TERA 2012

Joint Student Session

at 2-nd International Conference

"Terahertz and Microwave radiation: Generation, Detection and Applications“

Russia, Moscow

M.V. Lomonosov MSU

June 20 - 22, 2012

SPIE Student Chapter M.V. Lomonosov Moscow State University & OSA The Optical Society International Laser Center M.V. Lomonosov MSU Student Chapter

Program

WEDNESDAY, JUNE 20, 2012

17:45 - 19:45	Young scientists and students 5-minute talks & posters	
17:45 - 17:55	Kseniya Goroshko	Analytical investigation of THz radiation generated by long two-color femtosecond pulses in a dielectric third-order nonlinear medium
17:55 - 18:05	Egor Sedykh	Software for control of continuous wave terahertz spectrometer
18:05 - 18:15	Sergei Stremoukhov	Terahertz response in two-color arbitrary polarized light
18:15 - 18:25	Mariya Tsurkan	Review: Impact of terahertz radiation on cell systems
18:25 - 18:35	Anna Ezerskaya	Investigation of the possibility of diagnostic cataract lenses of human’s eyes in the THz rang
18:35 - 18:45	Vera Andreeva	Low-frequency few-cycle pulses generation by four-wave mixing in femtosecond filament in gases
18:45 - 18:55	Evgeniya Smetanina	Interference nature of supercontinuum anti-Stokes wing in filamentation under anomalous GVD
18:55 - 19:05	Irina Zhvania	Plasma filament and spectral modification in the intense laser-cluster interaction
19:05 - 19:15	Aleksander Dergachev	Filamentation of femtosecond IR and UV laser pulses in focused beams

Scientific school for students and young scientists

"Nonlinear optics and terahertz radiation"

June 20-21, 2012

M.V. Lomonosov MSU

Moscow, Russia

Book of Abstracts

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Student Chapter

Analytical investigation of THz radiation generated by long two-color femtosecond pulses in a dielectric third-order nonlinear medium

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***Abstract*— This study is unique in that it predicts generation of THz radiation in a field of two different-frequency fs pulses propagating in a third-order nonlinear medium without plasma occurrence (ie, at low intensities of input pulses).**

I. Introduction And Background

THz range could be considered as practically unexplored at the moment, since the commercial devices are still being developed and investigated. In contrast to the neighbouring ranges of microwave and infrared radiation, THz range is quite difficult to obtain in practice. Despite the fact that many research laboratories possess plants to generate and research THz waves each experiment stays costly and difficult in performance. Therefore, it is important to develop theoretical and modeling methods of these phenomena.

Effects that arise in the interaction of femtosecond pulses in third-order nonlinear medium are investigated in details by many scientific groups [1].

II. Results

In this work it is shown that the intensity of the generated combination frequencies has a quadratic dependence on the intensity of the main pulse and the linear dependence on the intensity of second-harmonic pulse.

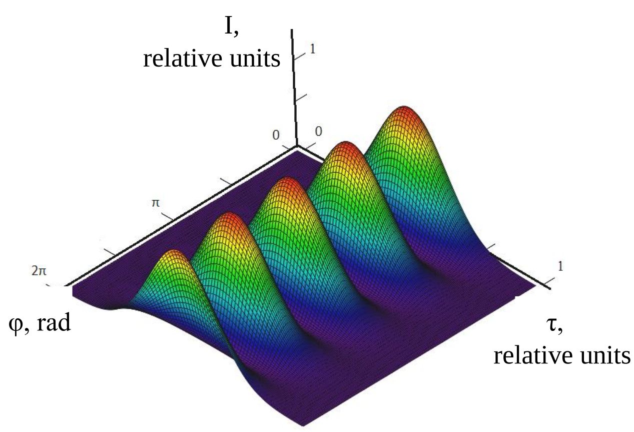

Figure 1 Intensity of THz radiation as a function of the phase shift between the input pulses

Generation efficiency varies depending on the spatial shift of the input pulses by a harmonic law, and the change period is quarter period of the fundamental radiation, or half period of the second harmonic.

It is shown that the efficiency of energy transfer in THz power increases linearly with the increasing of cubically nonlinear medium layer. When the typical time of input pulses is less than 1 ps, generation efficiency remains constant, of the order of $10^{-7}\%$, when typical time of the input pulses is greater than 1 ps, efficiency decreases logarithmically.

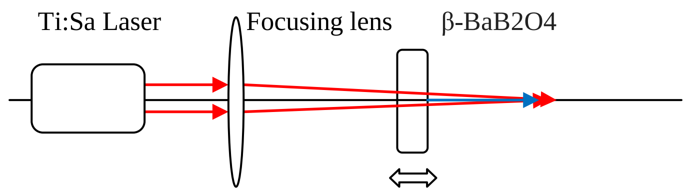

Figure 2 Schematic diagram of the titanium-sapphire femtosecond laser system for generation of THz radiation

These results can be used for interpreting and predicting the results of experiments on the generation of THz radiation in the field of two femtosecond optical pulses in a medium with cubic nonlinearity and for optimization of input parameters to improve the efficiency of generation of THz radiation.

References

[1] Jianming Dai, Jingle Liu, Xi-Cheng Zhang, “Terahertz Wave Air Photonics: Terahertz Wave Generation and Detection With Laser-Induced Gas” , IEEE Journal of Selected Topics in Quantum Electronics - IEEE J SEL TOP QUANTUM ELECTR , vol. 17, no. 1, pp. 183-190, 2011

Software for control of continuous wave terahertz spectrometer.

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Abstract

We have assembled a CW THz spectrometer and designed software to control the installation and automatically acquire the data.

