IX International Conference on Ultrafast Optical Science
«UltrafastLight-2025»
Moscow, 2025

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Book of Abstracts

IX International Conference
on Ultrafast Optical Science

UltrafastLight-2025

September 29 – October 2, 2025
Lebedev Physical Institute, Moscow

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Scope

High intensity laser plasma interaction
Laser particle acceleration
Secondary processes with laser accelerated particle beams
Nuclear photonics & Compton sources
Ultrarelativistic field physics
Ultra-high intensity & high reprate laser facilities

Secondary sources of radiation and high-energy particles under interaction of femto- and subpicosecond laser pulses with near-critical plasma targets

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Low-density polymer foam converted into plasma using a well-controlled nanosecond pulse is an excellent plasma target for effective direct laser acceleration (DLA) of electrons using relativistic laser pulses. Over the past five years, a highly efficient and robust DLA process by irradiating such plasma targets with the PHELIX laser pulse (700 fs, 10^{19} W/cm^2, f/5, a_0 = 3.5–4) was demonstrated. This resulted in the generation of well-collimated, high-current beams of superponderomotive electrons with energies above 100 MeV and effective temperatures of 10–20 MeV [1,2].

PW-class laser systems capable of generating subpicosecond and femtosecond pulses focused to ultrarelativistic intensity, are good candidates for creating high-current beams of ultrarelativistic electrons in extended plasma with a density close to critical in the DLA process [2–4]. These electron beams can be used to produce bright betatron radiation, MeV bremsstrahlung, isotopes, and neutrons with record-breaking conversion efficiencies [5–8].

3D PIC simulations show that the charge of the DLA electron beam grows near linearly with laser energy. This paves the way for the application of low-density foams in kJ-PW-class laser facilities used in HED and ICF-relevant research such as ARC (NIF) and PETAL (LMJ), where the beam-times in 2026 and 2027–28 were granted.

Application of such advanced plasma targets to generate GeV electrons and MeV betatron radiation [9] at ELI Prague is also under discussion.

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Generation of bremsstrahlung X-rays in a microcluster target irradiated by un ultrashort duration laser pulse

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Using 3D modeling by the particle-in-cell method, we studied the volume stochastic heating of a cluster (dust, droplet) plasma with submicron particles of heavy atoms (gold) under irradiation of the cluster medium with an ultrashort (15 fs) laser pulse of moderately relativistic intensity ($\gtrsim 10^{18}$ W/cm^2) [1]. The characteristics of the generated short X-ray pulse due to the dominant contribution of bremsstrahlung are obtained; the contribution of synchrotron-type X-ray radiation of electrons with stochastic wandering trajectories between clusters to the obtained radiation yield is also discussed. The generation of hard bremsstrahlung X-rays is due to the appearance of a high-energy pronounced plateau-like plateau of the "tail" of the distribution function of laser-heated electrons. The calculated values of the conversion coefficient into broadband X-ray radiation from the microcluster medium exceed 10^{-5}. This allows us to consider the cluster environment as competitive with respect to optimized solid targets, with the advantage of using it for the laser operating mode with a high pulse repetition rate.

The study was carried out with partial support from the scientific program of the National Center for Physics and Mathematics (project “Physics of High Energy Densities. Stage 2023–2025”).

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Fano resonance in high harmonic generation by intense laser pulses and its classical analogy

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High-order harmonic generation (HHG) of intense laser field is a promising tool to obtain coherent extreme ultraviolet radiation (XUV) in femtosecond or attosecond time domain [1]. However, the typical efficiencies of the HHG process remain below the level required for many applications. One of the ways to increase the efficiency is using resonances of the generating particles. A very pronounced resonant enhancement of HHG was observed in plasma plume and in xenon. Moreover, resonant features were also observed in XUV generated in argon and helium. In these studies they observed enhanced generation of XUV with frequency close to the frequency of a transition from an autoionizing state (AIS) to the ground state of the generating atom or ion. Several theoretical approaches were suggested to describe this phenomenon. In particular, paper [2] generalizes the non-resonant HHG theory [3] to the case when the generating particle has an AIS. It was shown that the XUV spectrum emitted by such a system is a product of the non-resonant spectrum and the resonant factor, similar to the one found by Fano [4].

In this paper we integrate numerically the Schrödinger equation for the model helium atom irradiated by intense few-cycle laser pulse and find the emitted XUV spectra. They demonstrate resonant peaks at the frequencies of transitions from the doubly-excited AIS to the ground state. We study [5] the properties of these peaks depending on the laser pulse duration and find that the decay of the AISs due to photoionization by the laser field affects them. Moreover, we consider the classical double pendulum system and find that both the quantum (the atom with AIS in the field) and the classical (the double pendulum with friction) systems demonstrate Fano-like resonant peak described by an essentially complex asymmetry parameter. We find a remarkable similarity in the behavior of these systems and conclude that the classical double pendulum system with friction is an analogy of the AIS having an extra decay channel in addition to the autoionization one.

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Multi-MeV proton beam collimation using strong magnetic fields excited by ultrashort relativistic laser pulses

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Ultrashort relativistic laser pulses hold promising potential for creation of directed beams of energetic charged particles, electrons [1-3] and ions [4-6]. Despite high beam charge surpassing that achievable in conventional accelerators, the use of laser-driven ion sources for prospective applications is often limited due to the poor beam quality and its high angular divergence. One possible way to overcome this limitation is based on the use of the so-called magnetic lenses for divergent beam collimation. For modest particle energies, e.g. for protons up to 10 MeV, devices based on the electric discharge through a $\sim$ 10 cm long solenoid can be utilized [7]. At the same time, collimation of more energetic ions, e.g. $\sim$ 100 MeV protons, remains a challenge, as the required solenoid length in this case starts to exceed 1 m.

The work considers a sub-mm scale magnetic lens based on a "snail" target with the quasistationary magnetic field excited by its irradiation with an ultrashort relativistic laser pulse. Experimental [8] and theoretical [8,9] studies showed that the magnetic fields in such targets can reach $\sim (10^3 - 10^5)$ T, depending on the interaction parameters, and may be sufficient for collimation of $\gtrsim$ 10 MeV protons on a sub-mm scale length.

The process of collimation of $\gtrsim$ 10 MeV protons is studied in this work using numerical modeling based on a test-particle approach. Different collimating field profiles and proton source parameters are considered. The obtained results confirm the possibility of efficient collimation for protons with characteristic energies up to $\simeq$ 100 MeV. The proposed scheme based on the magnetic lens approach can be used in an all-optical setup for producing collimated proton beams for fundamental studies and prospective applications.

The work was funded by the Russian Science Foundation under Grant No. 24-22-00402.

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Efficient laser-based particle acceleration in the "bullet" and "bubble" regimes using J-class ultrashort pulses

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A compact source of laser-accelerated protons from various targets irradiated by powerful femtosecond laser pulses is currently considered as an effective tool for numerous applications, including applications in biology and medicine, and particularly nuclear pharmacology [1]. The main parameter characterizing the efficiency of ion acceleration is the ratio of their maximum energy to the energy of the laser pulse. Among the targets that enable optimal proton acceleration characteristics, thin foils are considered the most attractive [1, 2]. Previous studies have shown that, in this regime, characteristic values are of the order of 1 MeV/J for the ratio of the maximum proton energy to the laser pulse energy. However, some studies report this ratio reached the level of 10 MeV/J [2]. A key challenge is that the use of thin and ultra-thin foils requires laser pulses with ultrahigh contrast. Meanwhile, studies involving gas targets, particularly near-critical-density gas targets, have already demonstrated promising results in generating large numbers of high-energy, laser-accelerated protons. The need for some applications to obtain a proton beam with high average flux allows considering gas near-critical density targets competitive in relation to thin foils. In this paper, we investigate proton acceleration via directed Coulomb explosion, resulting from the explosion of a cavern formed during the relativistic self-trapping regime (RSC) of a laser pulse propagating in a near-critical-density target (e.g., a hydrogen or helium gas jet). Three-dimensional PIC simulations were performed using the moving-window method for laser pulses with the same energy $W_L = 2.2$ J and different durations in the range of 6-20 fs. Previously it has been shown that the "laser bullet" regime is optimal for obtaining bunches of electrons with a charge of 10 nC and energies exceeding 30 MeV [3]. When such an exploding cavern crosses the plasma-vacuum boundary, it also produces laser-accelerated protons with a characteristic charge of $\tilde{1}0$ nC, energies above 2 MeV, and a maximum energy-to-laser-energy ratio exceeding 10 MeV/J. Particle tracking reveals that the highest-energy protons originate from the boundary, emerging from transverse points across the entire cavern radius before being collimated. The proton beam's angular divergence decreases as pulse duration increases. For a given pulse duration, the maximum proton energy increases with optimal gas target thickness, exhibiting a roughly proportional dependence on density.

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Interaction of charged particles with a structured orbital angular momentum light beam.

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In addition to energy and linear momentum, light beams may also carry angular momentum. The latter is often separated into spin and orbital parts. Spin angular momentum arises due to polarization of the light beam, and orbital angular momentum (OAM) due to a spatial structure of the beam. For instance, circularly polarized electromagnetic waves may carry a spin angular momentum, while linearly polarized electromagnetic waves may possess a well-defined OAM [1].

An angular momentum exchange between electromagnetic waves and matter finds multiple applications, such as compact information storage, optical tweezers, particle acceleration and quasistatic magnetic field generation. Usually, the process of the interaction of light waves with matter involves collective effects. However, in rarefied medium single particle effects may dominate, as it was demonstrated in [2], where the angular momentum transfer from an OAM beam to rarefied plasma was considered. It was demonstrated numerically, that the transfer of OAM of a structured linearly polarized light wave is possible and occurs mainly as a single particle effect. Analytical consideration of the process revealed, that the low order perturbation theory is not sufficient to describe the net OAM gain analytically. In the work [3] it was also discussed that the lowest order paraxial approximation is not sufficient for the analytical description. Hence, an accurate consideration of higher orders of the perturbation theory and paraxial approximation expansions are required for a self-consistent analytical description of the process.

This work discusses angular momentum gain by charged particles in plasma interacting with structured light beam with an orbital angular momentum. The process of the angular momentum gain is considered analytically, based on the analysis of the corrections to the lowest order paraxial approximation. Numerical simulations are performed to verify the predictions of the analytical model.

The work was funded by the Russian Science Foundation under Grant No. 24-22-00402. The calculations were performed on the hybrid supercomputer K60 installed in the Supercomputer Centre of Collective Usage of KIAM RAS.

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Non-linear effects in laser-electron sources and their numerical simulation

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The development of compact but intense, spectrally brilliant and tunable hard X-ray and gamma radiation sources is an important goal that can bring about significant advances in the fields of material sciences, high resolution X-ray imaging and spectroscopy as well as enable high resolution nuclear spectroscopy [1]. One possible solution of this problem is laser-electron (also known as Thomson or Compton) sources of X-ray and gamma radiation, where high energy photons are produced in collisions of counter-propagating ultra-relativistic electron bunches and short laser pulses [2–3]. Among various designs of such sources the schemes where electron bunches with low emittance from linear accelerators encounter powerful laser pulses has been becoming more and more popular [4–5]. However in such a case due to high intensity of the laser radiation at the interaction point non-linear effects become non-negligible [6]. They include, for instance, the non-linear broadening of the emitted X-ray or gamma radiation spectrum as well as the generation of higher non-linear harmonics. The theory and numerical simulation of laser-electron sources working in the linear regime have been the subject of numerous previous publications [7]. In the present contribution a classical program code for the numerical modeling of the radiation of laser-electron sources, which takes into account non-linear effects, is presented. The influence of non-linear processes on the characteristics of laser-electron sources including polarization of the emitted radiation is discussed.

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Modeling of electron acceleration processes in dense plasma with a petawatt power laser driver

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Laser Wakefield Acceleration (LWFA) [1] and Direct Laser Acceleration (DLA) [2] are two distinct mechanisms for electron acceleration in subcritical-density laser-plasma interactions. In LWFA, electrons are accelerated by a plasma wakefield driven by an intense laser pulse. The DLA mechanism accelerates electrons in an ion channel that the laser pulse breaks through in the plasma or plasma bubble due to betatron resonance.

This study investigates the influence of plasma density on electron acceleration under irradiation by a high-intensity laser pulse 10^{22} W/cm^2 using PIC code EPOCH [3]. As a target we used fully ionized argon (gas density of 10^{19}–10^{22} cm^{-3}). Figure 1 shows the electron energy spectra across the simulated density range.

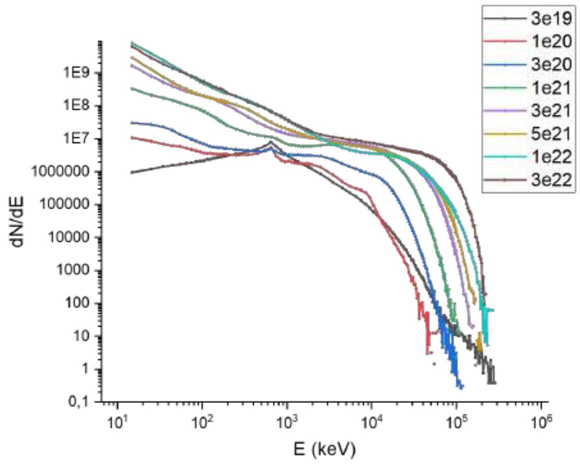

Figure 1: Electron spectra depending on plasma density.

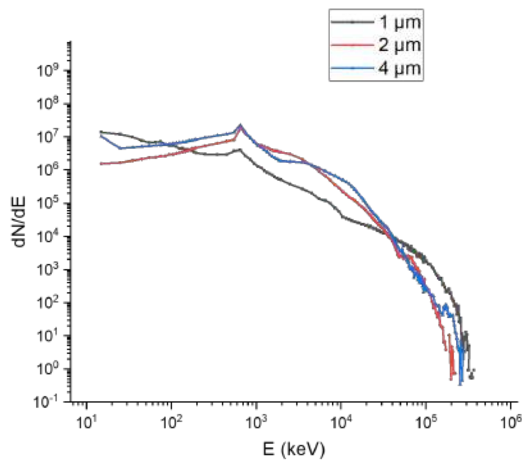

Figure 2: Electron spectra depending on the laser pulse radius.

In the study, the dependence of laser pulse absorption on plasma density was examined. We determined electron spectra and angular distributions. Figure 2 illustrates the electron spectra depending on the laser pulse radius. For a plasma density of 10^{20} cm^{-3}, the dependence of the beam intensity of the initial radius of the laser pulse was analyzed, and how the pulse radius changes over time was determined.

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On collisionless dissipation of a relativistic discharge pulse

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Irradiation of a this metal wire by a short relativistically intense laser pulse may result in formation of strong discharge pulsed current, which propagates along the wire with relativistic velocity. This phenomenon was observed experimentally, see e.g. [1] and in numerous simulations, e.g. in [2]. It was found that it may be robustly realized when the laser driver intensity exceeds the relativistic threshold, which is related to the fast local charging, when electrons are expelled from the interaction region during the irradiation process. Some parametric studies were performed numerically [2] which show that in a wide range of parameters, the propagation velocity of the discharge front is very close to the light velocity, and that the intensity of the propagating discharge pulse is scaled roughly as the intensity of the laser driver. Though, there are several principal questions which are still debated. These are the spatial shape of the pulse and particularly its width, its absorption rate and the propagation distance, its propagation velocity, etc. All these properties are probably dependent on the conductor size, geometry, material, as well as on the discharge amplitude and initial profile.

In this work, based on the qualitative analytical model, presented in [1], and on several sets of numerical modeling, it was shown, that the important parameters of the conductor, which define the physics of the discharge pulse propagation are the cross-section geometry and and the surface quality. For equivalent initial conditions, the propagation velocity appears to decrease for a conductor with a cross-section of a smaller curvature [3] and for a conductor with a non-ideal surface. In these cases, along with the velocity decrease, the pulse width increases.

The observed trends may probably be attributed to a higher absorption rate of the propagating discharge pulse. According to the analytical model in [1], it relates to the collisionless absorption of the electromagnetic wave energy to electrons in the co-moving plasma cloud. These findings propose a way to control the properties of the fast relativistically-intense discharges in thin wires, opening possibilities for novel applications.

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Efficient generation of few-cycle mid-infrared pulses by Doppler shifting of ultraintense laser pulses reflected from near-critical-density targets

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The work is devoted to a theoretical study of the process of generation of low-frequency radiation when relativistically intense laser pulses are reflected from the surface of ionized targets. Based on the previously developed model of a relativistic electron spring [1], it is shown that, along with the known effect of high harmonics generation, generation of a low-frequency radiation is also observed, caused by the averaged motion of the plasma boundary under the action of the ponderomotive force deep into the target. The model's predictions were confirmed by direct numerical simulation using the particle-in-cell method [2].

It has been shown that the efficiency of low-frequency radiation generation increases with increasing pulse amplitude and decreasing target density. When using targets of near-critical density, generation of radiation in the mid-infrared range is observed. The efficiency of generation of radiation with a wavelength > 3 μm in that case has been demonstrated to reach several percent. The duration of the generated pulses can be 10–20 fs, that is, they contain only 2–3 optical periods. With appropriate focusing, such pulses can achieve relativistic amplitudes.

The possibility of using several laser pulses is also considered. It has been shown that when irradiated with two or more pulses, the generation efficiency increases due to an increase in the radiation amplitude [3].

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Matching conditions for relativistic self-trapping of a laser beam

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The implementation of the relativistic self-trapping mode of an electromagnetic beam in plasma, in which a stable channeled propagation of relativistically intense laser light is observed, providing effective acceleration of electrons, depends on the fulfillment of the matching conditions for laser-plasma parameters. A theoretic-analytical approach is presented [1] that allows formulating these conditions at a quantitative level, taking into account the effects of relativistic nonlinearity of the electron mass and electron cavitation in plasma. The proposed approach is confirmed by numerical modeling and a number of experimental facts and is applicable for a wide, practically required range of laser intensities [1,2].

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Producing X-ray and gamma-ray pulses in the Compton backscattering mode using multi-petawatt lasers and plasma films

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X-ray and gamma-ray pulses are very important tools in different fields of science and technology. Among the various methods of generating high-energy photon beams, the use of the Compton backscattering has significant advantages, as it allows one to control frequency and intensity of radiation. In addition, when using modern multi-petawatt laser systems, bunches of relativistic electrons with the required characteristics can also be formed using fully optical methods, which significantly increases the flexibility of parameter control and reduces the size and cost of the system. One of the possible optical methods for the formation of a relativistic electron bunch is associated with the vacuum direct acceleration of thin foil electrons by the field of a laser pulse with a sharp front during its normal incidence [1,2]. The maximum electron energy is determined by the intensity of the laser field and the surface charge density of the foil electrons. After the electrons gain the required energy, they begin to interact with a counter propagating laser pulse formed by the same laser system, and generate X-ray or gamma-ray pulses.

The generation of X-rays during interaction of a counter propagating laser wave with a relativistic electron bunch formed by intense accelerating laser pulse from a plasma layer was numerically investigated in [3] for the sub-petawatt laser power. The time structure and spectral density of the far zone radiation field and the angular distribution of the pulse energy were found. One of the most important parameters of a high-energy photon beam is its maximum frequency and the number of photons with an energy exceeding a given one. Both of these parameters increase with increasing laser power, so the transition to multi-petawatt regime is of great interest. In this work, the generation of X-rays and gamma rays using a laser system with a power of several tens of petawatts (normalized laser amplitudes is up to 200) are analytically and numerically investigated. Various types of targets are also analyzed: solid-state and foam films, and thin gas layers, for which maximum electron energies depending on the target parameters are found. It is shown that the energy of the photons produced can reach hundreds of MeV, and the angular beam width can be less than one degree.

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Ultra-intense and ultra-short laser and its applications

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Abstract: A series of ultra-intense and ultra-fast lasers (0.2 PW, 1 PW and 10 PW lasers) have been developed which have been in opening operation for international end users. The applications based on the lasers will be presented briefly.

A series of ultra-intense and ultra-fast lasers (0.2PW, 1PW and 10PW lasers) have been developed in SIOM (Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences), which have been in opening operation for the internal and international end users (fig.1). Some laser driven particle acceleration experiments have been carried out based on these lasers recently. In this talk, the laser performance and the applications based on the lasers will be presented briefly. With the improvement of a home build Ti:sapphire femtosecond laser, the stability of the 0.2 PW and 1 PW laser has been increased for the more stable electron acceleration [1]. Then the laser driven electron accelerator has been achieved with near GeV energy and <1% energy spread [2]. Finally, a free-electron lasing using a laser wakefield electron accelerator has been demonstrated [3]. Recently, collaborating with the end users, the strong field THz station [4] and proton accelerator station, have been built based on the home build Ultra-intense and ultra-short lasers. Based on these experimental stations, the first Muon production has been demonstrated by the collaborators from 9 groups, including China Academy of Engineering Physics, Institute of Modern Physics, and so on [5].

Figure 1: Ultra-intense and ultra-fast lasers in SIOM.

Figure 2

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(SULF), 100PW laser system in the Station of Extreme Light (SEL) at Shanghai XFEL facility (SHINE) (in building), and so on. Now, he acts as the director of State Key Laboratory of Ultra-intense laser Science and Technology. He is Fellow of Optica.

Spherically collapsing dipole wave theory

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We investigate exact nonstationary solutions of Maxwell's equations in vacuum, which describe electromagnetic dipole pulses [1, 2]. Using these solutions, it is possible to model highly efficient focusing of the electromagnetic field, applicable in high-energy laser physics to achieve high field densities, strong matter compression, charged particle acceleration and electron-positron pair production [3]. The particular case of a monochromatic dipole wave and a more general case of the arbitrary duration dipole pulse are considered and analyzed in detail. The structure of the electric and magnetic fields and the spatial distribution of the electromagnetic energy density are discussed. Also the amplitudes of the electric and magnetic fields at the focus are found. It is shown that the characteristic spacial focusing volume of a single-period pulse reaches the value $\approx 0.004\lambda^3$ in the case of a Gaussian envelope in the far-field region and the value $\approx 0.002\lambda^3$ in the case of a quasi-Gaussian envelope.

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The influence of the near-surface environment on the X-ray flux when creating a microfocus x-ray source using technological femtosecond lasers

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Obtaining an image of the internal structure of an object using X-rays is an important diagnostic tool in medicine and biology. The development of modern high-tech laser systems has enabled the creation of a compact laser-plasma x-ray source based on high repetition laser systems.

Previously, we developed a microfocus laser-plasma X-ray source using a fiber laser interacting with a copper target in ambient air [1]. However, the energy of the laser pulses in the laser was limited to 40 μJ per pulse at repetition rate of 200 kHz, and 10 μJ at an optimal repetition rate of 2 MHz. At the same time, the work observed effects associated with the saturation of the X-ray flux when the energy increased. The question of the influence of the near-surface environment on the generation of X-ray photons also remained unclear.

Therefore, the aim of this work is to study the dependence of X-ray flux on laser energy at comparable conditions of focusing, radiation wavelength, pulse duration, and pulse repetition rate, using a high-repetition rate laser that provides higher energy per pulse than fiber laser. The aim of the work also was to study the effect of ambient pressure on X-ray flux and to determine the optimal laser parameters for creating a microfocus x-ray source.

The experiments were conducted using a TETA-20 ytterbium femtosecond fiber laser ($\lambda = 1030$ nm, pulse energy up to 400 μJ, repetition rate up to 200 kHz, pulse duration 200 fs, NA = 0.2).

We measured the X-ray flux at 50 kHz, 100 kHz, and 200 kHz, with a maximum pulse energy of up to 400 μJ. We show that increasing the laser pulse energy to 100 μJ at 200 kHz enhances to 10^{10} photons/pulse/2π. This X-ray flux is nearly 10 times higher than X-ray flux obtained using a fiber laser with pulse energy up to 40 μJ. Measurements taken at repetition rate of 100 kHz and 50 kHz and pulse energies up to 400 μJ demonstrate saturation of X-ray flux when the target is located in air at energies above 80 μJ.

The measurements obtained at low pressure demonstrate an increase in X-ray flux by 2–5 times at energies of 100–400 μJ (Figure 1a). Thus, at a repetition rate of 50 kHz and an energy of 400 μJ, the X-ray flux is comparable to the data obtained in air at 200 kHz and 100 μJ. Notably, at low pressure, ablated particles accumulated on the vacuum chamber walls and the

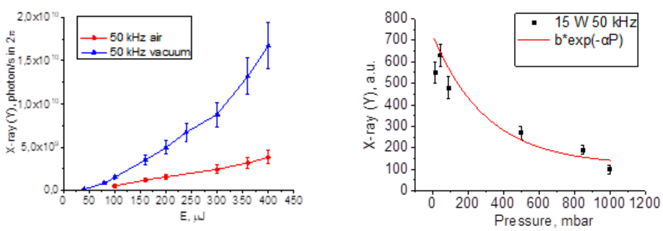

Figure 1: a) Dependence of X-ray yield on laser pulse energy in air and at a pressure of 20 mbar, measured at a frequency of 50 kHz, b) dependence of X-ray yield on pressure.

focusing objective. To avoid this, we implemented a system of nozzles that "evacuated" the particles and "blowed them away" with air. The optimal pressure in the found in experiment was 20–50 mbar, which provided the highest yield of X-ray photons (Figure 1b).

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Relativistic electron acceleration with oxygen small clusters

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Laser acceleration of electrons in plasma waves allows achieving record values of the accelerating field of 1–100 GV/m, exceeding the limiting values for classical accelerators. Gas clusters can effectively inject electrons into a plasma wave under laser irradiation with relativistic intensity ($I > 10^{18}\,\mathrm{W/cm^2}$). It is considered that efficient injection will occur when the electrons leave the cluster during laser exposure. However, to date, the optimization of cluster sizes for laser acceleration of electrons has not been thoroughly investigated. We propose using oxygen, nitrogen, argon in the low-pressure mode and minimal cluster size as a laser target. This made it possible to obtain a stable, narrow (5–10 mrad) electron beam with a charge of tens of pC [2] and a thermal spectrum with $E = 4\,\mathrm{MeV}$ [1].

Radiation from a multi-terawatt Ti:Sa laser complex at the Kurchatov Institute NRC was used (pulse duration $\Delta t > 30\,\mathrm{fs}$, pulse energy $E < 300\,\mathrm{mJ}$, repetition rate $\nu = 10\,\mathrm{Hz}$). Radiation focusing provided a relativistic laser intensity of $I = 8 \times 10^{18}\,\mathrm{W/cm^2}$. The target was formed as a result of supersonic expansion of gas into a vacuum in a conical nozzle. Powerful THz radiation [2], X-rays and ions are registered in parallel with electrons. For each gas, pressures and energies were found when a high charge and high directivity of the accelerated electron beam are simultaneously observed, while the cluster size is extremely small (3–5 nm), and their concentration is high. The presence of clusters in the target is checked by bright X-ray radiation, observed scattering, and analytical estimates. The best e-beam divergence (5 mrad) with sufficient charge (up to 30 pC) was obtained in gases with the lowest atomic number. Electron beam properties are consistent with a bubble or SM-LWFA acceleration regime [3]. At high pressure (and always in heavy gases), a high electron beam divergence is observed (100–200 mrad) with several nC charge, this is consistent with the DLA mode.

The results are relevant for obtaining betatron X-ray, bremsstrahlung gamma radiation flash-therapy studies with an electron bunch with a large charge and a short duration.

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Refocusing high-power fs-pulses using cone-shaped curved channels

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Currently, methods for increasing the peak intensity of laser pulses are being actively developed, and the pulses themselves are used in the study of various laser-plasma effects [1]. There is a problem of transporting high-power laser pulses and focusing them on the target, which also implies matching the target and the focal spot parameters. The solution to this problem can be based on the effects that occur when laser pulses propagate in hollow channels, either with straight parallel walls or not. In many studies, the interaction of laser pulses with cone-shaped channels is investigated, the effects of refocusing laser beams [2], the generation of electron bunches [3], and other phenomena are observed. In this work, using 2D PIC modeling, the effect of refocusing a laser beam using a channel with curved walls in the form of solid-state cylinders and increasing the field by a factor of 2 or more is shown. It is shown that by adding a thin wall at the channel outlet, protons can be accelerated, the energy of which is significantly higher than in the case without refocusing. The study was supported by the Russian Science Foundation grant No. 25-62-00019, https://rscf.ru/project/25-62-00019/.

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Preplasma formation and ion acceleration from ultrathin foils

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Laser methods of ion acceleration attract the attention of researchers due to the wide possibilities of using a compact source of a directed beam of fast protons [1,2]. For a long time, active work has been carried out to increase the acceleration of ions from a thin foil using a preplasma formed by the contrast of a laser pulse, or using an additional preliminary pulse. In this case, the preliminary pulse can lead to the destruction of the target, thereby reducing the number and energy of accelerated protons. Thus, there are optimal preplasma gradients, at which there is a significant increase in the number and maximum energy of accelerated protons due to self-focusing of the laser pulse. In this paper, we investigate the properties of proton beams and the formation of preplasma when a target is irradiated with a laser pulse with an energy of about 2 J.

We simulated the expansion of the target under the action of a nanosecond laser pulse and obtained density profiles of the preplasma formed on the irradiated side of the target. The simulation was carried out using the hydrodynamic code FRONT [3], which solved a system of two-temperature hydrodynamics, including the equation of continuity and the equation of motion of plasma density, as well as equations for the internal energy of electrons and ions. The calculations were carried out in three-dimensional (cylindrical) geometry. Three-dimensional modeling of laser acceleration of protons was carried out using the VSim code, which solves the Vlasov-Maxwell system of equations using the particle-in-a-cell method.

The calculations used laser pulses with an intensity from 10^{11} W/cm^2 to 10^{13} W/cm^2 and a duration of up to 5 ns. Aluminum, silicon, iron, and tungsten were considered as target materials. It follows from the calculations performed that there are no significant differences between different target materials at the considered laser pulse intensities in the low-density plasma region. However, in the solid-state part of the targets, there are differences in shear values and target thickness. For example, targets made of aluminum and silicon are shifted by $\sim$14 microns, 3.5 times less than heavy targets made of iron and tungsten at an intensity of 10^{13} W/cm^2 at a time of 5 ns. Complete destruction of lighter targets (aluminum and silicon) occurs at an intensity of 10^{13} W/cm^2 at a time of 5 ns, which corresponds to an embedded energy density of 50 kJ/cm^2.

A series of calculations of proton acceleration was performed for a laser intensity of 3×10^{20} W/cm^2 from targets with different preplasma gradients. Calculations show that, taking into account the plasma, protons can be accelerated to energies of the order of 5-10 MeV with sufficiently flat plasma density profiles. Also, shifting the position of the focus point of the laser pulse avoids the destruction of the back of the target. The shift of the focus point makes it possible to realize the self-capture mode of the laser pulse, which leads to an increase in the conversion efficiency of the laser pulse and an increase in the energy of accelerated protons.

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Generation of MeV-level multicharged ions from Kr clusters under irradiation with relativistic laser pulses

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Cluster jet is a promising target for interaction with relativistic laser pulses ($I > 10^{18}\ W/cm^2$) due to more efficient energy absorption than solid-state or gas targets [1]. In this work, we experimentally investigate the energy spectra of multicharged ions generated in krypton gas-claster target by relativistic femtosecond laser pulses.

