VII International Conference on Ultrafast Optical Science
«UltrafastLight-2023»
Moscow, 2023

VII International Conference «UltrafastLight-2023»

Book of Abstracts

VII International Conference on Ultrafast Optical Science

UltrafastLight-2023

October 2 – 4, 2023
Lebedev Physical Institute, Moscow

AVESTA
LASERS AND OPTICAL SYSTEMS

"UltrafastLight-2023" is the broad-scope, annual international symposium dedicated to the most important aspects of ultrafast phenomena in different fields of natural sciences and engineering.

The Conference topics:

1. Extreme light
2. Ultrafast phenomena in ionized gases, semiconductors and metals
3. Ultrafast laser technologies and structured light in micro-optics and nanophotonics
4. Diamond photonics
5. Frequency combs in spectroscopy and optical clocks
6. Ultrafast optical technologies and nonlinear optical phenomena
7. Ultrafast laser technologies in biomedicine

Website: www.ultrafastlight.ru
E-mail: ultrafastlight@lebedev.ru
ultrafastlight@yandex.ru

Chair - Nikolay Kolachevsky (The Lebedev Physical Institute of the Russian Academy of Sciences (LPI)),
Vice-chair - Andrey Ionin (LPI),
Vice-chair - Sergey Kudryashov (LPI)

Section 1: Extreme light

Section Chair:

Andrei Brantov, e-mail: brantovav@lebedev.ru
(P.N. Lebedev Physical Institute, Russia)

Program committee:

Nikolay Andreev
(Joint Institute for High Temperatures, Russia)

Valery Bychenkov
(P.N. Lebedev Physical Institute, Russia)

Andrei Savel'ev
(Lomonosov Moscow State University, Russia)

Scope

Laser particle acceleration

Secondary electromagnetic processes

Nuclear photonics

Extreme field physics

Ultra-high intensity facilities

Super-strong magnetic fields generation in laser nanostructure plasma

A. A. Andreev[1,2], K. Yu. Platonov[3] and L. A. Litvinov[1]

[1] St. Petersburg State University, St. Petersburg, Russia;
[2] Ioffe Phys. Tech. Institute, RAS, St. Petersburg, Russia;
[3] St. Petersburg State Technical University, St. Petersburg, Russia
e-mail: alexanderandreev72@yahoo.com

In the previous publications [1-4], we proposed a method for generating large-amplitude magnetic-dipole moment based on the electron inertia in cluster rare-gas targets irradiated by circularly polarized ultrashort laser pulses. This magnetic field is stable and remains nearly constant over the timescale of modern short laser pulses (femtosecond durations).

Here, the interaction of high intensity, circular polarized, short laser pulse with cluster plasma was considered, taking into account ion motion, by analytical modelling and numerical simulations. The optimal (for multi GGs, quasi-stationary magnetic field generation) density and size of clusters, as well as laser pulse intensity and duration, were found by using the upgraded analytical model and detail 3D PIC simulations. At relativistic high laser intensity the electrons of cluster plasma are completely magnetized, but heavy ions are magnetized as well only in cluster core and compressed by the magnetic field to a density many times bigger than the initial one. Fast ions of outer shell are not magnetized and move (partly) in radial direction, according to thermal (Coulomb) expansion model. Gold ion energy reaches above GeV level after few tens of femtosecond interaction.

It is found that a field of such strength slows down the thermal expansion of the cluster core in the direction transverse to the laser beam axis, which can be used in nuclear (fusion) physics and provides very specific spiral ion motion, which is absent at a cluster irradiated by linear-polarized pulse of the same parameters.

We also analyze the cases of nano-shell(tube) targets (similar to [5,6]) of different sizes instead of bulk clusters. The implosion of such targets irradiated by intense laser pulse was investigated and we obtained magnetic field amplification in comparison with cluster case of about the same size.

REFERENCES

[1] A. Andreev, K. Platonov, JETPL, 112, 598 (2020).
[2] Zs. Lecz and A. Andreev, Phys. Rev. R 2, 023088 (2020).
[3] A. Andreev, K. Platonov, Quantum Electronics, 51, 446 (2021).
[4] A. Andreev, K. Platonov, Zs. Lecz, N. Hafz, Sci. Rep. 11:15971 (2021).
[5] A. Andreev, K. Platonov, A. Sharma, M. Murakami, Phys. of Plasmas, 22, 093106 (2015).
[6] Zs. Lecz, A. Andreev, New Journal of Phys. 20, 033010 (2018).

High energy particles and gamma rays in relativistic laser-matter interaction

N. E. Andreev[1,2]

[1] Joint Institute for High Temperatures of RAS, Moscow, Russia;
[2] Moscow Institute of Physics and Technology (State University), Dolgoprudnyi, Moscow region, Russia
e-mail: andreev@ras.ru

Intense beams of photons and particles in the MeV energy range are effective tools in many areas of research, such as the creation and diagnostics of matter in extreme states, nuclear physics and materials science, as well as in other applications. Various processes of laser-plasma acceleration of electrons are considered, starting with the mechanism of wakefield acceleration in the regime of self-modulation of a laser pulse [1]. This mode of generation of ultrarelativistic electrons underlies the creation of a platform for diagnosing compressed target matter in a number of large laboratories conducting research in the field of thermonuclear fusion with inertial confinement [2].

A more efficient concept for creating sources of γ-radiation and neutrons based on the generation of relativistic electrons in the regime of direct laser acceleration is currently being discussed. 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 an extended plasma with a density close to critical [3, 4], which was confirmed in experiments [5].

The dependences of the parameters of laser-generated electron bunches and hard radiation on the laser radiation intensity and plasma density for subpicosecond and femtosecond laser pulses are obtained and analyzed taking into account current and future experiments [5, 6]. The results obtained indicate a way to improve the efficiency of a wide class of secondary laser sources, such as sources of electrons, positrons, betatron and bremsstrahlung radiation, and sources of protons and neutrons for various purposes [7, 8].

REFERENCES

[1] N.E. Andreev, L.M. Gorbunov, Physics–Uspekhi. 42 (1), 49–77 (1999).
[2] Joshi C. `https://www.orau.gov/stri/ssap2021/HEDP_Feb17/HEDP_Feb17_3.00pm_Joshi.pdf`
[3] L.P. Pugachev, N.E. Andreev, P.R. Levashov, O.N. Rosmej, Nuclear Instruments and Methods in Physics Research A, V. 829. P. 88–93 (2016).
[4] N.E. Andreev, V.S. Popov, O.N. Rosmej, et al., Quantum Electronics, 51, 1019–1025 (2021).
[5] O.N. Rosmej, N.E. Andreev, S. Zaehter, et al., New J. Phys. V. 21, P. 043044 (2019).
[6] N.E. Andreev, I.R. Umarov, V.S. Popov, Kvantovaya Elektronika, V. 53, P. 236 (2023).
[7] X. F. Shen, A. Pukhov, O. N. Rosmej, N. E. Andreev, Phys. Rev. Applied, 18, 064091 (2022).
[8] M. Gunther, O.N. Rosmej, P, Tavana, et. al., Nat. Commun., V. 13, P. 170 (2022).

Radiation of optical and terahertz unipolar pulses by solitary polarization pulse moving at the superluminal velocity and the velocity of light

R. M. Arkhipov[1], M. V. Arkhipov[1,2], A. V. Pakhomov[1], O. O. Diachkova[1,2] and N. N. Rosanov[1,2]

[1] St. Petersburg State University, St. Petersburg, Russia;
[2] Ioffe Institute, St. Petersburg, Russia
e-mail: arkhipovrostislav@gmail.com

It is well known that material objects such as charges, dipoles etc. cannot move at the speed of light in vacuum c or faster it, because such motions are "forbidden" by the special theory of relativity. However, in optics, there are exists a huge amounts of "artificial" objects examples, such as spots of light, effective dipoles created by external laser pulses. Such objects can propagate at an arbitrary speed, in particular at superluminal one being a source of Vavilov-Cherenkov radiation [1]. Radiation and creation of such superluminal objects was considered by B.M. Bolotovskii and V.L. Ginzburg [1] and other authors [2-7]. To date, the superluminal motion of laser focus have the fundamental interest in the problems of laser-plasma interactions [3]. Besides the radiation of superluminally moving current sheet forming in a neutron stars is a subject of current research in astrophysics [5]. Another example of such an object is the so-called "solitary polarization pulse" (SPP) – is an artificial dipole (pulse of medium polarization) that also can propagate at the speed of light and even faster it [5]. Such SPP for example can be created in a resonant medium excited by a pair of ultrashort light pulses separated by the half period T0/2 of the medium resonant transition [5-7]. In this case, the first laser pulse creates oscillations of the medium polarization at the resonant frequency, while the second one switches off them. In this talk, we will discuss the unusual features of the emission of such SPP in homogeneous and inhomogeneous resonant medium. Among them are generation of unipolar terahertz and optical pulses in an inhomogeneous medium. In this case, the results of our theoretical consideration showed the possibility to generate unipolar pulses of an unusual shape – such as rectangular and triangular ones [5-7]. This work is supported by Russian Science Foundation (project 21-72-10028).

REFERENCES

[1] B.M. Bolotovskii, V. L. Ginzburg, Sov. Phys. Usp. 15, 184 (1972).
[2] B. M. Bolotovskii, A. V. Serov, Phys. Usp. 48, 903 (2005).
[3] T. M Jeong et al., Optics Express, 29, 31665 (2021).
[4] H. Ardavan. Monthly Notices of the Royal Astronomical Society, 507, 4530 (2021).
[5] R.M. Arkhipov et al., JETP Lett., 117, 574 (2023).
[6] A. Pakhomov et al., Physical Review A., 106, 053506 (2022).
[7] A. Pakhomov, N. Rosanov, M. Arkhipov, R. Arkhipov, submitted (arXiv:2303.11116).

A source of incoherent synchrotron radiation based on a submicron cluster medium irradiated by an ultrashort laser pulse

O. E. Vais[1,2], D. A. Gozhev[1], S. G. Bochkarev[1,2] and V. Yu. Bychenkov[1,2]

[1] P.N. Lebedev Physics Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] The Federal State Unitary Enterprise Dukhov Automatics Research (VNIIA), Moscow, Russia
e-mail: bochkarevsg@lebedev.ru

Among the whole variety of structured targets and laser-plasma sources, which are used to optimize the characteristics of laser-heated and accelerated particles and also secondary radiation, cluster targets are widely available and diverse. Until recently, nanoscale clusters have been widely used, due to the fact that the technique for their production is well developed. Such targets are transparent to laser radiation, and on the other hand, they are characterized by almost complete absorption of laser radiation. The transition to large clusters (of submicron and micron sizes, which are already quite widespread at present, see, for example, [1]), will increase the efficiency of generation of charged particles [2] and broadband secondary radiation [3]. This report presents the results of a study of incoherent synchrotron radiation generation, based on the optimization of the efficiency of laser acceleration of electrons with the help of 3D PIC ("particle-in-cell") simulations.

We simulated the interaction of an ultrashort intense laser pulse of 15 fs duration with cluster targets. This was carried out using the VSIM ("Vorpal") code. Based on the analysis of the trajectories of randomly selected particles, the spectral-angular distribution of incoherent synchrotron radiation is determined for optimized laser-target parameters [2]. The revealed feature of the energy distribution of electrons with a plateau region, associated with the presence of particles that perform complex motion in the combined laser and Coulomb fields, leads in turn to the formation of a wide frequency spectrum of secondary synchrotron radiation with a critical frequency (as well as the cutoff frequency of the spectrum), which monotonically increases in proportion to laser intensity in the range 10^{18}-10^{20} W/cm^2. The estimated value of the conversion coefficient of laser energy into synchrotron soft X-ray radiation is not high (10^{-6}-10^{-4}). At the same time, incoherent synchrotron radiation has the form of short pulses with an expected duration of no more than 1 ps, which may be of practical interest. In conclusion, our study highlighted the laser-heated cluster medium is a source of broadband synchrotron radiation with a tunable frequency in the range from terahertz, vacuum ultraviolet to hard X-ray radiation.

This work was supported by Ministry of Science and Higher Education of the Russian Federation under contrast No. 075-15-2021-1361. O.E. Vais acknowledges Foundation for the Advancement of Theoretical Physics and Mathematics ("BASIS") for the financial support (grant # 22-1-3-28-1).

REFERENCES

[1] S Jinno, M Kanasaki, M Uno, R Matsui, M Uesaka, Y Kishimoto and Y Fukuda, Plasma Physics and Controlled Fusion., 60:4, 044021 (2018).
[2] D.A. Gozhev, S.G. Bochkarev, and V.Yu. Bychenkov, JETP Letters 114, 200 (2021).
[3]. A.A. Andreev and K.Yu. Platonov, Quantum Electron., 52:2 195 (2022).

Intense source of polarized terahertz radiation based on laser-driven discharge currents

N. D. Bukharskii, E. O. Dmitriev and Ph. A. Korneev

P. N. Lebedev Physical Institute, Moscow, Russia
e-mail: n.bukharskii@gmail.com

Terahertz (THz) technology is an actively developing field of science encompassing a broad range of research areas with numerous possible applications resulting from the benefits of electromagnetic radiation in the THz domain [1]. Generation of powerful THz radiation with specific polarization is a promising line of research, as the polarization may offer additional control of THz-matter interaction in certain studies, e.g. molecular orientation and alignment [2], while its high intensity may further increase the induced effects in matter and lead to the development of new technologies for fundamental studies and practical applications.

The work provides design-theoretical description of a source of intense polarized THz radiation based on laser-driven discharge currents [3,4]. As have been demonstrated in previous works [5,6], efficient generation of THz radiation is possible if short discharge current pulses are excited in a shaped target and stay well-localized on the target scale. Here, it is shown via kinetic modelling that a compact discharge current pulse can be created in a closed coil target with elliptically shaped external surface. The performed analysis indicates that the electromagnetic radiation produced by this current pulse oscillating along the target surface will have an elliptic polarization with rotation direction defined by the discharge current propagation direction and the degree of ellipticity and frequency spectrum defined by the geometrical parameters of the target. The peak power of THz radiation that can be reached in the considered setup with modern petawatt laser facilities extends to terawatt range, making the proposed scheme promising for various applications where intense THz radiation with controlled properties is required.

REFERENCES

[1] A. Leitenstorfer et al., Journal of Physics D: Applied Physics, 56 (22), 223001 (2023).
[2] S. Fleischer et al., Physical Review Letters, 107 (16), 163603 (2011).
[3] K. Quinn et al., Physical Review Letters, 102 (19), 194801 (2009).
[4] M. Ehret et al., Physics of Plasmas, 30 (1), 013105 (2023).
[5] N. Bukharskii, Iu. Kochetkov, Ph. Korneev, Applied Physics Letters, 120 (1), 014102 (2022).
[6] N. Bukharskii, Ph. Korneev, Matter and Radiation at Extremes, 8 (4), 044401 (2023).

Numerical simulation of coherent combining of laser beams in the presence of non-idealities in the dipole focusing system

D. N. Bulanov, A. V. Korzhimanov, E. A. Khazanov and A. A. Shaikin

Federal Research Center Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
e-mail: denisbulanov1999@yandex.ru

One of common techniques for obtaining radiation of record high intensity is the coherent combining of several laser beams. Additionally, it is theoretically shown [1] that in order to achieve the maximum possible magnitude of electromagnetic field for fixed beam parameters (duration, power) one should use a dipole focusing scheme, which requires the radiation to have the structure of a convergent main spherical mode, corresponding to the time-reversed harmonic dipole radiation.

The XCELS (eXawatt Center for Extreme Light Studies) facility [2] is an example of a planned project, in which the aforementioned method is used to produce laser radiation with high peak power and intensity. For laser systems of this kind, it is important to study how various factors, such as the number of laser beams, the focusing scheme or non-idealities in the system, which lead to the appearance of aberrations, influence the coherent combining efficiency.

As part of this work, a library for numerical simulation of laser beams reflection was developed. The Stratton-Chu diffraction integrals [3] were chosen to calculate the fields in the focal volume. Based on the results of numerical simulations, the possibility of increasing the intensity of radiation in the focus by using different number of beams and different focusing schemes was evaluated. It was found that intensity above 3×10^{26} W/cm^2 is attainable in a system of 12 beams of 50 PW each — this configuration corresponds to the design characteristics of XCELS. The influence of phase distortion, inaccuracies of mirror alignment and aberrations in the incident radiation on the efficiency of coherent combining of laser beams is also studied — it is shown that at the current level of technological development it is possible to achieve about 90% of the intensity value of the ideal configuration.

REFERENCES

[1] I.M. Bassett. Limit to Concentration by Focusing. Optica Acta: International Journal of Optics 33:3, 279–286 (1986).
[2] E.A. Khazanov, A.A. Shaikin et. al. International Exawatt Center for Extreme Light Field Studies (XCELS). Kvantovaya Elektronika 53:2, 95–122 (2023).
[3] J. A. Stratton, L. J. Chu. Diffraction theory of electromagnetic waves. Physical Review 56, 99–107 (1939).

On electron acceleration governed by quasi-static fields in laser plasma channel produced by a short relativistically intense laser pulse

A. J. Castillo[1,2], S. G. Bochkarev[2,3], M. G. Lobok[2,3] and V. Yu. Bychenkov[2,3]

[1] Peoples' Friendship University of Russia (RUDN University), Moscow, Russia;
[2] P.N. Lebedev Physics Institute of the Russian Academy of Sciences, Moscow, Russia;
[3] The Federal State Unitary Enterprise Dukhov Automatics Research (VNIIA), Moscow, Russia
e-mail: 1142220668@rudn.ru

With the advent of high-power ultrashort laser pulses, the interaction of a relativistically intense laser with a near-critical plasma has become a source of laser-generated plasma channels, laser-accelerated charged particles, synchrotron radiation, and quasi-static long-lived intense magnetic fields. [1-5]. In the case of a relativistically intense laser pulse, the nonlinear response of the plasma breaks the adiabaticity between the electrons and the laser wave, which leads to the absorption of the laser energy by the plasma electrons.

In this paper we discuss direct laser electron acceleration in the laser plasma channel produced by ultrashort relativistically intense linearly or circularly polarized laser pulses as well as the post electron dynamics governed by quasi-static fields in empty channel. The electron dynamics is studied by using a test particle simulation, where the joint effect of the Gaussian laser fields with the self-generated quasistatic fields [2] includes the radial quasistatic electric field, the azimuthal quasistatic magnetic field. We also include a quasistatic axial magnetic field term for the case of circularly polarized laser pulse, the influence of localized electric field that was reviled in PIC (particle in cell) simulations [3]. The stochastic behavior of electron trajectories in a complex laser and quasistatic field has been revealed employing Lyapunov exponent and phase portrait analysis. We show that non-reversible gain of energy due to breaks of adiabaticity between the electrons and the laser wave strongly depends on the amplitude of quasistatic field and find threshold values for effective energy gain depending on laser pulse amplitude. We partially consider laser parameters of MultiTera laser system, 20TW, 40 fs [6]. The distribution of particles accelerated in the channel is characterized by superponderomotive electrons with a temperature much higher than the ponderomotive value. We also discuss the stability of the electron dynamics in the process of post acceleration in empty channel after laser pulse has already left and electrons proceed to ExB acceleration, governed by quasistatic long-lived magnetic fields and quasistatic electric fields. Detailed numerical analysis predicts that in the case of circular polarization, the quasistatic longitudinal magnetic field, which is the same order as azimuthal magnetic field [5], collimates electrons toward channel axis, providing better quality of accelerated electron beam.

This work was supported by Ministry of Science and Higher Education of the Russian Federation under contract No. 075-15-2021-1361.

REFERENCES

[1] A. Pukhov, Z.-M. Sheng, and J. Meyer-ter-Vehn, Phys. Plasmas 6, 2847 (1999).
[2] G.D. Tsakiris, C. Gahn, V.K. Tripathi, Phys. Plasmas 7, 3017 (2000).
[3] K. Jiang, C. T. Zhou, T. W. Huang, et al., Phys. Rev. E 98, 033206 (2018).
[4] S.G. Bochkarev, A.V. Brantov, V.Yu. Bychenkov, et al., Plasma Phys. Rep. 40, 202 (2014).
[5] M. Lama, U. Chaulagain, J. Nejd, S.V. Bulanov, Scientific Reports 17, 1701 (2023).
[6] https://www.atomic-energy.ru

Generation of high harmonics by dipole electromagnetic pulse evolving in vacuum

R. M. Feshchenko

P.N. Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia
e-mail: rusl@sci.lebedev.com

It is well known that in presence of a strong electromagnetic field the conventional Maxwell equations in free space are modified by vacuum fluctuations and become non-linear [1], which leads to appearance of many new and interesting physical effects [2]. For instance, in a strong magnetic field the vacuum behaves like a birefringent medium. In addition, in a strong electromagnetic field (e.g. of a dipole) the light generally does not propagates along straight lines but follows geodesics in some pseudo-Riemannian space [3].

In this presentation another non-linear electromagnetic problem is considered: generation of high harmonics by a strong finite dipole electromagnetic pulse evolving in free space [4]. Using the well known non-linear vacuum Maxwell equations [1–2] an analytical solution of this problem is obtained and the angular, temporal, spectral properties of the resulting high harmonics pulses are studied. It is shown that the emitted high harmonics does not maintain the dipole shape of the initial pulse and can be represented as a linear combination of several multipole terms. Different temporal profiles of the initial dipole pulse are considered and it is demonstrated than the characteristics of the emitted high harmonics pulses depend strongly on the profile chosen.

REFERENCES

[1] Berestetskii, V. B., Lifshitz, E. M., Pitaevskii, L. P.: Quantum Electrodynamics. Butterworth-Heinemann, v.4 (1982).

[2] Sorokin, D.P.: Introductory Notes on Non-linear Electrodynamics and its Applications, Fortschr. Phys. **70**, 2200092 (2022).

[3] Vasili'ev, M.I., Denisov, V.I., Kozar', A.V., Tomasi-Vshivtseva, P.A.: The Effects of Vacuum Nonlinear Electrodynamics in a Electric Dipole Field, Theoretical and Mathematical Physics. **72** (6), 513–517 (2017).

[4] Artyukov, I.A., Dyachkov, N.V., Feshchenko R.M. and Vinogradov A.V.: Collapsing EM wave—a simple model for nonparaxial, quasimonochromatic, single-and half-cycle beams, Physica Scripta **95**, 064006 (2020).

Hybrid DLA-LWFA acceleration of electrons in near-critical density plasma

D. A. Gorlova[1,2], I. N. Tsymbalov[1,2], E. M. Starodubtseva[1], K. A. Ivanov[1,3], R. V. Volkov[1], I. P. Tsygvintsev[4], Yu. V. Kochetkov[4], A. B. Savel'ev[1,3]

[1]Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[2]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[3]P.N. Lebedev Physical Institute, Moscow, Russia
[4]Keldysh Institute of Applied Mathematics, Moscow, Russia
e-mail: gorlova.da14@physics.msu.ru

It has been experimentally demonstrated that the interaction of a femtosecond laser pulse with an intensity of 5×10^{18} W/cm^2 with a several hundred microns plasma layer with an $\approx 0.1 n_e/n_{cr}$ electron density leads to the generation of an electron beam with a charge of tens to hundreds of pC, an exponential spectrum with an average energy 2-3 MeV, angular width 0.1-0.3 rad in the direction of laser pulse propagation (see Fig.1). Using 3D PIC simulations it has been established that electrons are accelerated via hybrid acceleration mechanism: direct laser acceleration - self-modulated wakefield acceleration (DLA-SM-LWFA). The injection mechanisms are ionization injection and wavebreaking of SRS plasma waves. It is shown that, due to hard focusing and relativistic self-focusing, the laser pulse has a longitudinal field $E_{\vec{A},x}$ of significant amplitude ($a_0 \approx 0.05 - 0.1$). Thus, to establish electron acceleration mechanism, it was necessary to separate the fields into curl-free and divergence-free components. Further simulations indicate that electron beam charge increases nonlinearly with laser pulse energy.

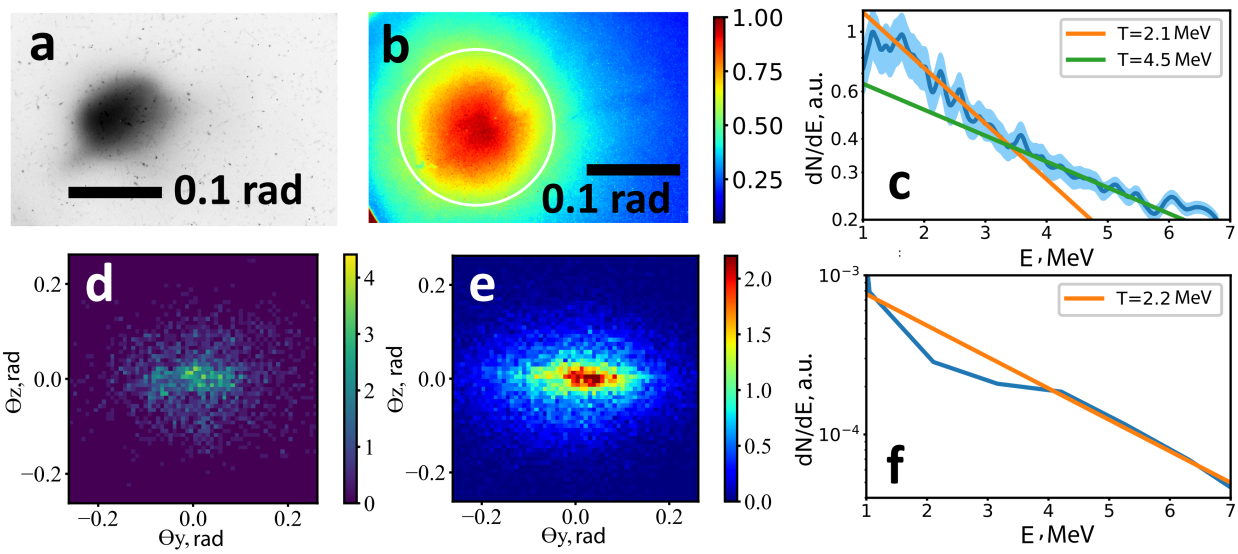


Figure 1: Experimentally measured spatial shape of the electron beam in a single laser pulse (a) and averaged over 500 successive pulses (b) for energies $E > 3$ MeV, as well as the energy spectrum (c) with exponential approximation. Obtained in 3D PIC simulations angular distribution of the electron beam obtained at the end of the calculation (d) and averaged over the 25 μm region at the end of the calculation (e) for electrons with $E > 3$ MeV, as well as the energy spectrum of electrons with exponential approximation (f).

Accurate calculation of laser and plasma fields contribution to electrons acceleration in PIC simulation

D. A. Gorlova[1,2], I. N. Tsymbalov[1,2], A. B. Savel'ev[1,3]

[1]Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[2]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[3]P.N. Lebedev Physical Institute, Moscow, Russia
e-mail: gorlova.da14@physics.msu.ru

To establish electron acceleration mechanism in laser-plasma interaction one needs to analyze the work of electric fields of laser pulse and plasma waves along the trajectories of individual test particles. The approximation in which plasma waves are represented by the longitudinal field E_x, and the laser pulse is represented by transverse fields E_y and E_z is often used. Such an approximation is admissible for problems of wakefield acceleration, where the amplitude of plasma waves is large and the particles interaction with the laser pulse is limited. However, if there exists a longitudinal laser pulse field of significant amplitude (strong focusing) or a reflection from the target boundary, this approximation is not applicable.

To study such interaction regimes, an approach utilizing customized field solver in azimuthal simulation geometry was recently proposed in [1]. In this work, however, a straightforward approach via Helmholtz decomposition of full 3D vector field was used. It was implemented during post-processing of 3D PIC simulation results (see Fig. 1) and allowed us to establish a hybrid DLA-LWFA acceleration mechanism. In practice, is is of greatest importance to decompose the components of the field E_x. When analyzing works without fields decomposition, the contribution of longitudinal plasma waves to the acceleration is significantly underestimated.

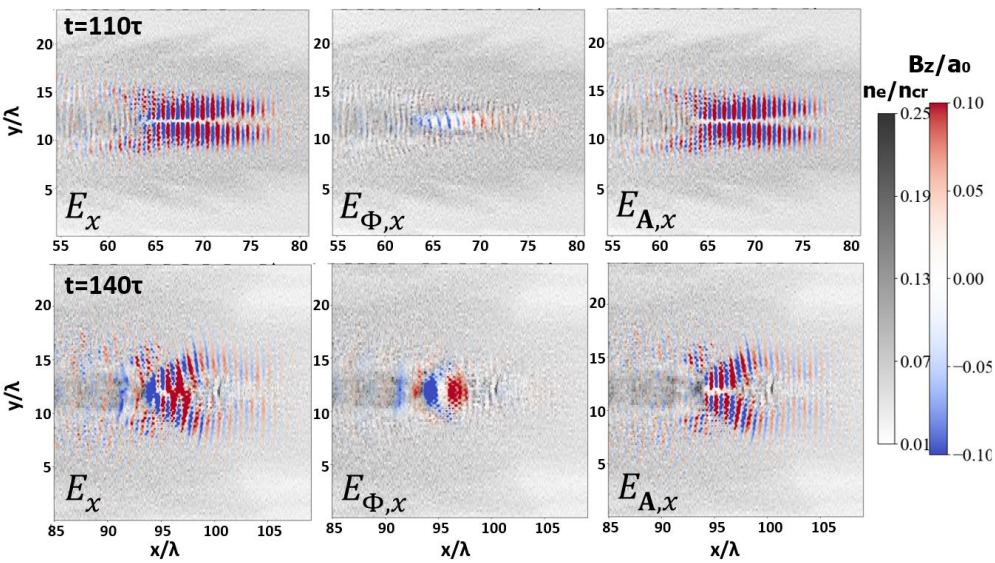


Figure 1: Full electric field E_x, as well as its curl-free $E_{\Phi,x}$ ($\propto$ longitudinal plasma waves) and divergence-free $E_{\vec{A},x}$ ($\propto$ laser pulse) components (in color) and electron density n_e (in grey) at times $t = 110\tau, 140\tau$ (τ - laser pulse period) and at the OZ center are shown.

REFERENCES
[1] K. Miller et. al., Physics of Plasmas 30, 073902 (2023).

End-to-end modeling of droplet target heating and neutron generation under irradiation by an ultrashort laser pulse at relativistic intensities

D. A. Gozhev[1], S. G. Bochkarev[1,2], M. G. Lobok[1,2], A. V. Brantov[1,2] and V. Yu. Bychenkov[1,2]

[1] P.N. Lebedev Physics Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] The Federal State Unitary Enterprise Dukhov Automatics Research (VNIIA), Moscow, Russia
e-mail: gozhevda@lebedev.ru

The use of cluster targets when interacting with relativistically intense femtosecond laser radiation makes it possible to significantly increase the number of hot particles, the efficiency of X-ray generation, and increase the yield of nuclear reactions, for example, the generation of neutrons in the DD reaction. [1–4]. In this case, it is necessary to optimize various parameters of the interaction of laser clusters, especially for the cases of large sub-micron and micron-scale clusters, which is now in practical use, see e.g. [4], in order to increase the conversion of laser energy into energetic particles, secondary radiation, and neutrons. Previously, we have already performed the optimization of the parameters of a cluster target of D_2O cluster target at a sub-relativistic intensity of 2×10^{18} W/cm^2. It was shown that there is an optimal cluster target diameter corresponding to the maximum neutron yield $\geq 10^7$ neutr./J [3].

In this work, we have extended the optimization of the parameters of a cluster target of heavy water (D_2O) for the relativistic intensity range. Using the Mandor PIC code, we performed the end-to-end simulation of the interaction of high-power femtosecond laser radiation with intensities from 2×10^{18} W/cm^2 to 3.4×10^{19} W/cm^2 with large sub-micron droplets. The droplet diameter varied from 0.05λ to 0.8λ, where λ is the radiation wavelength. The neutron yield was calculated using the GEANT4 code and estimated with overlap integral. The simulation shows that with increasing intensity, the optimal diameter of the cluster target increases. Also, at a given energy of the laser pulse, the neutron yield increases when two processes compete: a decrease in the volume of interaction and an increase in the number of hot deuterons in the optimal region of the cross section of the DD reaction. As a result, the simulated neutron yield is in excess of 10^7 neutr./J. We partially estimated the neutron yield for the laser parameters of the MultiTera laser system, 20 TW, 40 fs [5] and found that it exceeds 10^7 neutr. per one laser shot.

This work was supported by Ministry of Science and Higher Education of the Russian Federation under contract No. 075-15-2021-1361.

REFERENCES

[1] A. Ya Faenov, T. A. Pikuz, Y. Fukuda, et al., Contributions to Plasma Physics 53.2, 148 (2013).
[2] S. Jinno, M. Kanasaki, M. Uno, et al., Plasma Physics and Controlled Fusion., 60:4, 044021 (2018).
[3] D. A Gozhev, S.G. Bochkarev, A.V. Brantov, V.Yu. Bychenkov, Bulletin of the Lebedev Physics Institute, 49:2, 42 (2022).
[4] S. Jinno, M. Kanasaki, T. Asai, et al., Scientific Reports, 12: 16753 (2022).
[5] https://www.atomic-energy.ru

Peculiarities, principles and prospects of bunched electron generation in near-critical plasma with terawatt class high repetition rate lasers

K. A. Ivanov[1,2], I. N. Tsymbalov[1], D. A. Gorlova[1,3], S. A. Shulyapov[1], E. M. Starodubtseva[1], I. P. Tsygvintsev[3], Yu. V. Kochetkov[4], R. V. Volkov[1] and A. B. Savel'ev[1,2]

[1] Physics Faculty of M. V. Lomonosov MSU, Moscow, Russia;
[2] P. N. Lebedev Physical Institute of RAS, Moscow, Russia;
[3] Institute of Nuclear Research of RAS, Moscow, Russia;
[4] Keldysh Institute of Applied Mathematics of RAS, Moscow, Russia;
[5] National Research Nuclear University MEPhI, Moscow, Russia
e-mail: akvonavi@gmail.com

Laser-driven compact source of high charge energetic electron bunch is a promising laboratory tool for various applications and fundamental research. For successful implementation one should combine the ability to operate at high repetition rate of pulses for high average flux and the new approaches and mechanisms of efficient particles acceleration in under-critical plasma to take advantage of the newly developed laser systems capable to deliver a few TW pulses at up to 1 kHz. A very important role here also plays the appropriate targetry, ensuring simple design, stability and long-term operation.

We consider in this work the various types of targets, which may be efficiently utilized in our recently developed approach of high charge electron bunch generation in a plasma with under-critical longitudinally modulated density. It is shown that the electron beam with a few MeV energy and charge up to nC/J level may be achieved using 1 TW (50 fs, 50 mJ $>10^{18}$ W/cm^2) laser pulse, incident onto the plasma slab. The mechanism is based on electrons energy gain by Direct Laser Acceleration and Wakefield Acceleration preceded by injection and preheating via breakdown of parametric plasma waves and ionization processes.

Experimentally it is demonstrated that the plasma with optimal density profile may be formed with three different targets: thin film, liquid jet/droplets, continuous gas jet. The density modulation is introduced by interaction of powerful nanosecond prepulse, delivered by NdYAG laser coming a few nanoseconds ahead of the femtosecond driver pulse. The main properties of each target are analyzed experimentally and numerically. Routine generation of low divergent electron bunch with high charge is achieved at 10 Hz repetition rate. Prospects and peculiarities are discussed.

The targets allow long-term high repetition rate operation and may be efficiently combined with novel laser systems to build a compact high average power electron source for nuclear physics, radiography, neutron generation etc. The work was done under the support of Russian Science Foundation grant #21-79-10207 (film and liquid targets) and 22-79-10087 (gas jet) with the use of equipment purchased with the support of national project "Science and universities".

Optimization of a laser electron source due to the use foam targets of near-critical density

A. V. Kotov[1], S. E. Perevalov[1], R. S. Zemskov[1], E. S. Blinov[1,2], A. A. Kuzmin[1,2], N. D. Bukharskii[3], N. G. Borisenko[3], N. E. Andreev[1,4], O. N. Rosmej[5] and A. A. Soloviev[1,2]

[1] Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[3] Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia;
[4] Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia;
[5] GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany
e-mail: kotov@ipfran.ru

The efficiency of secondary radiation sources based on laser-plasma interaction directly depends on the efficiency of laser pulse energy transfer to electrons, which strongly depends on the parameters of the target and laser pulse. The use of near-critical density targets makes it possible to realize the mode of direct laser acceleration of target electrons, in which the laser gives off a significantly larger fraction of its energy than in the cases with solid-state and gas targets. This regime provides a high conversion coefficient of laser energy into electron energy and shows itself well in experiments on the interaction of subpicosecond laser pulses with foam targets [1]. Nevertheless, the question of the effectiveness of such targets in the interaction with femtosecond pulses has previously remained open. However, earlier calculations [2] for the parameters of the PEARL laser [3] predicted a high conversion efficiency. The experiment was carried out on a PEARL laser facility. A femtosecond laser pulse at a central wavelength of 910 nm with a duration of 60 fs and an energy of up to 12 J was used as a driver of interaction with the plasma. Focusing was carried out with an off-axis parabolic mirror (OAP) f/4, with a corresponding peak intensity of about 5×10^{20} W/cm^2 in a spot with a FWHM diameter of 4.5 μm. The effective direct laser acceleration of electrons in the interaction of a femtosecond laser pulse with foam targets close to the critical density has been demonstrated for the first time. An effective electron temperature of up to 13 MeV and a maximum recorded electron energy of up to 70 MeV were achieved. The scheme for the formation of preplasma was developed with the support of the Ministry of Science and Higher Education of the Russian Federation (0729-2020-0035).

REFERENCES

[1] Rosmej, O. N., Gyrdymov, M., Günther, M. M., Andreev, N. E., Tavana, P., Neumayer, P., Zähter, S., Zahn, N., Popov, V. S., Borisenko, N. G., Kantsyrev, A., Skobliakov, A., Panyushkin, V., Bogdanov, A., Consoli, F., Shen, X. F., Pukhov, A., Plasma Physics and Controlled Fusion, 62(11), 115024 (2020).
[2] Andreev, N. E., Popov, V. S., Rosmej, O. N., Kuzmin, A. A., Shaykin, A. A., Khazanov, E. A., Kotov, A. V., Borisenko, N. G., Starodubtsev, M. V., Soloviev, A. A., Quantum Electronics, 51(11), 1019–1025 (2021).
[3] V. V. Lozhkarev, G. I. Freidman, V. N. Ginzburg, E. V. Katin, E. A. Khazanov, A. V. Kirsanov, G. A. Luchinin, A. N. Mal'shakov, M. A. Martyanov, O. V. Palashov, A. K. Poteomkin, A. M. Sergeev, A. A. Shaykin, and I. V. Yakovlev, Laser Phys. Lett. 4(6), 421–427 (2007).

Generation of attosecond pulses of incoherent X-ray and gamma radiation using a subpetawatt laser and plasma films

V. V. Kulagin[1,2], V. A. Cherepenin[2], V. N. Kornienko[2] and H. Suk[3]

[1] Sternberg Astronomical Institute, Lomonosov Moscow State University, Moscow, Russia;
[2] Kotel'nikov Institute of Radio-engineering and Electronics of RAS, Moscow, Russia;
[3] Department of Physics and Photon Science, Gwangju Institute of Science and Technology, Gwangju, South Korea
e-mail: victorvkulagin@yandex.ru

Generation of attosecond pulses of incoherent X-ray and gamma radiation through probe laser pulse Thomson scattering off electron bunches formed by an accelerating laser from plasma layers is investigated. The idea of synchronous acceleration of electrons by a super-intense non-adiabatic laser pulse from a nanofilm was proposed in [1], and in [2], the characteristics of the formed relativistic electron bunches were investigated. When a non-adiabatic laser pulse of relativistic amplitude falls normally at a plasma film, a simultaneous longitudinal (relative to the axis of the laser beam) displacement of all electrons can occur under the action of the longitudinal component of the Lorentz force. With a sufficiently large field amplitude, this force accelerates electrons to relativistic velocities. As a result, a relativistic electron bunch with a diameter of the order of several microns with a thickness of several nanometers or less can be formed.

For solid-state targets, the formation of a single electron bunch takes place when the amplitude of the laser pulse exceeds a certain threshold depending on the thickness and material of the nanofilm. Here, the target thickness decrease is negligible, and the scattering of electrons in the bunch is significant. In the case of a gas target of subcritical density, the reflection of the laser pulse is small, and the pulse propagates in the plasma, accelerating and capturing an increasing number of electrons. Here, with a certain ratio of the pulse amplitude, electron density and target thickness, it is also possible to completely displace all electrons from the plasma and form a single relativistic bunch of electrons with a thickness of tens to hundreds of nanometers. These bunches can have a much smaller charge and electron energy spread, which can be useful in applications.

Using numerical 2D simulations, it is shown that for relatively moderate dimensionless laser amplitudes of the order of 20 (laser power of about 200 TW), relativistic electron bunches with a minimum thickness of about ten nanometers and an electron energy of hundreds of MeV are formed. The characteristics of the Thomson scattering of a probe laser pulse at such electron bunches are investigated. It is shown that the energy of scattered quanta can achieve several MeVs with the brightness of radiation at the level of the best sources currently available.

REFERENCES

[1]. V.V. Kulagin, V.A. Cherepenin, M.S. Hur et. al, Phys. Rev. Lett. 99, 124801 (2007).
[2] V.V. Kulagin, V.A. Cherepenin, Y.V. Gulyaev et. al, Phys. Rev. E 80, 016404 (2009).

Terahertz and microwave generation from solid surfaces irradiated by intense near- and mid-infrared laser pulses

A. V. Mitrofanov[1,2,4], M. V. Rozhko[1], M. M. Nazarov[1,3], N. V. Yakushkin[1,3], A. A. Voronin[1,3], A. B. Fedotov[1,3] and D. A. Sidorov-Biryukov[1,3,4]

[1] Russian Quantum Center, Moscow, Russia;
[2] ILIT RAS — Branch of FSRC "Crystallography and Photonics" RAS, Shatura, Moscow region, Russia;
[3] Physics Department, M.V. Lomonosov Moscow State University, Moscow, Russia;
[4] National Research Center "Kurchatov Institute", Moscow, Russia
e-mail: mitralex@inbox.ru

Terahertz pulsed radiation is a highly desired tool for biomedical application, molecular spectroscopy, remote sensing and time-resolved studies of ultrafast charge-carrier dynamics in metals and semiconductors [1]. Thin-foil irradiation by high intensity laser pulses is considered as one of the most promising mechanism of high-yield THz generation. In this work we experimentally investigate efficiency of THz generation by 1-10 terawatt Ti:Sa laser pulses irradiating foils of different thickness on the order of few tens of microns as well as solid surfaces of thick dielectric plates (Fig. 1). THz pulses with energy up to 10 μJ are observed. High-power microwaves are also detected as a low-frequency part of transition radiation (TR) emitted by relativistic electrons traversing vacuum-plasma boundary [2,3].