INTRODUCTION

The frequency domain from 100 GHz to 10 is often referred as the “terahertz gap”. Depending on the techniques employed for the generation of the radiation it is called either a sub-mm or a far-infrared region. For a long time the THz frequency had been suffering from a significant lack of technological development, thus this part of the electromagnetic spectrum has recently drawn attention of scientists all over the world. For many applications it is alluring to use THz radiation, due to its transient position, which makes possible to gain detailed molecular information and easily penetrate normally diffusive materials. The most well-known THz application is security screening of airline passengers, however the astrophysical community has successfully been utilizing THz radiation for a number of decades during which it was providing significant information such as the visualization of objects hidden behind interstellar dust clouds. New applications of THz radiation heavily depend on the availability of powerful sources that can cover the entire THz band, and sensitive detectors with short response times at room temperature [1].

One of the most promising approaches for generation and detection of tunable terahertz radiation with large scanning bandwidths and good signal-to-noise ratios is based on photomixing in photoconductive switch (PCS) devices fabricated in low-temperature-grown gallium arsenide (GaAs) and erbium arsenide:gallium arsenide (ErAs:GaAs). In the frequency-domain technique, continuous-wave (CW) terahertz radiation is produced through photomixing of the combined output of two single-frequency diode lasers in a PCS. In this heterodyne approach, the wavelength of one (or both) of the lasers is tuned to vary the terahertz output frequency. It is necessary to have special software to control laser parameters and tune laser wavelength. In this work such software has been developed.

RESULTS

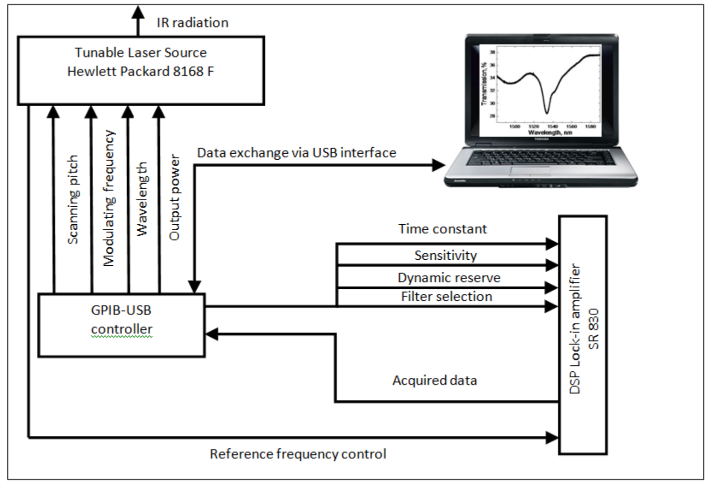

Figure 1: Installation diagram.

Our CW THz software module to control parameters of infrared laser is a simple-to-use program designed for researchers who need to study materials properties at THz frequencies with high resolution. The module was developed using NI LabVIEW graphical development environment. The software can sweep from 100 GHz to 18 THz in a single linear rapid scan with frequency resolution better than 0.125 GHz or can 'frequency hop' between frequencies of interest to scan specific regions of the spectrum with varying degrees of resolution. It allows modifying of laser wavelength, laser power, modulation mode and other laser parameters. The software module has friendly user interface and it can be fully integrated into software for CW THz spectrometer.

REFERENCES

1. S. Preu, G. H. Dö hler, S. Malzer, L. J. Wang, Tunable, Continuous-Wave Terahertz Photomixer Sources and Applications, Journal of Applied Physics 109, 061301 (2011)

Terahertz atomic response in two-color arbitrary polarized light

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***Abstract*— We present and analyze the result of theoretical investigations of the terahertz emission generated by an atom interacting with two-color laser field in ionization-free regime.**

I. Introduction And Background

Terahertz (THz) radiation generation is under an intensive investigation both experimentally [1-3] and theoretically [4-5]. For theoretical study of this process the phenomenon of four-wave mixing rectification is widely used [4]. For this phenomenon it is important to have plasma. Here we present a new mechanism of the THz generation, which is based on the intra-atomic non-linearities. We apply the non-perturbative theory of single atom interaction with arbitrary polarized laser field for explanation of this mechanism [6].

Our non-perturbative theory is based on the consequent transformation of the time-dependent Schrödinger equation

$$i\hbar \frac{\partial \psi(\bar{r},t)}{\partial t} = \left[\frac{1}{2m} \left(\bar{p} - \frac{q}{c} \bar{A}(t) \right)^2 + U(\bar{r}) \right] \psi(\bar{r},t)$$

to the set of differential equations for probability amplitudes of discrete and continuum states

$$i\hbar \frac{da_n}{dt} = \sum_{m,k} (e^{i\frac{q}{\hbar c}\bar{A}(t)\bar{r}})_{nk} E_k (e^{-i\frac{q}{\hbar c}\bar{A}(t)\bar{r}})_{km} a_m . \qquad (1)$$

The set of equations (1) contains an infinite number of equations because the basis of discrete and continuum states of any hydrogen-like atom is infinite. That is why it is important for numerical solving of the (1) to truncate them. The consistent mathematical procedure of truncation has been proposed in [6].

The theory is semi-analytical. That means that only the set of equations (1) are calculated numerically, at the same, time the matrix elements (for example matrix elements for total atomic current and the coefficients of the equations in (1)) are calculated analytically without any assumptions. Moreover, the mutual orientation the atomic angular momentum and direction of the two-color laser field polarization is taken into account in consistent form.

II. Results

In our numerical calculations we use 13th level Argon atom model and investigate the interaction between this atom and two-color laser field formed by the fundamental and the second harmonic of Ti:Sapphire laser.

The main idea of the numerical experiments is to investigate the interaction of an atom with laser field in ionization-free regime. This means that in atom's model there are no continuum states.

