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Arkhipov Rostislav Mikhailovich

Extremely short and unipolar pulses in coherent optical processes

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Scientific consultant:
Dr. Phys. Math. Sc.
Professor,
Academician of the RAS N.N. Rosanov

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Work structure

The text is composed of two main parts.

The first part contains the following: the justification of the relevance of the research, the degree of development of the subject, the scientific novelty, the degree of reliability and the independent expert evaluation of the results, the approval of the work, the statements for the defense and the list of the applicant's publications.

The second part of the work contains the text of the applicant's scientific report, where the main scientific problems are formulated, lists of the most significant results published and the bibliography.

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Part I

Main points

Justification of the relevance

In the natural sciences, optics and the related disciplines connected with using light and electromagnetic radiation in the various spectral ranges have always played an important specific role. Since the works of Newton, which initiated the formation of the scientific world view, light has been a source of information for men not only about the world visible to them, but also about an optical research providing the information about the microcosm invisible to the eyes, the structure of matter, allowing the study of processes taking place in it. The study of electricity and magnetism made it possible to understand the nature of electromagnetic phenomena and begin to put them to practical use. This led to the development of radio engineering and electronics. Optical methods played a crucial role in creating the two most important scientific theories in modern physics. They are quantum mechanics and relativity. There are countless applications of optical devices in the fields of chemistry, biology, medicine and many other areas. The complex of scientific results obtained has provided the basis for the extremely rapid development of information and communication, which in a short historical period has already radically changed and will continue to change the everyday life of people, their economic, cultural and social relations.

At all stages in the development of physics, there have always been problems with the production of electromagnetic radiation pulses having the shortest duration. The interest in shortening radiation pulses has been maintained for two main reasons. Firstly, short pulses of light made it possible to study a wide variety of processes in detail. It was possible to take instantaneous pictures of the development of rapidly occurring phenomena. The way was paved from mile- and microsecond pulses, which created non-laser light sources, to femto- and attosecond durations, which were achieved using lasers. Secondly it is the study how light affects matter. Laser radiation is highly directional and monochromatic in nature. By accumulating energy in the amplifying medium of the laser, it was possible to highlight it within extremely short time in the Q-switching and mode-locking regimes. While focusing the laser radiation, it was possible to have light fields with very high field strengths. This opened up a new field in optics called nonlinear optics.

A nanosecond pulse from a typical solid-state laser operating in Q-switching regime contains nearly a million of field oscillations. Picosecond laser pulses achieved 40 years ago with the help of mode-locking contained one thousand of periods. Light pulses contain dozens of oscillations in today's typical femtosecond laser systems. However they are still long durations. The shortest values are from two to one and a half cycle range. Such pulses are extremely short because they contain one oscillating cycle.

It's worth mentioning that the works carried out in the mid-1980s by Gerard Mourou and Donna Strickland played a great role in the developing physics. They were awarded the Nobel Prize in 2018 as "a method for generating high-intensity, ultrashort optical pulses".

We should note that the term "extremely short" used in our work and in the title of this thesis makes sense in relation to a range of wavelengths. For example, a single cycle pulse in the infrared (IR) range will be longer than a pulse in the visible range. What can be done to shorten the duration of an extremely short pulse? Of course, one can try to "compress" the pulse. It means to shift it to a shorter wavelength region of the spectrum. For example, a femtosecond pulse will be shifted into the attosecond range, i.e. from the visible to the ultraviolet (UV).

There is another way. An extremely short one-cycle pulse can be halved immediately by removing half a field oscillation period. Such a pulse seems very unusual. It does not resemble the usual light pulses consisting of several oscillation cycles. How is this pulse radically different from the known ones? Can it be obtained and what unusual properties will it have? How can it be used?

In fact, unipolar light pulses are not mentioned in any modern textbook on optics and laser physics. Traditional light sources such as lasers, for example, do not produce such radiation. In quantum emitters, light emission occurs at transitions between discrete atomic and molecular (or solid) energy levels as a result of processes with finite and rather large atomic timescales. From the point of view of quantum mechanics, the radiation processes results from a quantum system remaining in a superposition state. In case of dipole radiation, the system behaves like an oscillating dipole that goes through many oscillatory cycles. Oscillations lead to emission and energy loss as the system moves from a higher to a lower energy state. Such an interpretation of the transition between energy levels is used in the semi-classical theory of the interaction of light with matter when describing the processes of the coherent interaction.

The absorption of light between levels in a quantum system is also not a one-step process from this point of view. For the process to occur effectively, the emitting frequency must coincide with or be close to the transition frequency in the quantum system. The process of stimulated emission in a laser is also not instantaneous. Thus, we deal with expressed resonance processes, in which optical radiation in conditions of resonances swings "oscillators" slowly enough in time scales of atomic systems.

The invention of intense monochromatic laser sources has made it possible to reduce the number of field cycles in a light pulse. However it has not been possible to reduce them to single cycles or half-cycles. It is thought that half-cycle pulses are almost impossible to implement practically in optical and related fields.

On the other hand, according to electrodynamics, there are no fundamental prohibitions against the existence of unipolar electromagnetic radiation. It should be noted that unipolar pulses are used in so-called ultra-wideband radiolocation in radio technology, where the wavelengths of electromagnetic radiation are much longer than in optical bands. Radar antennas emit short unipolar pulses, unlike conventional locators where the pulses are filled with carrier frequency.

Taking into consideration the electromagnetic nature of the radio, visible light and other spectral regions, unipolar pulses are possible in the relevant bands. The problems here lie in the sources of such radiation. In optics, as we have seen, the radiation from atoms and molecules is generated by resonance processes. As a result, it is thought that it is impossible to obtain pulses with a duration of half the period of the oscillations in the optical and adjacent regions. From the point of view of Maxwell's equations, to generate such pulses we need sources producing unidirectional current pulses of duration comparable to the field oscillation period in the given region. It seems nearly impossible to realize such a process, which implies instantaneous acceleration and deceleration of charges.

However, it is only at first sight that such processes cannot be carried out using modern techniques. The possibility of obtaining unipolar and quasi-unipolar pulses and controlling their shape have been demonstrated in recent articles and research by the author and co-authors. In particular the possibility of obtaining unipolar pulses with unusual shapes, such as rectangular and triangular, in the optical and terahertz frequency range was demonstrated. The possibility of their integration and differentiation was also presented.

Unipolar pulses allow fast unidirectional transfer of a mechanical pulse to both free and bound charges in an atom or a molecule for a short time interval. This opens new perspectives to apply such pulses for ultrafast control of properties of quantum systems, charge acceleration, holography with ultra-high time resolution. Finally, the standard theories of the interaction of such radiation with matter (Keldysh theory, etc.) become inapplicable and require revision when the duration of the half-cycle pulse becomes shorter than the orbital period of the electron along the Bohr orbit in the hydrogen atom.

The above makes it actual to study both the methods of generating unipolar subcycle pulses and their interaction with quantum systems, which is the subject of the present study. At the same time the interaction with quantum systems takes place within the framework of their coherent interaction. Therefore, it is necessary to consider the finite time of the polarization decay of quantum transitions in the medium, which is longer than the duration of the radiation pulses.

Degree of the theme development

Work on the material covered by this thesis began in 2011 when the applicant was working on his PhD thesis entitled "Modelling of Mode-Locking Regimes in Lasers". It was singled out that there is a limitation in pulse duration and a repetition period in passively mode-locked lasers, which use monolithic semiconductor structures of quantum dots as amplifying and absorbing media to modulate losses in the cavity. One part of such a structure is directly biased and acts as an amplifying medium. The other part is reverse biased and acts as a saturable absorbing medium. This type of laser is compact, with a cavity length of only a few millimetres and a pulse repetition period of dozens of picoseconds. The repetition rate is from dozens to hundreds of GHz. The amplifier and the absorber have similar energy structures. Basically their quantum dot parameters can be varied to provide generation in different spectral ranges from visible to IR.

However, the theoretically achievable pulse duration was limited by the theoretical considerations with the only loss-modulating mechanism based on saturable absorption. It meant researchers limited themselves and excluded ways to shorten pulses. In such approximations, absorbing and amplifying media interacted with radiation without considering the possibility of realizing the coherent character of the interaction with light. Thus, the theoretical description was limited to pulse durations longer than the polarization relaxation time T_2. The T_2 time ranged from hundreds of femtoseconds to several picoseconds in such structures at room temperature. Therefore, the theoretical models for the description of such lasers excluded the possibility of reducing the pulse duration below this limit.

The author has been actively involved in developing the idea that it is possible to overcome the above mentioned limitations imposed by absorber and amplifier linewidths on pulse duration in the regime where light interactions are coherent with them. In fact, the self-induced transparency (SIT) effect discovered by McCall and Hahn occurs when the pulse duration is short, less than the time T_2, i.e. the spectrum of such a pulse is broader than the linewidth of the absorber.

This idea did not find much support in the scientific community. The main arguments against it were as follows. For example, the experimental difficulties accompanying the observation of SIT effect in different media, which did not allow to use it in the intracavity variant. There were also methodological difficulties for experimental researchers in relation to the understanding of the mechanisms of coherent interaction of radiation with matter. In this case the spectrum of the pulse appears to be broader than the absorption spectrum of the absorber. Finally, the lack of any successful experimental work at that time did not help develop researchers' interest in this subject. These problems are reflected in the recent review in the journal "Quantum Electronics" [65a] (In the following, the letter "a" after the publication number means that this reference is included in the list of publications of the author of the thesis. Otherwise, the cited publication is included in the general list of references).

Only a few theoretical papers attempted to provide a convincing theoretical justification for such mode-locking in lasers at that time. The work of V.V. Kozlov [101] should be mentioned here. He considered a homogeneous mixture of a two-level absorber and an amplifier, which modelled a real laser, and showed the possibility of a pulse with a duration shorter than the time T_2 due to the formation of a 2π SIT pulse in the absorber and a π pulse in the amplifier at a twofold difference of the dipole moments of the transition in the absorber and the amplifier. Coherent mode-locking (CML), as the title of his paper, became a common term in the scientific literature for this type of mode-locking.

In addition to the optimistic conclusion about the removal of the duration constraint, another conclusion was very unpleasant. Prof. V.V. Kozlov claimed that such a mode-locking cannot be self-starting. To develop the generation in the CML regime an additional laser is needed, which would produce a seed pulse for the CML to appear. Such a conclusion would require a significant experimental complication. If we compare the titanium-sapphire lasers being already available and not self-starting which can generate short pulses of several oscillations cycles without an external initiating laser simply by modulating the resonator parameters, the CML was no longer of great interest to researchers.

The first step taken by the applicant was the theoretical demonstration of the self-starting character of the CML, not in the unusial situation of a mixed absorbing and amplifying medium, but in the case of a real laser, where the absorber and the amplifier have finite dimensions and are separated in space in the ring and the linear cavity of finite length [6a, 10a, 11a]. A diagram technique based on the area theorem of McCall and Hahn [11a, 69a] was used to describe the self-starting of CML and its stability in a laser with an absorber and an amplifier of finite length. The results of this research are included in the thesis. The results of these publications gave optimism for further studies, including experimental studies in this field.

Simultaneously with the overcoming of the limitations on pulse duration imposed by the time T_2 and the possibility to approach a single-cycle pulse in a laser with the CML regime, the question of further reduction of pulse duration has arisen.

The idea of further shortening of the pulse duration came down to one oscillating period where a half-wave removing happens. This idea was even more controversial than the possibility of using lasers to produce radiation with a spectrum wider than the gain linewidth. In fact, such radiation was not presented in textbooks and monographs on nonlinear optics and laser physics. Nevertheless, there were some rarely-cited and little-known papers mentioning such unipolar field bursts in one context or another. For example, the old work of Bülow and Ahmad on the unipolar SIT soliton [19], also the works of S.V. Sazonov, A.I. Maimistov, E.G. Bessonov, E.M. Belenov and co-authors [24-29] and the works of N.N. Rosanov [22-23] from the beginning of the 2000s, in which the rule of the conservation of the pulse area was considered. The applicant turned to N.N. Rosanov and joined his research in this area.

It should be noted that 10 years ago the works on unipolar pulses were perceived critically. They were treated rather as formal mathematical works. In addition, not only the possibility of the existence of unipolar pulses, but also the possibility of their propagation was in question. All these issues are discussed in detail in the review [65a]. It was possible not only to prove that the existence of unipolar pulses does not contradict any known physical principles, but also to show what conditions must be fulfilled for their generation thanks to the work of the applicant in co-authorship with N.N. Rosanov.

It was shown for the first time that the electric area of short light pulses is an important property of these pulses in addition to their spectral, energy and polarization parameters. The electric area is governed by the law of the conservation of electric area. The first formulation of this law was by Prof. N.N. Rosanov. In co-authorship with N.N. Rosanov, fundamental results were obtained for the first time. New conservation laws in the electrodynamics of dissipative media were demonstrated in optical problems of the propagation of subcycle and unipolar pulses [44a,121a]. The fundamental importance of the conservation laws was demonstrated for the first time using the example of a mental experiment to observe the optical Aharonov-Bohm effect [60a].

It was shown that the effect of subcycle and unipolar pulses on media is determined by a new physical quantity, the pulse electrical area, rather than pulse energy ([45a, 79a, 86a, 91a, 108a, 110a, 119a, 126a]). A new quantity in the physics of the interaction of light with matter is the "atomic scale" of the electric area of the pulse, which characterizes the degree of influence of the extremely short pulse on quantum systems [79a]. The concept of "electric pulse interference" was introduced too [81a, 92a, 111a].

At present unipolar pulses are being discussed in the works of more authors and their possible use is being studied in several scientific groups. There has been a change of attitude towards this work. It is due to the efforts of the scientific team in which the applicant is a member. The publications on this topic have increased significantly in recent years as well as the invited talks at conferences.