Experiment was done on Ti:Sa laser system at the NRC "Kurchatov Institute" (central wavelength: 800 nm, pulse duration: 30 fs, repetition rate: 10 Hz, and target energy up to 200 mJ) with the intensities $> 5 \cdot 10^{18}\ W/cm^2$. Krypton was used to generate the clusters at initial pressures P_0 = 1 - 20 bars and room temperature. The average radii of the clusters were in the range of R_{cl} = 4 - 24 nm [2]. Multiply charged ions were detected using a magnetic deflection time-of-flight (TOF) spectrometer with a grounded drift tube with magnetic field at the entrance aperture (0.6-0.7 T) and a microchannel plate (MCP) detector at the end for positive particle detection.

As a result, an increase in the charge (up to Kr^{5+}) and energy (up to ~3.2 MeV) of accelerated ions was detected when large Kr clusters with a radius of more than 12 nm (P_0 > 7 bar) were irradiated with relativistic laser pulses, as shown in Fig. 1.

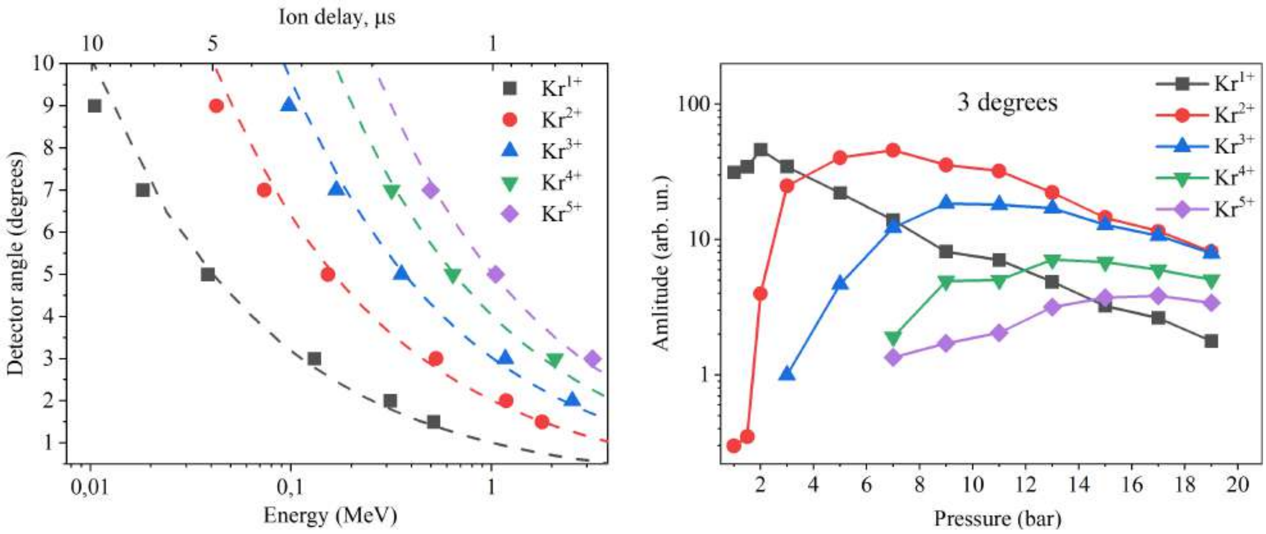

Figure 1: Detected with magnetic TOF spectrometer ion peaks of krypton (left) and their amplitude as a function of krypton pressure (right).

Ya.O. Romanovskii is a scholarship holder of the Theoretical Physics and Mathematics Advancement Foundation “BASIS”.

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Extending Monte-Carlo simulation of QED effects to account for leptons spin and photons polarization

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It is well-known that spin of an electron represents its inherent, purely quantum degree of freedom which plays a crucial role in determining its behavior in various scenarios. Although, only relatively recently has its significance been acknowledged in the context of strong field quantum electrodynamics (QED). In particular, recent research shows that accounting for the electron spin and the photon polarization in processes such as nonlinear Compton scattering and nonlinear Breit-Wheeler process might lead to new effects observed in the interaction of extremely intense laser radiation with matter, such as significant increase of pair production during QED cascade development [1], production of highly polarized high-energy particles [2, 3], spatially-inhomogeneous polarization [4], signatures of vacuum polarization [5], etc.

In this work we discuss how resolving particles spin/polarization affects the probabilities of QED effects and what numerical techniques can be used in order to efficiently simulate QED processes in modern particle-in-cell codes. We introduce our recently developed C++ library which allows for a simple and efficient way of incorporating the relevant algorithms into existing codes. We have also implemented Python interface to the library which additionally allows to simulate relativistic particle motion in given fields with account of QED processes and spin dynamics. We demonstrate how both some well-established and only recently discovered effects caused by resolving the particles spin/polarization can be reproduced using our library.

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Features of the distribution of highly charged ions when irradiating metal foils with ultra-relativistic femtosecond laser pulses

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This paper presents the results of a numerical simulation using the Particles in Cells (PIC) method, which illustrates the evolution of the parameters of a laser plasma generated by irradiating steel foils with a thickness of 2-5 μm with femtosecond laser pulses with an intensity of $\geq 5 \cdot 10^{21}$ W/cm^2. The results of the PIC calculation are compared with the experiment in which X-ray spectroscopic methods were used to diagnose the plasma parameters. Atomic kinetic calculations performed for the concept of plasma zones [1] were used to analyze the X-ray spectra of the femtosecond laser plasma measured in the experiment. The results of the PIC simulation allowed for the first time a numerical estimation of the parameters of the plasma zones, their size and lifetime.

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Optics for compressors and post compression in petawatt lasers: challenges and solutions

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Femtosecond petawatt (fs-PW) ultraintense lasers are important tools for exploring high-field effects, such as laser plasmas [1], particle acceleration [2], intense radiation [3], etc. Nowadays, 10-PW laser facilities have been built in China [4] and Romania [5] based on the Ti: sapphire chirped-pulse amplification. However, the available crystal size and the inherent transverse parasitic lasing effect in the Ti: sapphire crystal limit the significant increase in the maximum pulse energy, as well as the highest intensity. To further increase the peak power to 100-PW or even higher, optical parametric chirped-pulse amplification and post-compression technologies are two promising ways, which relies heavily on advanced optics capable of handling ultrahigh peak powers.

Pulse compressed gratings and chirped mirrors as the key components face critical challenges in pulse compression and post-compression stages, respectively. For gratings, the primary limitations stem from the need to simultaneously achieve broad bandwidth with high diffraction efficiency, exceptional damage resistance - all while scaling to meter-sized apertures with sub-wavelength wavefront precision. These competing demands create severe manufacturing constraints, particularly in maintaining nanoscale groove uniformity across large areas while mitigating electric field enhancements. Similarly, post-compression chirped mirrors must satisfy extreme requirements including ultra-broadband operation, precise dispersion control, high damage thresholds at large apertures, and negligible nonlinear effects - a combination that pushes current thin-film coating technologies to their limits. The stringent specifications for both components represent fundamental bottlenecks in advancing petawatt laser performance to the 100-PW frontier and beyond.

This work presents innovative solutions to these challenges, including the design, manufacture and laser-induced damage analysis of advanced broadband gratings with high diffraction efficiency, as well as ultra-broadband chirped mirrors with precise dispersion control. By addressing these optical bottlenecks, we pave the way for next-generation PW lasers with higher peak powers and shorter pulses, opening new parameter spaces for extreme light-matter interactions.

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Laser-plasma electron acceleration diagnostics via second harmonic radiation from the plasma channel sheath

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One of the most popular laser plasma electron acceleration mechanisms is Direct Laser Acceleration (DLA, [1]). Efficient electron energy gain by DLA is observed under a resonance condition, which is determined by the phase velocity of a laser pulse in a plasma channel v_ϕ [2]. The method of the plasma channel diagnostics by second harmonic generation from the plasma channel sheath proposed is based on the matching condition defined by v_ϕ, which makes it most suitable for characterizing DLA efficiency. We demonstrated the experimental implementation of the DLA diagnostics (see fig. **??**). The PIC-simulations we have performed show that this method allows us to obtain information about the phase velocity with very good accuracy $\sim 0.05\%$.

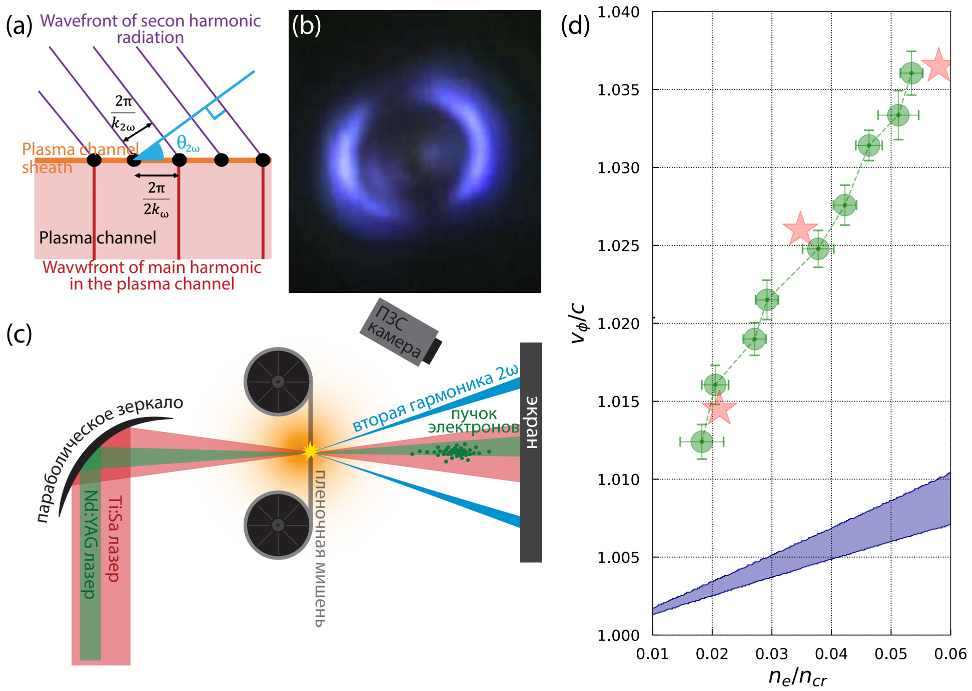

Figure 2: (a) Phase-matching conditions for second harmonic generation from the plasma channel sheath. (b) Second harmonic radiation recorded by the CCD camera. (c) Experimental setup. (d) Dependence of phase velocity on the electron density outside the channel: green – experiment, red – PIC-simulation, blue – analytical area of efficient low-energy electrons acceleration.

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Role of polarization in femtosecond laser-plasma driven electron acceleration

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The effect of polarization on the acceleration efficiency of an electron beam in a laser-plasma accelerator operating in the relativistic self-trapping regime was investigated. Numerical simulations of the acceleration process were performed using a three-dimensional Particle-in-Cell (PIC) method. The main characteristics of the generated beams—such as total charge and energy—were compared for cases of linear and circular polarization. The comparison was conducted using optimal laser-plasma interaction parameters for each polarization type. These parameters were determined by varying the target plasma density, pulse duration, and laser focus spot size while keeping the laser energy constant at 2.2 J. The results showed that, in all cases considered, the total beam charge was higher for a circularly polarized laser pulse than for a linearly polarized one.

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Influence of a single-cycle, strong THz pulse on a bunch of relativistic electrons

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A strong singlecycle THz field generated by terawatt laser radiation can be used to accelerate or deflect a bunch of relativistic electrons obtained from a linear accelerator or in an all-laser experiment [1]. We investigated of the possible influence of a single-cycle picosecond THz pulse in a simplest scheme on bunch of electrons accelerated in a gas-cluster laser plasma.

An analytical model was developed to describe the effect of a co-directional THz pulse on bunch of electrons with broad energy spectra. We calculate the angle of deviation and the magnitude of electron's deviation from a initial trajectory (fig. 1, left). Calculations also take into account the transverse and longitudinal dimensions of the interaction region of THz pulse with electrons. Transverse dimensions are limited by the diameter of THz beam, and longitudinal dimensions are limited by the difference in the velocities of the electrons and the pulse. THz absorption in the laser plasma is also considered.

Related experiments were produced on laser-synchrotron complex at the NRC "Kurchatov Institute" (pulse duration $\tau = 30$ fs, energy in laser pulse $E = 200$ mJ, repetition rate $\nu = 10$ Hz, intensity $I = 5 \times 10^{18}$ W/cm^2) . The laser irradiated a gas-cluster jet (nitrogen N_2, pressure $P = 10 - 20$ bar, temperature $T = 298$ K, open angle $2\alpha = 10°$, critical section $d_{cr} = 700$ μm, length $Z = 10$ mm). Electrons had wide energy spectrum from 0.3 to 10 MeV and total beam charge $Q = 25$ pC in a collimated beam. The source of THz radiation was the previously studied thin crystal of $LiNbO_3$ (electric field $E_{THz} = 1$ MV/cm) [2], radiation in which was generated just before the gas nozzle.

As a result, experiments showed that the results coincided with the calculations using the model (fig. 1, right). Big difference between velocity of non-relativistic electrons and THz wave limits deflection efficiency. Electrons with energy 1.2 MeV or higher interact with THz pulse too long, and they returns back to initial trajectory.

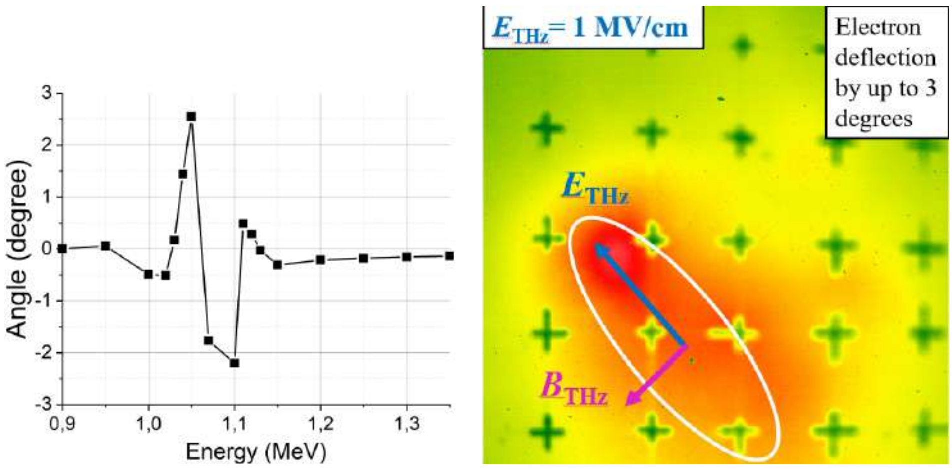

Figure 1: Left – Dependence of the angle of deviation on electron energy. Right – Electron beam broadened by THz pulse.

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Generation of collimated quasi-monoenergetic electron beams on a terawatt laser system

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The generation of electron beams with high average and peak powers by an intense (over 10^{18} W/cm^2) laser pulse is largely associated with the engineering of a plasma target, the parameters of which determine both the efficiency of the particle acceleration process and the ability to rapidly resume upon the arrival of the next impulse. This work is aimed at creating a bright laser-plasma source of high-energy electrons and neutrons for the above applications based on the interaction of intense laser radiation with the plasma of a gas jet shaped by shock waves of additional laser pulses. Here controlled modification of a gas jet by shock waves of individual laser pulses will be used for electron acceleration.

A nitrogen gas jet (nozzle diameter 400 μm) was used to form the plasma target. Interferometric measurements enabled reconstruction of the gas concentration profile. At pressures of 2–3 bar and 200 μm above the nozzle, the concentration reached 0.01 critical density over a length of about 300 μm. Hydrodynamic modeling showed that a shockwave generated by an additional nanosecond laser pulse caused a sharp density jump with fivefold concentration increase, featuring a 5 μm thick leading edge and 25 μm thick trailing edge. The shockwave position could be adjusted by changing the nanosecond laser focus position relative to the gas jet.

Two main regimes of electron beam acceleration were studied. In the first regime, the shockwave created a low-density region before femtosecond pulse focusing, suppressing ionization defocusing and increasing plasma wave amplitude. This produced electron beams with up to 10 pC charge, exponential energy spectrum (slope ∼5 MeV), and maximum energies reaching 20 MeV. In the second regime, the shockwave terminated acceleration, preventing electron dephasing and generating quasi-monoenergetic beams with 6–12 MeV energy and ∼1.5° divergence.

Experimental results and PIC simulations demonstrated tunable quasi-monoenergetic electron beams in the 6–12 MeV range with narrow energy spread (∼2.5 MeV), achieved by shockwave-induced acceleration termination at different electron deceleration stages. An analytical model of electron acceleration in nonlinear plasma waves explained the quasi-monoenergetic beam formation mechanism and predicted the tuning range (6–12 MeV) and energy spread (2.5 MeV). Plasma wave damping due to laser pulse absorption by a plasma was shown to reduce energy spread.

In addition, by selecting the parameters of the target and the focusing parameters of the laser pulse, a regime with the generation of a quasi-monoenergetic electron beam in the pump depletion regime was obtained. When introducing astigmatism by tilting the parabolic mirror, the electron beam became quasi-monoenergetic with a maximum energy of about 20 MeV with a spectrum width of several MeV.

Energy spread of a finite charge electron bunch in LWFA

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The dynamics of energy spread is investigated, taking into account the effect of the accelerating electron bunch on the accelerating fields (beam loading effect). The possibility of additive consideration of the own charge field [1,2] in a nonlinear wakefield acceleration is shown (Fig. **??**).

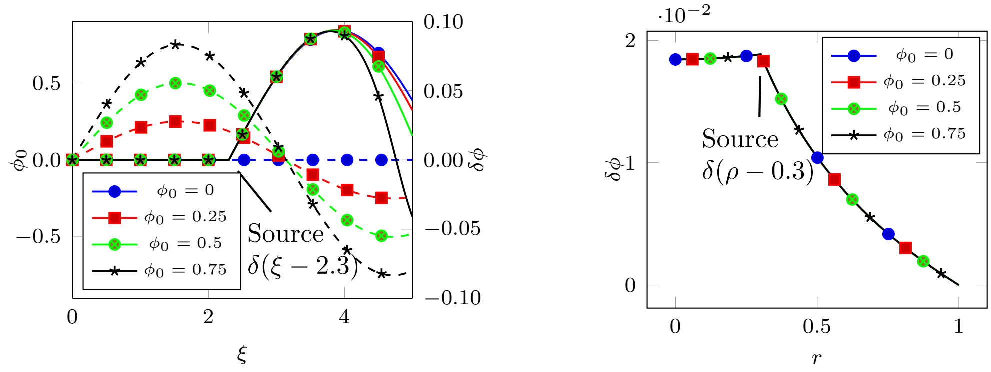

Figure 1: Comparison of solutions for point source (solid lines) for different predefined wakefield potentials ϕ_0 (dashed lines). Difference between solutions is negligible within the length of an electron bunch ($l_\xi \ll 1$).

The analysis is based on dividing the energy spread into different contributions:

$$\sigma_{\mathcal{E}}^2 = (\sigma_{\mathcal{E}}^{\text{init}})^2 + (\sigma_{\mathcal{E}})^2 + (\sigma_{\mathcal{E}}^{\text{long}})^2, \quad (1)$$

where $\sigma_{\mathcal{E}}^{\text{init}}$ is the initial energy dispersion of the bunch at the moment of injection, $\sigma_{\mathcal{E}}$ is the energy dispersion of the bunch slice and $\sigma_{\mathcal{E}}^{\text{long}}$ is the dispersion of average slice energy over all bunch slices.

Based on the theory, we derived an expression for the energy spread depending on the acceleration parameters. A comparison with the results of full-scale PiC simulation demonstrated good agreement. For different parameters of the accelerating wakefield, the optimal parameters of the accelerated electron bunch (charge, length, emittance) were found, for which the minimum energy spread at the end of wakefield acceleration is achieved. Based on these results, we demonstrated via PiC simulation the possibility of the wakefield acceleration of a 70 pC bunch to an energy of 20 GeV with an energy spread of ~ 1–2% over 2 m of the accelerating stage.

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On the optimization of bremsstrahlung γ-quanta generated by high-current relativistic electron beams

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Using analytical estimates and numerical modeling with the Geant4 code, the optimal choice of converter target parameters and electron beams for generating bright gamma-ray sources, or sources that provide the maximum photon yield in a given energy range, is investigated. It is shown that when high-current, high-energy electron beams act on metal foil converters, the maximum photon yield can be achieved with a converter thickness comparable to the radiation length of electrons. Such beams can be generated using powerful laser pulses interacting with near-critical density plasma obtained from foam targets [1]. The choice of converter material is also discussed. On the other hand, to achieve high brightness and small size of the photon source, it is necessary to use significantly thinner targets with a minimum thickness determined by the size of the electron beam and practical requirements for the number of generated quanta [2].

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The nano-fuzz low-density laser targets and spontaneous emergence of nanograss in some physical processes

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Nano-grass or nano-fluff, or nano-fuzz, etc. are fractal porous organometallic compounds, which may appear on the surface of metal electrodes in a different field of physics, from microelectronics [1], to plasma and nuclear physics [2], also in catalytic processes, interaction of laser radiation with various types of condensed matter [3], during etching of surfaces, sintering of powder layers, formation of surfaces with certain rippled properties, metallization of aerogels in electrochemical processes and many others. For example, tungsten is being considered as one of the materials from which all surfaces of the divertor of the international tokamak ITER in contact with plasma are created [2]. This is why the interaction of plasma namely with the tungsten parts is of special relevance. Nano-grass appears in many experiments on intention or spontaneously. In each case it may have desirable or negative effect (as in the field of controlled thermonuclear fusion, for instance). These need a profound study in order to understand the phenomena and to control the necessary evolution or to prevent unwanted. Suppose in microelectronics the formation of nanograss can be useful for the assembly of microelectronic elements and thus should have positive effect. Whereas similar spontaneous processes in the metal constructions for nuclear physics cause unpredicted behavior and give negative results. But in both cases mechanisms of nano-grass growth and their properties are important.

Here we study a number of differing processes to produce nano-fuzz laser targets and report appearance of nano grass by bringing the cathode and anode closer together at a distance of about tens of microns (Figure 1) [4]. The processes are numerically modeled by Monte Karlo method. The results are analyzed for application in microelectronic, for laser targets in ICF and for secondary radiation sources under laser irradiation [5]

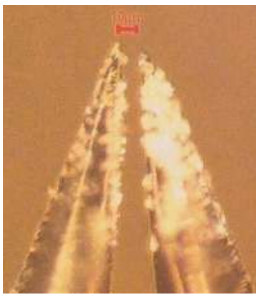

Figure 1: Tungsten microware with nanograss.

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Ablation and surface structuring of copper plates using single pulses of different duration of Nd:glass lasers

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During the process of laser ablation, the surface structure of the materials changes [1], and the change in structure is associated with the parameters of laser radiation, the properties of the substance itself, and the ablation conditions. Controlled ablation allows the creation of desired surface structures. In our work, we studied the effect of laser pulse duration on changes in the surface structuring of copper plates.

In the experiments, two Nd:glass lasers with different full widths at half maximum (FWHM) of pulse durations were used: 170 ns for the laser assembled in our laboratory and approximately 16 ns for the industrial laser. For both lasers the wavelength of radiation was the same – 1060 nm, and the energy per pulse was approximately 140 mJ. In the case of the industrial laser, similar experiments were also conducted for comparison, but with the maximum possible energy per pulse, which was 180 mJ. We consider structures obtained under the influence of a single pulse without focusing the laser radiation, at the focus of a converging lens (F = 100 mm), and also with the target positioned 5 to 40 mm away from the focal position in 5 mm increments. A gradual increase in the ablated area and a decrease in its depth are observed with increasing distance from the focal position for both lasers.

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Ablation and surface structuring of copper plates using single pulses of different duration of Nd:glass lasers

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Section 2: Ultrafast phenomena in ionized gases, semiconductors and metals

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Scope

Strong-field and ionization-induced phenomena

Instabilities and high-frequency phenomena in ionized gases

Non-linear phenomena in low-temperature plasmas and semiconductors

Kinetic processes in plasmas and metals

Hot electrons in nanoplasmonics

Ultrafast spectroscopy and imaging of optical, electronic and hot-carrier dynamics

Ultrafast spectroscopy and imaging of structural dynamics, including electron-phonon relaxation, coherent phonons and phase transitions

Influence of intense THz dressing field on the harmonic generation in semiconductors

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Understanding of the underlying processes of high order harmonic generation (HHG) is of paramount importance in intense-field laser-matter interactions. Even though HHG is a well-known phenomenon in atomic gases, experimental application of strong fields to solids was reported much later [1] and has serious limitations related to strong absorption in the volume of the bulk material and significantly lower laser damage threshold of solid materials.

HHG has proven to be a useful tool for studying electronic dynamics and structure in crystals. The low efficiency of the HHG process we believe can be solved by using multi-color fields reducing the symmetry of crystals allowing the observation of even harmonics in centrosymmetric crystals [2].

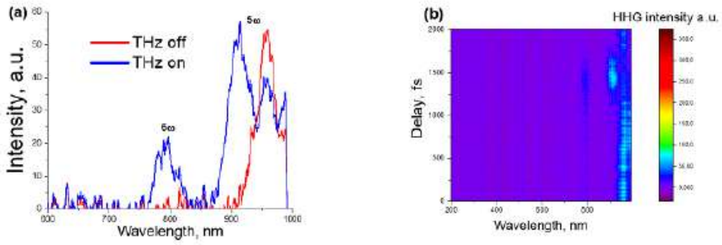

Figure 1: (a) detected 5th and 6th harmonics in CdS with (blue) and without (red) THz field dressing. (b): HHG spectrum generated in thick CdS sample (1,4 mm) using mid-IR pulse of signal wave accompanied by intense THz field (7 MV/cm) for varying delay times;

We study HHG in crystalline thick (1,4 mm) CdS (type wurtzite, 0001-cut) from idler wave of optical parametric amplifier (4,8 μm; 90 fs; 60 μJ) accompanied by a strong (up to 10 MV/cm) THz field. We observe (fig. 1) generation of the 6th harmonic due to THz-induced symmetry breaking as well as frequency shift of the 5th harmonic. Similar effect was observed in [3] with hydrogen atom interaction with driving laser pulse combined with a tunable quasi-static electric field. In addition, in thin sample (300 μm) of CdS we observed even harmonics up to 8-th order with intensity modulation.

The work is supported by the RSF grant #25-22-00084. The equipment used in this work was purchased with the support of the Program for the Development of Moscow State University and National Project “Science and Universities”.

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High harmonic generation under the conditions of multiphoton atomic excitation by a strong short-wave laser field

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Technological progress dictates the need to develop sources of coherent electromagnetic radiation in the extreme ultraviolet and soft x-ray ranges. Nowadays, the highest coherence of such radiation is provided by sources based on the high-order harmonic generation (HHG) of a laser field. Historically, the study of HHG began with the regime of tunnel ionization of matter by a strong long-wave field, which corresponds to small values of the Keldysh parameter ($\gamma \ll 1$). In this regime, the highest order harmonics corresponding to photon energies up to 1.6 keV [1] and the shortest pulses with durations less than 50 as [2] were generated. However, its main limitation is low efficiency, varying from 10^{-4} to 10^{-9} depending on the harmonic order.

Recently, it has been shown that this limitation can be overcome by switching to the regime of multiphoton excitation and ionization of matter, corresponding to large values of the Keldysh parameter ($\gamma \gg 1$). However, in most studies on HHG in the multiphoton regime, a weak long-wave, predominantly, infrared (IR) field was considered.

In this contribution, we consider the HHG by a strong short-wave ultraviolet (UV) field with photon energy sufficient for resonant excitation of an atom with the absorption of only a few photons, and its subsequent single-photon ionization from the excited states. For such a field, the photon multiplicity of resonances decreases several times compared to the IR field, which greatly increases the efficiency of atomic excitation and substantially enhances the harmonic power [3]. As we have recently shown, in this case the bound atomic states play a decisive role in HHG [4].

We derive an analytical solution, which shows that the most energetic part of the HHG spectrum generated by a short-wave UV field in a noble gas is produced via transitions between the hydrogen-like excited atomic states with nonzero mean dipole moments and the ground state of the atom. This analytical solution qualitatively agrees with the results of numerical solution of the time-dependent Schrödinger equation from first principles, and shows the possibility to produce harmonics with photon energies considerably exceeding the sum of atomic ionization potential and maximum kinetic energy of an ionized electron, which determines the cut-off frequency in the high-harmonic spectrum, generated by a long-wave laser field.

This work was supported by the Russian Science Foundation (grant No. 24–12–00461).

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Unipolar Light Pulses: Fundamental Advances and Applications

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This talk reviews recent breakthroughs in the fundamental physics of unipolar ultrafast light pulses, including the issue of their existence and the conservation rule of electric pulse area, as discussed in the following papers, reviews [1–3] and book chapter [4]. We discuss mechanisms of their generation in nonlinear media and plasma. We emphasize the role of electric pulse area in light-matter interactions. We present experimental demonstrations of unipolar pulse generation methods and a theoretical study of the control of quantum systems at subcycle attosecond timescales.

We briefly outline potential applications in attosecond science and petahertz optics, highlighting how these fundamental studies pave the way for novel physics. The collision of such pulses in a medium enables the creation of dynamical structures, such as high-Q optical microcavities, and their control on an ultrafast timescale [4-5].

This work was supported by the Russian Science Foundation (project 23-12-00012).

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Generation of Unipolar Half-cycle Light Pulses in Ionized Plasma Layers

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Unipolar light pulses contain a dominant half-wave of electric field with non-zero area, enabling unique applications in ultrafast optics through direct momentum transfer to charged particles [1-4]. We demonstrate theoretically how reflection of single-cycle pulses from thin plasma layers ($d \ll c\tau$) generates attosecond-scale half-cycle pulses. When the incident Gaussian field $E(x,t) = E_0 e^{-(t-x/c-t_0)^2/\tau^2} sin[\omega(t - x/c - t_0)]$ (Fig.1) ionizes the medium, it creates a half-cycle current pulse (right panel, Fig.1) that produces a near-field reflected half-wave pulse (red curve, Fig.1). The thin layer geometry provides temporal compression of incident field into a single dominant half-cycle, with trailing edge governed by plasma recombination dynamics. Our 1D Maxwell-plasma model confirms generation of half-cycle pulses, suggesting compact plasma mirrors as efficient unipolar pulse sources for attosecond electron control. This work was supported by the Russian Science Foundation (project 23-12-00012).

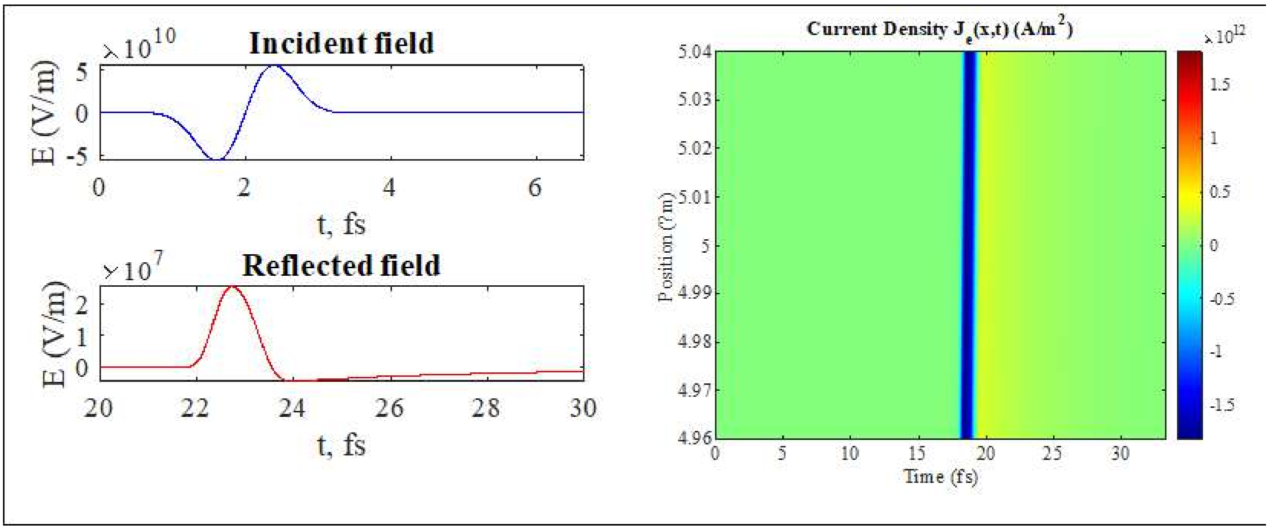

Figure 1: Incident field, reflected half-cycle pulse and current density in layer $d = 0.08\,\mu$m.