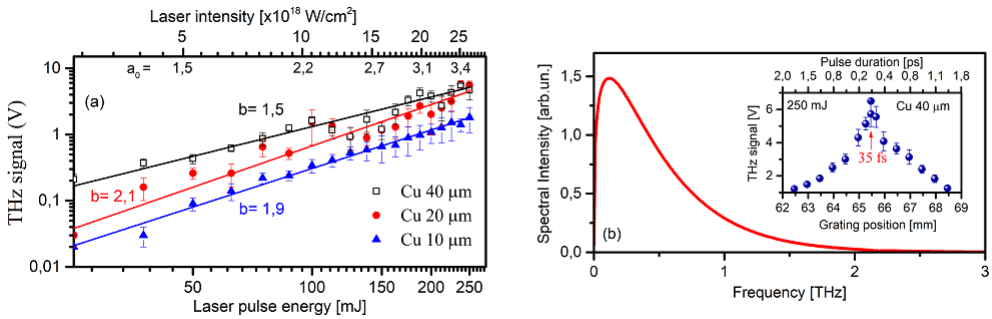


Figure 1: (a) THz signal collected in the direction of specular reflection from the front surface of the copper foil (0.1 sr collection angle) as a function of 0.8 μm-laser pulse energy. (b) Spectrum of THz radiation generated from solid surface of a 1mm-thick polystyrene plate. In the inset the dependence of the THz yield as a function of initial pulse duration for 40 μm-thick copper foil is shown.

We have also observed week THz signal from a surface of a BK7 glass plate irradiated by sub-relativistic intensity $I \approx 6\times10^{16}$ W/cm^2 pulses ($a_0 \approx 0.8$) at the central wavelength of $\lambda = 3.9\,\mu$m delivered by an OPCPA mid-infrared laser system. The same level of THz radiation is observed with the Ti:Sa system at intensity $I \approx 1\times10^{18}$ ($a_0 \approx 0.8$) in correspondence with $I0\lambda_0^2$ scaling [3].

REFERENCES

[1]. D.M. Mittleman, J. of Appl. Phys.,122, 230901 (2017).
[2] A.M. Zheltikov and R.D. Nevels, Las. Phys.Lett., 16, 015401 (2019).
[3] P.B. Glek, A.M. Zheltikov, Sci. Rep., 12, 7660 (2022).

Experimental demonstration of electron acceleration in laser peeler regime

S. E. Perevalov[1], A. V. Kotov[1], R. S. Zemskov[1], E. S. Blinov[2], A. A. Soloviev[2] and M. V. Starodubtsev[1]

[1] Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] University of Nizhny Novgorod, Nizhny Novgorod, Russia
e-mail: perevalov@ipfran.ru

Solid-state sources of high harmonics in comparison with gas sources make it possible to use more intense laser pulses and obtain more energetic attosecond pulses. Such sources currently continue to require optimization of the parameters of targets and laser pulses. It has recently been shown that the interaction of a high-power laser pulse along a solid target [1] leads to a regime with a long interaction length, in which high harmonics are efficiently generated due to the simultaneous acceleration of electron bunches and their oscillations, while the output of high harmonics depends on the gamma factor involved in the generation of electrons. A numerical study shows that electrons accelerate along the target surface more than across it [2].

For the experimental optimization of the target parameters, it is necessary to test the electron acceleration in this regime of high harmonic generation. In this work, an experimental demonstration of electron acceleration in the laser peeler regime in the geometry of a grazing incidence of a laser pulse on a solid target has been performed. Such a geometry was described in [3], where a numerical study of harmonic generation was carried out. The results are confirmed by calculations using PIC simulation. In the experiment, electrons with energies up to 70 MeV were obtained, and an increase in the efficiency of electron generation using serrated targets was shown.

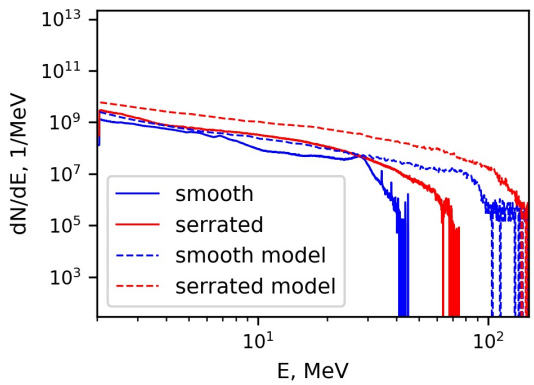


Figure 1: The comparison of experimental and simulated electron spectra for smooth and serrated targets.

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (0729- 2020-0035).

REFERENCES

[1] X. Shen, A. Pukhov, B. Qiao. Preprint at https://doi.org/10.48550/ARXIV.2009.12918 (2020).
[2] X. Shen, A. Pukhov, S. Perevalov, A. Soloviev. Quantum Electronics vol. 51 833–837 (2021).
[3] S. Perevalov, A. Pukhov, M. Starodubtsev, A. Soloviev. Matter and Radiation at Extremes 8, 034402 (2023).

Hydrodynamic simulation of target modifications due to pre-pulse

M. A. Rakitina[1], S. I. Glazyrin[2] and A. V. Brantov[1,2]

[1] Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[2]Center for Fundamental and Applied Research, Dukhov Research Institute, ROSATOM, Moscow, Russia
e-mail: rakitinama@lebedev.ru

A micrometer scale-length plasma has been predicted to yield a signifcant enhancement of the energy and weight of the fast electron population. Enhancement in the maximum proton energy and laser-to-proton energy conversion efficiency is observed at optimum preplasma density gradients, due to self-focusing of the incident laser pulse.

The control of the target expansion and the selection of optimal parameters of the pre-plasma make it possible to significantly increase the efficiency of ion acceleration from the rear side of the target. In the course of hydrodynamic calculations, we studied the expansion of an aluminum target under the action of a nanosecond laser pulse.

In the course of calculations, laser pulses were used with an intensity from $I = 10^{10}$ W/cm^2 to $I = 10^{13}$ W/cm^2 , the duration varied from 2 ns to 5 ns. Carbon, aluminum, and titanium were considered as target materials. The simulation was carried out in two-dimensional cylindrical geometry using an Euler-type hydrodynamic code. Also in this work, we considered targets of finite thickness in order to determine under what conditions a breakdown of the target can occur.

The pre-plasma density profile can be roughly represented as the sum of two exponents, one of which describes the plasma near the target, and the other describes the sub-critical plasma. The resulting function describing the density profile is written as follows:

$$n(z) = n_1\theta(\delta z - z)Exp[-\frac{z}{dz_1}] + n_2\theta(z - \delta z)Exp[\frac{z}{dz_2}]$$

where θ is the Heaviside function, δz is the point corresponding to the transition between two characteristic gradients, dz_1 and dz_2 are the plasma density gradients.

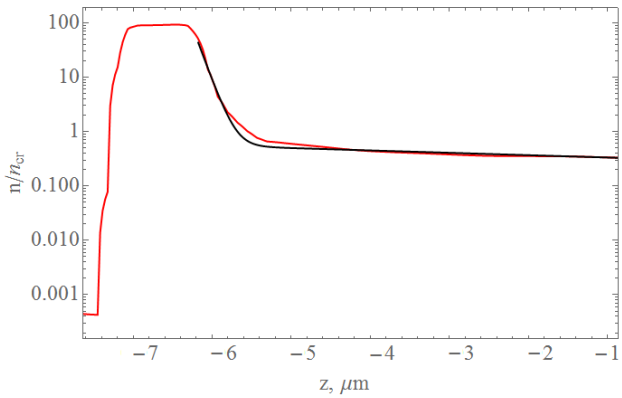


Figure 1: Plasma density profile under irradiation with a laser pulse with intensity $I = 10^{12}$ W/cm^2 and duration 5 ns. Approximate formula is shown in black.

You can see the simulated density profile and suggested fit in Figure 1. In the future, such an approximation can be used to calculate the effective acceleration of electrons by a powerful femtosecond laser pulse.

Optimization of the parameters of a cluster X-ray source

M. V. Sedov[1,2], S. N. Ryazantsev[1,2], I. Yu. Scobelev[1,2] and S. A. Pikuz[1,2]

[1] Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Moscow, Russia;
[2] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
e-mail: sedov_max@mail.ru

The study of the interaction of super-intense laser radiation with cluster targets is of great interest, especially to obtain high-energy ion beams [1]. Accelerated ions are formed as a result of the Coulomb expansion of the cluster after the laser pulse has removed most of the electrons. X-rays from such a source are also interesting for diagnostics due to their high brightness and short duration. There are two main problems of such sources: the low conversion factor and the complexity of experimental implementation.

In this work we consider the interaction of intense laser radiation with cluster targets and their X-ray emission both in the continuous spectrum (Bremsstrahlung) and in characteristic lines (Heα and Lyα). The calculations were performed using PIC code EPOCH 3D [2], taking into account both field and collisional ionization. The bremsstrahlung was calculated using the intrinsic EPOCH method [3]. The characteristic line emission was calculated in coronal approximation. The data necessary for this calculation were obtained from the PIC simulation. Thus, the time dependences of the plasma emission in both continuous and line spectra were determined for the range of laser intensities $3x10^{19}$-10^{22} W/cm^2 and cluster size 0.5-1 μm in diameter. It is found that the duration of plasma emission in the characteristic lines as well as the peak brightness depend on both cluster size and laser intensity, and in different ways for the He and Ly lines. Thus, by changing the laser intensity and the cluster size, it might be possible to obtain the optimal X-ray duration and the maximum yield, respectively.

REFERENCES

[1] S Jinno et al. Plasma Phys. Control. Fusion 60 044021 (2018).
[2] T. D. Arber et al Plasma Phys. Control. Fusion 57 113001 (2015).
[3] J. Vyskočil, O. Klimo, S. Weber. Plasma Phys. Control. Fusion, 60 (5), 054013 (2018).

X-ray and particle images of region laser-plasma interaction high intensity laser pulse with a solid target by the pinhole camera.

M. A. Shamaeva, K. V. Safronov, V. A. Flegentov, S. A. Gorokhov, D. S. Gavrilov, E. S. Borisov and A. V. Potapov

Russian Federal Nuclear Center – All-Russia research institute of technical physics named after academician E.I. Zababakhin, Snezhinsk, Russia
e-mail: rakitinama@lebedev.ru

The pinhole camera is a simple but at the same time very informative diagnostic tool for the exploration of high intense laser-matter interaction. Here we present the results of experiments where spatial properties of the interaction region on solid targets irradiated by picosecond laser pulses at relativistic intensity (10^{19} W/cm^2) were measured by the use of a pinhole camera. Laser plasma was imaged onto photoluminescent image plate detectors and plastic track detectors CR 39 through pinhole camera. Experiments were carried out with tungsten targets with thicknesses of 0.5 mm and 2 mm at the laser pulse energies from 16.2 to 40.4 J. Images of up to 10 MeV proton source on the irradiated surface of a laser target were obtained. It has been established that X-rays and charged particles are emitted from spatially separated sources, it can be due to the influence of powerful magnetic fields in laser plasma, in particular, the so-called "fountain effect". The intensity of the magnetic field, which causes Estimates of the conversion efficiency of the laser pulse energy into proton beam energy and proton beam fluence are presented.

REFERENCES

[1] G. Sarri, A. Macchi, et al. "Dynamics of self-generated, large amplitude magnetic fields following high-intensity laser matter interaction" arXiv:1210.4366v1 (2012).
[2] A. Macchi "Toy model of the "fountain effect" for magnetic field generation in intense laser-solid interactions" arXiv:1202.0389v1 (2012).

Liquid target formation for electron beam generation in laser-plasma interactions

S. A. Shulyapov[1], K. A. Ivanov[1,3], I. N. Tsymbalov[1,2], D. A. Gorlova[1,2], E. M. Starodubtseva[1] and R. V. Volkov[1,3]

[1] Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia;
[2] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia;
[3] P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: Ser270489@yandex.ru

Femtosecond laser plasma is a brilliant source of ultra-short bursts of high energy electrons. A collimated beam of electrons with GeV energies can be obtained by the wakefield acceleration. In this case, a gas jet is usually used as a target for an intense femtosecond laser pulse. But its low electron density limits the beam charge. Electron beam with highly charge can be generated using solid [1] or film targets [2]. However, they are not applicable at high repetition rates of laser pulses, since require shifting to an undamaged area after each shot.

The liquid targets created with the help of a piezocapillary can be an alternative to solid targets. The liquid targets have high stability and can be used at high laser pulse repetition rates. In this work we present liquid target configurations that are promising for electron acceleration: continuous jet, single drop and their modifications by additional ns pulse on the µs time scale. Also we present results of electron beam generation (divergence – 0.1 rad, charge – 10 pC, energies – up to 10 MeV) on a continuous jet previously ablated by a ns pulse on a ns time scale.

In our experiments we used Ti:Sa laser system (p-pol, pulse duration – 50 fs, intensity – 5×10^{18} W/cm^2, wavelength – 805 nm, repetition rate – 10 Hz, ASE level – 10^{-7}). The drops (diameter 10-100µm) and the continuous jet (diameter 60 μm) were created by a MicroFab MJ-SF-02 capillary with 50µm nozzle diameter. The liquid is ethyl alcohol. The liquid target modification on the µs time scale was made by a ns pulse of a Nd:YAG laser (5×10^8 – 10^{10} W/cm^2, 532 and 1064 nm), and the ablation on the ns time scale was made by another ns pulse (10^{12} W/cm^2, 1064 nm). This work was supported by RSF grant # 21-79-10207.

High order harmonics driven by mid and near IR laser pulses near the solid target

A. V. Mitrofanov[1,3,4], M. V. Rozhko[1], M. M. Nazarov[4], N. V. Yakushkin[1,2], A. A. Voronin[1,2], A. B. Fedotov[1,2] and D. A. Sidorov-Biryukov[1,2,4]

[1] Russian Quantum Center, Moscow, Russia;
[2] Physics Department, M.V. Lomonosov Moscow State University, Moscow, Russia;
[3] ILIT RAS - Branch of FSRC "Crystallography and Photonics" RAS, Shatura, Moscow region;
[4] National Research Center "Kurchatov Institute", Moscow, Russia
e-mail: sbd@rqc.ru

Focusing of the super-intense laser pulses on the surface of a solid target provides for relativistic electrons, which give rise to a wide range of nonlinear optical phenomena, such as the broadband continuum generation and the attosecond waveforms synthesis. In this context, the generation of high-order harmonics[1, 2] is not only a promising way to obtain ultrashort X-ray pulses but also a unique tool for diagnosing plasma when it is exposed to ultra-high-power laser pulses. The use of long-wavelength radiation in the mid-IR range makes it possible to increase the ponderomotive energy of electrons in proportion to the square of the wavelength [3, 4]. This paper presents the results of an experimental study of the spectra of high-order harmonics generated in the field of laser pulses with a central wavelength of 800 nm and 3900 nm on the solid surfaces. We observed harmonics up to the 51st and 21st order from the mid-IR and near-IR radiation, respectively (Fig. 1). The generation efficiency for different types of targets and different chirps of exciting laser pulses was thoroughly analyzed.

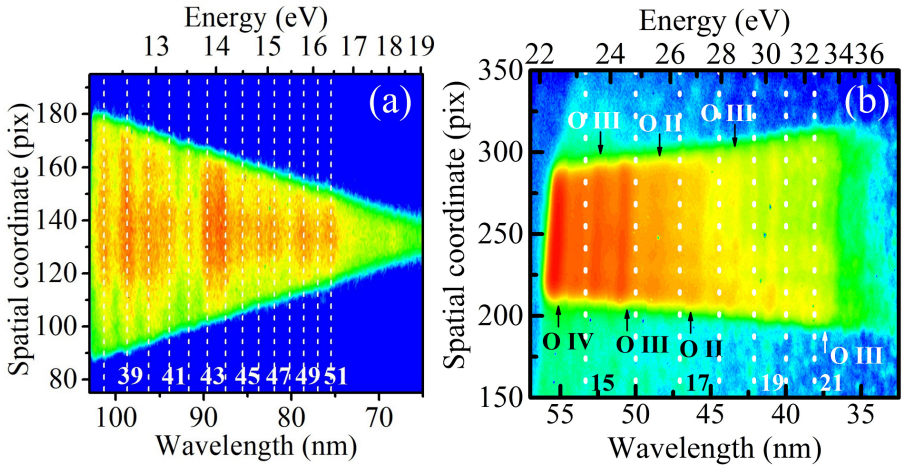


Figure 1: High harmonics spectra for laser radiation with central wavelength a) 3900 nm and b) 800 nm.

REFERENCES
[1] P. Gibbon, Phys. Rev. Lett. 76, 50 (1996).
[2] A. Tarasevitch, K. Lobov, C. Wünsche, et al., Phys. Rev. Lett. 98, 103902 (2007).
[3] A. V. Mitrofanov et al. Optics Letters, 43(22):5571–5574, (2018).
[4] A.M. Mitrofanov et al. J. Exp. Theor. Phys. 136, 430–435 (2023).

The influence of high power femtosecond pulse parameters on the X-ray generation and hot electrons acceleration in plasma

A. I. Sivko[1], K. A. Ivanov[1,2], A. A. Kologrivov[2], [1,3], I. N. Tsymbalov[1,3], E. A. Bolkhovitinov[2], A. A. Rupasov[2], R. V. Volkov[1] and A. B. Savel'ev[1,2]

[1] Physics Faculty of M.V.Lomonosov MSU, Moscow Russia;
[2] P.N. Lebedev Physical Institute of RAS, Moscow, Russia;
[3] Institute for Nuclear Research of RAS, Moscow, Russia
e-mail: sivko.ai19@physics.msu.ru

Accurate measurement and evaluation of the key properties of plasma (mechanisms of energy absorption, heat transfer processes, plasma expansion and other phenomena) is of great importance in the studies of laser-plasma interaction. In this paper, the X-ray plasma spectra in the range from hundreds of eV to hundreds of keV are experimentally studied with the use of ultra-wide range diagnostics. The spectral emission properties of plasma are investigated in dependence on the parameters of laser radiation (intensity, contrast, etc.)

In our experiments, a 50 fs pulse from the TiSa system is focused to an intensity 10^{16}-10^{18} W/cm^2 on the surface of a molybdenum target. We used pulses with two picosecond contrasts: 5×10^7 and 109 100 ps prior to main pulse.

It was found that the contrast of the laser pulse determines mainly the absorption of laser pulse and efficiencies of hot electron generation and characteristic X-ray emission.

Exploring the hot electron temperature of the most energetic component in plasma it was found that with the growth of laser intensity from moderate to relativistic (2×10^{16} - 3×10^{18} W/cm^2) the measured value increases from 30 to over 200 keV. For the contrast value 5×10^7 the preplasma scalelength may be estimated on the level of several microns, which is optimal for resonant absorption. However at highest intensity the transition to ponderomotive acceleration is observed. At the same time for the pulse with high contrast (10^9) we observe lower temperature estimates for moderate intensity, which may be related to high target reflectivity, and higher temperature value at relativistic interaction. This phenomenon is also connected with extended preplasma at moderate pulse contrast leading to laser pulse scattering during propagation in low density corona.

Experimentally we demonstrated that the efficiency of K-α generation is directly dependent on hot electron temperature behavior. One also find an optimal temperature of hot electrons (200 keV), where the maximal flux of 4×10^9 photons is achieved.

In the low energy range X-ray spectra different values of pulse contrast show a slight increase in temperature with the increase in intensity (200-300 eV at 5×10^7 contrast and 250-600 eV at 10^9). Generation at high contrast is more efficient, which may be due to the presence of an extended low-density plasma at a pulse with less contrast. Experimental estimates correlate well with the theoretical curve of the inverse bremsstrahlung absorption.

This work was carried out under the support of RSF grant #22-79-10087 with the use of equipment purchased within the national project "Science and universities".

REFERENCES

[1] S. Fujioka et al., Review of Scientific Instruments 81, 10E529 (2010).
[2] B. Albertazzi et al., High Power Laser Science and Engineering, 6, UNSP e43 (2018).
[3] P. Mabey et al., Scientific Reports 9, 8157 (2019).

Circular polarized high-intensity laser pulse obtained with lavsan film

E. M. Starodubtseva[1], I. N. Tsymbalov[1,2], D. A. Gorlova[1,2] and A. B. Savel'ev[1]

[1] Faculty of Physics, M. V. Lomonosov Moscow State University, Moscow, Russia;
[2] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
e-mail: starodubtceva.em19@physics.msu.ru

One of the most promising applications of ultra-intensive lasers is the laser plasma acceleration of charged particles [1]. In order to study and optimize the laser acceleration of particles, it is urgently necessary to obtain a circular polarized high-intensity laser radiation. For example, the Direct Laser Acceleration of electrons mechanism has a characteristic feature – dependence of beam shape on polarization of laser radiation [2]. Thus, the production of circular polarized high-intensity laser radiation is an important aspect of the study of this electron acceleration mechanism.

The nature of the birefringent effect in some films, such as cellophane, was described by Feynman in his lectures [3]. It is based on the fact that the molecules are elongated in one direction, so along this direction the index of refraction has a different meaning. As described further, circular polarization of high-intensity TW laser pulses is possible with the help of a lavsan film 19 μm.

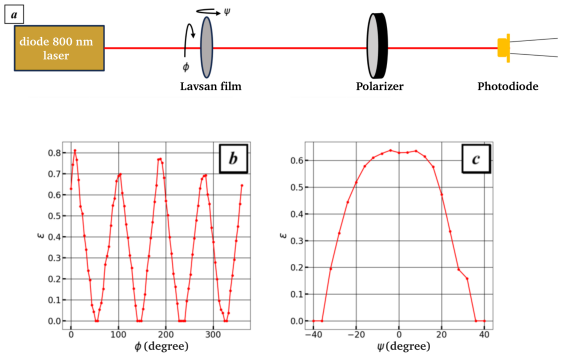


Figure 1: (a) Experiment scheme for measuring the effect of lavsan film on laser polarization. (b, c): Laser polarization ellipticity depending on the angle of rotation of the film: (b) – in vertical plane (film plane), (c) – in horizontal.

The diode 800 nm laser was used to study the polarization of laser radiation when passing through the lavsan film, and the resulting polarization was analysed by polarizer, radiation passes throught was registrated by photodiode (fig.1(a)). The fig.1(b,c) shows the dependence of laser radiation ellipticity $\epsilon = \sqrt{\frac{I_{min}}{I_{max}}}$ when passing through the film depending on its rotation angle in vertical ϕ (fig.1(b)) and horizontal ψ (fig.1(c)) planes. Thus, it is possible to create sufficiently elliptically polarized high-intensity laser radiation using the lavsan film to analyze the effects of polarization in an experiment.

This work was supported by RSCF grant # 21-79-10207. D.A. and E.M. acknowledge Foundation for the advancement of theoretical physics "BASIS" for the financial support. The study was performed under the scientific program of the National Center for "Physics of high energy density. Stage 2023-2025").

REFERENCES

[1] V. Malka et al. Nature physics, 4(6),447–453 (2008).
[2] H. Y. Niu et.al. Laser and Particle Beams, 26(1),51–60 (2008).
[3] R.P. Feynman et.al. The feynman lectures on physics. (1977).

Plasma channel parameters diagnostics by optical plasma radiation in electron acceleration experiment

E. M. Starodubtseva[1], I. N. Tsymbalov[1,2], D. A. Gorlova[1,2] and A. B. Savel'ev[1]

[1] Faculty of Physics, M. V. Lomonosov Moscow State University, Moscow, Russia;
[2] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
e-mail: starodubtceva.em19@physics.msu.ru

One of the most promising mechanisms for electron acceleration is direct laser acceleration in the plasma channel (DLA [1]). With this mechanism it is possible to create electron beams with high charge (up to hundreds nC).

Considering the motion of electrons in the plasma channel by DLA mechanism using phase portraits [2,3] demonstrates that the main determining parameter is the phase velocity of the laser pulse in the channel, that define the refraction index in it. Thus, for DLA electron acceleration experiments, the measurement of the refractive index in the plasma channel is extremely important. Below we will describe the method of obtaining its value directly from the experiment. Another parameter necessary to determine the electron acceleration topology is the electron density of unperturbed plasma $n_{e_{out}}$.

The last-mentioned can be determined by registering backward stimulated Raman scattering (BSRS) [4], when the incident pump laser pulse scatters on the electron plasma wave. BSRS, unlike forward stimulated Raman scattering (FSRS), does not have a high threshold intensity, therefore, when the laser pulse is propagated through a plasma with increasing density, it will start to appear earlier and will give information about the unperturbed plasma. Thus, the maximum electron density of unperturbed plasma $n_{e_{out}}$ can be obtained using the maximum wavelength in the spectrum of BSRS registered.

In addition to the BSRS, in the DLA electron acceleration experiments it is also observed a second harmonic radiation from the walls of the plasma channel. The angle of emission of the second harmonic θ_c satisfies the relationship: $\cos\theta_c = \frac{k_\omega}{k_{2\omega}} = \frac{\eta_\omega}{\eta_{2\omega}}$, where k – wave vector, ω – incident laser pulse frequency, η – refractive index.

Thus, knowing the electron density outside the channel $n_{e_{out}}$ from the BSRS spectrum and the emission angle of the second harmonic, it is possible to know the refractive index inside the plasma channel: $\eta_\omega = \cos\theta_c\sqrt{1 - \frac{n_{e_{out}}}{4n_{cr}}}$, where n_{cr} – critical density.

The developed technique of plasma channel parameters measurement by plasma optical radiation recording: the spectrum of BSRS and the second harmonic radiation angle allows to analyze the electron energy gain by DLA mechanism using analytical treatment and PIC-simulations, thereby achieving a more efficient electron acceleration.

This work was supported by RSCF grant # 21-79-10207. D.A. and E.M. acknowledge Foundation for the advancement of theoretical physics "BASIS" for the financial support. The study was performed under the scientific program of the National Center for Physics and Mathematics (project "Physics of high energy density. Stage 2023-2025").

REFERENCES

[1] V. Malka et al. Nature physics, 4(6),447–453 (2008).
[2] H. Y. Niu et.al. Laser and Particle Beams, 26(1),51–60 (2008).
[3] R.P. Feynman et.al. The feynman lectures on physics. (1977).

Influence of laser pulse polarization on the characteristics of accelerated electrons in the relativistic self-trapping regime

O. D. Sviridova[1,2], M. G. Lobok[2] and V. Yu. Bychenkov[2]

[1] Peoples' Friendship University of Russia (RUDN University), Moscow, Russia;
[2] P.N. Lebedev Physics Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: 1142220669@rudn.ru

One of the possible ways to reduce the size of traditional particle accelerators and create compact laboratory-scale accelerators is to use laser-plasma acceleration methods. Such methods, among others, can be based on the use of a longitudinal electric field of a plasma wake wave formed during the propagation of a laser pulse inside a plasma target [1]. In this case, the dynamics of the laser-plasma accelerating structure is determined by the dimensionless laser pulse amplitude a_0. When $a_0 \gg 1$ (highly nonlinear regime) the laser pulse completely pushes the electrons away forming a region almost absent of electron ("bubble") [2]. The highly nonlinear wake field regime provides largest accelerating gradients. Plasma electrons are captured inside the plasma cavity and accelerated to high energies. To obtain accelerated electron beams, no external sources of electrons are required, it is sufficient to use a laser pulse and a gas target [3].

In this paper we have studied the influence of linear and circular polarization of a laser pulse on the characteristics of a beam of accelerated electrons. Numerical simulations using PIC ("particle-in-cell") method have been carried out for the case of an ultrashort laser pulse (10 fs) with a dimensionless amplitude $a_0 = 24$. We consider the case when the laser pulse is incident on a homogeneous plasma layer with a constant density profile ($ne = 0.05n_c$ and $n_e = 0.1n_c$).

REFERENCES

[1] Tajima T., Dawson J. M., Physical review letters 43, 267 (1979).
[2] Kostyukov I. Y., Pukhov A. M., Physics-Uspekhi 58, 81 (2015).
[3] Bychenkov V. Y., Lobok M. G., JETP Letters 114, 579-584 (2021).

On laser plasma production from tungsten fuzz - surface nanostructure of helium-filled nanowires

M. M. Tsventoukh[1]

[1]Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia
e-mail: mmtsv@lebedev.ru, elley@list.ru

Recently an unprecedented efficiency has been achieved in X-ray production from fs laser plasma [1]. The target was a "nest" of carbon nanotubes [1,2] of average material density comparable to the critical one for the laser wave length ($\sim 10^{21}$ cm^{-3}).

Tungsten “fuzz” nanostructure consists of nanowires filled by helium nanobubbles can be produced under the plasma-surface interaction related to the fusion first wall [3]. Average atomic density of the W fuzz may fall down to $\sim 5\%$ of normal tungsten id est $\sim 3 * 10^{21}$ cm^{-3} – close to the critical one [4]. Using of the large-atomic-number metal – W (Z = 74) could be favorable for X-ray production rather than light elements – carbon C (Z = 6). Average helium He content W fuzz was measured to be He/W=(13±4)% [5].

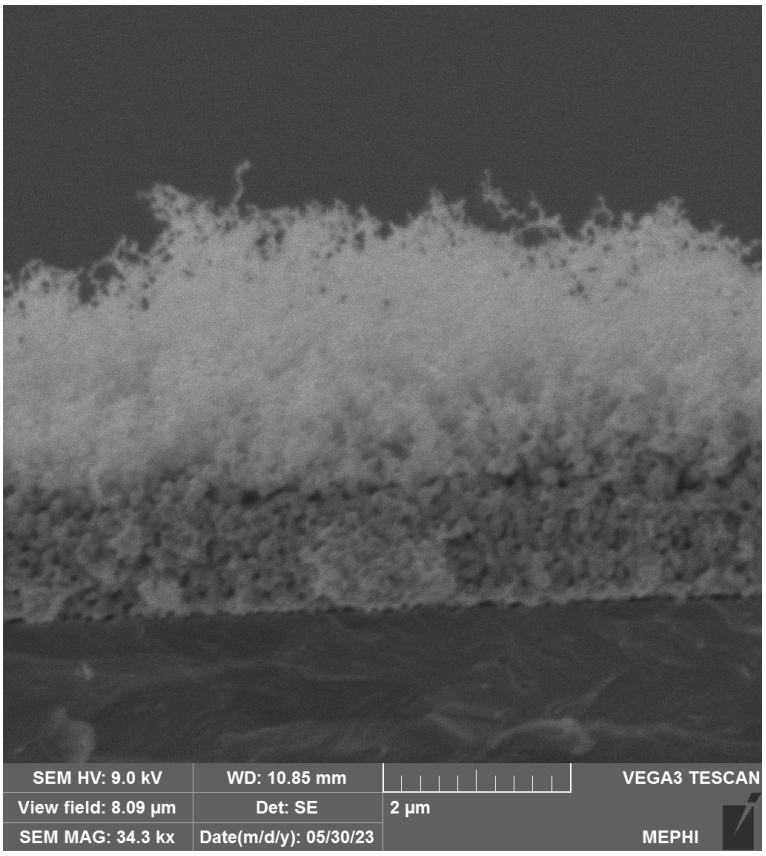


Figure 1: W fuzz produced in project supported by RSF grant # 22-12-00274.

REFERENCES

[1] Yinren Shou, Pengjie Wang, Seong Geun Lee, ... Wenjun Ma 2023 Nature Photonics **17** 137

[2] Andrea Macchi & Francesco Pegoraro 2023 Nature Photonics **17** 129

[3] S. Kajita, W. Sakaguchi, N. Ohno, N. Yoshida and T. Saeki 2009 Nucl. Fusion **49** 095005

[4] D. Nishijima, M. Baldwin, R. Doerner, J. Yu, 2011 J. Nucl. Mater. **415(1)** S96

[5] Yu. Gasparyan, V. Efimov and K. Bystrov 2016 Nucl. Fusion **56** 054002

Laser generation of accelerated electron beams and neutrons in the plasma of a gas jet shaped by shock waves

I. N. Tsymbalov[1,2], K. A. Ivanov[1,3], D. A. Gorlova[1,2], E. M. Starodubtseva[1], and A. B. Savel'ev[1]

[1] Physics Faculty of M. V. Lomonosov MSU, Moscow, Russia;
[2] Institute of Nuclear Research of RAS, Moscow, Russia;
[3] P. N. Lebedev Physical Institute of RAS, Moscow, Russia
e-mail: ivankrupenin2@gmail.com

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 for the first time, controlled modification of a gas jet by shock waves of individual laser pulses will be used for electron acceleration.

When studying the interaction of a laser pulse with a duration of 50 fs and a power of 1 TW with a modified gas target, two regimes were found. The first - with the excitation of strongly nonlinear plasma waves and the second - with the generation of quasi-monochromatic electron beams. In the first mode, an electron beam is generated with a collimation of 50 mrad, a charge of up to 10 pC, and an exponential spectrum with a slope of 5 MeV; the maximum energy reaches 20 MeV. The use of a secondary target makes it possible to generate on such a beam a neutron flux of 4×10^4 per shot in photonuclear reactions. The shock wave in this mode created a rarefied region in front of the laser pulse waist, suppressing defocusing and increasing the amplitude of the pulse field and, as a consequence, of plasma waves. In the second mode, the shock wave interrupted the plasma channel, thereby preventing dephasing and deceleration of the generated electron beam. The beam charge in this case was 1 pC, the divergence was the same 50 mrad, and the spectrum was quasi-monochromatic with energies from 8 to 11 MeV. The optical spectra showed the presence of 900 - 1000 nm shifted components in the IR region, corresponding to stimulated Raman scattering. All the given characteristics of the beam and optical radiation observed in the experiment were also obtained in the numerical PIC simulation. There is a good agreement between the numerical and experimental results. Based on a comparison of the characteristics of optical radiation in simulation and experiment, it was shown that the mechanism of plasma wave generation is laser pulse self-modulation (SM LWFA). Characteristics of the electron beam, such as energy distribution and divergence, indicate that it was accelerated by the longitudinal field of plasma waves. This is confirmed by the analysis of the trajectory in the numerical simulation, which shows the predominance of work on the electron by longitudinal fields. An analysis of the simulation showed that the main injection mechanism is wavebreaking. The addition of a shock wave before the waist leads to an increase in the beam charge by an order of magnitude and a twofold increase in the maximum energy. In this configuration, the shock wave suppresses ionization defocusing.

Laser source of gamma radiation and neutron beams based on DLA-accelerated electron bunches

I. R. Umarov[1,2] and N. E. Andreev[1,2]

[1] Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia;
[2] Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia
e-mail: umarov.ir@phystech.edu

The development of an efficient method of particle acceleration is one of the priority tasks of modern physics. Laser-plasma accelerators are among the most promising candidates for solving this problem of efficient acceleration. However, in accelerators of this type, at the values of the charge of accelerated beams required for applications, the influence on the acceleration process of the own charge of the accelerated electron beam (beam loading effect) begins to play a significant role [1,2]. To take into account this effect, a modification of the quasi-static code WAKE [3] was made. Based on the linear theory and also on the self-consistent non-linear simulation performed using this code, the influence of the beam loading on the final parameters of the accelerated beam is investigated. The optimization method of accelerated electrons beam parameters are proposed for efficient acceleration of this beam in Laser-WakeField accelerator, taking into account the beam loading effect.

REFERENCES

[1] M. Günther, O. Rosmej, P. Tavana, M. Gyrdymov, A. Skobliakov, A. Kantsyrev, S. Zähter, N. Borisenko, A. Pukhov and N. Andreev, Nat. Commun., 13, 170 (2022).
[2] N. Andreev, I. Umarov and V. Popov, Quantum Electronics, 53 (3), 236-241 (2023).

High-energy high-charge electron bunches under direct laser acceleration in a near critical density plasma

M. E. Veysman[1], N. E. Andreev[1,2], V. S. Popov[1] and O.N. Rosmej[3,4]

[1] Joint Institute for High Temperatures, Moscow, Russia;
[2] Moscow Institute of Physics and Technology, Dolgoprudnyi, Russia;
[3] Helmholtzzentrum GSI-Darmstadt, Darmstadt, Germany;
[4] Goethe University, Frankfurt am Main, Germany
e-mail: bme@ihed.ras.ru

Studies of electrons acceleration, their betatron oscillations and synchrotron radiation in ion channels created by powerfull laser pulses in near-critical density plasma had become important issues during past few years [1,2].

By comparison with the results of PIC simulations it is shown, that simple model containing some assumptions on dynamics of i) number of electrons accelerated in ion channels by direct laser acceleration mechanism, ii) their distribution function over energies, iii) their distribution over betatron oscillations amplitudes, can describe spectrum of synchrotron radiation of these electrons. This can be used for estimation of electron distribution function over energies, that can be important taking in mind the fact that not all electrons leave the interaction region where they are accelerating.

Besides that, we consider estimates of synhrotron radiation spectrum of electrons, accelerated in wakefields generated behind a powerfull (petawatt) laser pulse propagating in a rarefied plasma with parameters corresponding to the currently proposed XCELS [3] laser installation.

REFERENCES

[1] V. Khudik, A. Arefiev et. al., Phys. Plasmas, V 23, P. 103108 (2016).
[2] O.N Rosmej, N.E. Andreev et. al., New J. Phys., V. 21, P. 043044 (2019).
[3] O.N. Rosmej, X.F. Shen et. al., Matter Radiat. Extremes, V. 6, P. 048401 (2021).
[4] N.E. Andreev, V.S. Popov et. al., Quantum Electronics, V. 51, P. 1019 (2021)
[5] N.E. Andreev, I.R. Umarov, V.S. Popov, Kvantovaya Elektronika, V. 53, P. 236 (2023)
[6] N. Naseri, D. Pesme D. et. al., Physics of Plasmas, V. 20, P. 103121 (2013).
[7] A. Pukhov, Z.M. Sheng, J. Meyer-ter-Vehn, Phys. Plasmas, V. 6, P. 2847 (1999).
[8] M. Gunther, O.N. Rosmej et. al., Nat. Commun., V. 13, P. 170 (2022).

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

Section Chair:

Sergey Uryupin, e-mail: urypinsa@lebedev.ru
(P.N. Lebedev Physical Institute, Russia)

Program committee:

Alexander Popov
(Lomonosov Moscow State University, Russia)

Vasily Kostin
(Institute of Applied Physics RAS, Russia)

Konstantin Vagin
(P.N. Lebedev Physical Institute, Russia)

Igor Smetanin
(P.N. Lebedev Physical Institute, Russia)

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

Petahertz-bandwidth amplified spontaneous emission from an optically dressed neon-like plasma-based X-ray laser

V. A. Antonov[1], I. R. Khairulin[1] and M. Yu. Ryabikin[1,2]

[1] Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia
e-mail: antonov@appl.sci-nnov.ru

Plasma-based soft X-ray lasers (SXRLs) are powerful sources of coherent extreme ultraviolet (XUV) and soft X-ray radiation in the 3-50 nm wavelength range [1]. Ordinarily, a SRXL operates as a source of amplified spontaneous emission (ASE) produced at the inverted transition of multiply charged ions. In this case, the picosecond duration of the emitted pulses prevents from using SXRLs for study of the ultrafast femto- and attosecond processes.

Recently, we have shown the possibility to drastically broaden the gain spectrum of a SXRL by irradiating it with a strong optical laser field [2]. Under the action of the optical field the lasing energy levels of a SXRL experience Stark shifts, oscillating in space and time along with the optical field strength. As a result, the frequency of the inverted transition becomes space-time modulated, and the gain spectrum of the SXRL is enriched with a set of equidistant induced gain lines, spaced from the inverted transition frequency by multiples of the frequency of the optical field. This allows to amplify a set of high order harmonics (HHs) of the modulating field, tuned in resonance with the induced gain lines. If the HHs constitute a train of attosecond pulses in the time domain, then the pulses can be amplified with (approximate) preservation of their duration and shape [2]. Moreover, in the case of neon-like SXRL, it is possible to control the polarization state of the amplified set of HHs, namely, either (i) preserve an arbitrary elliptical polarization (including circular), or (ii) increase an ellipticity in the process of amplification [3], or (iii) transform a set of linearly polarized HHs into circularly polarized [4] with simultaneous increase in the harmonic energy.

In this talk, we focus on the other property of an optically dressed SXRL, – the spectral, spatial and temporal characteristics of its ASE. We show that the ASE of an optically dressed neon-like SXRL is a combination of two orthogonally polarized frequency-shifted spectral combs. Each comb has petahertz bandwidth and corresponds to a train of attosecond bursts in the time domain. The shape and duration of the sub-optical-cycle bursts is fully deterministic, while stochasticity of the ASE affects only the intensity of the bursts. We present the results of both analytical and numerical calculations and discuss the possibilities for their experimental verification using Ti12+ SXRL with 32.6 nm inverted transition wavelength.

This work was supported by the Center of Excellence «Center of Photonics» funded by The Ministry of Science and Higher Education of the Russian Federation, contract № 075-15-2022-316.

REFERENCES

[1] S. Suckewer and P. Jaeglé, Laser Phys. Lett. 6, 411 (2009).
[2] V. A. Antonov et al., Phys. Rev. Lett. 123, 243903 (2019).
[3] I. R. Khairulin et al., Sci. Rep. 12, 6204 (2022).
[4] I. R. Khairulin, V. A. Antonov, M. Yu. Ryabikin, JETP Lett. 117, 652 (2023).

Non-linear response and polarization-resolved high harmonic generation in bulk ZnO irradiated by mid-infrared ultra-short laser pulses

T. Apostolova[1,2]

[1] Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria;
[2] Institute for Advanced Physical Studies, New Bulgarian University, Sofia, Bulgaria
e-mail: tzveta.apostolova@nbu.bg

We report an extension of our computational method [1] for the description of ultrashort laser-matter interactions that produces finite results for the non-linear optical response of crystals [2]. We also present perturbative results of the second-harmonic generation response of ZnO over a large frequency range. The electro-optic susceptibility of ZnO is evaluated below the band gap and compared to available experimental data.

It is shown that the spectra of generated high harmonics result from the semi-classical motion of charged carriers in the bands combined with intense inter-band transitions. The polarization properties of the emitted harmonics in ZnO are studied with respect to the laser polarization and linked to the structural symmetry of the material.

The results obtained may facilitate understanding and modelling of attosecond electron dynamics and other non-equilibrium band-structure-related phenomena in photo-excited bulk solids.

Support from the BNSF under Contract No. KP-06-COST/7 is acknowledged.

REFERENCES

[1] C. Aversa and J. E. Sipe, Phys. Rev. B 52, 14636 (1995).
[2] T. Apostolova, B. Obreshkov, I. Gnilitskyi, Appl. Surf. Sci. 519, 146087 (2020).