In 2021, the project "Single-cycle, subcycle and unipolar light: generation and applications" was supported by Russian Science Foundation grant, in which the applicant is a supervisor. Since 2022, at the well-known conference "All-Russian School Seminar "Wave Phenomena: Physics and Applications named after Professor A.P. Sukhorukov", held at the Lomonosov Moscow State University, a separate section "Optics of Extremely Short Pulses" has been organized with the direct participation of the applicant. In this section the results of the latest research in the field of unipolar pulses were presented. All these ongoing studies have led to developing and creating a new direction in modern physics called "unipolar and subcycle light optics" [98a]. This is a rapidly developing area of modern physics.

Degree of reliability and independent expert assessment of results

The reliability of the applicant's results is ensured by the use of modern equipment in the performance of the experiments, by their multiple repetition and by the performance of control experiments. In theoretical studies, the numerical codes have been thoroughly checked. The numerical calculations carried out in mathematical modelling have been compared with the values obtained analytically for particular cases. Analytical calculations have been verified by numerical modelling.

The results of this work were published in 133 peer-reviewed papers, more than half of them in the first and second quartile journals. The full list of publications is presented below.

Approbation of work

The presented results were honored with invited lectures and presentations at international and all-Russian scientific schools and conferences (more than 6 lectures and invited talks), as well as more than 30 oral presentations at international conferences.

The invited talks and lectures have been held at the following events:

- XXXIV All-Russian School Seminar "Wave Phenomena: Physics and Applications" named after Professor A.P. Sukhorukov (“Waves-2023”), from 28 May to 2 June 2023, invited lecture "Peculiarities of radiation of a solitary polarization pulse moving with light and superluminal velocities" (http://waves.phys.msu.ru/).

- II Congress of Young Scientists in Sochi, 1-3 December 2022 at the Sirius Park of Science and Art, invited talk at the Russian Science Foundations Scholars School "Light pulses of extremely short duration: recent results and perspectives" (https://rscf.ru/news/found/bolee-250-pobediteley-prezidentskoy-programmy-rnf-prinyali-uchastie-v-shkole-fonda-na-kongresse-molo/).

- Invited talk "Single-cycle and unipolar half-cycle light pulses". "XXXIII All-Russian School Seminar "Wave Phenomena: Physics and Applications" named after A.P. Sukhorukov ("Waves-2022"), 5-10 June 2022.

-XVII All-Russian School Seminar "Wave Phenomena in Inhomogeneous Media" named after A.P. Sukhorukov ("Waves-2020"), 23-28 August 2020, Lomonosov Moscow State University, online format, invited paper - "Holography in the absence of mutual coherence between reference and subject beams" (http://waves.phys.msu.ru/files/docs/2020/Waves20Program.pdf).

- XX International Conference “Foundations & Advances in Nonlinear Science September”, 28 - 2 October 2020, Minsk 2020, online format, invited paper - "Self-induced transparency mode-locking: theoretical analysis, experimental observation and single-cycle pulse generation" (http://fans.j-npcs.org/programme.pdf).

- The 19th International Conference on Laser Optics ICLO 2020, St. Petersburg, Russia, 2-6 November 2020, online format. "Self-induced transparency mode-locking: towards single-cycle pulses"- Invited talk.

- XII international conference "Fundamental problems of optics - 2020", Saint-petersburg, 19-23 October 2020, "Experimental extreme events in generation of titanium-sapphire lasers with coherent absorber" - invited talk.

- 4th Smart Nanomaterials: Advances, Innovations and Applications Conference, 7-10 December 2021, Paris, France, online format. Invited talk: "Advances in Optics of Subcycle and Unipolar Pulses".

- Oral presentation at the Scientific Seminar at the Institute of Spectroscopy of the Russian Academy of Sciences (ISAN), Troitsk. The title of the talk is "Unipolar, Subcycle and Unipolar Light: Current State and Prospects", 22 April 2021. (https://isan.troitsk.ru/novosti/novosti/novost-2021/nauchnyij-seminar-isan-(22-aprelya-2021).html).

This report is timed to award the applicant with the Professor V.S. Letokhov Medal of the Russian Optical Society, named after D.S. Rozhdestvensky in November 2020. It is the medal for young scientists aged under 35 for pioneering work in laser physics and spectroscopy and their applications.

Evaluation of the results by independent experts

The results of the thesis have been awarded with the following prestigious prizes for scientific achievements in the field of optics and physics.

1. 2023: the first prize named after Y.I. Ostrovsky of the Ioffe Institute (together with M.V. Arkhipov, A.V. Pakhomov and N.N. Rosanov) for the best scientific works in the field of

optical holography and interferometry for the paper "Interferometry and holography with finite time resolution without coherence of reference and object beams" (http://ostrovsky-award.ru/novosti/).

2. 2023: the paper "Self-stopping of extremely short light pulses in a homogeneous medium" was awarded with a diploma of the Russian Academy of Sciences and noted by the Council of Experts of the Russian Academy of Sciences as one of the most important results in the field of optics and photonics in 2022 during a special scientific section at the 17th International Specialized Exhibition of Laser, Optical and Optoelectronic Technologies (www. photonics-expo.ru). photonics-expo.ru) (https://clck.ru/3533or), and also among the achievements recognized by Ioffe Institute (https://new.ioffe.ru/ru/nauka/rezultaty/dostizheniya/205/).

3. 2020: L. Euler Prize of the Government of St. Petersburg and the St. Petersburg Scientific Centre of the Russian Academy of Sciences for outstanding scientific achievements in the field of science and technology, nomination "Natural and Technical Sciences", for a cycle of work on the search for new ways of generating single-cycle and unipolar extremely short light pulses.

4. 2020: Prof. V.S. Letokhov Medal of D.S. Rozhdestvensky Optical Society for pioneering work in laser physics, spectroscopy and their applications for young scientists for the cycle of works "Unipolar, subcycle and single-cycle light".

5. 2020: the first Y.I. Ostrovsky Prize of Ioffe Institute (together with M.V. Arkhipov, A.V. Pakhomov and N.N. Rosanov) for the best scientific work in the field of optical holography and interferometry for the paper "Interference of polarization waves with extremely short light pulses for ultrafast creation and erasure of light-induced gratings in resonant media" (http://ostrovsky-award.ru/novosti/).

The presented results were financially supported by grants from the Russian Foundation for Basic Research, the Russian Science Foundation and Theoretical Physics and Mathematics Advancement Foundation “BASIS". The results were reviewed by experts from scientific foundations at the stage of grant award and annual reports. In the following grants the applicant was a supervisor:

1. Theoretical Physics and Mathematics Advancement Foundation “BASIS", "Development of the theory of coherent mode-locking in lasers" grant "Leading Scientist (Theoretical Physics)", supervisor, 2022-present.

2. Russian Science Foundation grant 21-72-10028 "Single-cycle, subcycle and unipolar light: generation and applications", supervisor, 2021-2024.

3. Russian Science Foundation grant 19-72-00012 "Self-induced transparency based generation of extremely short optical pulses in lasers and their application for ultrafast coherent control of the parameters of resonant media", supervisor, 2019-2021.

4. RFBR Grant "Stability" 20-32-70049 "Obtaining unipolar and quasiunipolar sub-cycle pulses in the optical and terahertz frequency range: theory and experiment", 2019-2021 - supervisor.

Practical importance

The results have fundamental and applied significance. Emphasizing the main point of the above mentioned statements for the defense and points of the novelty section, it can be said that the results have practical significance on the fundamental and applied level.

At the level of fundamental significance, the main point is that the results obtained prove the existence and demonstrate the possibilities of unipolar and subcycle pulses. They show the differences between the influence of unipolar pulses on quantum objects and of bipolar pulses with a few and many cycles, and the possibilities of their ultrafast influence on quantum systems. The results demonstrate the value of the electric area of the pulse, the role of the laws of electric area conservation. The effect of self-stopping light is predicted.

The results obtained show the prospects of the CML regime for the creation of compact laser sources of extremely short pulses with an ultra-high repetition rate. The first experimental realization of CML in lasers plays an important role. The possibility of obtaining generation with a duration of one cycle of field oscillations in the CML regime is substantiated. Schemes for the self-compression of single cycle pulses have been proposed. A method for the generation of non-harmonic pulses by the emission of a "stopped polarization" pulse is proposed. A scheme for ultrafast holographic recording of information about an object with the help of unipolar light is presented. You can also see other results described above in the statements for defense and in the scientific report below.

Goals and objectives of the research

Intensive theoretical and experimental studies which describe various methods of obtaining extremely short pulses (ESPs) with durations of the order of the period of the electromagnetic wave in various parts of the spectrum from terahertz to ultraviolet and X-ray are currently being carried out. The demand and relevance of such work is related to the unique opportunities for the researchers to use such pulses in various fields of science and modern technologies. Firstly such ESPs are a unique tool to study and control ultrafast processes in matter due to their short duration. Such pulses can follow ultra-high repetition rates up to dozens of THz. This allows to use such pulses for ultra-fast data transmission and processing. Secondly due to the short duration of such low-energy pulses while focusing, it is possible to achieve electric field strengths exceeding the intra-atomic value (~ 10^9 V/cm). In such a regime of extreme nonlinear optics, new possibilities are opened for generating extremely short pulses of coherent X-rays, controlling nuclear reactions, observing nonlinear effects of quantum electrodynamics, etc. Studies of the interaction of ESPs with various media are not only of applied but also of fundamental importance. They allow us to investigate various processes in matter and understand their nature more deeply.

The transition to single-cycle and subcycle pulses in particular unipolar pulses containing a half-wave of the field is the next step in reducing pulse duration. Currently the production of unipolar pulses has been a very difficult task in practice. Firstly in the optical and adjacent range there are no real sources of unipolar pulses. Secondly there is a lack of understanding of the interaction of unipolar pulses with matter.

The aim of this research was to develop new approaches for the generation of extremely short unipolar and subcycle pulses and study their interaction with matter.

Statements for defense

(In this paragraph, references from the list of the candidate's works are given in each statement, then marked with the symbol "a" after the reference number and in the rest of the text of the thesis.)

1. The existence of quasi-unipolar subcycle pulses with non-zero electric area is not in contradiction with Maxwell's equations. Non-zero electric area obeys the conservation of the electric area rule in absorbing and amplifying media [25a, 26a, 34a, 39a, 44a, 48a, 65a, 75a].

2. For quantum systems, including atoms, molecules, and nanoscale structures, the probability of excitation and ionization by an extremely short pulse which duration is less than the specific time associated with the energy of the particle in the ground is determined by the ratio of the electric area of the pulse to its atomic scale $\hbar/ea$ [79a, 86a, 88a, 119a, 121a, 126a, 131a]. Here $\hbar$ is the reduced Planck constant, e is the electron charge and a is the characteristic size of the quantum system. When several short unipolar pulses are applied to a quantum system, their overall effect is determined by the interference of the electrical areas of the pulses [81a, 92a, 111a]. A sequence of non-resonant short unipolar pulses selectively excites a quantum system despite the non-resonant nature of their interaction with the medium [56a, 59a, 67a].

3. When unipolar pulses are used in interferometry and holography, extreme temporal resolution is achieved. Coherence between the reference and the subject wave is not required in contrast to the well-known methods of interferometry and holography [62a]. In an extended resonant medium, short unipolar pulses allow the generation of population gratings with controlled spatial period and erasure them [18a, 19a, 29a, 30a, 31a, 33a, 36a, 43a, 50a, 56a, 59a, 66a, 67a, 70a, 76a, 80a].

4. Unipolar pulses cannot produce the optical Aharonov-Bohm effect in the Aharonov-Bohm electron interferometer. This is due to the vortex-free nature of the electric area vector field [60a].

5. The unipolarity of the pulses is registered experimentally and quantitatively in the radiation pulses obtained by the optical rectification of femtosecond pulses in a lithium niobate crystal and in the filamentary radiation pulses generated by high-power femtosecond pulses

in water. The unipolarity of the radiation obtained in the above purely optical experiments is registered by radio-technical means and by processing of the time dependence of the field strength of terahertz pulses registered by the standard electro-optical method [87a].

6. The diagrammatic method of describing coherent mode locking (CML) allows us to find the limiting cycles in the laser, analyze their stability and predict the dynamic modes in the laser system without complex calculations [11a,69a]. In the CML regime, there are self-starting scenarios of the mode evolution that do not require any external initiation [6a,10a,11a,69a,98a]. CML allows the generation of single cycle pulses with the terahertz repetition rate [89a].

7. In the case of lasers with an absorber and an amplifier, there are scaling rules that establish the correspondence between the characteristics of the radiation when the main parameters of the system are varied together: the length of the cavity and the medium, the relaxation times of the medium [69a, 89a].

8. Coherent mode locking (CML) is experimentally achieved in the Rhodamine 6G dye laser with the absorber as a molecular iodine vapor [7a,40a]. In the titanium-sapphire laser with rubidium and cesium vapors as absorbers, CML is also achieved experimentally. In the CML regime, the pulse duration decreases with the increase of the generation power [47a, 49a, 51a, 52a, 55a].

9. Extreme events occur in the radiation of a titanium-sapphire laser with an absorber - rubidium or cesium vapors. These are extremely rare short bursts with an intensity more than three times higher than the average level [84a].

10. In an optically dense resonant two-level medium, single-cycle pulses exhibit self-compression under certain conditions, i.e. their duration decreases and the cycle period decreases proportionally [68a,73a]. In such media, a single and few-cycle pulse can slow down, stop and turn into a stationary oscillon [93a].

Main scientific results

(This section is formatted according to the current rules for formatting dissertations at St. Petersburg State University. Cited publications in first and second quartile journals, Q1 and Q2, are highlighted in bold)

1. For the first time, the possibility of obtaining unipolar and subcycle pulses with non-zero electric area has been systematically investigated. Schemes for their realization have been proposed [**25a**, **26a**, 34a, 48a, 65a, 75a, **117a**, **118a**]. The rule of conservation the electric area in the tasks of propagating short unipolar pulses in resonant media, both absorbed and amplified, is confirmed [**39a**, **44a**, **75a**, 121a]. Experimental evidence for the unipolarity of radiation is given and methods for detecting it are proposed [**87a**].