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PIC modelling of plasma gradient formation and electron kinetics on the surface of the solid target

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The geometric characteristics of the laser-induced plasma gradient on the surface of a solid-state target are important parameters that affect the efficiency of frequency conversion effects, such as the high-order harmonics (HOH) and terahertz radiation (THz) generation [1,2]. However, direct measurement of plasma parameters is difficult, which makes it possible to use numerical methods like PIC calculations [3] as an additional tool for better interpretation of a physical experiment.

In the present work, the interaction of laser radiation forming a surface plasma on an initially neutral dielectric target is considered. Two laser configurations for wavelengths of 3.9 μm ($I_0 = 55\,\mathrm{TW/cm^2}$, $t_p = 80\,\mathrm{fs}$) and 0.8 μm ($I_0 = 1340\,\mathrm{TW/cm^2}$, $t_p = 16.5\,\mathrm{fs}$) are shown. When the laser pulse interacts with the target, ionization assumed according to the Keldysh model. Our calculations demonstrate that ionized electrons are exposed to the laser pulse and accelerated. Further, the dynamics of these particles lead to the blurring of media interface and the formation of a plasma gradient (fig.1a). During this interaction, two groups of electrons are formed as shown in the particle distributions of the normal momentum projection (fig.1b). High-speed electrons appear after the formation of a reflecting plasma layer (left-side wing on the momentum histogram). However, the low-velocity electrons symmetrically distributed on the histogram are ionized at the depth of the solid target and accelerated by a laser pulse before plasma layer formation, since after this moment the pulse is reflected and cannot interact with them. Such electrons mainly compose the plasma layer due to its population. Therefore, their velocity magnitude determines the rate of change for characteristic length parameter (fig.1c). So the duration of the laser-plasma interaction until the moment of the supercritical plasma layer formation affects the changes in the geometric characteristics of the plasma gradient.

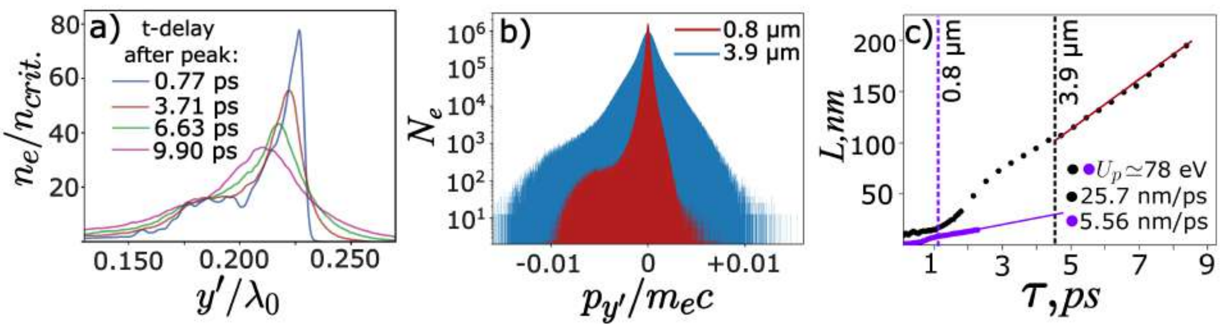

Figure 1: a) Temporal dynamics of plasma gradient. b) Electron momentum distribution after the moment of reflecting plasma layer formation. c) Temporal dynamics of the plasma gradient characteristic length L (black dots: case of 3.9 μm laser pulse, violet dots: case of 0.8 μm)

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On the possibility of controlling the process of laser microstructuring in fused silica in the presence of reflecting materials

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Nowadays, the technology of direct laser writing of nano- and microphotonic structures in the volume of transparent solid dielectrics by ultrashort laser pulses is widely used to create new types of metamaterials, volume diffraction elements, microwave circuits, polarization transducers, as well as elements and devices of 5D optical memory, where in addition to three spatial coordinates there are two optical dimensions - orientation of the slow axis and phase delay [1,2]. One of the proven microfabrication technologies is based on the method of creating a seed in a transparent dielectric in the form of localized material anisotropy (micro- or nanocavity) using a powerful femtosecond laser pulse. Further self-ordering of microstructures occurs in the process of laser writing by lower energy pulses due to the effects of near-field enhancement [2]. We have proposed and verified a new mechanism of laser microstructuring which can be realized under conditions of tight focusing of laser radiation [3]. This mechanism does not imply the formation of a seed in the volume of the material, but is based on the self-organization of matter due to the effects of scattering and interference of the laser field on the dense plasma formed in the pre-focal region. Here we plan to investigate the possibility of obtaining microstructures of different morphologies by controlling the interference pattern of the laser field in the near-focal region, which in turn will allow controlling the process of self-organization of plasma and final material structures. This task assumes the presence of an additional reflecting layer placed on fused silica. The main problem here is a significant difference between the damage thresholds of fused silica and existing reflecting materials, so one needs the detailed search and characterization of materials, including various samples of silica and materials used as reflectors, as well as the optimal regimes of laser exposure for the implementation of the proposed mode. We believe that by controlling the interference pattern of the laser field in the presence of reflecting materials it will be possible to lower the threshold of plasma formation, which will allow to obtain more regular structures with less energy input and the number of pulses per point. This work was supported by the Russian Science Foundation (Grant № 22-72-10076-P).

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Dynamic characteristics and formation mechanism of the complex dynamics in subnormal glow discharge systems: Mixed-mode oscillations and period-adding bifurcation

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Mixed-mode oscillation (MMO) is a type of complex dynamic behavior commonly observed in multiscale dynamical systems, where distinct mechanisms dominate different phases of system evolution, driving the system to alternate between slow and fast motions. In this work, a period-adding bifurcation sequence of MMOs (i.e., 1^0-1^1-1^2-…1^n-0^1) was observed in a subnormal glow discharge system by using the ballast resistance as the control parameter, where the number of large-amplitude relaxation oscillations in each oscillation period is fixed and the number of small-amplitude near-harmonic oscillations increases sequentially [1]. Intermittently chaotic regions caused by inverse saddle-node bifurcation exist between adjacent periodic windows, exhibiting an alternating periodic-chaotic phenomenon. Time series analyses including the largest Lyapunov exponent and correlation dimension confirmed the deterministic nature of chaotic states and demonstrated that the complexity of strange attractors increases with the order of bifurcations. A self-consistent fluid model reveals that the localized avalanches between the cathode and the virtual anode acted by the bulk plasma play a crucial role in shaping the MMO structure [2]. These localized avalanches arise from the combined effects of rapid voltage increases and delayed bulk plasma dissipation. The findings deepen our understanding of the formation mechanism of the MMOs in subnormal discharge systems and provide helpful inspiration in a wide range of spatially dependent nonlinear dissipative systems.

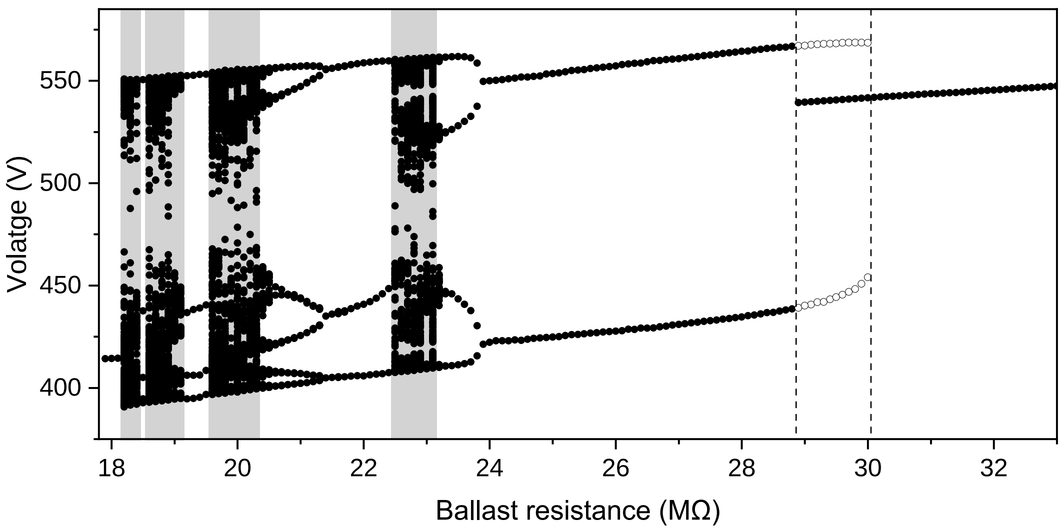

Figure 1: The amplitude bifurcation diagram.

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Laser sound generation in a homogeneously heated metal film

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One of the effects observed during the interaction of short laser pulses with metals is generation of picosecond acoustic pulses. Such pulses are of great interest due to their broad applicability in sample diagnostics. In metals, sound generation is associated with rapid heating of the lattice and electrons. In many experimental setups, picosecond acoustic pulses are generated in metal films whose thickness is smaller than the characteristic thermal diffusion depth. Sound generation in such films is analyzed in paper [1].

Ref. [1] describes the displacement of lattice atoms in a homogeneously heated metal film on a dielectric substrate at the effect of a femtosecond laser pulse. Expressions are obtained for both the atomic displacement and the reflectivity change $\Delta R(t)$ of the metal, associated with lattice deformation. The behavior of $\Delta R(t)$ is analyzed for different film thicknesses L (see Fig. 1). It is shown that $\Delta R(t)$ consists of a constant and an oscillatory component. The constant part corresponds to the nonequilibrium lattice displacement that appears after thermalization. The oscillatory part arises from sound excitation within the film. A decrease in film thickness leads to an increase in both the frequency and amplitude of the oscillations (see Fig. 1). The frequency increase is attributed to the higher acoustic frequencies as L decreases, while the amplitude increase is due to higher absorbed power, resulting in stronger sound generation. The analysis shows that if L exceeds the skin depth, the amplitude of sound and of $\Delta R(t)$ increases as $\sim 1/L$. Such amplitude increase is due to the fact that in this interval of L, a decrease in thickness leads only to a decrease in the volume in which the energy is distributed. When L becomes smaller than the skin depth, the amplitude increases as $\sim 1/L^2$. This additional growth is due to the enhancement of the electromagnetic field inside the film, caused by the reflection of the laser pulse from the dielectric substrate.

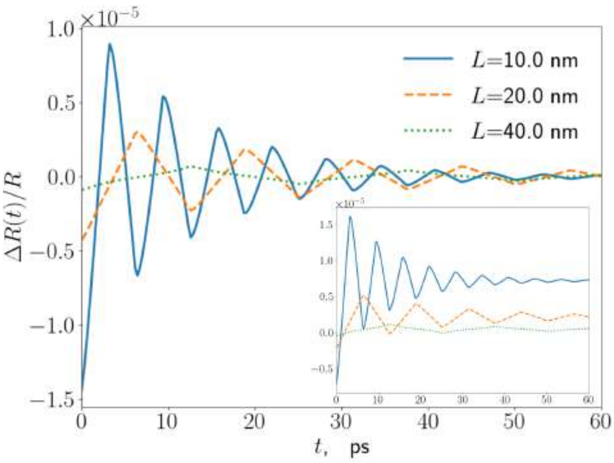

Figure 1: Plots of the function $\Delta R(t)/R$ for gold with thickness $L = 40$ nm (solid curve), $L = 20$ nm (dashed curve) and $L = 10$ nm (dotted curve). The main figure shows curves from which the equilibrium value has been subtracted, and the inset shows curves without such a subtraction.

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Symmetry of Polariton Field in a Crystalline Medium

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Nowadays there is a great interest in modeling strong field phenomena through a condensed matter. For example, a resonant density of quantum states in polariton Bose-Einstein condensate (BEC) can be used to investigate the non-linear quantum electrodynamics at a lab [1]. Since these processes widely took place in the early Universe, studying BEC may be particularly helpful for a better understanding the Universe just after the Big Bang. This paper deals with the symmetry of polariton field in a crystalline medium, and reports that normally the symmetry is broken, but restores in BEC, that allows to explore the physics of spontaneous symmetry breaking in a laboratory within a controllable experiment.

In crystal, electromagnetic quanta, photons, strongly couple with crystalline excitations, e.g. phonons, and form hybrid quasiparticles, polaritons. The analysis shows that for polaritons the triple $\mathbf{k}, \mathbf{E}, \mathbf{B}$ is always right-handed, but not the triple $\mathbf{k}, \mathbf{E}, \mathbf{B}$ which is right-handed at the normal dispersion region and left-handed at the anomalous one [2]. This can be considered as a broken chiral (P-) symmetry for the polariton field with a different (right-handed or left-handed) breaking in different (normal or anomalous dispersion) regions. In the same way, during normal dispersion polaritons propagate with the wavefront, and backward when dispersion is anomalous. It gives the time reversal (T-) symmetry broken differently at the different spectral ranges.

Despite normally the polariton field symmetry in crystal is broken, there is an opportunity to restore it in the critical point of a Brillouin zone where the normal and the anomalous dispersion dock, and polariton are able to form BEC [3] with a wavefunction that is a superposition of the "normal" (i.e. right-handed and direct-timed) and the "anomalous" (left-handed and revert-timed) ones. This restores both P- and T-symmetries (and also C-symmetry via the CPT-theorem) for polariton field and makes its symmetry complete.

When heating, BEC collapses causing polariton field symmetry breaks spontaneously (each ex-BEC polariton randomly becomes "normal" or "anomalous"). This makes possible to investigate in optics the mechanisms of the spontaneous symmetry breaking and especially the nuances of the Higgs mechanism [4] to inspect the Higgs multiplet for a presence of possible extra-components.

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Time delay of laser pulse at its reflection from boundary of supercritical plasma

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In this article, we consider the incidence of s- and p-polarized laser pulse on the boundary of supercritical plasma and show that the reflection of the pulse is also accompanied by its time delay, and this time delay can significantly exceed the period of the laser field [1]. The dependence of the delay time on the incidence angle of the laser pulse, its polarization, and plasma density is studied. It is shown that in a sufficiently dense plasma, the delay time of the reflected pulse is always less than the period of laser radiation. If the electron density is close to the critical value, then the delay time can be equal to several periods of the laser field oscillations, but does not exceed its duration. It is shown that the time delay of the reflected s-polarized laser pulse is maximum, for its normal incidence. When a p-polarized laser pulse is reflected, the maximum value of the delay time depends on the plasma density. The time delay of the reflected p-polarized pulse is maximum for the grazing incidence in dense plasma and for the small incidence angles in near-critical plasma (Fig.1).

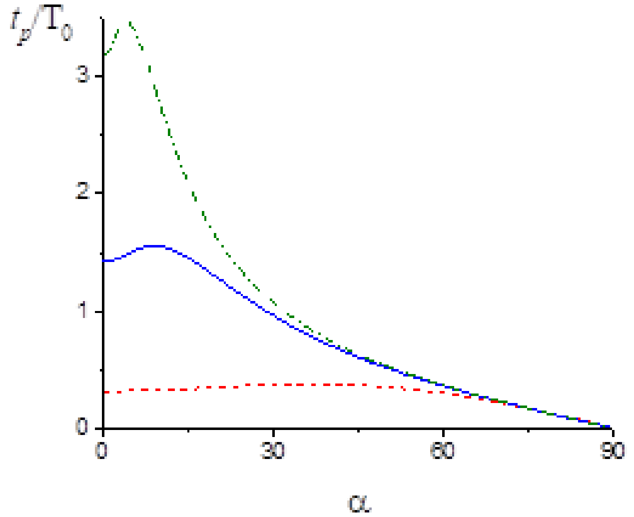

Figure 1: The delay time of the reflected p-polarized laser pulse (t_p) as the function of the incidence angle α for various electron densities, where T0 is laser period. Dashed, solid and dash-dotted curves correspond to the following values of the dimensionless electron density N_{0e}/N_{cr}=2, 1.1, 1.01, where N_{cr} is critical density.

It should be noted that the time delay of the reflected laser pulse is due exclusively to the dependence of the plasma permittivity on frequency, and this effect is absent for media with a constant refractive index. We note once more that the time delay of the reflected pulse is explained by the fact that the laser pulse is not reflected at the boundary, but penetrates deep into the plasma to the depth of the skin layer. That is, the time during which the laser pulse travels the distance of the order of the skin depth determines the time delay of the reflected pulse.

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Terahertz radiation generation in doped n-GaAs placed in magnetic field

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Studies of terahertz (THz) radiation generation in semiconductors have been initiated quite a long time ago. In particular, a large number of works have been devoted to studying the generation of THz radiation semiconductors located in a magnetic field. Given the prevalence of experiments on the generation of THz pulses in doped semiconductors, this study is devoted to the consideration of the THz radiation generation features in doped n-GaAs in a magnetic field under the impact of low-intensity laser radiation. Using equations for the average velocity of electrons and holes, the currents in the semiconductor are found. Then, using the field equations and boundary conditions on the semiconductor surface, the electric field strength of THz pulse on the semiconductor surface is found. Numerical calculations of the THz pulse total energy are performed for n-GaAs (see, Fig. 1). It was found that with decreasing doping level the generated pulse total energy increases. The influence of the semiconductor doping level on the THz pulse weakens as the magnetic field increases. The latter is due to the relative decrease of the semiconductor permittivity in a strong magnetic field.

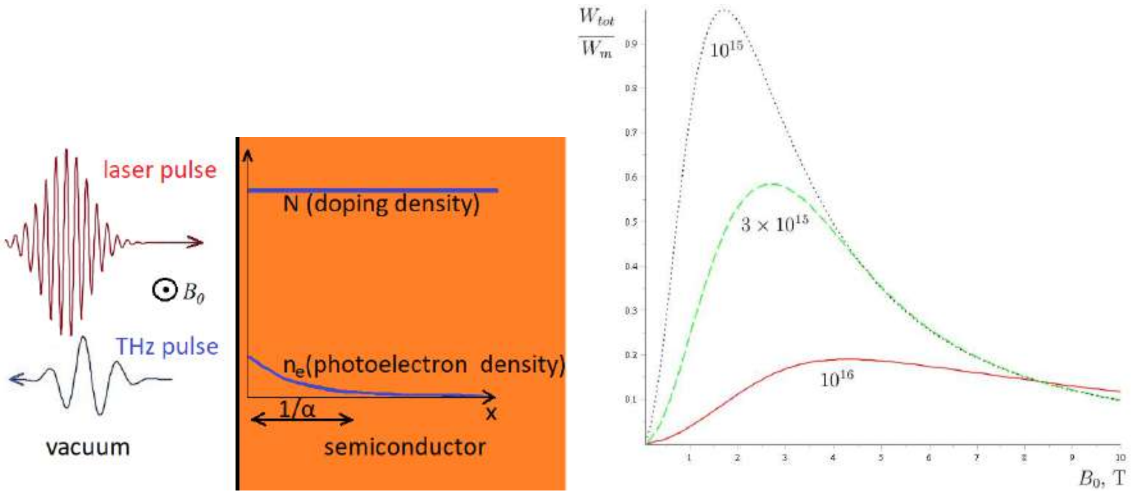

Figure 1: Left: Scheme for generation of terahertz radiation. (α is the absorption coefficient at the carrier frequency). Right: Dependence of the THz pulse total energy W_{tot} on the constant magnetic field B_0. The solid, dashed, and dotted curves correspond to doping level $N = 10^{16}, 3 \times 10^{15}, 10^{15}$ cm^{-3}, respectively. W_{tot} accounts for the contribution from the frequency range 0.1-10 THz.

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Effects of Tamm state on bulk electron photoemission in metal-semiconductor nanostructures

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Utilizing plasmonic nanoparticles can increase the efficiency of light-matter interaction, phenomenon that is widely used in practice especially in energy conversion technologies because these nanoparticles allow localization and enhancement of electric field inside and in the vicinity of them. In particular, plasmonic nanoparticles can be used for more efficient conversion of light energy in photodetectors and in photovoltaic devices [1], electron photoemission from the plasmonic nanoantennas into vacuum has its applications in the metal photocathode technology [2]. Also, the hot electrons can leave the metal nanoparticle and stimulate chemical reactions in its surroundings (so called "hot electron chemistry") [3-4].

Tamm levels [5] at the semiconductor interface can act as quasi-discrete levels in thin 2D semiconductor layer in hybrid structures, strongly affecting photoemission [6]. In the present work, we theoretically study the effects of the Tamm states on electron tunneling through the Schottky barrier and on bulk electron photoemission in metal-semiconductor structures.

In our work a model has been developed to calculate the Tamm quasi-level in metal-semiconductor structures with Schottky barrier. The model was used to show that electron resonance tunneling from metal to semiconductor through the Schottky barrier can occur with the Tamm quasi-level at the metal-semiconductor interface. We have showed that the resonance tunneling with the Tamm quasi-level can strongly affect the electron photoemission in plasmonic structures from the metal to the surrounding semiconductor, lowering the red limit of the photoeffect and significantly increasing the internal quantum efficiency of photoemission and the quantum yield of hot carrier generation in plasmonic structures, especially for photochemistry.

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Attosecond bursts generation via multiphoton interaction of intense short-wave laser field with helium atoms

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High-order harmonic generation (HHG) of a laser field is the source of the shortest attosecond pulses of electromagnetic radiation available to mankind. Such pulses are formed from the radiation of extreme ultraviolet (XUV) or soft-x-ray range, and are mainly produced in gases in the regime of their tunnel ionization by a long-wave laser field. In this case, a plateau is formed in the spectrum of generated harmonics, which is a region of photon energies significantly exceeding the ionization potential of the medium, where the amplitudes of harmonics of different orders are comparable. The HHG in the plateau region is described by a three-step (Corkum's) model that includes ionization of an atom, acceleration of a released electron in a laser field, and, upon returning to the atomic core, its subsequent recombination with the parent ion that leads to transforming the electron kinetic energy into a high-frequency photon. The proximity of the amplitudes and the orderliness of the harmonic phases in the plateau region make it possible to form pulses from them with a duration of less than 50 as [1]. However, generation of attosecond pulses in this case relies on the spectral and spatial filtering of the harmonic signal (necessary to suppress the lower-order harmonics and the contribution of "long trajectories", respectively) and phase adjustment of the harmonics (required for compensation of "attochirp") [2]. Along with the relatively low efficiency of HHG by a long-wave laser field this typically results in the low power of the attosecond bursts.

In this talk, we discuss the possibility of producing attosecond pulses from the most energetic near-threshold harmonics (with photon energies comparable to the ionization potential of the medium) of a short-wave laser field, generated by the helium atoms under the conditions of their resonant multiphoton excitation. As we have recently shown [3], such harmonics are generated mainly due to transitions between the bound atomic states. In the present contribution, we show the possibility of generating attosecond pulses without filtering and phase-adjustment of the harmonic signal (except for suppression of the fundamental frequency laser field), and analyze the influence of the parameters of a resonant multiphoton transition, such as the order of resonance and the principal quantum number of the excited state, on the pulse formation.

This work was supported by the Russian Science Foundation (grant No. 24–12–00461).

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Petahertz-bandwidth amplified spontaneous emission of an optically modulated collisional plasma-based x-ray laser

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The basis of modern scientific and technological progress is largely the use of short-wave electromagnetic radiation of the extreme ultraviolet (XUV) and x-ray ranges. One of the main classes of sources of such radiation are plasma-based x-ray lasers, relying on the creation of a population inversion at the transition of multiply charged ions during the evolution of plasma produced due to ionization of a solid target by a sequence of laser pulses in the near-infrared (IR) range [1]. A modern plasma-based x-ray laser pumped by a traveling wave of an IR field is a source of unidirectional amplified spontaneous emission (ASE) in the XUV/x-ray range [2], which is characterized with a high degree of temporal coherence and a sufficiently high energy, varying from μJ for radiation with a wavelength of about 10-20 nm to several mJ for radiation with a wavelength of about 50 nm. However, the lack of frequency tuning capability of plasma-based x-ray lasers limits their spectroscopic applications, while the picosecond duration of the generated pulses prevents their use for studying and controlling physical processes occurring on femto- and attosecond time scales.

In this contribution, we propose a method of generating petahertz-bandwidth ASE by a collisional plasma-based x-ray laser. The method is based on irradiating of the active plasma medium by a strong linearly polarized laser field of the near-IR range. The laser field leads to sub-IR-field-cycle quadratic Stark modulation of frequencies of the inverted transitions. In this case, the variable component of Stark shift is responsible for redistribution of the medium gain to the combinational spectral components, separated from the time-averaged frequencies of the inverted transitions by an even multiples of the IR field frequency, while its constant component leads to frequency tuning of the gain spectrum as a whole. This allows generating petahertz-wide spectral combs of ASE, the interference between the components of which leads to deterministic beats in the time dependence of ASE intensity on the scale of the IR field cycle. It is shown that under certain conditions these beats take the form of a train of subfemtosecond pulses. The proposed method is considered using the example of experimentally available active plasma of neon-like Ti^{12+} ions [3].

The work was supported by the Theoretical Physics and Mathematics Advancement Foundation "BASIS", Grant No. 24-1-2-43-1.

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Dynamics of movement of a spalling plate for films of various thicknesses during femtosecond heating

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Thin films with thickness from 20 to 150 nm demonstrate different mechanisms of removal of ablation layers at different threshold energy densities. Femtosecond ablation of metal films with thickness less than 100 nm occurs in two stages. First, the upper layer is partially removed under the action of tensile stresses and cavitation inside the film melt, and at the second stage, the complete removal of the metal layer is associated with heterogeneous nucleation of bubble at the metal- substrate interface [1]. In samples with thickness more the 100 nm, classical ablation of a massive sample is observed: under the action of tensile stresses, the upper layer is partially removed, and when the critical energy is exceeded, further material removal occurs by the phase explosion. The interferometric method with picosecond time resolution was used to study the dynamics of spall plate motion for thin metal films of different thicknesses under femtosecond laser action [2]. For experimental studies, a titanium-sapphire laser with a wavelength of 800 nm and a laser pulse duration of 70 fs was used; the chirped interference microscopy technique allowed achieving a time resolution of 1 ps in the range of 0-200 ps in single measurement. Data on the speed of movement of the spall layer with different laser ablation mechanisms were obtained. The experiments were performed using the unique scientific facility "Terawatt Femtosecond Laser Complex" in the "Femtosecond Laser Complex" Center of the Joint Institute for High Temperatures of the Russian Academy of Sciences.

The study was funded by the Russian Science Foundation, grant 24-19-00311.

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Strong boost in terahertz generation with ionizing three-color pulses from mid- and near-infrared pumps

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We present a theoretical and experimental study on the generation of terahertz (THz) radiation from air plasma driven by a three-color femtosecond field composed of the three lowest harmonics of a fundamental pulse in the near-infrared (1.7 µm and 0.8 µm) and mid-infrared (3.9 µm) ranges [1]. Using an inline optical setup for three-color pulse generation with relative phase control, we demonstrate a strong enhancement of THz pulse energy with the addition of the third harmonic—up to six times greater than that achieved with conventional two-color excitation—depending on the fundamental pulse energy and wavelength. For 3.9 µm driving pulses, the THz pulse energy reaches 39.4 µJ, with a conversion efficiency of approximately 1%.

To investigate the underlying mechanisms, we employ a plasma current model and simulate THz generation with three-color fields, successfully reproducing the observed yield enhancement and its dependence on pulse intensity. Our analysis reveals two distinct enhancement modes: One mode features high enhancement factors (≥ 3), but they decrease rapidly with pulse intensity (observed with 1.7 and 3.9 µm fundamental pumps). In this mode, the optimal phases correspond to an asymmetric three-color waveform. The other displays lower enhancement factors, with weak dependence on intensity (as seen with the 0.8 µm fundamental pump). In this case, the optimal phase arrangement corresponds to a symmetric (sawtooth-like) field, as proposed in [2, 3]. These observations suggest that the THz enhancement arises from two additional ionization wave mixing channels enabled by the third harmonic. Our method offers a straightforward and robust approach to enhancing the THz pulse energy and generation efficiency in air plasma pumped with femtosecond laser pulses.

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Decay of a Video Pulse into Traveling and Evanescent Waves

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In recent years, theoretical studies of the effects of extremely short unipolar electromagnetic pulses (video pulses) on matter have attracted much interest of researchers (see, e.g., review [1]). Attention to such surges of a single-polarity field is, in particular, due to the possibility of their anomalously strong effects on atomic structures [2].

Using the general solution of the wave equation for the empty space (vacuum), it has been shown that spatially limited video pulses necessarily consist of two components: traveling and evanescent waves.

The traveling and evanescent components are illustrated for a video pulse with Gaussian temporal and spatial profiles. It has been shown that the traveling wave on the beam axis is initially is a one-and-half cycle pulse and its duration is determined by the ratio of the transverse and longitudinal dimensions of the video pulse. The same ratio also determines the distance at which the evanescent wave decays, and the video pulse becomes a few-cycle traveling wave.

Using Gauss's theorem, it has been demonstrated that transversely limited video pulses are not unipolar. The transverse and longitudinal components of their field perpendicular and parallel to the wave propagation axis, respectively, can be comparable in magnitude and differ in the character of their time evolution.

The features of diffraction of Gaussian video pulses are considered. It is shown that both the transverse and longitudinal field components of both the traveling and evanescent components of the video pulse initially have different time structures along the beam cross-section. In the far diffraction zone, the evanescent component of the video pulse field disappears, and its transverse and longitudinal components transform into single-cycle waves.

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Calculation of neutron yields at the initiation of the photo-nuclear reaction ^{9}Be(γ,n)2α by the intense laser light

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We present results of derivations of neutron yields at the initiation of the nuclear reactions ^{9}Be(γ,n)2α и ^{181}Ta(γ,n)^{180}Ta in the compound target consisting of the isotopes ^{9}Be and ^{181}Ta irradiated by the picosecond intense laser pulses. Gamma-radiation is appeared due to the Bremsstrahlung of relativistic electrons that are produced at the laser ponderomotive heating after multiple above-barrier laser ionization of target atoms. Theoretical calculations are in good agreement with the recent experimental data.

Photoionized plasma layer in a magnetic field as a medium for radiation amplification

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The interaction of a circularly polarized electromagnetic wave with a layer of photoionized gas plasma in a constant magnetic field is studied. The plasma layer is formed by multiphoton ionization of inert gas atoms under femtosecond laser irradiation at atmospheric pressure. In such a plasma, the resulting electron velocity distribution remains highly non-equilibrium, isotropic and can be approximated by a delta-like function over timescales greater than the electron-neutral collision time and shorter than electron-electron thermalization time.

A detailed kinetic analysis is carried out to determine expressions for the dielectric permittivity of the plasma, taking into account the velocity-dependent collision frequency of photoelectrons with neutral inert atoms. Particular attention is paid to the conditions of the electron cyclotron resonance, when the frequency of the incident electromagnetic wave matches the cyclotron frequency of photoelectrons. Under these conditions, the imaginary part of the dielectric permittivity can be small and negative, which leads to a significant increase in both reflection and transmission coefficients.