Formation of plasma periodic structures in the process of laser writing in the volume of solid dielectrics

A. V. Bogatskaya[1,2], A. M. Popov[1,2], Yu. S. Gulina[2], I. V. Gritsenko[2] and A. E. Rupasov[2]

[1] Lomonosov Moscow State University, Physics Department, Moscow, Russia;
[2] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: annabogatskaya@gmail.com

Femtosecond laser writing of birefringent subwavelength nanolattices in the dielectric volume has been studied for almost two decades [1] since it reveals a number of applications for optical memory devices, optical waveguides, microfluidic channels etc. [2,3]. Despite a large number of experimental works in this field, the technical progress of direct laser writing of nano- and microstructures in dielectrics goes without a clear understanding of the fundamental physical picture of the interrelationships of field, plasma and material subsystems. In this work a theoretical study of the formation and evolution of plasma periodic structures in a fused silica sample in the propagation direction of a focused laser pulse is carried out. The key parameters of the interaction of radiation with matter, namely, multiphoton ionization coefficients of fused silica for the studies wavelengths, are determined from the experiment [4]. We consider the problem of propagation and absorption of the focused subpicosecond pulse of wavelengths 515 and 1030 nm in fused silica together with the dynamics of electron generation and recombination. Within the one-dimensional approximation beam focusing was taken into account by introducing a geometric factor. It is shown that the focused beam creates a layer of electrons with overcritical concentration which provides an effective reflection of incident laser leading to formation of a standing wave. In the bundles of standing wave an effective ionization emerges and forms a plasma lattice with a period equal to the period of the standing wave in the medium $\lambda/2n'$ (λ is the wavelength of laser radiation, n' is the real part of the refractive index, which is determined by the parameters of the forming plasma). This model is able to describe the previously obtained experimental data on microstructuring in solid dielectrics [5].

The work was supported by Russian Science Foundation (grant № 22-72-10076).

REFERENCES

[1] A. Bogatskaya, N. Klenov, A. Popov, M. Tereshonok, Tech. Phys. Lett 44 (8), 667–670 (2018).
[2] A. Shchegolev, A. Popov, A. Bogatskaya, P. Nikiforova, M. Tereshonok, N. Klenov, JETP Letters 111 (7), 443–447 (2020).
[3] A. Bogatskaya, N. Klenov, P. Nikiforova, A. Popov, A. Shchegolev, Tech. Phys. Lett. 47, 838–842 (2021).
[4] O. Reshef, I. De Leon, M. Alam, R. Boyd, Nat. Rev. Mater. 4, 535–551 (2019).

Laser generation of terahertz sound in metal.

E. A. Danilov and S. A. Uryupin

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: danilovea97@gmail.com

The effect of laser pulses leads to various physical effects, one of which is the generation of sound in the terahertz frequency range. Sound generation is usually considered due to the temperature gradients of the lattice and electrons, which arise due to inhomogeneous heating of the metal [1]. However, the ponderomotive effect on electrons is not taken into account usually. At the same time, it is known that in the case when few electron collisions take place during the effect of a laser pulse, the ponderomotive effect has a greater effect on the motion of electrons than their temperature gradient [2].

In paper [3] the generation of sound in a metal film on a dielectric substrate is considered, both due to the lattice and electron temperature gradients, and also due to ponderomotive effect. A comparative analysis of these generation mechanisms has been carried out. It is shown that in the case of high effective electron collisions frequencies in a metal, the contribution from the ponderomotive effect to the amplitude of the generated sound turns out to be insignificant (see Fig. 1a). On the contrary, when the effective electron collisions frequencies are relatively low, which occurs in cooled metals when they interact with laser pulses in the near infrared frequency range, the generation of terahertz sound is manly determined by the ponderomotive effect (see Fig. 1b).

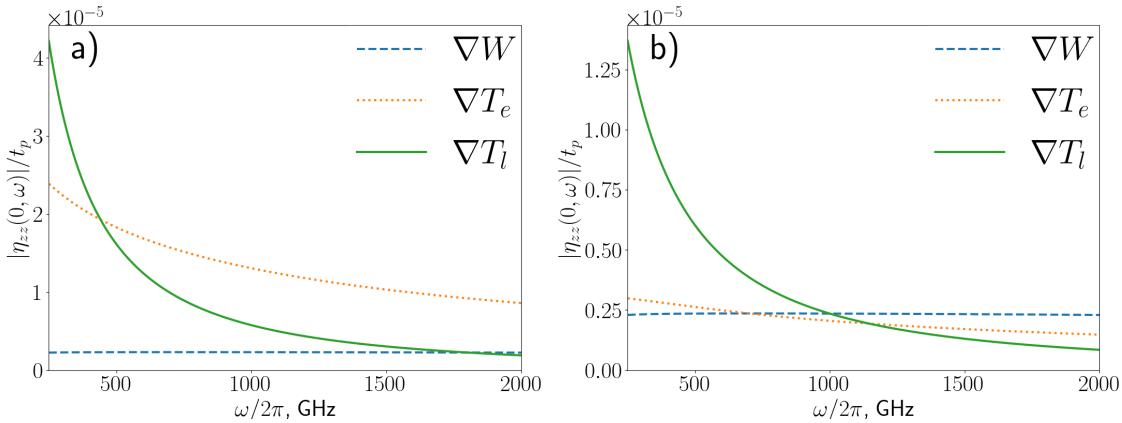


Figure 1: Plots of the Fourier image of a longitudinal component of the strain tensor on the metal surface $|\eta_{zz}(0,\omega)|$ for gold in the frequency range 250 GHz - 2 THz at a) $T_0 = 300$ K and $\omega_0 = 2.3 \times 10^{15}$ s^{-1} and b) $T_0 = 77$ K and $\omega_0 = 1.0 \times 10^{15}$ s^{-1}, where T_0 is the initial temperature and ω_0 is the carrier frequency of laser radiation. The dashed curves correspond to the contribution from the ponderomotive effect, the dotted curves correspond to the electron temperature gradient, and the solid curves correspond to the lattice temperature gradient.

REFERENCES

[1] O. Matsuda, M. C. Larciprete, R. Li Voti, and O. B. Wright, Ultrasonics, 56, 3 (2015).
[2] E. A. Danilov and S. A. Uryupin, Opt. Lett., 46 (10), 2521 (2021).
[3] E. A. Danilov and S. A. Uryupin, Opt. Lett., 48 (8), 2170 (2023).

Sub-cycle pulse generation and carrier-envelope phase control of soliton self-compression in waveguide regime

A. B. Fedotov[1,2], A. A. Voronin[1,2], E. A. Stepanov[1,2], A. A. Lanin[1,2] and I. V. Savitsky[1]

[1] Physics Department, M.V. Lomonosov Moscow State University, Moscow, Russia;
[2] Russian Quantum Center, Skolkovo, Moscow Region, Russia
e-mail: a.b.fedotov@physics.msu.ru, lanin@physics.msu.ru

Analyzing the phenomena associated with the usage of ultrashort laser pulses with a duration about single cycle of electrical field, one cannot ignore the influence of the carrier-envelope phase (CEP), that is critically important for the generation of extremely short pulses [1,2], high order harmonics generation [3] and attosecond physics [4].

In high-intensity regimes beyond perturbative approximation, not only such physical effects as harmonics generation and ultrafast tunneling ionization depend on CEP, but also self-phase modulation and soliton self-compression leading the spectral and temporal CEP dependence on the forming ultrashort pulses. In our work, we have demonstrated the influence of the carrier-envelope phase 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. In our experiments, we used Ti:Sapphire laser system and optical parametric amplifier to produce tunable pulses with an energy about 180 μJ, central wavelength 2000 nm and duration 60 fs. These pulses are coupled into anti-resonant hollow-core fiber (AR HCF) filled with argon. The sequence of nonlinear transformations of the femtosecond pump pulse in an AR HCF leads to spectral broadening (supercontinuum generation (SC)) and near single-cycle waveform generation. The spectrum broadening follows the soliton self-compression (SSC) scenario, with additional enhancement from the self-steepening effect and parametric generation of four-wave components in the blue wing of the soliton spectrum [5,6]. In such condition it is possible to form very short pulses with the duration less than on cycle of the field, and for such pulses the influence of CEP could play noticeable role.

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 μm, a pulse with a duration of about one optical period is formed. The spectrum of such pulse is broadened to the region of 400–800 nm, where interference with the broadband third harmonic generated by the same pulse is observed. The interference pattern turns out to be sensitive to CEP of the laser pulse. An analysis of the interference pattern provides information on the difference between the spectral phases of the soliton and the third harmonic in the spectral range greater than an octave, and also makes it possible to control the duration of pulses formed in the process of soliton self-compression.

The work was supported by the Russian Science Foundation with grants No.22-12-00149.

REFERENCES

[1] A.Wirth et al, Science 334, 195 (2011).
[2] S.-W. Huang et al, Nat. Photonics 5, 475–479 (2011).
[3] P.B.Corkum and F. Krausz, Nat. Phys. 3, 381 (2007).
[4] O.Schubert, et al Nat. Photonics 8, 119, (2014).
[5] E.A.Stepanov, et al Phys. Rev. A 99, 033855 (2019).
[6] I.V.Savitsky, et al ACS Photonics 9, 1679 (2022).

XUV rectification effect in the IR-dressed atomic system

A. V. Flegel[1,2] and M. V. Frolov[1,2]

[1] University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[2] Voronezh State University, Voronezh, Russia
e-mail: flegel@cs.vsu.ru

The optical rectification effect is one of the well-known phenomena in nonlinear optics [1], which consists in inducing of the quasi-static dipole moment (QSDM) in a target system. Since the optical rectification is forbidden in the dipole approximation for centrally symmetric systems, this effect has not drawn too much attention to atomic targets. In this work we show that QSDM can be induced in an atomic system jointly interacting with a short XUV and intense IR laser pulses. We emphasize that the realization of the proposed XUV rectification effect is possible in the dipole approximation.

Our main result consists in the following analytic expression for QSDM $d(t)$

$$d(t) = \frac{F_{\mathrm{XUV}}^2}{4} f_{\mathrm{XUV}}^2(t-\tau)\frac{\partial\alpha(\omega_{\mathrm{XUV}}, \mathcal{F}_t)}{\partial\mathcal{F}_t},$$

where F_{XUV}, f_{XUV}, and ω_{XUV} are the peak strength, envelope, and carrier frequency of the XUV pulse respectively; τ is the time delay between XUV and IR pulses, and α is the dynamic polarizability of an atomic system in DC field with the strength $\mathcal{F}_t$ equal to the instantaneous IR-field strength, $\mathcal{F}_t = F_{\mathrm{IR}}(t)$. For XUV-photon energy exceeding the ionization potential, the atomic polarizability has the imaginary part indicating a dissipative process through the one-photon ionization. The real and imaginary parts of complex QSDM represent respectively the polarization of an atomic target and the total current at the near zero frequencies. We illustrate the XUV rectification effect within the δ-potential model, for which the analytic expression for α is known [2]. The short duration of QSDM and its IR-controllable direction make possible to use the XUV rectification effect for ultrafast optical gating.

This work was supported by Russian Science Foundation through the Grant No. 22-12-00223.

REFERENCES

[1] J. A. Armstrong, Phys. Rep., **127**, 1918 (1962).
[2] N. L. Manakov et al, J. Phys. B: At. Mol. Opt. Phys., **33**, R141 (2000).

Excitation of high-intensity terahertz surface modes at interaction p-polarized two-frequency laser radiation with plasma slab

A. A. Frolov and Yu. M. Aliev

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: frolovaa@lebedev.ru

The excitation of the high-intensity terahertz (THz) surface mode under the action of two waves of p-polarized laser radiation with different frequencies on the plasma slab with the subcritical electron density, when along its boundary the laser fields propagate towards each other is studied [1]. The boundary value problem for the two-frequency p-polarized laser radiation is solved, and the spatial distribution of the laser field in the plasma slab is found. It is shown that when laser radiation is incident at the angle of total reflection, the significant amplification of the p-polarized laser field occurs in the plasma slab with a near-critical electron concentration. The ponderomotive potential at the difference frequency is calculated and it is shown that the strongest ponderomotive effect on electrons occurs when laser radiation falls on the near-critical plasma slab at the angle of total reflection, the value of which is determined by the small imaginary part of the dielectric constant.

The problem of the excitation of THz fields in plasma under the action of ponderomotive forces of laser radiation at the difference frequency is considered, and it is shown that their space-time distribution in the plasma slab is determined by the values of the ponderomotive potential at the slab boundaries. It was found that when the laser radiation is incident at the angle of total reflection, only the symmetric mode of the plasma slab is excited. It is shown that if the frequency difference of the laser fields coincides with the eigenfrequency of the symmetric mode of the plasma slab, its resonant excitation occurs and, as the result, the significant increase in the electromagnetic fields of the THz mode take place.

The Poynting vector of the THz mode of the plasma slab is calculated and the dependence of its absolute value on the incidence angle of laser radiation and the slab thickness is investigated. It is shown that the THz energy flux density is maximum when two-frequency p-polarized laser radiation is incident at the angle of total reflection on the near-critical plasma slab with the thickness comparable to the laser wavelength under resonance conditions, when the difference between the laser frequencies coincides with the eigenfrequency of the plasma slab mode. It is shown that the energy flux density of the THz mode of the plasma slab under the conditions of its resonant excitation can significantly exceed the intensity of laser radiation.

REFERENCES

[1] Yu. M. Aliev and A. A. Frolov, Phys. Rev. E 105 (4) 045203 (2022).

Channel separation of secondary generated radiation induced by orthogonal XUV and IR pulses

A. A. Romanov[1,2], A. A. Silaev[1,2], T. S. Sarantseva[1,3], A. V. Flegel[1,3], N. V. Vvedenskii[1,2] and M. V. Frolov[1,3]

[1] Department of Radiophysics, University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[2] Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia;
[3] Department of Physics, Voronezh State University, Voronezh, Russia
e-mail: frolov@phys.vsu.ru

Interaction of an intense infrared (IR) pulse with an atomic target in the presence of extreme-ultraviolet (XUV) pulses induces additional channels of secondary generated radiation (SGR) for the high-order harmonic generation (HHG) process. One of these additional channels (XUV-assisted HHG channel) originates from the absorption of XUV photon ω_{XUV} at the moment of recombination resulting in the formation of a second XUV-induced plateau with an extended cutoff from ω_c to $\omega_c+\omega_{\mathrm{XUV}}$, where ω_c is the classical plateau cutoff in the IR field. Harmonics on the additional plateau can be utilized for several practical applications, such as HHG-based spectroscopy [1], attosecond pulse metrology [2, 3], and visualization of contributing closed classical trajectories in the IR field [4]. Another channel is the second-harmonic generation (SHG) of the XUV pulse by an IR-dressed atom [5]. If the XUV pulse is much shorter than the IR-field period, the amplitude of SHG is proportional to the magnitude of IR field at the instant corresponding to the time delay between IR and XUV pulses. Thus, the measurement of the time-delay dependence of SHG yield makes possible to retrieve the temporal profile of the squared IR field and it provides an alternative to the streak camera for detecting an IR field. However, if the doubled XUV frequency belongs to the interval from ω_c to $\omega_c + \omega_{\mathrm{XUV}}$, the XUV-assisted HHG channel interferes with the XUV SHG channel which can thereby negatively affects the use of these channels in mentioned applications.

This work shows that the XUV SHG and the XUV-assisted HHG channels can be well separated in the orthogonal geometry of the linearly polarized XUV and IR pulses. Measuring the components of secondary-generated radiation along IR and XUV field polarization vectors provides access to the XUV SHG channel and the XUV-assisted HHG channel. Our numerical results based on the solution of the three-dimensional time-dependent Schrödinger equation for moderate intensities of the IR and XUV pulses, which do not significantly ionize an atomic target, confirm the applicability of proposed technique of SGR channels separation [6].

REFERENCES

[1] T. S. Sarantseva et al., Phys. Rev. A 98, 063433 (2018).
[2] T. S. Sarantseva et al., Phys. Rev. A 101, 013402 (2020).
[3] T. S. Sarantseva et al., Opt. Expr. 29, 38298 (2021).
[4] T. S. Sarantseva et al., Opt. Expr. 29, 1428 (2021).
[5] A. A. Romanov et al., Phys. Rev. A 106, 063101 (2022).
[6] A. A. Romanov et al., Opt. Lett. 48, 3583 (2023).

Directionality patterns of electron photoemission from plasmonic nanoparticles

R. Sh. Ikhsanov[1], I. E. Protsenko[2], I. V. Smetanin[2], N. V. Nikonorov[3] and A. V. Uskov[2]

[1] National Research University Higher School of Economics, Moscow, Russia;
[2] P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[3] ITMO University, hird affiliation, St. Petersburg, Russia
e-mail: rihsanov@hse.ru

Utilizing plasmonic nanoparticles can increase the efficiency of light-matter interaction, because these nanoparticles allow localization and enhancement of electric field inside and in the vicinity of them. In particular, plasmonic nanoparticles can cause intensive generation of hot photoelectrons and consequently be used for more efficient conversion of light energy in photodetectors and in photovoltaic devices [1]. Also, enhanced electron photoemission from the plasmonic nanoantennas into vacuum has its applications in the metal photocathode technology [2].

The directionality pattern of electron photoemission from nanostructured photocathodes becomes one of the most essential characteristics of such cathodes because the photoemission pattern can highlight physics of electron photoemission. For example, the dominating mechanism of electron photoeffect from metal nanoparticle (volume or surface one) can be determined from measurement of the electron photoemission directionality pattern.

We present (semi-)analytical theory of the photoemission directionality pattern from plasmonic nanoparticles within framework of the model of single photon absorption by metal electrons. The case of multiphoton absorption can be easily generalized.

In our work, concepts of the local (the "near photoemission zone" of the nanoparticle) and global photoemission (in "far photoemission zone" of whole nanoparticle) patterns were introduced, and the relationship between them was established. Formulas for the local photoemission pattern for surface and volume photoemission mechanisms were obtained for a given field distribution inside in plasmonic modes in nanoparticles of arbitrary shape.

The general theory has been illustrated with calculation of the local and global photoemission patterns for a spherical nanoparticle with excited dipole and quadruple plasmonic modes.

Finally, the developed theory shows that measurements of photoemission patterns can be useful both in development of plasmonic nanostructure based photocathodes, in plasmonic photodetectors, in plasmonic photocatalysis and other plasmonic applications, and in highlighting of physics of electron photoemission from metal nanostructures.

A.U., I.S., I.P., and N.N. are thankful to the Russian Science Foundation (Grants 20-19-00559) for support. R.I. is thankful to the Basic Research Program and the Project Mirror Labs of the HSE University for the support of numerical calculations.

REFERENCES

[1] M. Brongersma, N. Halas, P. Nordlander, Nature Nanotech. 10, 25 (2015).
[2] J. Pettine, D. J. Nesbitt, J. of Phys. Chem. C 126, 14767 (2022).

Efficient calculation of anisotropic relaxation times and kinetic coefficients in metal

P. F. Kartsev and I. O. Kuznetsov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
e-mail: PFKartsev@mephi.ru

The excitation kinetics in solid state can be often conveniently described by kinetic Boltzmann equation. Typical metals are well described by the Fermi Liquid theory giving the value of relaxation time which depends on the temperature and kinetic energy of electron [1]. On the other side, many modern and promising materials including high-temperature superconductors, demonstrate essentially anisotropic relaxation characteristics [2,3].

In this work, we calculate the kinetic coefficients and relaxation times of the metal taking into account the finite size of Brillouin zone and the shape of Fermi surface. The effects of Umklapp processes, depending on the temperature and problem topology, are demonstrated. The calculation process consists of linearization of the initial collision integrals, appropriate analytic transformation and Monte Carlo integration over the Brillouin zone. The results are checked using the direct simulation of kinetics on discrete momentum lattice [4] and compared to the isotropic theory [1]. We show the calculation results and discuss the possible limitations.

The work was supported by MEPhI Program Priority 2030.

REFERENCES

[1] V. V. Kabanov, A. S. Alexandrov, Phys. Rev. B **78**, 174514 (2008).
[2] J. Chang *et al.*, Nature Comm. **4**, 2559 (2013).
[3] Sh. Sur, S.-S. Lee, Phys. Rev B **94**, 195135 (2016).
[4] I. O. Kuznetsov, P. F. Kartsev, Phys, Rev. E **107**, 055304 (2023).

Role of multiphoton ionization in the resonant generation of near-threshold harmonics of a strong laser field in helium

I. R. Khairulin[1], V. A. Antonov[1], M. Yu. Emelin[1], M. M. Popova[1,2,3], E. V. Gryzlova[1,3] and M. Yu. Ryabikin[1,4]

[1] A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] Department of Physics, Lomonosov Moscow State University, Moscow, Russia;
[3] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia;
[4] Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia
e-mail: khairulinir@ipfran.ru

The appearance of coherent sources of vacuum ultraviolet and X-ray radiation based on high-order harmonic generation (HHG) of a laser field in a gas in tunneling ionization regime resulted in the emergence of attosecond physics, a branch of knowledge aimed at study and control physical and chemical processes in atoms, molecules, nanostructures and solids on attosecond time scales [1]. However, the efficiency of HHG in tunneling ionization regime is relatively low mainly due to spreading of the wave packet of the released electron in free space and the mismatch between the phase velocities of the generated harmonics and the fundamental frequency laser field in the emerging plasma. On the other hand, the efficiency of HHG can be dramatically increased by the resonances of the generated harmonics with transitions between certain excited states and the ground state in the condition of multiphoton and intermediate ionization regimes [2]. However, in this case the HHG description is a complicated task because of necessity to accurately take into account the real structure and properties of atomic states.

In the investigation reported in this talk, based on the multilevel model of multiphoton processes in an atom in a strong laser field [3] and numerical solution of the time-dependent Schrödinger equation, we study the main properties of generation of near-threshold harmonics in a helium atom in the conditions of its multiphoton resonant excitation and analyze the effect of multiphoton ionization on the harmonic generation efficiency. The optimal conditions, under which a certain near-threshold harmonic is generated with maximum efficiency, are considered.

This work was supported by the Russian Science Foundation (grant No. 22-12-00389).

REFERENCES

[1] F. Krausz, M. Ivanov, Rev. Mod. Phys. 81, 163 (2009).
[2] M. Chini et al., Nature Photon. 8, 437 (2014).
[3] I.R. Khairulin, V.A. Antonov, M.Yu. Emelin, M.M. Popova, E.V. Gryzlova, M.Y. Ryabikin, Opt. Spectrosc. 131, 128 (2023).

Femtosecond laser structuring of selenium-based thin films

A. V. Kolchin[1], D.V. Pepelyaev[1, 2], S.A. Kozyukhin[1], A.S. Lipatiev[3], V.N. Sigaev[3], E.V. Kuzmin[4] and O.V. Boytsova[5, 6]

[1] Kurnakov Institute of General and Inorganic Chemistry RAS, Moscow, Russia;
[2] National Research University of Electronic Technology (MIET), Zelenograd, Russia;
[3] Mendeleev University of Chemical Technology of Russia, Moscow, Russia;
[4] Lebedev Physical Institute RAS, Moscow, Russia;
[5] Lomonosov Moscow State University, Faculty of Chemistry, Moscow, Russia;
[6] Lomonosov Moscow State University, Faculty of Materials Science, Moscow, Russia
e-mail: avkolchin432@yandex.ru

Selenium-based chalcogenide semiconductors such as Indium (InSe) and Gallium Selenides (GaSe) are widely used for development of novel photonic and optoelectronic devices [1,2]. In turn, femtosecond laser structuring is attractive way to improve thin films based on these materials [3].

InSe and GaSe thin films with thicknesses 114±10 nm and 111±10 nm, respectively, were deposited on crystalline silicon substrates via thermal sputtering of crystalline targets. The samples were irradiated by femtosecond laser system Pharos SP (central wavelength 1030 nm, pulse duration 180 fs, repetition rate 200 kHz). The obtained two-dimensional array of spots was inscribed with of variation of pulse energy (5-100 nJ) and pulse number (1-10^6). Phase composition was investigated by Raman spectroscopy (SOL Confotec NR500) and X-ray diffraction (XRD; Bruker D8). Surface morphology was studied by scanning electron microscopy (SEM; Tescan Vega 3).

Raman spectra and XRD data confirm amorphous structure of initial InSe and GaSe thin films. Furthermore, these experimental methods show that femtosecond laser irradiation possesses driven crystallization. Surface morphology is also changed under such treatment. Defined period of obtained ripples 1020±10 nm, which is close to the incident wavelength, as well as orientation, which is orthogonal to laser polarization. These properties indicate that observed grating was formed due to surface plasmon-polariton mechanism [3].

REFERENCES

[1] A. Politano et al., Sci. Rep. 7, 3445 (2017).
[2] J. Guo et al., Light: Sci. Appl. 4, e362 (2015).
[3] J. Bonse, J. Kruger, Appl. Phys. A 129, 14 (2023).

Spectrum of terahertz radiation generated by ionizing two-color femtosecond laser pulses

Zhiwen Zhang[1], Zefu Liu[1], Shixiang Wang[1], Chenhui Lu[2], Zhengquan Fan[1], Vasily. A. Kostin[3, 4], and Yi Liu[1,5]

[1] Shanghai Key Lab of Modern Optical System, University of Shanghai for Science and Technology, Engineering Research Center of Optical Instrument and System, The Ministry of Education, Shanghai, China;
[2] School of Mechanical and Automotive Engineering, Shanghai University of Engineering Science, Shanghai, China;
[3] A. V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia;
[4] Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[5] CAS Center for Excellence in Ultra-Intense Laser Science, Shanghai, China
e-mail: vk1@ipfran.ru

The generation of terahertz (THz) radiation by the laser-created plasma attracts considerable attention due to possibilities of obtaining pulses with ultrabroad spectrum, which can span from one to tens of THz. One of the most popular laser-plasma schemes for THz generation employs two-color femtosecond pulses containing fundamental field together with its second harmonic. In last two decades, this two-color laser-plasma scheme was studied extensively both experimentally and theoretically, and the experimental generation of high-amplitude (upto several MV/cm) and ultrabroadband pulses was demonstrated. The relative phase, i.e., the phase shift between second harmonic and fundamental field, plays important role here since the amplitude of the obtained pulses depends strongly (in oscillatory manner with polarity change) on this relative phase. As for spectral shape of the produced pulses, there is still lack of comprehensive understanding of what defines this shape in general case and what features and parameters of the generation process can affect the spectrum and the respective THz waveforms. In particular, there is still a question of how the THz spectrum can be varied with the relative phase.

Here, we report on experimental and theoretical analysis of the spectrum of the THz emission from air plasma excited by the phase-controlled two-color femtosecond pulses. It was found that the low- and high- frequency components of the THz radiation exhibit different levels of modulation contrast for varied relative phase which indicates the variation of the spectral shape. To explain the experimental results, we developed the nonlocal plasma current approach which was employed to calculate broadband THz spectral shapes and study their dependence on the pulse parameters. Unlike the local photocurrent models, this approach takes into account the action of inhomogeneous plasma fields on the free electrons (including the effects of the local field enhancement due to the plasma resonance). As turns out, these plasma phenomena can significantly affect the THz spectral shapes. It was also found that the modulation contrast in the high-frequency part of THz spectrum is sensitive to the pulse duration and the frequency detuning between doubled fundamental frequency and the central frequency of the second harmonic field in the focal region (such detuning arises naturally due to the ionization blueshift during the femtosecond pump propagation). The results obtained indicate that the shape of THz spectrum is affected by fine details of the frequency and phase structure of the two-color pulse which can be used both for simple experimental tailoring of the THz spectrum and probing the two-color pulses undergoing lengthening and spectral shifts while propagating.

V. A. K. acknowledges support from the Russian Science Foundation (Grant No. 22-72-10133).

Relaxation in superconductor excited with fs pulse, simulated with high energy resolution

P. F. Kartsev and I. O. Kuznetsov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
e-mail: PFKartsev@mephi.ru

Our research group studies the kinetics and relaxation processes in solid state using the numerical solution of the Boltzmann equation on discrete momentum lattice [1]. The high-performance algorithm allows to simulate realistic problems with the momentum grid resolution as high as 64×64×64. Both electron-electron and electron-phonon processes can be taken into account. Using this approach, earlier we studied the relaxation of the nonequilibrium state of superconductor excited with femtosecond laser pulse [2,3]. As the energy of the optical quantum, is high compared to the energy gap width, it allows to treat the elementary excitations as a standard Fermi gas described by the Boltzmann equation. As a result, the early stages of relaxation process can be replicated reliably [4]. The simulation demonstrates the multiplication of quasiparticle count as they descend on the energy axis to the Fermi level, due to breaking of more Cooper pairs [2,3].

On the other side, to study the kinetics of the quasiparticles closer to the Fermi surface, or take into account the nonzero temperature comparable to the gap width, the calculation should have much higher energy resolution. In this talk, we present the necessary corrections for our approach. The analytics is described in detail, and the experimental possibilities are discussed. The simulation results show the effects of superconductor temperature and energy gap width on the relaxation process and characteristic times.

The work was supported by the Ministry of Science and Higher Education of the Russian Federation (state task Project No. FSWU-2023-0031).

REFERENCES

[1] I. O. Kuznetsov, P. F. Kartsev, Phys. Rev. E **107**, 055304 (2023).
[2] P. F. Kartsev, I. O. Kuznetsov, J. Phys.: Condens. Matter **33**, 295601 (2021).
[3] I. O. Kuznetsov, P. F. Kartsev, IEEE TAS **32** 4, 9000805 (2022).
[4] J. Demsar, J. Low Temp. Phys. **201**, 676 (2020).

Analysis of the secondary radiation generated by multicolor ionizing pulses

I. D. Laryushin[1,2] and A. A. Romanov[1,2]

[1] A.V. Gaponov-Grekhov Institute of Applied Physics, Nizhny Novgorod, Russia;
[2] Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia
e-mail: ilaryushin@mail.ru

Gas ionization by femtosecond laser pulses makes it possible to obtain secondary radiation with unusual properties due to the extremely non-linear nature of the ionization process [1,2]. Currently, the possibilities of using multicolor ionizing pulses are being actively studied in order to optimize the parameters of the generated secondary components at combination frequencies [3-5].

In this work, we present a new approach to calculating the amplitudes of the combination components of the secondary radiation, which allows, among other things, to solve the problem of optimizing the pump parameters for the most efficient generation of a certain component. We also show that by using three-color pulses with certain frequency ratios, which can be obtained in optical parametric generators, a smooth ultra-broadband supercontinuum can be generated in the range 1000 – 100 nm.

The work was supported by Russian Science Foundation (Grant №20-11-20289).

REFERENCES

[1] A. Mitrofanov et al., Optica, 7, 15 (2020).
[2] F. Brunel, J. Opt. Soc. Am. B, 7, 521 (1990).
[3] V. A. Kostin, I. D. Laryushin, N. V. Vvedenskii, JETP Letters, 112, 77 (2020).
[4] I. D. Laryushin, A. A. Romanov, Photonics, 9, 444 (2022).
[5] S. Wang et al., Phys. Rev. A, 105, 023529 (2022).

Effect of irradiation wavelength on the photocatalytic properties of hybrid metal-semiconductor Ag-AgBr nanoparticles synthesized in ion-exchange layers of silicate glass

D. V. Marasanov[1], P. A. Bezrukov[1], E. M. Sgibnev[1], I. V. Smetanin[2], A. V. Uskov[2] and N. V. Nikonorov[1]

[1] ITMO University, St Petersburg, Russia;
[2] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: dmitriymarasanov@bk.ru

Currently, photocatalysis is used for wastewater treatment, air purification, carbon dioxide reduction, hydrogen production, self-cleaning surfaces, and disinfection [1]. Photocatalytic reactions proceed by excitation of electrons and holes in semiconductor materials, which then migrate to the surface of the semiconductor, activating catalytic redox reactions. The use of hybrid nanostructures consisting of a metal core and a semiconductor shell is a very promising method for increasing the yield of electron–hole pairs and photocatalytic activity [2]. In this work, we demonstrate the photocatalytic activity of glass ceramics doped with Ag-AgBr hybrid metal-semiconductor nanoparticles upon irradiation with a UV lamp and compare it with the photocatalytic activity of glass ceramics upon irradiation at visible wavelengths of 405, 532, and 633 nm.

Silicate glasses, based on the Na_2O-ZnO-Al2O_3-SiO_2 system, undoped and doped with NaBr were synthesized. Silver ions were introduced into the polished glass samples via Na^+ -Ag^+ ion exchange by immersing samples in $AgNO_3/NaNO_3$ salt melt at 320 °C for 2h. Subsequent heat treatment at 500 °C during 3h was used to promote growth of Ag, AgBr or Ag-AgBr nanoparticles depending on the glass dopants. The photocatalytic properties were studied by measuring absorption spectra of an aqueous solution of methyl orange (MO) dye (1 mg dye per 100 ml H_2O) under UV-VIS irradiation of a mercury lamp in the UV-visible region and lasers with a wavelength of 405, 532 and 633 nm with and without a sample in a cuvette.

During the experiment, effective degradation of the MO of the dye was observed in the presence of a photocatalyst based on Ag-AgBr hybrid nanostructures after irradiation with a mercury lamp and a laser with a wavelength of 405 nm. Hybrid Ag-AgBr nanoparticles successfully combine the high rate of generation of hot electrons in a metal core and a much longer lifetime of hot electrons and holes in a semiconductor shell. The efficiency of formation of electron-hole pairs decreases with an increase in the irradiation wavelength from 405 to 633 nm due to a decrease in the absorption of silver nanoparticles near the red and IR spectral regions.

REFERENCES

[1] L. Han, P. Wang, C. Zhu, Y. Zhai, S. Dong, Nanoscale 3 (7), 2931-2935 (2011).
[2] R. Dong, B. Tian, C. Zeng, T. Li, T. Wang, J. Zhang, The Journal of Physical Chemistry C 117 (1), 213-220 (2013).

Verification of the second excited state during charge transfer by stationary spectra fitting in acridine-dione derivative compounds

T.V. Mikhailova[1], A.I. Ivanov[1], S.L. Bondarev[2], T.F. Raichenok[2], S.A. Tikhomirov[2], N.G. Kozlov[3]

[1] Volgograd State University, Volgograd, Russia;
[2] B.I. Stepanov Institute of Physics of the NAS of Belarus, Belarus, Minsk;
[3] Institute of Physical Organic Chemistry of the NAS of Belarus, Minsk
e-mail: mikhailova.tv@volsu.ru

The charge transfer reaction - proton and/or electron - is the fundamental stage of more complex processes in chemical and biological systems. Therefore, an interest in its comprehensive study among both experimenters and theorists is constantly growing.

The aim of this work is to develop a model for charge transfer kinetics description in systems of an acridine dione derivative (3,3,11,11-tetramethyl-8,16-diphenyl-3,4,8,10,11,12,13 ,16-octahydroacridino[4,3-c]-acridine-1.9(2H,5H)dion quadrupole molecule) [1] in a set of aprotic compounds (dimethylformamide (DMF), acetone (ACE), acetonitrile (ACN), methylene chloride (DCM)) and protic (alcohols) solvents. The molecule selected for the current study is of the quadrupole type. In such molecules, the process of charge transfer can be accompanied by a violation of the symmetry of the molecule. In the framework of the current study, it is proposed to use the multichannel stochastic approach, which was previously successfully tested for describing the reactions of multistage electron transfer in donor–acceptor complexes [2–5]. The developed model takes into account the dynamics of solvent relaxation and reorganization of intramolecular high-frequency vibrations.

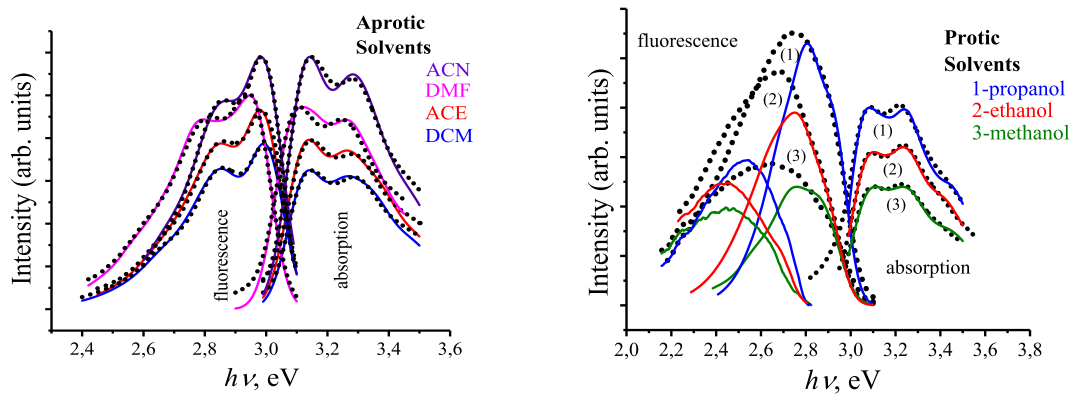


Figure 1: Fitting of experimental stationary absorption and emission spectra in a set of solvents. The experimental data are shown by black colour, the data obtained with the fitting are presented by red and blue lines.

A quantitative description of the charge transfer kinetics in the framework of a multichannel stochastic model requires knowledge of the main energy parameters of the model [4, 5]. Most of the parameters (the parameter of exergonicity and reorganization energy of the medium, the reorganization energy of high-frequency intramolecular vibrational modes, as

well as their frequencies in the ground and excited states) can be determined by approximating experimental stationary absorption and fluorescence spectra.

To describe charge transfer processes in aprotic solvents, it suffices to use a two-level model. Simultaneous fitting of absorption and fluorescence bands in aprotic solvents gives a very satisfactory result (see Figure 1, left panel). In this case, the stationary absorption and emission spectra together determine the values of the energy parameters at the stage of photoexcitation of the system. In alcohols, however, the numerically simulated spectra are much narrower than the experimental ones, which indicates the possibility of the presence of two or more electronic excited states from which emission occurs. A shift in the position of the emission spectrum with a change in the polarity of the medium may indicate a possible breaking of the symmetry in the molecule [1]. Thus, the second excited state of the structure under study in protic solvents can be interpreted as a state with broken symmetry [1]. Therefore, a model for describing charge transfer processes in protic solvents must take into account at least three diabatic states: the ground state, the locally excited state, and the state of the reaction product. It is assumed that the second emission band determines the values of the energy parameters of the reaction product, and the parameters of the locally excited state can be determined from the stationary absorption spectra and the first fluorescence band. Thus, simultaneous fitting of the experimental fluorescence and absorption spectra makes it possible to reveal the presence of the second emission band in the broadened experimental spectrum [1]. The existence of a second fluorescence band in alcohols was confirmed by high resolution spectroscopy [1].

The study was performed by a grant from the Russian Science Foundation (Grant № 22-1300180).

REFERENCES

[1] S.L Bondarev, T.F .Raichenok, S.A. Tikhomirov, N.G .Kozlov, T.V. Mikhailova, A.I. Ivanov. J. Phys. Chem. B (125) 8117 (2021).
[2] S.V. Feskov, V.A. Mikhailova, A.I. Ivanov, J. Photochem. Photobiol. C (29) 48 (2016).
[3] V.N. Ionkin, A.I. Ivanov, J. Phys. Chem. A (113) 103 (2009).
[4] V.A. Mikhailova, R.E. Malykhin, A.I. Ivanov, Photochem. Photobiol. Sci (17) 607 (2018).
[5] T.V. Mikhailova, V.A. Mikhailova, A.I. Ivanov, J. Phys. Chem. C (122) 25247 (2018).

Peculiarities of bolometric detection of THz signals by a resonant structure for inclined incidence of radiation

A. V. Bogatskaya[1,2], P. M. Nikiforova[1,2] and A. M. Popov[1,2]

[1] Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia;
[2] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: nikiforova.pm16@physics.msu.ru

In this work we consider a general physical approach to enhancing the efficiency of terahertz and infrared bolometric detectors. The approach is based on the concept of resonant tunneling of an electromagnetic wave [1]. Our previous studies have shown [2,3] that placing a sequence of doped and undoped semiconductor layers under the external absorbing film of bolometer allows one to obtain wide passband for detected THz signals. We now study the inclined incidence of the THz waves on the structure shown in the fig.1. The wave vector lies in xz-plane, permittivity of the medium only depends on one spatial coordinate $\epsilon = \epsilon(z)$ so we consider TM-wave propagation along z-axis. What is important, for such a structure there are epsilon-near-zero areas [4] for which plasma resonance is observed for z-component of the electric field (see E_z on the fig.1) if we consider TM electromagnetic waves. This circumstance allows one to obtain an efficient absorption of electromagnetic signals even for large ($\theta > \pi/4$) angles of incidence.

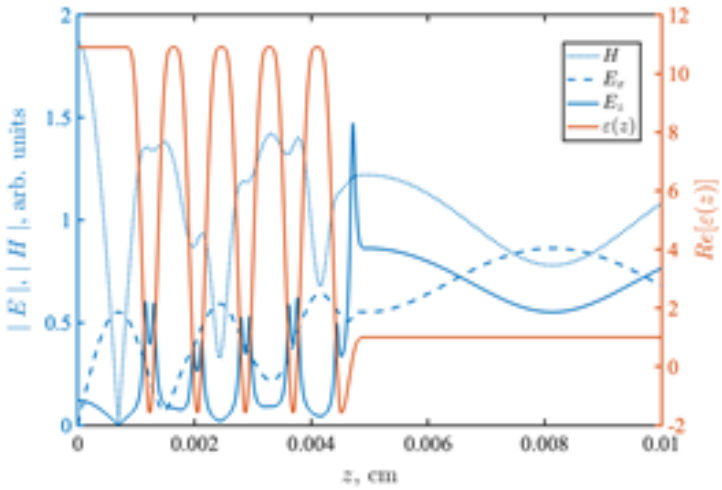


Figure 1: Spatial distribution of electric and magnetic field strength for TM-wave. Angle of incidence ($\theta = \pi/4$). Signal (f=3.3 THz) is coming from the right. Periodic structure consists of doped (to the maximum concentration of $n = 0.5 \times 10^{18} cm^{-3}$) and undoped GaAs layers.

This work was supported by the Theoretical Physics and Mathematics Advancement Foundation "BASIS" (project 22-2-10-20-1).

REFERENCES

[1] A. Bogatskaya, N. Klenov, A. Popov, M. Tereshonok, Tech. Phys. Lett 44 (8), 667–670 (2018).
[2] A. Shchegolev, A. Popov, A. Bogatskaya, P. Nikiforova, M. Tereshonok, N. Klenov, JETP Letters 111 (7), 443–447 (2020).
[3] A. Bogatskaya, N. Klenov, P. Nikiforova, A. Popov, A. Shchegolev, Tech. Phys. Lett. 47, 838–842 (2021).
[4] O. Reshef, I. De Leon, M. Alam, R. Boyd, Nat. Rev. Mater. 4, 535–551 (2019).