2. Methods of obtaining unipolar subcycle pulses of non-harmonic form with the superradiation of "stopped polarization" are proposed [14a, **15a**, **16a**, **17a**, **20a**, **41a**, **46a**, **57a**, **71a**, **94a**, **95a**, 103a, 118a, 127a].

3. In the physics of the interaction of ultrashort pulses with matter, the quantity "atomic scale" of the electric area of a short unipolar pulse is introduced and its quantitative definition is given [**79a**, **86a**, 88a, **91a**, **119a**, 121a, 126a, 131a].

4. The concept of "electric area interference" is introduced in the physics of electromagnetic radiation interaction with quantum systems [**81a**, 92a, 111a].

5. For short unipolar pulses the probability of excitation and ionization in quantum systems is determined by the electrical area of the pulse but not by its energy [**45a**, **64a**, 79a, **86a**, 88a, **110a**, **119a**, **120a**, 121a, 126a, 131a]. The characteristics of the radiation of extended media from such systems are considered in articles [**9a**, **82a**].

6. The sequence of short subcycle pulses can have a selective effect on resonant quantum transitions, despite the nonresonant nature of their effect on quantum objects [56a, **59a**, 67a].

7. Holography is possible with the use of incoherent subject and reference beams [**62a**]. The requirement of coherence between the reference wave and the subject wave, which is considered to be unconditional in holography, is not necessary if ultra-short unipolar pulses are used.

8. The impossibility of the observation of the optical Aharonov-Bohm effect with unipolar subcycle pulses is demonstrated [**60a**].

9. Schemes for integrating and differentiating the time dependence of the electric field strength of ultrashort pulses are proposed [**77a**, 83a].

10. Coherent mode-locking in lasers with a coherent absorber is experimentally realized [**7a**, **40a**, **47a**, **49a**, 51a, 52a, **55a**].

11. The self-starting character of the coherent mode-locking is theoretically predicted and experimentally demonstrated [**6a**, **10a**, **11a**, **47a, 49a**, 51a, 52a, 55a, **99a**, **112a**, **123a**], the features of controlling mode-locked radiation pulses in a medium without pronounced coherence are studied in [**8a, 12a, 21a, 63a**].

12. Extreme events, soliton gas and soliton molecules are found in the system of dissipative solitons of self-induced transparency [**22a**, 84a].

13. The diagrammatic method is used to describe the coherent mode-locking (CML) in lasers due to the phenomenon of self-induced transparency in an absorbing medium [**11a**, **69a**]. The limit cycles in the system are found. Their stability is analyzed.

14. The generation of single-cycle pulses with terahertz repetition rate due to the CML in a two-section ultrashort cavity laser is predicted [**89a**].

15. Creation, erasure and ultrafast control of population difference gratings are shown in a resonant medium by a sequence of subcycle pulses interacting coherently with the medium and not overlapping in the resonant medium [18a, **19a**, **29a**, **30a**, **31a**, **50a**, **70a**, 76a, **80a**, **101a**, **116a**, **132a**].

16. A single-cycle pulse compressor based on an optically dense resonant medium is considered [**73a**].

17. The effect of light self-stopping in a homogeneous resonant medium is theoretically predicted for a few-cycle pulse [**93a**].

List of publications containing the main applicant's scientific results

The results of this work have been published in 133 articles in high-impact journals indexed in the Web of Science, Scopus and RISC databases [1a-133a] and in one chapter of a collective monograph [134a]. They are also summarized in more than 8 review articles in the reference list below. In most of the publications, the applicant is the first or last author, which emphasizes his decisive role in the research carried out. In sections of a scientific report, the literature cited is taken from the general list which includes the applicant's works; this list is duplicated by references to works from the list of the applicant's works in the list below, with the addition of the letter 'a' after the reference number.

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Part II

Scientific report

Introduction

The emission of quantum systems (atoms, molecules, nanostructures, solids) in the process of spontaneous emission or its stimulated emission in case of laser sources has the form of multicycle harmonic waves of electric and magnetic field strength. The time integral of the electric field strength at any point in space along the path of such

$$S_E(x,y,z,t) = \int E(x,y,z,t)dt, \qquad (1)$$

light is always zero [1].

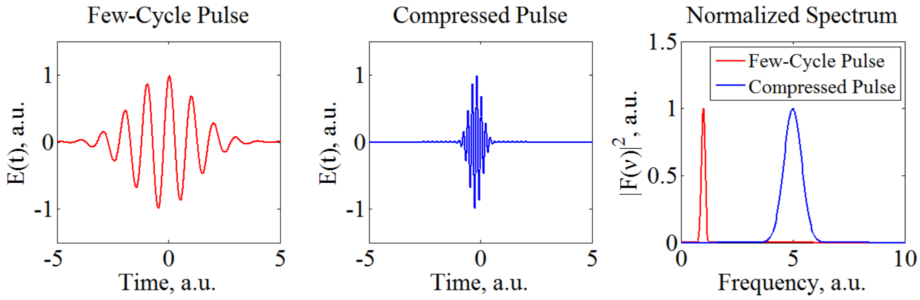
The emission of quantum systems (atoms, molecules, nanostructures, solids) in the process of spontaneous emission or its stimulated emission in case of laser sources has the form of multicycle harmonic waves of electric and magnetic field strength. The time integral of the electric field strength at any point in space along the path of such light is always zero.

A situation in which the value of this integral would be different from zero in the absence of static fields from charges seems impossible to realize. There is no mention of light fields with non-harmonic dependence leading to a non-zero value of this integral in classical and modern textbooks on optics. The exception seems to be the classic textbook by J. Jackson "Classical Electrodynamics", where the electric area of the pulse is called the "time integral of the fields" [2]. The possibility of field pulses with non-zero electric area during relativistic motion of a charge was shown. The possibility of generating a sequence of pulses with a characteristic subcycle shape in synchrotron radiation is also shown in classical reviews and monographs by Academician V.L. Ginzburg and co-authors [3-5], published in the middle of the last century.

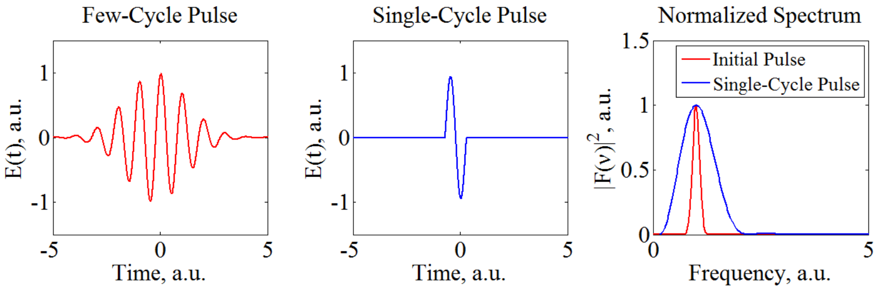
The reason for the apparent impossibility of pulses with a non-zero electrical area is connected with the fact that at present there are no sources of radiation with a non-zero electrical area in the visible range and in the adjacent spectral ranges. From our point of view, this situation has led to the widespread opinion among physicists that such waves are impossible for electromagnetic fields.

In the last few years, pulses of up to one oscillation cycle have become available in the practice of physical experiments [6-12]. In some studies, pulses have been obtained that have a pronounced intense burst of the field of one polarity and small amplitude oscillations at the leading and trailing edges of the opposite polarity [13-18]. These oscillations compensate for the short unipolar burst and reset the integral (1). Situations like these make us wonder: Is it possible to leave only a burst of one polarity in the radiation? However, such radiation will have a non-zero electrical area, which, as we have already mentioned, raises certain doubts. Nevertheless, some isolated works appeared in different years. They were of a mathematical nature and not widely recognized. Figure 1 illustrates the transformations in the form of electromagnetic pulses that occur when their duration is reduced. An example of such work is the 1971 paper by Bullough and Ahmad [19], which theoretically studied the effect of self-induced transparency in a two-level system under the action of a half-wave with a non-zero integral of the electric field strength over time. In the Russian literature, N.G. Bessonov considered the problem of fields with a non-zero integral of the field strength over time in connection with the non-uniform motion of a charged particle [20, 21]. The name that N.G. Bessonov gave to such impulses, "strange waves", expresses the unusual nature of these pulses.

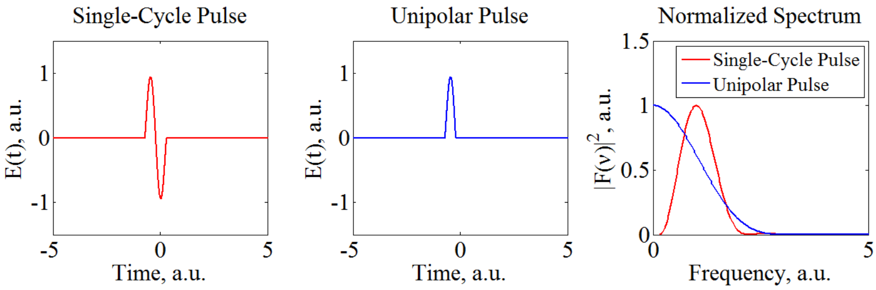
In the first decade of the 21st century, N.N. Rosanov was one of the first to deal with the problem of waves with a non-zero integral of the field strength [22]. (A review of earlier work is given in [23-29]). In [22] he discovered that, under certain conditions, the value of the mentioned integral (1) obeys rules that can be considered as conservation laws. The term "electrical pulse area" was introduced. The integral (1) is thus associated with the physical conservation law. It therefore has a special and important physical meaning. It does not only reflect the fact of belonging to unipolar or bipolar radiation.



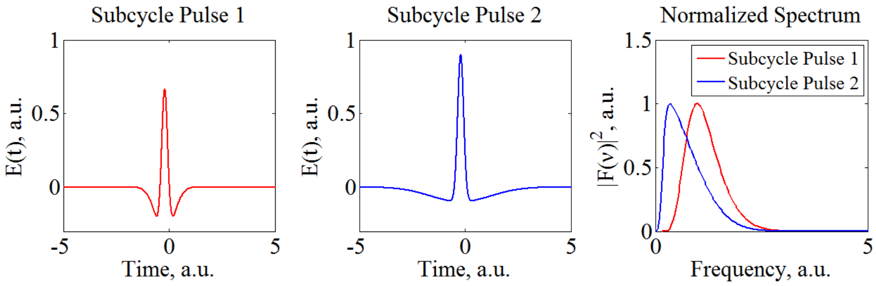
A) The duration is reduced by increasing the carrier frequency while maintaining the number of field oscillation cycles in the pulse. In this case, the radiation spectrum shifts to the short wave region.



B) Reduction of the duration by reduction of the number of cycles to one. The pulse spectrum is broadened. Its maximum does not shift.



C) Elimination of one of the field half-waves from a single-cycle pulse. The pulse becomes a half-cycle (the term subcycle is also used). A zero-frequency component appears in the spectrum. The electrical area of the pulse is not zero.



D) A subcycle pulse is not necessarily unipolar. It may have long tails of low amplitude. Because of their presence, the electrical area is zero. And there is no spectrum component at zero frequency.

Figure 1. Possibilities for the modification of the shape of a pulse and the reduction of its duration. The pulses are bipolar in situations A and B. In case C the pulse is unipolar. In case D it is quasi-unipolar. The term "quasi-unipolar" is used to indicate the presence of a short burst of high amplitude field of one polarity that makes the pulse appear unipolar-like, but due to the presence of tails it is not unipolar.

On the existence of unipolar pulses in optics

The above works have not been the focus of attention of the scientific community. They were the cause of misunderstandings and were regarded as formal mathematical calculations without any significant physical meaning or practical significance. Moreover, the impossibility of the existence of such radiation, its generation and the propagation of such pulses in space was considered (see, for example, [30-31] and the cited literature).

In order to understand and solve the problem of unipolar radiation, the following aspects need to be emphasized.

First. A rigorous justification within the framework of classical electrodynamics for the possibility of the existence of unipolar pulses and a description of their propagation in space is necessary.

Second. To propose principles for obtaining such pulses.

Third. The practical aspect of unipolarity. Here it is important to understand that radiation cannot be unipolar according to the strict mathematical definition of unipolarity given by Eq (1). The integral is zero. However, the radiation itself can take the form of short bursts of field strength in opposite directions, with, for example, a large time interval between them. Or it may appear as a single burst with a long trailing edge of small amplitude. In this case, the effect of such pulses can be equivalent to the effect of a unipolar pulse.

There is a rigorous justification for the existence of pulses with non-zero electric area. This has been done in the works [32-38] ([25a, 65a]). Examples of obtaining such pulses are given in the works of the applicant [14a-17a, 20a, 26a, 68a, 87a, 95a, 103a, 117a, 118a, 127a], see also the reviews [37-40] ([25a, 48a, 54a, 65a, 90a, 98a, 134a]) and the cited literature). In addition, both experimental works showing the possibility of obtaining unipolar pulses in the radio range [41,42] and the work of the applicant showing the presence of unipolarity in the terahertz range [43] ([87a]) have recently appeared.

Electrical pulse area, its physical meaning

The resonant interaction of radiation with matter is a common situation in linear and nonlinear optics. Even far away from absorption lines, multicycle radiation causes a small but periodic movement of charges. This causes the frequency of oscillations in the polarization of the medium to follow the frequency of the driving field. It is clear that the developed theoretical approaches and conclusions of the theory of interaction of such radiation with matter are not applicable to unipolar radiation. A short unipolar pulse has a broad spectrum. It has a non-zero component at the zero frequency of the spectrum. Such radiation will have an effect simultaneously on all transitions in a quantum system (atom, molecule, solid, etc.) whose frequencies cover the spectrum of such a unipolar pulse.

Regarding the effect on a quantum system, a short unipolar pulse transmits a mechanical impulse in a chosen direction to the quantum system. The width and shape of the spectrum is not as important as its electrical area. The system then enters a superposition state. It remains there for the phase relaxation time. The population distribution between the levels depends mainly on the dipole moments and the location of the energy levels.