Our results show that when the plasma layer thickness equals the odd multiples of quater-wavelengths, the amplitude of the transmitted or reflected THz radiation may be amplified by more than two orders of magnitude. Numerical calculation confirm this enhancement and reveal optimal conditions in terms of magnetic field strength, plasma parameters, and geometrical configuration.

The work was supported by the Foundation for the Advancement of Theoretical Physics and Mathematics “BASIS” №24-1-4-3-1.

Above-threshold ionization in the presence of a single-cycle terahertz pulse

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Above-threshold-ionization (ATI) is one of the central strong-field laser-matter interaction scenarios that has led to the development of attoscience [1], the area of physics in which the dynamics of systems is explored on the timescale of attosecond. Lasers with longer wavelength in the mid-infrared has enabled the discovery of new effects and a better understanding of the dynamics of strong-field processes [2]. Recently it has been shown in numerical simulations that additional terahertz (THz) field of low amplitude may significantly alter the dynamics of ATI process [3]. Here we present an experimental demonstration of ATI in argon driven by 25 fs pulses at 1030 nm central wavelength in the presence of slowly varying THz field with up to 1 MV/cm amplitude. Single-cycle THz field with strongly advanced half-cycle have been generated via two-color ionization scheme in air [4]. Depending on the delay between the pulses, both the electron yield and the high-energy cutoff in the electron spectrum change significantly (Fig. 1 a). Furthermore, the THz field affects the spectra by altering the energy spacing between the ATI peaks which becomes not equal to the photon energy of 1.2 eV of the 1030 nm ionizing field (Fig. 1 b,c).

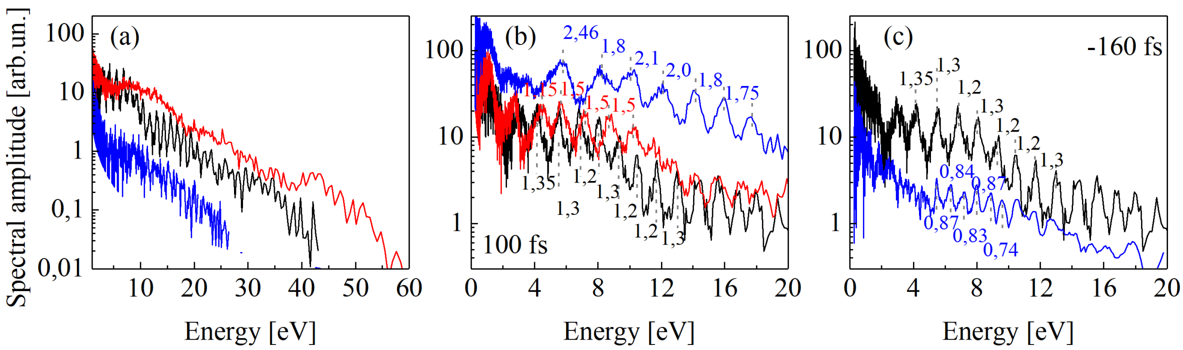

Figure 1: ATI spectra for different delays between THz and 1030 nm ionizing pulse, black curve – reference spectrum without THz field, (a) red curve – spectrum at 100 fs delay, blue – spectrum at -160 fs delay, THz field amplitude ETHz ≈0.4 MV/cm; (b) spectra at 100 fs delay and THz field amplitude: blue curve ETHz ≈0.3 MV/cm, red – ETHz 0.06 MV/cm; (c) blue curve – spectrum at -160 fs delay and ETHz 0.4 MV/cm. Energy distance between adjacent peaks is shown.

This work is supported by the Russian Science Foundation, project number 24-22-00425.

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C-band Broadband Emitter Integrated on a Silicon Nitride Photonic Chip via Luminescent Particle Embedding

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The integration of active broadband emitters into passive photonic circuits is a critical challenge for realizing fully functional, CMOS-compatible photonic platforms. In this work, we demonstrate a hybrid method for integrating light-emitting microparticles onto silicon nitride waveguides to create a broadband C-band spontaneous emission source. The approach leverages monodisperse $NaYF_4$:Er^{3+},Yb^{3+} microparticles embedded into lithographically defined wells directly above a silicon nitride coupler structure. These particles exhibit strong down-conversion luminescence when optically pumped at 950 nm, emitting across the 1500–1600 nm range, covering the entire optical telecommunications C-band. The device fabrication process was based on a 200 nm-thick PECVD silicon nitride layer deposited on a thermally oxidized silicon wafer, followed by waveguide and coupler patterning, particle well etching, and planarization. The taper coupler, shaped as a circular sector with a 48 μm radius and 40° opening angle, transitions into a 1.4 μm-wide waveguide. Microparticles were deposited in the rear region of the taper where they were confined within etched wells (1 μm deep), enabling close contact with the waveguide structure. A final silicon dioxide passivation step sealed the particles within the structure without disrupting their optical functionality. Under diode laser excitation at 950 nm, the device emits intense near-infrared light with a peak at 1530 nm and a 60 nm spectral width (FWHM). Emission was collected from the waveguide output facet using infrared optics and spectrometry. At saturation pump power (51 mW), the coupled emission reached an integrated power of approximately 52 pW. Finite-difference time-domain (FDTD) simulations modeled the microparticles as randomly placed in-plane dipoles and indicated a coupling efficiency of 0.25% (–26 dB) into the fundamental TE waveguide mode. The simulations also revealed that coupling is strongest near the taper base and decreases exponentially with the vertical distance between the dipole and the waveguide surface.

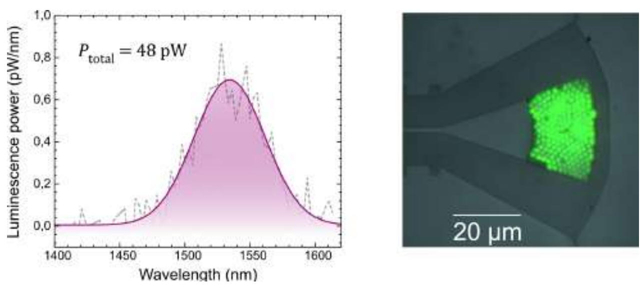

Figure 1: Left panel: Spectral power of the luminescent emission measured at the chip output. The gray curve represents the experimental data, while the red curve shows the corresponding Gaussian fit. Right panel: Optical micrograph of the taper region, displaying visible upconversion emission.

On a possible mechanism of structuring semiconductors in strong THz field

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Structuring of metals and semiconductors is a well-known phenomenon, typically attributed to surface plasmon-polariton (SPP) excitation and material heating by their interference field [1, 2]. Under visible or near-IR irradiation, laser-induced periodic surface structures (LIPSS) usually form perpendicular to the incident wave polarization, with a period comparable to the pump wavelength — consistent with the classical model proposed by J. Sipe et al. [3] and later developed.

Despite extensive research on LIPSS formation in the optical range, extending this understanding to the THz and far-IR regions remains challenging. Experiments [4, 5] have shown that silicon irradiated at 4–6 THz and 26.3 THz forms periodic surface structures with a spatial period of just 1/25–1/10 of the pump wavelength. Such sub-wavelength LIPSS cannot be explained by linear scattering or interference of the incident radiation. Also, previous studies on silicon's avalanche ionization [6, 7] revealed that intense THz fields (several MV/cm) induce ultrafast carrier generation (up to $\sim 10^{19}\text{cm}^{-3}$), rapid heating, and a permittivity drop to large negative values, enabling SPP existence at frequencies up to 20–30 THz.

Here, we analyze possible mechanisms for sub-wavelength LIPSS formation on silicon. We first examine (analytically and numerically) the formation of a near-surface conductive layer under strong THz irradiation, accounting for pump screening. Our results suggest that the experimentally observed periodic structures under 4–6 THz pumping arise from SPP interference at 15–20 THz frequency. Building on this, we propose a model where LIPSS result from Raman scattering of the pump on silicon's optical phonons, upshifting the frequency to 20 THz with a $\pi/2$ polarization rotation (due to symmetry). This explains the period and orientation of structures observed in [4, 5].

The study was supported by the Russian Science Foundation (project N 25-12-00353).

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New 3 ns AlGaAs injection laser with 50 ps prepulse

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For the first time, to the best of our knowledge, the generation of a 50 ps prepulse simultaneously with a typical 3 ns pulse envelope of a current-pumped AlGaAs injection laser has been detected. It is especially important to note that the AlGaAs laser was commercial without any modifications, which are strictly and carefully performed when developing ps pulse injection lasers [1].

Earlier [2], when studying the possibility of reducing the generation pulse of a commercial AlGaAs laser to 3 ns and analyzing the pulse envelope shape with a fast receiver and 7 GHz oscilloscope, we noticed that a step with a 200 ps front is observed at the pulse front. Continuing to study this step formation factor provided the discovery of a new phenomenon: the generation of a 50 ps prepulse simultaneously with a typical 3 ns pulse envelope of a commercial current-pumped AlGaAs injection laser by using Tektronix DPO75002SX, 33 GHz oscilloscope. The current generator circuit is shown in Fig.1(a) together with the oscillogram of a 3 ns generation pulse with a 50 ps prepulse. The physical mechanism of the first discovered mode is discussed.

This work was supported by the Russian Science Foundation (project No. RSF-23-42-10019)

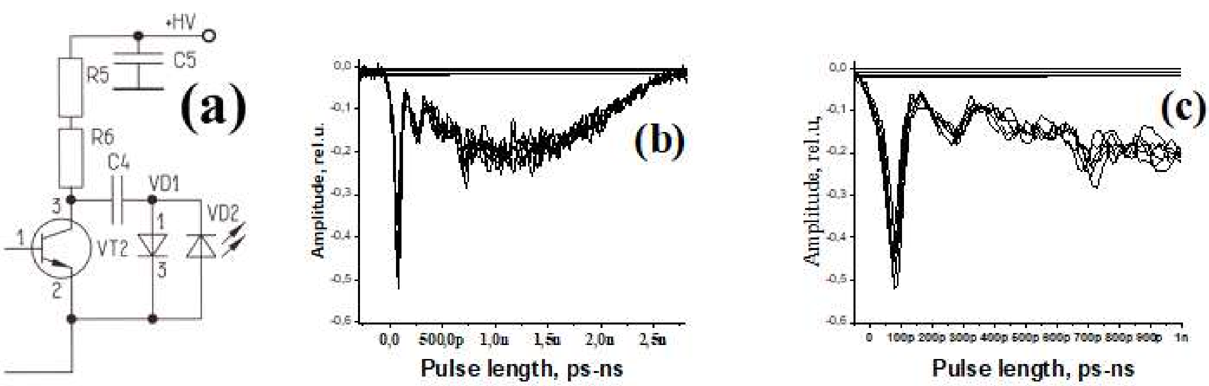

Figure 1: Scheme (a) and pulse oscillogram of AlGaAs laser: full (on left) and the first part of pulse (right).

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Propagation effects in detection of terahertz pulses using Brunel harmonics generation

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The generation of below-threshold harmonics of laser pulses in gases offers a powerful tool for reconstructing waveforms of lower-frequency (LF) radiation in the terahertz range [1,2]. When a short optical pulse propagates in a gas alongside an LF pulse, even harmonics are generated, whose intensities encode the instantaneous LF-field strength. By varying the arrival time of the optical gating pulse and using the bias quasi-static field, one can retrieve the entire LF-pulse waveform. Currently, air-biased coherent detection (ABCD), based on second-harmonic generation due to the third-order nonlinear response of neutral atoms and molecules, is often used to detect terahertz radiation. Recent studies have demonstrated that Brunel harmonics (originating from the acceleration of free electrons produced during tunneling ionization [3]) can enhance temporal resolution compared to the conventional ABCD method [4-6]. However, the robustness of this method under realistic conditions, where laser-produced plasma may affect phase matching and distort the LF field, remains unverified.

In this work, we numerically investigate the impact of propagation effects on Brunel-harmonic-based LF detection. Using the joint numerical solution of the Maxwell equations and the three-dimensional time-dependent Schrödinger equation for hydrogen gas, we analyze how plasma formation affects the LF field and the generation of below-threshold harmonics. Our simulations reveal that while high plasma concentrations at atmospheric pressure can significantly alter the LF waveform, the dominant Brunel harmonic emission occurs during the rapid increase in plasma density before substantial distortion takes place. Consequently, the detection method based on Brunel harmonics remains robust, with minimal impact on the LF-field waveform.

The work is supported by Russian Science Foundation (Grant No. 25-72-10172).

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High-harmonic probe of the plasma density gradient build-up induced by femtosecond mid-infrared laser pulses

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Coherent wake emission (CWE) paves the way to attosecond pulse trains and bright VUV radiation sources [1]. The optimal plasma scale length $L \sim \lambda/60$ is crucial for the highest efficiency of CWE-harmonic generation, while the study of harmonic spectra at the shorter plasma scale lengths $L < \lambda/60$ may shed light on the ultrafast plasma dynamics [2]. Mid-infrared laser systems based on optical parametric chirped-pulse amplification provide high-contrast pulses and sharp enough plasma gradients [3], so can be used for tracking the initial stage of plasma density formation.

To experimentally probe the plasma density gradient build-up by high harmonics we focus obliquely two collinear and delayed beams of the positively chirped, p-polarised, $\lambda_0 = 3.9$ μm, $\tau_0 \approx 200$ fs laser radiation on the polished surface of glass target placed inside the vacuum chamber. The VUV-VIS high-harmonic spectral intensity depending on the delay between the pre-ionizing pulse ($I_i \approx 0.5 \cdot 10^{15}$ W/cm^2) and CWE-generating pulse ($I_g \approx 10^{16}$ W/cm^2) was detected in the direction of specular reflection. As a result, in the 0-1.3 ps delay range a rapid quasilinear increase of the harmonic signal is observed (Fig. 1a), the steepness of which does not depend on the harmonic order (Figs. 1b). The similar feature is also observed in our particle-in-cell (PIC) simulations (Fig. 1c), which allows us to relate the linear fits of the harmonic intensity increase for the simulated plasma scale lengths and the experimental delay values, giving the gradient build-up velocity of 97 ± 11 nm/ps.

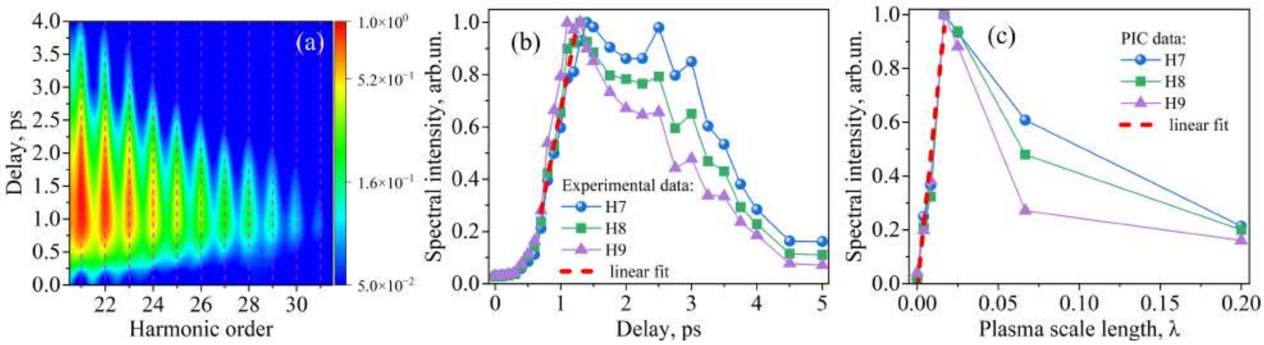

Figure 1: (a) VUV harmonic delay-frequency map, (b) experimental intensity-delay dependence of the VIS harmonics, (c) PIC-simulated harmonic intensity dependence on the plasma scale length. Red short-dash lines sign linear fit of the plasma gradient build-up.

This work is supported by the Russian Science Foundation, project № 24-22-00425. Ya. Romanovskii and N. Iakushkin are scholarship holders of the Theoretical Physics and Mathematics Advancement Foundation "BASIS".

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Coherent control of a high harmonic spectrum by a synthesized near-IR and mid-IR laser field

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The modern research interests in the field of high harmonic generation (HHG) are aimed at expanding the HHG spectrum towards higher photon energies [1], increasing the HHG efficiency [2, 3] and obtaining ultrashort attosecond pulses [4]. One of the promising approaches to overcome the limitations that arise with HHG in a single-color laser field [5] is the use of a synthesized laser field consisting of near-IR (0.8-2.5 µm) and long-wavelength mid-IR radiation (2.5–25 µm).

In the experiment near-IR radiation from a Cr:Forsterite (1.24 µm, 100 fs, up to 16 mJ) and mid-IR radiation from an Fe:ZnSe (4.5 µm, 200 fs, up to 5 mJ) laser systems with collinear polarizations were used for HHG in Ar gas. In the single-color scheme (1.24 µm, 300 MV/cm) HHG spectrum was discrete and limited to 85 eV (Fig. 1a red curve). In contrast, the two-color scheme (1.24 µm, 300 MV/cm and 4.5 µm, 30 MV/cm) exhibits spectral expansion up to 100 eV, along with the formation of a quasi-continuous HHG spectrum (Fig. 1b, red curve), attributed to the generation of combination frequencies. The results were supported by numerical simulation based on the solution of the time-domain Schrödinger equation (TDSE) (Fig. 1a,b blue curves) and demonstrate the possibilities of coherent control of the width and frequency filling of the HHG spectrum, which is important for high-resolution XUV and soft X-ray spectroscopy.

The work is supported by the RSF grant #25-22-00084. The equipment used in this work was purchased with the support of the Program for the Development of Moscow State University and National Project "Science and Universities". B.V. Rumiantsev is the scholar of the foundation for the advancement of theoretical physics and mathematics "BASIS".

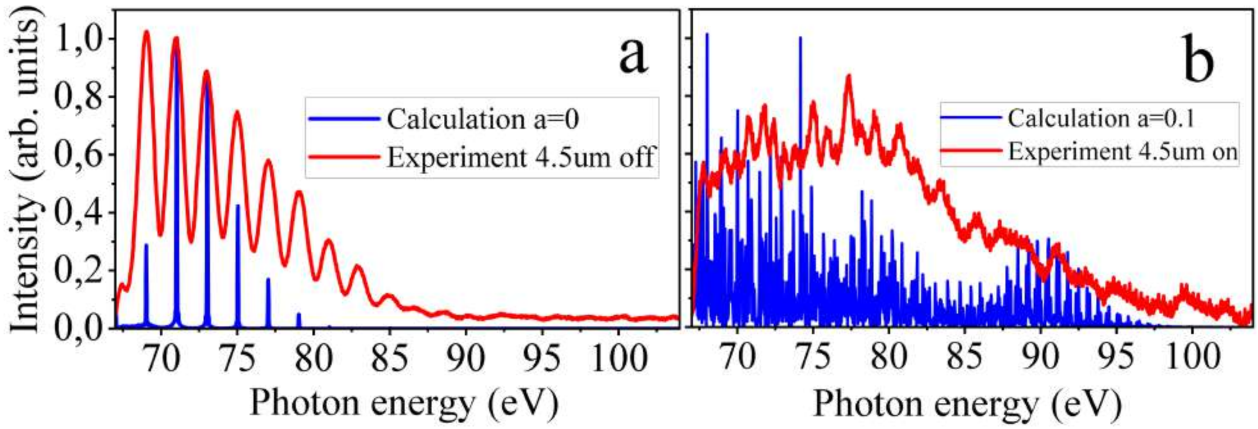

Figure 1: Experimental (red) and calculated TDSE (blue) HHG spectra at the different ratio a between 4.5-μm and 1.24-μm electric field strengths: (a) a=0; (b) a=0.1.

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Frequency-resolved optical gating using ionization multiwave mixing for measuring terahertz and mid-infrared pulses

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One commonly-used sampling method for measuring terahertz (THz) pulses relies on the second-harmonic generation of a short optical pulse during its propagation together with a THz pulse in a gas or liquid [1-3]. The second harmonic is produced due to the cubic (Kerr) nonlinearity of neutral atoms and molecules, and its amplitude is proportional to the THz field strength at the moment when the laser pulse arrives. The complete waveform of the THz pulse is obtained by measuring the intensity of the second harmonic at various delay times of the gating pulse in the presence of an external static field. In recent papers [4-6], we proposed the use of even Brunel harmonics (low-order harmonics caused by free-electron current excitation during the tunneling ionization of atoms and molecules) to increase the temporal resolution of THz radiation detection compared with the use of cubic nonlinearity. This improvement is due to the significantly shorter duration of Brunel harmonic pulses, which is determined by the plasma density growth scale, compared with the duration of the laser pulse.

In this paper, to further increase the detection resolution, we develop an approach that is based on measuring the spectral intensity near the low-order even harmonics of the ionizing pulse as a function of the delay time relative to the measured field. The waveform of the low-frequency pulse is reconstructed using a special iterative mathematical procedure. This method is analogous to the frequency-resolved optical gating (FROG) method, which utilizes four-wave mixing in gases [7]. In our case, the signal near even harmonics is generated through multi-wave ionization mixing. The latter can allow for measuring wider-band pulses (including pulses with sufficiently sharp frequency modulation). We demonstrate the robustness of the proposed method using numerical calculations based on solving the time-dependent Schrödinger equation of the excited current density in a two-color field comprising an ionizing infrared pulse and a reconstructed broadband pulse in the THz and mid-infrared ranges.

The work is supported by Russian Science Foundation (Grant No. 25-72-10172).

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Resonant high-order harmonic generation and attosecond pulses production in intense laser field

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High-order harmonic generation (HHG) via interaction of intense laser radiation with matter provides a unique source of coherent collimated XUV radiation [1]. As was experimentally demonstrated in the early 2000s, under certain conditions the harmonics can be phase-locked so that they are added up constructively to form a train of attosecond pulses in the UV or X-ray region. As the shortest of the electromagnetic pulses produced to date, these pulses provide a unique tool for the direct measurement of attosecond dynamics of processes important for various branches of physics, chemistry, biology, applied sciences, etc. [2].

Using the resonances of the generating medium is a natural way to boost the HHG efficiency: when the high-harmonic frequency is close to the transition from the ground state to an autoionizing state (AIS) of the generating atom or ion, the harmonic can be much more intense than the nonresonant ones.

A decisive role in understanding the mechanism of the generation of higher-order harmonics, as well as in explaining a number of other nonlinear processes associated with atomic ionization in an intense laser field, has been played by a so-called semiclassical model [3]. According to this model, HHG proceeds basically as a three-step process in which the elementary acts are: (i) ejection of electron from an atom via tunneling ionization; (ii) its acceleration by the laser field which pushes the electron first away from the parent ion and then back toward it as the field changes sign, and (iii) the recombination of the electron with the parent ion, resulting in high-energy photon emission. To describe the resonant HHG we have suggested the model [4] in which the first two steps are the same as in the three-step model, but instead of the last step the free electron is trapped by the parent ion, so that the system (parent ion + electron) lands in the AIS, and then it relaxes to the ground state emitting XUV. The interference of the recombination channels (the direct one and the one involving the AIS) leads to a Fano-like factor in the resonant harmonic line-shape [5].

The phase-locking of the resonant harmonics and relatively high conversion efficiency make them interesting for the attosecond pulse generation. The attosecond duration of the XUV pulse assumes broadband resonant enhancement; such enhancement due to a giant resonance was observed in xenon. We study the effect of giant resonance on the phase difference between consecutive resonantly enhanced harmonics and calculate the duration of the attosecond pulses produced by these harmonics. The harmonic synchronization allows attosecond pulse shortening in conjunction with the resonance-induced intensity increase of more than an order of magnitude.

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The nonlinear dynamic behaviors in an undriven direct current glow discharge: bifurcation-remerging process, intermittency and hysteresis

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As a typical highly nonlinear medium, laboratory plasmas can exhibit abundant nonlinear phenomena. It is well known that the presence of negative differential conductivity can make the system exhibit chaos phenomena when a DC glow discharge is operated in the subnormal glow discharge mode. Besides, for a nonlinear system, the hysteresis phenomenon often appears due to the existence of multiple equilibrium solutions. In this work, a two-dimensional plasma fluid model based on drift-diffusion approximation is developed to study the hysteresis phenomenon of the nonlinear dynamical behaviors of low-pressure DC glow discharge. The results show that the initial discharge conditions selected in the calculations will influence the nonlinear dynamical behaviors that the system exhibits significantly. When the applied voltage is changed so that the system is operated between the Townsend mode and the oscillation mode or the oscillation mode and the glow discharge mode, the hysteresis is observed from the voltage waveform. In the hysteresis region, the system exhibits bi-stable characteristics. Near the critical point, the dynamical behavior of the system will jump from stable state to oscillation state under small disturbances and the reverse adjustment of the control parameters will not immediately restore the original stable state, which is a typical characteristic of the subcritical Hopf bifurcation. In addition, the complete period-doubling bifurcation and inverse period doubling bifurcation processes in the oscillation region are found. Additionally, this study showed that the intermittent chaos appears near the period-3 window, and the bursts appearing in the approximate periodic motion becomes more and more frequent as the control parameters move away from the saddle-node bifurcation point, which shows the typical type-I intermittent chaos characteristics.

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Section 3: Ultrafast laser technologies in micro-optics, nanophotonics, integrated optics and optoelectronics

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Scope

Femtosecond laser inscription of nano- and micro-optical elements in dielectrics: physical mechanisms of sub-wavelength structuring

Laser technologies in optoelectronics

Femtosecond laser fabrication in bulk and planar integrated optics: waveguides, Bragg gratings, sensors, amplifiers, photodetectors

Ultrafast nanophotonics: plasmonics, dielectric nanostructures, metasurfaces, quantum emitters, nanocrystals, ...

Novel effects and technologies in diamond photonics

Self-organization of surface structures and amorphization of crystalline silicon via infrared femtosecond laser pulses

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Different surface structures and amorphization regions were formed on a 380-μm thick crystalline Si(111) wafer exposed to infrared femtosecond laser pulses. Firstly, scanning of surface by laser radiation with a wavelength of 1.95 μm led to formation of periodic gratings, which upon the increase of laser intensity are transformed by Plateau-Rayleigh mechanism [1] into resolidified nanodroplets. Secondly, laser radiation with a wavelength of 4.0-5.4 μm was used for amorphization of the silicon surface and evaluation of amorphization fluence threshold [2] for this spectral range.

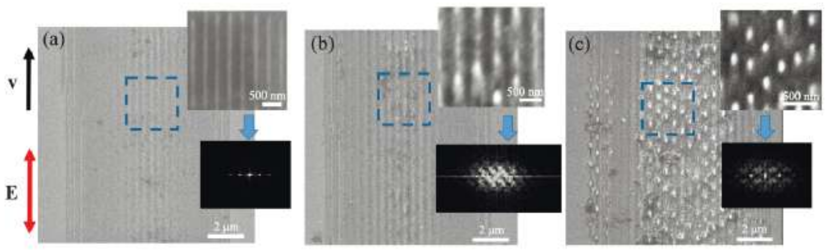

Figure 2: : (a) detected 5th and 6th harmonics in CdS with (blue) and without (red) THz field dressing. (b): HHG spectrum generated in thick CdS sample (1,4 mm) using mid-IR pulse of signal wave accompanied by intense THz field (7 MV/cm) for varying delay times;

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Twisted fiber Bragg grating as a polarization insensitive element

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Fiber Bragg gratings (FBGs) are one of the key groups of elements widely used in modern fiber optics, laser technology, and optoelectronics. FBG is a periodic structure inscribed in a fiber core along the axis of an optical fiber. Such structure can be used as narrow-band filters, mirrors for fiber lasers, dispersion elements, and sensitive elements of physical quantity sensors. Along with the “classical” methods of their creation using ultraviolet laser radiation [1], methods of directional inscription using femtosecond laser radiation have recently become widespread [2]. Such methods have a number of advantages, including technology flexibility and the ability to inscribe gratings without removing the protective polymer coating. However, FBGs inscribed in this way also have their own features. Thus, due to the asymmetry of the formed grating’s strokes, the optical response of such FBG depends on the polarization of the radiation propagating along the fiber [3]. In this paper, an original method for creating such gratings is proposed, minimizing the polarization dependence of their optical response. The method is based on inscribing the Bragg structure in a fiber pre-twisted along its axis. Figure 1 shows the dependences of the grating strength (κL) on the polarization direction of the radiation propagating in the fiber for FBGs inscribed both by the standard method and in a pre-twisted fiber.

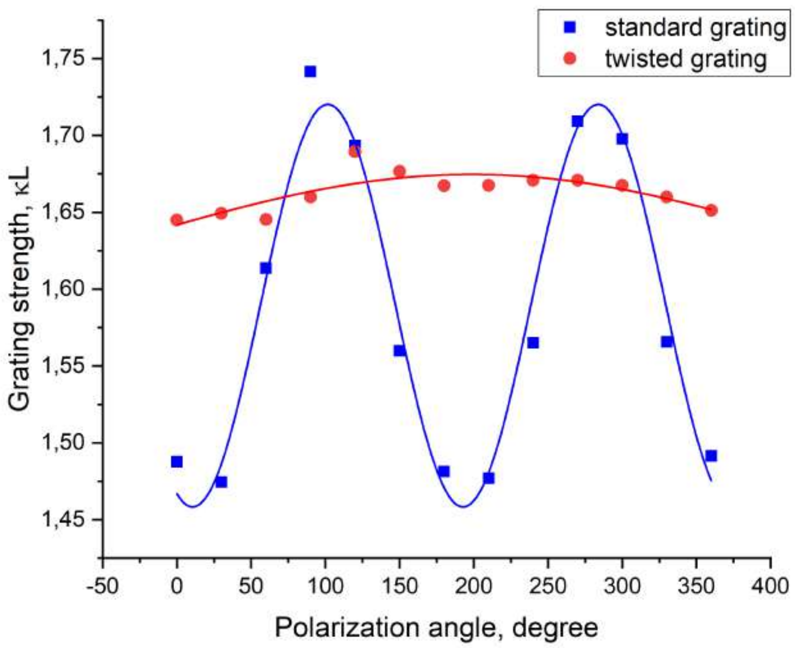

Figure 3: Polarization dependence of gratings’ strength () for straight and pre-twisted fiber.

The work was carried out within the framework of a state assignment.

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Photo-physical characteristics of N3-center in diamond

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Diamond appears as an excellent crystalline material for diverse optoelectronic devices. Natural and synthetic diamonds contain a number of nitrogen impurities in form of N3, H3 and NV-centers, which were considered for solid-state lasers in the past. For the last two centers, the lasing in the green and red regions were obtained [1, 2]. Furthermore, compared to other centers H3, NV, the brightest N3-centers in natural diamonds are still not calibrated in terms of relationship between their measured absorption coefficient at the 415-nm ZPL wavelength and N3-center concentration. The prospects for using N3-centers as active centers in laser materials were empirically considered low, as also recognized in the 80s by Rand [1]. For this reason, the basic photophysical characteristics (absorption and emission cross sections, relaxation rates) of these centers have not been the subject of numerous studies.

In this work, using selected samples of natural and CVD-diamond plates with predominant N3 (ZPL≈415 nm) centers the absorption cross-section were measured ($\sigma = 4-8\times10^{-17}\,\mathrm{cm}^2$) for the first time using absorption saturation method pumped by 415-nm femtosecond laser pulses. These values allowed us to measure the concentration (0.1-2.4 ppm) of N3-center in the samples. Our estimation of N3-centers content was verified by alternative EPR measurements. These experimental results are very important for blue-region diamond lasing and can be useful for measuring the concentration of N3-center in natural and synthetic diamonds.