We numerically demonstrate the existence of the THz signal in the emission spectra in ionization-free regime. We also illustrate the strong dependence of the THz spectra and the conversion efficiency on the parameters of two-color laser field. From these parameters, the two of them (the angle between the polarizations of two-color laser field and the chirp of the components) impact significantly on the THz signal.

We also demonstrate the dependence of THz polarization on the angle between the polarizations of two-color laser field. This dependence has non-monotonic behavior.

Thus, the presented results of computer simulations demonstrate clearly that the THz signal does exists in ionization-free regime; the THz signal parameters (spectrum, conversion efficiency, and polarization) strongly depend on the variation of temporal profiles of the two-color field pulses.

References

[1] D. Cote, J. M. Fraser, M. DeCamp, P.H. Bucksbaum and H.M. van Driel, "THz emission from coherently controlled photocurrents in GaAs". Appl. Phys. Lett, Vol. 75, 3959-3961, 1999.
[2] D.J. Cook and R.M. Hochstrasser, "Intense terahertz pulses by four-wave rectification in air", Opt. Lett., Vol. 25, 1210-1212, 2000.
[3] K.Y. Kim, A.J. Taylor, J.H. Glownia and G.Rodriguez, "Coherent control of terahertz supercontinuum generation in ultrafast laser-gas interactions", Nat. Phot., Vol. 2, 605-609, 2008.
[4] D. J. Cook, R. M. Hochstrasser, "Intense terahertz pulses by four-wave rectification in air", Opt. Lett., Vol. 25, 1210–1212, 2000.
[5] M. Kress, T. Löffler, S. Eden, M. Thomson, H. G. Rokos, "Terahertz-pulse generation by photoionization of air with laser pulses composed of both fundamental and second-harmonic waves", Opt. Lett., Vol. 29, 1120–1122, 2004.
[6] A.V. Andreev, S.Yu. Stremoukhov, O.A. Shoutova, "Nonlinear Optical Response of an Atom in the Field of Femtosecond Laser Pulses with Near-Atomic Intensity", JETP Letters, V. 93, No. 8, pp. 476–486, 2011.

Review: Impact of terahertz radiation on cell systems

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***Abstract*—The terahertz radiation corresponds to wavelengths from 30 µm to 3 mm. With relatively low photon energy of 0.41 to 41 meV, radiation within this frequency range is considered non-ionizing. The peculiarity of the terahertz radiation lies in the fact that a significant part of the vibrational-rotational spectrum of water and many organic molecules including biologically active macromolecules (i.e. proteins and nucleic acids), as well as the frequencies of intermolecular interactions are located in its frequency range. Despite the recent technological applications of THz radiation in biology and biomedicine, which are based on the specific spectroscopic fingerprints of biological matter in this spectral region, very little is known about its interaction with biological systems. This is reflected in an increasing number of works, related to the study of possible effects that are caused by the absorption of THz radiation by various biological objects at different levels of biological organization. This review will consider some of them, devoted to effects on cellular systems.**

I. Introduction And Background

The recent development of new sources to generate terahertz radiation with high spectral sensitivity and resolution allowed the creation of new technologies, ranging from telecommunication to biology and biomedicine. The study of the potential effects of THz radiation on biological systems is then an important issue in order to safely develop a large number of applications. Since energy of this radiation is comparable to the energy of hydrogen bonds, van der Waals forces of intermolecular interactions and charge-transfer reactions, it can cause nonlinear resonance mechanisms in biomolecules. This can lead to profound effects on the chemical and enzymatic kinetics. That may affect the normal functioning of a cell, an organ or an organism. It is better to start a systematic investigation of the effect of terahertz fields on simple objects like cell cultures.

A number of papers describe the changes of cell morphology and viability, as well as the ability to maintain the membrane potential, using THz radiation of different frequencies and power densities. Several studies have indicated both stimulatory and inhibitory effects on cell systems. Thus at paper (1) the authors report that an exposure to THz radiation at a frequency of 0.136 THz for 150 and 240 min results inhibition of cell growth at 2 and 7 times, respectively. Interestingly, other researchers do not observe these effects when they try to repeat the results of this work using the same methodology (2). Morphological changes and cell death of 7% of rat kangaroo kidney epithelial cells have been described in the paper (3).These effects were achieved by radiation with a frequency of 1.5 THz, a power density of 0.1 mW/cm^2 and irradiation times from 1-10 minutes. The same result was statistically confirmed by significant increases in the inhibition of DNA synthesis in THz exposed cells, which was furthermore confirmed in a subsequent paper from the same authors (4). In the paper (5) authors observed an increase and decrease, respectively, in growth of yeast cells (Saccharomyces CEREVISIAE) under the influence of a continuous source of THz radiation with frequencies of 0.2-0.35 THz and a power density of 5.8 mW/cm^2. The appearance of lipid droplet-like inclusions in the cytoplasm of mouse stem cells was observed after a prolonged (540min) exposure to broadband THz radiation (centered at 10 THz with a power density of 1 mW/cm^2) (6). In work (7) broadband pulsed THz radiation in the frequency range of 0.05 to 2 THz increases the stimulating effect on nerve cells growth with decreasing power of the used radiation (0.5 µW/cm^2).

II. Conclusions

THz radiation, with a fundamental period in the pico-second range, is uniquely suited to control functions in molecular systems of central importance for living organisms. Unfortunately, the available data related to the influence of THz radiation on biological systems, and the understanding of the precise mechanisms governing this influence, are limited and the subject of debate. Due to the fact that both positive and negative effects are relevant, the study of the potential effects of THz radiation on biological systems and their mechanisms is an important issue.