A short unipolar pulse will obey the rules of conservation of electric area during propagation from an electrodynamical point of view. Note that the question of electrical area did not arise in the optics of multi-cycle pulses, and there were no problems in converting multi-cycle pulses into unipolar ones.

Rule of conservation of electrical area and its verification

The formulation of the rule of conservation of the electrical pulse area was first given by N.N. Rosanov in [22]. For the magnitude of the electric pulse area in a dissipative system, it holds that $rot\,\mathbf{S}_E = 0$. In the one-dimensional case, this expression takes the form: $\frac{d}{dz}\mathbf{S}_E = 0$. In nonlinear optics and laser physics, the one-dimensional model is most commonly used. This rule seems contrary to physical intuition.

The fulfilment of this rule is shown in numerical calculations. These are given in [44-46] ([29a, 44a, 75a, 121a, 133a]) for the propagation of a short light pulse in an absorbing and amplifying medium. In these works, it is also shown that the area conservation rule has a predictive power. Another consequence of this rule is that unipolar pulses can be formed from a bipolar pulse by division into sub pulses of opposite polarity [68a]. The reflection of an incident single-cycle pulse from the boundaries of the medium [47] can also form a unipolar pulse in one-dimensional geometry ([26a]). It should be noted that in spite of the elaboration of the issue of the possibility of the existence of unipolar pulses, the discussions on this issue and on the terminology are still going on [48].

Examples of calculations showing the implementation of the rule of conservation of electrical area and the behavior of the degree of unipolarity in the case of amplifying and absorbing media are shown in Fig. 2.

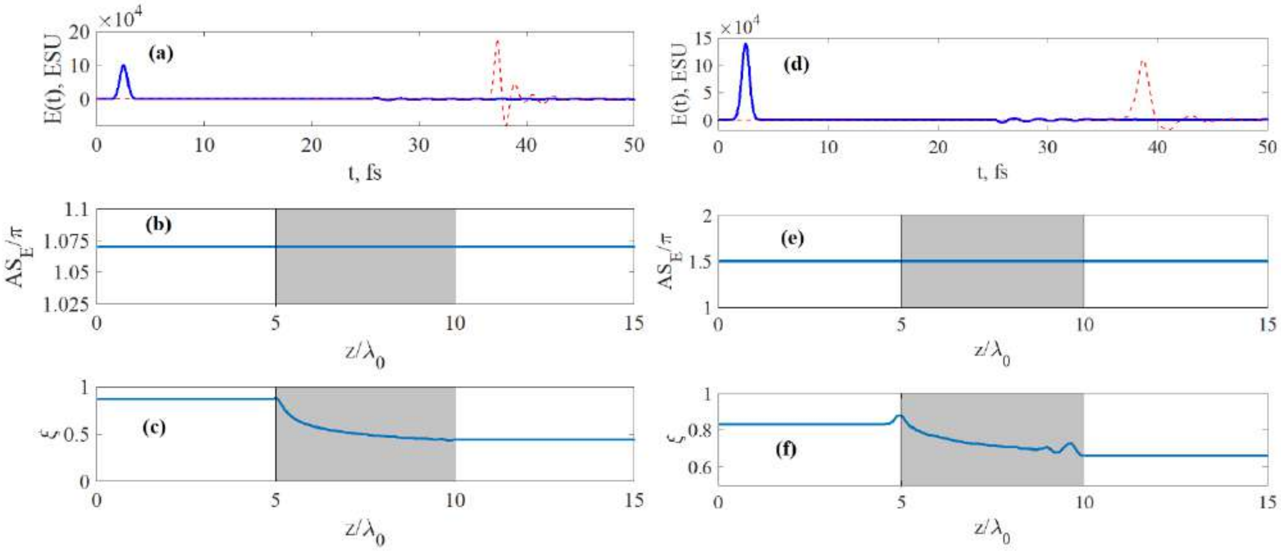


Figure 2. Propagation of a unipolar pulse with initial electrical area $S_E \cong 1.07\pi/A$ in a two-level amplifying medium (a)-(c). (a): Electric field strength as a function of time at the entrance to the gain medium (blue line) and at the exit from the medium (red line), (b): Electric area as a function of coordinate along the propagation path, parameter $A = 2d_{12}/\hbar$, (c): Dependence of the degree of unipolarity ξ on the coordinate along the propagating path. The amplifying medium is located between the points $z_1 = 5\lambda_0$ and и $z_2 = 10\lambda_0$. In figure (b), (c) the area where the medium is located is marked with a grey background.

Calculation parameters: resonance transition wavelength $\lambda_0 = 700$ nm, transition dipole moment d_{12}=20 D, relaxation times $T_1 = 50$ fs, $T_2 = 5$ fs, amplifying particle concentration $N_0 = 10^{20}$ cm^{-3}, excitation pulse amplitude $E_0 = 10^5$ ESU, pulse duration $\tau = 500$ as.

(d)-(f): Propagation in a two-level absorbing medium of a unipolar pulse with initial electric area $S_E = 1.5\pi/A$. (d): Dependence of the electric field strength on time at the entrance to the absorbing medium (blue line) and at the exit from the medium (red line), (e): Dependence of the electric area on the coordinate along the propagation path, parameter $A = 2d_{12}/\hbar$, (f): Dependence of the degree of unipolarity ξ on the coordinate along the propagation path. The absorbing medium is located between the points $z_1 = 5\lambda_0$ and $z_2 = 10\lambda_0$. The region where the medium is located is marked with a grey background in Fig. (e) and (f). amplitude of the excitation pulse $E_0 = 1.4 \cdot 10^4$ ESU. The other parameters are the same as in Figs. 2a-c.

Generation of quasi-unipolar pulses

If there are still practical difficulties in obtaining "pure" unipolar pulses containing only one burst of the field, the formation of pulses with an intense burst and low amplitude oscillations of opposite polarity at the fronts of this burst, reducing the electrical area to zero, does not have the same limitations as the reception of "pure" unipolar impulses. Such pulses are also of practical value, since their effects may not differ from those of purely unipolar pulses [59a]. A short intense burst will play the main role in nonlinear processes. The spectrum of a short burst is broader than the spectrum of field oscillations of the opposite polarity. Therefore, the range of problems considered also includes sub-cycle pulses whose electrical area may be 0.

A single-cycle bipolar pulse with zero area and one period of field oscillation is also an interesting object. It can be transformed into a quasi-unipolar and unipolar pulse. Therefore, the production of such radiation and its transformation were part of the interest of the study. The applicant has proposed a number of methods for obtaining unipolar and quasi-unipolar pulses, for example by reflecting a single-cycle pulse from a thin metal or dielectric film [47] ([26a]). Theoretically, the possibility of obtaining quasi-unipolar pulses of unusual shape (rectangular, triangular) by superradiance of a stopped polarization pulse in both homogeneous and spatially inhomogeneous media has been demonstrated [49-57] ([14a-17a, 20a, 95a, 103a, 118a, 127a]). Examples of the temporal shape of such pulses are shown in Fig. 3.

The possibility of converting unipolar pulses by time integration and differentiation of the electric field strength during interaction with thin metal films has been demonstrated (similar operations could previously be performed in radio engineering with electrical signals in RC circuits or with the envelopes of long multi-cycle pulses) [77a,83a]. Non-zero values of the electric area of terahertz radiation from various sources have been experimentally obtained [43] ([87a]).

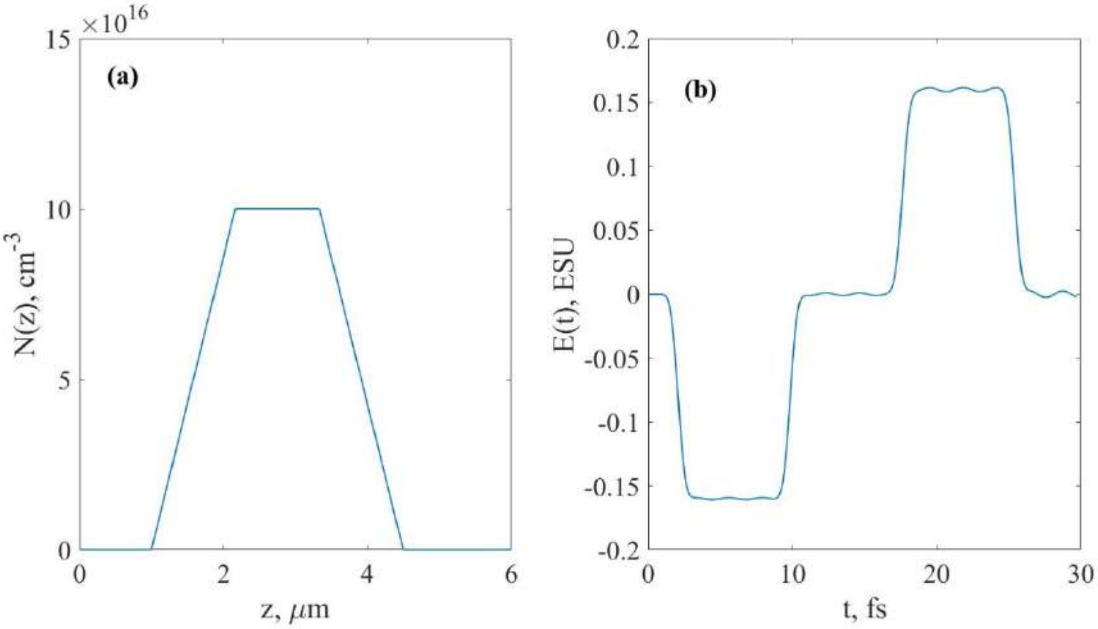


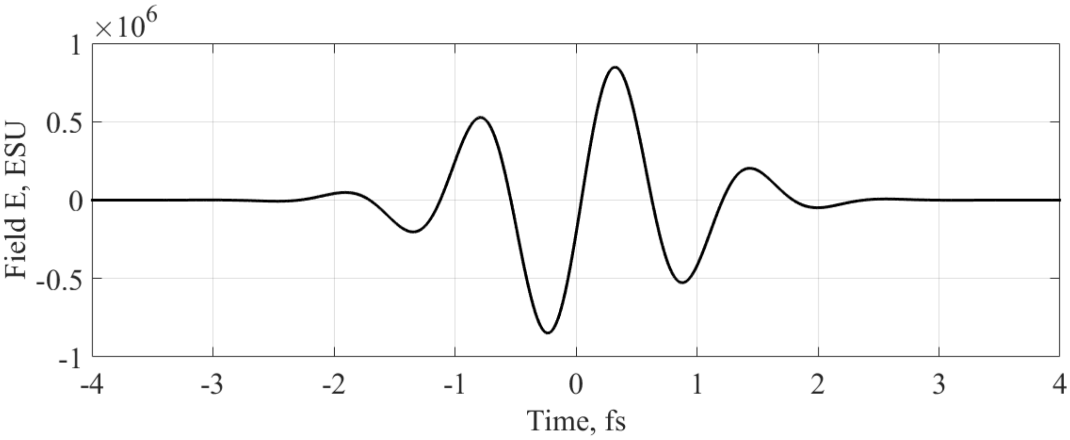
Figure 3. Example of the possibility of generating unipolar pulses of unusual temporal shape (in this case rectangular) by emission of a stopped polarization pulse in a spatially inhomogeneous medium. (a): Spatial concentration profile of the medium, (b): Radiation field strength generated by the layer of the medium. The spatial density of the medium at the edge of a 3.5 μm thick layer increases according to a linear law, is constant inside the medium for a length of 1.3 μm, and decreases according to a linear law to zero at the next boundary of the medium. The linear rise and fall results in the emission of a pair of approximately rectangular pulses of opposite polarity. The resonant medium is excited by a pair of half-cycle pulses with amplitude $E_0 = 10^5$ ESU, duration $\tau = 400$ as. The delay between the pulses is equal to half the period of the resonance transition of the medium, $\frac{T_0}{2} = 1.2$ fs. In this case, the first excitation pulse causes the polarization of the medium to oscillate at the resonance transition frequency and the second pulse stops this oscillation. This leads to the formation of a so-called half-wave stopped polarization pulse in the medium. This pulse propagates through the medium together with the excitation pulses and radiates back a pair of rectangular pulses as shown in the figure on the right. For more details see [56-57] ([14a-17a, 20a, 95a, 103a, 118a, 127a]).

Subcycle pulses in extreme nonlinear optics: self-compression and self-stopping of light

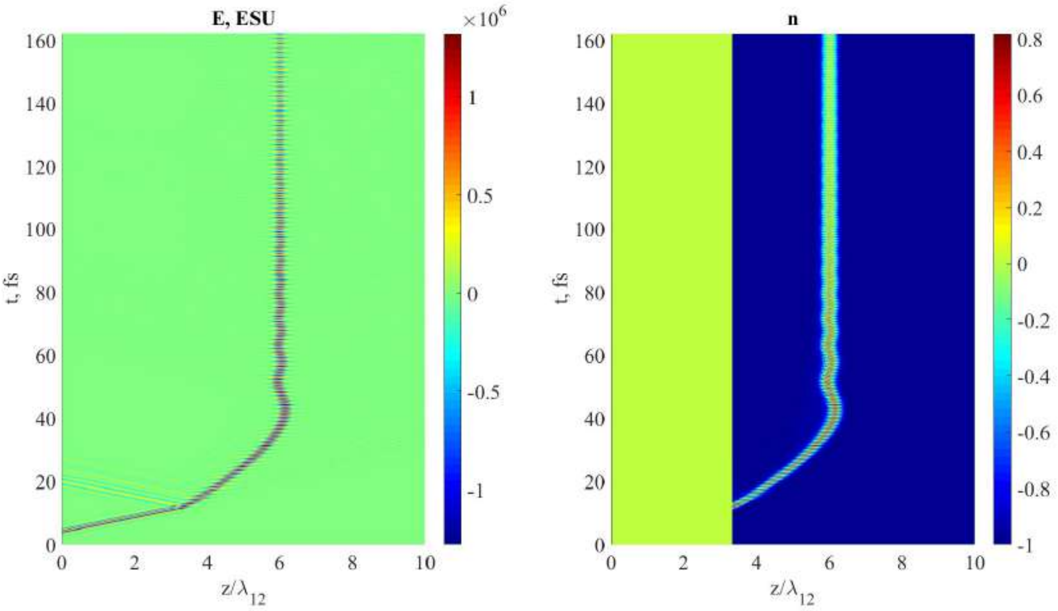
Traditionally, many problems in nonlinear optics are solved in the two-level approximation. On the one hand, the two-level model has no mathematical complexity. On the other hand, it is not always an adequate description of the interaction with complex multilevel systems. The results obtained within its framework are of heuristic value. They point to some interesting questions that require further detailed study. It is relevant to recall the work of Bullough [19], where a unipolar pulse formed a soliton of self-induced transparency. Another example is the well-known work of Kaplan et al [60]. They showed the possibility of unipolar soliton formation in a gaseous medium. At present, for example in the works of S.V. Sazonov, quite realistic multilevel (and two-level) media in which such solitons take place are being considered [24, 28, 29, 61-64].

