսական (սլավոնական) համալսարան

Ատենախոսության պաշտպանությունը կայանալու է “03“ փետրվարի 2018թ. ժամը 12:00 - ին, Երևանի պետական համալսարանի 049 ֆիզիկայի մասնագիտական խորհրդի նիստում:

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The dissertation will be presented "03" February 2018, on (12:00 p.m.), at the session of 049 academic council in Yerevan State University.

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To be acquainted with the dissertation, visit the library of Yerevan State University.

Abstract distributed: 29 December 2017

The scientific secretary of the academic council,
PhD in physiscs, Associate Professor, V.P.Kalantaryan

GENERAL DESCRIPTION OF THE WORK

Relevance of the study: The progress in the technology of manufacturing of silica optical fibers leads to not only a revolution in the field of optical communications, but also to the formation of a new direction in science – nonlinear fiber optics.

Although silica glass is not a material with strong nonlinearity, the large length of the fiber with low optical losses and small dimensions of cross-section of the fibers significantly reduce the threshold of occurrence of various nonlinear phenomena. On the other hand, the study of the femtosecond range of durations of optical pulses [1-3] leads to the possibility of propagation of radiation with high intensity in optical fibers and observed nonlinear phenomena which are observed rare in the field of large pulse durations[4].

All this leads to a wide interest in nonlinear fiber optics and many interesting results have been obtained which are applied in optical communications, laser technology, technology of information processing, optical computing machines, optical sensors of various physical quantities, etc. The transition to the new femtosecond time scale brought new physical and technical challenges related to self-interaction and interaction of powerful pulses with extremely short duration in optical fibers [5], their synthesis, control, transmission, and registration. For the solution of these problems in femtosecond time scale, particularly it is used methods of nonlinear and adaptive optics, Fourier-optics and holography, spectral interferometry. The pulse compression based on the nonlinear process of self-phase modulation (SPM) of radiation in fiber and subsequent dispersive delay line (DDL) allows reach 10^3 times compression and the formation of extremely short pulses for optical range with the durations of units femtoseconds [6-8].

Along with the important directions, the spectral compression has demonstrated the potential applications in the analysis-synthesis problems in ultrashort optics [9, 10]. Generally, the spectral compressor has DDL and a nonlinear fiber as its members [11, 12]. Lately, the spectral self-compression was numerically [13] and experimentally [14] implemented in a single-mode fiber (SMF) with anomalous dispersion.

Although there is a wide research in the directions mentioned above, numerous unsolved problems existed until now. The research of spectral self-compression was at a premature level, and in order to achieve a more holistic physical pattern of the process, a detailed study was necessary for all the values of system parameters. The peculiarities of spectral compression and self-compression were studied only for the initial regular pulses.

The aim of the dissertation is to fill in the gaps in the research introduced above. The study of the characteristics of spectral compression and self-compression is done not only for the regular pulses but also for the randomly modulated pulses by examining the impact of coherency on the process. In addition, via the method of the compensation of third-order dispersion by initial pulse asymmetry we increase the effectiveness of pulse compression. In order to obtain needed asymmetry and random pulses, the use of liquid crystal spatial light modulators is offered.

Objectives of the work:

The relevance and the pragmatic value of the research fields presented above and the further observation of unresolved problems determine the aim and scope of this dissertation. Particularly:

- The studies of pulse self-interaction in a fiber with anomalous dispersion in order to detect the opportunity to realize the soliton spectral self-compression (soliton self – SC) in standard silica fiber.
- The studies of analogue between soliton self – SC and soliton-effect self-compression.
- The studies of high-order effects preventing the effective regime pulse compression and possibilities to optimize the pulse compression process.
- To study the characterizations of spatial light modulators based on twist nematics with cholesteric mixtures and with homeotropic boundary conditions for ultrashort pulse shaping and to develop the relevant mode extraction method.

Scientific Novelty:

Through detailed studies and innovative investigations the following unprecedented results have been obtained:

- We demonstrate the soliton self – SC process, realized in the fiber "directly", without DDL, and reveal the characteristics and regularity on the basis of the physical pattern of the process.
- We show that there is an analogue between the processes of soliton-effect self-compression and soliton self – SC which is implemented in a single - mode fiber with Kerr-nonlinearity and anomalous dispersion. The studies are done not only for the transform-limited pulses but also for pre-chirped pulses.
- Through detailed investigations, we study the evolution of the pulse and the spectrum of transform-limited pulses during the propagation in the fiber and it is shown that the soliton self – SC is implemented for various initial pulses: the main difference is the periodicity of the process. The approximation curves which show the frequency of the soliton self – SC and stretching dependence on nonlinearity parameter are studied.
- Through numerical study, we show that it is possible to compensate the third-order dispersion by initial pulse asymmetry manipulation. This opportunity is conditioned by the fact that the phase which is obtained during the propagation in the fiber depends on the initial pulse shape.
- Via the method of the compensation of third-order dispersion by initial pulse asymmetry we increase the effectiveness of pulse compression as compared to the compression of regular pulses. The pulse compression with a ratio corresponding to the pulse spectral broadening in the fiber is obtained.
- The spectral compression for randomly modulated pulses in view of the noise nonlinear suppression and filtering is studied. The impact of coherency on the process efficiency is demonstrated. The study shows that the spectral compression ratio decreases as coherence time of the initial randomly modulated optical signals increases.
- Our numerical studies show the possibility of the spectral self-compression for randomly modulated signals in a single - mode fiber with negative dispersion. The study is implemented for the additive noise model. The characteristic features of

the spectral self-compression for various values of the fiber length and the nonlinearity parameter are studied.

- We developed the relevant mode extraction method for the calculation of mask patterns which can generate multiple pulse sequences with arbitrary relative amplitudes and phases. As the mask we used liquid crystal spatial light modulator based on the cell with twist structure of nematic and cholesteric mixture and with homeotropic boundary conditions on the walls.
- By the choosing relevant distribution of the electric field voltages (≈ 0.1V) across the mask with spatial light modulator we get very different pulse shaping. This approach allows to control of the relative amplitudes of different pulse within pulse train. By varying the modulation depth (by altering the amplitude of the electric field voltages distribution), we generate different number of pulses and intensity ratio of them.