References

[1] Webb, S. J. and Dodds, D. D., “Inhibition of bacterial cell growth by 136 gc microwaves,” Nature 218(5139), 374–375 (1968).

[2] Blackman, C. F., Benane, S.G.,Weil, C.M., Ali, J.C., “Effects of nonionizing electromagnetic radiation on single cell biologic systems,” Annals of the New York Academy of Sciences, 247(1), 352–366 (1975).

[3] Berns, M. W. and Bewley, W., “Inhibition of nucleic acid synthesis in cells exposed to 200 micrometer radiation from the Free electron laser,” Photochemistry and Photobiology, 46(2), 165–167 (1987).

[4] Berns, M. W., Bewley, W., Sun, C.H., Templin, P., “Free electron laser irradiation at 200 microns affects DNA synthesis in living cells,” Proc. Natl. Acad. Sci. 87(7), 2810–2812 (1990).

[5] Hadjiloucas, S., Chahal, M. and Bowen, J., “Preliminary results on the non-thermal effects of 200–350 GHz radiation on the growth rate of S. cerevisiae cells in microcolonies,” Phys. in Med. and Biol., 47(21), 3831 (2002).

[6] Bock, J., Fukuyo, Y., Kang, S., Phipps, M. L., Alexandrov, L. B., Rasmussen, K. Ø., Bishop, A. R., Rosen, E. D., Martinez, J.S., Chen, H.-T., Rodriguez, G., Alexandrov, B. S. and Usheva, A.,“Mammalian stem cells reprogramming in response to terahertz radiation,” PLoS ONE 5(12), e15806 (2010).

[7] Tsurkan M.V. et all., “Changing growth of neurites of sensory ganglions by terahertz radiation,” in Proc. of SPIE, 2012, vol. 8261, 82610S-1.

Investigation of the possibility of diagnostic cataract lenses of human's eyes in the THz range

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Was revealed correlation between the optical density of the nucleus of the lens in terahertz range with its density, determined according to the classification of L. Buratti. Sealing of the lens fibers caused by senile cataract, increases the reflectivity of the lens in the THz range. The temporal structure of reflected THz signals allows to determine the spatial distribution of density in the lens.

Terahertz radiation, having a high penetrating power and a relatively small scattering in the absence of ionizing effects[1], can be used to diagnose eye diseases such cataract, which is the lead reason for the reduction vision in the world.

Due to the urgency of implementing a number of problems the THz reflection spectra of modified lens cataract human's eyes with varying degrees of density of the nucleus was investigated in this paper. They were the lenses of the third and fourth degrees of density of classification L.Buratto. Medium Borzenka-Moroz was used to store lenses in the most natural state.

To study reflection spectrum was used the THz spectrograph. It was found that the reflection of THz radiation frequency range from 0.6 to 0.9 THz from the cataract modified lens with 4-th power density of the nucleus was 20-30%, while the reflection from the cataract modified lens with 3 - th power density of the nucleus was about 5-15% (Fig. 1).

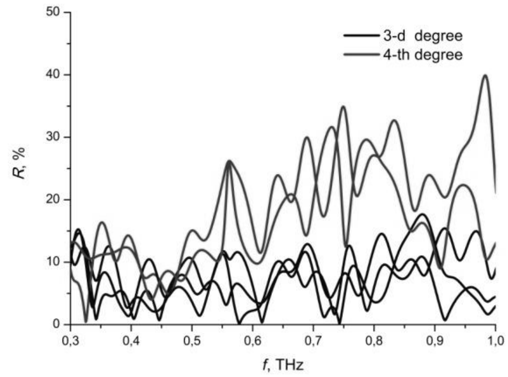

Fig. 1. Reflection spectra of the cataract modified lens with varying degrees of density of the nucleus.

The amplitude of the THz pulse reflected from the surface of the lens (Fig. 2) with the 4-th power density of the nucleus exceeds almost twice the amplitude of the pulse reflected from the surface of the lens of the 3-d degree of density.

For a lens with a 3-d degree of density we observed two reflection THz pulse with a time delay between them 6 ps, for 4-degree density of kernels we observed only one reflection, because virtually all lens is opacification.

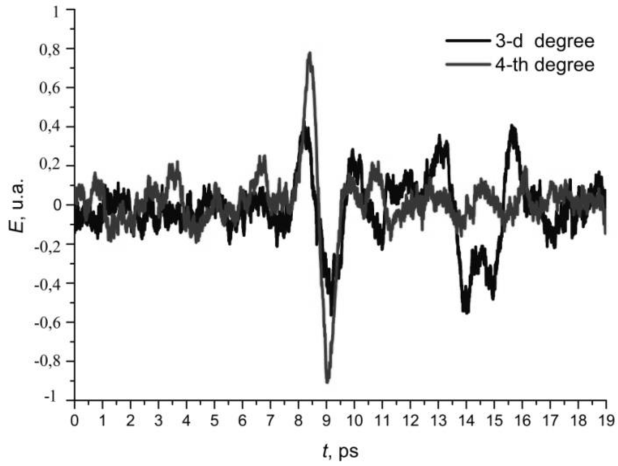

Fig. 2. Wave form of terahertz pulse reflected from the cataract modified lens with varying degrees of density of the nucleus

The use of the THz reflectometric spectrometer allows to establish a correlation between the optical density of the lens's nucleus in the terahertz range with its density, according to the classification of L. Buratto.

Hardening of the lens's fibers caused by senile cataract increases the reflectivity in the THz range, that may allow the diagnosis of stage of disease development.

The temporal structure of signal of the THz reflectometric spectrograph allow to determine the spatial distribution of density in the lens.