With a heuristic sense, the co-researcher's work was also carried out, in which a single-cycle pulse in a two-level medium was transformed into a shorter single-cycle pulse - undergoing resonant compression [65] ([73a]). Also, a single-cycle pulse could be transformed into a sub-cycle pulse when colliding with another single-cycle pulse and, when propagating in a resonant medium, into a pair of time-dispersed unipolar pulses of opposite polarity [66] ([68a]).

Light self-stopping [67] ([93a, 98a]) is another interesting effect in a two-level medium. It was found that the pulse is slowed down until it stops completely and forms a local oscillation, see Fig. 4. The short pulse starts to propagate in the self-induced transparency regime, then slows down and stops. In the stopping region there is a complete energy exchange between the medium and the field. The radiation is completely absorbed and the medium is excited. The medium then gives energy to the field. An oscillating stationary half-wave of the field is present in the medium. The structure has the character of a stationary oscillon. In the stationary structure, there was a rapid exchange of energy between the field and matter in a region of space half the wavelength of the resonance transition. At times when the field was zero, all the energy was in the excited matter. Then all the energy went out of the matter into the field, and the matter was in the unexcited state. And so on [93a, 98a].



(a)



(b)

Figure 4. Self-stopping of light [93a].

(a): Dependence of the electric field strength E in the initial pulse.

(b): Dependence of the field strength E and the inversion n on the coordinate and time, demonstrating the self-stopping of the pulse in a dense resonant two-level medium.

The concentration of absorbing particles N_0=1.8·10^{22} cm^{-3}, the dipole moment of the transition is 5 Debye. Relaxation times T_1=T_2=10^{-13}s. Transition wavelength in the medium λ_{12} =0.7 μkm.

The paper has given rise to discussion. In real multilevel systems, can this happen? In our opinion, the value of the obtained result is that it demonstrates a possible scenario of the effect of self-stopping of light in optically dense resonant media in which few-cycle light pulses propagate.

This is a slowing down of the pulse due to a partial loss of energy, and then the formation of a structure where there is a full reversible exchange of energy between the pulse field and the medium. If we draw an analogy with the effect of self-induced transparency, in which the leading edge of the pulse gives energy and the trailing edge of the pulse takes it away, then at the moment of stopping these processes occur in a region of space, the leading and trailing edges disappear, and the moments of energy exchange are separated in time.

Atomic scale of the electrical area

The study of the interaction of unipolar and subcycle pulses with matter raises the question of evaluating the degree of their effect on micro-objects. To characterize the effect of unipolar pulses on quantum objects, the applicant proposed a new physical quantity - the "atomic scale" of the electric area S_0 [68-70] ([79a, 86a, 88a, 91a, 108a, 126a]). It is equal to the ratio of Planck's constant $\hbar$ to the characteristic size of a micro-object a multiplied by the electron charge q, $S_0 = \hbar/aq$. This value is universal in the sense that it can be used to estimate the degree of efficiency of the action of extremely short pulses on various quantum systems - atoms, molecules, ions, excitons in solids, etc. The physical meaning of S_0 is that it determines the scale of pulse action on a quantum system. In a quantum system of characteristic size $\sim a$, the momentum is of the order of $\hbar/a$ due to the Heisenberg uncertainty relation. On the other hand, the electrical area of the pulse coincides with the change under its action of the mean quantum mechanical value of the momentum attributed to the unit electrical charge of the system [71]. Thus, the atomic scale of the electric area of the pulse corresponds to the change in the momentum of the quantum system caused by it, which is equal to the characteristic quantum mechanical momentum of the “free” system.

The obtained expressions of “area scale” for the simplest quantum systems - hydrogen-like system, harmonic oscillator, rigid rotator and a particle in a potential box - are identical in physical meaning. For them, the scale of the electric momentum is inversely proportional to the characteristic size of the system. It is possible to consider that this quantity, together with the Bohr radius and the value of the atomic field strength, which play a role of a scale of atomic sizes and fields, has a sense of a scale of influence of extremely short unipolar pulses on quantum systems. The relationship obtained has a simple form and a simple meaning. It is very convenient for estimating the parameters of non-resonant pulsed radiation necessary for excitation of electrons in atoms, hydrogen-like formations (excitons) in solids, excitation of vibrations and rotation of molecules. It can be applied to the evaluation of the possibility of excitation of electrons in nanoparticles when their motion is well approximated by a box potential with high walls.

Interference of electric pulse areas

The area of a pulse is a measure of its effect on quantum systems. An interesting situation is when a system is affected by several short unipolar pulses. After each of them, the mechanical momentum of the system changes. But there is no direct summation of the pulses. This is due to the fact that in the bound states of a quantum system, the motion of a particle is accompanied by a change in direction and, accordingly, the direction and magnitude of the momentum change periodically. For small excitations of the system, the analogy with the classical harmonic oscillator, where the amplitude of the oscillations is proportional to the magnitude of the excitation, is admissible. If two identical unipolar pulses act on the oscillator, the result of the action depends on the time interval between the pulses. If the 2nd pulse comes after half the oscillation period of the oscillator, it will stop the oscillator movement. And if it passes through the oscillation period, it will increase the amplitude of the oscillator movement. These considerations illustrate the basic idea of interference of electrical areas when influencing a quantum system. Under the conditions of the applicability of perturbation theory, it is not important in which order the impulses act, but what is important is the time interval between them. Rigorous calculations show that the formula for the excitation populations of a quantum system is externally similar to the intensity formula for the interference of two monochromatic waves, but instead of wave intensities there are squares of electrical areas of the pulses [81a, 92a, 111a]. The idea of electrical areas of pulses is also applicable to the interference of the electrical area of a unipolar pulse with a multicycle pulse. Only in the case of multicycle pulses is the area of their envelope taken [81a, 92a, 111a].

Formation of population difference gratings and polarization waves under the influence of unipolar and subcycle pulses

Monochromatic and pulsed quasi-monochromatic laser radiation is actively used for the generation of spatially periodic gratings of atomic population differences in a resonant medium, which are the result of the interference of two or more light beams [74]. However, even if the laser beams do not overlap in the medium, the creation of such gratings can still occur. This possibility was first demonstrated in the first photon echo experiments [75-76]. The theoretical foundations of this phenomenon with respect to photon echo in the case of long multicycle pulses were laid by

E.I. Shtyrkov et al. [77-78] and summarized in the review by E.I. Shtyrkov [79]. Early and recent results are also summarized in a review by the author [80a]. To produce gratings, it is necessary that the interaction of the pulses with the medium be coherent, i.e. the pulse duration and the time interval between their arrival in the region of registration would be much shorter than the relaxation time of the polarization T_2 of the medium. The physical mechanism of grating formation here is related to the interference of the incident pulse with the macroscopic polarization wave of the medium induced in the medium by the previous pulse. And the interaction of the running polarization wave generated by the first pulse after itself with the second pulse due to the interference of the electrical areas (or envelope areas) of the incident pulses leads to the creation of population gratings.

The use of unipolar and subcycle pulses to create gratings has been studied in detail by the author [18a, 19a, 29a, 30a, 31a, 70a, 80a]. Grating control using such pulses has the advantage that, due to the short duration of the pulses (of the order of the period of the field fluctuations and less), it is possible to control the properties of the medium on attosecond time scales. This is important for the development of ultrafast optical devices.

The applicant's work established a theory and demonstrated for the first time the possibility of creating, erasing and ultrafast controlling polarization and population difference gratings using a sequence of attosecond subcycle and unipolar pulses that do not overlap in the medium. In this case, in contrast to previous studies in which long nanosecond pulses were used to create gratings, in the theoretical studies carried out by the applicant:

- the theory of grating generation by counterpropagating extremely short pulses with a broad spectrum [81-85] ([18a, 19a, 29a, 30a, 31a, 70a, 80a]) has been developed, when both bipolar single-cycle pulses and unipolar sub-cycle pulses are applied to the medium;

- the possibility of ultrafast (attosecond scale) generation of gratings and control of their properties - erasing, multiplication of spatial frequency [81-85,91] ([18a, 19a, 29a, 30a, 31a, 70a, 80a]) has been demonstrated;

- the possibility of the existence of slow polarization waves of the medium propagating at a speed many times lower than the speed of light c [82] ([19a]) was shown;

- for the first time investigated the scenario of grating formation under conditions where extremely short pulses meet in the central region of the medium [86-87] [32a, 36a]. It is shown that the state of the medium to the right of the pulse overlap region can be different from the state of the medium to the left of this region [36a]. For example, they produce polarization waves with a spatial period that is three times different. These waves travel in opposite directions with significantly different phase velocities [36a];

- the possibility of guiding gratings using short terahertz (THz) pulses at vibrational transitions whose frequency is also in the THz range [88, 91] ([43a, 70a]);

- the possibility of using THz pulses with amplitudes several orders of magnitude smaller than the amplitude of attosecond pulses for guiding gratings has been shown, indicating that experimental observation of the effect in the THz frequency range and THz holography is promising [91] ([70a]);

- demonstrated for the first time the possibility of guiding gratings in a multilevel quantum system based on the solution of the Schrödinger equation, in contrast to the previous studies of the authors carried out in the two-level approximation [89-93] ([50a, 59a, 70a, 97a, 100a, 124a]);

- the possibility of inducing non-harmonic gratings in the form of light-induced channels, peculiar microresonators, with a size of the order of the wavelength of the resonance transition of the medium, whose parameters can be controlled, for example, by the amplitude of the incident pulses [95-96] (96a, 101a, 122a). These structures arise from the collision of a sequence of non-harmonic unipolar pulses of rectangular shape in a resonant medium. In this work, the author used non-harmonic electromagnetic radiation pulses. The variants of obtaining pulses of non-harmonic form, for example, rectangular and triangular, which can create non-harmonic grating forms in the form of channels, microresonators, are proposed;

- the possibility of holographic recording of information about an object with ultra-high temporal resolution using unipolar pulses without mutual coherence between the reference and object beams has been demonstrated [97] ([62a]).

The methods considered for the fabrication of gratings are promising for the fabrication of all-optical deflectors of laser radiation at exceptionally high speeds. This may find application in ultrafast information transmission and processing systems.

Typical examples of the dynamics of such gratings are shown in Figure 5. This example illustrates the possibility of creating, erasing and multiplying the spatial period of the grating as a result of the interaction of a pulse with a polarization wave propagating slower than the speed of light.

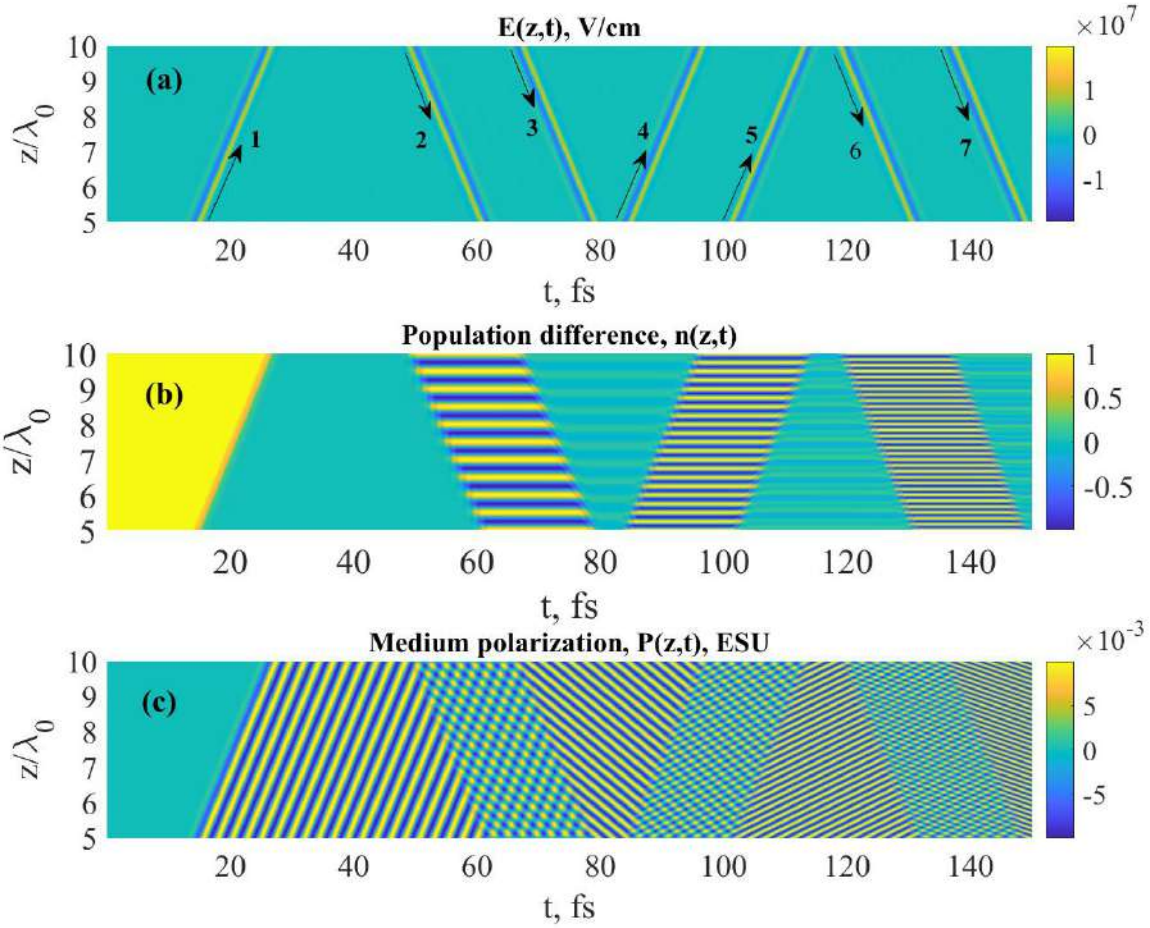


Figure 5. (a): Scheme of the propagation of single-cycle light pulses acting on a two-level medium (the directions of their propagation at given times are indicated by arrows, the number of pulses is indicated by numbers), (b): example of the spatio-temporal dynamics of the behavior of the population difference $n(z,t)$, (c): polarization of the medium $P(z,t)$. The results are obtained from the numerical solution of the Maxwell-Bloch equations for a two-level medium. Calculation parameters: The incident pulse had the form $E(t) = E_0 e^{-\frac{t^2}{\tau^2}} \sin \omega_0 t$. The amplitude $E_0 = 12 \cdot 10^6$ V/cm, the duration $\tau = 1.1$ fs. Parameters of the two-level medium: transition dipole moment: $d_{12} = 20$ D, particle concentration: $N_0 = 5 \cdot 10^{14}$ cm^{-3}, relaxation times $T_1 = T_2 = 1$ ns, wavelength of the resonance transition $\lambda_0 = 700$ nm.