Practical significance:

The results introduced in the thesis can be used as a base for the improvement of productive methods in ultrafast optics and laser physics. They have potential applications in analysis-synthesis problems in ultrafast optics, in problems of registration and the measurement of characteristics of ultrashort pulses, in nonlinear optical filtering of noise, etc.

Pulse shaping technique is a widely used for applications such as pulse compression and dispersion control, coherent control of quantum systems, laser control of matter, telecommunications, optical metrology, bio-imaging, microscopy and multidimensional spectroscopy.

Defending statements:

1. The soliton spectral self-compression implemented due to the self-interaction of pulse in the fiber with anomalous dispersion when the dispersive length in the fiber is shorter than the nonlinearity length is a spectral analogue of soliton-effect self-compression. In the range of values of nonlinearity parameter for 0.25 to 1 and fiber lengths of 1 to 20000, up to 30 times soliton spectral self-compression is possible to obtain.
2. In the pulse compression process, the third-order dispersion preventing the process efficiency can be compensated via shaping of asymmetric pulses at the system input. This approach improves the effectiveness of pulse compression as compared to the compression of regular pulses: an effective pulse compression is achieved, with a ratio corresponding to the pulse spectral broadening in fiber.
3. The mask patterns with the structure based on twist nematic with cholesteric mixture with homeotropic boundary conditions can be used for the effective shaping of ultrashort pulses.
4. The ultrashort pulse shaping is possible to realize by very low fields (≈ 0.1V) in the cell of twist nematic with cholesteric mixture with the homeotropic boundary conditions due to the effect of Fréedericksz transition without an external field.

Approbation of the work: The main results presented in dissertation are reported in following conferences:

1. The Int. Simp. Optics & its Applications, Yerevan-Ashtarak, Armenia, 2011.
2. Int. Conf. Laser Physics 2011, Ashtarak, Armenia, 2011.
3. Int. Conf. IONS-Armenia, Yerevan-Ashtarak, Armenia, 2013.
4. Int. Conf. Laser Physics 2013, Ashtarak, Armenia, 2013.
5. Optics-2014, 2nd Int. Symposium Optics & Its Applications, Yerevan-Ashtarak, Armenia, 2014.
6. Frontiers in Optics / Laser Science Conference (FiO/LS), in San Jose, California, USA, 2015.
7. Int. Conf. Laser Physics 2017, Ashtarak, Armenia, 2017.
8. Second Panarmenian Scentific Forum, Yerevan, 2017.

Publications: On the theme of dissertation 6 articles and 9 theses have been published, which list is presented in the list of publications.

The contents of the work are described below*:*

Introduction, four chapters, summary, and the list of the literature. The work consists of 107 pages, and contains 66 figures, the bibliography including 212 names.

In the introduction, the urgency and the objective of the thesis are presented. The content and summary of dissertation, scientific novelty, the practical significance and defending statements.

In chapter 1, the review of the literature related to the dissertation is introduced.

Chapter 2 is dedicated to the research of soliton self – SC process for ultrashort pulses in a SMF with anomalous dispersion, when the dispersive length is less than the nonlinearity length ($L_D < L_{NL}$ .i.e. R<1). We study the soliton self - SC, which occurs when the dispersive length in the fiber is shorter than the nonlinearity length ($L_D < L_{NL}$, i.e. $R < 1$). Therefore, at first the group-velocity dispersion (GVD) stretches the pulse by acquiring a chirp. Afterwards, the accumulated impact of nonlinear SPM leads to the chirp compensation, and as a result, the spectrum becomes compressed [4].

In the SMF, the pulse propagation is described by nonlinear Schrödinger equation for normalized complex amplitude of field, considering only the influence of GVD and Kerr nonlinearity [1].

$$i\frac{\partial\psi}{\partial\zeta} = \frac{1}{2}\frac{\partial^2\psi}{\partial\eta^2} + R|\psi|^2\psi \qquad (1)$$

where $\zeta = z/L_D$ is the dimensionless propagation distance, $\eta = (t - z/u)/\tau_0$ is the running time, which are normalized to the dispersive length $L_D = \tau_o^2/|k_2|$ (k_2 is the coefficient of second - order dispersion), and initial pulse duration τ_0, respectively. The nonlinearity parameter R is given by the expression $R = L_D / L_{NL}$, where $L_{NL} = (k_0 n_2 I_0)^{-1}$ is the nonlinearity length, n_2 is the Kerr index of silica, I_0 is the peak intensity and k_0 is the light wave number. The first and second terms of the right side of Eq. (1) describe the impact of GVD and nonlinearity, respectively. We use the split-step Fourier method during the numerical solution of the equation, with the fast Fourier transform algorithm on the dispersive step [15,16].

The subject of our research is the process of the soliton self - SC revealing its nature, peculiarities and general regulations on the basis of physical pattern of the process.

The behavior of pulse and spectrum for different initial pulses, particularly, for Gaussian, secant-hyperbolic and super-Gaussian pulses in the case of different values of fiber length is investigated. The research shows that the soliton self – SC has periodical character: in the first step of propagation, we have spectral compression which leads to the reduction of the impact of dispersion, resulting in the decline of the value of dispersive length L_D and consequently the nonlinearity parameter *R*. When the $R > 1$ ($L_D > L_{NL}$) condition is satisfied, the pulse is compressed. Afterwards, the spectrum is stretched within pulse compression. This leads to the gradually increase of dispersion role causing the reduction of L_D and *R*. When $R < 1$, the $L_D < L_{NL}$ condition is satisfied, and spectrum is again compressed.

The research is done for the different values of nonlinearity parameter. The dependence of the process periodicity on the nonlinearity parameter is studied: the approximations of the curve introducing nonlinearity parameter dependent frequency (the frequency of the spectral compression and stretching) are introduced.

In §2.1. and §2.6, the introduction and conclusion are presented.