1. S. Wang, X.-C. Zhang. Pulsed terahertz tomography // J. Phys. D: Appl. Phys. – 2004. –V.37. – P. 1.

Low-frequency few-cycle pulses generation by four-wave mixing in femtosecond filament in gases

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The possibility of few- and single-cycle infrared pulses generation by for-wave mixing of visible seed radiation with high power femtosecond filament field with central wavelength of 800 nm is shown in argon.

I. Introduction And Background

The phenomenon of femtosecond laser pulse filamentation has been actively studying since 90s of 20th century [1] and causes a great interest at the present time [2 — 6]. High intensity in filament [7] provides the developments of different nonlinear effects: terahertz radiation generation [8, 9], 3rd harmonic generation [10, 11], polarization ellipse rotation on fundamental frequency [12, 13] and 2nd harmonic frequency [14 — 16], four-wave mixing (FWM) [17] etc.

FWM occurs when intense pump pulse with carrier frequency ω_0 propagates in filament formed by high power femtosecond laser pulse together with seed pulse with frequency ω_1 and leads to generation of signal pulse [18]. It has been experimentally observed for different spectral ranges [17 — 21] In the stationary approximation of non-degenerate FWM [18] signal pulse frequency ω_2 could be found as

$$\omega_2 = \omega_0 + \omega_0 - \omega_1. \qquad (1)$$

Duration of compressed femtosecond laser pulses in filament at the fundamental laser frequency is 2 — 3 oscillations of the light field [23, 24]. If the seed pulse has the central wavelength ω_1 in the range 420 — 490 nm, the signal pulse, according to (1), will be generated in IR spectral range with the period of 7 — 28 fs. As the signal pulse duration is determined by duration of compressed pulse in filament, it is possible to generate single-cycle IR pulses. This propagation and generation regime is of great interest because of the possibility to apply such pulses for ultra short process studying, high optical harmonic, attosecond pulses, etc.

The purpose of this work is to study the possibility of IR signal pulses generation by FWM of seed and pump radiation in filament.

II. Results

We apply field model [25] without pulse duration and spectral wide restrictions for simulation of FWM in filament in argon. For z-propagated laser radiation the scalar equation for unidirectional pulse propagation could be obtained [25]

$$2ik_z \frac{\partial}{\partial z}\hat{E}(\omega, z) = 2k_z^2 \hat{E}(\omega, z) + \frac{\omega^2}{c^3}\hat{P}(\omega, z) + \frac{4\pi i\omega}{c^3}\hat{j}(\omega, z) \qquad (2)$$

where E is electric field, P — nonlinear part of polarization, j — current density, c — speed of light, ω — radiation frequency, k_z — longitudinal wave number. Terms marked by "^" in equation (2) are Fourier transforms, without marks — depends on time.

We consider IR signal radiation generation by FWM of pump (with subscript "0") and seed radiation (with "1")

$$E(z=0, \tau) = \exp\left(-\frac{r^2}{2a^2}\right) \times \left(E_0 \exp\left(-\frac{\tau^2}{2\tau_0^2}\right)\cos(\omega_0\tau) + E_1 \exp\left(-\frac{\tau^2}{2\tau_1^2}\right)\cos(\omega_1\tau)\right) \qquad (3)$$

Pump pulse energy is $W_0 = 3.2$ mJ, duration — $2\tau_0 = 54$ fs, carrier frequency ω_0 corresponds to wavelength $\lambda_0 = 800$ nm; seed pulse — $W_1 = 10$ μJ, $2\tau_1 = 100$ fs, $\lambda_1 = 420$ — 490 nm; $2a = 1$ mm — beam diameter, $r = \sqrt{x^2 + y^2}$.

It is shown that wide IR wing with central wavelength 2.2 μm generates at the beginning of the filamentation. Period of IR radiation oscillations is 6.5 fs in a good comparison with its central wavelength. IR pulse duration is less than its doubled period. Thus, there is a possibility to form IR single-cycle pulse due to generation of difference-frequency in the FWM process at the beginning of the filamentation.

(2)

References

[1] A. Braun, G. Korn, X. Liu et al., Opt. Lett., 20, 73 (1995).
[2] S.L. Chin, S.A. Hosseini et al., Can. Journ. of Phys. 83, 863 (2005).
[3] A. Couairon, A. Mysyrowicz, Phys. Rep. 441, 47 (2007).
[4] L. Bergé, S. Skupin, R. Nuter et al., Rep. Prog. Phys. 70, 1633 (2007).
[5] В.П. Кандидов и др., Квант. электрон. 39, 205 (2009).
[6] S.L. Chin, T.-J. Wang, C. Marceau et al., Las. Phys. 22, 1 (2012).
[7] O.G. Kosareva, W. Liu, N.A. Panov et al., Las. Phys. 19, 1776 (2009).
[8] X. Xie, J. Dai, X.-C. Zhang, Phys. Rev. Lett. 96, 075005 (2006).
[9] C. d'Amico, A. Houard et al., New Journ. Phys. 10, 013015 (2008).
[10] N. Akozbek, A. Iwasaki et al., Phys. Rev. Lett. 89, 143901 (2002).
[11] N. Akozbek, S.A. Trushin et al., New Journ. Phys. 8, 177 (2006).
[12] M. Kolesik et al., Phys. Rev. E, 64, 046607 (2001).
[13] Н.А. Панов, О.Г. Косарева и др., Квант. электрон. 41, 160 (2011).
[14] P. Béjot, Y. Petit, L. Bonacina et al., Opt. Express 16, 7564 (2008).
[15] O. Kosareva, N. Panov, V. Makarov et al., Opt. Lett. 35, 2904 (2010).
[16] S. Yuan, T.-J. Wang et al., Phys. Rev. A 84, 013838 (2011).
[17] F. Theberge, N. Akozbek et al., Phys. Rev. Lett. 97, 023904 (2006).
[18] И.Р. Шен «Принципы нелинейной оптики» (M: Наука, 1989).
[19] T. Fuji, T. Suzuki, Optics Letters 32, 3330 (2007).
[20] F. Théberge, M. Châteauneuf et al., Phys. Rev. A 81, 033821 (2010).
[21] T. Fuji, T. Horio, T. Suzuki, Opt. Lett. 32, 2481 (2007).
[22] P. Zuo, T. Fuji, T. Suzuki, Opt. Express 18, 16183 (2010).
[23] C.P. Hauri, W. Kornelis et al., Appl. Phys. B 79, 673 (2004).
[24] D. Uryupina, M. Kurilova et al., Journ. Opt. Soc. Am. B 27, 667 (2010).
[25] M. Kolesik, J.V. Moloney, *Phys. Rev. E* **70**, 036604 (2004).