In this example, single-cycle pulses, which do not overlap in the medium, propagate through the medium. Pulse 1 acts as a π/2-like pulse, putting the medium into a zero-inversion state and forming a polarization wave propagating at the speed of light c. The counter-pulse 2 forms a population difference grating and generates a standing polarization wave. Pulse 3 erases the grating, forming a slow polarization wave that travels from right to left at the speed $c/3$. This is followed by a counter-pulse 4 which, as a result of interaction with this polarization wave, creates a grating with twice the spatial frequency, and so on. This process can be continued by sending the next pulses into the medium at a certain time. More details can be found in [81-85] ([18a, 19a, 29a, 30a, 31a, 70a, 80a]).

Using unipolar pulses in holography

The author [97] ([62a]) proposed the use of unipolar pulses in holography. As it is known, holographic recording of information about an object is based on an interference pattern created by a reference wave and a wave scattered by the object. In traditional holography, it is necessary for the reference and object beams to be mutually coherent. As shown by the applicant, it is possible to make a holographic recording of information about an object without coherence between them, even using radiation from different sources. Such recording can be achieved using unipolar or subcycle pulses when a resonant medium with a long phase memory time T_2 is used as the recording medium. Figure 6 shows a schematic of a holographic recording.

In this case, the interference pattern of a subcycle or unipolar pulse reflected from the object with the polarization wave of the medium generated by the same short pulse is recorded in the medium, see Fig. 5. The coherence is provided by the polarization wave which, when interacting with the radiation reflected from the object, will induce a population grating in the medium. This grating will repeat the interference pattern in a similar holographic process using a monochromatic source with a wavelength equal to the wavelength of the resonance transition in the medium.

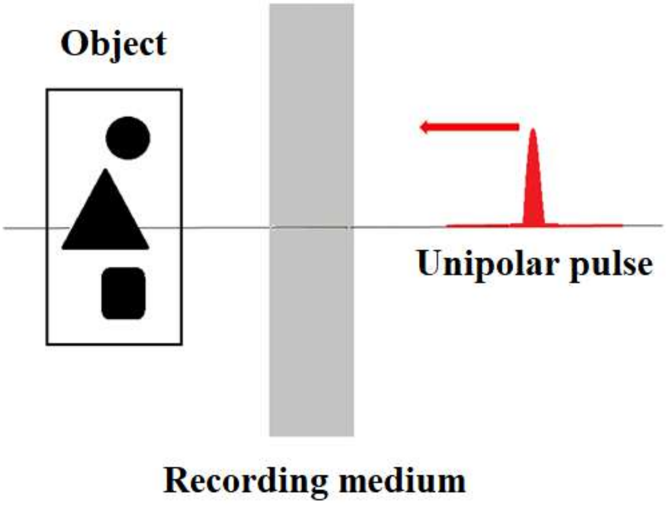


Figure 6. Scheme of a hologram recording by means of a unipolar pulse and a resonant absorbing medium [97] ([62a]). The unipolar pulse passes through the recording medium. A wave (or several waves in the case of multiple transitions) of polarization appears in the medium with a resonance transition wavelength λ. This wave moves towards the object. The pulse reflected from the object interacts with the polarisation wave and a population grating is formed. The population maxima coincide exactly with the maxima of the interference pattern that would be produced by monochromatic radiation of wavelength λ. The scheme shown in the figure corresponds to the recording of holograms in counter beams.

The optical Aharonov-Bohm effect and unipolar pulses

A number of fundamental questions arising from the properties of unipolar pulses have been addressed by the author. Unipolar pulses have a non-zero electric area and thus change the vector potential in space. In 1959, the work of Aharonov and Bohm [98] theoretically considered experiments in which it would be possible to demonstrate the physical significance of electromagnetic potentials, which in classical electrodynamics play the role of mathematically introduced auxiliary quantities. The physical significance is the electric and magnetic field strengths, which determine the forces acting on charges and currents. According to the authors [98], potentials play a special, even primary role in quantum mechanics. To this end, they propose experimental schemes in which, unlike in classical mechanics, it is possible to detect the influence of electromagnetic potentials on a charged quantum particle, even though in the region in which it is located all fields, and hence all forces acting on the particle in the classical sense, disappear.

Such situations lead to paradoxical conclusions in the case of unipolar pulses. At first sight, space should remember the fact of the passage of unipolar pulses. The Aharonov-Bohm interferometer should determine the fact of the existence of a potential in the absence of a field.

This situation was treated by the author in [99] ([60a]). It was shown that due to the vortex-free nature of the electric pulse area, no phase shift is recorded in the interferometer. It is therefore pointless to discuss the possibilities of improving the interferometer. The fact that a potential exists after the unipolar pulse has passed through will not show up as an influence on quantum systems. This conclusion can be extended - empty space has no memory of the electromagnetic phenomena occurring in it.

Coherent mode locking in lasers - theory and experiment

Theoretical description of the coherent mode locking regime (CML)

Coherent mode locking (CML) makes it possible to obtain pulses with a duration shorter than the relaxation time T_2 of the amplifying and absorbing media, in contrast to lasers with a saturable absorber. The history of the development of the ideas is presented in the first part of our review [100] ([84a]). Briefly, passive mode locking in a two-section laser containing an amplifying and an absorbing medium, due to the nonlinear properties of the absorbing medium with the effect of self-induced transparency (SIT), was discussed at the beginning of the laser era. However, as mentioned in the review, the first experiments were unsuccessful. From a practical point of view, the use of saturable absorbers proved to be easier.

The appearance of some theoretical works in the field of CML did not arouse the enthusiasm of experimentalists to carry out experiments with the proposed schemes for the realization of CML. The works considered difficult to implement situations when the amplifying and absorbing media were mixed in the volume of the resonator. According to the results of these works, there was no self-starting of generation [101-105].

In the applicant's works, for the first time, the case was considered when the absorbing and amplifying media are not uniformly mixed in the volume of the resonator, but are separated in space [106-111] ([6a, 10a, 11a, 69a, 89a, 99a]. Cases of unidirectional lasing in the travelling wave in a ring resonator and the generation of two counterpropagating waves typical of a linear resonator. These problems were solved both in the slow envelope approximation and without the slow envelope approximation. For the first time, it has been shown theoretically that the CML regime is self-starting. This is in contrast to the disappointing results of the first studies, which concluded that injection from an external source was necessary to start the CML regime.

The theoretical description of a laser in the CML regime is a complex task. It does not lend itself to a visual and simple theoretical description. However, in order to provide a clear understanding of the processes occurring in this regime, the applicant has developed a diagrammatic method based on the rules of the area theorem of McCall and Hahn [108] ([11a]). It shows how the area of the pulse envelope in the laser cavity evolves as a function of the amplifier, absorber and cavity loss parameters. Stable limit cycles can be constructed using this method. The application of the diagrammatic method to CML has been made in three publications [108,109,111] ([11a, 69a, 99a]). In total, the applicant has 6 theoretical works on CML, the results of which were included in statements for defense 10-11 [106-111] ([6a, 10a, 11a, 69a, 89a, 99a]).

Scaling rules for lasers

Because of the known difficulties in describing the CML regime, the only method of analysis remains numerical simulation. At first sight, it is only applicable to the range of parameters for which it was carried out. However, there are situations in physics where the applicability of calculations is extended by the application of scaling rules. For lasers, these have been formulated by the applicant in the works [109-110] ([69a, 89a]). Based on the rule for lasers in the slow envelope approximation model, it was concluded that reducing the pulse duration and bringing it closer to a single cycle requires a reduction in the length of the resonator and not an increase in the pump power, as might appear at first glance from the relationship between the Rabi frequency and the amplitude of the electric field of the pulse [109] ([69a]). If we increase the generation power without changing the length of the resonator, then there will be a transition from the regime with one pulse in the resonator to regimes with an increasing number of pulses simultaneously present in the resonator.

Generation of extremely short pulses in the CML regime in ultrashort cavity lasers

The slow envelope approximation is not applicable to the description of the interaction of radiation of the order of magnitude of one oscillation cycle with the resonant medium. The analysis of the single-cycle pulse generation regime in a laser with an ultrashort cavity was carried out using the full system of Maxwell-Bloch equations without the slow envelope approximation in the work of the applicant [110] ([89a]). The existence of such regimes and the influence of the relaxation parameters of the laser medium on the regime are demonstrated. The result of this work was included in the statements for the defense, number 6. Examples of solutions are shown in Figure 7. Note that the generation in this regime also has a self-starting character.

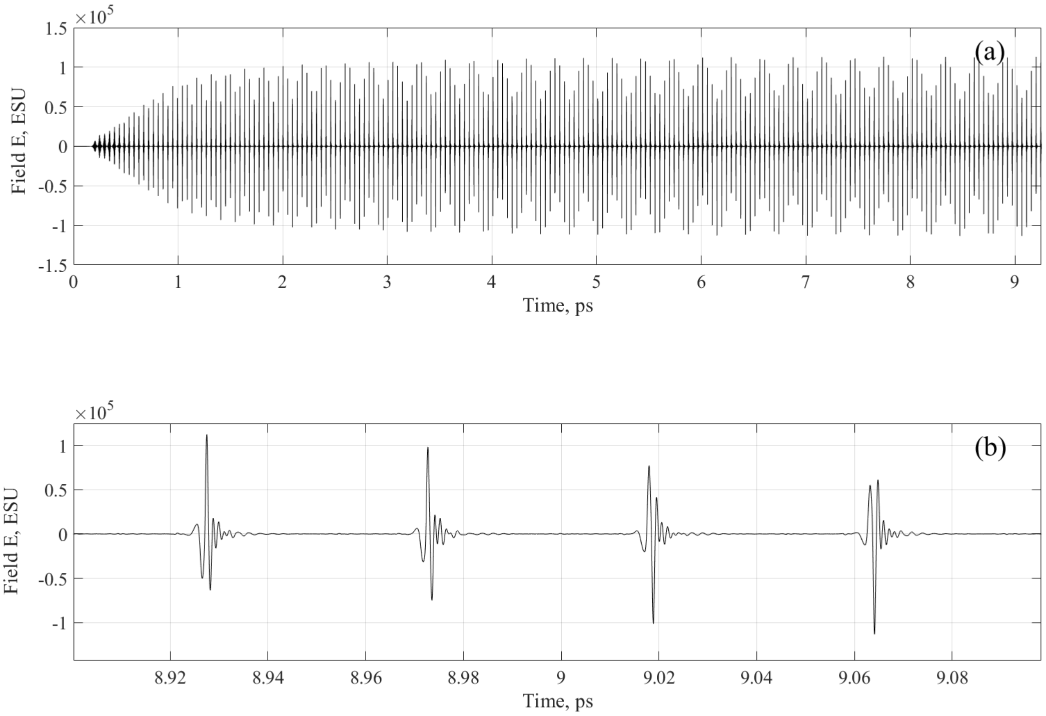


Figure 7. The result of modelling the self-starting CML regime with single-cycle pulse generation in a linear resonator of 6.65 μkm length.

(a) Field strength at the laser output as a function of time from the moment of self-start to the establishment of the stationary mode of the QSM.

(b) Fragment in steady state.

Model parameters

	Gain	Absorber
Length	2.8 μkm	1.75 μkm
Concentration	$2 \cdot 10^{20}$ cm^{-3}	$2 \cdot 10^{20}$ cm^{-3}
Transition dipole moment	4 D	8 D
Relaxation time T_1	$1 \cdot 10^{-13}$ s	$1 \cdot 10^{-13}$ s
Relaxation time T_2	$1 \cdot 10^{-14}$ s	$1 \cdot 10^{-14}$ s

Parameters of the metal mirrors of the linear resonator: layer thickness 0.035 μkm, free electron concentration 10^{21} cm^{-3}, electron relaxation time in the Drude model 10^{13} s^{-1}. The reduction of the laser pulse duration in the CML regime requires a reduction of the resonator length [110] ([89a]).

Experiments demonstrating the CML regime

Having obtained theoretical results demonstrating the possibility of self-starting CML in a laser with a spaced absorber and amplifier, and having simulated these regimes, the applicant moved on to practically demonstrating this regime in different types of lasers. The first task was to demonstrate the effect of a coherent absorber as a nonlinear loss modulator leading to mode locking in lasers.