In § 2.2 and § 2.3, the mathematical modeling of propagation process and the self-interaction of ultrashort pulses in SMF and the method of numerical solution of Schrödinger equation are introduced. In §2.4.and §2.5 the physical pattern of soliton self – SC is describe introducing the numerical results.

Fig. 1 illustrates the process of propagation of Gaussian (a, b, $R = 0.6$) and secant-hyperbolic (c, d, $R = 0.4$) pulses and their spectra, where $\Omega \equiv (\omega - \omega_0)/\Delta\omega_0$ (ω is the current frequency, ω_0 is the central frequency, $\Delta\omega_0$ is the half of width of spectra on the level 1/e from peak intensity). In this case, we study the process for short fiber lengths where the efficiency of the process is high for the nonlinearity parameter values of R=0.6 (Gaussian pulse) and *R*= 0.4 (secant-hyperbolic pulse). It can be observed that the pulse is stretched and the spectrum is compressed in the initial propagation step. Afterwards, the width of central peak of the spectrum decreases and the main part of the pulse energy goes to the spectral satellites. At the certain fiber length, the reverse process starts the pulse self-compression.

Fig. 2 shows the peak value of spectra (1) and pulses (2) for initial Gaussian (a) and secant-hyperbolic (b) pulses, which shows that the process has a periodic character not only for Gaussian pulses but also for secant-hyperbolic pulses. The difference between Gaussian and secant- hyperbolic pulses is the speed of the process: as we see in Fig. 2 every next spectrum compression occurs in the short distance in the case of Gaussian pulses as compared with the case of secant-hyperbolic pulses.

In the process of propagation, the behavior of the spectrum is similar to the pulse behavior in the case of the soliton compression. As it is known, the propagation of the high - order solitons have periodic character with a $(\pi/2)L_D$ periodicity. On the distance equal to the periodicity, at first pulse is compressed, then it is stretched taking initial shape. In our case, the spectrum has similar behavior. However, due to the incomplete cancellation of the chirp, the changing of the spectrum does not have the strict periodic character.

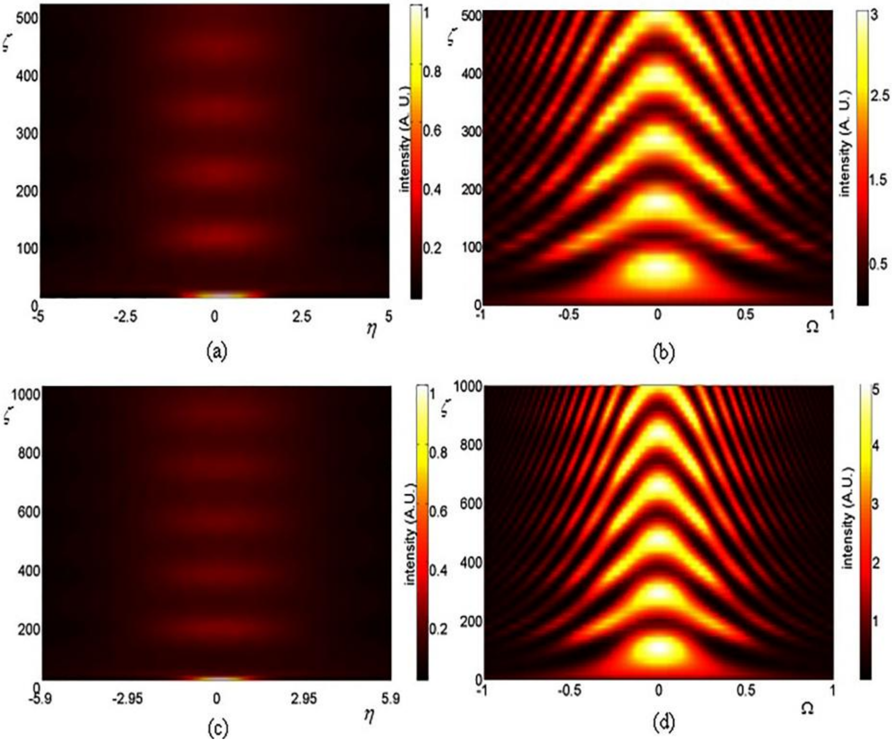

Fig. 1. *The 3D map of the propagation of Gaussian (a, b) and secant-hyperbolic (c, d) pulses and their spectra.* $\Omega = (\omega - \omega_0)/\Delta\omega_0$.

The process is different from soliton compression due to the fact that spectrum changes depend on a nonlinear phase, which depends on the shape of the pulse. In the case of soliton propagation, the changes of the pulse depend on a dispersive phase, which depends on neither spectral nor temporal shape of the pulse.

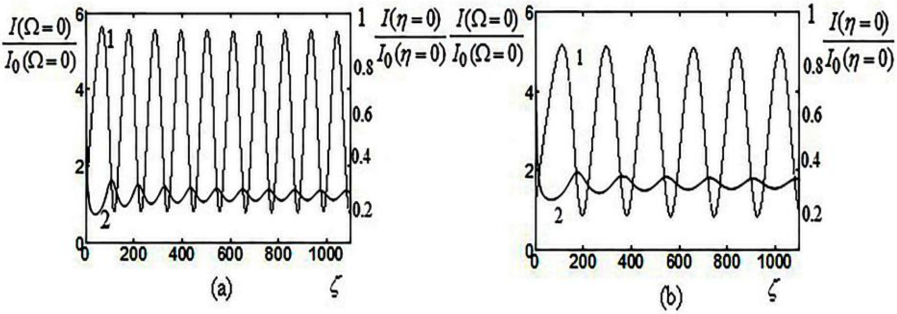

Fig. 2. *The peak values of spectra (1) and pulses (2) vs fiber length for initial Gaussian (a) and secant-hyperbolic (b) pulses (for fiber length up to 1000).*

The study shows that the periodicity of the spectral compression and stretching decreases with the reduction of nonlinearity parameter (Fig. 3). It is shown that there are polynomial (Eq. (2), (3)) and exponential (Eq. (4), (5)) approximations of the curve introducing nonlinearity parameter dependent frequency (Fig. 3), which is the frequency of the spectral compression and stretching.

$$1/T = 1/(1.6\cdot 10^{7}\cdot 10^{-30\cdot R} + 7821\cdot 10^{-4.79\cdot R}) \tag{2}$$

$$1/T = 1/(5.09\cdot 10^{6}\cdot 10^{-19.8\cdot R} + 731.3\cdot 10^{-3.83}\cdot R) \tag{3}$$

$$1/T = 1/(0.004\cdot e^{3.08\cdot R}) \tag{4}$$

$$1/T = 1/(0.001\cdot e^{3.73\cdot R}) \tag{5}$$

There is another situation for small values of nonlinearity parameter. So, in the case of R=0.25, it is formed such pulses which changes its sizes but save the shape during propagation in fiber.

