Properties of laser beam passed through cluster plasma studied with diffraction pattern method

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Abstract. The diffraction method is used to study the properties of laser radiation interacting with a gas-cluster plasma. Based on the simulation of propagation a laser beam with a wavelength 800 nm through a hexagon Cu-mesh and subsequently compared with the obtained experimental diffraction pattern, the contribution of the second harmonic to the laser radiation was considered. The capability of this method to reveal the spectral composition of laser radiation is discussed. Also, the dependence of the visibility of the diffraction pattern on the intensity of the laser beam is considered. Besides, the contribution of x-ray radiation generated from the laser-cluster interaction into the observed diffraction pattern signal was estimated.

1. Introduction

Investigations of the interaction of high-intensity lasers with cluster targets are of great interest for many physics applications. The plasma induced by high-intensity femtosecond laser is considered for a long time as versatile compact source of fast ion beams, protons, electrons and x-ray radiation [1–3]. The use of gas-cluster targets provides a set of definite advantages such as the absence of debris, high efficiency of laser energy absorption by submicron clusters, easily and fast renewable target, wide-angle ion emission and others. Many studies have shown that nonlinear effects can occur during the laser-cluster interaction such as filamentation of femtosecond laser radiation, formation of a plasma channel, self-focusing of laser radiation and generation of its harmonics [4–6]. In the frame of our investigation, we will consider only the last effect. There are different methods for the investigation of harmonic generation. For example, the mechanisms of harmonic generation for laser interaction with clusters by analyzing the shapes of the spectral lines of the Ar XVII were discussed in work [7].

One of the methods for revealing the coherent and spectral properties of x-ray radiation is diffraction method. So, based on the analysis of diffraction patterns formed during the
propagation of an x-ray free-electron laser beam through a test grid, the presence of harmonics \((2\omega, 3\omega)\) in the beam and the degree of beam coherence were determined in work [8]. The focus of this paper is to demonstrate the capability of a diffraction method for analysis of the properties of laser beam interacting with the gas-cluster medium.

2. Experimental method

The experiment has been performed using a JLITE-X Ti:Sapphire laser facility (the wavelength is 800 nm) at Kansai Photon Science Institute [9], which generates 40 fs pulses with energy of 160 mJ. For the investigation of dependence of diffraction pattern visibility on the laser intensity, three experiment cases were realized (figure 1). For the first case, a parallel laser beam with a diameter of 40 mm passed through a hexagonal copper grid and was registered by a lithium fluoride (LiF) detector, see figure 1(a). The expected laser intensity \(I_{\text{laser}}\) on the LiF was \(2.5 \times 10^{11} \text{ W/cm}^2\) for this geometry. For the second case, see figure 1(b), the laser beam was focused by an off-axis \(f/13\) parabola at the spot size around 50 \(\mu\)m, what corresponded to the intensity of laser radiation in vacuum \(4 \times 10^{17} \text{ W/cm}^2\) (the expected laser intensity \(I_{\text{laser}}\) on the LiF was \(2.5 \times 10^{12} \text{ W/cm}^2\)). For the last case, see figure 1(c), the supersonic gas jet nozzle allowed producing clusters with a big (up to 1 \(\mu\)m) sizes from CO\(_2\) and mixture of 90% He and 10% CO\(_2\) gases was put. The laser beam focused about 1.5 mm below the nozzle outlet. The LiF detector with diameter of 20 mm was used to record the full size of beam in our geometry of experiment. It should be noted that the expected full width at half maximum (FWHM) of the laser beam in the plane of the detector was of 8 mm, that is less than the size of the crystal. Thus, we were able to detect the total distribution of laser intensity over the incident beam in the plane of detector. The photoluminescence signal (PL) of the irradiated LiF crystal was observed using a laser scanning confocal microscope.

For comparison, the experimental diffraction pattern with calculated one, a simulation of the laser beam propagation was performed using the software framework Wave PropaGator (WPG) [10, 11]. For this, the following conditions were simulated: the laser beam with the wavelength of 800 nm and its second harmonic 400 nm propagated through the hexagon Cu-mesh with size of 200 \(\mu\)m and the resulting intensity distribution in the diffraction pattern (in the plane of LiF crystal) were calculated at the distance of \(d = 5\) mm.

3. Result and discussion

LiF images obtained for three experimental cases are shown in figure 1 (right side). It is clear seen that the signal on the surface of LiF crystal is absent when the non-focused laser beam was used, see figure 1(a). Generally the LiF crystal can be used for registration of ionizing radiation with energy more than 14 eV [12]. However LiF can detect visible and near ultraviolet radiation if it at extremely high intensities and involving multiphoton absorption processes. So the laser intensity of \(2.5 \times 10^{11} \text{ W/cm}^2\) on the surface of LiF was not enough to activate such processes.

