Simultaneous Generation of Terahertz and X-ray Radiation with Ultrashort Femtosecond Laser Pulses in Nano-cluster Medium

A. V. Balakin[1], **A. V. Borodin**[1,2], **M. S. Dzhidzhoev**[3], **M. G. Evdokimov**[1], **M. N. Esaulkov**[2], **I. A. Zhvaniya**[1], **N. A. Kuzechkin**[2], **A. Yu. Sidorov**[1], **P. M. Solyankin**[1], **and A. P. Shkurinov**[1,2]

[1]Faculty of Physics, M. V. Lomonosov Moscow State University
Leninskie Gory, Moscow 119991, Russia
[2]Institute on Laser and Information Technologies of the Russian Academy of Sciences
1 Svyatoozerskaya Str., Shatura Moscow Region 140700, Russia
[3]International Laser Center
M. V. Lomonosov Moscow State University, Leninskie Gory, Moscow 119991, Russia

Abstract— We have studied for the first time the simultaneous generation of terahertz and X-ray radiation from noble gas based nano-cluster supersonic jet under "one-" and "two-color" (fundamental and its second harmonic) excitation with high-power femtosecond laser pulses. It was shown that optimal conditions for effective generation of terahertz and X-ray radiation are different. That makes possible efficiently control the magnitudes of terahertz and X-ray signals simultaneously generated from gas nano-cluster jet. Controlling could be provided by different means: by varying of time delay between laser pulse and cluster jet formation moment, or by varying of chirp parameter of laser pulses. Also we shown that efficiency of THz generation from cluster jet could be effectively controlled by varying of ratio between clustered and buffer (carrier) gases in mixture. Angular distribution of terahertz beam generated near by optical axis under "two-color" laser excitation conditions has been measured as well.

1. INTRODUCTION

High-temperature plasma initiated by irradiation of target with high-power femtosecond laser pulses with intensities of 10^{15}–10^{16} W/cm^2, is a source of high-energy particles, as electrons, ions and neutrons. The plasma possesses strong nonlinear optical properties, and such interaction is accompanied by plenty of nonlinear processes, as self-focusing, stimulated Raman scattering, optical-harmonic generation, X-ray and terahertz (THz) generation

Cluster medium is a subject of special worldwide interest recent years. These nano- and microparticles are aggregated from atoms or molecules and contain from few to 10^7 atoms or molecules, which are held together due to different type bonds with energies from few tenth eV to few eV [1]. Recently, it has been shown that there are many nonlinear effects mentioned above take place under interaction of high-power femtosecond laser pulses with gas-cluster jet such as self-focusing [2], filamentation followed by plasma channel formation [3], optical harmonics generation [4], characteristic X-ray [5, 6] and terahertz [7–10] generation. Noteworthy, that efficiency of spectrally bright characteristic X-ray radiation from the cluster nano-plasma is comparable with efficiency in the case of a solid target [11].

In present paper we have investigated interaction of high-power ultrashort laser pulses with atomic and molecular clusters generated by means of supersonic expansion of gas into vacuum through specially shaped nozzle [12]. We suppose that the gas-cluster jet is the most promising and attractive medium for elaboration of nano-plasma generator of electromagnetic radiation, because:

- Such target combines advantages of both solid and gaseous media at the same time. Cluster density is close to the density of condensed phase of the matter, and this leads to high efficiency of interaction of such target with intense laser radiation — gas-cluster jet is able to absorb up to 90–95% of laser pulse energy, and generated plasma is heated to high temperatures. But there is no ablation and spreading of drops and fragments.
- The initial properties of the medium are restored to each subsequent interaction act. Thus, there is no accumulation of medium degradation occurs, and such target is a unique one for efficient interaction with high-power femtosecond laser pulses.
- Cluster size and number of atoms therein may be easily controlled by varying of gas back-pressure [12, 13]. Efficiency of clustering and hence concentration of clusters in the jet could be controlled by adding of carrier gas.

Here we have demonstrated the possibility of simultaneous generation of terahertz and X-ray radiation in nano-cluster medium — gas-claster jets under excitation by high-power femtosecond laser pulses, shown existence of optimal conditions for these processes, and thereby complemented usage range of nano-plasma-gas-cluster pulsed electromagnetic field generator with terahertz frequencies.