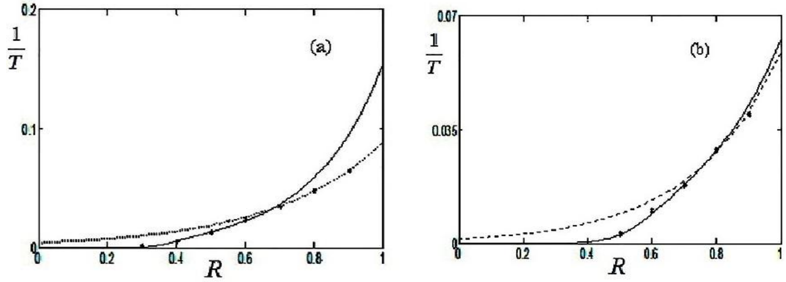

Fig. 3. *The frequency vs nonlinearity parameter for initial secant-hyperbolic (a) and Gaussian (b) pulses. The points correspond to the numerical investigations, solid lines introduce the approximation of results (Eq. (2), Eq. (3)) by all points, while the dotted lines correspond to the approximation by last 3 points (Eq. (4), Eq. (5)).*

The investigations are done for fibers length of $\zeta \approx 17000$, in this case the ratio of soliton self-SC is 4. However, the efficiency of compression decreases within distance, and for example after $\zeta \approx 11000$ the changes of spectra equal $\approx 1\%$ (Fig. 4). The reason of this is the following: because of pulse broadening (≈ 6000 times), the peak of the pulse drops so much that self-phase modulation is practically absent.

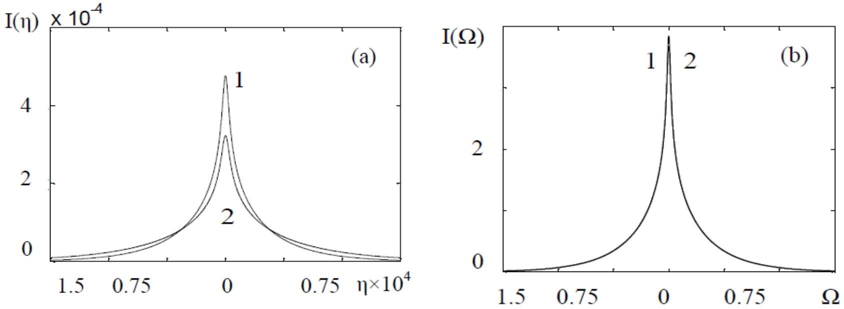

Fig. 4. *Pulses (a) and compressed spectra (b)* $\zeta \approx 11000$*(1),* $\zeta \approx 17000$*(2).*

<u>In chapter 3,</u> the possibility to compensate the third-order dispersion via shaping of asymmetric pulses at the system input is introduced. Due to the fiber nonlinearity, the pulse obtains a phase depending on its initial intensity $I_0(t)$. This allows controlling its phase at the end of the fiber by the initial pulse intensity. This approach of the use of asymmetric pulses has improved the efficiency of pulse compression, as compared to the compression of regular pulses.

The pulse compressor consists of SMF and DDL [17,2]. In single-mode fiber, the pulse obtains a positive phase and its spectrum expands due to self-phase modulation. This phase should be compensated by the negative parabolic phase obtained in the DDL; as a result, the pulse is compressed. Maximum pulse compression is achieved when transform-limited pulses are obtained. However, for short pulses, the high-order nonlinear and dispersive effects limit the pulse compression ratio substantially. The influence of the third-order dispersion is the most substantial among all high-order effects.

The pulse compression efficiency can be increased by third-order dispersion compensation through pulse asymmetry manipulation at the fiber input.

In Chapter 3, the spectral compression process and spectral self-compression for randomly modulated pulses are also presented.

In §3.1. and §3.6, the introduction and conclusion are presented.

In §3.2, the results of numerical studies on the compression of a Gaussian pulse is presented. In this case, the compression is not effective: the compressed pulse has many satellites and the compression ratio is less than the spectral broadening coefficient ~3 times: the maximum value of pulse compression was ~3, when the spectrum was broadened ~10 times [4].

Low compression efficiency is conditioned by the incomplete cancellation of phases, which are obtained in fiber and DDL. The incomplete cancellation of phases is a result of the third-order dispersion contribution in DDL and fiber [4].

Since SPM is conditioned by the pulse intensity, in the case of asymmetric pulses the asymmetry in the phase is caused not only by third-order dispersion but also by the self-phase modulation.