Interference nature of supercontinuum anti-Stokes wing in filamentation under anomalous GVD

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***Abstract*—Supercontinuum (SC) spectrum formation in filamentation under anomalous GVD regime in fused silica was investigated experimentally, numerically and analytically. It was found that the separate anti-Stokes wing of SC is the result of interference of the radiation from broadband source, that moves along the filament emitting region in dispersive media.**

I. INTRODUCTION AND BACKGROUND

Filamentation of femtosecond laser pulses in transparent media is accompanied by generation of a supercontinuum (SC) ranging from the UV to the near IR [1-3]. The maximum positive frequency shift of the SC spectrum does not depend on the intensity of the laser pulse and the spectrum remains constant at different pulse energies that generate single and multiple filamentation [4]. The analytical, numerical and experimental investigation of frequency-angular SC spectra in filamentation under different GVD is presented in [5].

In this paper we demonstrate experimentally and analytically that in the regime of anomalous dispersion in fused silica an isolated anti-Stokes wing (ASW), which is located in the visible region of SC, is formed in femtosecond filament. We found that with increasing of femtosecond pulse central wavelength the spectral band of isolated ASW becomes narrower, the intensity of its spectral components and the detuning from the pulse central wavelength increases. We showed that ASW of the SC is formed due to peculiarities of interference and self-phase modulation of the light field in the anomalous GVD regime.

The experimental setup consisted of a femtosecond laser source based on a tunable parametric amplifier (TOPAS) combined with a regenerative amplifier Spitfire Pro. Femtosecond laser pulses were focused by 50-cm silica lens on the front face of the fused silica sample, which represented an optically polished acute-angled wedge. The diameter of the beam waist was about 100 microns. Generated SC was collected by an achromatic lens to the monochromator with a matt plate at the entrance window. Spectroscopic measurements of SC in the range 400 ÷ 1100 nm were carried out with a monochromator Solar TII MS2004, the spectrometer dynamic range was about 10^3.

In the experiment the central wavelength of fs pulses was varied within the range from λ_0 = 1200 nm, which corresponds to the zero GVD, up to λ_0 = 2100 nm, which corresponds to the strong anomalous GVD in fused silica. Initial duration of used pulses was 70 ÷ 80 fs (FWHM). Their energy was increased from 2.2 μJ for pulses at the central wavelength λ_0 = 1200 nm to 4.1 μJ for pulses at λ_0 = 2100 nm, so the ratio $P_{peak} / P_{cr} \approx 5$. Analytically we have considered the interference of SC radiation, which according to [6] is coherent. Following the interference model [7] we obtained the pulse spectrum in the form of:

$$S_{interf}(\lambda) = \frac{1}{4\pi}\int |\varsigma_0(\theta,\lambda)|^2 \, \mathrm{sinc}^2\left(\frac{\Delta\varphi(\theta,\lambda)}{2}\right) d\Omega, \quad \Delta\varphi(\theta,\lambda) = \frac{2\pi l}{\lambda_0}\left(\left(1-\frac{\lambda_0}{\lambda}\right)\frac{c_0}{v_g} - \left(1-\frac{\lambda_0 n(\lambda)}{\lambda n_0}\cos\theta\right)n_0\right)$$

where $\varsigma_0(\theta,\lambda)$ is a spectral amplitude of the broadband SC point source (we took $\varsigma_0(\theta,\lambda) = 1$), which moves with pulse group velocity v_g along the emitting region with length *l*.

II. RESULTS

We have shown that the formation of isolated anti-Stokes wing of the SC in the femtosecond pulse at a wavelength of 1200 ÷ 2100 nm in fused silica is a consequence of the characteristics of filamentation in the anomalous GVD. Effect of anomalous GVD on the spectrum of the supercontinuum is determined by two factors: first - increasing anti-Stokes spectral broadening due to a strong steepening of the pulse front, the second - the destructive interference of broadband supercontinuum radiation in the band between the isolated anti-Stokes wing and the broadened spectrum of the pulse. Interference model spectra $S_{interf}(\lambda)$ agree qualitatively with spectra $S_{exp}(\lambda)$, which were obtained experimentally (Fig.1).

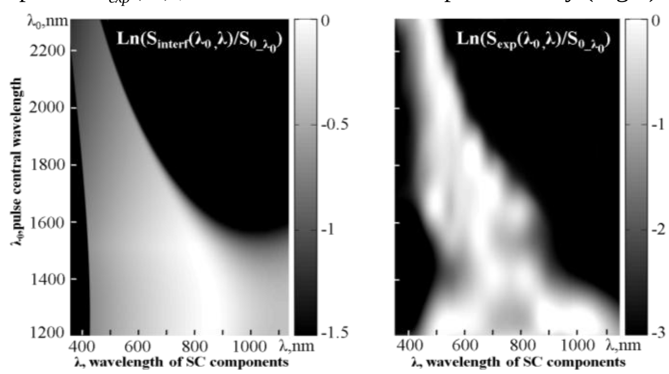

Fig.1. SC Anti-Stokes wing spectra.