2. EXPERIMENT AND RESULTS

As excitation source we used radiation of Ti-Sa laser with wavelength of 810 nm amplified in regenerative amplifier, pulses rate 10 Hz, pulse energy up to 30 mJ, pulse duration 76–300 fs. Pulse duration could be varied by changing the distance between diffraction gratings in compressor, providing negatively and positively chirped pulses. Laser radiation was focused around 6 mm below the nozzle in a cluster jet by f/20 lense. Maximum value of laser radiation intensity at lense focus was estimated as around 10^{16} W/cm^2 and it was 10^{15}–10^{16} W/cm^2 in experiments when chirped pulses were used for excitation.

Gas-cluster jet was formed with use of cluster generator on the base of vacuum and high-pressure chambers and conical nozzle. Initial vacuum in vacuum chamber is 10^{-3} Torr, and working one is 10^{-2} Torr. Working pressure in high-pressure chamber could be varied between 10^{-2} atm and 50 atm. Input and output diameters of conical nozzle are 0.75 mm and 4 mm respectively, half-angle is 5 degrees.

PMT equipped with a NaJ scintillator and a beryllium filter of 90 um thick was used to detect and control the integral X-ray yield ranging over 2.5 keV. The PMT was placed at the cross direction to the laser pulses propagation. Liquid helium cooled bolometer was used for detection of THz radiation. Experimental scheme provided possibility to measure THz signal along laser pulses propagation direction and at 45 degrees direction.

Figure 1 demonstrates dependencies of terahertz and X-ray radiation yields from Argon gas-cluster jet as a function of the delay between laser pulse and cluster jet formation. Zero delay corresponds to valve opening moment and coming of the laser pulses at the interaction point. Both, the X-ray and terahertz signals arise after 0.3–0.4 ms delay required for the formation of clusters flow and its arriving at the interaction point. Maximum X-ray yield is achieved at 0.4–0.45 ms delay, while the THz signal efficiency nearly unchanged throughout the duration of the jet.

Amplitude of THz and X-ray signals generated in Ar clusters under "two-color" excitation along direction of laser pulses propagation as a function of pulse duration τ and its chirp paramentr $\mathbf{a}$ is shown at Figure 2. Efficiency of X-rays generation demonstrates maximum value in the region of negative chirp, while the THz generation yield is minimal under these conditions. And vice versa relation between values of THz and X-ray and THz signals is observed for the positively chirped excitation pulses, i.e., decreasing of X-ray singnal on the way from negative to positive chirp is accompanied by increasing of THz signal.

Also we have measured THz beam cross-section in the on-axis corner area of 15 degrees generarted under the same conditions, and demostrated that THz signal is localized inside a cone with half-angle of around 3,5-4 degrees with a deep minimum in the center on the laser beam axis.

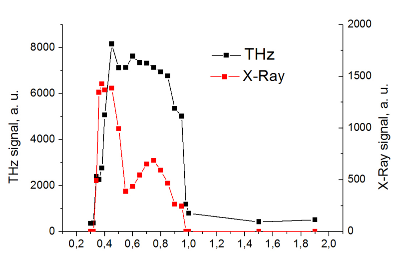

Figure 1: Amplitude of THz and X-ray signals generated in Ar clusters jet along laser pulses propagation direction under "two-color" (fundamental and its second harmonic) excitation versus the time delay between laser pulse and the opening of the nozzle valve.

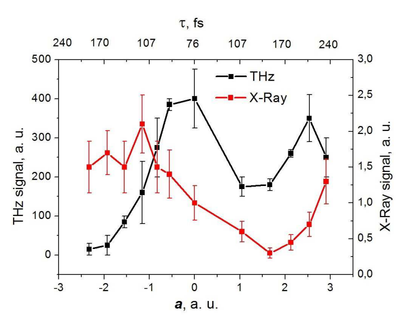

Figure 2: THz and X-Ray signals as a function of laser pulse width and chirp. Pulse width τ was varied by alteration of chirp parameter $\mathbf{a}$ (here chirp parameter corresponds to phase factor $\exp(\mathbf{a}t^2/\tau_0^2)$, where τ_0 is minimal pulse duration).

3. CONCLUSION

To summarise, we have shown that optimal conditions for effective generation of THz and X-ray radiation in nano-cluster supersonic jet under high-power ultrashort laser pulses excitation are different, and that makes possible efficient control by ratio between values of THz and X-ray signals generated simultaneously from gas based nano-cluster jet by means varying of time delay between laser pulse and cluster jet formation and by varying of laser pulse's chirp. Also it has been demonstrated that efficiency of THz generation in clusters jet could be efficiently controlled by varying the ratio between clustered and carrier (buffer) gases in gas mixture.

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