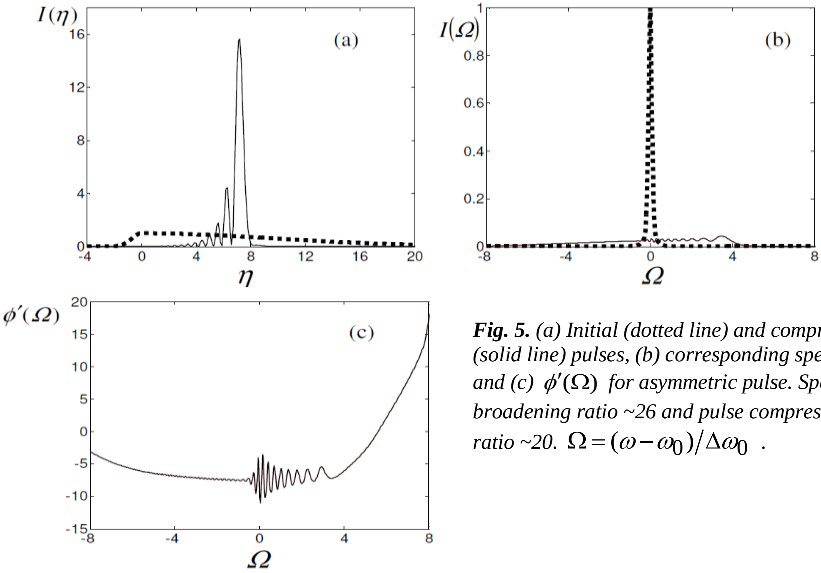

Fig. 5. *(a) Initial (dotted line) and compressed (solid line) pulses, (b) corresponding spectra, and (c)* $\phi'(\Omega)$ *for asymmetric pulse. Spectral broadening ratio ~26 and pulse compression ratio ~20.* $\Omega=(\omega-\omega_0)/\Delta\omega_0$.

This allows to control the phase of the pulse at the fiber output by the initial pulse intensity, and to achieve effective pulse compression. The numerical studies were implemented for pulses with different asymmetries.

Fig. 5 shows the initial (dotted line) and compressed (solid line) pulses (a), corresponding spectra (b), and $\phi'(\Omega)$ (c) in the case of the initial asymmetric pulse. The figures correspond to the maximum pulse compression, which was achieved when the parameter of nonlinearity was R = 20, the fiber length was $5L_D$, and the DDL length was $5.4L_D$. The maximal value of the pulse compression was ~20 in case when the spectrum was broadened ~26 times [4].

In Fig. 6, initial (dotted line) and compressed (solid line) pulses (a), corresponding spectra (b), and $\phi'(\Omega)$ (c) for another asymmetric pulse are depicted. In this case, the maximal value of pulse compression was ~10, when spectrum was broadened 10 times. The chirp is practically constant at the central energy-carrying part of the compressed pulse, which means that the pulse is approximately transform-limited. Fig. 6 corresponds to the case of maximum pulse compression, which was obtained when the parameter of nonlinearity was R = 7, the fiber length was $5L_D$, and the DDL length was $\approx 5.6L_D$ [4].

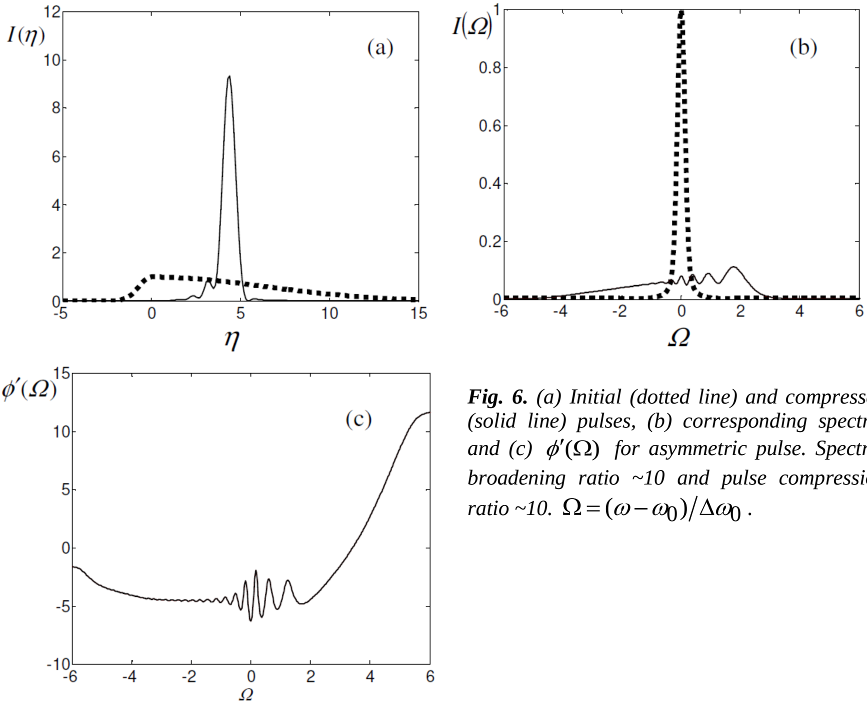

Fig. 6. *(a) Initial (dotted line) and compressed (solid line) pulses, (b) corresponding spectra, and (c)* $\phi'(\Omega)$ *for asymmetric pulse. Spectral broadening ratio ~10 and pulse compression ratio ~10.* $\Omega = (\omega - \omega_0)/\Delta\omega_0$.

In §3.3 and §3.4, the impact of coherency on the process of spectral compression of randomly modulated pulses is described introducing the numerical results.

The spectral compression process for randomly modulated pulses in view of the noise nonlinear suppression and filtering is studied. Particularly, the impact of signal coherency on the spectral compression process based on numerical solution of nonlinear Schrödinger equation for signals with different coherence time is numerically studied.

The statistic parameters of radiation are determined by sampling of a large number realizations (N =100), which are solutions of Schrödinger equation. The studies are carried out for signals with the same value of the noise component amplitude ($\sigma = 0.6$) and different coherence time (τ_c).

The impact of coherency on the process efficiency is demonstrated. The study shows that the spectral compression ratio decreases as coherence time of the initial randomly modulated optical signals increases.

In this work, we carried out detailed numerical studies on the process of spectral self-compression for randomly modulated pulses. The spectral self-compression is shown in the fiber with anomalous dispersion, without DDL, when the impact of group velocity dispersion in the fiber stronger than the influence of self-phase modulation.

The maximal value of the spectral self-compression for different values of the nonlinearity parameter and the fiber length (the fiber length is less than 100) is studied. The maximum value of the spectral self-compression ($\Delta = \max(I(\Omega)/I_0(\Omega))$) is ~3, where the nonlinearity parameter and the fiber length equal to 0.4 and 65, correspondingly.