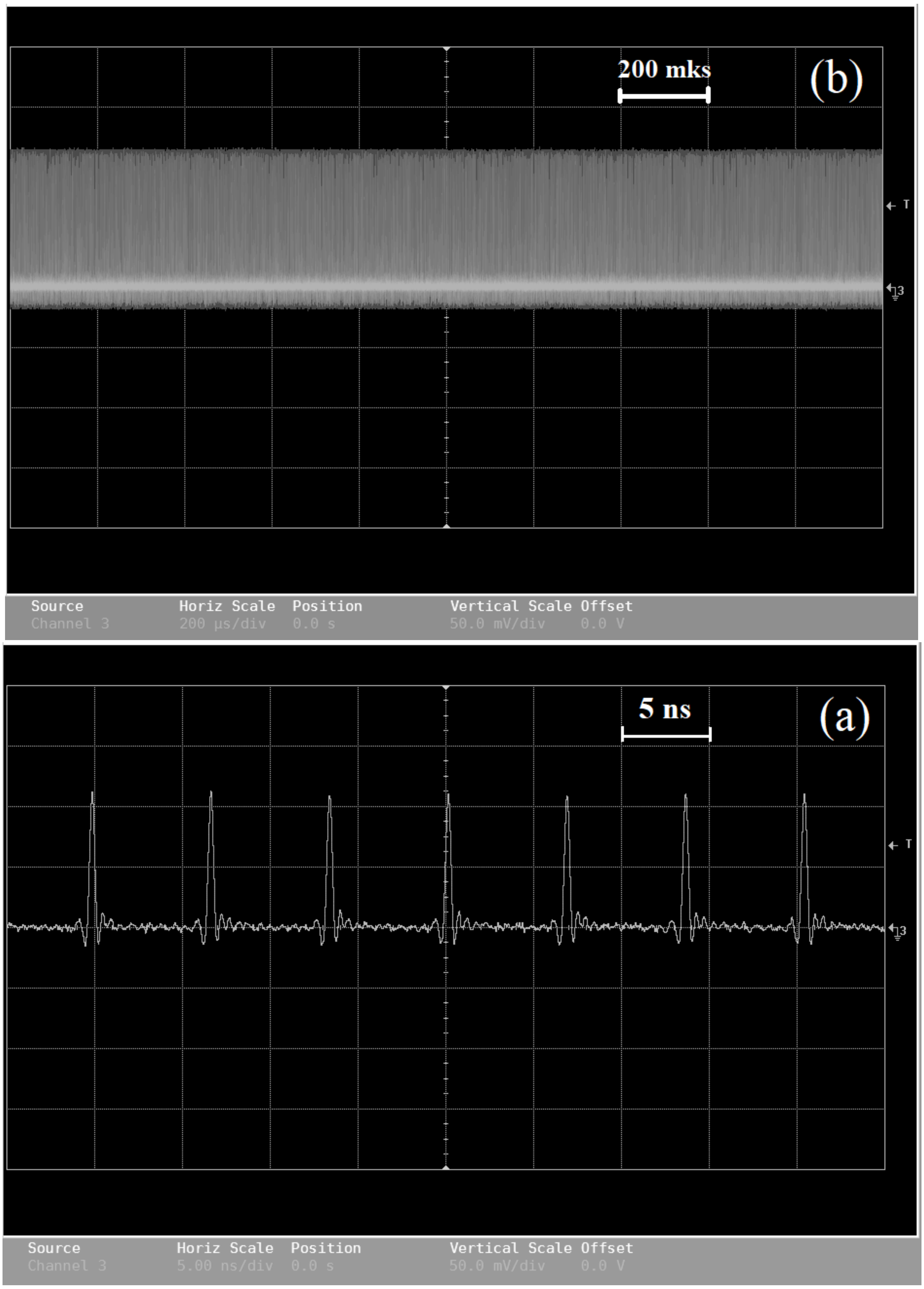
A continuous-wave dye laser was used for the first experiments. The active medium was rhodamine 6G [112,113] ([7a, 40a]). Molecular iodine vapor was used as a coherent absorber. They had transitions in the dye generation region. They had a long phase relaxation time T_2 of several hundred ns. The width of the dye enhancement line was several orders of magnitude larger than the width of the transitions in the molecular iodine. A dye laser with an iodine vapor cell did not show mode locking when its generation spectrum did not coincide with the absorption lines. Frequency locking by the absorption lines did not occur. Therefore, spectrally selective elements were placed in the resonator. This allowed the generation to be tuned to the absorption line.

In these experiments, when tuned to the absorption line, we were able to clearly demonstrate mode locking under the influence of a coherent absorber. However, contrary to the expected appearance of 2π pulses of self-induced transparency, only 0π pulses could be observed. The experimental result was disappointing for the applicant. In view of the fact that all models of the CML regime do not take into account the peculiarities of real experiments, numerous parameters of the real parameters of the amplifier and absorber, the achievement of a self-induced transparency regime with the generation of 2π pulses is indeed impracticable in practice due to numerous difficulties pointed out by sceptics and opponents.

In [114], a rubidium vapor cell was placed in a titanium-sapphire laser with a saturable absorber, providing mode locking with a pulse duration of 1 ps. Intracavity coherent population trapping in rubidium was demonstrated, but the CML regime was not achieved. And when tuning the absorption line, an increase in the duration of the mode-locking pulse and a decrease in the pulse repetition period were observed, which the authors interpreted as a transformation of the mode-locking pulse into a pulse of self-induced transparency in rubidium. The authors did not find the occurrence of mode self-locking in the absence of a saturable absorber in the presence of rubidium vapor in the resonator. The applicant and his colleagues, using the equipment of the Laser Centre of St. Petersburg State University, carried out experiments with a titanium-sapphire laser in whose cavity there were no modulators other than cells with rubidium or cesium vapor

[115-120] ([47a, 49a, 51a, 52a, 55a, 114a]. The resonant transitions of these atoms fall within the generation band of a titanium-sapphire laser.

As in the case of a dye laser, there was no automatic locking of the lasing frequency by cesium and rubidium vapor; selective elements had to be placed in the resonator and the lasing frequency had to be tuned to the absorption line of rubidium or cesium. In all cases, a self-starting mode of coherent mode locking with the generation of 2π pulses of self-induced transparency was detected on each of the two components of the resonant doublet of cesium or rubidium. A detailed description of the main experimental results is given in publication [116] ([55a]). These are self-starting generation, reduction of pulse duration with increasing generation power, and constancy of pulse area with power variation. Figures 8 and 9 show the results of these experiments. An example of the laser oscillograms obtained is shown in Fig. 8. The self-starting nature of the CML is shown in Fig. 9.



Source Channel 3
Horiz Scale 200 µs/div
Position 0.0 s
Vertical Scale 50.0 mV/div
Offset 0.0 V

Source Channel 3
Horiz Scale 5.00 ns/div
Position 0.0 s
Vertical Scale 50.0 mV/div
Offset 0.0 V

Figure 8. Example of an experimentally obtained oscillogram of coherent mode locking in a titanium-sapphire laser based on the DII transition of the rubidium line. Linear resonator length 96 cm, generating power. (a) - Fragment of an oscillogram, scale 5 ns/div, (b) - Oscillogram demonstrating the stability of this generation regime, scale 200 µs/div. Generation power 50 mW.

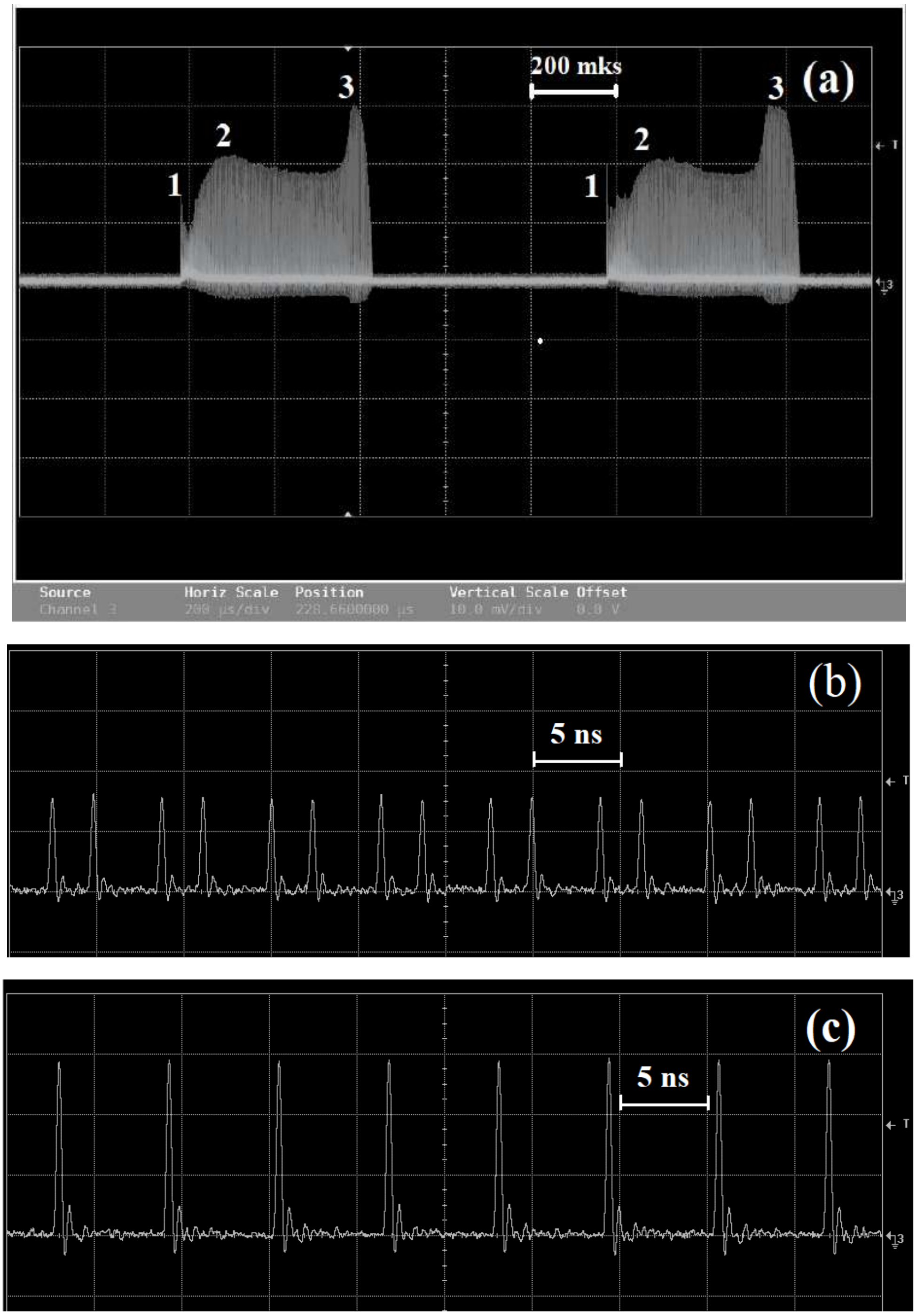


Figure 9. An example of laser oscillograms showing the self-starting nature of coherent mode-locking in a titanium-sapphire laser based on the rubidium absorbing DII transition. A mechanical chopper, a rotating disc with holes, periodically blocked the pump radiation. The frequency of the chopper was 1000 Hz. At the moments when the chopper opened the beam, lasing took place in the titanium-sapphire laser, Fig. 9a. In this oscillogram, at the beginning of generation, marked 1, spikes were clearly observed. These spikes are characteristic of solid-state lasers in the transient process at the beginning of generation. Coherent mode locking then developed. At first, two pulses were simultaneously present in the resonator, the region marked 2, then only one pulse remained, region marked 3. These oscillograms are shown in Fig. 9b and Fig. 9c.

Characteristics of the CML regime in a titanium-sapphire laser

Experiments always reveal details not predicted by theory. In a titanium-sapphire laser in the CML regime, regimes of self-modulation of relaxation oscillations have been discovered. A mode-locking regime during self-Q-switching (Q-switch mode-locking) was also discovered. The coherent absorber acted as a Q-switch of the resonator at the same time as mode locking. This was due to three circumstances. First. In a titanium-sapphire laser, mode locking is possible due to Kerr nonlinearity. However, this mode is not self-starting and requires initialization. Second. A titanium-sapphire laser is a solid-state laser with a slow relaxation time, which is prone to relaxation oscillations in transient processes and allows the implementation of a Q-switched regime. Third. The evolution of the CML, as our experiments have shown, is not instantaneous but takes some time. Therefore, the mode locking due to a coherent absorber is accompanied by an increase in the Kerr nonlinearity, which cannot enter the Kerr mode locking regime due to the presence of a coherent absorber in the resonator, which does not allow a radical reduction of the pulse duration. At the same time, the quality factor of the cavity is increased, resulting in faster depletion of the upper laser level. For a solid-state laser, this is a mechanism for modulating the radiation at the frequency of the relaxation oscillations. This was observed in the experiment. When the modulation depth of the relaxation oscillations became extremely large, the CML mode was interrupted and switched to the Q-switched mode. Here we have given a general description of the picture of the emerging phenomena. Our experiments have shown that the dynamics of a laser with a real nonlinear absorber is extremely complex, as the results in the next section show.

Extreme events in a system of dissipative solitons with self-induced transparency. Experiment and theory.

The results of experiments demonstrating the existence of regular mode-locking regimes are presented above. Alongside these, experiments were carried out to investigate what happens when irregular regimes occur. In the laser cavity, there could be more than one mode-locking pulse. Their amplitudes and the number of them could vary. According to the applicant, it proved possible to analyze such a system from the viewpoint of the concept of dissipative solitons proposed by N.N. Rosanov [121]. These are dissipative solitons of self-induced transparency. The applicant was the first to experimentally demonstrate the existence of soliton molecules, soliton gas and, most interestingly, the existence of extreme events in a system of dissipative solitons of self-induced transparency (SIT) [84a]. It is interesting to note that extreme events and soliton molecules have already been observed experimentally in optical fibers and fiber lasers [122-125]. Examples of soliton molecules and extreme events are shown in Figures 10 and 11.