The work was done under the State Assignment of the Lebedev Physical Institute, FFMR-2024-0009.

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Features of fiber Bragg gratings formed with femtosecond pulsed laser radiation

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The report demonstrates the results of the study regarding fiber Bragg gratings inscribed via direct methods with femtosecond pulsed laser radiation (fs-FBG) and their application in fiber sensing. Fs-FBG is a periodic structure located along the core of an optical fiber, each element of which is a point defect – a localized anisotropic change in the density of the fiber core formed by laser radiation [1]. A characteristic feature of such fs-FBGs is the excitation of fiber cladding modes when interacting with radiation propagating along the core. These cladding modes manifest themselves in the transmission spectrum of such a grating as a periodic pattern of peaks and dips. The condition of total internal reflection at the fiber boundary for some cladding modes can cease to be fulfilled depending on the refractive index of the external medium. It results in leakage of these modes, which is observed in the transmission spectrum as a sharp decrease in the amplitude of spectral peaks in the short-wavelength region (so-called cutoff) [2]. As the cutoff wavelength directly depends on the refractive index of the external medium, it provides possibilities of using fs-FBG as sensing elements for fiber refractometers. In the course of the study, fs-FBG samples were formed in a standard telecommunication fiber Corning SMF-28e and the effect of the refractive index of the medium surrounding the samples on their spectral characteristics was studied. Based on the results of the study, a theory of two-component interaction of the fundamental mode with an fiber Bragg structure inscribed via point-by-point method using laser radiation with a femtosecond pulse duration was proposed. An ultra-wide operating range of such structures was demonstrated, opening prospects of using such structures as fiber refractometers, *inter alia* for gaseous media.

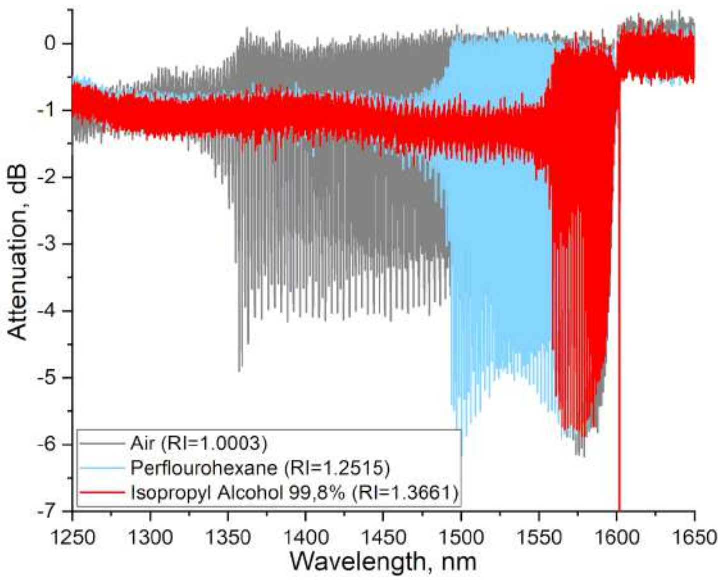

Figure 4: Typical transmission spectra of a fs-FBG immersed in different media.

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Laser methods of information recording in perovskite materials

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Perovskite materials represent attractive platforms for optical data storage due to their tunable bandgap, high carrier mobility, and strong light-matter interactions [1]. Laser-based recording techniques leverage nonlinear photomodification processes in these materials, enabling high-density information encoding through localized phase transitions, defect generation, and stoichiometric changes [2]. However, achieving high-level resolution and reversible switching remains challenging under ambient conditions, particularly for hybrid perovskites susceptible to environmental degradation [3].

Despite significant progress, the fundamental mechanisms of laser-induced structural transformations in perovskites—especially under ultrashort pulsed irradiation—are not fully understood for most compositions. Critical parameters such as acti

In this study, femtosecond laser writing regimes were systematically optimized for some sorts of perovskite materials. Multilevel data encoding via controlled phase transitions and defect-mediated luminescence modulation was demonstrated.

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Double harmonic mode-locking in soliton fiber lasers

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Passive harmonic mode-locking (HML) of a soliton fiber laser locked to optoacoustic resonance (OAR) in the cavity fiber ensures high-frequency laser operation, high pulse stability, and low timing jitter [1]. However, the pulse repetition rate (PRR) of such lasers is limited to $\tilde{1}$ GHz for standard fibers due to the available acoustic modes [2]. Here, we address these limitations by transforming the laser into an optomechanical oscillator, where laser light and the fiber's acoustic vibrations are strongly coupled. This not only increases PRR but also introduces a new laser operation regime called Double Harmonic Mode Locking (DHML) [3]. In our experiment, the laser adjusted to operate at 15-th harmonic of its cavity matching the OAR (TR2,9 GAWBS mode) at 200 MHz (Fig.1) could be driven to operate at a high harmonic of this particular OAR frequency, thus reaching $\tilde{1}2$GHz (Fig.2, a). This breakthrough is made possible through controllable optoacoustic interactions in a short, 50 cm segment of unjacketed cavity fiber implemented through its stretching (Fig.1). We propose that the precise alignment of the laser cavity harmonic and fiber acoustic modes leads to a longlived narrow-band acoustic vibration. This vibration sets the pace for pulses circulating in the cavity by suppressing modes that do not conform to the Vernier principle. The surviving modes, equally spaced by the OAR frequency, in cooperation with the gain depletion and recovery mechanism, facilitate the formation of stable high-frequency pulse sequences, enabling DHML. In this process, the OAR rather than the laser cavity defines the elementary step for laser PRR tuning (Fig.2, a). Throughout the entire PRR tuning range, the soliton fiber laser exhibits enhanced stability, demonstrating a better than $\tilde{4}0$ dB supermode suppression levels (SSL), improved pulse timing jitter and relative intensity noise (RIN) (Fig.2, b-d).

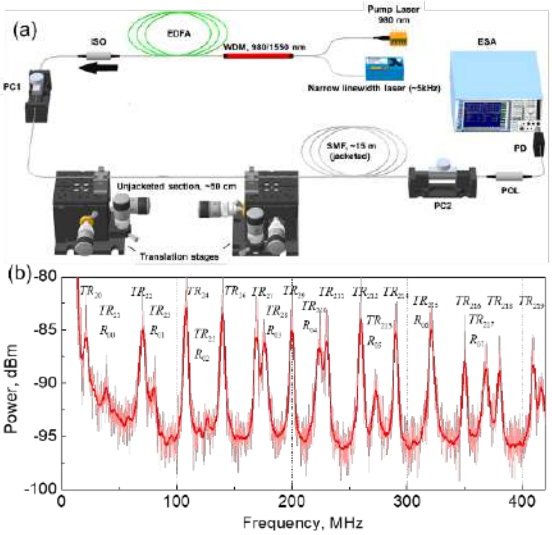

Figure 1: Experimental setup of the soliton NPE laser (a); Guided acoustic wave Brillouin scattering (GAWBS) spectra recorded with 1-km G.652.D fiber (Fujikura) (b).

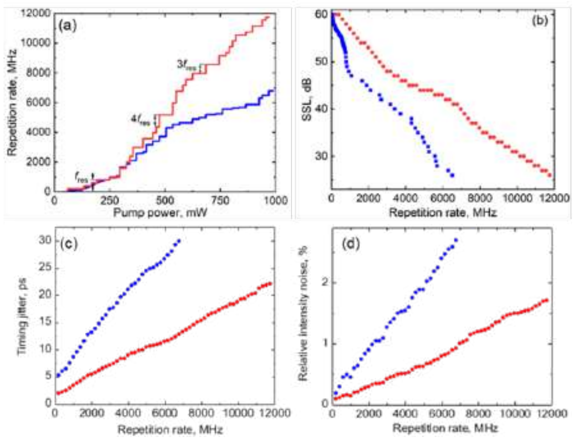

Figure 2: The PRR as a function of the increasing pump power (a) and the SSL (b), timing jitter (c) and RIN (d) as functions of the PRR measured in HML (blue) and DHML (red) regimes.

The work was funded by the Russian Science Foundation (23-79-30017).

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Simulation of plasma interferometry of a cathode spot at a wavelength of 532 nm

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This work is devoted to the study of the passage of electromagnetic radiation at a length of 532 nm through a cathode spot for solving interferometry problems. The cathode plasma spot that occurs during the initial stages of spark discharge development is a complex phase microstructure consisting, as a rule, of a spherical region with a maximum electron density of 5e19 closer to the periphery and a dip in the electron density in the center to 3e19, and a cathode flare with a smoothly varying electron density from 5e19 to 1e18. Electron density profiles were selected similar to those used in [1]. As a result of numerical simulation using the Rytov approximation, the electromagnetic wave field was calculated after passing through the plasma object under study. The resultant field was used in the modeling of interferometry images, taking into account the effect of optical system defocuses. In addition to the interferometry images, shadowgrams of the studied object were obtained, where the effect of defocusing on the final picture of the plasma microobject was considered in detail. The images obtained are consistent with the results obtained in experiment [2].

The work was supported by the Russian Science Foundation (RSF grant number 24-79-10167)

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Surface swelling of undoped polymethylmetacrylate by mid-infrared ultrashort laser pulses

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Laser swelling of polymers is based on subsurface photothermal laser-matter interaction and enables creation of various surface structures for manufacturing microlens arrays, diffraction gratings, and various phase optical elements [1–5]. This technique produces higher surface quality than laser ablation, does not require post-processing such as wet etching, and may be used to change the optical power of an existing lens by means of additive surface modification. In contrast to many works focused on microlens fabrication by front- or rear-side swelling of polymethylmetacrylate (PMMA) doped by dyes absorbing at the wavelength of the modifying laser [1–3], we studied formation of arbitrarily shaped phase elements via front-side surface swelling of undoped commercial grade PMMA by repetitive (5–10 kHz) ultrashort (300 fs) laser pulses with 3.2 μm wavelength, which falls into the high absorption range of PMMA.

According to measurements by an interferometer and a white-light profilometer, scanning of the PMMA surface with a focused laser spot produced bulges with up to 0.6 μm height (about $\lambda/2$ phase change at 633 nm) and 6–30 μm width (FWHM) without surface degradation, loss of transparency or chemical modification detectable by Raman microspectroscopy. We demonstrated the use of laser power, focal position, scanning velocity, and number of passages to control the parameters of the fabricated structures and confirmed applicability of the method by writing a 20 μm period sinusoidal phase diffraction grating. The obtained results indicate the potential of this technology for production of non-standard phase elements or high-quality templates for their replication and modification of existing elements.

The results have been obtained as a part of the implementation of state assignment No. FSFN-2024-0018.

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Domain engineering in KNN single crystals: a strategy for polarization orientation optimization

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As a lead-free and environmentally friendly material, KNN-based compounds are extensively used in sensors and MEMS devices due to their high Curie temperatures, excellent piezoelectric coefficients, and strong mechanical quality factors. Materials with excellent piezoelectric properties are indispensable for mechanical and electrical equipment. There is a close relationship between the domain structure and piezoelectric properties of piezoelectric materials. In-depth study of micro domain structure can provide important support for the improvement of piezoelectric properties. In this work, we propose three methods of domain structure regulation to achieve enhanced piezoelectricity in KNN single crystals.

The distribution of domain structure and its relationship with piezoelectric properties were investigated at different polarization temperatures and electric fields. The experiment revealed that as the polarization electric field increased, large domains gradually transformed into smaller ones under a microscope, with a noticeable change in domain orientation. Additionally, during the polarization processes at low temperature and high pressure, as well as high temperature and low pressure, similar domain structures were formed, exhibiting identical piezoelectric properties. And a schematic model of the domain structure was proposed to explain the distribution of electric domains and analyze their evolution during the polarization process. Beside this, we improved the piezoelectric properties of KNN single crystals by controlling the polarization orientation and domain structure via heat treatment. The piezoelectric coefficient (d_{33}) of the annealed KNN crystals without poling (unpoled) can increase by 90% (from 86 pC/N to 164 pC/N); this was achieved by constructing a high-net-polarization configuration composed of in-plane and out-of-plane polarization orientations. As well as, by applying high electric field stimulation to the movement of charged defects through direct current polarization, a significant internal bias field is generated. Alternating current polarization is used to eliminate the pinning effect of electric domains, achieving more complete polarization and resulting in crystals with smaller domain sizes. Ultimately, the piezoelectric constant d_{33} is increased by 71.9%, and the coercive field Ec is reduced compared to traditional DC polarized crystals.

Our findings provide new insights into modifying piezoelectric performance, which may promote research on the refined design of piezoelectric materials and the development of piezoelectric devices.

Single NV^- centers in diamond produced by low-intensity laser pulses

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This report investigates fundamental aspects of multipulse laser irradiation of single crystal diamond. The focus is on irreversible laser-stimulated changes in the atomic structure of diamond that allow the formation of paramagnetic color centers in the affected zone. The multipulse laser formation of single nitrogen vacancy centers in diamond is reported for the first time.

To create NV centers near the crystal surface, different doses of Ti:sapp laser pulses (100 fs, third harmonic, 266 nm) with energy well below the graphitization threshold were used. Photoluminescence spectroscopy, scanning confocal mapping of the irradiated surface, photon statistics measurements with sub-nanosecond time resolution, and optically detected magnetic resonance were used to identify the emitting centers formed, to prove their singleness, and to estimate the decoherence time of the NV center spin state.

The work was supported by the Ministry of Education and Science of the Russian Federation (grant 075-15-2024-556).

Study of thresholds of laser ablation of porous silicon in air and liquid media

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Porous materials based on semiconductors, metals and their compounds are widely used in the chemical and electronic industries, they are used as filter elements, thermal insulation materials, gas separators and sensors, sensors [1]. A promising and in-demand area of application of porous materials is the creation of means of encapsulation and drug delivery in the human body, as well as the creation of composite materials combining the properties of several substances at once.

The porous structure is a key factor because it increases the specific surface area and leads to a change in the properties of the material as a whole. An actively researched material with a porous structure is porous silicon. It has important properties of biomedical applications such as biocompatibility and biodegradability.

It is important to note that it is necessary to use high-performance and pure methods for the synthesis of nanostructures. One of these methods is laser ablation. This method makes it possible to qualitatively synthesize the necessary nanoparticles for biomedical applications. However, the ablation threshold of the material and the required laser radiation energy are important parameters for the effective synthesis of nanomaterials.

This paper presents the results of an experimental study of the thresholds of laser ablation of porous nanosilicon when exposed to femtosecond laser radiation in air and water. The experiment was carried out on a femtosecond laser installation with a pulse duration of 270 fs and an energy of 1-10 μJ. The obtained samples were examined by scanning electron microscopy. Based on the experimental results, a comparative analysis of laser ablation thresholds in different media was carried out.

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Domain evolution and properties in KN-based single crystals

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Due to the excellent piezoelectric performance and nontoxic character, potassium niobite (KN) based materials have attracted a great amount of attention since the report of Saito et al. in 2004. In order to increase the piezoelectric properties of KN-based ceramics, the grains were oriented in a preferred direction with reactive templated grain growth method[3]. The KNN-based single crystals therefore also exhibit excellent performance along certain crystal directions and absence of grain-boundaries. With the purpose of studying the potential of KN-based materials in piezoelectric field, we grew a few of KN-based single crystals with large size and high quality via top-seed solution growth (TSSG) method and carried out investigations of their performance. The as-grown crystal displayed outstanding properties at room temperature without annealing, including the low loss, a saturated hysteresis loop, as well as a high piezoelectric coefficient, which is also caused by the engineered domain structure. In addition, the domain evolution is also investigated.

The impact of post-growth processing on the spectral-temporal characteristics of stimulated emission in NV^-, C: HPHT-diamond

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The paper presents experimental data on spectral and temporal characteristics of stimulated emission (SE) on the example of two plates, growth sector 111, cut from one HPHT-crystal with calculated nitrogen concentration at the level of 64 ppm. The difference in the conditions of creation of NV -color centers in the samples was only in the values of irradiation doses - 1 and $2*10^{18}$ e/cm^2. Optical pumping was carried out by a laser beam focused by a cylindrical lens at a wavelength of 532 nm and pulse energy of 17.2 mJ. The volume in the samples in which the population inversion was created was chosen such that the spectra and SE pulses had a smooth shape [1]. It was found that at approximately equal concentration of C centers (≈50 ppm), the concentration of NV− centers increased from 8.3 to 11.2 ppm with increasing irradiation dose. Increasing the irradiation dose led to a sharp increase in the SE intensity with a significant reduction in the duration of the radiation pulse. Similar spectral-dynamic characteristics of the SE also led to laser generation on this crystal. The correlation between the shapes of spectra and radiation pulses, which was found earlier in [1], was also confirmed.

The paper was supported by the Ministry of Science and Higher Education of the Russian Federation, grant agreement No. FSRF-2023-0003.

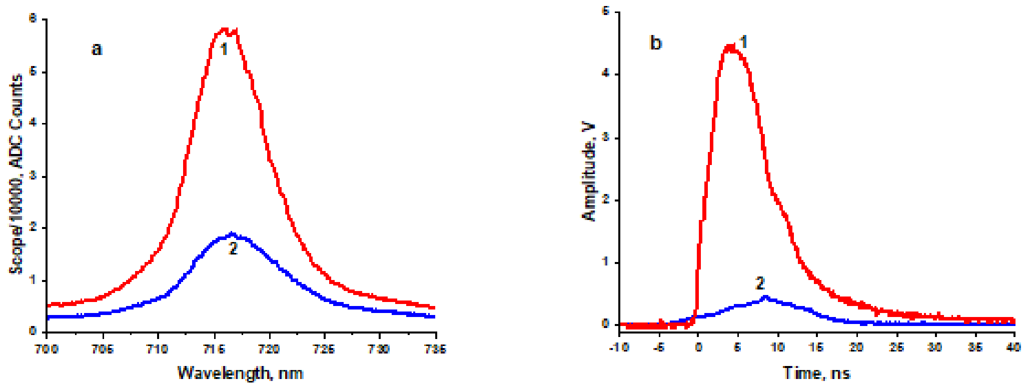

Figure 1: Shapes of spectra (a) and pulses (b) of SE for irradiation doses of 1 (curves1) and $2*10^{18}$ e/cm^2.

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PECVD-synthesized silicon nitride waveguides for nonlinear optical integrated devices

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Silicon nitride (SiN) is a promising platform for integrated photonics, widely used in nonlinear optical applications, including microwave photonics, wavelength conversion, supercontinuum generation, optical frequency comb generation and others [1].

For the development of such complex photonic integrated devices, it is essential to use high-quality silicon nitride (SiN)-based waveguides. The most widely used synthesis method for silicon nitride waveguides is low-pressure chemical vapor deposition (LPCVD), which ensures high uniformity of films in both thickness and composition. However, the main limitation of this method is the occurrence of significant mechanical stresses during deposition process, leading to cracks and defects at thicknesses exceeding 400 nm [2]. This significantly reduces the efficiency of nonlinear optical processes, which typically require thick waveguides (>700 nm) to control dispersion properties.

Plasma-enhanced chemical vapor deposition (PECVD) enables the growth of SiN films with significantly lower stress, minimizing cracking risks and eliminating thickness limitations. Furthermore, optimization of deposition parameters combined with high-temperature annealing allows PECVD-grown silicon nitride to achieve uniformity and material loss values comparable to those obtained by LPCVD technology.

In this work, we demonstrate the PECVD-based techniques for low-loss silicon nitride photonic platform, providing fabrication of an optical waveguides featuring thickness up to 1 μm. Utilizing the proposed approach, we have successfully fabricated high-Q microring resonators, featuring Q-factor over 1 million and anomalous group veloocity dispersion, require for soliton microcombs generation.

This work was supported by the Ministry of Science and Higher Education of the Russian Federation under Project No. 125020501540-9. Fabrication and characterization were carried out at large scale facility complex for heterogeneous integration technologies and silicon+carbon nanotechnologies.

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Control and application of soliton microcombs

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In recent years, with the advancement of micro-nano fabrication processes, microcavity optical frequency combs generated through nonlinear effects in optical microcavities have attracted widespread attention. Benefiting from the unique properties of microcavities, soliton microcombs demonstrate advantages such as miniaturization, high repetition rates, and broad spectral coverage, finding distinctive applications in microwave photonics, precision spectroscopy, ranging, optical clocks, and other fields. Here, we present microcavity frequency combs based on diverse nonlinear effects in various materials including silicon nitride and lithium niobate, and explore their applications in precision spectral measurements and optoelectronic oscillators[1].

Firstly, by implementing two distinct approaches for microcavity dispersion engineering, we achieved adaptive stabilization of the pump mode frequency and independent control of the comb repetition rate. This enabled rapid, programmable tuning of arbitrary comb teeth frequencies, which was subsequently applied to precision wavelength measurement. We demonstrated a wavemeter featuring kHz-level measurement accuracy and multi-wavelength simultaneous detection capability.

Secondly, we generated an electro-optic comb spanning 40 nm bandwidth in a lithium niobate microring resonator through the electro-optic effect, and applied it to high-precision wavelength measurement. A telecom-band pump laser was frequency-doubled via a periodically poled lithium niobate waveguide and locked to rubidium atomic transition lines, while the microwave modulation signal was referenced to a rubidium clock. Based on this fully stabilized electro-optic comb system, we realized a wavemeter with sub-kHz frequency measurement accuracy, representing a three-order-of-magnitude improvement compared to previous dual-comb-based systems.

Additionally, leveraging silicon oxynitride microcavity frequency combs and optical frequency division techniques, we demonstrated a low-noise integrated optoelectronic oscillator on a chip. This achievement shows promising potential for applications in radar systems, communications, ranging, and velocity measurement technologies.

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C-band Broadband Emitter Integrated on a Silicon Nitride Photonic Chip via Luminescent Particle Embedding

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The integration of active broadband emitters into passive photonic circuits is a critical challenge for realizing fully functional, CMOS-compatible photonic platforms. In this work, we demonstrate a hybrid method for integrating light-emitting microparticles onto silicon nitride waveguides to create a broadband C-band spontaneous emission source. The approach leverages monodisperse $NaYF_4$:Er^{3+},Yb^{3+} microparticles embedded into lithographically defined wells directly above a silicon nitride coupler structure. These particles exhibit strong down-conversion luminescence when optically pumped at 950 nm, emitting across the 1500–1600 nm range, covering the entire optical telecommunications C-band. The device fabrication process was based on a 200 nm-thick PECVD silicon nitride layer deposited on a thermally oxidized silicon wafer, followed by waveguide and coupler patterning, particle well etching, and planarization. The taper coupler, shaped as a circular sector with a 48 μm radius and 40° opening angle, transitions into a 1.4 μm-wide waveguide. Microparticles were deposited in the rear region of the taper where they were confined within etched wells (1 μm deep), enabling close contact with the waveguide structure. A final silicon dioxide passivation step sealed the particles within the structure without disrupting their optical functionality. Under diode laser excitation at 950 nm, the device emits intense near-infrared light with a peak at 1530 nm and a 60 nm spectral width (FWHM). Emission was collected from the waveguide output facet using infrared optics and spectrometry. At saturation pump power (51 mW), the coupled emission reached an integrated power of approximately 52 pW. Finite-difference time-domain (FDTD) simulations modeled the microparticles as randomly placed in-plane dipoles and indicated a coupling efficiency of 0.25% (–26 dB) into the fundamental TE waveguide mode. The simulations also revealed that coupling is strongest near the taper base and decreases exponentially with the vertical distance between the dipole and the waveguide surface.

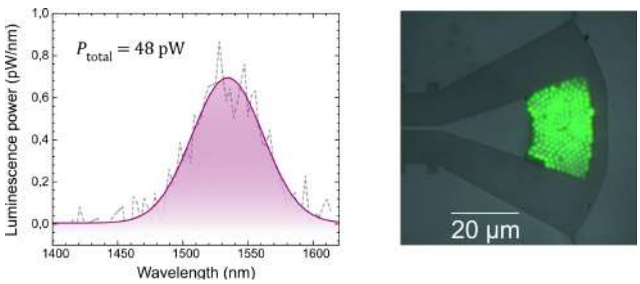

Figure 1: Left panel: Spectral power of the luminescent emission measured at the chip output. The gray curve represents the experimental data, while the red curve shows the corresponding Gaussian fit. Right panel: Optical micrograph of the taper region, displaying visible upconversion emission.

Femtosecond infrared bulk micromarking of diamond through a Ge_7Se_{93} solid-state immersion layer

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Ultrashort laser pulses make it possible to carry out structural modification of impurity defects in the diamond volume. Due to this, it is possible to create micro-scale modified luminescent areas (micromarks) [1]. The creation of luminescent micromarks in the diamond volume can be used for non-invasive diamond micromarking.

The irregular shape of rough diamonds and surface defects make it difficult to introduce laser radiation inside the diamond [2]. The complex shape of the cut of some diamonds can also interfere with the introduction of laser radiation. An immersion medium with a refractive index close to that of the diamond can be used to improve the introduction of radiation into the diamond. Since no suitable liquids are available, fusible chalcogenide glasses can be used as a solid immersion medium [3]. However, due to the opacity of these glasses in the visible range, the use of infrared laser pulses is required.

In this work, diamond was irradiated with femtosecond pulses with wavelengths of 1.035, 3.3 and 5 μm through a layer of Ge_7Se_{93} chalcogenide glass. Matrices of micro marks were obtained at different pulse energies and exposures.

The work was done under the State Assignment of the Lebedev Physical Institute, FFMR-2024-0009.

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Direct measurement of absorption cross-section of H3-center in diamond

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Impurity color centers in diamond are of considerable interest for new laser materials, yet a lack of precise absorption cross-section data complicates device modeling and design [1]. While NV centers have been extensively studied [2], H3 centers have received less attention [3].

Here, we present the first direct measurements of absorption cross-section using absorption saturation analysis in diamond samples with different H3-center content. The obtained value, 1.43×10^{-16}cm^{-1}, agrees well with literature data (1.6×10^{-16}cm^{-1}) [1,3]. Using the obtained data, we estimated the concentration of the H3-centers in samples. These experimental results are an important step toward realizing laser generation with H3-centers and advancing diamond photonics technologies.

This research was funded by Russian Science Foundation (grant number 25-42-02002).

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Formation features and annealing dynamics of fiber Bragg gratings inscribed with femtosecond laser radiation

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Fiber Bragg gratings are widely used in modern fiber optics and optoelectronics. As a rule, such structures are formed by means of laser inscription. Of particular interest is the inscription technology using femtosecond laser radiation. The effect on the silica glass material of the optical fiber is achieved through multiphoton processes providing conditions for the interaction of laser radiation with the fundamental absorption region of the glass. Such Bragg gratings have stable characteristics and are able to withstand significant heating and a high level of ionizing radiation, which is particularly important for creating Bragg grating-assisted fiber sensors for harsh operating conditions [1,2].

This paper presents the results of a study on the features of fiber Bragg gratings formation via point-by-point inscription with femtosecond pulsed laser radiation. By means of a new method of multi-pass inscription [3], it was possible for the first time to study the dynamics of changes in the parameters of a Bragg grating during its formation.

Data on long-term thermal annealing of gratings are presented. The process of their regeneration in low-doped fiber without molecular hydrogen pre-loading is demonstrated.

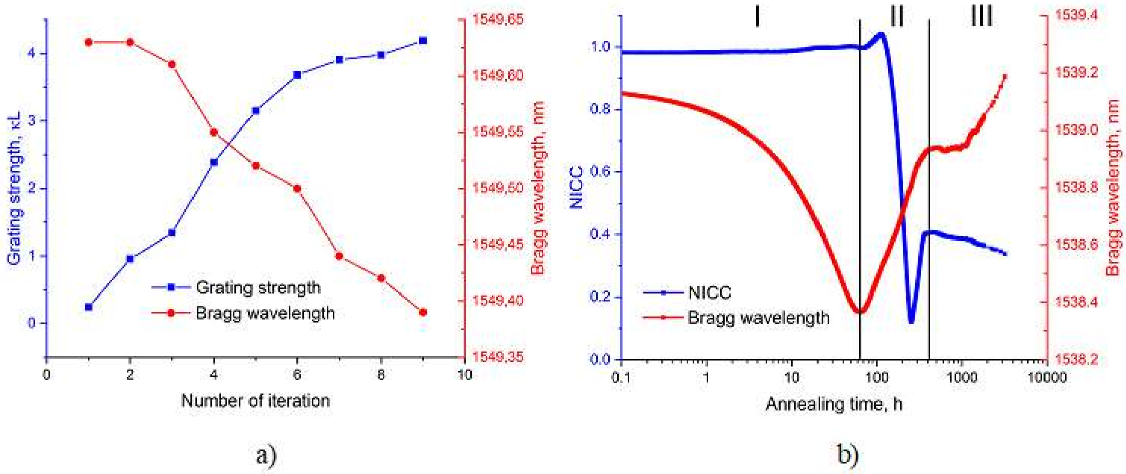

Figure 1: The formation dynamics (a) and high-temperature annealing (b) of Bragg gratings, inscribed with femtosecond radiation.

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Color centers NBOHC in birefringent microtracks induced by laser radiation in the bulk of fused silica

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The method of laser writing of birefringent microstructures forms the basis for developing optical memory [1–3], creating optical elements such as polarization components [4], wave phase plates [5], microfilters [6], and photonic components and devices [7–9]. However, a critical issue arises when forming birefringent microstructures in fused quartz: the emergence of color centers, which reduce the transparency of the resulting structure. This significantly limits the practical applicability of these technologies. In this work, we investigated the distribution of non-bridging oxygen hole centers (NBOHCs) along birefringent microtracks as a function of the energy density of the inducing laser radiation. The obtained results were compared with the subwavelength substructure of the microtracks visualized using scanning electron microscopy (SEM). During photoluminescence visualization of NBOHCs in the microtrack formation region, a micron-scale structure aligned with the wave vector of the inducing laser radiation was discovered.

The study was supported by a grant from the Russian Science Foundation (project No. 22 72-10076).

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Deeply Subwavelength Blue-range Perovskite Nanolaser

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We study the polariton lasing spectra from the $CsPbCl_3$ nanocuboid having a lateral size of about two hundred nm. The experimental spectra is characterized by few discrete bright lines, which are attributed to the exciton-polariton resonances. Here the polariton states emerge due to strong coupling of exciton to Mie eigenmodes of the nanocuboid [1]. The emission spectra demonstrates a highly nonlinear behavior. Along with rapid increase of photoluminescence intensity and line narrowing above lasing threshold, a notable redistribution of the relative intensity of polariton levels is observed. We attribute this to scattering between different polariton levels mediated by longitudinal optical phonons. The corresponding modeling based on coupled rate equations on the joint dynamics of bright polariton states and dark exciton reservoir demonstrate a satisfactory agreement between experimental observations and numerical calculations, as shown in Fig. 1.

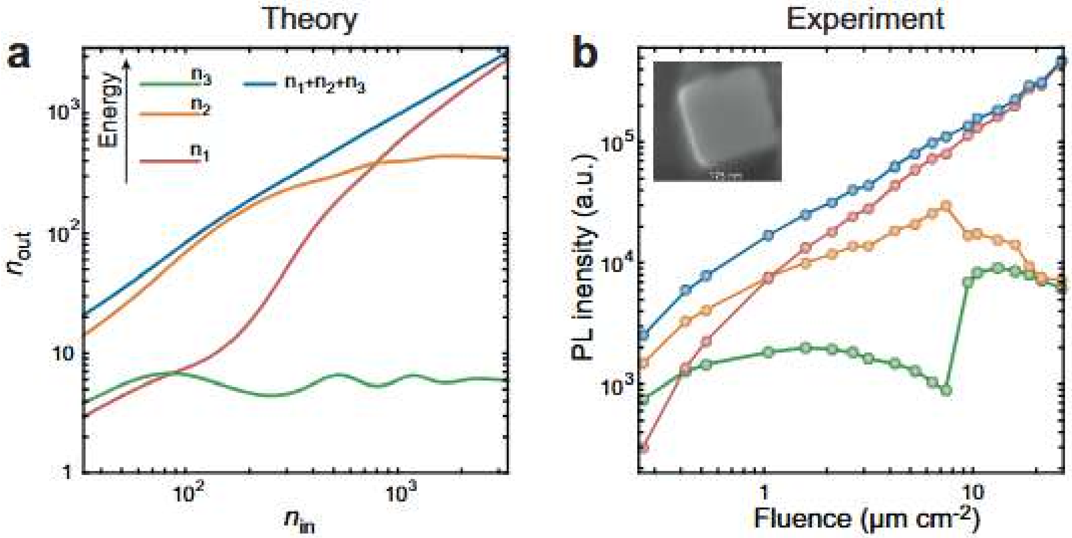

Figure 1: Polariton lasing at 80 K. **(a)** The calculated emission power from the discrete polariton states versus the injected exciton number governed by the pump fluence for the nanocuboid. Polariton levels n_i are counted from the lowest in energy as shown in the label chart. **(b)** Weights of the emission lines extracted from the measured PL spectra of the nanocuboid with the edge size 175 nm.

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Extended defects in natural diamonds with Y-defects in IR absorption spectra

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In some natural diamonds peculiar bands in one-phonon infra-red absorption spectra are assigned to a so-called Y-defect. No widely accepted model for this defect exist at present. In this work we present spectroscopic (IR and luminescence) data on such crystals and discuss results of microstructural investigation using Transmission Electron Microscopy.

Several foils were extracted from different growth zones of the crystal, characterized by widely variable set of IR-active defects. Transmission Electron microscopy reveals presence of multi-phase inclusions with sizes up to 300 nm and various types of dislocations. Configuration of the dislocations differs in the diamond growth zones. At least in some parts of the crystal non-conservative motion of the dislocations has occurred, leaving debris trails. Besides, an unusual type of extended defects was observed: strongly flattened octahedra with lateral sizes up to 10-20 nm. These defects might represent peculiar type of vacancy clusters. These defects and their possible correlation with spectroscopic properties is discussed.

Periodic structures on thin telluride films induced by femtosecond laser pulses

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Phase-change materials based on thin chalcogenide films are attractive for various applications due to the simplicity of fast reversible switching between amorphous and crystalline phase states. It was previously found that exposure of thin $Ge_2Sb_2Te_5$ films to femto- and picosecond laser pulses can lead to the formation of non-ablative laser-induced periodic surface structures (LIPSS) consisting of alternating lines of amorphous and crystalline phases with a period close to the wavelength and oriented perpendicular to the polarization of the light field [1,2].

In this study, we considered the LIPSS formation on the surfaces of several chalcogenide compounds of the quasi-binary line $(GeTe)_n$–$(Sb_2Te_3)_m$ with film thicknesses of about 120 nm, deposited by DC magnetron sputtering on identical glass substrates. Films modified with ultrashort pulses (1030 nm, 250 fs, 100 kHz, 1 μJ) were analyzed using ellipsometry, optical and atomic force microscopy, and Raman spectroscopy. In a narrow range of energy fluences, amorphous-crystalline LIPSS were observed in GeTe and $Ge_2Sb_2Te_5$ films, while two-phase periodic structures were not formed in Sb_2Te_3 at any fluences. Possible reasons for the presence of periodic structures in the studied amorphous films are different crystallization mechanisms and differences in the conductivity of the materials.

The study was carried out with contributions from the research laboratory “Active photonic materials and devices” (FSMR-2025-0002).

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Nonlinear optical properties of silicon in the mid-IR range (3-6 μm)

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While direct laser writing methods for laser-induced periodic surface structures (LIPSS) are actively developed for various materials including metals, dielectrics and semiconductors, the nonlinear optical behavior of silicon under the action of ultrashort mid-IR laser pulses (3-6 μm) is less studied [1]. This work is devoted to investigating this aspect. In particular, we present the results of nonlinear absorption experiments in silicon irradiated through an aspherical CaF lens (NA 0.25). The goal is to understand the nonlinear optical properties of silicon excited by intense ultrashort mid-IR laser pulses.

The study was supported by the Russian Science Foundation grant No. 24-22-00290, https://rscf.ru/project/24-22-00290

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Laser-induced amorphization of thin phase-change films

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Thin chalcogenide films such as $Ge_2Sb_2Te_5$ are promising materials for metasurfaces, optical modulators, 3D visualization and data storage devices. This is explained by their ability to rapid and reversible phase transitions between amorphous and crystalline states, which can be precisely controlled by means of laser irradiation. The use of ultrashort laser pulses allows increasing the speed of photonic devices. The phase transitions in $Ge_2Sb_2Te_5$ thin films have been extensively studied, but the amorphization process induced by ultrashort laser pulses remains poorly understood, although it is amorphization that is primarily responsible for the energy consumption of the optical device.

Amorphous thin films were deposited onto glass substrates using DC magnetron sputtering. Then the films were annealing at 200^{o}C for 15 minutes to obtain the crystalline $Ge_2Sb_2Te_5$ structure. Single femtosecond laser pulses with a wavelength of 1030 nm, a pulse duration of 233 fs were used to amorphize the films.

This study demonstrated the feasibility of amorphization of $Ge_2Sb_2Te_5$ thin films by ultrashort laser pulses. Phase transformations were confirmed by Raman spectroscopy. The morphology of the modified areas was studied using atomic force microscopy. We determined that the threshold energy fluence for the amorphization process is in the range 650–690 μJ/cm^2.

The study was funded by the Russian Science Foundation no. 20-79-10322,

https://rscf.ru/project/20-79-10322/. The work was carried out in the research laboratory "Materials and Devices of Active Photonics" with the support of the Ministry of Science and Higher Education of the Russian Federation (project FSMR-2025-0002).

Nonlinear response of CdSe/ZnS quantum dots embedded in liquid crystal-based matrix under phase transition

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Quantum dots (QDs) spatial distribution control is a promising research area to create new radiation sources. It is known that some azochromophore molecules (AX) are capable of photoisomerization by E-Z transition. Being added to liquid crystal (LC) they become isotropization agents activated by UV irradiation. [1]. Thus, an mixture of LC and AX can be an UV-reconfigurable matrix which can control QD concentration. [2].

AX of extended (EA) or branched (BA) structure (10 wt.%) were used as isotropization agents for nematic LC matrix. The study was performed for CdSe/ZnS QD (1 wt.%) in LC matrix.

The migration of QDs in phase-changing LC matrix was studied by polarization optical microscopy with QD fluorescence excitation (CW laser, 532 nm) and UV photoinduced (365 nm) phase transition in LC matrix. Within UV illuminated region sample isotropization accompanied by QDs homogeneous distribution was observed, and in LC areas QDs tend to be in an aggregated state such as microspheres and microtubules.

Third harmonic (TH) and upconversion luminescence (UC) signals (Cr:forsterite laser, 1250 nm, 80 fs, 80 MHz, 150 mW) along with transmission signal (diode laser, 652 nm) were measured. Sample isotropization was conducted by heating managed with a PID controller. For the LC+QD+EA mixture at room temperature throughout all sample depth TH signal has a constant magnitude and UC signal magnitude increased with focus displacement deeper into the sample due to reabsorption. Upon heating the mixture LC+BA possessed rapid increase in TH and transmission signal variance at 50oC and 61oC correspondingly which can be associated with refractive index fluctuation near nematic-amorphous phase transition. Transmission signal temperature dependence for NM+BA+QD mixture was nonmonotonic with rapid decrease near 61oC. In conclusion, an LC phase transition accompanied by QD migration has been demonstrated and third harmonic signals are markers for these structural changes.

This research was funded by the Russian Science Foundation, grant number № 23-19-00246, https://rscf.ru/project/23-19-00246/

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APE waveguides in mixed lithium niobate-tantalate solid solutions: defect structure and optical properties

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The mixed lithium niobate-tantalate (LNT) solid solutions promising materials for integrated and nonlinear photonics [1,2]. The aim of this work is to calculate the main parameters of annealed proton-exchange (APE) waveguides in mixed LNT crystals and to establish the structure-optical loss relationship.

Optical waveguides are characterized by three main parameters: optical losses, quantity of optical modes and refractive index increment (contrast Δn).

Optical losses of APE waveguides were made by fiber-to-chip alignment on 1550 nm with standard SMF-28 optical fiber. APE waveguide parameters were simulated using the vector mode solver in OptiBPM. A variable-width straight waveguide directed along the crystallophysical Z-axis was simulated to find the edge of TE-mode single-mode regime at $\lambda = 1550$ nm. The effective refractive index of APE waveguides was determined by the prism coupling method [3] at the wavelength of λHe-Ne = 632 nm (n_e =2.202). The simulation showed that the waveguide becomes multimode at a width of 7 μm.

Bulk optical losses of APE waveguides depend on the number of internal defects and nonuniformities of the LNT composition. The homogeneity of the structure of APE waveguides was estimated by two parameters: the density of defects and deformations of the crystal lattice. The density of defects (dislocations) was calculated from the number of etch pits on the surface of the LNT samples and compared with LN single crystal. Selective chemical etching was applied to identify etch pits. LNT showed higher defect densities than LN, with distinct etch pit morphologies (triangular for Z-cut, rhombic for X-cut).

LNT crystal lattice deformations were quantified using a double-crystal diffractometer. The Selyakov equation and Gaussian approximation were applied to separate contributions from coherent-scattering regions (CSR) and deformations. X-ray diffraction showed lattice deformations, with LNT's α-phase stability reducing stress compared to LN's κ_1-phase. The relationship between optical losses and structural defects of LNT has been identified.

This work was funded by the state assignment № FSNF-2024-0001

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Numerical model for ultrafast optical switching based on half-space non-radiating modes

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A model of fully optical ultrafast switching based on the excitation of non-radiating states [1] in half-space in microparticles is considered.

Our approach consists in combining the calculation of ultrafast nonlinear dynamics in semiconductors based on the Maxwell-Bloch system of equations [2] and the switching condition of light scattered by a particle in two half-spaces [3], creating a strong contrast in the radiation pattern with relatively small changes in the properties of matter.

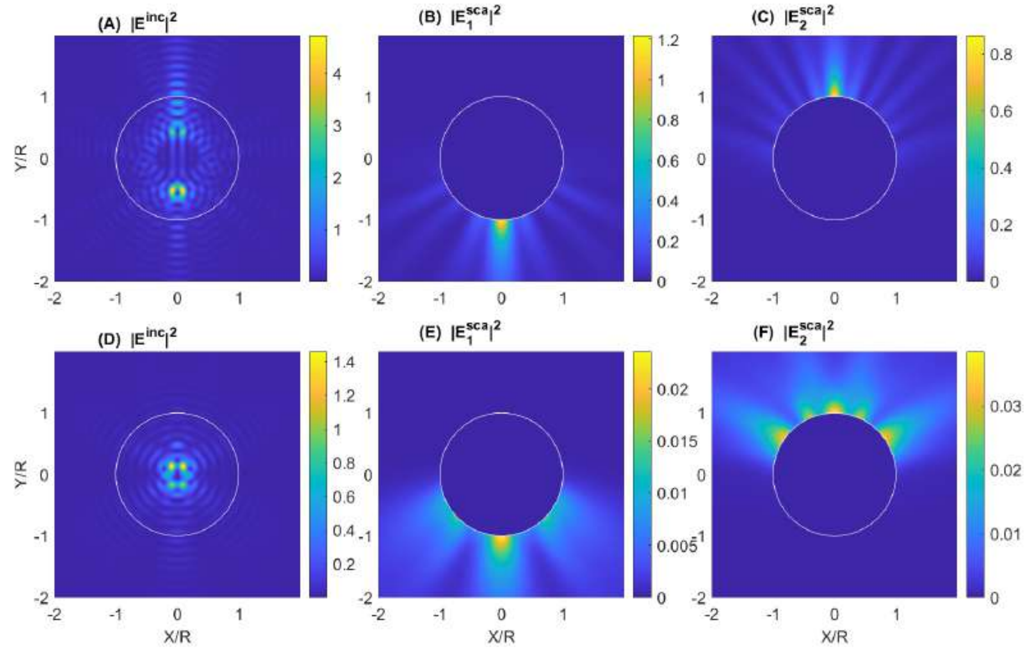

Figure 2: (A) Incident radiation on the particle. (B) Scattered field at carrier concentration $N = 10^{18}$ cm^3. (C) Scattered field at $N = 10^{19}$ cm^{-3} for AlGaAs. Radiation and particle parameters: $\lambda = 0.8474$ μm, $R = 3.1572$ μm. (D)-(F) Similar quantities for InP. Radiation and particle parameters: $\lambda = 0.8519$ μm, $R = 2.9169$ μm.

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Conjugacy of C and NV centers in natural and synthetic diamond

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Diamond with NV centers is a promising material for various applications, but it always contains other defects, the interaction of which must be taken into account. The substitutional nitrogen atom C is the simplest impurity defect in diamond. Its vacancy complex NV is the most studied defect in diamond. Both defects have ionized states, NV^- and C^+ respectively. The positively charged state of NV is theoretically discussed, but has not been described in the experiment yet. Perhaps stable NV+ centers can be obtained in boron-doped diamond. NV centers are created in the laboratory in diamond with C defects – donor centers. Diamond is a wide Band Gap (5.5 eV) semiconductor. In pure or compensated diamond, position of Fermy level is at half of CB (2.25 eV under CB). In that case, the NV^0 with ground state 4.29 eV under CB is equilibrium state of NV. The presence of donors shifts the position of the Fermi level above 1.74 eV under CB. In this diamond, the ground state of NV- (2.55 eV under CB) is under the Fermi level: NV is conversed to negative charged form; the C is conversed to the C^+ for the charge compensation [1]. If there is lack of C centers for the charge compensation, both NV^0 and NV^- coexist. In natural diamonds, NV is more often generated during plastic deformation from other nitrogen centers - A, B1, H3. The stable form is NV^0, in this case. In rare natural diamonds with donor C defects, both NV^0 and NV^- are obscured by photoluminescence, most often together with the H2 (986 nm) – negative charged state of H3. Thus, the NV^0/- and C0/+ centers are conjugated, and the interaction between them can significantly complicate the interpretation of various experimental results. Photoionization ($NV^- \rightarrow NV^0$)/($C^+ \rightarrow C^0$) is the effect, that had shown the existence of positively charged nitrogen [2]. The ratio of NV^- /NV^0 concentrations (and C^+/C^0, respectively) after photoionization may be stable - this is a photochromic effect; or the ratio may change only during illumination - this is photoblinking (dynamic photochromism). These optical effects are controlled by the limiting mechanism of charge transfer between NV and C centers: it depends on the distance between the defects. Various studies have identified three characteristic distances at which the dominant mechanism (and the rate of charge transfer) changes [3]. The distance 0.5 nm is the edge for electron tunneling between NV and C. The distance of 1 nm corresponds to the convergence of the energy of one- and two-photon excitation of NV^-, 1.2 nm is the minimum distance for the stable state of NV^-. These patterns must be taken into account when creating optically active materials on base of diamond [4]. For example, the charge transfer rate limits the maximum pulse frequency for narrow-band stimulated emission at NV^-. It is fundamentally impossible to obtain a concentration of NV^- centers higher than half of the initial nitrogen concentration, but it is possible to convert all nitrogen into the NV^0 form. Some cases of the interaction of C and NV centers in natural and synthetic diamonds will be demonstrated during the presentation.

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Tunable functional materials and devices in terahertz band

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The terahertz (THz) spectral region holds great potential for applications in communication, imaging, and security detection, driving the demand for high-performance, tunable functional devices. However, conventional THz modulators often face challenges such as limited modulation depth, slow response. To address these issues, this work explores the design and implementation of tunable materials and devices in the THz band, focusing on efficient, dynamic modulation strategies to support advanced functionalities in photonic information processing.

Tunable metasurfaces based on lattice-induced transparency (LIT) and polarization- independent plasmon-induced transparency (PIT) were developed by engineering the coupling of distinct resonance modes. The integration of GST enables multilevel, nonvolatile modulation of the transparency peaks, with clear elucidation of the underlying coupling mechanisms. Furthermore, by combining amplitude holography encoding with GST-based metasurface design, we demonstrate encrypted information storage and reconstruction. The encryption strength is enhanced by introducing Shamir's visual cryptography scheme and exploiting the phase-transition threshold of VO_2 as an additional security dimension.

In parallel, tunable liquid crystal-based THz devices are realized, enabling broadband phase modulation with low driving requirements. Structured transparent electrodes are fabricated to guide liquid crystal orientation, allowing precise spatial control of THz wavefronts. Electrically tunable focusing and beam shaping are demonstrated, highlighting the potential of this approach for high-transmission, low-voltage, and fully reconfigurable THz modulation. These results offer a promising route toward multifunctional THz devices for future integrated photonic systems.

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NV– diamond megawatt laser for shadow recording of fast processes

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Shadow photographic recording is a widely used method for studying the dust phase in gas dynamic experiments. This method consists in transferring the image of an object formed by scattered rays of illumination light to a photosensitive area. When using a pulsed light source with high brightness, short duration (less than 1 ns) and low temporal coherence to illuminate the object under study, shadow photographic recording makes it possible to characterize objects moving at speeds up to 10 km/s with a size comparable to the wavelength of the illuminating pulse.

According to [1, 2], all the specified requirements for the illumination source for shadow photographic recording can be satisfied using an NV– diamond laser pumped with a picosecond 532-nm Nd:YAG laser. The 200-ps pulse at the carrier wavelength of 715 nm generated by the NV– diamond laser has a spectral band with a width of 12 nm, which ensures low temporal coherence of a pulse and, consequently, high resolution of a shadow method. The report presents the results of a shadow photographic recording of a dispersed phase that occurs during the explosion of a copper wire bridge using an NV– diamond laser as an illumination source.

Fig. 1a shows a shadow image of the explosion of a copper wire bridge when illuminated with the picosecond pulse of an NV– diamond laser with low temporal coherence. For comparison, fig. 1b shows a similar shadow image obtained when illuminated with a picosecond pulse of a Nd:YAG laser with a high temporal coherence. In both cases, the delay of the illumination pulse was 20 s. As one can see, in the shadow image in fig. 1a there are practically no noise interference speckles, which makes it possible to distinguish individual particles of the order of 5 m in size, while due to the noise components in fig. 1b, small-scale fragments of wire cannot be distinguished.

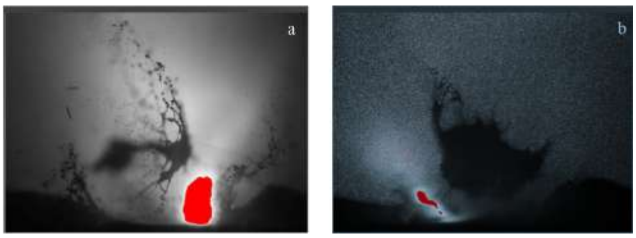

Figure 1: Shadow image of the bridge explosion with a 20-s delay of the illumination pulse (a) with low temporal coherence, (b) with high temporal coherence.

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Study of thresholds of laser ablation of porous silicon in air and liquid media

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Defects of diamond crystal lattice have a significant impact on its physical properties. Therefore it is possible to use natural and synthetic diamonds in quantum technologies, employ defects as nanomarkers in industrial tracing and study laser generation of defects [1]. At present, there is a lot of data on the dynamics of nitrogen atoms and the dynamics of vacancies separately, but their cooperative behavior and the transformation of one center into another has not been sufficiently figured out.

At the previous stage of the work, calculations related to the dynamics of nitrogen-vacancy centers were performed. They demonstrated a new mechanism of vacancy-mediated diffusion of the nitrogen atom [2], that nitrogen actively diffuses in the presence of 3 vacancies in neighboring positions, while the vacancies dissociate and attach to other nitrogen atoms. In this work, the dynamics of point defects of the "nitrogen-vacancy" and "nitrogen-nitrogen" types is studied in the temperature range of 2200–3500 K using the molecular dynamics method in the LAMMPS package [3]. The calculations examine the interaction of centers containing both vacancies (from 1 to 4) and interstitials (from 1 to 3). The most stable structures of nitrogen defects, which can potentially participate as intermediate formations in diamond refinement (NV-H3-N3), were established. The results also show the possibility of the N3-center formation as a result of the B-center dissociation. The activation energy of a single interstitial atom was calculated, a qualitative and quantitative comparison with the data from the available literature and the results of calculations from first principles are presented. The work was carried out using an MTP-type machine learning potential, the learning process was carried out directly during the calculations [4].

The authors acknowledge financial support from Russian Science Foundation No. 25-73-20143.

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Section 5: Ultrafast optical technologies and nonlinear optical phenomena

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Scope

Ultrafast laser fabrication of bionanomaterials

Femtosecond and picosecond laser: solid-state, semiconductor, parametric, fiber, and hybrid laser systems

Optical devices: dispersion management, stretchers/compressors, phase control and stabilization, optoelectronic systems and switchers

Measurement and characterization of ultrashort pulses: autocorrelators and streak cameras, frequency-resolved optical gating (FROG), spectral phase interferometry

Nonlinear optical phenomena: stimulated scattering processes, harmonics, sum and difference frequency generation, supercontinuum and self-phase modulation, self-focusing and filamentation, multi-photon processes and nonlinear absorption

Nonlinear optical devices from the UV to THz range and IR: novel nonlinear materials, optical parametric amplifiers and generators, Raman converters

Effect of chirping of femtosecond laser radiation on its spectral characteristics during filamentation in compressed gas

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The formation of the supercontinuum spectrum during filamentation in compressed nitrogen of chirped femtosecond optical pulses in the sharp focusing regime has been investigated experimentally and theoretically. For the first time, to the best of our knowledge, we show that chirped pulses exhibit a decrease in the spectral broadening of the pulse with increasing gas pressure.

At the same time, pulses with a negative chirp demonstrate a wider supercontinuum than pulses equal in modulation depth but positive in chirp sign. The theoretical analysis and numerical modeling of the propagation of high-power chirped femtosecond optical pulses under conditions corresponding to the experiment are carried out, and an adequate analytical model explaining the main regularities of the formation of spectral characteristics of chirped optical radiation in compressed gas is elaborated.

Funding. Russian Science Foundation (24-12-00056); Ministry of Science and Higher Education of the Russian Federation (IAO SB RAS).

An experimental investigation of the optical properties of thin metal films under the influence of high-intensity THz pulses

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The results of an experimental study of the optical properties of thin titanium and nickel metal films in the terahertz spectral range, exposed to terahertz pulses with an electric field strength of up to 10 MV/cm, are presented herein. Metal films with a thickness ranging from 10 to 30 nanometres were deposited on silicon, glass, and sapphire substrates. The measurements were conducted utilising the time-domain terahertz spectroscopy method.

The experiments were performed using the unique scientific facility "Terawatt Femtosecond Laser Complex" in the "Femtosecond Laser Complex" Center of the Joint Institute for High Temperatures of the Russian Academy of Sciences. The study was funded by the Russian Science Foundation, grant 24-19-00311 https://rscf.ru/en/project/24-19-00311/.

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Approaches to overcoming energy limitations in post-compression techniques

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In post-compression techniques [1], intense pulses exiting a conventional CPA laser are spectrally broadened by self-phase modulation (SPM) in a nonlinear material, followed by dispersion compensation. The use of Herriott-type multipass cells (MPCs) with concave mirrors and various gases as nonlinear media have recently demonstrated post-compression of pulses with energies exceeding 100 mJ [2]. However, further energy scaling is limited by ionization of the gas. For Joule-level energy large size MPC setups are required to maintain a relatively large focal spot and prevent ionization, with the distance between the mirrors exceeding tens of meters.

To overcome the pulse energy limitation of spectral broadening a free beam propagation at high intensities was proposed and demonstrated [3]. The optical scheme with flat mirrors to fold the beam similar to MPC was used for reducing footprint of the setup. Self-focusing compensation by initial wavefront tailoring allowed achieving long propagation distance while avoiding beam collapse for pulses exceeding the critical power for self-focusing. A spherical convex initial wavefront is an example of this tailoring. A numerical estimation shows that the critical power for self-focusing can be significantly mitigated by increase of the beam divergence, which was demonstrated in our experiments. In this scheme the intensity of Gaussian beam remained nearly constant along the length of propagation, allowing efficient light-gas interaction throughout the entire beam volume. Furthermore, this configuration simplifies the need for complicated optical schemes and optical elements.

In our proof of principle experiments a Yb:YAG CPA laser system ($\lambda = 1030$ nm) was used to generate pulses of 65–300 mJ energy with duration of ∼6 ps at 10 Hz repetition rate [3]. The beam was directed to undergo folded beam propagation in atmospheric air in a compact set up, which consists of two 2.5 cm × 10 cm rectangular HR dielectric flat mirrors, positioned at near normal incidence. The distance between these mirrors was 2 m. After 20 passes between the mirrors, the beam was compressed. Experiments conducted in atmospheric air with the average pulse intensity of ∼0.05 TW/cm^2 allowed to reach the spectral broadening factor of ∼5.6, and subsequent compression of the pulse from 6 to 1 ps. Spectral inhomogeneities across the beam profile were characterized by a V-factor, which was over 85% within the FW1/e2M of the beam diameter. The Small Scale Self-Focusing (SSSF) prevented a further increase of energy. Nevertheless, two methods allowed to shift this limitation significantly far. The experiments with pulse energy of 130 mJ split by polarization on two equivalent channels like those discussed above was one of them. Another one was modernized SSSF filtration method [1] that allowed to enlarge the energy up to 300 mJ.

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Terahertz pulse shape modification by photoinduced charges in GaAs

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Femtosecond laser pulses in a pump-probe scheme are widely used to photogenerate charge carriers in a semiconductor to control terahertz radiation [1]. In terahertz semiconductor antennas, under the influence of a photon in the optical range, an electron-hole pair is created, which significantly changes the properties of the semiconductor in terms of the interaction of terahertz waves with it (transmission, absorption), and also allows the generation of terahertz radiation due to nonlinear interactions. If, using a femtosecond pulsed laser source, an image of a mask is projected onto a semiconductor crystal, for example, GaAs, an amplitude and phase mask corresponding to the image is formed on its surface [2]. The technique allowed the implementation of various active photonic elements suitable for THz range including tunable filters, beam steering devices, polarizers, waveguides, modulators, integrated into THz imaging systems, diffraction gratings, and more complex THz metasurfaces.

In this work the experimental results on propagating plasmon excitation in a tunable photoinduced gratings on GaAs surface are demonstrated above metallization fluence threshold. We realize a technique for photo-controlled terahertz pulse shaping in gallium arsenide slab by illumination with femtosecond optical pulses. A modified approach to time-domain spectroscopy has been developed to resolve and analyze individual terahertz pulses directly in the time domain using a satellite pulse, avoiding artifacts introduced by Fourier transformation and allowing precise analysis of field evolution in photoinduced plasmonic modes.

This work was supported by Russian Science Foundation (Grant No. 24-12-00210).

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Diode pumped 100 kHz femtosecond Ti:sapphire chirped pulse amplifier

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Titanium doped sapphire (Ti:Sa) is a unique laser material demonstrating broad gain profile centered around 800 nm sufficient to produce pulses as short as 5 fs [1]. Recently a number of research groups demonstrated stable femtosecond operation of Ti:Sa oscillators using affordable, compact and energetically efficient diode pump [2-4] making such lasers an attractive solution for a broad range of applications from biomed imaging to ultrafast photonics [5] where typical 1-10 nJ energies achievable directly from the oscillator are sufficient. However, such applications as ultrafast micromachining, 3D data laser recording, biocell surgery require significantly higher energies and motivates to develop a low-cost diode pumped Ti:Sa amplifier able to deliver 30-80 fs pulses at sub-μJ energy.

This paper presents experimental results on development of chirped pulse amplifier (CPA) system using a commercially available Ti:Sa crystal with FOM$\simeq$150 (CryLink, PRC). A commercial diode pumped Ti:Sa laser "TiS-Quantum" (FemtoVision, Russia) produced a train of 30 fs pulses at 107 MHz repetition rate, 150 mW average power at 825 nm central wavelength was used as a seed laser. Achieved energy per pulse and repetition rates are similar to [6] where a continuous wave (CW) argon ion laser was used to pump Ti:Sa regenerative amplifier (RGA) using acousto-optic modulators to control laser pulse build-up. The argon laser was replaced in our system by two diode modules DM-460 (FemtoVision, Russia) delivering 7 W total pump power at 465 nm using dual-side geometry. In order to take advantage of the full Ti:Sa gain profile and minimize material dispersion inside the RGA cavity a KD*P Pockels cell was used as an electro-optic modulator (EOM) [7] instead of AOMs [6]. CPA approach was chosen for safe laser operation and to ensure system upgradability in future. A combination of Offner stretcher and Tracy grating compressor were set at geometries optimized to minimize material dispersion introduced by the RGA. The best CW pumped RGA energy efficiency was achieved at $100-300$ kHz repetition rate, roughly corresponding to the inverse lifetime of the gain medium (3.2 μs). As a result, CW diode pumped system CPA system was built producing <80 fs pulses at 825 nm wavelength at energies in excess of 200 nJ at the compressor output, at up to 200kHz repetition rate. As in other similar systems, the RGA performance was strongly affected by thermal lensing [6, 8], which can be mitigated in future by better cooling of the crystal.

In summary, an inexpensive, energy efficient CW diode pumped Ti:Sa CPA laser system operating at room temperature was built with the parameters well suited to study multiphoton processes in dielectrics and their modification, manufacturing of photonic components and biomed microsurgery.

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Phase stable single-cycle pulses: generation, characterization and applications

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The intensive development of laser physics has led to the emergence of a broad area of research – the optics of ultrashort laser pulses [1–3]. The use of ultrashort pulses allows one to study non-stationary processes with femto and attosecond resolution [4], and their high peak power makes them a convenient tool for studying and applying nonlinear optical phenomena [5]. When switching to extremely short pulse durations, the field phase relative to the pulse envelope begins to play a significant role, strongly affecting the peak radiation intensity in this case. Therefore, the formation of single-period pulses with a stable and controllable phase opens up new possibilities in the problem of controlling ultrafast processes associated with the interaction of strong light fields with matter.

The current report presents an overview of the methods for the formation and characterization of single-cycle pulses, as well as approaches to stabilizing the field phase relative to the envelope of laser pulses (carrier-envelope phase (CEP)), with an emphasis on methods for passive stabilization of powerful pulses using nonlinear processes. The features and advantages of using phase-stable single-period pulses for current problems of ultrafast nonlinear spectroscopy are discussed. The possibilities of using such radiation for studying ultrafast electron dynamics in solids are especially highlighted, which is due to the active development of this area at present.

We present original results related to the demonstration of the possibilities of using soliton self-compression in gas-filled hollow anti-resonant waveguides as a convenient method for obtaining extremely short infrared pulses with stable phase [6,7]. The influence of the carrier-envelope phase (CEP) on the supercontinuum spectrum and the characteristics of extremely short pulses formed as a result of nonlinear optical conversion of pump pulses in an argon-filled hollow anti-resonant waveguide have been demonstrated. Experimental and theoretical analysis shows that as a result of soliton self-compression of pump pulses radiation with an initial central wavelength of about $2\,\mu$m, a pulse with a duration 0.4 optical cycles and peak power more than 2 GW less is formed. By means of CEP controlled pulses with a duration about one optical period, we experimentally demonstrated ultrafast modulation of ionization in a pump-probe circuit in a ZnSe crystal.

The work was supported by grants from the Russian Science Foundation 25-12-00211.

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Experimental study of nonlinear optical interaction of femtosecond laser pulses with PMMA

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Precision modification of the optical properties of transparent biocompatible polymers is of high practical importance for solving a number of tasks in ophthalmology [1], dentistry [2], the creation of implantable microfluidic devices [3] and biosensors [4]. Owing to its physical and chemical properties, polymethylmethacrylate (PMMA) remains one of the basic polymeric materials for these applications, so investigation of nonlinear optical parameters of the ultrashort laser pulses–PMMA interaction is of great interest.

We conducted an experimental study of the nonlinear optical interaction of 1030-nm and 515-nm femtosecond laser pulses with commercial-grade PMMA plates. An upgrade of the well-known z-scan method for estimating nonlinear absorption was proposed, which made it possible to exclude the effects of accumulation and modification of the material related to pulse duration and repetition frequency. Using it, the values of the multiphoton absorption coefficients and the nonlinear refractive index, as well as the critical power of self-focusing, were estimated. The obtained results were confirmed by a direct comparison of the theoretically estimated displacement of the nonlinear focus with the position of the laser-modified areas in bulk PMMA.

This research was funded by the Russian Science Foundation (project № 25-22-00488), https://rscf.ru/en/project/25-22-00488/.

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Generation of femtosecond pulses within wavelength range from 5.2 to 10 μm with $BaGa_2GeS_6$ nonlinear crystal

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The development of high-energy femtosecond laser systems operating in the mid-infrared (mid-IR) range is essential for a wide range of applications. Frequency conversion methods, such as difference frequency generation (DFG) in nonlinear crystals [1], are commonly used to produce femtosecond radiation in the mid-infrared range. In this study, we investigated a mid-IR femtosecond laser source based on femtosecond Ti:sapphire laser and DFG in a new promising $BaGa_2GeS_6$ (BGGS) crystal [2]. This nonlinear crystal is interesting due to its wide band gap, which excludes two-photon absorption of the pump wavelength, and wide transmission range from 0.41 μm to 11.8 μm [2]. The nonlinear BGGS crystal with size of 7×5.7×0.7 mm^3 was fabricated by D.V. Badikov at the High Technologies Laboratory of Kuban State University. The sample was cut at angles $\theta = 36^\circ$ and $\phi = 17^\circ$ to provide II type of phase-matching. The Ti:sapphire laser system produced pulses with energy reaching up to 10 mJ, a central wavelength of 0.95 μm, a pulse duration of 100 fs, and a repetition rate of 10 Hz.

DFG pulse spectra were recorded with the home-made scanning mid-IR spectrometer at variation of phase-matching angle of the crystal sample. In experiments, we obtained DFG wavelength tuning from $\tilde{5}.2$ to 10 μm. The highest pulse energy of the DFG radiation was at a wavelength of $\tilde{6}$ μm. In this case, the dependence of the DFG energy on the pump energy was measured. The highest pulse energy of the DFG was $\tilde{1}4\pm1$ μJ at pump pulse energy of 2 mJ with conversion efficiency 0.7%. At pump pulse energy of 1 mJ energy conversion efficiency was 0.75%. No multiphoton absorption was detected in the sample, as well as laser-induced damage at pump energy of 2 mJ. In addition, we investigated a dependence of DFG pulse energy on the pulse energy, Es, directing into the gas cell to form a signal wave, when pump energy remained fixed at 0.9 mJ. In this situation, the DFG appeared when Es reached 0.5 mJ. The DFG pulse energy jumped from zero to its maximal value of 4 μJ. A further increase of Es up to 2 mJ did not lead to a further increase of DFG energy.

The research was supported by Russian Science Foundation, grant number 22-79-10068.

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Barium tungstate crystal – a unique medium for high efficiency SRS of ultrashort laser pulses

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Conventionally presumed that achieving high (>10%) efficiency of stimulated Raman scattering (SRS) for ultrashort/femtosecond laser pulses is challenging because of the transient character of the phenomenon and competition from other nonlinear optical effects. The results of our studies on SRS of subpicosecond laser pulses revealed that this “rule” is not hold in the barium tungstate crystal, $BaWO_4$. It has been shown that the high, up to 20% on the main and up to 35% on the secondary vibrational mode, energy efficiency of the SRS conversion for 0.3 ps pulses with a wavelength of 515 nm in a simple one-pass interaction scheme is achievable [1,2]. Established that such ability with this crystal is a consequence of the unique for solids orientational Kerr nonlinearity with a subpicosecond decay time [3,4] – the feature, which may be attributed to the “hidden” crystal defects [5]. As a result of this feature, the significant self-phase modulation broadening in the Stokes direction which feeds SRS, the shift of the broadening maximum to the pulse maximum, and the suppression of the self-focusing caused beam radius collapse jointly make possible the high effectiveness of SRS for ultrashort pulses in this crystal.

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Robust, stable and repetition rate tunable Yb-doped fiber CPA for a soliton solid-state laser

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In the modern world sources of high power ultrashort pulses are widely used in fields of biology: nonlinear optical microscopy, micromachining and spectroscopy. Against this background, the realization in the fiber format also stands out due to such advantages as radiation quality, robustness, low temperature and fluctuating environmental influences, compactness and flexibility of amplification parameters.

The main method of obtaining powerful ultrashort pulses in fibers is chirped pulse amplification. Thus, this work demonstrates the developed compact fiber multistage chirped pulse amplifier using a tunable chirped fiber Bragg grating (CFBG) as stretcher. Before stretching in CFBG, the radiation from soliton solid-state laser is driven into the fiber pre-stretcher to reduce the self-phase modulation contribution. Next, the stretched pulses are amplified in three stages based on active fibers doped with Yb^{3+} ytterbium ions. After the first amplification stage, using an acousto-optic modulator, the pulse repetition rate is reduced to 1–5 MHz. Before the third amplification stage, the seed power is 23.4 mW and the amplified output power levels up to 8.9 W. A compressor, based on reflective diffraction gratings, is used for dispersion compensation with 6.0 W output power. The pulses are compressed to 180 fs with a good time profile and an energy of 2 µJ. CFBG adjustment allows to obtain radiation with good quality of pedestal and duration at energies from 1 to 2 µJ without changing the compressor parameters. The output radiation also has good stability (STD = 3.5 mW, RMS = 0.12 %), linear polarization ratio 27 dB and beam quality as good as $M_x^2 = 1.34$, $M_y^2 = 1.23$ at high output power.

Thus, because of its good beam quality, output power stability and spectral characteristics, this laser source can be used in nonlinear microscopy of biotissues: two-photon microscopy, three-photon microscopy [1] and nonlinear light-sheet microscopy.

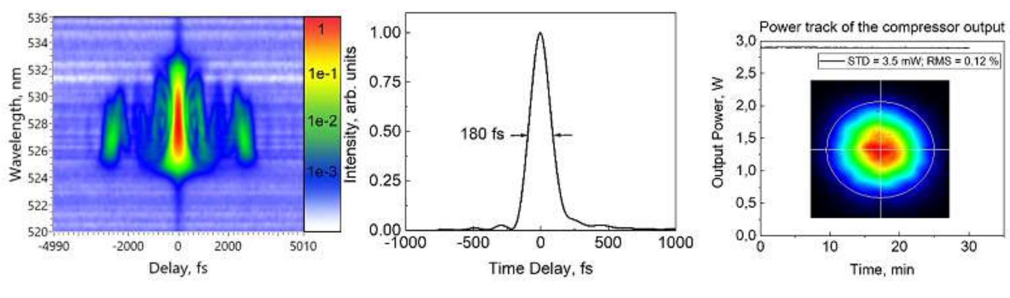

Figure 1: (a) – Compressed pulse FROG-spectrogram at 1 µJ and 3 MHz; (b) – Compressed pulse; (c) – Power stability and beam quality in far field.

With support of Russian Science Foundation (No. 22-72-10044).

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Ultrafast mode-locked fiber lasers for generation of infrared pulse sources

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Ultrashort infrared pulse sources were widely applied in the fields of industrial processing, optical communication and terahertz optics [1]. Ultrafast mode-locking technique by exploiting nonlinear saturable absorbers has become a dominant approach for ultrashort pulse generation, owing to its advantages of structural simplicity, low cost, and high stability [2]. In this presentation, I will introduce the recent development of ultrafast passively mode-locked Er- and Tm-doped fiber lasers for generation of pico- and femto-second pulses at 1.5 mm and 2.0 mm band, mainly with two-dimensional materials and mixed-dimensional heterostructure as saturable absorber, as well self-mode-locking mechanism without additional saturable absorbers [3]. Recent experimental and theoretical works by our group on Er- and Tm-doped mode-locked fiber will be presented. In particular, the mode-locking operation of Er-doped fiber lasers with various saturable absorbers of perovskite films, graphene oxide films, and mixed-dimensional MoS2/carbon nanotube heterostructures can produce ultrashort pulses at hundreds of femtosecond pulsewidth. All-fiber Er- and Tm-doped Mamyshev oscillator were demonstrated for generation of tens of femto-sencond ultrashort pulses through the dispersion management technique and accumulation of sufficient nonlinear phase shift. Additionally, the mode-Locking state switching effect and the dissipative soliton energy quantization effect in a mode-locked Er-doped fiber laser were found experimentally. Dynamics of mode-locked fiber lasers and analysis of hybrid mode-locking stability were discussed theoretically by use of the extended nonlinear Schrödinger equations. The results being presented here may be useful to expand the knowledge on ultrafast mode-locking regime and provide alternative approaches to ultrashort infrared pulse sources.

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Filamentation multifocal structure during propagation of high-power femtosecond laser pulses in pressured gases

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Important problems of atmospheric nonlinear optics are increasing the self-focusing distance of high-power ultrashort laser radiation [1] and controlling the structure of filaments and plasma channels at a given distance [2]. The relevance of their solution is due to the prospects for developing new methods for environmental control and wireless optical energy transmission. This assumes that radiation propagates over long paths under turbulence conditions and with radiation parameters varying in a wide range of values. An effective way to solve these problems for long-range atmospheric filamentation is to vary the pressure in the radiation propagation medium as shown in [3]. For example, modifying the propagation medium itself when using short laboratory paths and optical cuvettes with high-pressure gases. The advantages of scaling the results obtained in laboratory conditions to real long atmospheric paths are presented in [3]. In this study, the results of numerical simulation of self-focusing and filamentation of high power femtosecond laser pulses with varying pressure of the gas medium in which the radiation propagates are presented. The used numerical model of high-power femtosecond laser pulses propagation in pressured gases is detailed described in [3]. Its base is a form of (3D+1) nonlinear Schrodinger equation (NLSE) for time averaged electric field envelope, so-called 3D NLSE [4].

The modeling is carried out for cases of self-focusing and filamenation of high-power femtosecond pulses of Ti:sapphire laser in increased (by 16 times) gases. The formation of a filamentation multifocal structure is especially characteristic for these conditions. The angular divergence of the beam is estimated when varying the initial peak power of the pulse for different values of the pressure of the propagation medium. As a result, the possibilities of controlling the structure of the filamentation area, the angular divergence of the beam under conditions of varying pressure of the propagation medium are demonstrated. These results are planned to be used to predict the propagation of high-power femtosecond laser radiation on real atmospheric paths with a length of hundreds of meters and more within the scaling laws.

This study is supported by the Russian Science Foundation (Agreement No 24-12-00056).

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Comparative study of intra-cavity and external dispersion compensation in a SESAM mode-locked Ti:Sapphire oscillator

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We present an experimental and comparative analysis of two dispersion compensation schemes in a Kerr-lens mode-locked Ti:Sapphire oscillator incorporating a semiconductor saturable absorber mirror (SESAM). The first configuration employs a combination of a prism pair and double-chirped mirrors fully integrated within the laser cavity, while the second utilizes an intra-cavity prism pair with external DCMs following the output coupler. The aim is to evaluate the influence of dispersion management on pulse duration, spectral bandwidth, and the stability of the mode-locked regime. Our results show that the configuration with all dispersion compensation elements placed inside the cavity enables finer control of net cavity dispersion, allowing operation in a soliton-like regime. The second configuration, while simpler and more compact, offers less flexibility in dispersion tuning and is more sensitive to alignment. These findings have important implications for applications requiring high temporal resolution and broad spectral bandwidth, such as multiphoton microscopy, frequency comb generation, and precision metrology.

Synchronously pumped picosecond Raman laser in water with phase-conjugation instead of mirror

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It is known [1] that the high-Q resonator of picosecond Raman lasers with synchronous pumping by a train of picosecond pulses is formed by interference mirrors with reflection at the wavelength of the Stokes component of the Raman active medium. In this case, the optical length of the Raman laser resonator is equal to the length of the resonator of the master pump laser and the round-trip time of the Raman laser resonator is equal to the repetition period in the pump pulse train. Actually, the input mirror of the resonator is transparent, and the output mirror has a high reflection coefficient at the wavelength of the pump and Stokes components, which is the reason for damage to the mirror coating by optical breakdown during interference of the pump beams and the Raman component. The possibility of using an asymmetric resonator ([2]) with the phenomenon of phase-conjugation of the Stokes component in the Raman medium instead of a mirror remains unclear, which is the purpose of this work. A Raman laser on water with synchronous pumping by a train of picosecond (60 ps) pulses of the second harmonic (532 nm) of a Nd3+:YAG laser was assembled with a resonator of length 120 cm. A large Raman shift (3450 cm-1) of the Stokes component with a wavelength of 650 nm [3] provided visual control of the Raman laser generation. The input mirror was placed on a table with a micrometer feed back and forth along the optical axis of the resonator. Instead of the output mirror, a cuvette with an open surface of water was installed vertically under mirror, which deflected the pump beam into the cuvette along the normal to the water surface. A focusing lens (f = 10 cm) was installed in front of this mirror. The waist plane of the pump beam caustic coincided with the water surface. Varying the pump pulse energy allowed us to detect the Raman threshold in the backward direction, towards the pump. It is important that the beam diameter of the Stokes component "backward" coincided with the pump beam, which indicated the phase-conjugation of the Stokes component. Moving the mirror with simultaneous observation of the oscillogram of the pump pulse trains and the Stokes component backward allowed us to match the resonator's lengths of the Raman laser and pump one. This mode of synchronous pumping of the Raman laser manifests itself in the generation of a Raman pulse train a period after the dominant pulse in the pump train (see Fig. 6 in [1]).

Thus, for the first time, as far as we know, synchronous pumping of a Raman laser on water by a train of picosecond pulses of the second harmonic (532 nm) of a Nd3+:YAG laser with a phase conjugation of the Stokes Raman component instead of an output mirror was obtained. At the same time, a low-energy breakdown of water was detected at a depth of 20-24 mm with a threshold of about 10 μJ, which was (1/100) a part of the Raman threshold in water as in [3]. The variations of the Raman laser generation parameters in the synchronous pumping mode will be the subject of the next work. This work was supported by the Russian Science Foundation (project No. RSF-23-42-10019).

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RABBITT setup with missing harmonics

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Parity mixing, i.e., interference between channels of different parities, occurs if emitted electrons, due existence of several photoionization channels, have the same energy but different parity. The interference, due to the conservation laws, can only be observed in angle-resolved measurements and typically manifests itself in symmetry breakdown of photoelectron angular distributions (PADs). The simplest 'pure' scheme where the parity mixing can be seen is the classical '$\omega + 2\omega$' scheme [1].

In the traditional RABBITT [2], the XUV harmonics differ by double IR frequency 2ω, and parity mixing cannot be achieved. However, if one generates harmonics on triple IR 3ω on a free-electron laser [3], the resulting pulse will contain $3N$th frequencies of the seed ω field, i.e., with some its 'usual' odd harmonics missing and some additional even ones. Interaction of this pulse with an atomic target leads to the appearance of two sidebands (SB) between the main photoelectron lines (ML) in the spectrum caused by continuum-continuum transitions (panel (a) in Fig. 1). Population of the SBs are formed by two- and three-photon transitions, and this leads to the parity mixing.

We consider this 2-SB scheme for neon as target and pulse duration&intensity typical for modern facilities, analyze the symmetry breakdown of PADs for various polarizations of the incident pulse and discuss the possibility to reconstruct its form from the measurements. Some examples of such breakdown are presented in Fig. 1 (panels (b) and (c)).

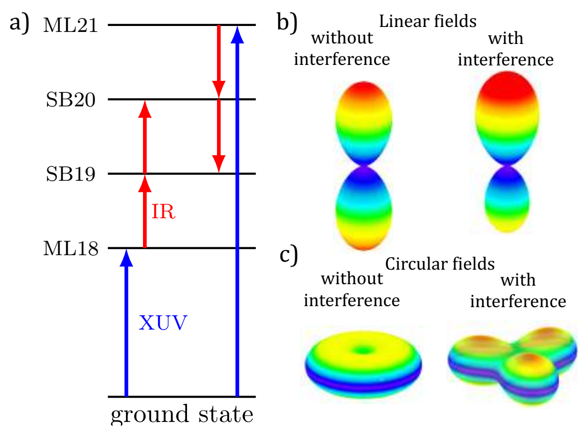

Figure 1: (a) Principal scheme of 2-SB RABBITT; (b) typical SB PAD for a linear 'XUV comb + IR' pulse for neon as target, with and without accounting the interference between the paths with one and two IR photons; (c) same for the circularly polarized fields.

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Investigation of the AC STARK effect in CdSe semiconductor nanoplatelets

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At the moment, investigation on semiconductor nanostructures is actively developing area of research, due to their optical and electronic characteristics. An important feature of such materials is the dependence of their optical properties, including absorption spectra, on the size and geometry of nanoparticles [1]. These unique properties open up new perspectives for the development of devices that control light with the help of light, which is especially in demand in the field of optical logic [2,3].

The purpose of this work is to study laser-induced transparency in CdSe nanoplatelets with an absorption maximum of 514 nm, due to the Stark effect and two-photon absorption, as well as to study the effect of surface defects in nanoplatelets on these optical effects. For this purpose, the pump-probe spectroscopy method was used with pumping pulses of a titanium-sapphire laser at a wavelength of 800 nm. The chosen experimental scheme made it possible to simultaneously observe the AC Stark effect, which leads to a shift in absorption bands, and two-photon absorption, which leads to sample transparency.

After exposure to a laser pulse, induced absorption is observed near the main band, which may indicate its broadening or splitting. This phenomenon is explained by the capture of charge carriers by surface traps. Samples with a high density of surface defects and passivated surface states were compared, which made it possible to evaluate the effect of defects on the optical properties of nanoplatelets.

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Multicycle terahertz generation by nonlinear mixing of *o*- and *e*-waves in lithium niobate

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Multicycle narrowband terahertz sources are in demand for many emerging applications of terahertz radiation. Multicycle narrowband terahertz pulses are often produced by optical rectification in periodically-poled lithium niobate (PPLN) crystals. However, the typical PPLN aperture is below ∼1 cm. This prevents scaling PPLN-based sources to higher energy pump laser pulses. Recently, it was proposed to generate multicycle terahertz radiation by nonlinear mixing of *o*- and *e*-components of a laser pulse in a bulk $LiNbO_3$ crystal [1]. Here, we experimentally demonstrate the workability of this method.

For our experiments, we used $LiNbO_3$ crystal with optical axis tilted at angle 65° to the crystal's entrance face. The crystal thickness was 1 cm. To excite both *o* and *e* optical waves in the crystal the laser beam polarization was at 45° to the principal plane of the crystal. A Yb-doped laser with 1030 nm wavelength, 1 kHz repetition rate, 270 fs pulse duration, and 1 mJ pulse energy was used as a pump. Terahertz radiation generated in the backward (with respect to the laser pulse propagation) direction was measured using electro-optic sampling technique.

Figure 1(a) shows the experimental waveform. It consists of several dozens of cycles. Correspondingly, the generated spectrum is as narrow as ∼12 GHz [Fig. 1(b)].

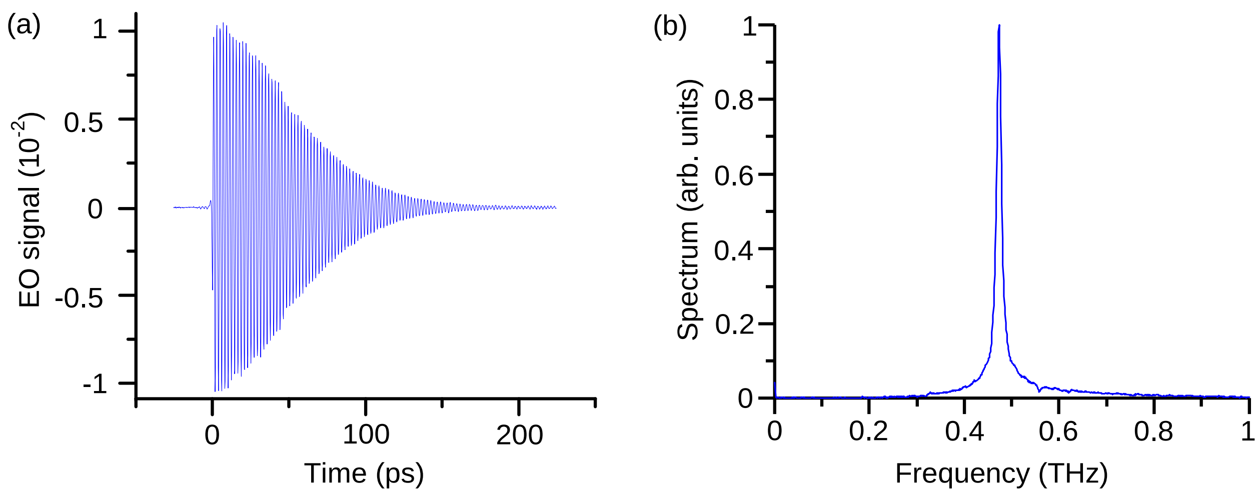

Figure 1: (a) Terahertz waveform and (b) its spectrum.

The work was supported by the Russian Science Foundation (22-19-00371).

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Peculiarities of electro-optical control in a multi-gigahertz chaos generator

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Systems with controlled chaotic dynamics are increasingly applied across scientific and technical fields. Chaotic signals can enhance data transmission security, for example, in chaotic masking schemes where information is embedded in chaotic carriers. Chaotic generators based on diode-pumped bulk and fiber lasers with electro-optic control can solve the last mile problem [1] in free space optical communication.

We present our findings related to the controlled chaotization of a laser governed by two-loop electro-optical feedback in the regime of harmonic self mode-locking [2]. The laser system dynamics is investigated through theoretical modelling, employing a nonlinear map approach, and high-resolution simulation.

The nonlinear map under consideration takes into account the nonlinearity of modulator transmission when bias voltage u_0 is different from 0.5 of half-wave modulator voltage:

$$x_{n+1} = r x_n \cos^2\left(\frac{\pi}{2}(x_n + u_0)\right) / \cos^2\left(\frac{\pi}{2}u_0\right), \tag{2}$$

where x_n is the energy of laser pulse at a round-trip number n and r is the overall round-trip gain. Typically, if the goal is to stabilize the pulse amplitude, values of u_0 are chosen to be in the range (0.3–0.5) for negative feedback to be linear with maximum derivatives. We demonstrate that variation of u_0 allows one to significantly reduce the required overall gain, facilitating experimental realization and practical applications of multi-gigahertz chaotic generators.

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Terahertz source based on single-color laser filamentation

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The plasma produced with femtosecond laser filamentation is a source of terahertz radiation. This research presents experimental data on the spatial and energy characteristics of terahertz emission during single-color filamentation. We investigated the effects of various laser pulse parameters, including energy, pulse duration, numerical aperture, and wavelength on terahertz emission. Our findings reveal that the angular distribution pattern of terahertz emission is mainly defined by its frequency and does not depend on the laser pulse energy or the numerical aperture of the beam. We found that terahertz generation efficiency grows with laser wavelengths increase. We determined a particular numerical aperture that optimizes terahertz emission within terahertz spectral range. However, for tightly focused laser beams, there is an optimal pulse duration for each terahertz frequency that maximizes generation efficiency. Overall, this study enables the control of terahertz emission characteristics for a wide range of practical applications by selecting the laser pulse parameters.

The research is performed under the financial support of the Russian Science Foundation, grant number 24-19-00461.

Generation of narrowband terahertz radiation in novel quaternary $BaGa_2GeS_6$ and $BaGa_2GeSe_6$ crystals

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Today, recently developed quaternary sulfide $BaGa_2GeS_6$ (BGGS) and selenide $BaGa_2GeSe_6$ (BGGSe) crystals have attracted much attention and appeared to be promising materials for highly efficient mid-IR radiation generation due to their unique properties [1-2]. Moreover, Ba compounds can provide narrowband THz radiation generation, that was observed recently in ternary $BaGa_4Se_7$ crystal [3]. The two probable explanations are associated with enhancement of the nonlinear susceptibility in the vicinity of phonon resonances and the excitation of phonon-polaritons, arising from the strong coupling between electromagnetic field and coherent lattice oscillations [4]. However, a thorough study of the mechanisms responsible for THz response of barium crystals still remains a subject of ongoing research.

In this paper, we report on a strong narrowband THz generation via the second-order nonlinear process of optical rectification from novel quaternary BGGS and BGGSe crystals pumped by Cr:Forsterite laser. Output THz radiation energy reached 15 nJ that corresponds to an optical-to-THz conversion efficiency of $4\text{x}10^{-6}$. The phonon-rich Ba compounds provide narrow-bandwidth THz pulses at the frequencies in the range from 1.9 to 2.7 THz, necessary for imaging for security or medical applications and narrowband spectroscopy [5].

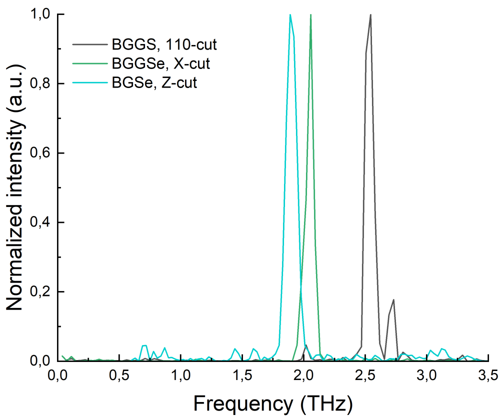

Figure 1: Output spectra for THz radiation generated from the quaternary BGGS and BGGSe crystals.

This work has been supported by Russian Science Foundation Project No. 25-22-00084. D.Z. Suleimanova is the scholar of the foundation for the advancement of theoretical physics and mathematics “BASIS”.

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Study of nonlinear optical properties of PDMS under femtosecond laser pulse interaction

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Polydimethylsiloxane (PDMS) silicon-based organic polymers have attracted significant attention in biomedical applications, flexible electronics, and microfluidic devices due to its excellent biocompatibility, tunable optical properties, and mechanical flexibility [1–2]. Precise control of PDMS's nonlinear optical parameters (e.g., multiphoton absorption coefficients and nonlinear refractive index) is crucial for optimizing localized modifications. At present, research on PDMS's nonlinear response under ultrashort laser pulses remains limited [3].

This study employs an improved Z-scan technique to systematically investigate the nonlinear optical interactions in 5 mm-thick PDMS samples at wavelengths of 515 nm and 1030 nm under varying pulse widths (250 fs, 500 fs, 1000 fs) and energy conditions. By maintaining fixed laser intensity, the regulatory effects of different pulse durations on multiphoton absorption and nonlinear refraction were compared. Based on nonlinear transmission equation fitting of the Z-scan data, the multiphoton absorption coefficients and nonlinear refractive index were quantitatively estimated, providing key parameter support and precise design guidelines for femtosecond laser modification of PDMS.

This research was funded by the Russian Science Foundation (project № 25-22-00488), https://rscf.ru/en/project/25-22-00488/.

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Section 6: Ultrafast laser technologies in biomedicine

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Scope

Ultrafast laser fabrication of bionanomaterials
Femtosecond laser biosensing
Ultrafast active biotherapy
Propagation of ultrashort laser pulses in highly scattering biological tissues
Multiphoton microscopy and tomography

Femtosecond laser fabrication of microstructures in elastic cartilage for tissue engineering of ear transplants

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The use of perforated decellularized ear cartilage for the regeneration of outer ear defects. The new approach was implemented to modify the surface of the transplant and enhance tissue regeneration efficacy using an infrared laser and the seeding of these scaffolds with nasal chondrocytes.

Currently, the regeneration of damaged organs and tissues is an urgent task in various fields of medicine due to the multitude of diseases and the shortage of full-fledged transplants. Due to the clinical necessity, there is a constant search for ways to stimulate the regeneration of cartilaginous tissue. The problem of full-fledged tissue regeneration has not been solved and needs new approaches. One of the promising methods for the regeneration of damaged tissues is the creation of tissue engineering structures based on cartilage tissue [1]. The development of effective tissue engineering structures of cartilage tissue is a complex and multifaceted task requiring an interdisciplinary approach. One of the effective directions of modern regenerative medicine is laser medicine. The introduction of laser technology into the medical field is taking place at an incredible rate, making medicine one of the main consumers of laser systems, far ahead of even industries such as materials processing. Moreover, it was the needs of medicine that stimulated the development of a number of laser systems. Recent advances demonstrate that pulsed and femtosecond laser systems can be used not only for shaping biomaterials but also for functional modification of cartilage surfaces, improving cell adhesion and integration [2,3]. To create more advanced and functional tissue engineering structures, laser radiation is used, as a well-established method in these fields.

Due to its high accuracy and control capabilities, laser radiation can solve a wide range of tasks in the process of creating tissue-engineered implants. Lasers can be used to precisely process biomaterials, forming complex three-dimensional structures that mimic the natural extracellular matrix of cartilage. Laser ablation can be used to selectively remove material from a tissue-engineered structure, forming microchannels and pores that promote the penetration of nutrients and oxygen, as well as improve the integration of the implant with the surrounding tissue. Furthermore, laser engraving has been successfully applied for the formation of microarchitectures in tracheal cartilage grafts, which subsequently underwent recellularization and demonstrated promising in vivo results [3]. Fast-track laser micromachining approaches are also being actively explored to produce elastic and structurally biomimetic scaffolds for cartilage tissue engineering [4].

In this study, we investigate the effect of ultrashort laser pulses on the cartilaginous tissue of a rabbit's auricle. Formed pores contribute to the migration of chondrocytes and ensure the formation of a cellular niche. The experiments were carried out using a TETA-20 femtosecond amplifier (AVESTA, Russia) using a 525 nm second harmonic with a pulse duration of 200 fs. We analyzed under which laser exposure mode it is possible to perform perforation of tissue with a hole diameter of about 150-200 microns without carbonization. We also compared the results obtained with the results of cartilage perforation using a UV laser (355 nm). Made perforated matrixs can be vilized with cells in a bioreactor.

The investigation is supported by Russian Science Foundation (grant № 24-14-00393) and partially within the framework of the state assignment of the Kurchatov Institute Research Center in terms of using equipment of the center for collective use "Structural diagnostics of materials" in part of femtosecond micromachining.

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Laser-induced synthesis of Pd/Au nanoparticles: morphology, size control and ablation parameter optimization

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This work presents a laser-induced forward transfer (LIFT) method for synthesizing Pd/Au alloy nanoparticles. The technique involves ablating metallic films (10-200 nm thick) using a nanosecond laser ($\lambda = 1064$ nm, pulse energy up to 1 mJ, repetition rate 20–80 kHz). The influence of laser parameters (energy, pulse frequency, scanning speed) on particle morphology and size was systematically investigated. Precise control of the process was achieved using an f-theta lens with a focal spot diameter of $\approx$70 μm[1].

The synthesized nanoparticles were analyzed by scanning (SEM) and transmission (TEM) electron microscopy, revealing their size, shape, and structure. Spectroscopic methods (EDS, XRD) confirmed the Pd/Au alloy composition and crystalline phase. By varying donor film thickness and laser parameters, we demonstrated control over nanoparticle concentration and distribution.

Optimal laser synthesis conditions were identified to ensure reproducible production of nanoparticles with tailored properties. Future research will explore the catalytic and plasmonic properties of Pd/Au nanoparticles to expand their functionality.

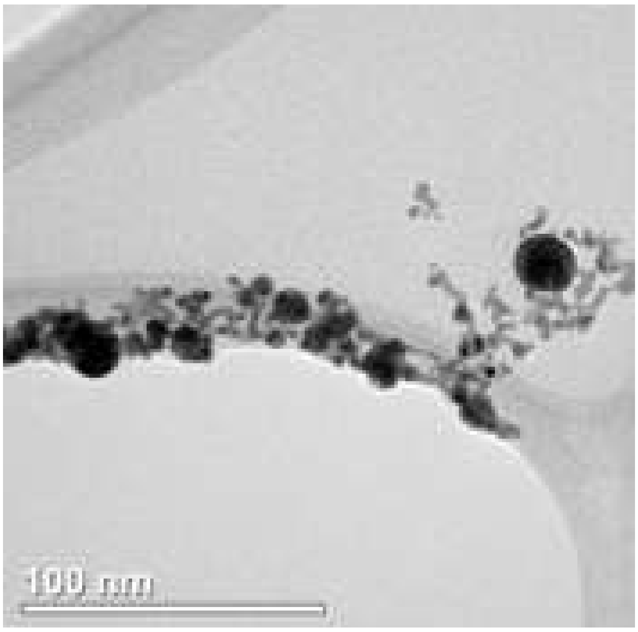

Figure 1: TEM image of Au/Pd nanoparticles synthesized by laser-induced forward transfer (LIFT).

This research was supported by the Ministry of Science and Higher Education of the Russian Federation (project no. 075-15-2023-603).

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Breast cancer diagnostics based on Raman spectroscopy with a laser excitation wavelength of 532 nm

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Breast cancer is one of the most common cancers among women. In 2022, it was diagnosed in 2.5 million patients and caused the death of more than 600,000 worldwide. Early detection is critical for successful treatment, but there are limitations: age, high probability of false positives, and dependence on doctor's experience.

To improve research, Raman spectroscopy is used. It aims to detect biomarkers and chemical changes in breast tissue, which can help differentiate healthy from cancerous tissue. This technique has attracted attention due to its sensitivity and ability to detect molecular changes associated with breast cancer. Successful use of Raman spectroscopy in diagnosing skin tumors has been reported [1].

The breast largely consists of adipose tissue. The structural component of this tissue is adipocytes, which consist of lipid droplets. These lipid droplets participate in fat metabolism and have the ability to accumulate triglycerides and other lipids, which are used by the body for energy production. Spectral analysis reveals a significant decrease in the number of lipid droplet in malignant tissues compared to healthy tissues, suggesting an active involvement of surrounding tissue lipid metabolism in tumor cell proliferation processes, which is confirmed in the study [2].

After analyzing the Raman bands, we noticed that the content of unsaturated fatty acids in breast cancer tissue increased compared to healthy tissue. Carotenoid bands were more frequently found in healthy breast tissue at $1005\,cm^{-1}$ (CH_3 rocking), $1155\,cm^{-1}$ (C–C stretch), and $1515\,cm^{-1}$ (C=C stretch). The main function of white adipocytes is to store energy reserves, but they also act as a reservoir for carotenoids, which may play a protective role in preventing cancer by increasing cell resistance to oxidative stress.

In this work we obtained *in vitro* Raman spectra of normal and tumor breast tissue samples from 59 women at 532 nm laser excitation wavelength, and analyzed them to find spectral biomarkers to differentiate between the two classes of samples. The sensitivity and specificity of diagnostic algorithm were 80 and 65% respectively, and the area under the ROC AUC was 0.81.

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Cross-peak two-dimensional nonlinear optical spectroscopy for ultrafast analysis of fluorescent proteins

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Two Dimensional Fourier Transform spectroscopy (2D FTS) is a non-stationary nonlinear optical method based on the process of four-wave mixing involving a sequence of three femtosecond pulses. The technique has become widely used to obtain information on the structure and ultrafast transformation of organic and inorganic complexes with characteristic molecular vibrations lying in the mid-infrared range, and in this configuration the technique has the most well-known name - 2D Fourier Infrared Spectroscopy (2D FTIR). In one of the possible configurations of the 2D FTS technique, excitation and probing of the objects under study are carried out in significantly different spectral ranges.

Our work presents the implementation of a two-dimensional Fourier spectrometer in both the classical (single-color) version, as well as the variant of two-dimensional electron-vibrational Fourier spectroscopy operating in a cross-range mode, allowing to obtain two-dimensional maps using visible pump radiation with a wavelength of about 470 nm and probing radiation of the mid-IR range with a spectrum in the frequency range of $\tilde{1}430$-1820 cm^{-1}.

The demonstrated visual effect of coupling of electronic and nuclear degrees of freedom in the DCM dye allowed testing the created experimental laser complex. On the measured two-dimensional electron-vibration Fourier spectrum of DCM, an vibration response of the molecule in the frequency range of 1530-1590 cm^{-1} is observed, which is excited by visible pumping at a wavelength of 514 nm. The results of the measurements show that the spectrometer is capable of correctly reconstructing the phase of the electron-vibration spectrum, distinguishing the effects that cause changes in the absorption of probe radiation of different signs. In the future, the developed technique of two-dimensional electron-vibrational Fourier spectroscopy can be used in studies of the photooxidation process of the EGFP protein. Cross-range two-dimensional spectroscopy could directly reveal the relationship between electronic excitation and vibration relaxation of the molecule, which directly affects the characteristic time of the photooxidation process. The work was carried out using equipment supplied under the MSU Development Program.

The work was supported by grants from the Russian Science Foundation 25-12-00211.

Investigation of lipofuscin granules by fluorescence lifetime imaging microscopy

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This paper is devoted to the fluorescence lifetime analysis of lipofuscin granules of retinal pigment epithelium cells by confocal FLIM combined with the large active area SSPD coupled with the multi-mode fiber. The studies were performed using a non–invasive diagnostic method [1] in ophthalmology - fundus autofluorescence (FAF) on a suspension of lipofuscin granules (LGs) from retinal pigment epithelium (RPE) cells obtained from cadaver eyes without signs of pathology from more than 100 patients aged 50-75 years.

Photo-oxidized for 20 min by UV 395nm led diode $3\,\mathrm{W/cm^2}$ lipofuscin granules were used as a model of age-related macular degeneration (AMD). After exposure of light radiation, changes were found in the VIS-NIR fluorescence spectra, as well as in the distribution of fluorescence lifetimes for LG using a three-exponential decay model [2]. Changes in the average fluorescence lifetime for lipofuscin granules from 200 ps before irradiation to 550 ps after photooxidation were recorded.

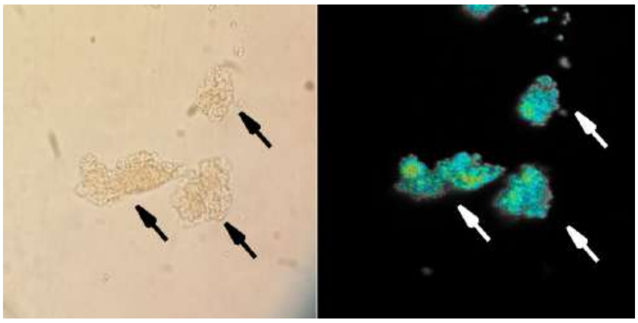

Figure 1: Transmitted and FLIM images of lipofuscin granules. 40× magnification, Image size 512x512 pixels.

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Wound healing properties of bactericidal silver and copper nanoparticles

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Nanoparticles with antibacterial properties are considered as one of the possible alternatives to the use of antibiotics [1]. Nanoparticles have unique physical and chemical properties that allow them to interact with biological systems at the molecular level, which makes them attractive for use in wound healing.

The work considered silver and copper nanoparticles deposited using the laser-induced forward transfer method. The wound-healing effect of nanoparticles was studied on Balb/c mice wounds infected with *Staphylococcus aureus* and *Pseudomonas aeruginosa* bacteria. The concentration of nanoparticles was regulated by selecting the thickness of the donor metal film and the application mode.

The study was supported by a grant from the Russian Science Foundation (RSF) No. 25-25-00512, https://rscf.ru/en/project/25-25-00512/.

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Assessment of albumin conformation in blood serum by ultrafast fluorescence spectroscopy of bilirubin

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Human serum albumin is the most abundant protein in blood serum and plays a vital role in the transport and regulation of various processes. Due to its high concentration and functional significance, conformational changes in albumin often reflect underlying pathological processes, making the assessment of its structural state crucial for disease diagnosis. Several methods are available to probe albumin conformation, including vibrational spectroscopy and fluorescence spectroscopy using exogenous labels [1-2], as well as intrinsic protein fluorescence, primarily from tryptophan and tyrosine residues excited in the ultraviolet range [3]. However, current techniques for the assessment of the albumin conformation are frequently constrained by their dependence on exogenous labels or the necessity for extensive sample preparation.

In this work, we demonstrate that bilirubin, a natural ligand of albumin, may serve as a sensitive intrinsic marker for albumin conformation. For the first time, our findings revealed that bilirubin predominantly contributes to the blood serum fluorescence signal on the picosecond timescale when excited at 400 nm. The bichromophoric nature of bilirubin provides it with unique photophysical properties that influence its ultrafast excitation state relaxation. Notably, bilirubin's photophysical properties are strongly dependent on its molecular configuration, specifically its binding to various proteins in different conformations, which results in distinct optical characteristics. The ultrafast fluorescence decay parameters of bilirubin in blood serum are sufficiently sensitive to detect age-related, naturally occurring modifications in albumin conformation in patients. These results establish bilirubin's ultrafast fluorescence signal in blood serum as a new analytical method for direct evaluation of albumin conformational modifications.

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Picosecond laser induced inactivation of tobacco mosaic virus

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For the first time, to the best of our knowledge, the tobacco mosaic virus (TMV) was inactivated by biharmonic picosecond laser pulses impact due to RNA destruction as revealed by electrophoresis. Conventional development of the vaccine for virus requires a lot of time as we recently observed during COVID-19 pandemic. However, the developed vaccine became low efficient after a few weeks due to ongoing virus mutation. A new instrumental technique for virus inactivation is of a high demand in modern medicine especially for new modification of viruses. Biharmonic generating of picosecond pulses was suggested to damage virus species. The resultant electro-magnetic field oscillations are in the GHz range which corresponded to the virus capsid mechanical oscillations. These vibrations are in the GHz range and quite high compared to that of human cells oscillations. The tobacco mosaic virus (TMV) is a well described so it was chosen for our experiments. TMV [1] is a single-stranded RNA - virus in the form of a hollow tube 300 nm long, 18 nm in diameter with an opening of ~2 nm with helical structure arranged from coat protein with the molecular weight 17 kDa,.TMV infects a wide range of plants. Virus suspension samples were provided by the Department of Virology of the Biological Faculty of Lomonosov Moscow State University [2].

First, we have demonstrated that resonant action in the microwave (2-100 GHz) frequency range resulted in TMV activity inactivation by 15%-40% when irradiating the suspension at a frequency of 9 GHz (0.3 cm^{-1}) with non-thermal intensity (100 $\mu W/cm^2$) [3]. The possibility of suppressing TMV activity in the field of picosecond (30 ps) pulses of the Nd^{3+}:YAG laser remained unclear. A 10 mm long cuvette with a TMV suspension (concentration 1.2 $\mu g/\mu l$) was placed inside the resonator and irradiated for 30 minutes at a frequency of 0.3 Hz. Control samples with a TMV suspension of the same concentration were stored in the laboratory (2 pcs) of virologists and one sample near the laser. Then, four samples of the aqueous TMV suspension (three control and one irradiated in a picosecond laser resonator) were analyzed twice sequentially using electrophoresis in 1% agarose gel. In order to isolate RNA, the TMV samples were heated for 10 minutes at 56 °C before being applied to agarose. The results of the first (a) and repeated (b) analysis are presented in Fig. 1. According to Fig. 1 the RNA signal is absent on the 3rd track so the tobacco mosaic virus RNA has been destroyed by laser pulses.

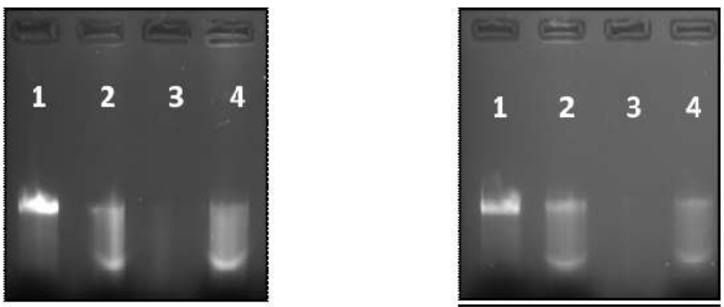

Figure 2: Two parallel analysis of TMV by the gel electrophoresis: 1,2 – control samples, 3 – sample alternated by biharmonic picosecond laser pulses pumping, 4 – control sample stored near laser.

Note that the approach discussed above was not mentioned in a recent review of physical influence on viruses [4]. This work was supported by the Russian Science Foundation (project No. RSF-23-42-10019).

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Enhancing male fertility diagnostics with seminal plasma Raman spectroscopy

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According to the World Health Organization (WHO), infertility is defined as the inability of couples of reproductive age to achieve pregnancy after one year of unprotected sexual intercourse. In particular, male infertility is a critical factor, contributing to around 50% of all infertility cases, either as a standalone.

Seminal plasma (SP) constitutes approximately 95% of the ejaculate volume and plays a crucial role in modulating sperm function [1]. The analysis of SP through Raman spectroscopy provides valuable insights into the molecular composition of its constituents, offering the potential for enhanced diagnostic approaches in male fertility assessment. In this pilot study, we obtained in vitro Raman spectra from 70 dried SP samples in the range from 400 to 1900 cm^{-1} using a laser excitation wavelength of 532 nm. We employed Multivariate Curve Resolution (MCR) analysis and decomposed the Raman spectra into three key components: tyrosine, spermine phosphate hexahydrate, and a protein-rich component. We identified notable differences in the Raman spectra of normal and abnormal samples, particularly in peak intensities at 625, 1440, and 1008 cm^{-1} providing reliable criteria for differentiation with a specificity of 79% and sensitivity of 95% [2]. Based on our literature review, this is the first study that highlights the biochemical distinctions between normal and abnormal SP samples in accordance with the criteria established by the WHO, which includes factors such as sperm count, progressive motility, and normal morphology. Our findings contribute to the growing body of knowledge surrounding male infertility diagnostics and emphasize the necessity for innovative approaches in understanding and addressing reproductive health challenges.

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Surface-enhanced IR absorption of P. aeruginosa bacteria

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Hyperthermia of living cells is a well-known technique, providing good results in anti-cancer therapy [1]. However, its effect on bacteria is mostly studied on the example of magnetic nanoparticles (NPs) [2]. Gd_2O_3 NPs are able to heat up to 60-70ºC under the near IR irradiation, which is suitable for deep in-tissue penetration [3].

We report the use of Gd_2O_3 micro- and NPs for the hyperthermia of bacteria (S. aureus, P. aeruginosa), continuing our previous studies [3]. NPs were obtained from micropowder via femtosecond laser ablation (Satsuma, 1030 nm, 6 μJ, 300 fs, 500 kHz) in water (fig. 1, a, b). The mix of NPs and bacteria was irradiated by unfocused nanosecond laser (HTFMark, 1064 ns, 0.2 mJ, 120 ns, 20 kHz). The resulting decrease of bacterial population reached 10^7 CFU/ml. According to the TEM analysis, bacterial death was caused by the temperature-driven membrane rapture (fig. 1, c-f).

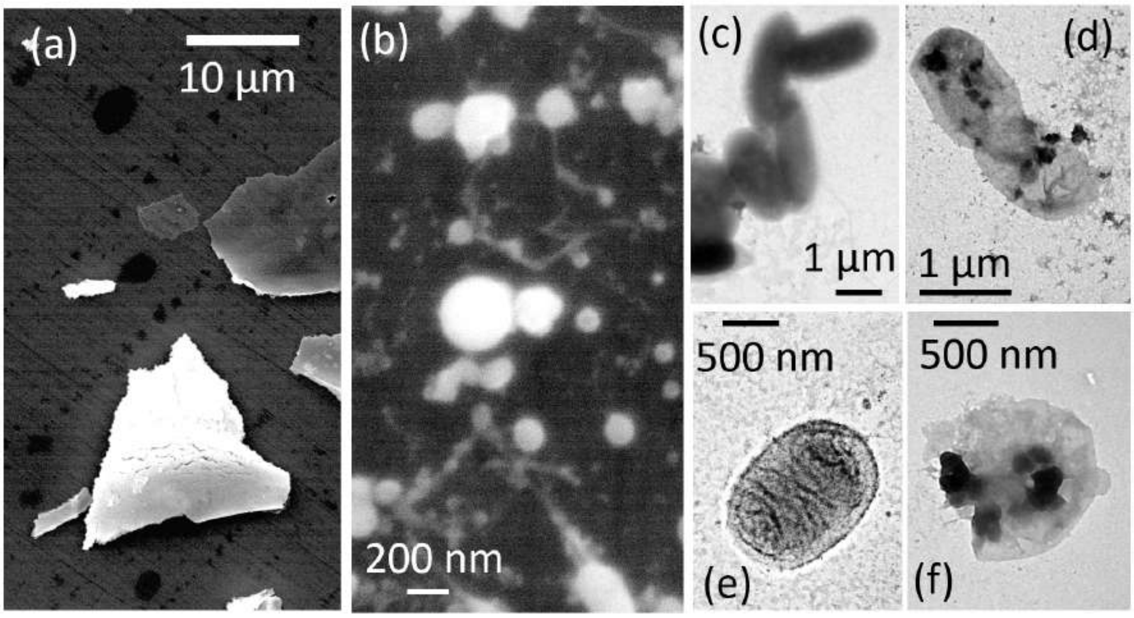

Figure 1: SEM images of Gd2O3 micro- (a) and NPs (b); TEM images of P. aeruginosa (c, d) and S. aureus (e, f) before (c, e) and after hyperthermia (d, f).

This research was funded by Russian Science Foundation (project № 24-25-00403).

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Surface-enhanced IR absorption of P. aeruginosa bacteria

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Infrared (IR) and Raman spectroscopy with surface enhancement of electromagnetic fields of probe radiation and signal due to plasmon effects of individual nano/microstructures (localized plasmons) or their arrays (lattice plasmon polaritons) are often used to analyze characteristic molecular vibrations of chemoanalytes and microorganisms. In the reflectance spectrum in the region of the resonant dip enhanced absorption of surface analytes may occur [1, 2].

We report the SEIRA effect of the P. aeruginosa bacteria on the laser-written arrays of microcraters. The IR measurements were performed using a MIKRAN-3 IR microscope-spectrometer (2–17 μm) equipped with an SF-801 Fourier spectrometer (SIMEX, Russia) in the range from 470 to 5700 cm^{-1}. A variation in the intensity (and width) of the peak of $C = O$ vibrations in amide I band (β-sheets, 1642 cm^{-1}) was observed, as well as a change in its ratio to the intensity of the peak at 1654 cm^{-1}(α-helices). An increase in the intensity of the peak at 1642 cm^{-1} is observed with decreasing laser energy, used for the arrays' fabrication, with a lattice period of 8 μm.

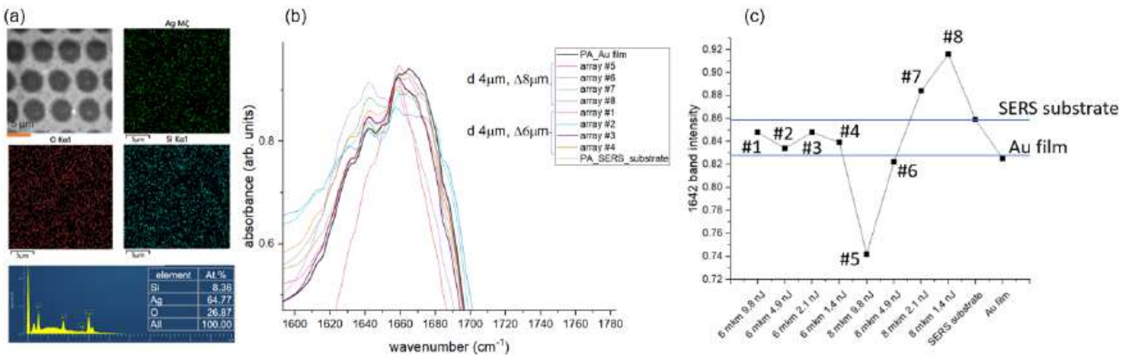

Figure 1: (a) SEM images and EDS analysis of microcraters' array; (b) FTIR spectra of P. aeruginosa on different substrates; (c) the 1642 cm^{-1} band intensity value for different types of arrays.

This research was funded by Russian Science Foundation (project № 25-42-01013).

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Light and temperature fields induced by pulsed laser radiation in biological tissues

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The ability of laser radiation to penetrate into biological tissues and precisely modify them is widely used in regenerative and aesthetic medicine and in cosmetology. Despite significant progress, the issues of providing the efficiency, reliability and safety of exposure to intense laser radiation on biological tissues still remain relevant. The main problem is that laser radiation propagates in a highly heterogeneous environment, the optical and thermophysical parameters of which can vary significantly depending on the type of tissue, age, race of the patient.

In the presented work, a series of experiments on the modification of collagen-containing tissues (skin of the rabbit auricle) by pulsed laser radiation with a wavelength of 1560 nm was carried out while varying pulse duration and the diameter of the laser beam on the sample surface (200 and 600 microns). Using an integrating sphere and the thermal imager FLIR 650sc thermophysical and optical parameters of used samples were obtained. The thermal data was analyzed and processed using a FLIR ResearchIR Max software. The measured optical parameters were used to calculate the light field and the spatial distribution of heat sources. Then an unsteady thermal problem with distributed heat sources using an original software package for Matlab was solved. The threshold values of laser power for collagen denaturation were found. It was determined that at threshold power the maximum temperature of the sample is around 75°C. Based on the model and the assumption that coagulation occurs at 75°C, the volumes of the coagulated regions were calculated.

Figure 1 shows the obtained coordinates of the points where temperature exceeds 75°C for a laser spot with a diameter of 200 and 600 μm and the power of 1 and 2 W, correspondingly, at different depths (z) of a 0.4 mm thick skin sample.

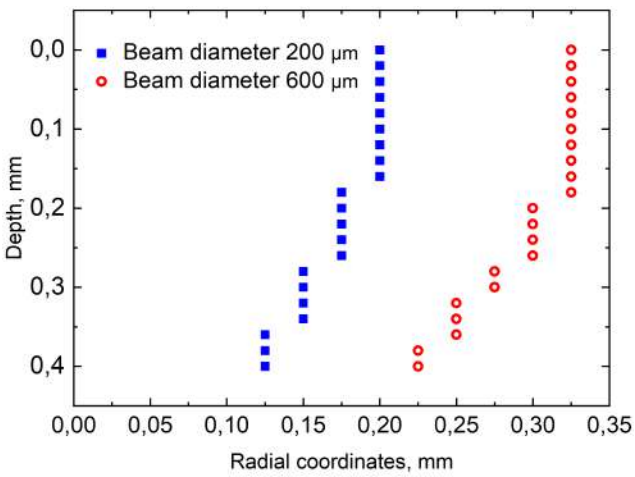

Figure 1: 1 Coordinates of points whose temperature exceeded 75°C during 70 ms pulsed heating under the following conditions: the center of a laser spot with a diameter of 200 and 600 μ and the power of 1 and 2 W correspondingly at different depths (z) of a 0.4 mm thick skin sample.

The obtained simulated results are in good agreement with the experimental results and the theory.

These results can be used for the development of a methodology for choosing optimal modes of local laser exposure to biological tissues during therapeutic, restorative or aesthetic procedures, taking into account the individual characteristics of the patient and the expected result.

Mechanisms of spectral-selective bacterial inactivation using the mid-IR femtosecond laser pulses

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The rise of new pathogens and antibiotic resistance requires new control methods. Mid-infrared radiation (∼6μm and ∼3μm) is promising as it targets key bacterial molecules, such as amide group bonds in proteins and nucleic acids, and C–H bonds in lipids. In this study, we examined the mechanisms underlying the inactivation of pathogenic P. aeruginosa bacteria through dynamic transmission spectroscopy using femtosecond laser pulses at wavelengths of 3.4 μm and 6 μm. By analyzing the spectra of relative transmittance changes induced by laser excitation at 6μm, which targets C=O and C–N vibration modes in proteins stabilized by hydrogen bonds, we identified three distinct interaction regimes:

1. At pulse intensities of 1–10 GW/cm^2, the fundamental absorption band corresponding to harmonic C=O and C–N vibrations in the amide groups of proteins was bleached.

2. At 10–100 GW/cm^2, the same amide vibration band continued to be bleached, along with induced absorption of C=O vibrations in the blue spectral region, which is associated with the disruption of hydrogen bonds.

3. At intensities above 100 GW/cm^2, induced absorption of anharmonic C=O and C–N vibrations in the red region of the spectrum was observed.

For laser pulses at 3.4 μm (targeting C–H bonds), the relative transmittance spectra showed bleaching of the fundamental C–H vibrational band and induced absorption of anharmonic C–H vibrations in the red spectral region.

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Microsurgery of *zona pellucida* of human embryos using infrared femtosecond laser pulses

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The results of *zona pellucida* (ZP) dissection of human embryos using infrared femtosecond laser pulses in various regimes are presented. Experiments were conducted using a "Femtosecond laser scalpel-optical tweezers system" setup [1]. ZP microsurgery was performed using a series of laser pulses (wavelength λ=1028 nm, pulse duration τ=280 fs, pulse repetition rate f=2500 Hz) to find the range of admissible parameters of pulse intensity and beam velocity. Human embryos from patients who had signed informed voluntary consent were transferred from the FSBI "National medical research center for obstetrics, gynecology and perinatology named after academician V. I. Kulakov" to JIHT RAS, then thawed and subjected to laser radiation. The laser beam was focused to a spot with radius of 1.56 μm at $1/e$ level in the plane of maximal diameter of the embryo cross section (equatorial plane) and moved along the trajectory with velocity v=2 μm/s.

A series of ZP cuts for laser pulse intensities in the range of $I = 4.5 - 8\,\mathrm{TW/cm^2}$ and $I = 5.5 - 7\,\mathrm{TW/cm^2}$ were made for $v = 0.5$ μm/s and $v = 2.5$ μm/s respectively. Intensities above $7\,\mathrm{TW/cm^2}$ resulted in optical breakdown within the ZP volume, as well as the formation of cavitation bubbles. Compared to experiments involving a radiation wavelength of $\lambda = 514\,\mathrm{nm}$, infrared pulses were found to require at least twice the pulse intensity and slower beam velocities to achieve the same cut width.

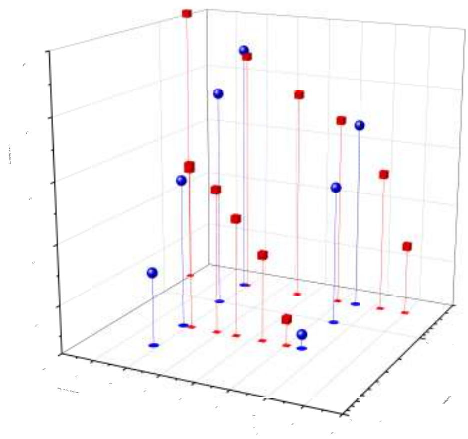

Figure 1: Cut widths of human embryo ZP as a function of laser intensity and beam velocity at $\lambda = 1028$ nm.

This work was supported by the Russian Science Foundation (Grant number 23-19-00424, https://rscf.ru/en/project/23-19-00424/).

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Size-shape effects in catalysis by laser-induced metal nanoparticles

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The influence of the size and shape of metal nanoparticles (NPs) when used in catalysis was considered. Such stable monodisperse particles were obtained using laser-induced forward transfer; their catalytic properties were assessed by hydrogen activity.

The laser transfer method allows precise control over the morphology of NPs. The laser radiation parameters (wavelength, pulse duration, energy density) allow one to regulate the particle size (usually in the range from 2 to 100 nm), their crystallinity and surface topology. Such controllability promotes the formation of active centers of various natures - edge, step and defective, which play a decisive role in heterogeneous catalysis.

Nanocatalysts based on noble metals combine reactivity and selectivity. This can be associated with the structural features of the colloidal state of the catalyst: a large specific surface, and, consequently, a higher percentage of metal atoms located on the surface. From the point of view of catalytic properties, the goal of obtaining catalysts with optimal structural sensitivity should be the optimal size of metal particles, but at the same time it is necessary to ensure a narrow (almost monodisperse) particle size distribution. After all, with a wide distribution, most particles with non-optimal sizes will not allow achieving the maximum level of activity [1].

A series of catalyst samples with a narrow particle size distribution and a variation in the average size up to 50 nm were obtained. The study of the catalytic properties of the prepared catalysts has shown that a decrease in mean size of supported metal particles leads to a sharp increase in specific catalytic activity. The activity maximum has been achieved for active component particles of a few nm in size. A conclusion has been made that the application of nanosize catalysts is promising for application in biomedicine.

Acknowledgement: This research was supported by the Ministry of Science and Higher Education of the Russian Federation (agreement No. 075-15-2023-603).

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Ultrafast Excited-State Dynamics of carotenoid pigment bound to AptaP protein

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Carotenoproteins represent a diverse and extensive class of biological pigments that are widely distributed among invertebrates. These pigments are formed by the stoichiometric binding of specific carotenoid molecules to various protein scaffolds. This binding enables the acquisition of new biological functions, including molecular transport and storage, protection against reactive oxygen species, and participation in the processes of directed energy transfer of excited electrons. Carotenoids, as chromophores, exhibit extremely complex and rapid dynamics of electron excitation, with characteristic times in the femtosecond to picosecond range. The structured protein environment can significantly alter the spectral properties of the bound carotenoid, often resulting in biologically important functional manifestations.

In this study, we focused on the ultrafast excitation dynamics of the newly discovered AspaP carotenoid-binding protein and its variants bound to zeaxanthin (ZEA) and canthaxanthin (CAN). To investigate the modulation of photoinduced electron excitation flow by the AspaP protein, we employed pump-probe spectroscopy with chirped pulses and femtosecond temporal resolution. This technique allowed us to compare the excitation dynamics of protein-bound carotenoids with those of free ZEA and CAN solutions

The results obtained from our experiments were interpreted in the context of the molecular structure of AspaP and the specific interactions that occur at the interface between the carotenoid and the protein scaffold. Understanding these interactions is crucial for elucidating the mechanisms underlying the spectral modifications observed in the bound carotenoids. The insights gained from this study could be valuable for future efforts aimed at modifying the spectral properties of AspaP. By manipulating these properties, it may be possible to improve the biological functions of the protein or to develop new applications based on its unique characteristics.

Research was supported by the Russian Science Foundation under grant number 25-74-20001.

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