In chapter 4, the properties of a twist nematic with cholesteric mixture spatial light modulator with homeotropic boundary conditions are theoretically characterized. The relevant mode extraction method for the calculation of mask patterns is offered. By the choosing relevant distribution of the electric field voltages (lower than 1V) across the mask with twist nematic with cholesteric mixture spatial light modulator we get very different pulse shaping. The generation of different number of pulses and intensity ratio of them are introduced by altering the amplitude of the electric field voltages distribution. The possibility of the generation of numerous types of wanted waveforms (square pulses, double pulses, triple pulses, multiple pulses, pulses train, symmetric and asymmetric pulses and random pulses) is offered.

In §4.1. and §4.6, the introduction and conclusion are presented.

In §4.2, the characterization of femtosecond pulse is presented.

In §4.3 the grating and lens apparatus action is introduced.

In §4.4 and §4.5 the liquid crystal spatial light modulator and mask pattern design and results are introduced.

We have theoretically characterized the properties of a spatial light modulator (SLM) based on the twist nematic with cholesteric mixture (TNCM) with homeotropic boundary conditions. We developed the relevant mode extraction method for the calculation of mask patterns which can generate multiple pulse sequences with arbitrary relative amplitudes and phases. By the choosing relevant distribution of the electric field voltages (lower than 0.1V) across the mask with TNCM SLM we get very different pulse shaping. By varying the modulation depth (by altering the amplitude of the electric field voltages distribution), we generate different number of pulses and intensity ratio of them. This method could allow us to generate much type of desired waveforms: square pulses, double pulses, triple pulses, multiple pulses, pulses train, symmetric and asymmetric pulses and random pulses.

The amplitude and the phase of the transmitted light trough TNCM with homeotropic boundary conditions in the present polarization combination can be expressed by the complex transmission coefficient

$$T(V) = \frac{\sin^2(\phi\sqrt{1+u^2})}{1+u^2}\exp(-i\frac{\pi u}{2}), \tag{6}$$

where $u(V) = 2L\Delta n(V)$ is the Mauguin parameter, $\Delta n = n_e(V) - n_o$ is the anisotropy of refractive index, L is the thickness of SLM, V is the electric field voltage and the twist angle could be equal to $\pi/2$. It is considered crossed polarizers before and after the SLM. So, u can be changed from 0 (complete transmission) at the moderate voltage to $\sqrt{3}$ (no transmission) without electrical field by changing the voltage applied to the SLM.

Solving the problem of ultrashort pulse transition through the system grating-lens-SLM-lens-grating by the simulated–annealing (SA) computer program it could be find the pulse shaping due to the mask on the twist nematic with cholesteric mixture and with homeotropic boundaries. For calculations, we have considered mask pattern giving the pixel number saw-tooth dependence of Mauguin parameter. This kind of TNCM SLM mask pattern generates the waveform shown in Fig. 7. The input pulse was assumed to be a 21 fs sech^2 pulse with unit intensity. The simulated waveform obtained by SA calculation has a high peak at 132 fs at the positive time direction. There remains, however, a peak at time zero with a comparable intensity, and several small peaks are also apparent at the negative times of -132fs, -264fs and -396fs. These peaks appear due to the coupling between the amplitude and phase of the shaping procedure.

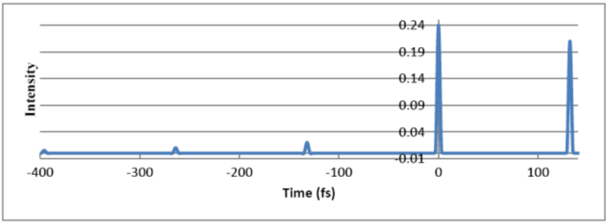

Fig. 7. *Waveform with a single pulse at 132 fs in the positive time region obtained by a simulated annealing calculation. The peak intensity of the input pulse is normalized to unity.*

SUMMARY

Thus, some new peculiarities of spectral compression and self-compression of regular and randomly modulated pulses are studied numerically. The new effective approach of pulse compression is offered. In addition, it is proposed new shaping method of receiving different form of regular and random pulses needed for compression.

The following main results were obtained in the thesis:

1. The physical pattern of soliton spectral self-compression process is studied. The process is realized in the fiber with negative dispersion when the impact of dispersion exceeds the nonlinearity in the SMF (dispersive length is shorter than the nonlinearity length in the fiber).
2. Our research shows that there is an analogue between soliton self-compression and soliton spectral self-compression processes. However, there is no strict periodicity for soliton spectral self-compression process because of incomplete cancellation of the chirp. The frequency dependence on the nonlinearity parameter is studied.
3. Our studies for soliton spectral self-compression processes are carried out for the Gaussian, secant-hyperbolic, and super-Gaussian pulses. The soliton spectral self-compression ratio is approximately 30 times in the range of parameters $R=0.25 \div 1$ and $\zeta \approx 1 \div 20000$. During numerical investigation of soliton spectral self-compression, the research shows that in the case of small values of nonlinearity parameter and the large lengths of fiber, the shape of spectrum is maintained, but the size is not. The changes in the spectrum slow down for fiber lengths of ≈ 11000: because of pulse broadening (≈ 6000 times), the peak of the pulse drops so much that self-phase modulation is practically absent. It is also shown that the quality coefficient of compression reduces as the length of fiber increases. This is caused by the incomplete cancelation of the phase.
4. We study the effects preventing the effective pulse compression and offer an opportunity to improve the process efficiency. The results show that the impact of third-order dispersion in a fiber and dispersive delay line can be compensated by initial pulse

asymmetry since the phase obtained due to the self-phase modulation in the fiber is conditioned by the pulse shape.