When generating a titanium-sapphire laser with a coherent absorber (Rb, Cs pairs), depending on the pump power, the position of the absorber and the resonator settings, there are modes in which two or more pulses can be present in the resonator simultaneously. The pulses can have different amplitudes. Two very different situations are possible. The first is when the number of pulses does not change over time. The amplitude of the pulses and the time interval between them can change in a regular way. In this case, so-called soliton molecules and their internal oscillations are observed (Fig. 10(a) and (b)). Secondly, if the number of pulses is large and irregular, the interval between them and their amplitudes change. This is the case of the so-called gas of dissipative solitons (Fig. 10c). Corresponding examples of frame-by-frame generation patterns are shown below in Fig. 10.

It has also been shown that in a soliton gas (a soliton gas corresponds to a situation where there are several SIT pulses in the resonator, moving at different speeds, colliding, merging into a soliton and decaying), extremely rarely, solitons gradually begin to merge with each other, leaving only 1 soliton of large amplitude and short duration. It exists for a short time and then quickly decays. Soliton gas is formed again. In this process, the behavior of solitons is partly similar to that of extreme events - rogue waves on the water surface. At first, there are many waves of small amplitude, then these waves disappear almost suddenly and a rogue wave of very large amplitude appears. The course of extreme events and the interval between them observed in experiments is shown in Figure 11.

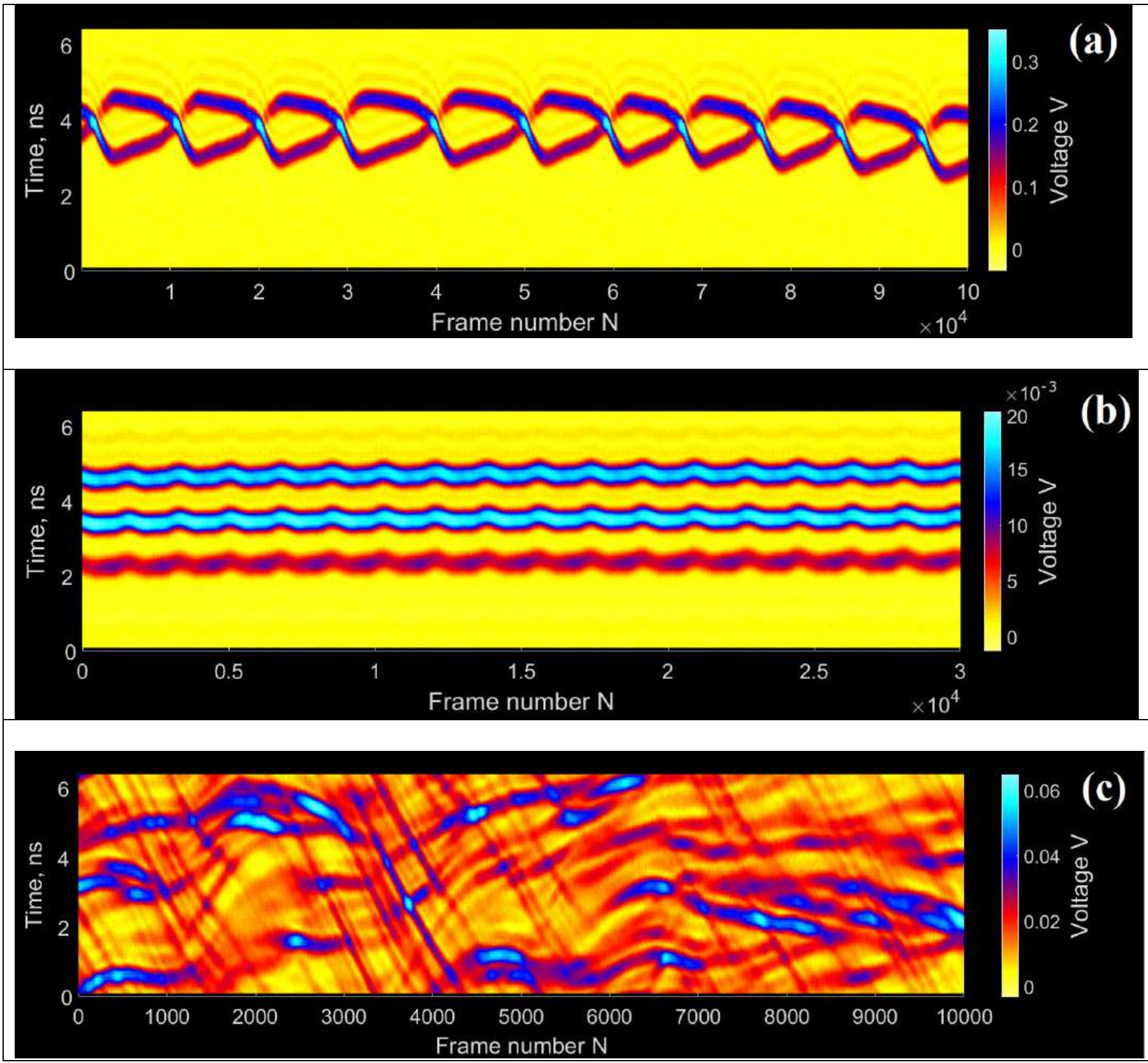


Figure 10. Molecules of two and three dissipative SIT solitons, and a gas of dissipative SIT solitons.

(a): A two-soliton molecule in which solitons attract and repel each other. (b): A three-soliton molecule consisting of three solitons of different amplitudes. The excitation shifts periodically as a whole. (c): Soliton gas with an average of ten solitons.

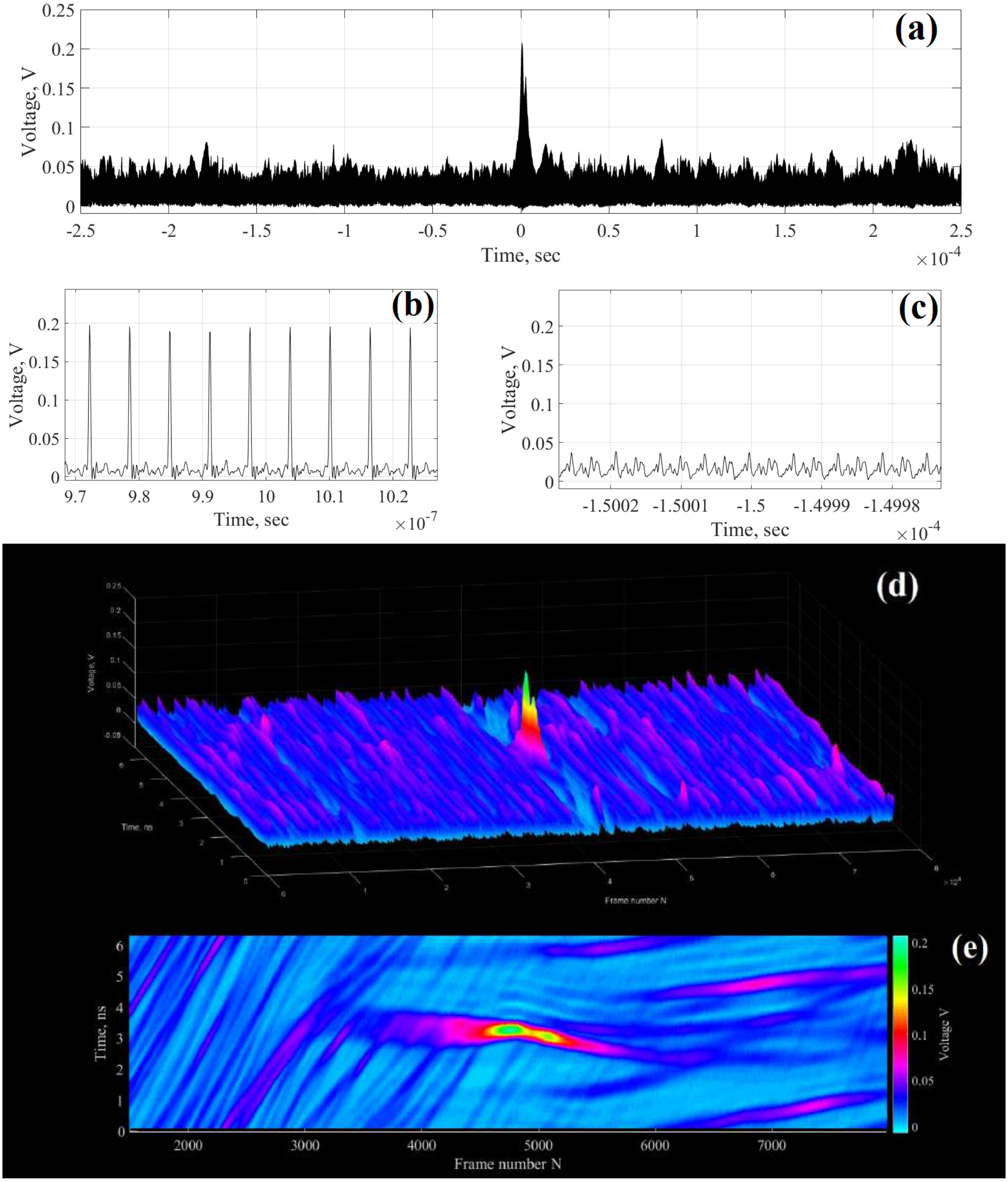


Figure 11. Extreme event in the lasing of a titanium-sapphire laser when the lasing wavelength is tuned to the DII Cs absorption line. Generation power 140 MW. (a) - Oscillogram with extreme event in the center. (b) - Fragment of the oscillogram (a) in the region of the extreme event. (c) - Fragment of the oscillogram (a) outside the extreme event. (d) - Frames of the oscillogram (a). (e) - Process in the vicinity of an extreme event - a frame-by-frame image of the transformation of a gas of dissipative SIT solitons into a soliton and its decay.

It should be noted that the applicant has proposed a simple and effective method for the study of dissipative solitons of SIT - radio spectroscopy of dissipative solitons. For this, in addition to observing the generation oscillograms, the signal from the high-speed photodetector is sent to a radio spectrum analyzer (RSP processor). Here, spectra near the fundamental frequency of the resonator bypass and its harmonics are recorded in a continuous mode. The radio spectrum makes it possible to detect the presence of solitons of different amplitudes, to detect soliton molecules, to observe vibrations in soliton molecules and to detect extreme events, since the speed of dissipative SIT solitons is strongly dependent on the pulse intensity.

The situation in real experiments with rubidium and cesium vapors is quite complex. The mode of generation is indeed affected by the fine structure of the levels. There is an extremely large variety of regimes observed experimentally. It is not associated with any technical factors. It is a consequence of the dynamics of a complex system where spatial factors and the specific scheme of coherent transition levels have to be taken into account. In spite of this, it is possible to point out significant circumstances and to give a physically correct picture of such an interesting effect as extreme events. There were two situations in the observation of extreme events and the simultaneous recording of the average intensity of generation. In the first case, despite the change in the number of solitons, the generation intensity did not change in the vicinity of the extreme events. In the second case, pulsations of moderate intensity were observed in the vicinity of extreme events. Correctly, taking into account the insensitivity of the intensity to the number of solitons, we can assume that in this case, if we know the characteristic time interval at which two solitons merge into one, we can estimate, without going into the dynamics, the probability of all the solitons merging into one using a statistical method. The estimates obtained in this way coincide with the time interval for the occurrence of extreme events in the experiment.

Main results and perspectives

Summary. In 2011, the candidate started working in areas related to the topic of the thesis. Ways of obtaining and properties of unipolar and subcycle, quasi-unipolar radiation, CML regime in a laser as a way of removing restrictions on the duration of generation pulses are the main topics of the dissertation research. At the initial stage, the topics of the work raised serious objections (although at that time there were a few works in these directions, which are mentioned in our reviews), up to its unscientificness, fallacy and practical impracticability when discussing ideas related to the topic. In the course of the research and the scientific community's acquaintance with it, the attitude towards the subject changed. The applicant has been able to demonstrate, through theoretical and experimental work, the realism and the promise of the subject of the unipolar pulse. The same applies to coherent mode locking in lasers. The work was supported by grants from the

Russian Foundation for Basic Research and the Russian Science Foundation, and received awards and prizes. At the time of writing, there was a clear tendency to increase the number of works devoted to subcycle and unipolar light, methods of its production and application.

The applicant will be able to assess the prospects of this field. The interest in this direction is naturally linked to the desire of researchers to obtain ever shorter pulses, not only by reducing their duration and increasing their frequency, but also by leaving a smaller number of oscillation cycles in the pulse, up to half the cycle. The method of reduction of the duration with the increase of the frequency transfers the field of application and research of such pulses only to the region of high energies (study of the internal electronic shells of atoms, nuclear processes) with the use of multi-cycle pulses, which does not change the nonlinear resonance mechanism in the physical processes accompanying the use of such radiation, which will be different only in the case of unipolar and sub-cycle pulses in any range of frequencies and durations.

Remaining in the THz, IR and visible ranges, where low cycle, sub-cycle and unipolar pulses are received, researchers will seek to simplify experimental techniques and to find ways to create compact and relatively cheap sources of such radiation.

In addition to the use of such radiation for research purposes, the main effort is likely to be on the prospects for using even shorter pulses in optoelectronic systems for transmitting and processing information. The movement will start with the development of the THz range. As the applicant's research has shown, it is possible to control the shape of the pulses and to obtain pulses of non-harmonic shape. Most likely, compact sources of single-cycle laser radiation will be created, operating in coherent mode-locking based on quantum cascade lasers. These pulses will be the basis for the formation of unipolar and quasi-unipolar pulses of non-harmonic shape. And from them, from the THz range, a movement towards unipolar pulses in the IR and optical range will begin. Here, the ideas of transforming such radiation in artificial quantum systems will be used, similarly to what has been demonstrated by the applicant using the example of nested quantum wells. Finally, the widespread use of unipolar and quasi-unipolar subcycle pulses will require solving the problem of implementing stimulated emission for unipolar pulses.

The next ten years will show the validity of this prediction.

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