This work was supported by Russian Fund for Basic Research grants № 11-02-00556-a and 11-02-90421-Укр_ф_а

REFERENCES

[1] S. L. Chin, et al., Canadian Journal of Physics **83**, 863 (2005).
[2] V. P. Kandidov, O. G. Kosareva, I. S. Golubtsov, W. Liu, A. Becker, N. Akozbek, C. M. Bowden, and S. L. Chin, Applied Physics B: Lasers and Optics **77**, 149 (2003).
[3] A. Couairon and A. Mysyrowicz, Physics Reports **441**, 47 (2007).
[4] S. L. Chin, S. Petit, W. Liu, A. Iwasaki, M.-C. Nadeau, V. P. Kandidov, O. G. Kosareva, and K. Y. Andrianov, Optics Communications **210**, 329 (2002).
[5] V.P. Kandidov, E.O. Smetanina, A.E. Dormidonov, V.O. Kompanets, S.V. Chekalin , ZhETF, 140 ,484 (2011)
[6] S. L. Chin, A. Brodeur, S. Petit, O. G. Kosareva, and V. P. Kandidov, Journal of Nonlinear Optical Physics and Materials **8**, 121 (1999).
[7] A. E. Dormidonov and V. P. Kandidov, Laser Physics **19**, 1993 (2009).

Plasma filament and spectral modification in the intense laser-cluster interaction

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***Abstract*—Production of plasma filament with multifocal structure under interaction of intense ($I \sim 10^{16}$ W/cm^2) chirped femtosecond laser pulses with argon clusters is accompanied with effective laser energy deposition. As a result, the amplitude of trailing spectral components of laser pulse drops.**

I. Introduction And Background

Nowadays the nonlinear processes induced by interaction of laser radiation with intensities exceeding $I > 10^{15}$ W/cm^2 with clusters is an active area of research. High energy ions, electrons and hard X-ray could be generated effectively in cluster plasma.

Propagation of focused femtosecond laser radiation in cluster media is accompanied with self-focusing and plasma channel formation, due to the evolution of the transient cluster polarizability induced by the laser pulse. The process of self-focusing influence on efficiency of energy absorption and, thus, hard X-ray generation.

Characteristic X-rays from cluster nanoplasma is an interesting problem since it contains information about the processes occurring in cluster nanoplasma and can be used for radiography of micro- and nanoobjects with high spatial and temporal resolution.

In this work we study the peculiarities of plasma filament, generated in cluster jet after its interaction with chirped laser pulse and its spectral modifications as a result of effective laser energy absorption.

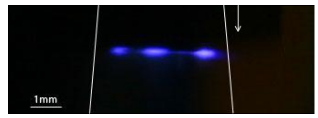
II. Results

In our experiments we monitored plasma filament, generated in the cluster jet by intense ($I \sim 10^{16}$ W/cm^2) chirped (t~300fs) laser pulses, with CCD camera. Simultaneously, we measured the integral X-ray yield in the range more than 2.5keV and registered the spectrum of laser radiation.

We have studied plasma filament structure depending on the lens focal plane position relatively to the jet axis. In the majority of cases we have observed long filament with the length that was much greater than the Rayleigh length.

When the focal point is positioned in front of cluster jet axis (in the area of front jet edge), the long nonuniform filament with multifocal structure is generated (Fig.1a). Such focal point position corresponds to the maximal X-ray yield from cluster nanoplasma. Effective energy absorption and X-ray generation occur in areas where the laser beam "collapses" and reaches its maximum intensity. That is, multifocal filamentation mode leads to effective laser-cluster interaction.

To confirm the presence of self-focusing effect we positioned the focal point at the distance of ~3 mm before the cluster jet edge. In this case the divergent laser beam interacts with the nonlinear media and the filament is produced (Fig. 1b). In this regime we also registered low X-ray yield. The interconnections between plasma filament structure and hard X-ray generation will be discussed in detail in “Laser Optics – 2012” conference[1].



a

b

Fig.1. Plasma filament image for focal plane (showed by arrow) positioned a) 3mm in front of the cluster jet; b) in the front edge of the cluster jet.

We observed modification of spectrum of the chirped laser pulse interacted with clusters (Fig. 2). It was found that the amplitude of the spectral components of the rising edge of the pulse remains practically unchanged, while the amplitude of the spectral components of the trailing edge (coming within a few hundred femtoseconds) drops.

The value of absorbed energy (that was estimated from the spectra) was of the order of 60% and corresponds to the value measured using opto-acoustic detector.

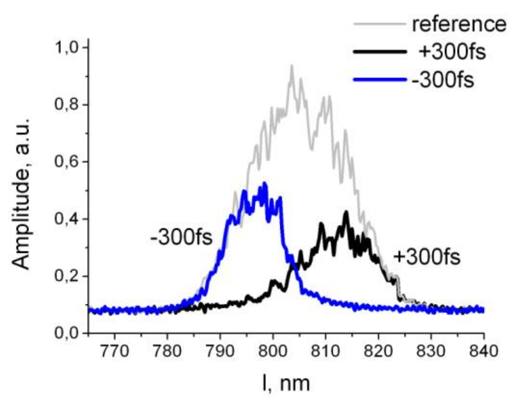


Fig. 2. Spectral modifications of the chirped laser pulse interacted with cluster jet.

References

[1] I.A. Zhvaniya,, et. al, “Hard X-ray generation accompanied with self-guided propagation of femtosecond laser radiation in molecular cluster beam”, Laser Optics-2012, will be published.

Filamentation of femtosecond IR and UV laser pulses in focused beams

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***Abstract*—Filamentation of IR and UV pulses in focused beams was studied numerically. Filament and plasma channel parameters for UV pulse show strong dependence from initial focusing whereas for IR pulse this dependence is insignificant.**

I. Introduction And Background

FEMTOSECOND laser pulse filamentation is characterized by the formation of high energy density region accompanied by plasma channel[1]. The values of laser field peak intensity and peak free electrons concentration are the product of dynamic balance of Kerr and plasma nonlinearities. Thus it is hard to influence on them by means of initial conditions. On the other hand these values determine filaments applications. We study how initial beam focusing influences on pulse filamentation in IR and UV ranges.

In numerical simulations we took 100 fs (FWHM) laser pulses with central wavelength 800nm and 248 nm. For both cases initial beam radius was 4 mm and 2 focal lengths were studied: 50 m and 5 m. Energy of the pulses was chosen so that peak pulse power was equal to 10 critical powers of selffocusing (2.5 GW for 800 nm and 70 MW for 248 nm).

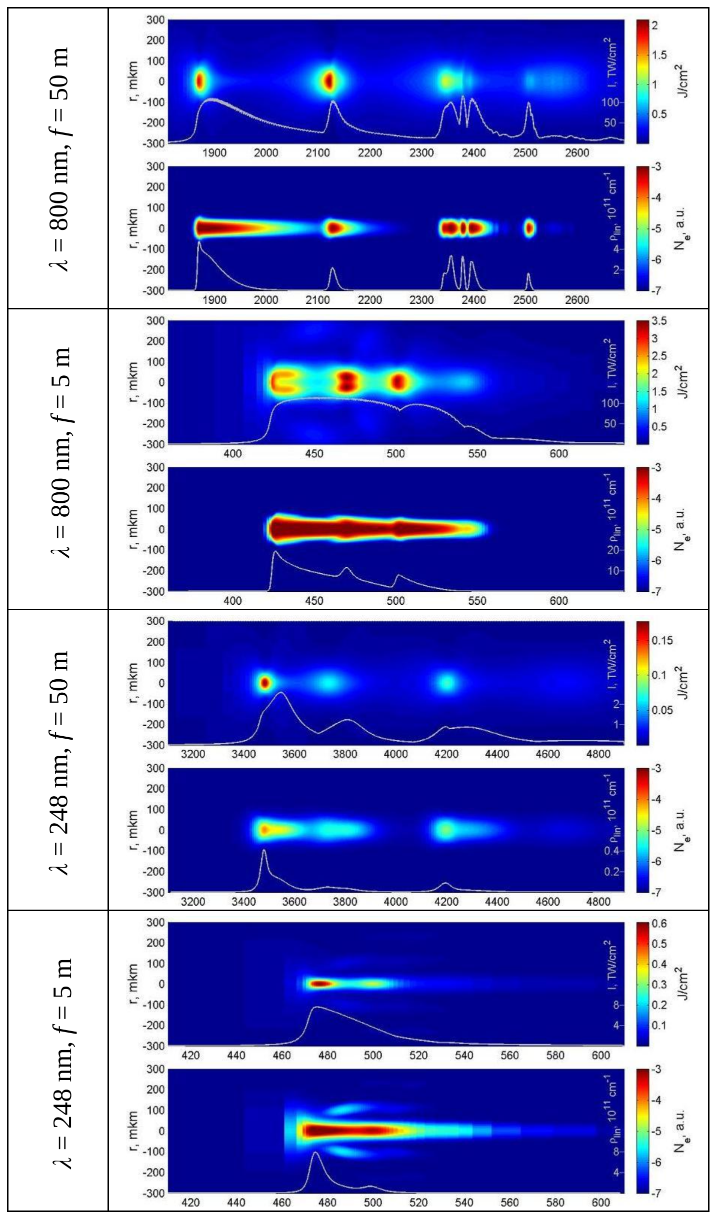
Mathematical model took into account effects of diffraction, dispersion in air, delayed Kerr and plasma nonlinearities and attenuation due to ionization. For 800 nm we took ionization model based on PPT, for 248 nm for the studied intensities multiphoton ionization took place.

II. Results

Fluence (top) and plasma concentration (bottom) distributions are presented for all 4 cases. We found that filament and plasma channel consist of several regions along propagation regions when geometrical focusing is weak. For tight focusing these regions merge into continuous one. Also for tight focusing filament propagates beyond linear focus whereas for weak focusing it disappears before it.

It was found that such filament and plasma channel parameters like their radii, peak intensity, peak fluence, peak plasma concentration, linear concentration of free electrons (ordinary concentration integrated over cross-section) remain practically the same for different focusing for IR pulse. But for UV pulse the decrement in focal length changes peak intensity and peak fluence by several times and plasma concentrations more than by one order.

This difference can be explained by different ionization rates for these wavelengths. For small intensities ionization rate is proportional to laser intensity to the power K, where K is minimal number of photons whose energy is more than ionization potential. For oxygen this parameter is 3 at 248 nm and 8 at 800 nm, for nitrogen – 4 and 11 respectively. Thus plasma nonlinearity is stronger for IR pulse and linear factors such as initial beam focusing influence slightly filament parameters. Therefore it is much simpler to control filament parameters for UV pulse.



References

[1] A. Couairon, A. Mysyrowicz, “Femtosecond filamentation in transparent media”, *Physics Reports*, vol. 441, iss. 2-4, 2007, pp. 47-189.

TERA 2012

Joint Student Session
at 2-nd International Conference
"Terahertz and Microwave radiation: Generation, Detection and Applications"

Russia, Moscow
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