5. The pulse compression by asymmetric pulses at the system input gives opportunity to increase the process efficiency to the point where the pulse compression ratio equals to the spectral broadening factor (spectral compression ratio is ≈ 10 for 10 spectral broadening). Pulse compression ratio equaling to ≈ 20 in the case of 26 times spectral broadening is also obtained.
6. We demonstrate the results of detailed numerical studies for spectral compression and spectral self-compression for randomly modulated pulses. The spectral compression efficiency dependence on the coherency of initial pulses is presented. The study shows that the maximum value of spectral self-compression of randomly modulated pulse is ≈ 3 for fiber lengths less than 100.
7. We developed the relevant mode extraction method for the calculation of mask patterns which can generate multiple pulse sequences with arbitrary relative amplitudes and phases. As the mask we used liquid crystal spatial light modulator based on the cell with twist structure of nematic and cholesteric mixture and with homeotropic boundary conditions on the walls.
8. By the choosing relevant distribution of the electric field voltages (≈ 0.1V) across the mask with spatial light modulator we get very different pulse shaping. This approach allows to control of the relative amplitudes of different pulse within pulse train.

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ГРИГОРЯН АРМИНЕ ПАПИНОВНА

ИЗУЧЕНИЕ ЗАКОНОМЕРНОСТИ СПЕКТРАЛЬНОГО СЖАТИЯ И САМОСЖАТИЯ ДЛЯ РЕГУЛЯРНЫХ И СЛУЧАЙНО МОДУЛИРОВАННЫХ ИМПУЛЬСОВ

Диссертация на соискание ученой степени кандидата
физико-математических наук по специальности
01.04.21 – Лазерная физика

ЗАКЛЮЧЕНИЕ

Таким образом, на основе численных исследований выявлены новые особенности спектрального самосжатия для регулярных и случайно модулированных импульсов. При первоначальном распространении импульса в световоде с отрицательной дисперсией под влиянием дисперсии групповых скоростей импульс удлиняется и приобретает отрицательный чирп. Затем, через накопленное влияние фазовой самомодуляции, происходит гашение приобретенного чирпа, что приводит к сжатию спектра.

Исследовано спектральное сжатие для случайно модулированных импульсов. Исследование проводилось для модели аддитивного шума. Проведены исследования спектрального сжатия для случайно модулированных импульсов с разной когерентностью на входе в систему. Характеристики спектрального сжатия были проводены для различных значений параметров компрессора.

Предложен новый эффективный подход к сжатию импульсов.

Кроме того, предлагается новый метод формирования импульсов для получения различной формы регулярных и случайных импульсов, необходимых для сжатия.

В диссертационной работе получены следующие основные результаты:

1. Исследована физическая картина процесса солитонного спектрального самосжатия. Процесс реализуется в световодах с отрицательной дисперсией, когда влияние дисперсии в одномодовом волоконном световоде сильнее влияния нелинейного самовоздействия (дисперсионная длина в световоде меньше длины нелинейного самовоздействия).

2. Исследование показывает, что есть аналог между процессами солитонного самосжатия и солитонного спектрального самосжатия. Однако, по причине неполного гашения чирпа, процесс солитонного спектрального самосжатия не имеет строго

периодического характера. Приведены кривые, показывающие частотную зависимость от параметра нелинейности.

3. Исследование для солитонного спектрального самосжатия было осуществлено для гауссовских, секанс-гиперболических и супер-гауссовских импульсов. Было достигнуто примерно 30-ти кратное солитонно спектральное самосжатие в диапазоне параметров $R=0,25\div 1$ и $\zeta \approx 1\div 20000$. Численные исследования для солитонного спектрального самосжатия показали, что в случае малых значений параметра нелинейности и больших длин световода, форма импульса сохраняется, а размер-нет. Изменения в спектре замедляются для длины световода ≈ 11000: из-за уширения импульса (≈ 6000 раз) пик импульса падает настолько, что фазовая самомодуляция практически отсутствует. Показано также, что коэффициент качества сжатия снижается по мере увеличения длины световода. Это вызвано неполным гашением чирпа.

4. Исследованы эффекты, препятствующие сжатию импульсов, и предложена возможность повышения эффективности процесса. Влияние дисперсии третьего порядка в световоде и в дисперсионной линии задержки можно компенсировать путем асимметрии начального импульса, поскольку в процессе фазовой самомодуляции в световоде фаза задается формой импульса.

5. Импульсное сжатие с помощью асимметричных импульсов дает возможность повысить эффективность процесса до точки, где степень сжатия импульсов равна спектральному удлинению (степень спектрального сжатия равна ≈ 10 при 10-ти кратном спектральном удлинении). Получено также сжатие импульсов ≈ 20 раз при 26-ти кратном спектральном удлинении.

6. Показаны результаты детальных численных исследований спектрального сжатия и спектрального самосжатия для случайно модулированных импульсов. Представлена зависимость эффективности спектрального сжатия от когерентности начальных импульсов. Исследование показывает, что максимальное значение спектрального самосжатия случайно модулированных импульсов составляет ≈ 3 для длин световода менее 100.

7. Развит соответствующий метод извлечения мод для расчета шаблона маски, которая сможет генерировать последовательность множества импульсов с произвольными амплитудами и фазами. В качестве маски служил жидкокристаллический пространственный модулятор света, основанный на ячейке с твист-структурой смеси нематика и холестерика и с гомеотропными граничными условиями на стенках.

8. Выбором соответствующего распределения напряженности (≈ 0.1В) электрического поля по маске с пространственным модулятором света получено многобразие форм импульсов. Этот подход позволяет контролировать относительные амплитуды различных импульсов в ряду.