For experimental case with using the focused laser beam, we observe diffraction pattern on the LiF crystal, however, the signal is strongly low, see figure 1(b). The best resolved diffraction pattern was obtained when the laser beam propagation through cluster jet, see figure 1(c). This fact indicates the appearance of the laser beam self-focusing in gas-cluster medium and increasing its intensity as result.

The left side of figure 2(a) shows the readout scheme from the surface of the LiF crystal for the experimental case in figure 1(c). To obtain the intensity distribution of laser beam, the 17 frames were taken along \(y\)-direction of crystal [see figure 2(a), left side]. In the central part of figure 2(a) the samples of magnified fragments of hexagon mesh on the LiF crystal are shown. The best experimental diffraction image of wire was observed for frame 8, which is corresponded to approximately the central region of the laser beam, while for frame 1 the diffraction pattern...
Figure 1. The experimental scheme (left) and the signal on the LiF crystal (right) for three experimental cases: (a) non-focused laser beam without gas-cluster target; (b) focused laser beam without gas-cluster target; (c) laser beam was focused in gas-cluster target.

is absent. In the last case, the absorption image was formed by only x-ray radiation from cluster plasma.

The intensity profiles for frames 1 and 8, as well as the calculated intensity distribution in the diffraction pattern in the plane of the detector (assuming that the diffraction pattern was formed by only of fundamental wavelength $\omega$—100%) are presented in figure 2(b). Comparing these profiles, we estimated that the contribution of x-ray yield in the overall signal is about 80%. Thus, for the characterization of laser beam properties we should subtract the x-ray radiation signal. It should be underlined that nonzero signal from laser radiation on the LiF crystal indicated on the realization of the multiphoton absorption processes. Taking into account the energy threshold of 14 eV for crystal LiF [12], we can conclude that ten-photon absorption process was realized.

The spatial distribution of laser intensity in the plane of LiF crystal is shown in figure 2(c). It is clear seen that the obtained shape differs from the expected gauss one. This fact may indicate the presence of nonlinear effects during the propagation of laser beam through cluster-based plasma in our experimental conditions. It is known that the threshold of laser intensity to be of the order of $10^{17}$ W/cm$^2$ for manifestation of nonlinear process, which requires a relativistic laser intensity.
Figure 2. (a) Experimental diffraction image of hexagonal mesh, obtained on the LiF (left), frames of full image observed with magnification 40× (central part) and corresponding intensity distribution profiles, which was traced along white dash line from frames 1 and 8 (right); (b) comparison traces taken through the same parts of experimental and calculated images for frames 1 and 8; (c) the spatial distribution of intensity across the laser beam in the single diffraction image obtained on the LiF—in y direction [white arrow in image (a)].

Now consider the capability of diffraction pattern method for revealing the spectral properties of laser beam. Modeled intensity distribution in diffraction patterns, traced across to the Cu-wire of mesh, are shown in figure 3 (red lines) for different ratio of ω and 2ω harmonics. Generally, the features in the distribution of diffraction pattern (period, contrast, structures of fringes) allow determining the spectral composition of radiation. As it seen from simulation in figure 3(a–d), such features begin to be shown when the contribution of second harmonic (SH) is defining [see figure 3(c, d), red lines] for our experimental geometry. It can be seen that the periods
of diffraction patterns and their intensities are in good coincidence with experimental one for modeling cases in figure 3(a, b). From the comparison of experimental and calculated pattern, we can conclude that if SH generation was present, its contribution is less than 10%, [see the case in figure 3(b)]. Thus, the above method does not allow us to accurately evaluate the contribution of the second harmonic in our experiments. However it should be noted that in work [7] the generation of SH in the cluster-based plasma for same experimental conditions ($I = 10^{17}$–$10^{18}$ W/cm$^2$) was revealed by analyzing shapes of the emitted spectral lines. The conversation laser light into $2\omega$ harmonic was established of 2%.

4. Conclusions
The interaction of fs-laser radiation with a gas-cluster medium is investigated. It was estimated that the contribution of x-ray radiation from the laser-cluster plasma to the total signal detected by the LiF detector was about 80%. Additionally, the capability of diffraction method for revealing the spectral composition of laser radiation was demonstrated. As a summary, the diffraction pattern method, based on the comparison of the simulated intensity distribution with the experimental one is informative, when the contribution of harmonics of fundamental wavelength is substantial.
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