Modelling of nonlinear scattering and inhomogeneous absorption of femtosecond laser pulses in metal

I. V. Oladyshkin and D. A. Fadeev

Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
e-mail: oladyshkin@ipfran.ru

Thermal nonlinearity of metals significantly influences their electromagnetic properties at subpicosecond timescales. For example, the increase of the electronic scattering rate due to ultrafast heating causes manifold increase of the absorption coefficients for intense femtosecond laser pulses. According to recent models, thermal nonlinearity can be one of the dominant mechanisms of the terahertz pulse generation during laser-metal interactions. Another well-known phenomenon, accompanying femtosecond irradiation of solids in damaging regimes, is the spontaneous formation of LIPSS, or laser-induced periodic surface structures.

In this work we study analytically and numerically the interaction of a femtosecond laser pulse with a realistic (slightly rough) metallic surface taking into account thermal nonlinear effects. We prove that nonlinear laser pulse decay to SPPs takes place at various initial conditions, which significantly enhances overall optical absorption and makes metal heating strongly inhomogeneous. We model femtosecond laser pulse interaction with a rough metallic surface in 2D geometry, using full system of Maxwell equations for the electromagnetic field and hydrodynamic equations for electron motion inside the metal. Electron gas heating and thermal energy redistribution are described by the heat conductivity equation with a source equal to the power absorbing by a single particle. We also take into account the collision frequency dependence on the electronic temperature.

Evolution of the electronic temperature distribution during the intense laser pulse reflection from a rough metallic surface is quite unexpected. While the initial temperature distribution follows the random surface shape (due to local field enhancement), the resulting heating pattern is clearly periodic, and the spatial period is equal to the SPP wavelength. Note that the observed temperature contrast is rather strong (up to 3-5 times and larger), so it is an important factor for metal melting.

Also, the remarkable dependence of the heating dynamics on the laser beam width was observed in numerical experiments. When we make the beam narrower, the decay process becomes slower, up to full suppression of the periodic pattern. We interpret this effect as the consequence of SPPs loss due to free propagation outside of the interaction area. When the SPP free path became larger than the beam width, their energy is mostly absorbed outside of the standing wave region, so that the feedback becomes weaker.

The work was carried out as part of the Program of World-Class Research Center “Center for Photonics” with the financial support of the Ministry of Science and Higher Education of Russia, agreement No. 075-15-2022-316. Personally I.O. is grateful for support to the Theoretical Physics and Mathematics Advancement Foundation “BASIS”, grant No. 22-1-3-49-1.

On the electric area of short electromagnetic pulses

A. V. Bogatskaya[1,2] and A. M. Popov[1,2]

[1] Lomonosov Moscow State University, Physics Department, Moscow, Russia;
[2] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: alexander.m.popov@gmail.com

Progress in the technology of generating ultrashort pulses in various frequency ranges has made the question of the possibility of generating (quasi)unipolar pulses, or pulses with a nonzero electric area, again topical [1,2].

The propagation of ultrashort electromagnetic pulses with a nonzero electric area in plasma media is analyzed. Within the framework of unidirectional propagation of an electromagnetic pulse [3,4] in a one-dimensional approximation, an equation for its area is obtained. It is shown that this area is not an invariant of motion and can either decrease or increase in the course of pulse propagation, depending on the properties of the plasma medium. We also note that the considered approach can be used to analyze the area of a pulse propagating in non-ionized gaseous media. In this case, the response function should describe the currents of bound electrons arising in the medium (polarization currents).

The work was supported by Russian Science Foundation (grant № 22-22-00225).

REFERENCES

[1] N. N. Rosanov, R. M. Arkhipov, M. V. Arkhipov, Phys. Usp., 61, 1227–1233 (2018).
[2] R. M. Arkhipov, M. V. Arkhipov, A. V. Pakhomov et al., JETP Lett., 117, 8 (2023).
[3] M. Kolesik, J.V. Moloney, Phys. Rev. E, 70, 036604 (2004).
[4] A. Couairon, O. G. Kosareva, N. A. Panov, et al., Opt. Express 23, 31240 (2015).

Radiation-dominated plasma dynamics in multi-petawatt laser beams

S. V. Popruzhenko[1,2]

[1] National Research Nuclear University MEPhI, Moscow, Russia;
[2] Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: sergey.popruzhenko@gmail.com

In this talk, we discuss the state of the art of the theory of plasma dynamics and radiation in laser fields of extreme intensity exceeding 10^{23}W/cm^2. Such intensities are currently becoming available in laser laboratories equipped by multi-petawatt femtosecond sources [1]. Even higher intensities will be achieved on sub-exawatt laser facilities [2,3] in a foreseeable future.

We summarize recent results obtained by several theoretical groups. The focus is made on phenomena emerging due to a strong back reaction of radiation emitted by the plasma electrons on the dynamics of these electrons and of the whole plasma. In this extreme-field domain, radiation reaction (RR) both modifies effects, which exist also at lower intensities when RR is negligible and induces new effects, which can be considered as markers of the classical or quantum RR force.

We address the following problems (see also recent reviews [4,5] for details and references):

- Possible radiation reaction effects on laser acceleration of electrons and ions. Generally, RR decreases the acceleration efficiency, however opposite counterintuitive situations are also possible.
- Can the radiation reaction force in extreme fields act coherently on a group of electrons? Is there a double-count of RR in PIC-codes?
- Generation of extremely strong magnetic fields in radiation-dominated laser plasma. Inverse Faraday effect induced by the RR force and its possible realization in multibeam schemes.
- Borders between the classical and the quantum regimes of interaction.

Our analysis suggests that in the intensity domain $10^{23} - 10^{24}$W/cm^2, which can soon become accessible for regular experiments, several qualitative effects of the classical RR force can be studied. At the same time, for many potentially realizable experimental setups, longitudinal acceleration of the plasma shifts the border of the quantum regime above this intensity interval.

REFERENCES

[1] J.W. Yoon, et al., Optica 8, 630 (2021).
[2] A. Gonoskov, T.G. Blackburn, M. Marklund, and S.S. Bulanov, Rev. Mod. Phys., 94, 045001 (2022).
[3] E. Khazanov, et al., High Pow. Las. Sci. and Eng. 11, (2023).
[4] A. Fedotov, A. Ilderton, F. Karbstein, B. King, D. Seipt, H. Taya, G. Torgrimsson, Phys. Rep., 1010, 1 (2023).
[5] S.V. Popruzhenko, A.M. Fedotov, Phys. Usp., 66 (5), 460 (2023).

Numerical simulation of high-order harmonics generation by Ba and Cs atoms

A. A. Romanov[1,2], A. A. Silaev[1,2] and N. V. Vvedenskii[1,2]

[1] Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] University of Nizhny Novgorod, Nizhny Novgorod, Russia
e-mail: romanoval@ipfran.ru

High-order harmonics generation (HHG) of intense laser pulses is one of the most well-known phenomena of strong-field physics, which is of great interest for numerous applications [1]. The physical mechanism of HHG is qualitatively explained in the framework of a three-step scenario [2]. In the first step, atoms or molecules are ionized by an intense field. In the second step, the electric field accelerates the free electrons in the continuum. In the third step, the electrons recombine with the emission of high-energy photons in a wide energy range. In the first and third steps, the multielectron dynamics associated with the motion of various electrons in an atom or molecule can significantly affect the HHG spectra. An example of the significant influence of multielectron effects at the recombination stage is the giant enhancement of HHG yield near 100 eV in xenon, associated with the interaction of the photoelectron, originating from the external $5p_0$ orbital, with the inner electrons of the atom [3-5]. As shown in paper [5], the giant HHG enhancement in xenon can be accurately described by the time-dependent density-functional theory that takes into account the multielectron dynamics of two outer shells of the Xe atom.

In this work, we numerically study HHG in barium (Ba) and cesium (Cs) atoms based on the time-dependent density-functional theory. Ba and Cs atoms have electronic configurations similar to the Xe atom but with an additional $6s$ outer shell with two (for Ba) and one (for Cs) electrons. We show that the HHG spectrum for Ba and Cs atoms also contains the giant enhancement region, which is slightly shifted to a higher frequency region from 100 eV. The manifestation of this enhancement is associated with a strong excitation of the 4th shell by a recombining photoelectron. The binding energies of the 4th-shell electrons in Ba and Cs lie lower than in the Xe atom, which explains the shift in the enhancement region. In contrast to the Xe atom, the Ba and Cs atoms also exhibit a resonance in the low-frequency part of the spectrum near 20 eV associated with the excitation of the 5th shell by the recombining photoelectron.

The work is supported by the Russian Science Foundation (Grant No. 20-11-20289).

REFERENCES

[1] F. Krausz and M. Ivanov, Rev. Mod. Phys., 81, 163–234 (2009).
[2] P. B. Corkum, Phys. Rev. Lett., 71, 1994–1997 (1993).
[3] M. V. Frolov, N. L. Manakov, T. S. Sarantseva, M. Yu. Emelin, M. Yu. Ryabikin, and A. F. Starace Phys. Rev. Lett., 102, 243901 (2009).
[4] A. D. Shiner et al., Nat. Phys., 7, 464–467 (2011).
[5] A. A. Romanov, A. A. Silaev, T. S. Sarantseva, M. V. Frolov, and N. V. Vvedenskii, New J. Phys., 23, 043014 (2021).

High-order harmonic generation in orthogonal IR and XUV pulses: XUV-initiated channel separation and polarization control

T. S. Sarantseva[1,2], A. V. Sviridov[2], A. A. Romanov[1], A. A. Silaev[1], N. V. Vvedenskii[1] and M. V. Frolov[1,2]

[1] Department of Radiophysics, University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[2] Department of Physics, Voronezh State University, Voronezh, Russia
e-mail: sartan86@gmail.com

We consider high-order harmonic generation (HHG) for an atom interacting with the linearly polarized intense infrared (IR) and synchronized time-delayed perturbative extreme ultraviolet (XUV) pulses, whose polarization vectors are mutually perpendicular to each other. Atom is considered within the single active electron approximation. We assume that atom is not polarized and an active electron is in p-state, which is triple degenerate in angular momentum projection m. The angular dependence of an initial state is described in terms of tesseral spherical harmonics, which are more appropriate than spherical harmonics for description p-state interaction with the laser field having two independent spatial components. We show that these states interact differently with orthogonal components of the two-color field making it possible to separate different IR-indused and XUV-induced HHG channels. Our theoretical analysis, based on the analytical and numerical treatment of HHG, show that harmonics generated from the state oriented along the IR polarization vector are formed according to the three step-scenario (tunneling, propagation, and recombination) driven by the IR field, while effects from the XUV component are neglegiable. However, the XUV-initiated HHG channel, consisting in XUV-induced ionization, propagation in an intense IR field with subsequent recombination, is realized through the state oriented along the XUV polarization vector. Our analysis shows that harmonics generated from the IR-induced HHG channel are linearly polarized along the IR polarization vector, while for the XUV-initiated HHG channel generated harmonics are linearly polarized along the XUV pulse polarization vector. The aforementioned polarization properties make possible to separate the XUV-initiated HHG channel from the IR-induced channel on a single-atom level by measuring harmonics with fixed polarization coinciding with XUV pulse polarization.

We also propose a new method for the polarization control of generated harmonics, which can be realized through the variation of the time delay between IR and XUV pulses. Since x-component of the laser-induced dipole momentum is determined by the amplitude for IR-induced HHG, it does not depend on the XUV pulse parameters and time delay between IR and XUV pulses. The magnitude and phase of the y-component in atomic dipole significantly depend on the time delay, thereby making possible complete polarization control through the time delay variation. Validity of the proposed methods is demonstrated by the numerical simulations of HHG for the Ne atom.[1]

This work was supported by the Russian Science Foundation through Grant No. 22-12-00223.

REFERENCES

[1] T. S. Sarantseva at al, Phys. Rev. A, 107, 023113 (2023).

Femtosecond laser-induced surface relief formation in the thin amorphous films of chalcogenide vitreous semiconductors

D. V. Shuleiko[1], P. A. Danilov[1,2], E. V. Kuzmin[1,2], S. A. Kozyukhin[3], T. S. Kunkel[1,3], M. V. Polyakov[4], L. S. Volkova[4], S. V. Zabotnov[1] and P. K. Kashkarov[1]

[1] Lomonosov Moscow State University, Faculty of Physics, Moscow, Russia;
[2] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[3] Kurnakov Institute of General and Inorganic Chemistry of the Russian Academy of Sciences, Moscow, Russia;
[4] Institute of Nanotechnology of Microelectronics of the Russian Academy of Sciences, Moscow, Russia
e-mail: shuleyko.dmitriy@physics.msu.ru

Chalcogenide vitreous semiconductors (ChVSs) are applied as a basis of the rewritable optical memory [1] and infrared photonic devices due to the possibility of fast and reversible phase transitions, as well as high refractive index and transmission in the near- and mid-infrared spectral range [2]. Laser-induced periodic surface structures (LIPSS) formation on such materials provides prospects for increasing information storage capacity and create polarization-sensitive optical elements of infrared photonics. LIPSS formation accompanied by laser-induced phase transitions currently is well studied for $Ge_2Sb_2Te_5$ films [4], however for infrared photonic applications, arsenic sulfide (As_2S_3) and arsenic selenide (As_2S_3) seem to be more promising materials [5].

In presented work, thin As_2S_3 and As_2S_3 films (576±5 nm and 842±5 nm, respectively) deposited on single-crystal silicon substrates with a chromium sublayer (100 nm) or on quartz glasses were irradiated with femtosecond laser pulses (300 fs) at the second optical harmonic frequency (515 nm) using Satsuma laser system (energy and number of pulses E = 0.1–0.4 μJ, N = 10–1200) at normal incidence.

As a result of femtosecond laser irradiation, LIPSS were formed on the surface of the films in the form of one-dimensional gratings with wavelength (515 nm) and subwavelength (150–185 nm) periods, oriented, respectively, orthogonally or along the polarization vector. The period and orientation of LIPSS varied depending on the number and energy of laser pulses and was consistent with the results of numerical simulation within the framework of the plasmon-polariton mechanism for the formation of these structures. It also was shown experimentally and confirmed by numerical simulation that both wavelength and subwavelength structures can be observed simultaneously within the same crater formed by a femtosecond laser impact, in the form of a hierarchical structure of two orthogonal gratings with different periods. Additionally, a possibility to produce large areas (5x5 mm^2) covered by hierarchical LIPSS using femtosecond laser raster scanning was demonstrated.

Raman spectra analysis (Horiba HR800, 488 nm excitation) demonstrated no structural changes in As_2S_3 films. However, femtosecond laser-induced phase transformations are possible for As_2S_3 films according to Raman data.

The work was supported by Russian Science Foundation (project 22-19-00035).

REFERENCES

[1] P. Guo, A.M. Sarangan and I. Agha, Appl. Sci. 9, 530 (2019).
[2] J.S. Sanghera, L.B. Shaw, et al., Fiber Integr. Opt. 19, 251–274 (2000).
[3] A.S. Lipatiev, S.S. Fedotov, et al., Appl. Opt. 57, 978 (2018).
[4] S. Zabotnov, A. Kolchin, et al. Micro, 2, 88–99 (2022).
[5] W. Ma, L. Wang, et al. Opt. Express 27, 30090–30101 (2019).

Low-order harmonics generation of intense laser pulses in atomic and molecular gases in the presence of a static electric field

A. A. Silaev[1,2], A. A. Romanov[1,2] and N. V. Vvedenskii[1,2]

[1] Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] University of Nizhny Novgorod, Nizhny Novgorod, Russia
e-mail: silaev@appl.sci-nnov.ru

The interaction of an intense laser pulse with a gaseous medium leads to the generation of odd harmonics of the laser pulse [1, 2]. When a quasi-dc electric field is applied, the system's symmetry is reduced, which opens up the possibility of generating even harmonics of the laser radiation. For a weak dc field, the strengths of even harmonics are linear in dc-field strength. The latter opens up the principal possibility of measuring the waveforms of low-frequency pulses (with frequencies much less than the inverse laser-pulse duration) using the dependence of the even harmonic intensities on the delay time of the probe laser pulse. Previously, this detection method, based on the second-harmonic generation of the laser pulse due to the cubic nonlinearity of the medium, was used in many experiments for measuring terahertz waves [3–5].

This work studies the mechanisms of even-order harmonics generation in different atomic and molecular gases for a wide range of laser-pulse intensities. Based on the numerical solution of the time-dependent Schrödinger equation and time-dependent Kohn-Sham equations, we calculate the intensity and duration of the low-order harmonics generated during the interaction of helium atom and oriented carbon monoxide molecule with femtosecond laser field in the presence of an external quasi-dc electric field in a wide range of the laser-pulse parameters. We find the ranges of parameters intensity and wavelength) of the laser pulse and ranges of the harmonic numbers corresponding to different mechanisms of harmonic generation: the response of bound electrons, the response of free electrons [6–8], or the recombination of the freed electron with the emission of an energetic photon [2]. It is shown that low-order harmonics generated due to the response of free electrons are attractive for realizing the sampling methods for detecting terahertz and mid-infrared radiation. The reason is the possibility of obtaining a temporal resolution of detection much less than the probe laser pulse duration [9]. It is also demonstrated that the use of oriented asymmetric molecules as a nonlinear medium makes possible the coherent detection of low-frequency radiation without using an additional constant field, which is necessary when using isotropic gases as a nonlinear medium.

The work is supported by Russian Science Foundation (Grant No. 22-72-10133).

REFERENCES

[1] F. Krausz and M. Ivanov, Rev. Mod. Phys., 81, 163–234 (2009).
[2] P. B. Corkum, Phys. Rev. Lett., 71, 1994–1997 (1993).
[3] X. Xie, J. Dai, and X.-C. Zhang, Phys. Rev. Lett., 96, 075005 (2006).
[4] X.Lu and X.-C. Zhang, Front. Optoelectron., 7, 121-155 (2014).
[5] F. D'Angelo et al., Opt. Exp., 22, 12475-12485 (2014).
[6] V. A. Kostin et al., Phys. Rev. Lett., 117, 035003 (2016).
[7] A. A. Silaev et al., JETP Letters, 107, 151 (2018).
[8] V. A. Kostin and N. V. Vvedenskii, Phys. Rev. Lett., 120, 065002 (2018).
[9] A. A. Silaev, A. A. Romanov, and N. V. Vvedenskii, Opt. Lett., 47, 4664 (2022).

The relaxation characteristics of solvents from time-resolve fluorescence spectra: the role of the gating pulse duration

I. P. Yermolenko, V. A. Mikhailova and A. I. Ivanov

Volgograd State University, Volgograd, Russia
e-mail: yermolenkoigor@volsu.ru

Theoretical approaches to the description of spectral dynamics are currently well developed and successfully applied to its simulation in real systems. Information about the relaxation of the solvent and the photoexcited molecule is contained in the spectral dynamics of fluorescence. The Stokes shift dynamics of the fluorophore fluorescence spectrum is usually identified with the dynamics of the relaxation of the medium, although recent studies show a significant contribution from intramolecular relaxation as well.

Obtaining the relaxation characteristics of solvents using the dynamics of the maximum of the fluorescence band faced a serious difficulty for decades due to the uncertainty of the initial position of the fluorescence band. This difficulty has recently been overcome by modeling the full non-stationary fluorescence spectrum and a consistent description of the pumping process. Recently, in [1], in the framework of perturbation theory in terms of the interaction operator of a molecule with an exciting pulse, an approach was developed to model the spectrum of nonstationary fluorescence. This approach includes the description of both the solvent relaxation and the relaxation of intramolecular high frequency vibrations. Since intramolecular relaxation makes a significant contribution to the spectral dynamics of fluorescence at short times, this approach makes it possible to substantially improve the accuracy of determining the relaxation times of solvent fast modes.

However, in [1], the duration of the gating pulse was completely neglected. In this work, we propose an approach with an explicit description of the gating pulse profile in the calculation of the nonstationary fluorescence spectrum. The fitting of such spectra to the experimental ones showed that neglecting the finite duration of the gating pulse leads to significant errors. Based on this approach, the relaxation characteristics of a number of widely used solvents, such as ethylene glycol, dimethyl sulfoxide, butyronitrile, ethyl acetate, diethyl ether, and di-i-propyl ether, have been refined. The relaxation time of intramolecular high-frequency vibrations of C153 coumarin, active in the optical transition, is much shorter than the resolution of the experimental setup, and it is difficult to determine it from non-stationary experimental spectra. However, there are many molecules for which the vibrational relaxation time is much longer. This approach will make it possible to determine the relaxation time of active intramolecular vibrations of such molecules.

REFERENCES

[1] R.G. Fedunov, I.P. Yermolenko, A.E. Nazarov, A.I. Ivanov, A. Rosspeintner, G. Angulo. J. Mol. Liq., 298, 112016 (2020).

Section 3: Ultrafast laser technologies and structured light in micro-optics and nanophotonics

Section Co-chairs:

Mikhail Kovalev, e-mail: m.s.kovalev@gmail.com
(Bauman Moscow State Technical University, Russia)
Sergey Babin, e-mail: potemkin@physics.msu.ru
(Institute of Automation and Electrometry of SB RAS, Russia)
Sergey Fedotov, e-mail: monteske@mail.ru
(Mendeleev University of Chemical Technology, Russia)

Program committee:

Vladimir Shur
(P.N. Lebedev Physical Institute, Russia)

Yulia Gulina
(P.N. Lebedev Physical Institute, Russia)

Vladimir Kesaev
(P.N. Lebedev Physical Institute, Russia)

Scope

Ultrafast nanophotonics in dielectric nano/microstructures

Ultrafast structured light

Femtosecond/picosecond laser writing in dielectrics

Novel optical materials for ultrafast photonics

Capillary-wave approach to describe the mechanism of periodic structures formation on solids by laser ablation

P. S. Kuleshov[1], E. V. Barmina[2], I. O. Bruslavskiy[2], E. Skoulas[3], E. Stratakis[3] and G. A. Shafeev[2]

[1] Moscow Institute of Physics and Technology, Dolgoprydny, Russia;
[2] Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, Russia;
[3] Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, Heraklion, Greece
e-mail: barminaev@gmail.com

This report summarizes experimental results about micro- and nanostructures formation by irradiation of solids ps- and fs pulses. It shown that combination of laser parameters allows to create hierarchical surface structures (HSFL and LSFL, coexistence with microsctructures) [1, 4, 6]. Comprehensive analysis of theoretical models [3, 7, 8] and experimental data [2, 5] let us to conception about of periodic structures formation in capillary-wave model. In other words we demonstrate analytic calculation of structures size from several nanometers (HSFL) to thousand nanometers (LSFL, microstructures). This calculation is based on the study of resonant wave processes on the melt surface [7, 8] and the hierarchy of times of various types of heat and mass transfer. Capillary waves are described in the approximation of "shallow water". Theoretical estimation of the period of nanostructures is in good agreement with experimental results on Al, Ti, Ta, W, and stainless steel. We thank Nanoscience foundries and fine analysis (NFFA) and IESL FORTH for FESEM images and laser equipment.

REFERENCES

[1] J. Bonse, S. Höhm, S. V. Kirner, A. Rosenfeld and J. Krüger IEEE Journal of Selected Topics in Quantum Electronics, vol. 23(3), p. 9000615, (2017).
[2] N. A. Kirichenko, E. V. Barmina and G. A. Shafeev, Physics of Wave Phenomena, vol. 26, pp. 264-273, (2018).
[3] A. Rudenko, A. Abou-Saleh, F. Pigeon, C. Mauclair, F. Garrelie, R. Stoian and J. P. Colombier, Acta Mater., vol. 194, pp. 93–105, (2020).
[4] J. Bonse and Gräf, S., Laser & Photonics Reviews, vol. 14(10), p. 2000215, (2020).
[5] F. Fraggelakis, G. D. Tsibidis and E. Startakis, Phys. Rev. B, vol. 103, p. 054105, (2021).
[6] U. Teubner, A. Andreev, V. Makin, and J. Imgrunt, vol. 6(11), p.115003, (2022).
[7] P. S. Kuleshov and V. D. Kobtsev, vol. 56(5), pp. 566-575, (2020).
[8] P. S. Kuleshov, M. M. Kuznecov, Yu. Kuleshova, vol. 1, pp. 41-51, (2022).

Structure of darkening tracks in soda-lime glass exposed to femtosecond laser radiation

N. I. Busleev[1], N. A. Smirnov[1], V. V. Kesaev[1], S. I. Kudryashov[1]

[1] Lebedev Physical Institute, 53 Leninsky prospect, 119991 Moscow, Russia
e-mail: busleevni@lebedev.ru

It has been shown that interaction of ultrafast laser pulses with soda-lime glass can produce coloration [1,2], which is caused by the accumulation of color centers (defects) in the irradiated volume. The darkened elongated regions were created in the volume of soda-lime glass by ultrafast laser radiation in the near-infrared range (λ=1030 nm, pulse energy 40-80 μJ, pulse duration 250 fs, exposure time 120 s) focused by F-theta lens with a focal length of 100 mm. The inner structure of created darkening tracks was investigated by confocal microscopy.

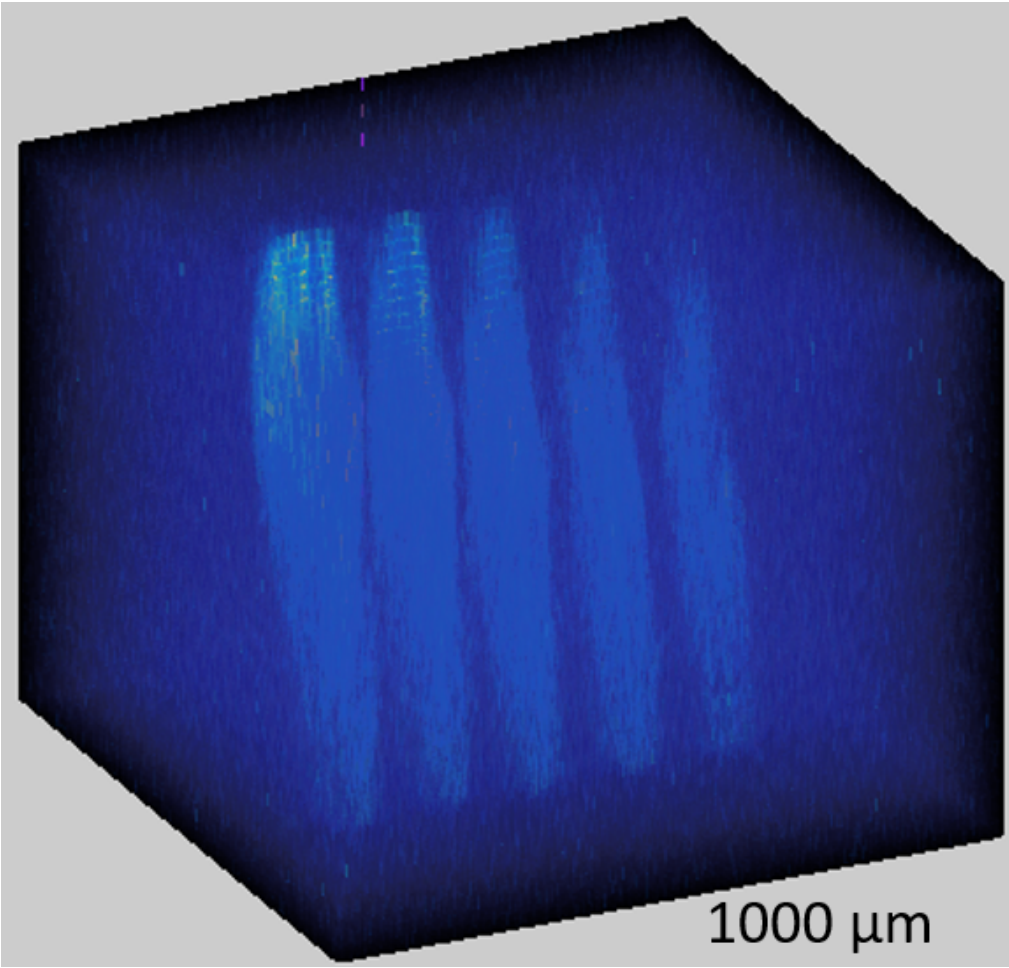


Figure 1: The 3d image of darkened elongated regions in soda-lime glass acquired by confocal microscopy.

REFERENCES

[1] J. T. Dickinson, et al. Color center formation in soda lime glass and NaCl single crystals with femtosecond laser pulses. Appl. Phys. A 79, 859 (2004).

[2] D. Ashkenasi and A. Lemke. Picosecond laser-induced color centers in glass optics. Journal of Laser Applications 23, 012007 (2011).

Nonlinear terahertz Kerr effect in quasi-2D $MnPS_3$

L. Cheng[1], F. Formisano[2], K. A. Grishunin[2], S. D. Gorelov[3], P. H. M. van Loosdrecht[5], J. Yan[4], X. Luo[4], Z. Sheng[1] and E. A. Mashkovich[5]

[1] Anhui Key Laboratory of Condensed Matter Physics at Extreme Conditions, High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei, China;
[2] Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands;
[3] University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[4] Key Laboratory of Materials Physics, Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences, Hefei, China;
[5] University of Cologne, Institute of Physics II, Cologne, Germany
e-mail: sdgorelov@yandex.ru

Quadratic electro-optic effect (Kerr effect) is shown to be efficiently induced by terahertz (THz) electric field in quasi-two-dimensional (2D) material $MnPS_3$ [1]. The response to the THz field closely follows the intensity of the nearly single-cycle THz pulse employed in the experiment. Interestingly, the observed effects do not include THz-induced absorption or linear electro-optical effects. Instead, we demonstrate that the THz electric field induces the refraction coefficient anisotropy experienced by light at the wavelength of 800 nm (Fig. 1). This anisotropy is a result of the high nonlinear refractive index of the $MnPS_3$ sample, which is found to be approximately $13 \times 10^{-14} \mathrm{W}^{-1} \cdot \mathrm{cm}^2$, which is an order of magnitude higher than typical bulk EO modulator materials. This promotes the quasi-2D $MnPS_3$ as a promising candidate for future practical applications in ultrafast electro-optical devices.

This work was supported by Ministry of Science and Higher Education of the Russian Federation (FSWR-2021-011).

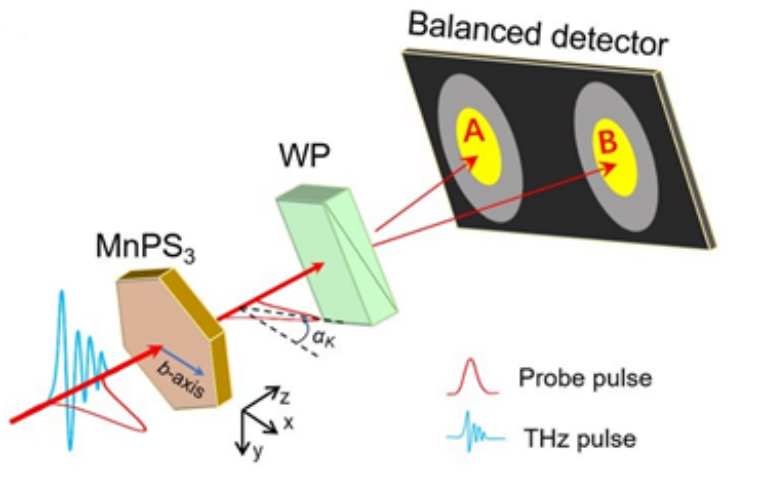


Figure 1: THz pump - IR probe technique combined with a balanced detection scheme is used to monitor THz induced probe polarization rotation αk over time. WP is the Wollaston prism. Adapted from [1]

REFERENCES
[1] L. Cheng et al., Optics Letters, Vol. 47 (16), pp. 4052 – 4055 (2022).

Femtosecond laser modification of ZnO:Ag thin films opto-electronic properties

V.R. Gresko, V. V. Smirnova, M. M. Sergeev and A. D. Dolgopolov

ITMO University, St. Petersburg, Russia
e-mail: gresko.97@mail.ru

ZnO thin films due to their physical properties are often used as photosensitive elements and layers of various optoelectronic devices, including photodetectors [1]. The addition of silver nanoparticles to the composition of films can significantly increase the sensitivity of sensors in a certain spectral wavelength range due to the phenomenon of localized plasmon resonance, as well as increase the conductivity of the material [2]. Laser radiation is a very convenient tool for a fast, highly efficient and at the same time easily implemented method of local modification of film properties with the possibility of their correction in real time. By selecting the radiation parameters, it is possible to influence the ZnO matrix itself or the metal nanoparticles contained in it. Thanks to this, it is possible to observe various mechanisms of laser action, as well as the properties of the modified material.

In this work, we studied the effect of femtosecond laser radiation on the optical and electrical properties of composite ZnO films with silver nanoparticles. The radiation wavelength (515 nm) was close to the plasmon resonance of nanoparticles. The surface of the samples was processed at different values of the pulse duration, radiation power, pulse repetition rate, and radiation polarization. It was found that the anisotropy of the sample properties increased as a result of laser exposure. The optical and electrical characteristics of the films have been studied. A change in the position of the plasmon resonance peak was observed, as well as a change in the electrical conductivity of the material.

This work was supported by the Russian Science Foundation (project no. 19-79-10208).

REFERENCES

[1] Ahmed A. A. et al.Ceramics International 48, №. 11, p.16142-16155, (2022).
[2] Tzeng S. K., Hon M. H., Leu C. Journal of the Electrochemical Society 159, №. 4, p. H440, (2012).

Two-temperature hydrodynamics, expansion of heated matter, and generation of shock wave

N. A. Inogamov[1-3], V. V. Zhakhovsky[2], Yu. V. Petrov[1], V. A. Khokhlov[1], Yu. R. Kolobov[4], S. I. Ashitkov[2], S. A. Romashevskiy[2], V. V. Shepelev[5] and E. A. Perov[2]

[1] Landau Institute for Theoretical Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, Russia;
[2] Dukhov All-Russia Research Institute of Automatics, Moscow, Russia;
[3] Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia;
[4] Institute of Problems of Chemical Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, Russia;
[5] Institute for Computer Aided Design, Russian Academy of Sciences, Moscow, Russia
e-mail: nailinogamov@gmail.com

In the report the peculiarities of two-temperature physics [1] and melting shock waves (SW) initiated by sub- and picosecond laser pulses are considered [2-5].

Ultrashort laser pulses with a duration from several to about a thousand optical cycles have significant importance in modern science and engineering. Such a pulse transfers a metal to an excited two-temperature (2T) state with hot electrons where the temperature of the electron subsystem is much higher than the temperature of the ion subsystem. New theoretical and experimental results [1] that make it possible to determine the key (for the 2T physics) two parameters for gold are reported. These parameters are: thermal conductivity and electron-phonon coupling.

Modification of titanium microstructure after propagation of a melting SW generated by a femtosecond laser pulse is investigated experimentally and analyzed using hydrodynamic and atomistic simulations. Scanning and transmission electron microscopy with analysis of microdiffraction is used to determine the microstructure of subsurface layers of pure titanium sample before and after modification [3-5].

REFERENCES

[1] N. Inogamov et al., JETP Lett., Vol. 117, No. 2, pp. 104-110 (2023).
[2] V. Shepelev et al., Optics & Laser Technology, Vol. 152, p. 108100 (2022).
[3] V. Khokhlov et al., JETP Lett., Vol. 115, p. 523 (2022).
[4] V. Zhakhovsky et al., arXiv 2306.09100, physics.flu-dy (2023).
[5] V. Zhakhovsky et al., submitted to Phys. Fluids (2023).

Interface effect on the LIPSS formation at femtosecond laser illumination of $Ge_2Sb_2Te_5$

D. O. Kuzovkov[1,2,3], M. P. Smayev[1,3], M. E. Fedyanina[3], P. I. Lazarenko[3], I. A. Budagovsky[1], D. N. Tuzhilin[2], D. L. Saprykin[2] and S. A. Kozyukhin[4]

[1] Lebedev Physical Institute of the RAS, Moscow, Russia;
[2] LLC SPC "Lasers and Equipment TM", Zelenograd, Russia;
[3] National Research University of Electronic Technology, Zelenograd, Russia;
[4] Kurnakov Institute of General and Inorganic Chemistry of the RAS, Moscow, Russia
e-mail: kdo@laser-app.ru

Chalcogenide semiconductors based on a ternary compound $Ge_2Sb_2Te_5$ (GST225) have unique properties consisting in significant, ultrafast and reversible changes in the internal electrical and optical characteristics that occur when switching their phase state between amorphous and crystalline. In particular, when exposed to ultrashort pulses, laser-induced periodic surface structures (LIPSS) can form on the surface of GST225 thin film, which are alternating crystalline and amorphous lines with a period equal to the wavelength and oriented perpendicular to the polarization direction [1]. The appearance of such a structure can be explained by the interference of the induced surface plasmon-polariton wave and the incident beam. Then, at the maxima of the interference pattern, local heating will occur leading to the formation of crystalline lines. In this work, the influence of the thickness of chalcogenide films and the characteristics of adjacent layers on the regimes of LIPSS formation is studied.

The substrate was a silicon wafer. For some of the samples, the substrate was covered with a conductive tungsten sublayer with a thickness of 200 nm. Amorphous layers of GST225 with a thickness of 30 and 130 nm were obtained by a DC magnetron sputtering. Half of the samples were coated with a 20 nm thick layer of silicon dioxide to protect against oxidation in an air atmosphere. The LIPSS was produced using a laser system with a wavelength of 1030 nm, a pulse duration of 250 fs, and a repetition rate of 100 kHz.

It was found that the passivating amorphous SiO_2 layer above GST225 does not affect the LIPSS writing regimes, which is in good agreement with the low absorption of SiO_2 at 1030 nm. In a sample with a thick GST layer (130 nm), the presence of a metal sublayer did not significantly affect the formation of periodic structures: the threshold energy fluence of LIPSS formation was $F_{th} = 4.1$ mJ/cm^2. However, in the samples with a thin GST layer (30 nm), the presence of a metal sublayer led to a decrease in the threshold fluence to $F_{th} = 2.2$ mJ/cm^2. This behavior can be explained by the fact that, in the latter case, the penetration depth of laser radiation (about 80 nm for 1030 nm) exceeds the GST thickness and, due to the reflection of radiation from the metal sublayer, the laser effect on the chalcogenide film is enhanced.

The study was funded by the Russian Science Foundation no. 23-29-00977, `https://rscf.ru/en/project/23-29-00977/`.

REFERENCES

[1] S. Kozyukhin, et al., Phys. Stat. Sol., 257, 1900617 (2020).

Filamentation of ultrashort infrared laser pulses in distilled water

I. D. Matyaev[1], P.A. Danilov[2], D.A. Pomazkin[2], P.Ya. Ilyushin[2,3]

[1] Bauman Moscow State Technical University, Moscow 105005, Russia;
[2] P.N. Lebedev Physical Institute, Moscow, Russia;
[3] Lomonosov Moscow State University, Moscow 119991,Russia

e-mail: ivan.matyaev@mail.ru

Physical phenomena of self-focusing and filamentation of laser radiation during propagation in various media have been known for over 60 years [1]. The emergence of high-power picosecond and femtosecond laser systems has led to a rapid growth of research in this field. It has opened up new possibilities for practical applications, including the formation of various functional structures such as phase wave plates, polarization elements, and optical memory [2]. The key aspect in this case is the ability to control the parameters of the recording laser radiation (filament) and achieve unique characteristics through spatial-temporal focusing, which is recognized as an effective method for reducing nonlinear self-focusing, which hinders the achievement of high peak intensities of filaments [3].

In this work, we completed experimental research on important characteristics of single filaments in distilled water for a wide range of wavelengths (1.05 - 2.7 μm), such as the threshold power of formation, longitudinal and transverse intensity distributions, plasma density and energy, critical self-focusing power. The obtained results make a unique contribution to the possibility of interpreting the physical processes underlying nonlinear optical interaction with matter.

The study was supported by the Russian Science Foundation (project no. 23-22-00453).

REFERENCES

[1] G. A. Askar'yan, Sov. Phys. JETP 15 1088 (1962).
[2] S. S. Fedotov, R. Drevinskas, S. V. Lotarev, A.S. Lipatiev, M. Beresna, A. Čerkauskaitė, V. N. Sigaev, P. G. Kazansky, Appl. Phys. Lett., 108, 071905 (2016).
[3] K. Sugioka, Y. Cheng, Light Sci Appl., 3, e149 (2014).

Advanced optical data storage based on ultrafast laser writing in silver-doped nanoporous glass

Yu. V. Mikhailov, A. S. Lipatiev, S. S. Fedotov, T. O. Lipateva, S. I. Stopkin, S. V. Lotarev and V. N. Sigaev

Mendeleev University of Chemical Technology, Moscow Russia
e-mail: golpertm@icloud.com

Multidimensional data writing in silica glass by femtosecond laser pulses exploiting birefringent properties of the laser-induced voxels is a very promising way to develop long-term archival optical data storage devices [1]. However, in silica glass, ten or more laser pulses are generally required to induce nanostructures with noticeable form birefringence, which limits the information recording speed. This limitation can be overcome using high-silica nanoporous glass (NPG) as a storage medium. The number of pulses producing readable birefringence in NPG can be reduced to 2. Therefore the recording speed increases by several times [2]. Moreover, a unique feature of NPG is the possibility to impregnate it by different solutions and, using a subsequent heat treatment, to obtain solid high-silica glasses doped by various chemical elements [3].

In this study, the possibility of ultrafast laser writing in nanoporous glass doped with silver has been investigated. The synthesized NPG plates [2] were soaked in $Ag(NO_3)_3$ aqueous solution stabilized by concentrated HNO_3, dried at 110 °C for 1 h and thermally treated at 700 °C for 1 h [3]. The data writing was performed by Pharos SP femtosecond laser. Pulses of 180 fs duration emitted at 1 MHz repetition rate were focused inside NPG by an objective lens (N.A. = 0.65). The control of pulse number, pulse energy and laser polarization enabled data encoding in luminescent and birefringent properties of voxels (Fig. 1).

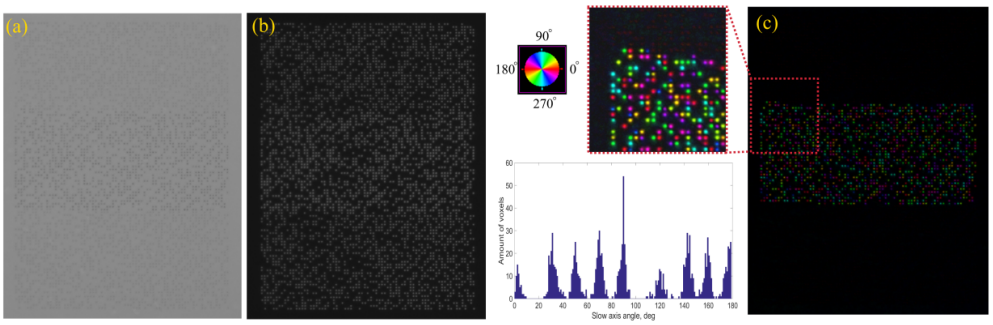


Figure 1: Brightfield optical image (a), luminescence image (b), pseudocolor polarized light Abrio image (c) of information cluster. Insets show the magnified part of the image (c) with adjusted retardance level range and a diagram of the distribution of the slow-axis orientation angles. The distance between voxels is 2 μm.

It was shown that the luminescent voxels can be inscribed by a single laser pulse whereas form birefringence appeared only after 2 or more pulses. A reliable readout with an accuracy over 99.8% was demonstrated. The proposed optical data storage provides a possibility to quickly switch between the ultrahigh speed of data recording in luminescence by a single pulse writing and ultrahigh recording density ensured by laser writing of additional data bits in birefringent properties of voxels.

This work was supported by the Russian Science Foundation (grant #22-79-10231).

REFERENCES

[1] Y. Lei et al., Opt. Mat. Express, 12 (2022).
[2] A. S. Lipatiev et al., Appl. Opt., 57 (2018).

LIFT method for high-performance non-contact additive laser printing of micro-macro-scale conductive elements

A. A. Nastulyavichus[1], N. A.Smirnov[1], S. N. Shelygina[1], P. P. Paholchuk[1], E. V. Ulturgasheva[1], D. A. Zayarnyi[1], S. I. Kudryashov[1]

P.N. Lebedev Physical institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: nastulyavichusaa@lebedev.ru

The LIFT method is of great interest for many areas, including microelectronics [1]. Using the innovative non-lithographic technology of high-performance non-contact additive laser printing of micro-macro-scale conductive elements and flexible electronic circuits, it is possible to obtain design structures controlled by digital graphic technologies.

In this work, laser transfer of silver and copper metal films of different thicknesses (10–300 nm) deposited without an adhesive sublayer on different substrates by magnetron sputtering was carried out. The substrates include object plates of silicate glass and flexible polyethylene terephthalate films. The transfer was carried out on glass substrates. The obtained samples were studied using scanning electron and probe microscopy, energy dispersive X-ray spectroscopy.

The study was supported by the Ministry of Science and Higher Education of the Russian Federation (agreement no. 075-15-2023-603)

REFERENCES

[1] J. M. Fernández-Pradas, P. Sopeña, S. González-Torres, J. Arrese, A. Cirera, P. Serra, Applied Physics A 124 (2), 1-8 (2018).

Elastic scattering on submicron particles enhances Raman scattering efficiency

O. I. Sokolovskaya and L. A. Golovan

Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia
e-mail: oi.sokolovskaja@physics.msu.ru

Elastic light scattering in a disordered medium may result in an increase in the volume of light-matter interaction compared to a homogeneous medium [1]. In this work, we have carried out both numerical simulation and experimental study of the light propagation and Raman scattering (RS) in scattering media. Suspensions of rutile particles with diameters of 350 and 500 nm and gallium phosphide particles with diameter of 3 μm in dimethyl sulfoxide (DMSO), which is Raman active liquid, were considered as a scattering medium. The volume fraction Φ of particles in suspensions ranged from 10^{-4} to 10^{-1}. To record the dynamics of the radiation scattered by suspensions, the optical heterodyning method [2] employing laser pulses with a duration of 80 fs (wavelength 1250 nm, pulse repetition rate 80 MHz) was used. Raman spectra were obtained with excitation wavelengths of 1064 and 532 nm.

Numerical simulation of light propagation in suspensions by the Monte Carlo method [3] showed that the dependence of the RS signal in DMSO on scatterer volume fraction is non-monotonic with the maximal 8-fold possible increase in the backscattered RS signal efficiency When GaP powder is added to DMSO, the mean photon path length and the RS signal decreased significantly with an increase in the scatterer volume fraction due to light absorption in them.

For 500 nm-sized rutile particle concentration more than $5 \times 10^{10}\text{cm}^{-3}$ both the results of numerical simulation of the temporal dynamics of laser pulses propagation in suspensions and experimental data indicate non-diffusion light propagation caused probably by scattered waves interference (see Fig.1a). Experiments on RS in rutile particle suspensions demonstrate maximum 3-fold increase in the RS signal achieved at excitation wavelength of 1064 nm with a scatterer volume fraction of 0.006 (see Fig.1b).

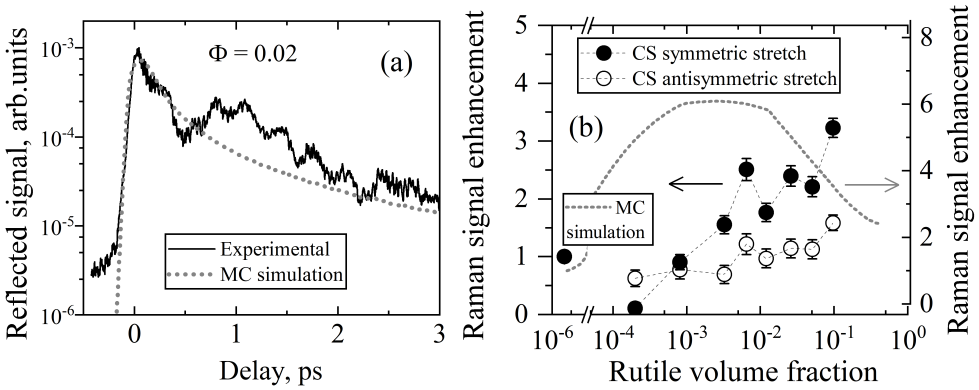


Figure 1: (a) Reflected signal dynamics and (b) Raman enhancement in rutile suspensions.

REFERENCES

[1] B.H. Hokr et al. Nature Communications, 5, 4356 (2014).

[2] K.P. Bestemýanov et al. Quantum Electronics, 34, 666 (2004).

[3] L. Wang, S.L. Jacques, L. Zheng. Comp.Met. and Prog. in Biomed, 47, 131-146 (1995).

Investigation of the anticorrosion properties of the surface of AISI 430 steel treated with laser radiation with a low power density

R. R. Suslov,V. M. Prokopiev, I. A. Filatov, R. I. Bogdanov, S. A. Khubezhov and G. V. Odintsova

ITMO University, St. Petersburg, Russia
e-mail: rrsuslov@itmo.ru

The study presents an investigation of the effect of steel surface characteristics after laser structuring on resistance to pitting corrosion. The surface treatment of stainless steel AISI 430 was carried out with a nanosecond ytterbium fiber laser with a wavelength of 1064 nm. The chemical composition and surface roughness of the steel were studied.

In the modern world, corrosion of metals is a big problem, therefore, in addition to traditional methods of protection, new methods are being actively explored to improve the anti-corrosion resistance of the metal. One of these methods is laser structuring, in which an oxide protective layer is formed on the metal surface.

In our work, we used the common stainless steel AISI 430, which shows good resistance to general corrosion, but insufficient to pitting corrosion. The processing was carried out by the MiniMarker-2 laser complex, available and applicable in the industry.

Electrochemical testing of AISI 430 stainless steel for resistance to pitting corrosion was carried out by taking anodic potentiodynamic curves (0.2 mW/s) in an aerated aqueous solution of 3.5 wt.% NaCl in a three-electrode cell using an IPC-PRO-MF potentiostat. The morphology of the steel surfaces was studied using an EDX Zeiss Merlin scanning electron microscope. The surface roughness after laser treatment was measured using a KLA TENCOR STYLUS PROFILER P-7 stylus profilometer.

Our previous studies have shown that XRD analysis does not give a complete picture of the chemical composition of the oxide film formed on the steel surface. Therefore, the study was carried out using XPS analysis (K-Alpha XPS, Thermo Scientific), which made it possible to obtain information on the amount and type of oxides formed.

The analysis of the dependence of anticorrosion properties on the chemical composition, wettability regime, roughness and morphology was carried out.

This research was supported by Priority 2030 Federal Academic Leadership Program.

Section 4: Diamond photonics

Section chair:

Sergey Kudryashov, e-mail: kudryashovsi@lebedev.ru
(P.N. Lebedev Physical Institute, Russia)

Program committee:

Victor Vins (VinsDiam Innovation Group, Russia)

Scope

CW and short-pulse photonics of optical centers: mid-IR, optical and UV ranges, EPR

Femtosecond laser-induced non-linear photophysicsin diamonds

Ultrafast structural modifications: graphitization, plastic deformation and annealing

Femtosecond laser inscription in diamonds and its applications

Visualization of structural inhomogeneties in diamond crystals by laser irradiation

K. K. Ashikkalieva[1], T. V. Kononenko[1], E. A. Obraztsova[2], and V. I. Konov[1]

[1] Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia;
[1] Shemyakin–Ovchinnikov Institute of Bioorganic Chemistry of the Russian Academy of Sciences, Moscow, Russia e-mail: kuralay.physics@mail.ru, AshikkalievaKK@nsc.gpi.ru

Laser irradiation is widely used to process the bulk of diamond crystals. It makes it possible to form various unique objects inside diamond. On the one hand, low-intensity laser pulses give an opportunity to controllably form peculiar defects inside diamond (color or NV centers). On the other hand, high-intensity laser pulses can lead to radical transformation of diamond to another form of carbon – graphite. In this case, an optical breakdown occurs in the waist of the laser beam tightly focused inside a diamond crystal. As a result, a buried graphitized region is formed in the bulk of the crystal. Uniform movement of the laser focus through the diamond crystal induces a wire-like graphitized region of unlimited length [1].

Recently we found that diamond crystals can considerably differ in optical breakdown thresholds [2]. Interestingly, values of the breakdown thresholds can vary not only for different samples, but also for different regions within one and the same crystal. Irradiation of CVD diamond single crystals by intense laser pulses revealed a specific spatial modulation of the optical breakdowns thus visualizing structural inhomogeneties presented in the examined crystals. It should be noted that synthesis of the crystals studied was carried out at fixed parameters (microwave power, substrate temperature, gas flow, etc.), which did not imply the occurrence of spatial modulations in the concentration of impurity defects. Here, we study a laser-induced specific pattern of the optical breakdown modulations in diamond crystals using optical, SEM microscopy, and photoluminescence spectroscopy.

This work was supported by the Russian Science Foundation (project no. 22-22-00055).

REFERENCES

[1] K. Ashikkalieva. Laser-Induced Graphitization of Diamond Bulk: The State of the Art (A Review). Physics of Wave Phenomena Vol. 30, P. 1–16 (2022).
[2] T. Kononenko, K. Ashikkalieva, V. Kononenko, A. Bol'shakov, V. Ral'chenko, V. Konov. Physics of Wave Phenomena Vol. 31, No. 2, P. 59–66 (2023).

Frequency characteristics of a diamond pin-diode on a Nitrogen-doped n-type substrate

S. G. Buga, G. M. Kvashnin, V. N. Kornilov, M. S. Kuznetsov, N. V. Luparev, D. D. Prikhodko, S. A. Tarelkin, V. D. Blank

Technological Institute for Superhard and Novel Carbon Materials, Troitsk, Moscow, Russia
e-mail: buga@tisnum.ru

Diamond p-i-n diodes are developed for use in advanced optoelectronic devices, like electrically driven sources of emission from optically active impurity centers [1], RF receiver protectors [2], high voltage diodes [3], and others. In most cases Phosphorus-doped diamonds are used as the n-type material [1]. The technology of making P-doped diamonds is complicated, thus the search for alternative ways of donor-doping of diamonds continues. The most abundant donor impurity in diamond is Nitrogen in the form of substitution atoms (C-centers). However, the energy level of 1.7 eV of separated C-centers is so deep, that only a very little fraction of them can be activated at heating. Whereas, this obstacle may be not very limiting for single-photon emission at room temperature and a bit higher. In this work, we have made experimental samples of diamond p-i-n diodes on a substrate of nitrogen-doped type Ib diamond grown by the temperature gradient method at high pressure and temperature (HPHT method) with concentration of C-centers $2.4*10^{19}$ cm^{-3}. On this substrate with dimensions of 4x4x0.3 mm^3, layers of high-purity diamond with a thickness of 6 microns (i-layer) and doped with boron at a concentration of $1*10^{20}cm^{-3}$ with a thickness of 7 microns (p+ layer) were sequentially grown by the method of homoepiatxial chemical vapor deposition (CVD) growth. Ti-Pt ohmic contacts were made on both sides of the diode. We studied the current-voltage, capacitance-voltage characteristics, and electroluminescence spectra of diodes at temperatures of 300-680°C. The maximum current density at 680oC, 10V bias was 1 A/cm^2. The admittance peak with the maximum at 2-20 kHz was observed at temperatures 500-620oC, and the half-amplitude of the capacity step took place at same frequencies. The temperature shifts of the admittance peak and capacity step on the frequency scale allowed to estimate the effective activation energy of charge carriers (free electrons) 1.1 eV. When direct current flows at high temperatures, a sufficiently bright glow of the diode emits from the i-layer. The electroluminescence spectrum has a wide band with a half-width of 100 nm, and a maximum at 590-610 nm. The intensity of the radiation is proportional to the magnitude of the diode current in DC mode. The dependencies of the radiation intensity on frequency in AC and short pulse current modes will be investigated.

The study was carried out with the financial support of the Russian Science Foundation in the framework of scientific project No. 22-22-00817, https://rscf.ru/project/22-22-00817.

REFERENCES

[1] D. Yu. Fedyanin and M. Agio. New J. Phys. 18, 073012 (2016).
[2] M. Dutta, F.A.M. Koeck, R. Hathwar et al. IEEE Electron Device Lett, 37 (9), 1170, (2016).
[3] V. Jha, H. Surdi, M.F. Ahmad et al., Solid-State Electronics 186, 108154 (2021).

Optical Properties and Structure Changes of Doped Nitrogen Centers in Diamond Under Laser Modification

J. Chen, S. I. Kudryashov, E. V. Kuzmin and P. A. Danilov

P.N. Lebedev Physical Institute, Moscow, Russia
e-mail: chenj@lebedev.ru

This study explores the structural and optical modifications of type Ib HPHT synthetic diamond and natural IaAB diamond induced by femtosecond laser exposure.

For the type Ib HPHT synthetic diamond, exposure to a highly focused ultrafast laser (515 nm, 0.3 ps) initiates the formation of several decolorized zones within the diamond. Fourier-transform infrared spectroscopy (FTIR) and transmission spectra indicated a decrease in the content of C, A, NV^0, and NV^- centers in the irradiated microzones. However, three-dimensional scanning confocal photoluminescence microspectroscopy revealed the presence of NV^0, NV^-, $H3$ or $H4$ centers with varied photoluminescence intensities in the irradiated microzones compared to the unirradiated material. This photo-stimulated aggregation process presumably occurs upon two-photon excitation of low-aggregated centers directly in the UV range [1].

Similarly, for the natural IaAB diamond, multi-pulse laser irradiation caused modifications of optical centers, which depend on the energy and exposure of the laser pulse. Notably, low pulse energy and exposure increased the concentration of vacancy-enriched nitrogen centers like $N3a$, $H3$, and $H4$. In contrast, energy pulses exceeding a threshold value led to laser-induced cleavage of highly aggregated nitrogen centers into weakly aggregated NV centers [2].

The experimental results underscore a novel mechanism for direct laser writing with structural and color modification of microzones within the diamond, opening pathways for the use of laser technologies for the enhancement and identification of synthetic diamonds.

REFERENCES

[1] Kudryashov, Sergey I., et al. "Permanent optical bleaching in HPHT-diamond via aggregation of C-and NV-centers excited by visible-range femtosecond laser pulses." Carbon 201 (2023).

[2] Kudryashov, Sergey, et al. "Nanoscale Vacancy-Mediated Aggregation, Dissociation, and Splitting of Nitrogen Centers in Natural Diamond Excited by Visible-Range Femtosecond Laser Pulses." Nanomaterials 13.2 (2023).

Productivity of concentration-dependent conversion of substitutional nitrogen atoms into nitrogen-vacancy quantum emitters in synthetic-diamond by ultrashort laser pulses

P. A. Danilov[1], S. I. Kudryashov[1], A.V. Gorevoy[1], V.G. Vins[2], E.V. Kuzmin[1], N.A. Smirnov[1], D.A. Pomazkin[1], P. P. Paholchuk[1], A.V. Muratov[1], A.N. Kirichenko[3], N.B. Rodionov[3] and E.A. Vasil'ev[4]

[1] P.N. Lebedev Physical institute of the Russian Academy of Sciences, Moscow, Russia;
[2] LLC VELMAN, Novosibirsk, Russia;
[3]Institution "Project Center ITER", Moscow, Russia;
[4] Saint-Petersburg Mining University, Saint-Petersburg, Russia
e-mail: danilovpa@lebedev.ru

Ultrashort-pulse laser inscription of photoluminescent NV-type color centers in high-purity synthetic diamonds is considered the most versatile technology for robust, controllable fabrication of NV-based single-photon sources for quantum optics applications [1]. The underlying physical mechanism was supposed to be an attachment of laser-generated vacancy to the single-atom substitutional nitrogen impurities (color C-centers) [2]. Moreover, the relative productivity of NV-center generation by ultrashort laser pulses in diamonds per one Joule of laser energy and one photo-generated electron-hole pair were not also studied yet.

We inscribed photoluminescent micromarks in the bulk of an Ib-type synthetic diamond with a known content of exceptionally nitrogen-impurity C-type centers, using ultrashort laser pulses of variable energy and exposure. The inscribed photoluminescent micromarks were characterized by FT-IR and optical transmission microspectroscopy, 3D-scanning confocal Raman, and photoluminescence microspectroscopy to visualize the laser-induced transformations both qualitatively and quantitatively, in order to estimate the NV-center productivity characteristics.

This research was funded by Russian Science Foundation (grant number 21-79-30063).

REFERENCES

[1] C. Bradac, W. Gao, J. Forneris, M.E. Trusheim, I. Aharonovich, Nat. Commun., 10, 5625, (2019).
[2] Y.C. Chen, P.S. Salter, S. Knauer, L. Weng, A.C. Frangeskou, C.J. Stephen, S.N. Ishmael, P.R. Dolan, S. Johnson, B.L. Green, G.W. Morley, M.E. Newton, J.G. Rarity, M.J. Booth and J.M. Smith, Nat. Photonics, 11, 77–80, (2017).

Mid-infrared single-cycle light bullets

A. E. Dormidonov[1], E. D. Zaloznaya[1,2], V. O. Kompanets[3] and S. V. Chekalin[3]

[1] Dukhov Automatics Research Institute, 127055, Moscow, Russia;
[2] Lomonosov Moscow State University, Moscow, Russia;
[3] Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow, Russia
e-mail: dormidonov@gmail.com

A retrospective analysis of the development of concepts in nonlinear optics is presented: from beam self-focusing and pulse filamentation to light bullets – wave packets extremely compressed in space and time during laser light propagation in transparent dielectric [1]. Light bullets result from coupled processes of wave packet self-focusing in space and self-compression in time, which occur at an anomalous group velocity dispersion in the bulk of a third-order nonlinear medium under laser plasma generation conditions [2-4]. A light bullet is characterized by strong spatiotemporal optical field localization: the spatial and temporal scales of the localization region are a few wavelengths and one or two periods of optical oscillation. Carrier-envelope phase shift during propagation of a near single-cycle light bullet causes synchronous oscillations of its spatial, temporal and energy parameters [5]. It causes periodical modulation of trace induced by light bullet in the medium (plasma channel or color centers structure). Such a dashed trace can be used to estimate the duration of a near single-cycle pulses [6]. Filamentation of mid-infrared light is accompanied by the generation of broadband supercontinuum, whose spectrum extends to the visible range and includes spectral components of the third, fifth, and subsequent odd harmonics of the fundamental frequency in the case of third-order nonlinearity and a continuous spectrum due to self-phase modulation. In the visible region of light bullet supercontinuum, an isolated anti-Stokes wing, separated by a broad minimum from the carrier wavelength band, is formed due to constructive interference of broadband light field [7]. The spectral maximum of the anti-Stokes band of the light bullet supercontinuum depends on linear parameters of the medium and can be determined by a simple dispersion equation [8].

REFERENCES

[1] Kandidov V.P., Zaloznaya E.D., Dormidonov A.E. et al., Quantum Electron., 52, 233 (2022).
[2] Silberberg Y., Optics Letters, 15, 1282 (1990).
[3] Bergé L., Skupin S. Physical Review Letters, 100, 113902 (2008).
[4] Smetanina E.O., Kompanets V.O., Dormidonov A.E. et al., Laser Phys. Lett., 10, 105401 (2013).
[5] Zaloznaya E.D., Kompanets V.O. et al., Laser Phys. Lett., 19, 075402 (2022).
[6] Dormidonov A.E., Zaloznaya E.D., Kompanets V.O. et al., JETP Letters, 116, 436 (2022).
[7] Garejev N., Tamošauskas G., Dubietis A. Journal of the Optical Society of America B, 34, 88 (2017).
[8] Dormidonov A.E., Kompanets V.O., Chekalin S.V., Kandidov V.P. JETP Letters, 104, 175 (2016).

Inscription of photoluminescent microbits in dielectric crystals by ultrashort laser pulses for archival optical storage

S. I. Kudryashov, P. A. Danilov, N. A. Smirnov, E. V. Kuzmin, A. E. Rupasov, R. A. Khmelnitsky, G. K. Krasin, I. N. Mushkarina and A. V. Gorevoy

P.N. Lebedev Physical Institute, Moscow, Russia
e-mail: a.gorevoy@lebedev.ru

3D optical memory storage in bulk transparent media is highly promising and competitive to the previous 2D surface laser patterning disks due to significantly higher capacity and potential resilience to radiation, humidity and thermal shocks. We report a brief experimental evaluation study of natural diamond, LiF and CaF_2 crystals as optical platforms for microscale photoluminescent encoding by ultrashort-pulse lasers for micromechanically-accessed archival optical storage.

The recording of photoluminescent microbits inside micromechanically positioned bulk natural diamond, LiF and CaF_2 crystals was performed in sub-filamentation (geometrical focusing) regime by 525 nm 0.2 ps laser pulses focused by 0.65 NA micro-objective for various values of pulse energy and exposure. The resulting micromarks were visualized by 3D scanning confocal photoluminescence microscopy as conglomerates of photo-induced color centers and tested regarding their spatial resolution and thermal stability via high-temperature annealing. Minimal lateral and longitudinal microbit separations, enabling their robust optical readout, were measured in LiF crystal as 2 and 15 micrometers, respectively. These results can be further improved by more elaborate focusing systems for laser writing and readout. The thermal stability tests revealed that the produced photoluminescent color centers could be easily annealed in the fluorides at moderate temperatures of 300°C, comparing to the relatively robust color (NV) centers in the diamond, persisting even at rather elevated temperatures up to 1200°C.

These findings highlight a way to novel optomechanical memory storage platforms, utilizing ultrashort-pulse laser inscription of photoluminescent microbits as carriers of archival memory.

This research was supported by Russian Science Foundation (grant № 21-79-30063), `https://rscf.ru/en/project/21-79-30063/`.

Numerical aperture dependent formation of plasma channels induced by ultrashort laser pulses in bulk of synthetic diamond

Y. S. Gulina[1,2*], J. Zhu [1], G. K. Krasin[1], E.V. Kuzmin[1] and S. I. Kudryashov[1]

[1] P.N. Lebedev Physical Institute, Moscow, Russia;
[2] Bauman Moscow State Technical University, Moscow 105005, Russia
e-mail: gulinays@lebedev.ru

Ultrashort pulse lasers, characterized by short pulse durations and high peak intensities, offer unprecedented precision and control for laser-induced modifications in bulk of materials, revolutionizing such fields as precise microfabrication [1], optical communication [2], and biomedical imaging [3]. Therefore, the investigation of ultrafast light-matter interactions, particularly those involving femtosecond laser pulses and dielectric materials is an area of great interest at present [4,5].

This research aims to investigate the relationship between the numerical aperture (NA) of focusing lens and parameters of luminous plasma channels induced by ultrashort laser pulses in bulk of synthetic diamond. Laser irradiation of HPHT diamond with ultrashort 1030-nm pulses at different NAs (NA=0.15-0.45) revealed strong dependence of size and position of the modified region on the used lens NA. It was shown that at loose focusing conditions, it is possible to significantly increase the length of the plasma channel with a slight increase in pulse power, while tight focusing allows to obtain more compact structures in the same range of used powers. Obtained results open up another degree of freedom in 3D processing in transparent dielectrics, allowing to vary shape and position if modified regions without changing the recording setup, but only by controlling the lens aperture, which seems very promising for industrial applications.

The reported study was supported by the grant of the Russian Science Foundation, project # 21-79-30063.

REFERENCES

[1] Sugioka, K.; Cheng, Y. Ultrafast Lasers—Reliable Tools for Advanced Materials Processing. Light: Science & Applications 2014, 3 (4), e149–e149. https://doi.org/10.1038/lsa.2014.30.

[2] Temprana, E.; Myslivets, E.; Kuo, B.-P.; Liu, L.; Ataie, V.; Alic, N.; Radic, S. Overcoming Kerr-Induced Capacity Limit in Optical Fiber Transmission. Science 2015, 348 (6242), 1445–1448. https://doi.org/10.1126/science.aab1781.

[3] Horton, N. G.; Wang, K.; Kobat, D.; Clark, C. G.; Wise, F. W.; Schaffer, C. B.; Xu, C. In Vivo Three-Photon Microscopy of Subcortical Structures within an Intact Mouse Brain. Nature photonics 2013, 7 (3), 205–209.

[4] Kudryashov, S. I.; Danilov, P. A.; Kuzmin, E. V.; Gulina, Y. S.; Rupasov, A. E.; Krasin, G. K.; Zubarev, I. G.; Levchenko, A. O.; Kovalev, M. S.; Pakholchuk, P. P. Pulse-Width-Dependent Critical Power for Self-Focusing of Ultrashort Laser Pulses in Bulk Dielectrics. Optics Letters 2022, 47 (14), 3487–3490. https://doi.org/10.1364/ol.462693.

[5] Krasin, G. K.; Gulina, Y. S.; Kuzmin, E. V.; Martovitskii, V. P.; Kudryashov, S. I. Polarization-Sensitive Nonlinear Optical Interaction of Ultrashort Laser Pulses with HPHT Diamond. In Photonics; Multidisciplinary Digital Publishing Institute, 2023; Vol. 10, p 106. https://doi.org/10.3390/photonics10020106.

Thermal conductivity of HPHT diamonds irradiated with electrons

A. V. Inyushkin[1], A. N. Taldenkov[1], D. A. Chernodubov[1], A. P. Yelisseyev[2] and V. G. Vins[3]

[1] National Research Center Kurchatov Institute, Moscow, Russia;
[2] V.S. Sobolev Institute of Geology and Mineralogy, Siberian branch of Russian Academy of Sciences, Novosibirsk, Russia;
[3] LLC VELMAN, Novosibirsk, Russia
e-mail: av_inyushkin@mail.ru

The influence of irradiation with 3 MeV electrons and subsequent high-temperature annealing on the thermal conductivity $\kappa(T)$ of pure and nitrogen-containing synthetic HPHT diamonds at temperatures from 5 to 410 K is studied. At each stage of the experiment, the optical absorption and photoluminescence spectra, magnetization and thermal conductivity were measured on plates from the diamond single crystals. Color centers and their concentration in different locations in the samples were determined from the optical spectra. The concentration of paramagnetic impurities in the samples was determined from the temperature and field dependencies of the paramagnetic magnetization. Thermal conductivity is suppressed by two orders of magnitude at temperatures from 35 to 50 K after irradiation to a fluence of 5×10^{18}cm^{-2}. Annealing at a temperature of 1800°C restored the thermal conductivity of diamond at moderate and high temperatures, but not at temperatures below 120 K. The influence of phonon focusing on thermal conductivity at low temperatures is estimated. The measured data on thermal conductivity were analyzed within the framework of the phenomenological Callaway model in order to understand the role of various phonon scattering processes and how it changes during irradiation and annealing.

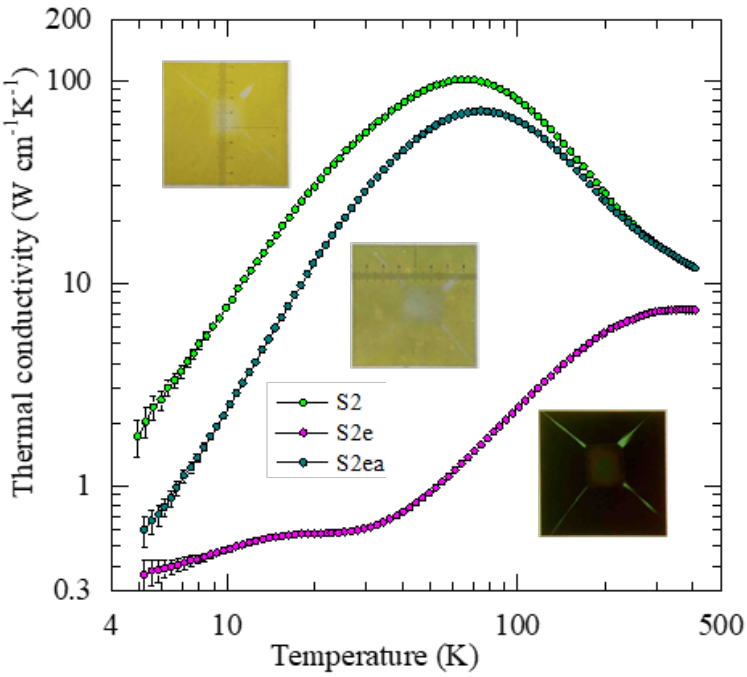


Figure 1: Temperature dependence of thermal conductivity for a diamond plate containing about 160 ppm impurity nitrogen atoms in the as-growth state. Data are given for the initial state (S2) irradiated with a dose of 5×10^{18}cm^{-2} and annealed at 1800°C for 10 minutes

A.V.I. and D.A.Ch. acknowledge support from the Russian Science Foundation (grant No. 23-29-00214) in the part of work related to thermal conductivity. A.P.Y. acknowledges support from the Institute of Geology and Mineralogy, Siberian Branch of Russian Academy of Sciences.

Confocal Raman scattering in the study of the impurity-defect structure of CVD diamond films

A. N. Kirichenko, N. B. Rodionov, A. G. Trapeznikov and V. P. Yartsev

Institution Project center ITER, Moscow, Russian Federation
e-mail: a.kirichenko@iterrf.ru

Raman spectroscopy is widely used in the study of carbon materials, and in particular, diamond. Also it is a diagnostic tool for the evaluation of diamond and chemical vapor deposited (CVD) diamond films. The technique is popular because each carbon allotrope displays a clearly identifiable Raman signature and it is non-destructive [1]. In addition, since diamond has good thermal stability and high thermal conductivity, sufficiently powerful lasers can be used to excite the Raman spectrum without of the sample destruction risk. This makes it possible to obtain a large number of spectra with a short exposure time.

This work presents the results of the polished growth surface studies the CVD diamond film as well as surface perpendicular to growth side of the sample after laser cutting and subsequent polishing by confocal Raman spectroscopy. The "Renishaw in Via Reflex" spectrometer (Renishow, UK) at backscattering geometry was used for the research. This spectrometer can provide automatic scan both the surface and the volume of the sample in the high confocality mode, followed by the two and three-dimensional maps construction.

The color maps revile the difference between the substrate material and the CVD diamond film. It is caused by different nature of impurities both in CVD and substrate.

Color maps are of practical importance: they allow both to clarify where the CVD diamond is located and to determine the thickness of the CVD diamond film. Also a transition layer is noticeable, which differs in the position of the main diamond line. Using photoluminescence spectroscopy, it was found that the transition layer has differences with the CVD diamond film in terms of the content of nitrogen-vacancy and silicon–vacancy complexes.

It should be noted that the results of determining the thickness of the diamond film obtained by these methods differ somewhat: when scanning through the polished upper face from the side of the CVD layer, it is about 100 microns, and when scanning the polished face (which is a more accurate method) – 120 microns. But at the same time, qualitative results: the presence of a CVD diamond film, an assessment of its thickness, the presence of a transition layer can be obtained using either of these two methods.

Thus, the expediency of using a confocal spectrometer for complex optical studies of optically transparent materials through one of the transparent faces is shown by the example of the study of CVD diamond films. Which can be useful if it is impossible to obtain chips or slices that open the inside of the sample.

REFERENCES

[1] Bergman, L. & Nemanich, R. J. 1995 Raman and photoluminescence analysis of stress state and impurity distribution in diamond thin films. J. Appl. Phys. (78), 6709 (1995).

Variation of optical breakdown threshold in diamond irradiated by IR femtosecond pulses

T. V. Kononenko, K. K. Ashikkalieva, E. V. Zavedeev, V. G. Ralchenko and V. I. Konov

Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: taras.kononenko@nsc.gpi.ru

Ultrashort-pulse laser microstructuring of diamond crystal interior makes it possible to create various unique objects like buried electrodes, waveguides, photonic and hollow microstructures, which significantly expands the scope of advanced diamond applications. The initial point of the microstructuring procedure is a laser-induced optical breakdown at surface of diamond or inside its bulk. Therefore, the predictability and reproducibility of the breakdown process have a significant impact on the quality of the obtained microstructures.

During last decades substantial progress in understanding of laser-induced ionization/ recombination processes in diamond was achieved due to extensive theoretical and experimental studies. Particularly, effect of fundamental laser parameters (wavelength, pulsewidth, irradiation doze) on the optical breakdown threshold was studied. It was reported also that examined diamond crystals differ insignificantly in optical breakdown thresholds. However, according to our experience in the laser processing of diamond, the breakdown threshold values can vary greatly not only for different samples, but also for different regions within the same crystal [1]. This report summarizes the results of our systematic investigation of the problem and gives a new insight into the optical breakdown of diamond.

It has been shown that the experimental data on diamond breakdown threshold can be correctly compared with one another only if they are obtained under the same parameters of the laser caustics including diameter and position relative to the crystal surface. The bulk-related breakdown threshold was found to vary by almost two orders of magnitude for different single-crystal diamonds. The threshold variations are accompanied by specific changes in the graphitic patterns, which occur within the laser caustics under the optical breakdown due to local material modification (graphitization). The low-threshold breakdown of diamond seems to be initiated by certain structural defects assembled in micrometer-scale clusters. Spatial distribution of clusters is inhomogeneous and shows signs of self-organization.

This work was supported by the Russian Science Foundation (project no. 22-22-00055).

REFERENCES

[1] T. Kononenko, K. Ashikkalieva, V. Kononenko, A. Bol'shakov, V. Ral'chenko, V. Konov. Physics of Wave Phenomena Vol. 31, No. 2, P. 59–66 (2023).

Polarization-sensitive nonlinear optical interaction of femtosecond laser pulses with diamond

G. K. Krasin, Y. S. Gulina, E. V. Kuzmin, and S. I. Kudryashov

P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: krasingk@lebedev.ru

Polarization effects in crystalline materials arise due to the symmetry of the axes along which nonlinear optical interaction occurs. Another huge role is played by the fact that the band structure is usually inhomogeneous, which is especially critical for wide-gap crystals. And even with the same direction of the wave vector, completely different effects can be expected for axes of different symmetries. Research has proven that these effects are quite strong and there is a point in studying their influence. Thus, there are studies of the surface polarization sensitive effects, where of ablation craters on Si crystals changed drastically at different angles of the polarization azimuth [1], as well as surface ablation of sapphire depending on the plane [2]. For the bulk effects the angular dependence of the relative change of the light absorption coefficient in a cubic lattice crystal, and a face-centered cubic lattice were shown [3]. Plus, there is also a study, where the transmission of crystal quartz as a function of the laser polarization [4].

In this work we studied the effect of femtosecond laser pulses polarization on nonlinear optical interaction with a synthetic type IIA HPHT diamond [5]. The study was conducted via registration of the exciton photoluminescence at the right angle to the sample. Additionally the transmitted spectra were registered. It was noted that the at the onset of the filamentation process at relatively low intensities the photoluminescence yield rate is sensitive to the polarization azimuth, while at high intensities photoluminescence yield is weakly sensitive to the polarization azimuth. The obtained results open up new possibilities for crystals processing, allowing one to vary the spatial parameters of the modified regions by controlling just the wave plate, which seems very promising for various applications.

The reported study was supported by the grant of the Russian Science Foundation, project № 21-79-30063.

REFERENCES

[1] [1] L. Jiang, W. Han, X. Li, Q. Wang, F. Meng, Y. Lu, Opt. Lett. 39, 3114 (2014).
[2] Q. Wen, P. Zhang, G. Cheng, F. Jiang, X. Lu, Ceram. Int. 45(17B), 23501 (2019).
[3] N. F. Perel'man, Zh. Eksp. Teor. Fiz. 73, 1526 (1977).
[4] M. Gertsvolf, et al. Phys. Rev. Lett. 101, 243001 (2008).
[5] G.K. Krasin, Y.S. Gulina, E.V. Kuzmin, V.P. Martovitskii, S.I. Kudryashov, Photonics, 10, 106 (2023).

Spectroscopic study of synthetic diamond co-doped with boron and nitrogen

I. N. Kupriyanov[1], Yu. N. Palyanov[1,2], Yu. M. Borzdov[1] and A. F. Khokhryakov[1,2]

[1] V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia;
[2] Novosibirsk State University, Novosibirsk, Russia
e-mail: spectra@igm.nsc.ru

Nitrogen and boron are the two principal impurities in diamond, which determine most of its optical and electronic properties. To date a plethora of data has been gained concerning the properties and structure of defects related to nitrogen in type I diamonds and boron in type IIb diamonds. At the same time, much less is known about possible defect structures and properties of diamonds containing both nitrogen and boron impurities in significant concentrations. Since single substitutional nitrogen and boron are known to act in diamond as donors and acceptors, respectively, B-N-doped diamonds may represent a specific case of highly compensated semiconductor and possess unique optical properties. To address these questions we have undertaken a study on HPHT growth of diamond crystals co-doped with boron and nitrogen and their spectroscopic characterization by a suite of techniques including FTIR, PL and UV-Vis absorption.

We found that depending on the solvent-catalyst composition and amount of boron addition the color of the produced diamond crystals varied from yellow to dark blue or almost black. The morphology of the crystals was significantly modified by particular development of the 113 faces. A pronounced growth sector dependence of incorporation of B and N impurities was observed. A remarkable feature of the spectra corresponding to the case of partial compensation of boron acceptors is weak appearance or complete absence of absorption peaks due to transitions to excited states of the boron bound hole. It is possible that relatively high concentrations of ionized donors (N^+) and acceptors (B^-) have caused these peaks to be broadened out via e.g. random electric fields. An absorption feature at 1263 cm^{-1} was found in the IR spectra and tentatively attributed to compensated boron (B^-). Under electron beam excitation (CL), the crystals emitted very bright greenish-yellow luminescence assigned to the donor-acceptor pair recombination. The effect of HPHT treatment on the transformation of defects in B-N doped diamonds was examined and the results will be presented at the conference.

Work is done on the state assignment of IGM SB RAS (No. 122041400159-3).

Photoluminescence microspectroscopy of plastic deformations in natural pink diamonds

E. V. Kuzmin, E. N. Rimskaya, P. A. Danilov and S I. Kudryashov

P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: kuzmine@lebedev.ru

Under ultrashort-laser irradiation, natural diamonds react differently due to wide variety defects existing in the crystal. It can be internal lattice defects, inclusions, impurities which together and separately have a significant impact on the result of exposure [1]. One of the most dramatic defects are plastic deformations, which pass through the entire crystal and significantly affect the impurities. Due to its growth conditions, pink diamonds are perfect choice for study of plastic deformations and redistribution of related optical centers [2].

In this work, a natural pink IaAB diamond of type IaAB is studied using two-wavelength three-dimensional Raman luminescence microspectroscopy. The types and concentrations of optically active nitrogen centers both on the surface and in the bulk of the crystal are studied.

It has been shown that combinations of nitrogen defects that determine the properties of diamond are sensitive to lattice stresses and are concentrated in plastic deformation zones. The possibility of laser action on nitrogen defects located both in the PD zone and in the intact diamond lattice is shown.

This work was supported by the Russian Science Foundation (Grant No. 21-79-30063).

REFERENCES

[1] Khmelnitsky, R.A. Introduction to Diamond Gemology [in Russian]; Moscow, (2021).
[2] Kudryashov S. I. et al. Advanced Mapping of Optically-Blind and Optically-Active Nitrogen Chemical Impurities in Natural Diamonds; Chemosensors. Vol. 11. Is. 1. No 24, (2023).

Exploring the dynamics of laser-induced phase transitions in dielectrics and semiconductors through phonon spectroscopy

E. I. Mareev[1] and F. V. Potemkin[2]

[1] FSRC "Crystallography and photonics" RAS, Moscow, Russia;
[2] Faculty of Physics, M.V. Lomonosov Moscow State University Moscow, Russia
e-mail: mareev.evgeniy@physics.msu.ru, potemkin@physics.msu.ru

The emergence of new MEGA facilities has paved the way for new avenues in experimental high-pressure physics, enabling the investigation of condensed matter dynamics with femtosecond precision. The rapid compression induced by laser-induced shock impact triggers a cascade of high-pressure phase transitions. Despite extensive research spanning several decades, a comprehensive understanding of the lattice response to such compression remains elusive. Furthermore, in the dynamic case, where loading is in contrast to quasi-static conditions, the thresholds of phase transitions can undergo significant changes. In this study, we employed the third harmonic pump-probe technique in conjunction with molecular dynamics simulations to investigate the dynamics of ultrafast laser-induced phase transitions in dielectrics (MgF_2) and semiconductors (Si) through an all-optical experiment [1]. By tightly focusing a femtosecond laser pulse into the transparent medium, sub-TPa shock waves and terahertz (THz) coherent phonons were generated. The propagation of the laser-induced shock wave resulted in substantial atomic displacements within the lattice, leading to phase transitions. The phase transitions P42/mnm ⇒ Pa-3 ⇒ Pnam in magnesium fluoride and Si-X ⇒Si-VII⇒Si-XI⇒Si-II⇒Si-I in Si were observed as a spectral change in coherent phonons, signifying a cascade of ultrafast laser-induced phase transitions [2]. Each phase transition exhibited a characteristic time of 5-10 ps, with a corresponding phase lifetime ranging from 40-60 ps. This research contributes to advancing our understanding of condensed matter dynamics under extreme compression conditions and opens new possibilities for studying high-pressure physics with femtosecond resolution.

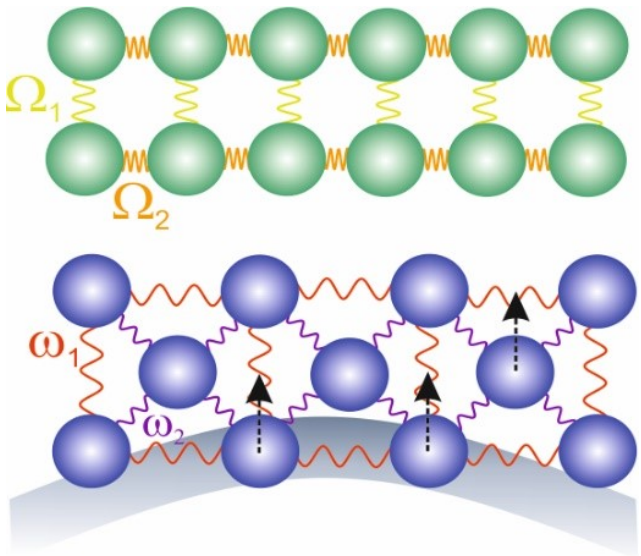


Figure 1: Schematic of pressure induced phase transition: shock wave shifts atoms in lattice, the phase transition is occurred, the phonon spectrum is changed

The investigation is supported by Russian Science Foundation (Project No. 23-73-00039).

REFERENCES

[1] E. I. Mareev and F.V. Potemkin, Scientific Reports vol. 12, p. 6621, (2022).
[2] E. I. Mareev, N. N. Obydennov, and F. V. Potemkin, Photonics, vol. 10, p. 380, (2023).

Impact of ultrashort near-UV laser pulses on diamonds

P. P. Pakholchuk, N. A. Smirnov, P. A. Danilov, and S. I. Kudryashov

P.N. Lebedev Physical Institute, Moscow, Russia

e-mail: petr.pakholchuk@mail.ru

Synthetic diamonds are widely used nowadays. It take place in the creation of single-photon sources, micro-optical and microfluidic devices and other applications [1]. Ultrashort laser pulses are used to modify diamonds [1, 2].

In this work, a colorless synthetic diamonds were exposed in its bulkwith a different number of pulses of 0,3-ps, 405-nm laser pulses focused by 0,65-NA micro-objective. The resulting arrays of spots spots produced at variable laser exposure and pulse energy was characterized by Raman spectroscopy.

The reported study was supported by Russian Science Foundation, grant number 21-79-300633.

REFERENCES

[1] S. I. Kudryashov, V. G. Vins et al., Carbon 201, 399-407 (2023).
[2] S. Kudryashov, P. Danilov et al., Micromachines 14 (7), 1397 (2023).

Natural diamond graphitization research

D. A. Pomazkin[1],P. A. Danilov[1], S. I. Kudryashov[1], I.V. Ermolayev[2], A.I. Smolsky[2], I.D. Matyaev[2]

[1] P.N. Lebedev Physical institute of the Russian Academy of Sciences, Moscow, Russia;
[2] Bauman Moscow State Technical University, Moscow, Russia
e-mail: dpomazkin@lebedev.ru

Laser induced graphitization is still little-studied question. This phenomenon can be as useful tool for diamond charge detectors as harmful for diamond laser marking. It is still unknown the graphitization laser energy of certain diamond and diamond breakdown properties dependence of laser pulse energy such as residual stress spatial and pressure ranges. There are some approaches to analyze diamond stress such as crossed polarizers and Raman peak shifting [1-3]. In this work, laser induced natural diamond graphitization in the bulk of two colored areas with various laser pulse energies was studied. Breakdown probability distribution on laser pulse energy was obtained. Residual stress was investigated with Raman peak shifting and splitting, Raman properties (peak position, amplitude, FWHM) dependencies on energy on different distances with breakdown epicenter were plotted. Profiles of Raman properties along tension and compression directions were also obtained for different energies.

This research was funded by Russian Science Foundation, grant number 21-79-30063 (https://rscf.ru/en/project/21-79-30063/).

REFERENCES

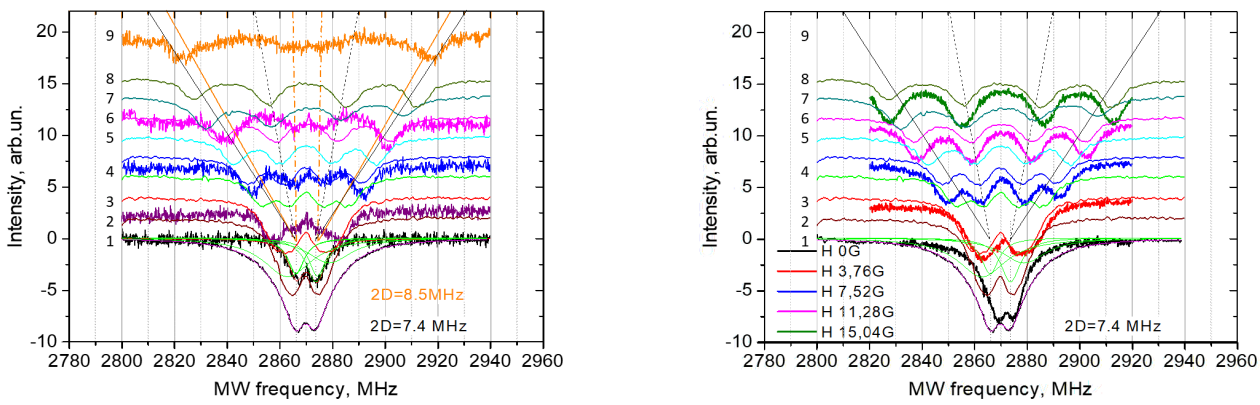
[1] K. H. Chen, Y. L. Lai, J. C. Lin, K. J. Song, L. C. Chen, C. Y. Huang, Diamond and related materials 4(4), 460-463 (1995).
[2] S. Salvatori, M. C. Rossi, G. Conte, T. V. Kononenko, M. Komlenok, A. Khomich, V. Ralchenko, V. Konov, G. Provatas, M. Jaksic, IEEE Sensors Journal 19(24), 11908-11917 (2019).
[3] E. Anastassakis, Journal of applied physics 86(1), 249-258 (1999).

NV centers in (111) diamond nanostructures after Ga^+ focused ion beam and chemical etching

V. P. Popov[1], S. N. Podlesny[1], V. A. Antonov[1], I. A. Kartashov[1,3,4] and Yu. N. Palyanov[2,3]

[1] A. V. Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia;
[2] V. S. Sobolev Institute of Geology and Mineralogy SB RAS, Novosibirsk, Russia;
[3] Novosibirsk National Research State University, Novosibirsk, Russia;
[4] Novosibirsk State Technical University, Novosibirsk, Russia
e-mail: popov@isp.nsc.ru

The photoluminescence (PL) spectral characteristics and optically detectable magnetic resonance (ODMR) are investigated for negatively charged nitrogen-vacancy (NV^-) centers (0.5-1.0 ppm) in the 50-300 nm nanolayers and nanopillars. They were formed on the (111) synthetic Ib and IIa diamond plates formed H^+ or N^+ implantation and annealing, respectively, with followed Ga^+ focused ion beam (FIB) nanostructuring. The lower spin sublevels were populated by green laser with the microwave radiation in 0-20 G magnetic fields (Fig.1). Both a significant decrease in the gyromagnetic ratio and luminescence quenching from the NV^- centers inclined to the nanopillar axis were revealed due to residual defects and stresses created by them during the FIB processing.



(a) (b)

Figure 1: (a) Normalized ODMR spectra of NV centers induced by protons with the energy of 36 keV (H_2^+, 72 keV, $3\times10^{16}cm^{-2}$) under continuous pumping by a focused laser beam with the 2 μm diameter at the wavelength of $\lambda = 532$ nm in the Ib diamond nanolayer (thin) and nanopillars (thick lines) in the magnetic field normal to the surface with a strength of 0– 20 G after FIB processing; (b) the same, but after chemical etching in aqua regis. The spectra are shifted vertically by the amount equal to the magnetic induction measured in the Gauss units.

The smallest nanostructures suffer the highest PL and ODMR perturbation due to the 40 nm amorphous supersaturated by Ga atoms subsurface layer (a-C:Ga). The chemical removing of this layer by aqua regis return the PL and ODMR spectra to the unperturbed characteristics, but with the small residual stresses in nanopillars (Fig.1b)

Impact of ultrashort mid-IR laser pulses on diamonds

N. A. Smirnov[1], P. A. Danilov[1], S. I. Kudryashov[1], N. I. Busleev[1], V. G. Vins[2] and P. P. Pakholchuk[1]

[1] P.N. Lebedev Physical Institute, Moscow, Russia;
[2] LLC VELMAN, Novosibirsk, Russia
e-mail: cna1992@mail.ru

The processing of materials by ultrashort laser pulses with a long wavelength of the near (0.75 - 3 μm) and mid-IR (3-8 μm) has great potential for processing materials that have weak absorption in the visible region of the spectrum (diamond, glass, sapphire polymers), but there are strong absorption bands in the IR region, which allows selective modification of materials. This paper presents the results of the impact of focused (NA$\sim$0.28) ultrashort laser pulses ($\sim$200 fs) with a laser pulse repetition rate of 10 kHz on a red diamond synthesized under high pressure and high temperature (HPHT) in the two-phonon absorption region (1650- 2665 cm^{-1}). The irradiated region was characterized by Raman spectroscopy and FTIR spectroscopy.

This work was supported by Russian Science Foundation (grant # 21-79-30063)

REFERENCES

[1] P. A. Zhokhov, A. M. Zheltikov. In Nonlinear Optics and Applications XI, Vol. 11026, pp. 1102603, (2019).

Section 6: Ultrafast optical technologies and nonlinear optical phenomena

Section Co-chairs:

Igor Kinyaevskiy, e-mail: kinyaevskiyio@lebedev.ru
(P.N. Lebedev Physical Institute, Russia)
Fedor Potemkin, e-mail: potemkin@physics.msu.ru
(Lomonosov Moscow State University, Russia)

Program committee:

Valery Kovalev
(P.N. Lebedev Physical Institute, Russia)

Leonid Seleznev
(P.N. Lebedev Physical Institute, Russia)

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

Cherenkov terahertz emission from a DKDP crystal

N. A. Abramovsky[1], S. B. Bodrov[1,2], S. N. Belyaev[2], A. P. Prohorov[2], A. N. Stepanov[2] and M. I. Bakunov[1]

[1] University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[2] Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, Russia
e-mail: bakunov@rf.unn.ru

KDP and DKDP crystals are widely used in nonlinear optics as harmonic generators. They were not, however, tested as terahertz generators, despite their relatively high values of the electro-optic coefficient ($r_{36} \sim 9$ and 24 pm/V, respectively). The drawbacks of large optical-terahertz velocity mismatch and strong terahertz absorption ($\sim$200 cm^{-1} at 1 THz [1]) in these crystals can be overcome by using the Cherenkov radiation scheme and surface-emitting geometry [2]. Here, we demonstrate it experimentally.

A 1 cm thick, 1.8 cm wide, and 1.4 cm long plate of DKDP (96% deuteration), attached to a Si prism [Fig. 1(a)], was used in the experiments. Ti:sapphire laser radiation (800 nm, 60 fs, 1 kHz) was focused by a cylindrical lens to a line-like focal spot (30 μm wide and 6.6 mm long) on the entrance facet of the DKDP plate. The nonlinear polarization induced in the crystal via optical rectification generated a wedge of Cherenkov radiation, which was emitted to free space through the Si prism [24° apex angle, Fig. 1(a)]. The radiation was collected by a parabolic mirror and focused to a Golay cell (energy measurement) or 1 mm thick ZnTe crystal (waveform measurement). To minimize the propagation distance of terahertz radiation in absorptive DKDP, the laser beam was directed at a small angle α to the DKDP-Si interface [Fig. 1(a)]. The optimal experimental value is $\alpha \approx 1°$ [Fig. 1(a)].

The optical-to-terahertz conversion efficiency saturates at $(3-7) \times 10^{-6}$ for the pump pulse energies 150-250 μJ [Fig. 1(b)]. The electro-optic sampling signal reaches $dI/I \sim 0.1$ [Fig. 1(c)]. The spectrum extends to 4 THz [Fig. 1(d)]. Thus, DKDP may be used as a generator crystal for THz-TDS.

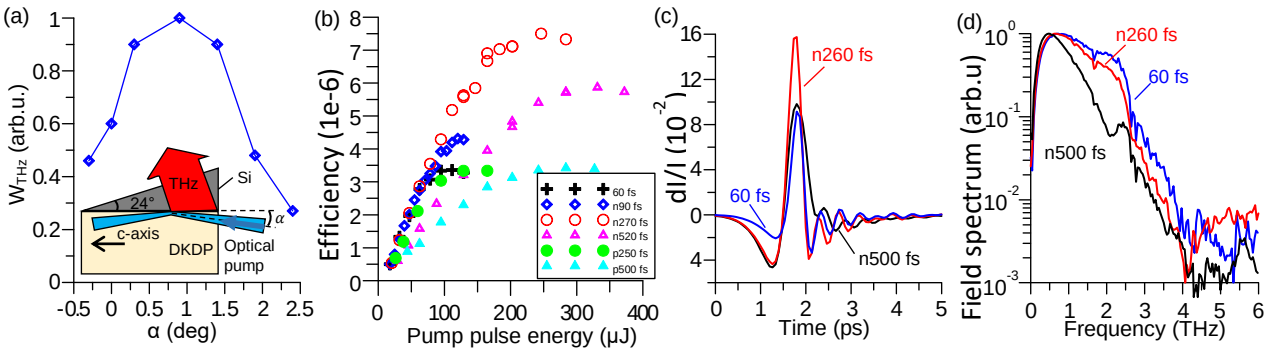


Figure 1: (a) Terahertz energy vs α. Inset: generation scheme. (b) Conversion efficiency vs the pump pulse energy for different pump pulse durations ("n" and "p" indicate negative and positive chirps). (c) Terahertz waveforms and (d) spectra for different pump pulse durations.

The work was supported by the Ministry of Science and Higher Education of the Russian Federation (0729-2020-0035).

REFERENCES

[1] P. Mounaix, L. Sarger, J. P. Caumes, and E. Freysz, Opt. Commun. **242**, 631, (2004).
[2] B. N. Carnio, O. Moutanabbir, and A. Y. Elezzabi, Laser Photon. Rev. **17**, 2200138 (2023).

Synchronously pumped ultrafast Cr:Forsterite oscillator

V. M. Alibaeva, A. V. Pushkin and F. V. Potemkin

Faculty of physics, Lomonosov Moscow State University, Moscow, Russia
e-mail: alibaeva.vm20@physics.msu.ru

Ultrashort laser pulse sources based on Cr:Forsterite active medium offer unique opportunities for a wide class of optical technologies [1]. In particular, such lasers make it possible to achieve high resolution at a high rate of imaging biological tissues, since the scattering and absorption of light in them at a wavelength of 1240 nm is significantly reduced compared to 800 nm (central wavelength Ti:Sapphire) and 1064 nm (Nd:YAG) [2]. Cr:Forsterite is also used in nonlinear spectral microscopy due to the transparency at these wavelengths of most of the used materials. In addition to the above advantages, Cr:Forsterite has a wide absorption spectrum, due to which an ytterbium laser, Nd:YAG, Ti:Sapphire or a diode laser can be used as a pump [3].

In current work, femtosecond generation in the Cr:Forsterite laser synchronously pumped by an ytterbium ultrafast laser is considered. The synchronous pumping method provides the opportunity to synchronize laser pulses involved in nonlinear optical interaction to obtain pulses in mid-IR spectral range. Pumping with femtosecond pulses contributes to the automatic capture and retention by the laser of the repetition rate of pumping pulses due to the effective cross-phase modulation of collinearly propagating generation pulses and pumping pulses through the Cr:Forsterite crystal [4].

The aim of the work is to study femtosecond generation Synchronous pumping opens route for multispectral nonlinear processes, for instance, difference frequency generation in a nonlinear LGS crystal with high repetition rate mid-IR output at a wavelength of 6 μm without implementing complex synchronization schemes of sources. Such an injection source is promising for development powerful chirped pulse amplification systems based on iron doped chalcogenide crystals, such as Fe:CdSe and Fe:CdTe [5-6].

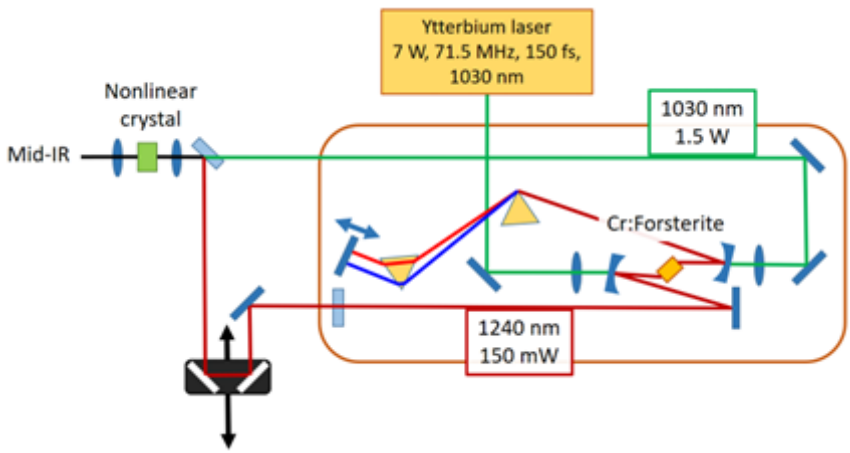


Figure 1: Synchronously pumped Cr:Forsterite oscillator with ytterbium ultrafast laser and difference frequency generation scheme with mid-IR output pulses.

REFERENCES

[1] A. Pushkin, E. Migal, D. Suleimanova, E. Mareev, F. Potemkin, "High-Power Solid-State Near- and Mid-IR Ultrafast Laser Sources for Strong-Field Science," Photonics, 9, 90, (2022).

[2] A. A. Ivanov, A. A. Voronin, A. A. Lanin, D. A. Sidorov-Biryukov, A. B. Fedotov, and A. M. Zheltikov, "Pulse-width-tunable 07 W mode-locked Cr: forsterite laser," Opt. Lett., vol. 39, no. 2, p. 205, (2014).

[3] V. V. Yakovlev, A. Ivanov, and V. Shcheslavskiy, "High-energy femtosecond Cr4+:forsterite oscillators and their applications in biomedical and material sciences," Appl. Phys. B, vol. 74, no. S1, pp. s145–s152, (2002).
[4] N.V. Didenko, A.V. Konyashchenko, D.A. Konyashchenko, P.V. Kostryukov, I.I. Kuritsyn, A.P. Lutsenko and A.O. Mavritskiy, "Ti:Sapphire laser synchronised with femtosecond Yb pump laser via nonlinear pulse coupling in Ti:Sapphire active medium," Quantum Electronics, 47(1): 7-13, (2017).
[5] E. Migal, A. Pushkin, B. Bravy, V. Gordienko, N. Minaev, A. Sirotkin, & F. Potemkin, "3.5-mJ 150-fs Fe: ZnSe hybrid mid-IR femtosecond laser at 4.4 μm for driving extreme nonlinear optics", Optics letters, 44(10): 2550-2553, (2019).
[6] A. Pushkin and F. Potemkin, "High-gain broadband laser amplification of mid-IR pulses in Fe:CdSe crystal at 5 μm with millijoule output energy and multigigawatt peak power," Opt. Lett., vol. 47, no. 22, p. 5762, (2022).

Terahertz generation by tilted-pulse-front laser pulses in the Cherenkov regime

S. B. Bodrov[1,2], N. A. Abramovsky[1] and M. I. Bakunov[1]

[1] University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[2] Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, Russia
e-mail: bakunov@rf.unn.ru

Optical rectification of ultrashort laser pulses in $LiNbO_3$ is an established method to generate strong terahertz fields in the low terahertz range. To overcome large optical-terahertz velocity mismatch in $LiNbO_3$, noncollinear excitation schemes, i.e., the tilted-pulse-front technique (TPFT) and Cherenkov radiation (CR) scheme, are used. The schemes have comparable efficiencies (∼0.1-1%) but operate at different pump pulse energies, i.e., ∼1 mJ for TPFT [1] and ∼10 μJ for CR [2]. As modern Yb-based lasers with high repetition rate and pulse energy up to a hundred of μJ appear, intermediate excitation regimes become relevant. Here, we experimentally study Cherenkov terahertz emission from tilted-pulse-front laser pulses (up to 100 μJ energy) in $LiNbO_3$.

A 0.5 mm thick and 13 mm long layer of $LiNbO_3$, attached to a Si prism [Fig. 1(a)], was used in the experiments. A Ti:sapphire laser system (800 nm, 60 fs, 1 kHz, 5 mJ) was used as a light source. The laser pulses were stretched to 120 fs by narrowing their spectrum with a bandpass filter. The laser beam width (a) was varied in one direction by a tunable cylindrical lens telescope. A diffraction grating and another telescope (F_1, F_2) were used to introduce a variable pulse-front tilt angle (ψ). Terahertz power was measured by a Golay cell. Terahertz spectrum was measured with terahertz band-pass filters.

Using tilted pulses with $\psi > 45°$ increases the conversion efficiency and energy of CR [Fig. 1(b)]. The spectrum is widest for $\psi = 63°$ [Fig. 1(c)]. For $\psi = 63°$, the efficiency drops with a but terahertz energy increases [Fig. 1(d)]. Thus, the combined TPFT-CR technique is promising for improving terahertz generation.

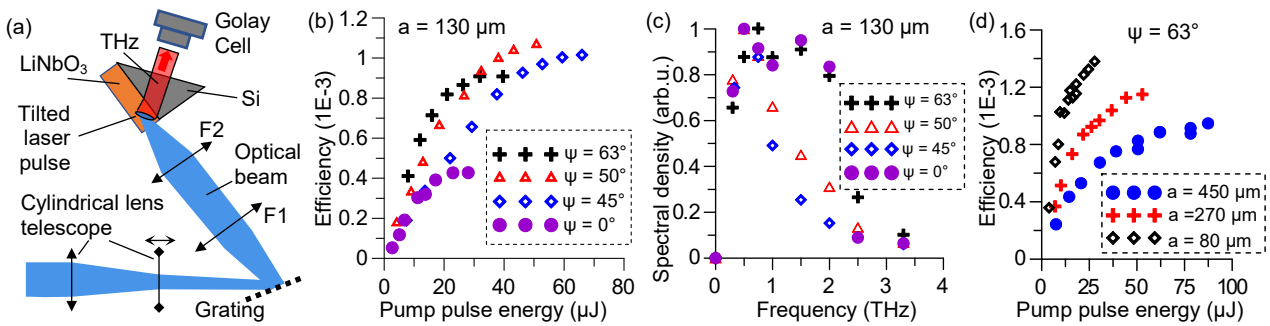


Figure 1: (a) Experimental setup. (b) Efficiency vs pump pulse energy for $a = 130$ μm and different ψ. (c) Terahertz spectrum for $a = 130$ μm and different ψ. (d) Efficiency vs pump pulse energy for $\psi = 63°$ and different a.

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

REFERENCES

[1] S. B. Bodrov, A. A. Murzanev, Y. A. Sergeev, Y. A. Malkov, and A. N. Stepanov, Appl. Phys. Lett. **103**, 251103 (2013).
[2] S. B. Bodrov, I. E. Ilyakov, B. V. Shishkin, and A. N. Stepanov, Appl. Phys. Lett. **100**, 201114 (2012).

Optical pump-THz probe spectroscopy as a non-destructive technique to study of semiconductors ultrafast carrier dynamics

V. V. Bulgakova[1], Yu. G. Goncharov[1], A. A. Ushakov[1], K. I. Zaitsev[1], M. G. Burdanova[2,3], M. I. Paukov[2], D. V. Krasnikov[4], A. G. Nasibulin[4] and S. V. Garnov[1]

[1] Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] Center for Photonics and 2D Materials, Moscow Institute of Physics and Technology, Dolgoprudny, Russia;
[3] Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Russia;
[4] Center for Photonic Science and Engineering, Skolkovo Institute of Science and Technology, Moscow, Russia
e-mail: vbulgakova573@gmail.com

Currently, optical pump-terahertz (THz) probe spectroscopy (OPTP), is being employed to gather insights into the rapid dynamics of photoexcited carriers in semiconductors and the nonlinear response in the far-infrared range. In OPTP experiments, an ultrafast laser pulse is used to generate free charge carriers, while broadband THz pulses (typically ranging from 0.3 to 3 THz, corresponding to photon energies from 1.2 meV to 12.4 meV) are utilized to probe the transmission of the sample. Unlike the usual optical pump-optical probe experiments, the OPTP technique allows observation of the evolution of the entire THz probe waveform as a function of the negative delay of the optical pump pulse. By utilizing Fourier analysis, it becomes possible to obtain the complete complex transmission spectrum, which encompasses both changes in amplitude and phase shifts. During OPTP experiments, the THz pulse is used to directly examine the extremely fast dynamics on picosecond or subpicosecond timescales. This means that the temporal evolution of the system under study involves frequency components that fall within or overlap with the THz range. As a result, frequency mixing can occur, leading to intriguing modifications in the THz waveform.

In this work, we proposed a fully automated OPTP scheme for measuring the dynamics of charge carriers. We employed OPTP spectroscopy as a tool to investigate the behavior of carriers and charge transport in several types of semiconductor structures, such as carbon nanotubes (CNTs) that underwent plasma treatment [1], iron doped zinc selenide, nitrogen doped diamonds. By utilizing OPTP spectroscopy, we were able to measure the lifetimes of carriers, which are determined by the trapping time at defect states. Through our measurements, we discovered both short and long lifetimes associated with these defects.

REFERENCES

[1] Tatiana N. Kurtukova, Daria S. Kopylova, Nikita I. Raginov, Eldar M. Khabushev, Ilya V. Novikov, Svetlana I. Serebrennikova, Dmitry V. Krasnikov, and Albert G. Nasibulin, Plasma-treated carbon nanotubes for fast infrared bolometers, Appl. Phys. Lett. 122, 093501 (2023).

Post-Compression of High-Energy Laser Pulses Due to Multipass Cells

V. V. Chvykov

Center for Extreme Ultraviolet Science and Technology, Colorado State University, USA
e-mail: vladimir.chvykov@colostate.edu

CPA laser systems have achieved extremely high-power levels, up to tens of petawatts [1], but two major challenges remain for widespread applications in science and industry. Firstly, increasing the pulse repetition rate and secondly, enhancing the energetic efficiency of the systems. Using the low quantum defect of the laser crystals such as Yb:YAG [2] for the increasing efficiency and average power with combination of a post-compression technique for the spectral broadening for growing the peak power due to pulse shortening it is possible to overwhelm both obstacles. Nevertheless, the existing methods of post-compression possess limited abilities for increasing the output pulse energy and/or repetition rate. A novel approach for the post-compression of high-energy laser pulses using the gas-filled multipass cells will be discussed in this report. To overcome the pulse energy limitation, we propose using flat mirrors for multipass cells (MPC) optical scheme instead of curved ones (like in Herriott-type MPC) [3]. This is made feasible by the reduction of beam divergence as the beam diameter increases, which is necessary with the pulse energy growing. For example, to avoid damage of the optical elements, a fluence below a few hundred mJ per cm^2 is required for the pulses of a few picoseconds. For energy of 10 J and fluence of 0.5J/cm2, a beam area of 20 cm2 is necessary. Calculations show that the beam diameter increases by only 0.1 % after 100 meters of beam propagation, which is negligible for a Gaussian beam profile. The results of proof-of-principal experiments of the application of suggested set up will be demonstrated [4]. Besides, the optimization of the beam propagation length by using the multistage system for the spectral broadening up to 100 times will be presented. And finally, the possibilities of increasing of the petawatt level peak power up to 10 times will be shown.

REFERENCES

[1] Fenxiang Wu, Jiabing Hu, Xingyan Liu, Zongxin Zhang, Peile Bai, Xinliang Wang, Yang Zhao, Xiaojun Yang, Yi Xu, Cheng Wang, Yuxin Leng and Ruxin Li, Dispersion management for a 100 PW level laser using a mismatched-grating compressor High Power Laser Science and Engineering,10, e38, (2022).

[2] Chi, H.; Wang, Y.; Davenport, A.; Menoni, C.S.; Rocca, J.J. "Demonstration of a kilowatt average power, 1 J, green laser", Opt. Lett, 45, 6803, (2020).

[3] Martin Kaumanns, Dmitrii Kormin, Thomas Nubbemeyer, Vladimir Pervak, Stefan Karsch, "Spectral broadening of 112 mJ, 1.3 ps pulses at 5 kHz in a LG10 multipass cell with compressibility to 37 fs", Optics Letters 46, 5, 929 (2021).

[4] Vladimir Savichev, Takil Tarkan, Jorge J. Rocca1, Vladimir Chvykov, "Novel Approach to Multipass Cells for Post-Compression of High-Energy Laser Pulses", Optics Letters, submitted (2023).

Self-induced second harmonic used as diagnostic of microfocus X-ray source size produced by tightly focused femtosecond fiber laser beam at copper target

A. A. Garmatina[1,2], E. I. Mareev[2], T. A. Semenov[1,2], Yu. S. Krivonosov[2], N. V. Minaev[2], V. E. Asadchikov[2] and V. M. Gordienko[2,3]

[1] National Research Centre «Kurchatov Institute», Moscow, Russia;
[2] FSRC "Crystallography and photonics" RAS, Moscow, Russia;
[3] Faculty of Physics M.V. Lomonosov Moscow State University, Moscow, Russia
e-mail: alga009@mail.ru

Radiographic phase-contrast imaging using X-rays is a valuable tool in various fields, including basic research, industry, materials science, and medical diagnostics. In this study, we implemented a novel approach for a microfocus X-ray laser-plasma source [1]. This system is based on a low-energy, high repetition rate femtosecond fiber laser (1030 nm, 280 fs, repetition rate 500kHz - 2,2 MHz, 20 W, puce energy up to 40 μJ) that is tightly focused (NA≈0.2, vacuum intensity I $\approx 10^{14}$ W/cm^2) on a rotated copper target. To achieve online control of the source size, we utilized backreflected second optical harmonic generated in the near-surface plasma by fiber laser. To observe microplasma a microscope was assembled, and a calibrated image was captured with CCD camera. Than profile of the beam was plotted and approximate with Gaussian curve (Fig. 1a). It has been observed that blowing with helium (compared to air) leads to an increase in the X ray yield and a decrease in the size of the X-ray source due to minimization of the ionization effect in the near-surface medium. We revealed that X ray yield is maximized at the level of 2x10^9 ph/s in 2π at 2 MHz, pulse energy 10 μJ. Measurements of the microplasma show that size slowly decrease with growing pulse repetition rate from 500 kHz to 2,2 MHz (and pulse energy from 40 μJ to 8 μJ) and constant power of 20 W (Fig.1b). Source size turns out to be about 8,5±1,5 microns at 1/e^2 level at optimal condition of 2 MHz, 10 μJ. These results fulfill the requirements for source size for phase contrast measurements.

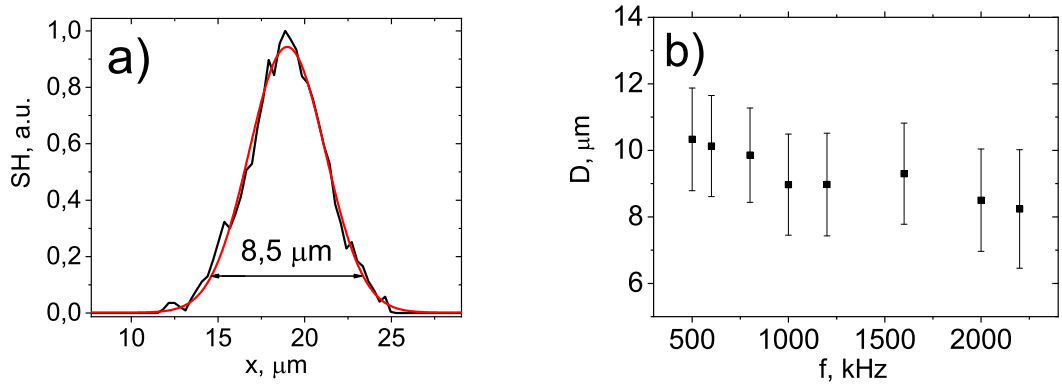


Figure 1: Second harmonic profile (SH) at 2 MHz, 20 W, 10 μJ (black line) and its Gaussian profile approximation (red line). Beam size is specified by power 1/e^2 (a), dependence of the beam diameter (1/e^2 level) on the pulse repetition rate at a fixed power of 20W (b)

The work was supported by the Ministry of Science and Higher Education under grant No. 075-15-2021-1362.

REFERENCES

[1] Garmatina, A.A., et al. Crystallogr. Rep., vol 67, pp. 1026–1033, (2022).

Long-wave infrared picosecond laser system based on $SrMoO_4$ Raman shifter and $LiGaS_2$ DFG converter

I. O. Kinyaevskiy, A. V. Koribut, L. V. Seleznev, Yu. M. Klimachev and A. A. Ionin

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
e-mail: kinyaevskiyio@lebedev.ru

Sources of ultrashort mid-IR laser pulses are under active developing because of their high demand for a lot of applications in fundamental and applied fields. Recently, the mid-IR laser source with 11 μm wavelength based on the femtosecond Ti:sapphire laser and successive frequency conversion in BaWO4 SRS crystal and $LiGaS_2$ DFG crystal was experimentally demonstrated in [1]. The choice of the Ti:sapphire laser is motivated by its well-developed technology and power scalability which can reach petawatts. It should be noted that SRS gain in crystals for femtosecond pulses is significantly reduced by a transient regime of SRS interaction and by an appearance of other undesirable nonlinear effects. Therefore, to reach reasonably high frequency conversion efficiency in [1], the chirped, temporally stretched to $\sim$200 ps, laser pulses were used [1]. The current research is aimed at energy and efficiency of this setup enhancement as well as at the study of additional aspects which were missed in [1].

In the current research the Ti:Sapphire laser emitted chirped, temporally stretched to $\sim$45 ps, pulses (transform-limited duration of 90fs), a $SrMoO_4$ SRS-active crystal and a $LiGaS_2$ DFG crystal were used. Under this setup, notable laser system improvements were realized: laser pulse of front-end laser was increased by two times, up to 12 μJ; energy efficiency of the SRS converter was increased by two times, up to 6 %; energy of the mid-IR pulse was increased by four times, up to 250 nJ. Also several important points were demonstrated which were missed in [1]: the main factor limiting SRS efficiency was nonlinear absorption; nonlinear absorption in DFG LiGaS2 was insignificant even at optical damage intensity; spectrum of the mid-IR pulse was not affected by phase-matching angle.

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

REFERENCES

[1] I.O. Kinyaevskiy, A.V. Koribut, Y.V. Grudtsyn, L.V. Seleznev, V.I. Kovalev, D.V. Pushkarev, E.E. Dunaeva, A.A. Ionin, Laser Physics Letters 19 (9), 095403 (2022).

Self-focusing and self-phase modulation of focused laser beam around critical power

A. V. Koribut, I. O. Kinyaevskiy, P. A. Danilov and S. I. Kudryashov

P.N. Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia
e-mail: andrew-koribut@yandex.ru

Propagation of ultrashort intensive laser pulse in media is associated with various nonlinear effects: self-focusing (SF), self-phase modulation (SPM), nonlinear absorption, stimulated Raman scattering (SRS), and others. Recently a constructive interference of SPM and SRS effects was demonstrated in $BaWO_4$ crystal [1,2]. These works were carried out with focused beams with power exceeding SF critical power. A properly description of this unusual effect requires studying the spectrum broadening due to SPM for focused laser beams. Therefore, the purpose of this work was an investigation of the spectrum broadening in fused silica due to SPM for focused beams (at the same experimental condition of [1,2]). Fused silica was chosen as a medium with a well known nature and values of non-linearities.

In the experiment second harmonic of laser complex Satsuma (Amplitude Systemes) was used with following parameters: pulse duration - 300 fs (FWHM), central wavelength - 515 nm, pulse repetition rate - 1 kHz, and pulse energy up to 1.8 μJ, which was varied by detuning second harmonic crystal. The laser beam was focused by a lens ($f = 40$ mm) into 10-mm fused silica sample. The linear focus was located at the sample center. The spectral and energy characteristics of the radiation transmitted through the sample were measured. In addition, a CCD-camera was installed behind the sample to observe changes in spatial distribution of radiation.

The dependence of the spectrum broadening on laser pulse energy was obtained. This dependence had three different areas: 1) linear (below 0.33 μJ); 2) non-linear (0.33 - 0.48 μJ); 3) close to linear with the initial slope angle (over 0.48 μJ). In the numerical model, it was found that the nonlinear region was associated with the radiation subfocusing due to Kerr-nonlinearity inside the sample resulting in increasing intensity without a nonlinear absorption and a plasma formation. At a radiation power above the critical power, a filament was formed. The numerical calculations showed that at pulse energy above 0.5 μJ the total spectrum broadening in the sample is determined primary by SPM in the filament.

Thus, it was found that self-focusing leads to a sharp spectrum broadening at powers of 0.7 – 1 of the SF critical power, which is associated with radiation subfocusing in the absence of nonlinear absorption. When the power exceeds the SF critical one, the spectrum broadening is close to linear with a slope corresponding to the linear case of propagation.

The study was supported by the Russian Science Foundation, Grant 22-79-10068.

REFERENCES

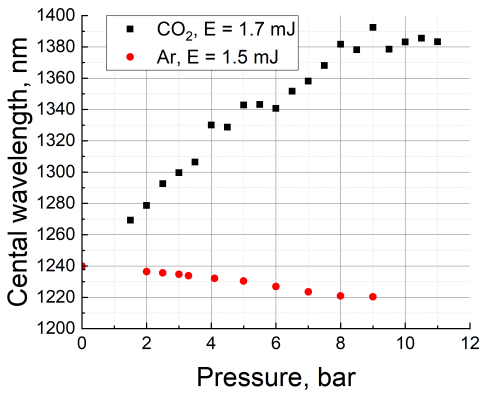
[1] I.O. Kinyaevskiy, V.I. Kovalev, P.A. Danilov, N.A. Smirnov, S.I. Kudryashov, L.V. Seleznev, E.E. Dunaeva, A.A. Ionin, Optics Letters, 45 (8), 2160-2163 (2020).
[2] I.O. Kinyaevskiy, V.I. Kovalev, P.A. Danilov, N.A. Smirnov, S.I. Kudryashov, A.V. Koribut, A.A. Ionin, Chinese Optics Letters, 21 (3), 031902 (2022).

Transformation of a linearly polarized high harmonic radiation into a circularly polarized radiation in neon-like X-ray laser modulated by an IR field

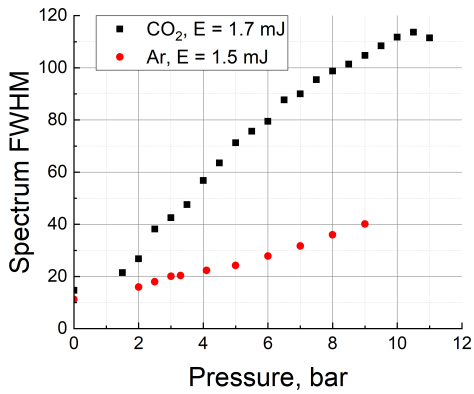
E. A. Lobushkin, M. M. Lunev, B. V. Rumiantsevand F. V. Potemkin

Faculty of physics, M. V. Lomonosov Moscow State University, Moscow, Russian Federation
e-mail: lobushkin.ea20@physics.msu.ru

Generation of ultrashort few-cycle laser pulses in the near and mid-IR spectral range with a multi-gigawatt power level is of interest for further generation of coherent ultraviolet and soft x-ray radiation with attosecond pulse duration [1]. But the problem is that obtaining of such emission is difficult to implement by direct laser generation in laser cavity due to the limited gain bandwidth. Thus the main goal of the work was to control the spectral and temporal properties of the laser radiation of the Cr:Forsterite (Cr:F) system (wavelength is 1.24 μm, pulse duration is 100 fs (FWHM), energy is up to 3.5 mJ) based on the self-phase modulation (SPM) during the nonlinear propagation of laser radiation in the extended media (gas). Macroscopic nonlinearity of the gas was controlled by changing the gas pressure. In the experiment dense (1-10 bar) atomic argon (Ar) and molecular carbon dioxide (CO_2) were used as a medium. Usage of both types of gases allowed addi-tionally control the SPM process due to the different nature of the nonlinear response in these gases [2].



(a) Fig 1. Dependence of the central wavelength on the gas pressure.



(b) Fig 2. Dependence of the spectrum FWHM on the gas pressure.

A series of experiments aimed to demonstrate the controlled changes in spectral and temporal properties of pulses of Cr:F laser system was conducted, its results was compared with PyNLO-based simulations [3]. It was shown (fig. 1, fig. 2), that spectrum broadening in CO_2 is more effi-cient in comparison with Ar due to the Raman response of molecular system. The conducted com-puter simulation was proved to be valid so it made it possible predict experimental results under giv-en initial parameters. The use of SPM in dense gases allowed to broad the spectrum in 3.3 and 8 times that corresponds to the bandwidth-limited pulse duration at the level of 30 fs and 13 fs (7.3 and 3.3 field cycles) for Ar and CO2 respectively. In case of Ar, the compensation of the induced chirp by the chirped mirrors allowed to obtain laser pulse with duration of 28 fs experimentally. This work was supported by the RSF grant #20-19-00148. Rumiantesev B.V. is the scholar of the foundation for the advancement of theoretical physics and mathematics "BASIS".

I.R.Kh. and V.A.A. acknowledge support by the Russian Science Foundation (grant No. 22-12-00389); O.K. appreciates support by the National Science Foundation (grant No. PHY-2012194).

REFERENCES
[1] T. Popmintchev, M.-C. Chen, P. Arpin, M. M. Murnane, and H. C. Kapteyn, 'The attosecond nonlinear optics of bright coherent X-ray generation', Nature Photon (12), 822–832 (2010).
[2] E. Migal, A. Pushkin, N. Minaev, B. Bravy, and F. Potemkin, 'Control of spectral shift, broad-ening, and pulse compression during mid-IR self-guiding in high-pressure gases and their mixtures', Opt. Lett. (4), 985 (2022).
[3] J. Hult, 'A Fourth-Order Runge–Kutta in the Interaction Picture Method for Simulating Super-continuum Generation in Optical Fibers', J. Lightwave Technol. (12), 3770–3775 (2007).

Low-order harmonic generation in an argon gas jet: numerical solution

K. V. Lvov and S. Yu. Stremoukhov

Lomonosov Moscow State University, Moscow, Russia
e-mail: lvov.kv14@physics.msu.ru

The generation of harmonics resulting from the interaction of femtosecond laser radiation with matter has been studied for many years in gas media [1–3], plasma media [4–5], and solids [6–7]. Phase matching of harmonics is sensitive to the generation parameters: the composition of the gaseous medium, its length and pressure, and the focusing conditions. In addition, an increase in the intensity of laser radiation, motivated by an increase in the harmonic energy, leads to undesirable nonlinear additions to the mismatch of the pump and harmonic wave vectors: self-phase modulation, defocusing in the emerging plasma. Determining the optimal conditions for generating harmonics and studying the features of phase matching is an important theoretical task, which is solved in close context with experimental studies.

In this paper, a theoretical study of the dependence of the energy of the 5th harmonic on the pressure of a gas jet is carried out and the features of the angular distribution of harmonic radiation are discussed.

The intensity distribution along the laser radiation propagation axis was calculated using the unidirectional pulse propagation equation (UPPE) [8]. Dynamics of free-carriers is calculated using a single-rate equation consisting of only the photoionization term in the context of Keldysh theory [9].

In numerical calculations, we used Gaussian laser pulses with a duration of 160 fs, a wavelength $\lambda = 4.5$ μm, and an energy of 1.6 mJ. The radiation was focused using a converging lens with a focal length f = 150 mm (the confocal parameter was b = 7.2 mm) into the middle of an argon jet with a width L = 7 mm and a pressure from 1 to 16 bar. The intensity of laser radiation in the waist was 10^{14} W/cm^2. The resulting distribution of laser radiation intensity on the propagation axis for different pressures of the gas jet is shown in Fig. 1a.

A high-intensity laser field of 10^{14} W/cm^2, falling into an argon jet, immediately creates an electron plasma with a density $\rho = 0.003\rho_{\mathrm{at}}$, which affects the noticeable absorption of laser radiation at the beginning of propagation. Since the nonlinear length is on the order of several millimeters, then the modulation of the laser radiation intensity becomes noticeable (Fig. 1a).

Fig. 1b shows the angular spectra of the 5th harmonic at the output of the argon jet at different gas pressures. The harmonic radiation has both a collinear component and a noncollinear one, the energy of the latter being no more than 1% of the entire harmonic radiation energy. It should also be noted that the angle of deviation of the noncollinear component from the direction of propagation increases with increasing pressure of the gas jet: for p = 1 bar, the angle is 4.6°, for p = 5 bar – 5.6°, for p = 10 bar – 9.1°, for p = 15 bar – 11.9°. However, these deflection angles are several times higher than those values that should be in the case of the influence of exclusively material dispersion on the phase matching. Indeed, according to the Selmeier formula for argon [10], the transverse component of the wave vector for generating the 5th harmonic is $125\cdot\sqrt{p}$ cm^{-1}, which is about 0.1° for p = 1 bar and 0.4° for p = 15 bar. Consequently, there is a significant negative addition to the wave vectors of the fundamental frequency, due to the plasma nonlinearity dominating over the self-phase modulation.

The results reported in this paper reveal the mechanisms that govern phase matching in the generation of low-order harmonics. Features of the angular distribution of harmonic radiation must be taken into account when designing systems for recording harmonic radiation.

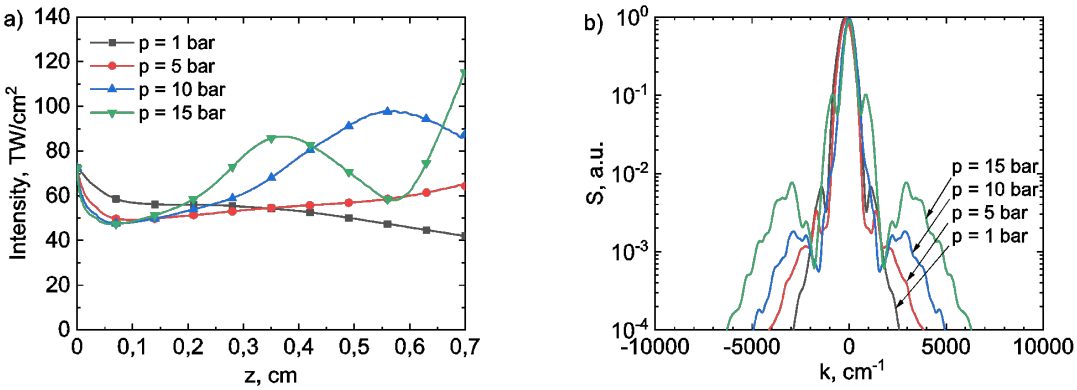


Figure 1: a) Modulation of the intensity of laser radiation during propagation in an argon jet. b) Angular spectrum of the 5th harmonic at the output of the argon jet.

REFERENCES

[1] Schafer K.J., Yang B., DiMauro L.F., Kulander K.C. Phys. Rev. Lett. 70, 1599–1602 (1993).

[2] Migal E.A., Potemkin F.V., Gordienko V.M. Laser Phys. Lett. 16, 04540 (2019).

[3] Andreev A.V., Stremoukhov S.Yu., Shoutova O.A. European Phys. J. D. 2012. V. 66. P. 16.

[4] Silin V.P. Sov. Phys. JETP 20, 1510 (1965).

[5] Ganeev R.A. Phys. Usp. 56, 772-800 (2013).

[6] Garejev N., Jukna V., Tamošauskas G. et al. Opt. Express 24, 17060-17068 (2016).

[7] Goulielmakis E., Brabec T. Nat. Photon. 16, 411–421 (2022).

[8] Couairon A., Brambilla E., Corti T. et al. Eur. Phys. J. Spec. Top. 199, 5–76 (2011).

[9] Keldysh L.V. JETP 20, 1307 (1965).

[10] Peck E.R., Fisher D.J. J. Opt. Soc. Am. 54, 1362-1364 (1964).

Thermo-optical nonlinearity in a system of two coupled WGM microresonators

M P. Marisova, A. V. Andrianov and E. A. Anashkina

A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), Nizhny Novgorod, Russia
e-mail: marisova.mariya@rambler.ru

Optical microresonators with whispering-gallery modes (WGMs) are now widely used in photonics. Although the majority of research is focused on phenomena in a single microcavity, systems of several coupled microresonators are a promising platform for the study of various unique effects, for example, spontaneous symmetry breaking, synchronized generation of optical frequency combs and coupled-resonator-induced transparency [1]. Thermo-optical effects are vital for a study of microresonators, as WGM frequency shifts caused by partial absorption of pump power can be several orders of magnitude larger than the resonance linewidths. The aim of our work is to theoretically investigate the peculiarities of these effects in a system of two coupled silica glass microresonators.

The considered system consists of two evanescently coupled circular microcavities with diameters of $50\,\mu$m; each of the microcavities is also coupled to a separate fiber taper. The system is pumped via one of the tapers with CW radiation with the wavelength of $\sim 1.55\,\mu$m. Nonlinear coupled-mode theory (CMT) was used to study the system [2]. We used previously developed and experimentally verified theoretical models of thermo-optical effects in a single microresonator to describe the thermally-induced shift of partial WGM frequencies as a function of intracavity optical power [3]. A specially developed finite-element model (FEM) was used to obtain the coupling coefficients. Only interactions between fundamental WGMs of similar structure were considered.

First, we assumed that the coupled WGMs have the same "cold" partial frequencies. We found that up to 9 stationary solutions are possible for the same pump parameters, and that not more than 4 of them are stable. This is remarkably different from the case of a single nonlinear microresonator where only 1 or 2 stable solutions are possible. Another interesting feature of the system of two microresonators is that for significant input powers one of the symmetrical solutions (i.e. with equal optical powers in each of the WGMs) becomes completely unstable, and two new asymmetrical stable solutions appear. We also investigated the role of a slight detuning Δ between the "cold" partial resonance frequencies. We found that it is still possible to achieve up to 4 stable states simultaneously with $|\Delta| > 0$, and that the sign of Δ significantly affects the behavior of the system. In a real experiment Δ can be controlled independently via the same thermo-optical effect, for example, using an auxiliary diode [4].

The work was supported by RSF, Grant No. 20-72-10188.

REFERENCES

[1] Y. Li et al., Laser & Photonics Reviews 11, 1600278 (2017).
[2] C. Huang et al., AIP Advances 2, 032131 (2012).
[3] A.V. Andrianov et al., Sensors 22 (12), 4636 (2022).
[4] E.A. Anashkina et al., Micromachines 13 (10), 1616 (2022).

Numerical simulation of high-power femtosecond laser pulse propagation under conditions of amplitude modulation by mesh-wire masks

Yu. E. Geints and O V. Minina

V.E. Zuev Institute of Atmospheric Optics SB RAS, Tomsk, Russia
e-mail: mov@iao.ru

The development of nonlinear atmospheric optics is currently associated with the possibilities of controlling the laser filamentation during the propagation of high-power ultrashort pulses along an extended air path. To this end, it is necessary to manipulate the distance of pulse filamentation onset, the overall length and longitudinal continuity of plasma regions, as well as the formation of plasma free post-filamentation channels with high intensity and low angular divergence. The main strategies for controlling these parameters are variation of the initial laser radiation parameters (beam radius, energy, and pulse duration), amplitude and phase modulation, and creation of profiled radiation. In this report, we theoretically consider a specific type of the amplitude modulation of a femtosecond laser pulse, when metal wire-mesh mask is used as a modulation element. In this case, an initially unimodal laser beam (e.g., a Gaussian intensity profile) is partitioned by the mask into several subbeams. Their spatial and energy characteristics are primarily determined by the size of the mesh cells., The study of high-power femtosecond laser pulses propagation in air have been performed within the framework of this problem formulation [1]. In the current study, changes in the condition of amplitude modulation due to varying the number of cells and the wire crossing thickness are additionally investigated. Upon changing the number of mesh cells makes it possible to establish the dependences of the filamentation region parameters both on the position of the mesh crosshairs relative to the laser beam center and on the area of overlap of the laser beam by the mesh mask (this case determines whether the radiation will be modulated completely or partially).

A detailed description of the used numerical model of propagation of high-power femtosecond laser pulses in air is presented in [2]. It is based on the reduced form of (3D+1) nonlinear Schrödinger equation (NLSE) for time averaged electric field envelope [3]. During numerical simulation, mesh masks are generated by a special home-made software procedure as a 2D plane amplitude screen consisting of regularly spaced areas with full optical transmission separated by a mesh constituted of opaque crossings.

The numerical simulation results show a strong dependence of the starting coordinate and length of filamentation region on the position of the mesh-mask relative to the laser beam axis and the fraction (depth) of radiation modulation. The filamentation region parameters exhibit high sensitivity to the mesh wire thickness that can dominate the influence of mesh position and cell size.

This study is supported by the Russian Science Foundation (Agreement No 21-12-00109).

REFERENCES

[1] Y.E. Geints et al., Sensors 22, 1 (2022).
[2] Y.E. Geints et al., Journal of Optics 23, 105502 (2021).
[3] L. Berge et al., Phys. Rev. Lett. 92, 225002 (2004).

Ultrafast train of half-cycle pulses generated by a nested quantum-well structure

A. V. Pakhomov[1], R. M. Arkhipov[1,2], N. N. Rosanov[1,2] and M. V. Arkhipov[1]

[1] St. Petersburg State University, St. Petersburg, Russia;
[2] Ioffe Physical Technical Institute, St. Petersburg, Russia
e-mail: antpakhom@gmail.com

One of the most important research mainstreams in modern photonics is related with the generation of shortest possible pulses down to few- and subcycle ones, specifically in the optical range, promoted by a number of potential applications in the control of different ultrafast processes in matter. Existing methods for the generation of subcycle pulses down to sub-fs duration and trains of such pulses, such as the high-harmonic generation or the optical attosecond pulse synthesis, require very bulky and complicated experimental setups. Hence, it is of great demand to find out more compact and feasible sources of subcycle pulses and pulse trains in the optical range.

In this work we come up with a simple quantum system, which can be used to produce a regular train of half-cycle pulses in the optical range, if an external homogeneous static electric field is applied. The suggested system represents a pair of two nested quantum wells with a large outer potential barrier. The presence of the inner quantum well allows to efficiently localize the ground state wave function within it. With a proper choice of the structure parameters, an external static electric field can cause the electron to leave the inner quantum well and periodically oscillate inside the outer quantum well, resulting in the production of a half-cycle pulse upon each reflection from the edge of the outer quantum well (see an example in Fig. 1). We have performed the theoretical study of such a structure's emission and shown that a regular output train of half-cycle pulses with the pulse repetition rates of tens of THz and pulse durations of a few fs can be achieved in some parameter ranges. We believe that the proposed structure can be used for the creation of ultra-compact sources of half-cycle pulses in the optical range.

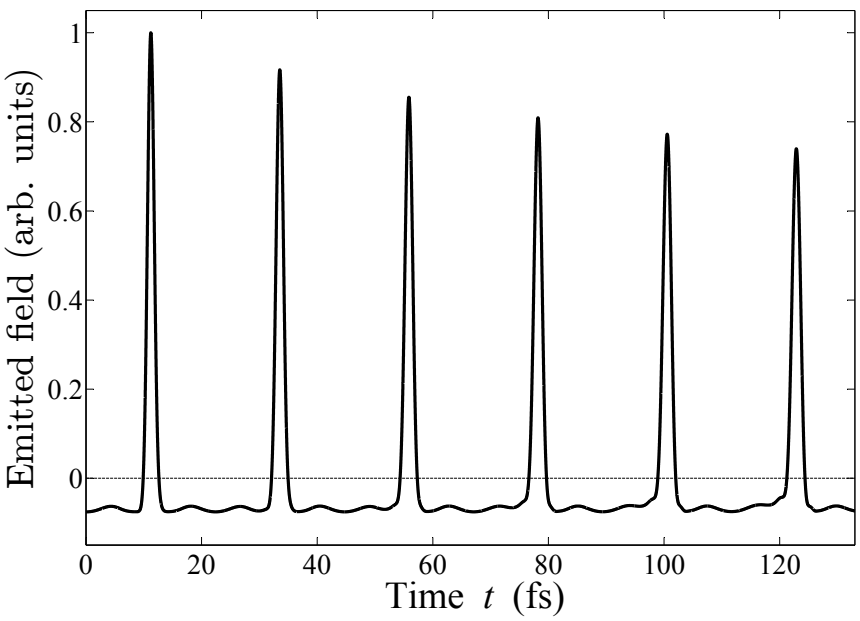


Figure 1: The emitted field from a nested quantum-well structure subject to an external static electric field.

This work was supported by the Russian Science Foundation (21-72-10028).

Multi-band powerful femtosecond laser driver: generation and applications

F. V. Potemkin

Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
e-mail: potemkin@physics.msu.ru

One of the most important directions in the modern photonics is the development of femtosecond laser sources in the infrared range. By themselves, ultrashort near-IR and mid-IR laser pulses, as a powerful source of coherent radiation, are of interest for physics, chemistry, and biomedicine, and the converted radiation in the range from terahertz to X-rays is very attractive for broadband dynamic spectroscopy with a time resolution of up to attoseconds. Thus, it is quite important to generate laser radiation with high spectral brightness over the broad spectral range.

Here we propose the approach with two synchronized high-power (more than 20 GW) laser radiation channels in the near (1.24 μm) and middle (4–5 μm) IR ranges based on CPA Cr:Forsterite [1] and Fe:ZnSe [2] lasers taken into account the advantages of each of the developed sources. Using near-IR laser driver and organic crystals make it possible to generate powerful (70 μJ, 400-500 fs) THz radiation whose temporal and spectral properties can be tuned from 0.1 THz up to 5 THz via chirping of the pump pulse and the molecular crystal [3]. Using binary gas mixture (molecular and nobble gases) as a perspective nonlinear object which nonlinear and dispersion properties can be tailored it becomes possible to control temporal (up to several optical cycles) and spectral (up to more than three octaves spanning supercontinuum) parameters of the mid-IR powerful pump and to convert it into UV radiation [4], [5]. As a result, the methods for efficient conversion of dual-band IR laser driver into the UV, mid-IR and THz wavelength ranges were developed which form the basis for the first multi-band source of coherent radiation which is fully based on domestic components and meets current challenges in our country.

This work has been supported by Russian Science Foundation Project No. 20-19-00148. The work has been conducted with the use of equipment purchased at the expense of funds by Program of development of Moscow university and National project «Science and universities».

This work was supported by the Russian Science Foundation (21-72-10028).

REFERENCES

[1] A. Pushkin, E. Migal, D. Suleimanova, E. Mareev, and F. Potemkin, "High-Power Solid-State Near- and Mid-IR Ultrafast Laser Sources for Strong-Field Science," Photonics 2022, Vol. 9, Page 90, vol. 9, no. 2, p. 90, Feb. 2022, doi: 10.3390/PHOTONICS9020090.

[2] E. Migal et al., "3.5-mJ 150-fs Fe:ZnSe hybrid mid-IR femtosecond laser at 44 μm for driving extreme nonlinear optics," Opt Lett, vol. 44, no. 10, p. 2550, May 2019, doi: 10.1364/ol.44.002550.

[3] B. V. Rumiantsev, A. V. Pushkin, D. Z. Suleimanova, N. A. Zhidovtsev, and F. V. Potemkin, "Generation of Intense Few-Cycle Terahertz Radiation in Organic Crystals Pumped by 1.24-μm Multigigawatt Chirped Laser Pulses," JETP Lett, vol. 117, no. 8, pp. 566–573, Apr. 2023, doi: 10.1134/S0021364023600416/FIGURES/7.

[4] A. Pushkin, B. Bravy, E. Migal, F. Potemkin, and N. Minaev, "Control of spectral shift, broadening, and pulse compression during mid-IR self-guiding in high-pressure gases and their mixtures," Opt Lett, vol. 47, no. 4, pp. 985–988, Feb. 2022, doi: 10.1364/OL.450508.

[5] E. A. Migal, S. Y. Stremoukhov, and F. V. Potemkin, "Ionization-free resonantly enhanced low-order harmonic generation in a dense gas mixture by a mid-IR laser field," Phys Rev A (Coll Park), vol. 101, no. 2, p. 021401, Feb. 2020, doi: 10.1103/PhysRevA.101.021401.

Induced fluorescence of NO fragments by a femtosecond laser pulse

A. V. Puchikin, Yu. N. Panchenko and S. A. Yampolskaya

Institute of High Current Electronics of the Siberian Branch of Russian Academy of Sciences, Tomsk, Russia
e-mail: apuchikin@mail.ru

Nitrogen dioxide laser remote spectroscopy uses various fluorescence-based optical methods such as SRS (stimulated Raman scattering), LIBS (elemental analysis), LIF (stimulated fluorescence). The highest values of the absorption cross section for NO_2 are in the UV and IR range $\sim 10^{-19}$ cm^2/mol. Under the action of ultraviolet radiation, nitrogen dioxide undergoes photodissociation with the formation of vibrationally excited fragments of nitrogen oxide. In the nanosecond range of laser exposure durations, an optical method of photofragmentation is used, followed by laser-induced fluorescence PF-LIF of nitro-containing substances [1].

The propagation of UV radiation in the atmosphere is limited due to absorption or scattering by gas and aerosol molecules. Using short-pulse laser systems of the femtosecond duration in the visible range, it is possible to carry out resonant nonlinear processes of multiphoton absorption in the ultraviolet region, leading to dissociation or excitation of the studied molecules [2]. In our experimental work, we report on the interaction of femtosecond laser radiation with vibrationally excited fragments of NO $X^2\Pi$, $v''(1)$ through the process of two-photon absorption from a wavelength of 475 nm. The vibrational population of NO $X^2\Pi$, $v''(1)$ is achieved by photodissociation of NO_2 by nanosecond laser radiation of 355 nm.

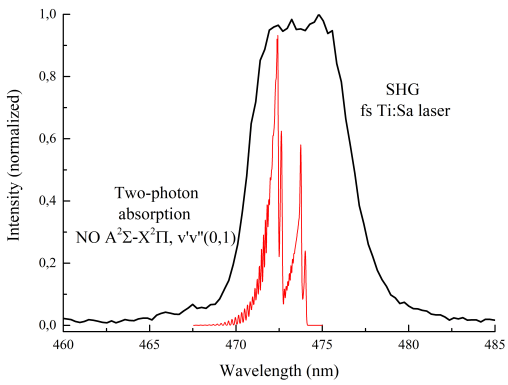


Figure 1: Femtosecond-laser induced two-photon absorption of NO $A^2\Sigma$-$X^2\Pi$,$v'v''(0,1)$.

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (No. FWRM-2021-0014).

REFERENCES

[1] A. V. Puchikin, Yu. N. Panchenko, Bull. Russ. Acad. Sci. Phys., 83, 273 (2019).
[2] Yu. N. Panchenko, A. V. Puchikin, IEEE J. Quant. Electr., 57, 1 (2021).

High-order harmonics generation under nonlinear propagation of femtosecond laser radiation of Cr:Fortserite laser system with wavelength of 1.24 μm in the dense argon jet

B. V. Rumiantsev, A. V. Pushkin and F. V. Potemkin

Faculty of physics, Lomonosov Moscow State University, Moscow, Russia
e-mail: rumjancev.bv15@physics.msu.ru

The generation of high-order harmonics (HHG) in the field of intense ($10^{14} - 10^{15}$ W/cm^2) femtosecond laser radiation is currently the object of active scientific research in the field of laser physics and nonlinear optics. The fundamental aspects of the interaction of laser radiation with matter within the plasma formation regime are at the heart of the HHG process. To date, sources based on this effect are the only desktop tool for the generation of coherent radiation in the vacuum ultraviolet and soft X-ray ranges, as well as for the generation of attosecond (10^{-18} s) pulses [1]. The most common sources used for HHG are Ti:Sapphire laser systems (wavelength is $\sim$ 0.8 μm) and systems based on the Yb-doped crystals (wavelength $\sim$ 1 μm) [10]. In the present work, HHG has been realised with the use of laser system on a Cr:Forsterite crystal (wavelength is 1.24 μm) for the first time, and the role of nonlinear propagation effects in the framework of HHG process with the use of this radiation has been investigated.

In the frame of present work the high-order harmonics (15-25, 83-50 nm) in the argon jet have been generated under the relatively high [2] numerical aperture of focusing $NA = 0.033$. It is demonstrated that the use of this focusing conditions requires high (up to 10 bar) gas jet backing pressure for the compensation of geometrical Gouy phase, that is neccesary for the optimization of generation efficiency. At the same time the use of dense gas jet leads to the noticeable manifestation of nonlinear propagation effects for the generating radiation, such as self-phase modulation, self-focusing and plasma generation with the electron density at the order of $\sim 10^{17}$ cm^{-3}. The joint action of these effects causes the quasi-filamentation regime of generating pulse propagation in the region of the gas target, that manifests, in particular, as a saturation of the dependence of the optimal gas jet pressure on the pulse energy, as well as an increase of the harmonics spectral width. Moreover, it is established, that the compensation of the positive generating pulse chirp, originating from the self-phase modulation, by the negative pre-chirping allows increase of the generation efficiency due to the nonlinear compression of the negatively chirped pulse under self-phase modulation. The use of this approach allowed generation of the 17th harmonic (73 nm) with the pulse energy of 2 pJ and corresponding generation efficiency $5.4 \cdot 10^{-9}$ that, as the estimates show, can be used for the single-shot maskless extreme ultraviolet (EUV) photolithography.

The work is supported by the RFBR grant #19-29-12030 and RSF grant № 20-19-00148. The work has been conducted with the use of equipment purchased at the expense of funds by Program of development of Moscow university and National project "Science and universities" in 2023. Rumiantsev B.V. is the scholar of the foundation for the advancement of theoretical physics and mathematics "BASIS".

REFERENCES

[1] M.Yu. Ryabikin, M.Yu. Emelin and V.V. Strelkov. "Attosecond electromagnetic pulses: generation, measurement, and application. Attosecond metrology and spectroscopy." Uspekhi Fizicheskikh Nauk 193.4 (2023).

[2] J. Rothhardt et al. "Absorption-limited and phase-matched high harmonic generation in the tight focusing regime." New Journal of Physics 16.3 (2014).

Direct laser writing in the volume of transparent dielectrics

A. E. Rupasov[1], S. I. Kudryashov[1] and A. B. Bogatskaya[1,2]

[1] Lebedev Physical Institute, Moscow, Russia;
[2] Department of Physics, Moscow State University named after M.V. Lomonosov, Moscow, Russia
e-mail: rupasovan@lebedev.ru

Femtosecond laser writing of birefringent subwavelength nanogratings in the bulk of dielectrics has been studied for almost two decades [1, 2], promising many interesting applications in the field of polarization macrooptics [3, 4]. The formation of subwavelength nanogratings in a plane perpendicular to the optical axis of laser radiation remained unexplained for a long time, and only in recent years have they begun to consider the interaction of incident ultrashort laser pulses with wide-gap transparent dielectrics.

In this work, experiments were carried out on the recording of birefringent microstructures under the action of focused ultrashort laser pulses with several fixed pulse energy levels at a fixed depth in the volume of fused quartz [5]. The phase shift was measured for various microstructure recording conditions, and as a result of this analysis, a mechanism was proposed that explains the formation of nanogratings responsible for birefringence, their location and orientation relative to the optical axis of laser radiation, and the nature of the dependence of the phase shift on the energy/intensity of laser pulses.

The study is funded by the grant of Russian Science Foundation (project № 22-72-10076).

REFERENCES

[1] Y. Shimotsuma, P. G. Kazansky, J. Qiu, and K. Hirao, Phys. Rev. Lett. 91(24), 247405 (2003).
[2] C. Hnatovsky, R. S. Taylor, P. P. Rajeev, E. Simova, V. R. Bhardwaj, D. M. Rayner, and P. B. Corkum, Appl. Phys. Lett. 87, 014104 (2005).
[3] R. Drevinskas and P. G. Kazansky, APL Photonics 2(6), 066104 (2017).
[4] M. Sakakura, Y. Lei, L. Wang, Y. H. Yu, and P. G. Kazansky, Light Sci. Appl. 9(1), 1 (2020).
[5] W. Hayes and A. M. Stoneham, Defects and defect processes in nonmetallic solids, Dover publications, N.Y. (1985).

Sum frequency mixing of femtosecond Ti:sapphire and nanosecond Nd:YAG laser pulses in KDP crystal

N. S. Semin[1,2], I. O. Kinyaevskiy[1], A. V. Koribut[1], Ya. V. Grudtsyn[1] and L. V. Seleznev[1]

[1] P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] National Research Nuclear University MEPhI, Moscow, Russia
e-mail: nikitos742345@gmail.com

Development of ultrashort mid-IR laser systems is a high demand problem for a lot of applications in fundamental and applied fields. Recently, the mid-IR laser source with ~ 11 μm wavelength based on the femtosecond Ti:sapphire laser and successive frequency conversion in $BaWO_4$ SRS crystal and $LiGaS_2$ DFG crystal was experimentally demonstrated in [1]. To get reasonably high ($\sim$3%) SRS efficiency in [1], a broadband nanosecond seed pulse was used. To increase the mid-IR laser system efficiency, we consider a narrow-linewidth nanosecond pulse of Nd:YAG laser as the seed pulse. In the current research, spatial and temporal combining of femtosecond Ti:sapphire and nanosecond Nd:YAG laser pulses was implemented and tested by sum frequency mixing in KDP crystal.

The Ti:sapphire laser (Avesta project Ltd., Russia) emitted $\sim$100 fs laser pulses with a central wavelength of 940 nm and energy 0.3 mJ. The Nd:YAG laser (LOTIS TII, Belarus) emitted 20 ns laser pulses with a wavelength of 1064 nm and energy $\sim$20 mJ. Spatial combining of the laser pulses was performed with a long wave pass filter LP02-980RU-25 (Semrock, USA). The lamp of the Nd:YAG laser was synchronized with a lamp of a Nd:YAG laser pumping the Ti:sapphire laser. Q-switching moment was controlled with a pulse synchronization unit with accuracy better than 1 ns.

The combined laser pulses were sent to KDP crystal of 2-mm length. In the spectral range of 400 – 550 nm, the spectrum of radiation transmitted through the crystal was measured, which consisted of three peaks: 1) Ti:sapphire laser second harmonic at 470 nm wavelength; 2) Nd:YAG laser second harmonic at 532 nm wavelength; 3) their sum frequency radiation at 499 nm. The pulse energy of sum frequency radiation was about 10 nJ. The registration of sum frequency radiation indicates successful spatial and temporal combing of femtosecond Ti:sapphire and nanosecond Nd:YAG laser pulses.

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

REFERENCES

[1] I.O. Kinyaevskiy, A.V. Koribut, Y.V. Grudtsyn, L.V. Seleznev, V.I. Kovalev, D.V. Pushkarev, E.E. Dunaeva, A.A. Ionin, Laser Physics Letters 19 (9), 095403 (2022).

Sum frequency mixing of femtosecond Ti:sapphire and nanosecond Nd:YAG laser pulses in KDP crystal

E. A. Stepanov[1,2], I. V. Savitskii[1], G. D. Ivanov[1], A. A. Lanin[1,2] and A. B. Fedotov[1,2]

[1] Physics Department, M.V. Lomonosov Moscow State University, Moscow, Russia;
[2] Russian Quantum Center, Skolkovo, Moscow Region, Russia
e-mail: a.b.fedotov@physics.msu.ru

The technique of two-dimensional infrared (2D IR) Fourier spectroscopy using ultrashort pulses of the mid-infrared range is a modern method for studying ultrafast dynamics in complex oscillatory systems, which is based on the nonlinear four-wave interaction of pulsed broadband infrared radiation with matter [1–7]. Femtosecond temporal resolution, combined with spectral selectivity and high spatial resolution, make it possible to use two-dimensional infrared spectroscopy for characterization of rapidly interconverting substances and recording ultrafast processes in complex biological and chemical systems. Two-dimensional infrared spectroscopy makes it possible to obtain more information compared with one-dimensional techniques: to reveal the relationship between interacting modes, observe the temporal evolution of vibrational frequencies, determine the influence of the environment on the behavior of individual elements in complex complexes and in solutions [1–7].

In this work, we present a universal laser platform for broadband 2D spectroscopy using ultrashort mid-IR pulses. The laser system developed for 2D spectroscopy generates radiation pulses with a duration of less than 70 fs and a wavelength tunable in the range of 2.6 – 10 mm. Broadband excitation and probing by pulses with such parameters, in combination with the heterodyne detection technique implemented in the mid-IR range, open up possibilities for studying ultrafast dynamics of molecular coherence, as well as ultrafast population kinetics and energy exchange between different degrees of freedom in a wide class of complex molecular systems. Implemented chirped-pulse up-conversion method enables the detection of mid-infrared spectra at a much higher framerate using a 1 kHz silicon CCD camera by sum-frequency mixing a mid-IR field with a highly chirped near-IR (800 nm) field. Additional quasi-phase-cycling achieved by sub-cycle delay modulation of pump pulses with original device, based on galvo-scanning head, was used to replace optical chopping in our 2D IR experiment in order to enhance the signal size, and, at the same time, eliminate scattering contamination.

The work was supported by the Russian Science Foundation with grant No. 22-12-00149

REFERENCES

[1] M.C. Asplund et al, PNAS 97(15):8219–8224 (2000).
[2] P. Hamm et al, The Journal of Physical Chemistry B, 102(31):6123–6138 (1998).
[3] S. Mukamel et al, Accounts of Chemical Research, 42(9):1207–1209 (2009).
[4] P. Hamm, M. Zanni, Cambridge University Press (2011).
[5] S.T. Cundiff, S. Mukamel, Phys. Today 66, 44–49 (2013).
[6] A.L. Le Sueur et al, Analyst 140, 4336-4349 (2015).
[7] J. M. Anna, K. J. Kubarych, J. Chem. Phys. 133, 174506 (2010).

High-efficient mid-infrared optical parametric amplifier with 1.24 μm pumping

D. Z. Suleimanova, A. V. Pushkin and F. V. Potemkin

Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
e-mail: dina020698@gmail.com

The creation of mid-IR (3–7 μm) femtosecond sources is of great interest for solving numerous scientific and applied problems, such as the generation of a broadband supercontinuum, spectroscopy and multispectral tissue imaging, since a large number of molecules undergo strong characteristic vibrational transitions in this domain [1,2,3]. Moreover, high-power mid-IR systems can be used as the driving sources for strong-field phenomenon, such as terahertz generation, high-order harmonic generation and attosecond pulse generation [4].

Such a source can be obtained by wavelength conversion into infrared spectral region, based on Cr:Forsterite laser, delivering 100 fs pulses at 1.25 μm with up to peak TW power. The use of longer wavelength pump allows the use non-oxide crystals which make it possible to obtain high-energy radiation up to 10–12 μm due to their wide transparency window combined with high nonlinearity [5]. In this paper, we perform an experimental and theoretical comparison of different non-oxide crystals (LGS, AGS and HGS) performance in a direct parametric amplification scheme for wavelength conversion into the near and mid-IR range (1.5–7 μm) with Cr:Forsterite laser pump.

We report on the generation of femtosecond radiation tunable from the near to mid-IR wavelength range with up to 150 and 25 μJ output energy in dual bands 1.5 – 1.9 μm and 4 – 7 μm, respectively. The mid-IR pulse duration was measured as 65 fs in FWHM, which is almost transform-limited duration (TBP $\sim$ 0.42). Exceptionally high total energy conversion efficiency into the idler and signal waves up to 15,7% was achieved when using HGS crystals and is due to its higher nonlinearity (25.7 pm/V) compared to LGS (4.45 pm/V) and AGS (10.3 pm/V) crystals, which makes it a preferable material for Cr:Forsterite laser based mid-IR optical parametric amplifiers.

This work has been supported by Russian Science Foundation Project No. 20-19-00148.

D.Z. Suleimanova is the scholar of the foundation for the advancement of theoretical physics and mathematics “BASIS”.

REFERENCES

[1] Dai S. et al., Applied Sciences 8(5), 707 (2018).
[2] Petersen C. R. et al., Optics letters 4(5), 999-1002 (2018).
[3] Schliesser, A., Picqué, N., & Hänsch, T. W., Nature Photonics 6(7), 440 (2012).
[4] Popmintchev T. et al., science 336(6086), 1287-1291 (2012).
[5] Tian K. et al., Photonics 8(8), 290 (2021).

Waveguide properties of ceramic capillaries for KrF laser radiation

P. V. Veliev[1,2], I. V. Smetanin[1], N. N. Ustinovskii[1], A. V. Shutov[1] and V. D. Zvorykin[1,2]

[1] P.N. Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia;
[2] National Research Nuclear University "MEPhI", Moscow, Russia
e-mail: p.veliev@levedev.ru

Hollow dielectric waveguides being firstly proposed for long-distance optical transmission lines and long laser cavities [1] in nowadays are widely used to extend a high-intensity region of focused laser radiation over many Raileigh lengths in laser-driven electron accelerators, THz and high-order harmonics generation, and also for an effective Stimulated Brillouin scattering (SBS) [2] or Stimulated Raman Scattering (SRS). A waveguide-like propagation of UV light in a channel and filamentation in semitransparent plastic materials allowed a high-aspect-ration channels drilling, e.g., in polymethylmethacrylate (PMMA) [3]. It was proposed to use such capillaries with a diameter of tens to a few hundred microns for a nonlinear temporal compression of KrF laser pulses in high-pressure SF_6 or CH_4 gases [3]. But large attenuation of UV radiation in the PMMA channels was measured due to the bad wall roughness produced in the stochastic low-threshold ablation process. Here we have studied ceramic hollow tubes with 1-mm inner diameter, which have a large ablation threshold and smoother wall, that is could be expected to be better waveguides for high-intensity UV laser light.

A double-chamber discharge-pumped KrF laser (Lambda Physik EMG TMSC model) with a narrow-band oscillator and power amplifier with an unstable resonator generated in injection-controlled operation 20-ns pulses (FWHM) with $\leq$ 200 mJ energy, a quasi-steady beam divergence of $\sim 2{\cdot}10^{-4}$ rad and spectral width of $\Delta\nu \sim 0.2\text{cm}^{-1}$. Otherwise, in free-running operation when coupling of the oscillator seed radiation into the amplifier was blocked, a broad-band radiation with $\Delta\nu \sim 50\text{cm}^{-1}$ was generated with lower time-dependent divergence. Radiation energy was focused by a lens with F = 0.8 or 2 m into the capillary, which length was varied from 0.9 to 34 cm. Energy distribution in the focal spot and at the capillary exit were measured with Spiricon SP-620U beam profiler combined with the UV convertor, the total transmitted energy - by the calorimeter.

It was shown that with increasing capillary length the output radiation was concentrated in a small central region along the capillary axis, i.e., the low-order transverse mode did survive with minimal losses while the others inclined to the axis were discriminated. Output radiation divergence decreased with the capillary length and it was approaching the diffraction limit. Note, that the initial laser beam divergence was about tenfold higher than the diffraction limit for the beam cross section 23×7 mm. It was mainly caused by the gas flow perturbations and discharge inhomogeneities during a rep-rate laser operation. As a result, the focal spot positioning occasionally changed shot by shot. A capillary waveguide acting as the mode selector eliminated a focal spot jitter.

This work was supported by Russian Science Foundation grant # 22-22-01021.

REFERENCES

[1] E.A.J. Marcatili and R.A. Schmeltzer, Bell Syst. Tech. J. 43, 1783 (1964).
[2] F. Yang, F. Gyger, L. Thévenaz, Nat. Photonics 14, 700 (2020).
[3] I.V. Smetanin, A.V. Shutov, N.N. Ustinovskii, et al., Materials, 15, 8347 (2022).

Experimental study of terahertz radiation generation in the interaction of high-power laser pulse with gas targets

R. S. Zemskov[1], S. E. Perevalov[1], A. V. Kotov[1], S. B. Bodrov[1,2], A. N. Stepanov[1], A. A. Soloviev[1,2] and M. V. Starodubtsev[1]

[1] Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia;
[2] N.I. Lobachevsky State University of Nizhny Novgorod, Russia
e-mail: roman.zemskov.6@gmail.com

The development high-power terahertz pulse sources with an electric field strength of more than 1 MV/cm is extremely important for many new applications, including terahertz particle acceleration, terahertz optomagnetism, and nonlinear terahertz spectroscopy (see references in [1,2]). A very promising method for generating high-power THz pulses is the excitation of a wake wave in a low-density plasma by a powerful laser pulse. The transfer of laser energy into the wake occurs quite efficiently, however in a uniform (slightly non-uniform) non-magnetically active plasma the group velocity of the wake is zero and therefore cannot leave the plasma. To solve that problem an external magnetic field was applied in the numerical work[2].

We present the first experimental results [1] of studying the processes of generation of terahertz radiation obtained on the PEARL laser facility (IAP RAS, Nizhny Novgorod) [3]. Using pulsed Helmholtz coils, we superimposed a strong magnetic field up to 14 T, but no increase of the THz signal was detected. In the course of our experiments, we found out the influence of dielectric collimating prisms on the formation of directional terahertz radiation. It was shown that when laser pulse is focused into a gas there is no noticeable generation of a terahertz signal. While during the interaction of a laser pulse with a gas target sandwiched between two closely spaced dielectric prisms, a terahertz signal is confidently observed and an energy of THz pulse increases with increasing energy E of the laser pulse as $\sim E^2$. In experiments, a wide range of plasma density N_e (from 10^{16} to $10^{18} cm^{-3}$) in the target was studied and it was found that the amplitude of the terahertz signal decrease with density increasing.

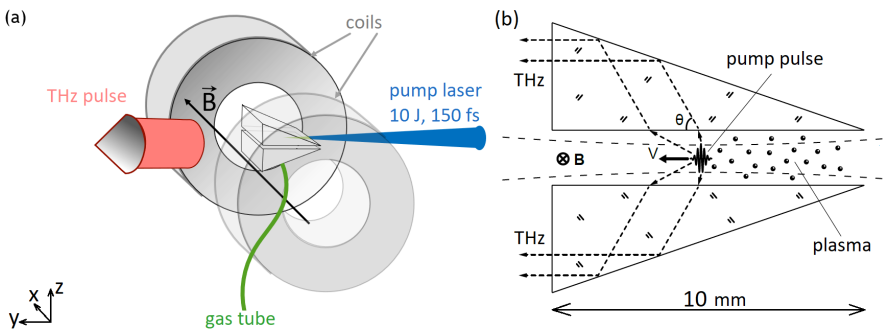


Figure 1: Experimental setup.

The development of THz radiation diagnostics was supported by the Ministry of Science and Higher Education of the Russian Federation (0729- 2020-0035).

REFERENCES

[1] R. S. Zemskov, S. E. Perevalov, et al., Radiophysics and Quantum Electronics, 12 (65), 965 (2022).
[2] M. I. Bakunov, S. A. Sychugin, et al., Applied Physics Letters, 122 (6), 061106 (2023).
[3] V. V. Lozhkarev, G. I. Freidman, et al., Laser Physics Letters, 4 (6), 421 (2007).

KrF laser pulse compression via SBS and SRS in pressurized SF_6 and CH_4 gases

V. D. Zvorykin[1,2], I. V. Smetanin[1], N. N. Ustinovskii[1], A. V. Shutov[1] and P. V. Veliev[1,2]

[1] P.N. Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia;
[2] National Research Nuclear University "MEPhI", Moscow, Russia
e-mail: zvorykin@sci.lebedev.ru

Compression of typical $\sim$ 20 ns pulses of the discharge-pumped KrF laser into ps and sub-ns pulses was obtained in nonlinear interaction with pressurized SF_6 and CH_4 gases. In the lack of suitable transparent liquids for the radiation wavelength $\lambda = 248$ nm these gases are promising media for Stimulated Bruellen scattering (SBS), Stimulated Raman Scattering (SRS), and four-wave mixing (FWM) [1-3].

A narrow-band radiation with pulse energy ≤ 200 mJ, beam divergence $\sim 2 \cdot 10^{-4}$ rad and spectral width $\Delta\nu \sim 0.2\text{cm}^{-1}$ was generated by Lambda Physik EMG TMSC laser with two discharge chambers. A narrow-band radiation of the oscillator was injected into the power amplifier equipped with an unstable resonator. Output radiation was focused by various lenses with focal lengths 0.5, 1 and 2 m into the high-pressure gas cells. Both highly directed back-reflected radiation with a wavefront conjugation and forward-scattered radiation were observed in SF_6 at 10-atm and CH_4 at 50-atm pressure. Time-integrated spectra, pulse-forms for various spectral components with time resolution $\sim$1 ns and reflected energy were measured by ASP 150 spectrometer, Thorlabs DET10A photodiodes with TDS 3054C 500 MHz oscilloscope combined with a monochromator, and a calorimeter, correspondingly. The streak camera PS-1/S1 was used to measure shorter radiation pulses.

The SBS and SRS spectral components were identified in the spectra. Energy conversion efficiency of pump radiation into the reflected radiation amounted 14% in both gases at input energy 100 mJ. The energy thresholds of backward SBS and SRS reflection in SF_6 were about 10 and 30 mJ, respectively. The reflected pulses were shortened via SBS down to $\sim$4 ns and via SRS down to 30 - 60 ps. In CH_4, the 1st Stokes component was generated in a course of forward and backward SRS scattering, the scattered pulses were shortened to $\sim 3 \div 4$ ns. Noticeable, that for a broad spectrum of pump radiation $\Delta\nu \sim 50\text{cm}^{-1}$ (when a narrow-band injection was blocked in the laser), the 1st, 2nd, and 3rd Stokes and 1st anti-Stokes components were observed in the forward direction while no back reflection was detected.

The obtained results allow choosing various layouts of the short-pulse front-end based on the SBS, SRS or FWM for the high-power multistage KrF GARPUN laser system [4].

This work was supported by Russian Science Foundation grant # 22-22-01021.

REFERENCES

[1] K. Kuwahara, E. Takahashi, Y. Matsumoto, et al. JOSA B, 17, 1943 (2000).
[2] E. Takahashi, K. Kuwahara, Y. Matsumoto, et al. Optics Commun. 185, 431 (2000).
[3] E. Takahashi, L.L. Losev, Y. Matsumoto, et al., Optics Commun. 215, 163 (2003).
[4] V.D. Zvorykin, N.V. Didenko, A.A. Ionin, et al, Laser Part. Beams 25, 435 (2007).

Lasing from molecular nitrogen ions at 391 nm

I. A. Zyatikov and V. F. Losev

Institute of High Current Electronics SB RAS, Tomsk, Russia
e-mail: kidnapper66@gmail.com

Cavity-free lasing from ionized nitrogen molecules is a phenomenon that has attracted much attention since 2011 [1-3]. By focusing a femtosecond laser pulse in ambient air or pure nitrogen, one observes a coherent radiation in forward direction at 391.4 and/or 427.8 nm. Such sources of radiation have great potential in remote atmospheric sensing, spectroscopy and other areas. Currently, the physical mechanisms underlying the lasing radiation are still controversially discussed. To determine these mechanisms, it is important to know all the characteristics of lasing.

This work presents the results of studies of spectral, temporal, and spatial characteristics of lasing at the wavelength of 391 nm in pure nitrogen at different values of specific pump power and dimensions of laser plasma. Pumping was carried out by a 70 fs laser pulse at the wavelength of 950 nm and energy of 6 – 10 mJ. The results of this study can be useful for the development of effective coherent source of short-pulse radiation in UV region.

The reported study was funded by Russian Science Foundation according to the research project No. 23-22-00023.

REFERENCES

[1] J. Yao, B. Zeng, et al., Phys. Rev. A. 84, 051802 (2011).
[2] I. Zyatikov, V. Losev, et al., Optics Letters 45, 6518 (2020).
[3] C. Zhuang, X. Zhang, et al., Optics Express 30, 17156 (2022).

Section 7: Ultrafast laser technologies in biomedicine

Section Co-chairs:

Sergey Gonchukov, e-mail: sagonchukov@mephi.ru
(National Research Nuclear University MEPhI, Russia)
Eteri Tolordava, e-mail: tolordava.eteri@yandex.ru
(N. F. Gamalei NRC E&M, Russia)
Valery Tuchin, e-mail: tuchinvv@mail.ru
(Science Medical Center, Saratov State University, Russia)

Program committee:

Kirill Zaytsev
(Prokhorov General Physics Institute of RAS, Russia)
Evgeny Shirshin
(Lomonosov Moscow State University, Russia)

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

Non-invasive *in vivo* application of two-photon tomography in dermatology

M. E. Darvin

Charité – Universitätsmedizin Berlin, Department of Dermatology, Berlin, Germany

e-mail: maxim.darvin@protonmail.com, max_darvin@mail.ru

Femtosecond near infrared laser pulse technology is widely used in life sciences. Clinical femtosecond two-photon tomography provides physicians and researchers with high-quality subcellular resolution multimodal morphological imaging of the skin based on two-photon excited autofluorescence (TPE-AF), second harmonic generation (SHG), and two-photon excited fluorescence lifetime imaging (TPE-FLIM). Imaging of the skin can be performed *in vivo*, stainingfree, and non-invasively to a depth of approx. 150 μm and is referred to as "optical biopsy" [1]. TPEAF is generated by various skin fluorophores (or rather skin structures) – keratin (corneocytes), NAD(P)H (cells of the living epidermis and dermis), melanin (melanocytes, melanosomes), and elastin (structural protein of the dermis), enabling their high-contrast visualization [1]. SHG is generated by non-centrosymmetric molecules, such as collagen type I (in the dermis) [1] and recently discovered crystallized urea dendriform structures (in the stratum corneum of glabrous skin) [2]. TPEFLIM is a time-resolved technique that enables the detection of fluorescence lifetime decay curves, which depends on the chemical composition of the target fluorophores and their interaction with the surroundings – considerably expand the possibilities for molecular imaging. Recent results show that, due to differences in TPE-FLIM characteristics, collagen type III [3], resting and activated mast cells [4], and M1 and M2 macrophages [5] can be visualized in the dermis *in vivo*. This opens a new perspective for *in vivo* research on the contribution of immune cells to the development of various skin diseases and monitoring of treatment efficacy. TPE-AF and TPE-FLIM visualizes *in vivo* the localization and kinetics of carbon black pigments in tattooed skin: the pigments have been found intracellularly within macrophages, mast cells and fibroblasts in the dermis and, unexpectedly, also within keratinocytes, dendritic cells, and basal cells in the constantly renewing epidermis, even in old tattoos [6]. TPE-AF, SHG and TPE-FLIM can also be used to determine the penetration depth of topically applied substances in the skin that is important for dermatology, cosmetology, and pharmacy [7]. Two-photon tomography of human skin may become an important tool for non-invasive *in vivo* diagnostics and therapy control in dermatology and immunology that target specific cells and skin structures and can advance the understanding of their role in health and disease.

REFERENCES

[1] K. König, A.P. Raphael, L. Lin, J.E. Grice, H.P. Soyer, H.G. Breunig, M.S. Roberts, T.W. Prow, Advanced Drug Delivery Reviews 63, 388–404 (2011).

[2] V.H.P. Infante, R. Bennewitz, M. Kröger, M.C. Meinke, M.E. Darvin, Experimental Dermatology (2023).

[3] E.A. Shirshin, Y.I. Gurfinkel, A.V. Priezzhev, V.V. Fadeev, J. Lademann, M.E. Darvin, Scientific Reports 7, 1171 (2017).

[4] M. Kroger, J. Scheffel, V.V. Nikolaev, E.A. Shirshin, F. Siebenhaar, J. Schleusener, J. Lademann, M. Maurer, M.E. Darvin, Scientific Reports 10, 14930 (2020).

[5] M. Kröger, J. Scheffel, E.A. Shirshin, J. Schleusener, M.C. Meinke, J. Lademann, M. Maurer, M.E. Darvin, eLife 11, e72819 (2022).

[6] M. Kröger, J. Schleusener, J. Lademann, M.C. Meinke, S. Jung, M.E. Darvin, Dermatology 239, 478–493 (2023).

[7] M.E. Darvin, Pharmaceutics 15, 2272 (2023).

Production of magnetic nanoparticles water colloids by pulsed laser ablation of thin Co films

I. O. Dzhun[1], V. Yu. Nesterov[2,3], D. V. Shuleiko[2], D. E. Presnov[1,2], E. A. Konstantinova[2], S. V. Zabotnov[2] and N.G. Chechenin[1,2]

[1] Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow, Russia;
[2] Lomonosov Moscow State University, Faculty of Physics, Moscow, Russia;
[3] Moscow Institute of Physics and Technology, Dolgoprudny, Moscow region, Russia
e-mail: irina.dzhun@gmail.com

Magnetic nanoparticles (MNPs) are widely used in biomedical applications such as magnetic targeting, magnetic hyperthermia, and biosensors. That is why one needs a method to produce pure MNPs colloids with desirable characteristics such as the MNPs size that, for example, is responsible for power absorption in magnetic hyperthermia. The pulsed laser ablation in liquids (PLAL) is a green method of synthesis even relatively large MNPs with no undesirable chemical impurities inside that is hardly achievable in chemical synthesis techniques. Generally, to produce MNPs the PLAL of bulk materials is applied, while using thin films as targets is less studied, although it seems promising to tune the MNPs size.

Herein, we prepared MNP colloids via PLAL in distilled water of thin Co films which were magnetron sputtered onto glass substrates. The Co film thicknesses range was 5–500 nm that covers both important for PLAL depths: the skin layer (typically about 30 nm) and the thermal diffusion length (about 500 nm). All produced colloids were examined by placing a magnet to cuvette surface and all of them demonstrated a magnetic response. Magnetic properties of the produced MNPs were also confirmed by ferromagnetic resonance investigations where typical for MNPs resonance fields of about 2700 Oe were observed.

The mean MNPs size in colloids was determined as the hydrodynamic diameter by dynamic light scattering measurements. At decrease of ablated Co film thickness from 500 to 50 nm, the MNPs size slightly increases from 80 to 100 nm while at further decrease to the skin layer region (25 and 15 nm) the tenfold growth in size up to 1 μm is observed. After, the size decays to 150 nm at 5 nm Co film. Generation of the MNPs from the films comparable to the skin layer was also characterized a narrower size distribution (the standard deviation of 20% vs 40% for 50-500 nm films). These effects seem to be caused by the difference of PLAL mechanisms and by peculiarities of thermal diffusion at the film-substrate interface and increased heating of the surrounding liquid medium. The scanning electron microscopy showed the coexistence of 100 nm sized MNPs and few-tens nanometer MNPs, as well as their agglomerates. Raman spectra for all obtained MNPs are typical ones for Guite ($Co^{2+}Co^{2}_{3+}O_4$) that points out to presence of different forms of Co oxide.

Thus, we showed that PLAL of thin cobalt films of different thicknesses can be an effective way to produce MNPs colloids with the desired MNPs size and standard deviation. Most likely, this approach can be used also with Fe films to produce high biocompatible magnetite MNPs colloids.

Investigation of laser melting and ablation thresholds of porous silicon

M. S. Grigoryeva[1,2], I. A. Kutlubulatova[1,2], E. I. Mavresko[1,2], A. A. Fronya[1,2], I. N. Zavestovskaya[1,2] and D. S. Ivanov[1,2]

[1] P.N. Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia;
[2] National Research Nuclear University MEPhI, Moscow, Russia;Russia, Moscow MEPhI
e-mail: grigorevams@lebedev.ru

Laser-synthesized silicon nanoparticles (SNPs) are widely used in different fields of biomedicine, for example, as contrast agents for bio visualization [1], as effective sensitizer of radiofrequency hyperthermia for the cancer theranostics [2], photodynamic therapy [3], as carriers of therapeutic radionuclides in nuclear nanomedicine [4] et al.

The laser ablation of a silicon (Si) target is widely studied and allows to obtain chemically pure silicon nanoparticles with a size of less than 100 nm and a relatively narrow size distribution [5]. The investigations are mostly performed for single-crystalline Si (c–Si), while interaction with a nanostructured substrate, such as porous silicon (PS), may be of particular interested. The use of PS as a target for ablation is promising from the point of view of a lower ablation threshold for this material as compared to traditionally employed single-crystalline silicon, which provides gain in the amount of ablation products formed under such conditions and, accordingly, the amount of SNPs.

In the present work, the modeling of laser melting and laser ablation of porous Si was carried out. A decrease in the melting and ablation threshold for PS relative to c-Si is shown. The results of modeling are validated by comparing the smelting and ablation threshold values for monolithic and porous Si targets obtained in the simulations and those measured in experiment. The obtained results can be used in the development of methodology for the production of colloidal solutions of Si NPs for biomedical applications with controlled mean sizes and narrow size distribution.

REFERENCES

[1] M.B. Gongalsky, L.A. Osminkina, A. Pereira, A.A. Manankov, A.A. Fedorenko, A.N. Vasiliev, V.V. Solovyev, A.A. Kudryavtsev, M. Sentis, A.V. Kabashin, V.Y. Timoshenko. Scientific Reports 6, 24732 (2016).
[2] A.V. Kabashin, V.Y. Timoshenko. Nanomedicine-UK 11, 2247-2250 (2016).
[3] V.Y. Timoshenko, A.A. Kudryavtsev, L.A. Osminkina, A.S. Vorontsov, Y.V. Ryabchikov, I.A. Belogorokhov, D. Kovalev, P.K. Kashkarov. JETP Letters 83, 423-426 (2006).
[4] V.M. Petriev, V.K. Tischenko, A.A. Mikhailovskaya, A.A. Popov, G. Tselikov, I. Zelepukin, S.M. Deyev, A.D. Kaprin, S. Ivanov, V.Y. Timoshenko, P.N. Prasad, I.N. Zavestovskaya, A.V. Kabashin. Scientific Reports 9, 2017 (2019).
[5] A.V. Kabashin, P. Delaporte, A. Pereira, D. Grojo, R. Torres, T. Sarnet and M. Sentis. Nanoscale Res. Lett. 5, 454 (2010).

Laser engineering microbial systems: a new tool for microbiology

N. V. Minaev[1], V. S. Zhigarkov[1], V. S. Cheptsov[1,2] and V. I. Yusupov[1]

[1] Institute of Photon Technologies, FSRC "Crystallography and Photonics" Russian Academy of Sciences, Troitsk, Moscow, Russia;
[2] Soil Science Faculty, Lomonosov Moscow State University, Moscow, Russia
e-mail: iouss@yandex.ru

Microbiology and medicine are currently in acute need of advanced diagnostic tools and technologies capable of expanding the repertoire of cultivable microorganisms [1]. This is necessary, for instance, in the search for producers of novel antibiotics and bioactive substances. The crux of the issue is that currently over 99% of microorganisms from natural habitats are not cultivable by conventional means, thus representing a distinctive "microbial dark matter" [2–4].

To tackle this ambitious task, a scientific team has been developing the technology of laser engineering of microbial systems (LEMS) for the past six years [5]. In LEMS, pulsed laser radiation is used to directly transfer microscopic gel droplets containing individual microorganisms or their consortia onto a nutrient medium [5–7]. This approach enables the preservation of the microorganism's natural environment while, at the same time, removing unwanted interactions between antagonistic species through high spatial separation.

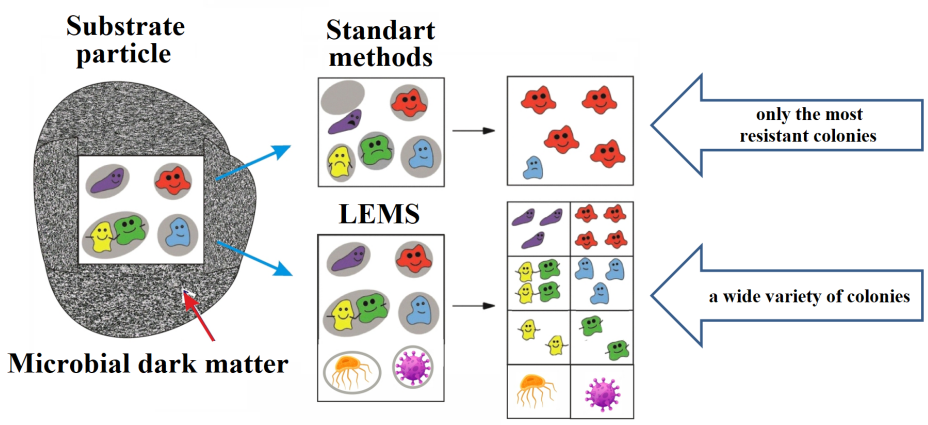


Figure 1: The advantage of the LEMS method over standard cultivation methods.

It has been shown that the LEMS technology significantly enhances cultivable biodiversity by allowing the isolation of bacteria that are challenging to cultivate or cannot be cultured using conventional methods [5]. LEMS facilitates the successful isolation of pure cultures from diverse sources, including extreme habitats (anaerobic and thermophilic microorganisms), complex heterogeneous environments [6][8], and the separation of stable symbionts [9]. This proposed technology, as a new tool in microbiology, holds significant potential for practical applications in biotechnology and medicine, while also being of interest from a fundamental biota science perspective.

The research is being conducted with the support of the Russian Science Foundation, grant No. 20-14-00286.

REFERENCES

[1] Lewis, W. H., Tahon, G., Geesink, P., Sousa, D. Z. & Ettema, T. J. G. Innovations to culturing the uncultured microbial majority. Nat. Rev. Microbiol. 19, 225–240 (2021).
[2] Dance, A. The search for microbial dark matter. Nature 582, 301–303 (2020).
[3] Jiao, J. Y. et al. Microbial dark matter coming to light: Challenges and opportunities. Natl. Sci. Rev. 8, 1–5 (2021).

[4] Zha, Y., Chong, H., Yang, P. & Ning, K. Microbial Dark Matter: from Discovery to Applications. Genomics. Proteomics Bioinformatics 20, 867–881 (2022).
[5] Yusupov, V. I. et al. Laser engineering of microbial systems. Laser Phys. Lett. 15, 065604 (2018).
[6] Cheptsov, V. S., Tsypina, S. I., Minaev, N. V., Yusupov, V. I. & Chichkov, B. New Microorganism Isolation Techniques With Emphasis on Laser Printing. Int. J. Bioprinting 5, 1–12 (2018).
[7] Zhang, Y. & Zhang, T. Culturing the uncultured microbial majority in activated sludge: A critical review. Crit. Rev. Environ. Sci. Technol. 53, 601–624 (2023).
[8] Gorlenko, M. V. et al. Laser microsampling of soil microbial community. J. Biol. Eng. 12, 27 (2018).
[9] Kochetkova, T. V. et al. Tepidiforma bonchosmolovskayae gen. nov., sp. nov., a moderately thermophilic Chloroflexi bacterium from a Chukotka hot spring (Arctic, Russia), representing a novel class, Tepidiformia, which includes the previously uncultivated lineage OLB14. Int. J. Syst. Evol. Microbiol. 70, 1192–1202 (2020).

Study of the possibility of using nanosecond laser radiation with $\lambda = 1.9\mu$m in sialolithotripsy

S. E. Minaev[1,2], Y. K. Sedova[1], D. V. Zhuchkova[3,4], S. P. Sysolyatin[3,4,5], V. P. Minaev[6], V. I. Yusupov[1] and N. V. Minaev[1]

[1] Institute of Photon Technologies, FSRC "Crystallography and Photonics" Russian Academy of Sciences, Troitsk, Moscow, Russia;
[2] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia;
[3] Patrice Lumumba Peoples' Friendship University of Russia, Moscow, Russia;
[4] «Endostom» Clinic, Moscow, Russia;
[5] Medical and Biological University named after A.I.Burnazyan, Moscow, Russia;
[6] NTO IRE-Polus, Fryazino, Moscow region, Russia
e-mail: minaevn@gmail.com

Sialoliths are concretions that form in the salivary glands, leading to the closure of salivary ducts and inflammation. Currently, sialolithiasis accounts for one-third of all salivary gland disorders and is a relatively common phenomenon, occurring in 1% of the world population aged from 20 to 45 years, and equally prevalent in men and women. Modern methods of treating sialolithiasis, including the use of laser technologies, are not without drawbacks. The main challenges faced by doctors and patients are the prolonged duration of the operation (lasting several hours) and the accompanying damage to the soft tissues adjacent to the site of salivary stone localization.

The present study examines the possibility of sialolithotripsy using an experimental pulsed laser system based on thulium (Tm)-doped fiber, specifically the ILT-20 model (NTO IRE-Polus, Russia), with an average output power of up to 20 W, pulse duration of 80 ns, pulse repetition rate ranging from 60 to 100 kHz, and pulse energy up to 300 μJ. The obtained results may prove useful in optimizing the process of laser fragmentation of salivary concretions.

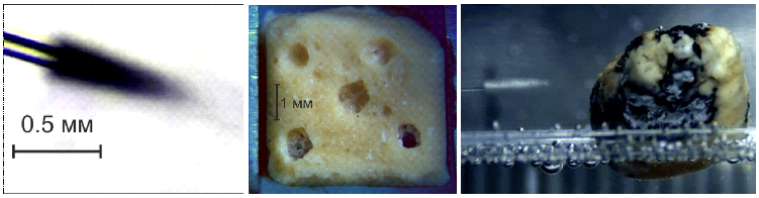


Figure 1: a) shadow photograph of a gas-vapor microjet near the end of an optical fiber. P = 17 W, f = 60 kHz; b) optical images of craters on the surface of the stone phantom; c) optical photograph of the process of the impact of a vapor-gas microjet on sialolite.

It has been shown that the achieved lithotripsy rate in the experiment exceeds the values previously achieved with continuous laser devices by 1.5 times. It has been established that the mechanism of concretion destruction is due to explosive boiling of water and the formation of a highly porous structure in the stone material as a result of complete combustion of organic compounds. It has been demonstrated that water irrigation plays a crucial role, as it not only helps maintain an acceptable temperature level but also positively affects the fragmentation speed and prevents contamination of the optical fiber tip. The effect of negative retropropulsion, attracting the concretion towards the optical fiber tip, has been discovered, which can be utilized to improve medical technology. This effect is known for lithotripsy in urology.

The author thanks NTO IRE-Polus for possibility to use the unical Thulium fiber laser.

This work was supported by State assignment Federal Scientific Research Centre «Crystallography and Photonics», Russian Academy of Sciences.

Laser-induced fabrication of tissue-engineering constructions with polymer materials and cell spheroids

E. D. Minaeva[1], A. A. Antoshin[1,2], V. I. Yusupov[1], T. S. Demina[2,3,4] and N. V. Minaev[1]

[1] Institute of Photon Technologies of FSRC "Crystallography and Photonics" RAS, Troitsk, Moscow, Russia;
[2] World-Class Research Center "Digital Biodesign and Personalized Healthcare", Sechenov University, Moscow, Russia;
[3] Enikolopov Institute of Synthetic Polymeric Materials RAS, Moscow, Russia;
[4] Moscow Aviation Institute (National Research University), Moscow, Russia
e-mail: minaeva.e.d@bk.ru

The aim of this study is to develop laser additive technologies for the formation of biocompatible scaffolds using the surface-selective laser sintering (SSLS) method [1] and to modify the laser-induced forward transfer (LIFT) method [2] for the seeding scaffolds with living cells aggregates – cell spheroids.

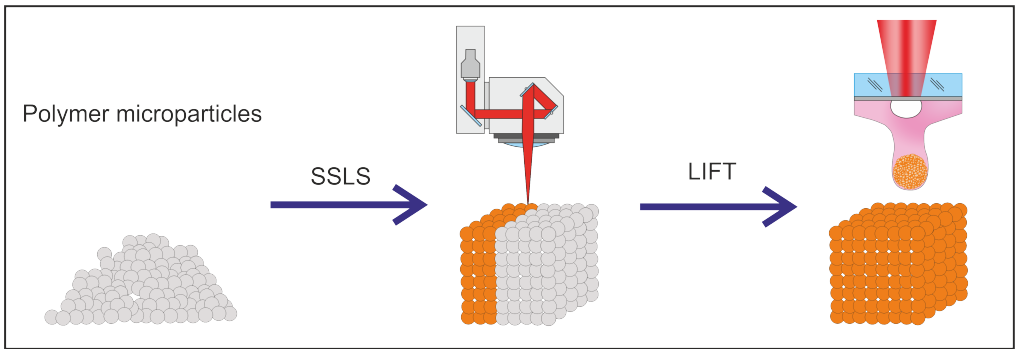


Figure 1: Scheme of laser-induced fabrication of tissue-engineering constructions with polymer microparticles and cell spheroids.

In this work, the processes of surface-selective laser sintering of polylactide microparticles with various shapes and compositions, coated with a hydrophilic shell of natural polymers are studied. It is shown that in the presence of water retained by the hydrophilic shell, the microparticles are sintered by their surfaces in the SSLS mode. It has been established that hybrid spherical microparticles with a polymer/hydroxyapatite nanoparticles ratio of 3/1 with a diameter of 100-200 μm can be successfully used as a "building blocks" for three-dimensional structures.

The process of bioprinting (spatial transfer) of cell spheroids was studied using different intensity distributions in the laser spot. It is shown that laser beam with a non-Gaussian intensity distribution profile close to a Π-shape and a spot diameter comparable to the spheroid diameter make it possible to transfer spheroids in accurate and gentle mode. At the same time, good cell survival ($\sim$ 80%) and high resolution of three-dimensional printing are provided.

This work was performed by the Russian Science Foundation project no. 20-14-00286 https://rscf.ru/project/20-14-00286/ and partly within the State Assignment of FSRC "Crystallography and Photonics" RAS in using the equipment of the Center for Collective Use.

REFERENCES

[1] N.V. Minaev et al. Bull. Russ. Acad. Sci. Phys. 84 (11), 1315 (2020).
[2] E.D. Minaeva et al. Micromachines. 14 (6), 1152 (2023).

Structural and optical properties of composite silicon-silver nanoparticles produced by laser ablation technique and potentials for biophotonics

V. Yu. Nesterov[1,2], D. V. Shuleiko[1], O. I. Sokolovskaya[1], D. E. Presnov[1,3], D. A. Kurakina[5], A. V. Khilov[5], M. Yu. Kirillin[5] and S. V. Zabotnov[1]

[1] Lomonosov Moscow State University, Faculty of Physics, Moscow, Russia;
[2] Moscow Institute of Physics and Technology, Dolgoprudny, Moscow region, Russia;
[3] Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow, Russia;
[4] P. N. Lebedev Physical Institute, Moscow, Russia;
[5] Institute of Applied Physics RAS, Nizhny Novgorod, Russia
e-mail: nesterovvy@my.msu.ru

Composite silicon-silver (Si/Ag) nanoparticles simultaneously have properties of dielectric and metallic nanoparticles [1,2]. Such nanocomposites (NCs) are promising for diagnostic and therapeutic applications in biophotonics [3] due to relatively high biocompatibility and low toxicity.

In our work, to fabricate Si/Ag NCs we applied the technique of laser ablation of monocrystalline silicon in water-ethanol solution containing $AgNO_3$. The irradiation was carried out with laser pulses (1064 nm, 34 ps, 10 mJ) for 60 minutes. The initial amount of the $AgNO_3$ and the ratio of water and ethanol in the aqueous solution were varied to optimize the technology. This relatively simple one-stage technology makes it possible to obtain stable and chemically pure Si/Ag NCs with a required morphology in quantities which are sufficient for further use in biomedical applications.

Energy dispersive X-ray spectroscopy confirmed that the Si/Ag NCs contain Si and Ag. Silicon cores about 120 nm in size are decorated with individual Ag nanoclusters ranging in size from 5 to 15 nm according to data of scanning electron microscopy (SEM). A detailed SEM analysis of the formed Si/Ag NCs additionally revealed morphological features of the NCs which depend on the initial amount of $AgNO_3$, the ratio of water and ethanol in the solution, and the pH-factor of a liquid (water, acetic acid, ammonia) where the nanoparticles were placed after fabrication. Spectrophotometric measurements of the Si/Ag NCs suspensions revealed a pronounced maximum of resonant absorption at the wavelength of 435 nm. This absorption peak is explained using the Mie theory by the presence of Ag nanoclusters and the polydisperse size distribution of silicon nanoparticles. The resonant absorption makes it possible to consider the fabricated Si/Ag NCs as promising agents for photohyperthermia because we can increase heating compared to pure silicon nanoparticles at the same mass concentration owing to the Ag inclusions.

REFERENCES

[1] S.O. Gurbatov, V. Puzikov, et al., Materials 15, 8091 (2022).
[2] S.O. Gurbatov, V. Puzikov, et al., Opt. Laser Technol. 147, 107666 (2022).
[3] A. Al-Kattan, G. Tselikov, et al., Nanomaterials 11, 592 (2021).

Confocal Raman scattering microspectrocopy for diagnostic skin tumors

E. N. Rimskaya[1], S. N. Shelygina[1], I. N. Saraeva[1,2] and K. G. Kudrin[1,3]

[1] P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] N.A. Semashko National Research Institute of Public Health, Moscow, Russia;
[3] I.M. Sechenov First Moscow State Medical University, Moscow, Russia
e-mail: rimskaya@lebedev.ru

Modern healthcare needs the development of methods for the early detection of skin tumors in order to improve the quality of the organization of oncological care. [1]. Therefore, a promising way to solve this problem is the use of confocal Raman scattering microspectroscopy with excitation in the visible range (532 nm) [2].

The paper presents an experimental substantiation of the use of the technology of confocal Raman scattering microspectroscopy at 532 nm wavelength in vitro as the first stage in the development of a method for early non-invasive express diagnostics of tumor diseases, in this case, basal cell carcinoma of the head and neck. We also analyzed Raman spectra without noise and without fluorescence of skin tumors in vitro, in normal and pathological conditions [3-5].

It is shown that confocal Raman scattering microspectroscopy with the analysis of Raman peaks has high sensitivity and specificity (>80%). Thus, this method can be effectively used as an objective non-invasive method for diagnosing skin tumors to identify the characteristic pathomorphological signs of tumors for their verification.

REFERENCES

[1] P.E. LeBoit, G. Burg, D. Weedon, A. Sarasain, World Health Organization Classification of Tumours. Pathology and Genetics of Skin Tumours, 2006.
[2] V.V. Tuchin (Ed.). Handbook of Optical Biomedical Diagnostics. Light-Tissue Interaction, PM262, Methods, PM263, SPIE Press, Bellingham, WA, USA; 2016.1420 p.
[3] V.V. Tuchin, J. Popp, V. Zakharov. Multimodal. Optical. Diagnostics of Cancer. 597. 2020.
[4] Khristoforova YA, Bratchenko IA, Myakinin OO, Artemyev DN, Moryatov AA, Orlov AE, Kozlov SV, Zakharov VP. Portable spectroscopic system for in vivo skin neoplasms diagnostics by Raman and autofluorescence analysis. J Biophotonics. 2019;12(4): e201800400.
[5] A. Tfayli, O. Piot, M. Manfait, V.1 (2), P.140-53. 2008.

Locally enhanced electric field treatment of *E. coli*: TEM, FT-IR and Raman spectrometry study

I. N. Saraeva[1], D. A. Zayarny[1], E. R. Tolordava[1], A. A. Nastulyavichus[1], R. A. Khmelnitsky[1], D. N. Khmelenin[2], S. N. Shelygina[1], S. I. Kudryashov[1]

[1] P. N. Lebedev Physics Institute of Russian Academy of Sciences, Moscow, Russia;
[2] Institute of Crystallography, Federal Scientific Research Centre "Crystallography and Photonics", Russian Academy of Sciences, Moscow, Russia

e-mail: rimskaya@lebedev.ru

We report the study of low-voltage locally enhanced electric field treatment (LEEFT) of *E. coli* bacteria via TEM analysis and FT-IR and Raman spectrometry. The formation of pores was confirmed by TEM, which revealed the membrane rupture and the formation of precipitates in the cell volume, and by propidium iodide photoluminescence spectra. LEEFT results in the alternation of DNA and RNA, indicated by the change in its α-helical and β-helical forms [1]. Several peaks of membrane fatty acids broaden, while the others narrow, which indicates the change of the molecular bonds in their moiety, and may result from the rigidification during the shrinkage of the inner membrane and the increase in fluidity of the outer membrane. The observed changes were partially confirmed by TEM images, which indicate the dense precipitates' formation in the cell volume and membrane, as well as the cytoplasmic membrane shrinkage away from the outer membrane.

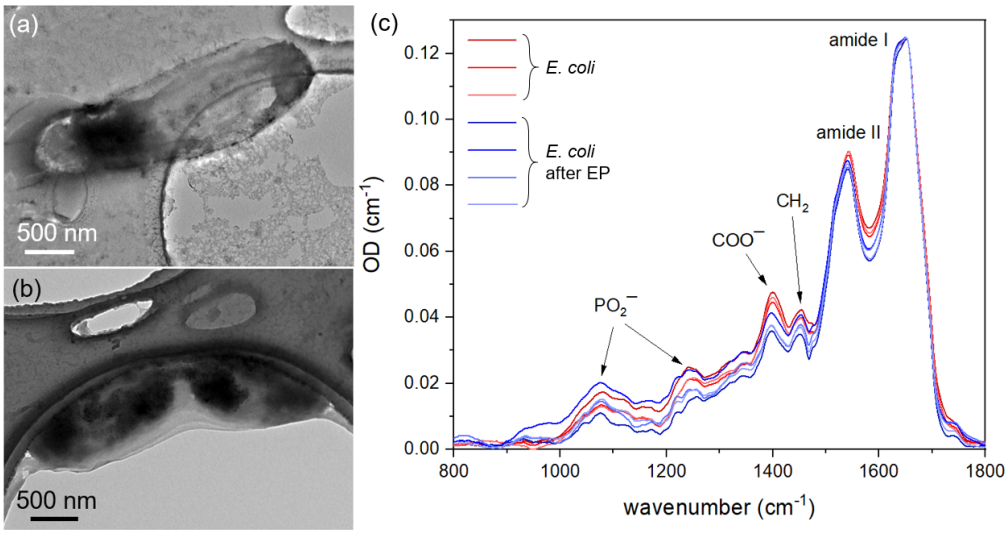


Figure 1: TEM images of *E. coli* bacteria before (a) and after (b) electroporation; (c) – the corresponding FT-IR spectra.

REFERENCES

[1] F. Author, S. Author, Journal Number (issue), page (year). A. Kamnev, L. Antonyuk, A. Tugarova, P. Tarantilis, M. Polissiou, P. Gardiner, J. Mol. Struct. 610, 127-131 (2002).

[2] N. Rowan, S. Macgregor, J. Anderson, R. Fouracre, O. Farish, Lett. Appl. Microbiol. 31, 110-114 (2000).

FT-IR analysis of pathogenic bacteria inactivation by femtosecond IR laser pulses

S. N. Shelygina[1], I. N. Saraeva[1], A. A. Nastulyavichus[1], E. R. Tolordava[1,2], R. A. Khmelnitskii[1] and S. I. Kudryashov[1]

[1] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] National Research Center for Epidemiology and Microbiology. N. F. Gamalei, Moscow, Russia
e-mail: shelyginasn@lebedev.ru

IR radiation have bacteriocidic effect against various spices of bacteria, spores and fungi's and is used for sterilization and pasteurization of food products. The IR radiation with a wavelength of 3 and 6 micrometers are the most effective for pathogen inactivation. These wavelengths corresponding to vibrations frequencies of C-H bond (3 mkm) and C=O, N-H bond of amide groups of proteins (6 mkm).

In our previous investigations, the inactivation effect of femtosecond IR pulses with wavelength of 3 and 6 mkm on *P.aeruginosa* bacteria was shown. We associate this effect with destraction of hydrogen bonds and proteins denaturation, since no visible damage to the cell membranes was identified by scanning and transmission electron microscopy. In this study we investigate molecular changes caused by effect of femtosecond IR laser pulses with wavelength of 3 and 6 mkm to *P.aeruginosa* bacteria by the stationary Fourier-transform IR spectroscopy, with the spectral peaks parameters being obtained by Lorentzian fitting with the hidden peaks revealed by the second derivative calculations. The results of analysis show changes in the characteristic band associated with proteins, lipids and fatty acids of bacteria.

This research was funded by the Ministry of Science and Higher Education of the Russian Federation (Ural Federal University Program of Development within the Priority-2030 Program).

REFERENCES

[1] V. Kompanets, S. Shelygina, E. Tolordava, S. Kudryashov, I. Saraeva, A. Rupasov, M. Kovalev, "Spectrally-selective mid-IR laser-induced inactivation of pathogenic bacteria", Biomed. Opt. Express, 12, 6317–6325 (2021).

[2] D. Hamanaka, T. Uchino, N. Furuse, W. Han, and S. ichiro Tanaka, "Effect of the wavelength of infrared heaters on the inactivation of bacterial spores at various water activities," Int. J. Food Microbiol. 108(2), 281–285 (2006).

Multispectral Raman and photoluminescence microanalysis of different malignant skin neoplasms

S. N. Shelygina[1], E. N. Rimskaya[1], A. B. Timurzieva[1,2], I. N. Saraeva[1], E. V. Perevedentseva[1], N. N. Melnik[1], K. G. Kudrin[1,3], D. Reshetov[4] and S. I. Kudryashov[1]

[1] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia;
[2] N.A. Semashko National Research Institute of Public Health, Moscow, Russia;
[3] I.M. Sechenov First Moscow State Medical University, Moscow, Russia;
[4] A.I. Evdokimov Moscow State University of Medicine and Dentistry, Moscow, Russia
e-mail: shelyginasn@lebedev.ru

Modern healthcare needs to develop methods for early detection of skin cancer. In this aspect, the use of optical technologies is of interest. Thus, confocal scanning Raman and photoluminescent microspectroscopy is a highly sensitive non-invasive method for measuring the chemical composition of tissue biomarkers.

In this work, various pathologies of the skin, as well as healthy skin, were studied by Raman spectroscopy with excitation wavelengths of 532 nm, 785 nm and 1064 nm. Significant differences in the spectra of basal cell carcinoma (BCC) and squamous cell carcinoma (SCC) and healthy tissue were found. The excitation wavelength affects the ratio of the intensities of the Raman peak of various biomolecules. The results of the study of Raman / photoluminescence spectra at different excitation wavelengths indicated that the spectral criteria, calculated as the ratio 23 of the selected Raman peak intensities, provide useful information assisting in differentiation of 24 healthy skin from BCC and SCC with sensitivity and specificity higher than 95%.

This research was funded by Russian Science Foundation, grant number 23-25-00249.

REFERENCES

[1] Elder, D.E.; Massi, D.; Scolyer, R.A.; Willemze, R. WHO Classification of Tumours, 4rd ed.; International Agency for Research on 474 Cancer Press: Lyon, France, 2018; Volume 11.
[2] Anastassopoulou, J.; Kyriakidou, M.; Malesiou, E.; Rallis, M.; Theophanides, T. Infrared and Raman Spectroscopic Studies of 515 Molecular Disorders in Skin Cancer. In Vivo 2019, 33, 567–572. DOI: 10.21873/invivo.11512.

Dissection of zona pellucida of mouse embryos in cryopreservation protocols by femtosecond laser pulses

D. S. Sitnikov[1], D. E. Mukhdina[1], D. C. Korshunova[1,2], M. A. Filatov[1,2], Yu. Yu. Silaeva[1,2] and I. V. Ilina[1]

[1] Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia;
[2] Institute of Gene Biology of the Russian Academy of Sciences, Moscow, Russia
e-mail: sitnik.ds@gmail.com

The zona pellucida (ZP) is an extracellular matrix that surrounds the oocyte at the preimplantation stages of development. At the blastocyst stage embryo starts hatching and leaves the shell. There is a number of factors preventing the embryo from successful hatching including impaired production of enzymes responsible for the ZP lysis, thick or dense ZP. There is some evidence that embryo cryopreservation by vitrification alters physical and chemical properties of the ZP, the so called zona hardening effect. The laser microsurgery technique is aimed to violate the ZP integrity and help the embryo to hatch.

In this paper we apply femtosecond laser pulses for laser assisted hatching (LAH) procedure of embryos underwent cryopreservation protocol (the so called thawed embryos). Detailed description of the experimental setup as well as the parameters for successful LAH procedure on fresh embryos can be found elsewhere [1]. Laser pulses at wavelength of 514 with a Gaussian intensity profile in space and time, 280 fs long (at half height), were focused by an Olympus UPLFLN 20× lens with a numerical aperture NA = 0.5 into a spot 2.3 μm in diameter at the 1/e level. The beam was focused in the plane of maximum embryo cross-section, i.e. in the equatorial plane of the embryo. ZP dissection was performed by a series of femtosecond laser pulses following with a repetition rate of 2.5 kHz with simultaneous embryo movement along the trajectory set by operator. We have studied the cut widths of the ZP as a function of laser pulse energy E for a given laser beam velocity v and vice versa (fig.1).

The obtained results demonstrate no significant difference in the cut widths of the ZP of thawed compared to fresh ones [2]. This suggests that parameters considered to be optimal for fresh embryos can be used for microsurgery of embryos in cryopreservation protocols.

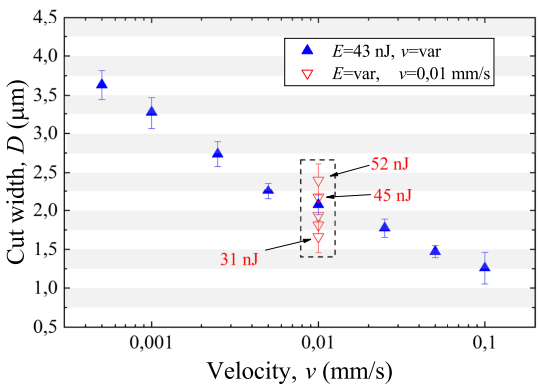


Figure 1: Cut width of the thawed embryos as a function of laser beam velocity and laser pulse energy for pulse repetition rate 2.5 kHz.

REFERENCES
[1] I. Ilina, Y. Khramova, J. Assist. Reprod. Genet., 38 (2), 517 (2021).
[2] I. Ilina, Y. Khramova, Biomed. Opt. Express, 10 (6), 2985 (2019).

Laser-ablated Si and Si/Ag nanoparticles: bioimaging, photohyperthermia, and biocompatibility

S. V. Zabotnov[1], D. V. Shuleiko[1], V. Yu. Nesterov[1,2], O. I. Sokolovskaya[1], L. A. Golovan[1], P. D. Agrba[3], A. N. Balashova[3], A. V. Khilov[4], D. A. Kurakina[4], E. A. Sergeeva[4] and M. Yu. Kirillin[4]

[1] Lomonosov Moscow State University, Faculty of Physics, Moscow, Russia;
[2] Moscow Institute of Physics and Technology, Dolgoprudny, Russia;
[3] N. I. Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia;
[4] Institute of Applied Physics RAS, Nizhny Novgorod, Russia
e-mail: zabotnov@physics.msu.ru

Silicon nanoparticles (SiNPs) are successfully used in various biomedical applications due to their low toxicity and biodegradability. In this paper we study the possibility of employment of laser-ablated SiNPs in biophotonics. The particles are formed by femtosecond (1250 nm, 150 fs) and picosecond (1064 nm, 34 ps) laser ablation of monocrystalline and porous silicon targets in various liquids: water, ethanol, liquid nitrogen, and aqueous ethanol solution with silver nitrate. In the latter case, it is possible to decorate the SiNPs surface with silver nanoparticles (Si/Ag).

As a result of the ablation, SiNPs suspensions were fabricated with the nanoparticles mean size varying from 25 to 120 nm depending on the parameters of laser pulses (energy, duration, and number), the targets used, and the buffer liquids.

An analysis of the measured values of the scattering and absorption coefficients of the prepared SiNPs suspensions showed that such nanosystems have high potential as contrast agents in optical coherence tomography. This assumption was confirmed by experiments on contrasting structural inhomogeneities of agar gel with the embedded SiNPs.

A numerical experiment of a photohyperthermia process with the SiNPs embedded into a human subcutaneous basal cell carcinoma showed that it is possible to provide hyperthermia of the entire tumor without significant overheating the surrounding healthy tissues. A real experiment on heating was carried out with a phantom simulating the optical properties of human skin (agar gel with lipofundin and red ink) and confirmed that the adminisration of the SiNPs on the phantom increases its heating under equivalent irradiation conditions compared with the phantom without nanoparticles. Additionally, the decorated Si/Ag nanoparticles are of interest for further research as agents for photohyperthermia, since the silver inclusions may increase heating without increasing the mass concentration of the agents.

In vivo monitoring of the reaction of laboratory mice after administration of the SiNPs was carried out using the “Open field” test, which makes it possible to estimate the general (locomotor) and exploratory animal activities. Low toxicity of the SiNPs was shown for oral and topical administration, however, an increase in the stress level in the experimental groups relative to the control ones was revealed. Thus, the biocompatible SiNPs formed by laser ablation in liquids are of undoubted interest for solving problems of biological tissues theranostics .

Author Index

Editors:

Tatiana Mamontova

Sergey Bochkarev

Abstracts are published in the author's edition

Printing design:

Daria Mokrousova