ԳՐԻԳՈՐՅԱՆ ԱՐՄԻՆԵ ՊԱՊԻՆԻ

ՍՊԵԿՏՐԱԼ ՍԵՂՄԱՆ ԵՎ ԻՆՔՆԱՍԵՂՄԱՆ ՕՐԻՆԱՉԱՓՈՒԹՅՈՒՆՆԵՐԻ ՈՒՍՈՒՄՆԱՍԻՐՈՒԹՅՈՒՆԸ ԿԱՆՈՆԱՎՈՐ ԵՎ ՊԱՏԱՀԱԿԱՆ ՄՈԴՈՒԼԱՑՎԱԾ ԻՄՊՈՒԼՍՆԵՐԻ ՀԱՄԱՐ

Ա.04.21 «Լազերային ֆիզիկա» մասնագիտությամբ
ֆիզիկա-մաթեմատիկական գիտությունների թեկնածուի
գիտական աստիճանի հայցման ատենախոսության

ԱՄՓՈՓՈՒՄ

Այսպիսով՝ թվային հետազոտությունների միջոցով ուսումնասիրվել է սպեկտրային սեղմման և ինքնասեղմման օրինաչափությունները կանոնավոր և պատահական մոդուլացված իմպուլսների համար: Առաջարկվել է նոր, արդյունավետ մոտեցում իմպուլսի սեղմման համար: Առաջարկվել է նաև իմպուլսների ձևավորման նոր մեթոդ՝ կանոնավոր և պատահական իմպուլսների տարբեր տեսքեր ստանալու համար, որոնք անհրաժեշտ են իմպուլսի սեղմման համար:

Ատենախոսական աշխատանքում ստացված հիմնական գիտական արդյունքները ներկայացվում են ստորև:

1. Ուսումնասիրվել է սոլիտոնային սպեկտրային ինքնասեղմման ֆիզիկական պատկերը: Պրոցեսը կատարվում է բացասական դիսպերսիայով միամոդ լուսատարում, երբ լուսատարում դիսպերսիայի ազդեցությունը գերակշռում է ոչ գծայնությանը (լուսատարում դիսպերսային երկարությունը ոչ գծայնության երկարությունից կարճ է):

2. Հետազոտությունների միջոցով ցույց է տրվել, որ սոլիտոնային ինքնասեղմման և սոլիտոնային սպեկտրային ինքնասեղմման միջև գոյություն ունի համանմանություն: Այնուամենայնիվ, չիրպերի ոչ լրիվ մարման պատճառով սոլիտոնային սպեկտրային ինքնասեղմման համար հստակ պարբերականություն չկա: Ուսումնասիրվել է հաճախության կախվածությունը ոչ գծայնության պարամետրից:

3. Սոլիտոնային սպեկտրային ինքնասեղմման համար ուսումնասիրությունները կատարվել են նախնական գաուսյան, սեկանս-հիպերբոլական և սուպերգաուսյան իմպուլսների համար: Ստացվել է 30-անգամյա սոլիտոնային սպեկտրային ինքնասեղմում $R=0.25 \div 1$ և $\zeta \approx 1 \div 20000$ պարամետրերի համար: Սոլիտոնային սպեկտրային ինքնասեղմման թվային հետազոտությունները ցույց են տվել, որ ոչ գծայնության պարամետրի փոքր արժեքների և լուսատարի մեծ երկարությունների դեպքում սպեկտրի տեսքը պահպանվում է, իսկ չափերը՝ փո-

փոխվում: Սպեկտրում փոփոխությունները դանդաղում են լուսատարի ≈ 11000 երկարություններից սկսած. իմպուլսի լայնեցման պատճառով (≈ 6000 անգամ) իմպուլսի պիկը ընկնում է այնքան, որ, կարելի է ասել, փուլային ինքնամոդուլացիան գործնականում բացակայում է: Նաև ցույց է տրված, որ սեղմման որակի գործակիցը ընկնում է լուսատարի երկարությանը զուգընթաց: Դա պայմանավորված է փուլերի ոչ լրիվ մարմամբ:

4. Ուսումնասիրվել են արդյունավետ իմպուլսի սեղմմանը խոչընդոտող երևույթները, և առաջարկվել է հնարավորություն պրոցեսի արդյունավետությունը բարձրացնելու համար: Արդյունքները ցույց են տալիս, որ երրորդ կարգի դիսպերսիայի ազդեցությունը լուսատարում և դիսպերսային հապաղման գծում կարելի է մարել մուտքային իմպուլսի ասիմետրիայի միջոցով, քանի որ լուսատարում փուլային ինքնամոդուլացիայի շնորհիվ ստացված փուլը պայմանավորված է իմպուլսի ձևով:

5. Մուտքային ասիմետրիկ իմպուլսների միջոցով իմպուլսի սեղմումը հնարավորություն է տալիս բարձրացնել պրոցեսի արդյունավետությունն այնքան, որ կարելի է ստանալ սպեկտրի լայնեցմանը հավասար իմպուլսի սեղմում (ստացվել է ≈ 10 անգամյա իմպուլսի սեղմում՝ 10 անգամ սպեկտրի լայնացմամբ): Նաև ստացվել է ≈ 20 անգամ իմպուլսի սեղմում, երբ սպեկտրը եղել է 26 անգամ լայնացված:

6. Բերված են սպեկտրային սեղմման և ինքնասեղմման թվային հետազոտությունների արդյունքներ մուտքային պատահական մոդուլացված իմպուլսների համար: Ներկայացված է սպեկտրային սեղմման արդյունավետության կախվածությունը մուտքային իմպուլսների կոհերենտությունից: Ուսումնասիրությունները ցույց են տվել, որ պատահական մոդուլացված իմպուլսների համար սպեկտրային ինքնասեղմման առավելագույն չափը ≈ 3 է լուսատարի 100-ից փոքր երկարությունների համար:

7. Մշակվել է մոդերի տարանջատման համապատասխան մեթոդ այնպիսի դիմակի հաշվարկման համար, որը կարող է գեներացնել կամայական լայնույթներով և փուլերով իմպուլսների շարք: Որպես դիմակ կիրառվում է հեղուկ բյուրեղային տարածական լուսային մոդուլատոր՝ հիմնված նեմատիկ և խոլեստերիկ խառնուրդով, թվիստ կառուցվածք ունեցող բջջի վրա, որը ունի հոմեոտրոպ սահմանային պայմաններ պատերի վրա:

8. Դիմակի՝ հեղուկ բյուրեղային տարածական լուսային մոդուլատորի մակերեսով, ընտրելով էլեկտրական դաշտի լարման (≈ 0.1V) համապատասխան բաշխում, կարող ենք ստանալ իմպուլսների բազմազան տեսքեր: Այս մոտեցումը թույլ է տալիս իմպուլսների շարքի մեջ կառավարել տարբեր իմպուլսների հարաբերական լայնույթները: