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Characterization of multi-jet gas puff targets for high-order harmonic generation using EUV shadowgraphy

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ABSTRACT

Characterization measurements of multi-jet gas puff targets, developed for investigations on high-order harmonic generation (HHG) by a focused laser beam in a gas medium of modulated density, are presented. The targets produced by pulsed injection of gas through a nozzle in a form of a chain of small orifices have been characterized by EUV backlighting at 13.5 nm wavelength. Measurements were performed for nozzles with 5, 7 and 9 orifices of 0.5 mm in diameter each. Density profiles for argon targets have been obtained for the first time.

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1. Introduction

Since its discovery [1,2] high-order harmonic generation (HHG) has become one of the main topics in the ultra-short laser pulse interaction with matter. HHG is one of the most promising methods to obtain tunable, short-pulse, coherent radiation in the soft X-ray (SXR) and extreme ultraviolet (EUV) regions [3]. Such pulses of femtosecond to attosecond time duration are essential to applications in ultrafast science [4], coherent imaging in a nanoscale [5], interferometry [6] and seeding of free electron lasers (FELs) [7]. However, the possibility of using high-order harmonics in these applications is strongly related to the improvement of harmonic generation efficiency.

Efficient harmonic generation requires phase matching between generated harmonics and driving laser pulse, as well as an efficient coupling of an intense laser pulse with a large number of atoms. These conditions can be fulfilled by harmonic generation in a hollow-core fiber [8,9] and elongated gas-jet targets [10–12], however, ionization of gas prevents the laser pulse propagation and limits efficient HHG. It was theoretically demonstrated that quasi-phase-matching (QPM) of high-order harmonic generation in gases with modulated density may strongly increase harmonic generation efficiency [13–16]. This approach has been proved experimentally using gas-filled hollow-core fiber with a modulated inner diameter [17] and coherent superposition of harmonics generated in two successive sources by the same laser pulse [18]. Strong enhancement of HHG has been observed for an array of gas jets [19] and dual-gas multi-jet arrays [20], however, no characterization measurements of gas density profiles in the laser interaction region have been performed.

In this paper we present the first characterization measurements of multi-jet gas puff targets developed for high-order harmonic generation experiments. The targets were formed by injection of gas through a nozzle in a form of an array of small orifices. The characterization measurements have been performed with the use of EUV backlighting at 13.5 nm. Density profiles for argon targets have been obtained for the first time. The results of the studies will be useful for research on high-order harmonic generation and for understanding of the HHG process.

2. Experimental arrangement

2.1. Electromagnetic valve to produce multi-jet gas puff targets

The nozzle was supplied with gas using a fast-acting electromagnetic valve, developed at the Institute of Optoelectronics, Military University of Technology. The valve can operate with gas backing pressure up to 10 bars. The valve, when equipped with the nozzle in a form of a $0.5 \times 15\ mm^2$ slit, makes possible to create an elongated gas puff target with uniform gas density profile. The use of the nozzle in a form of an array of small orifices allows producing a multi-jet gas puff target with modulated gas density profiles. Photographs of the valve (a) and the nozzles (b–d) are depicted in Fig. 1. The gas density profiles depend on the nozzle structure, the gas backing pressure in the valve, and the time duration of gas flow. Information on the gas density profiles is very important for research on HHG and understanding the generation

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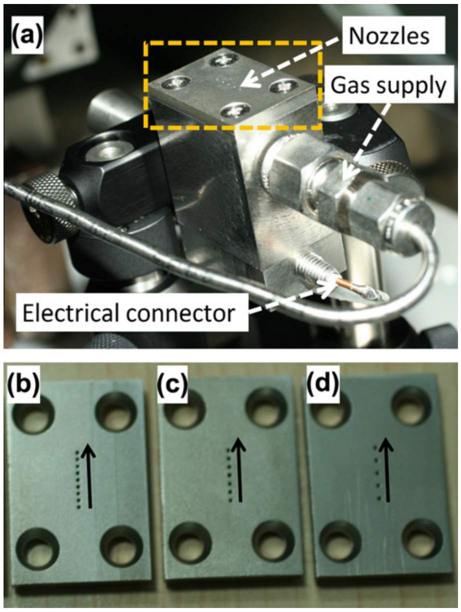

Fig. 1. Photograph of the valve equipped with nozzles (a) having 9- (b), 7- (c) and 5- (d) in-line orifices. Arrows indicate the modulation vector.

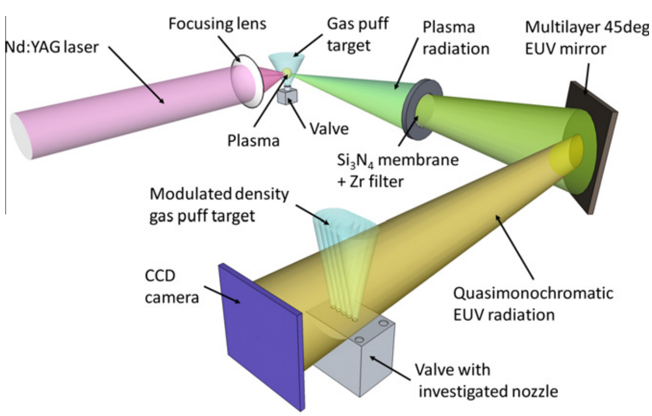

Fig. 2. Experimental arrangement for EUV backlighting imaging of a modulated gas-puff target.

process. In this study we used three arrangements of orifices in in-line geometry: 5, 7 and 9 orifices, each 0.5 mm in diameter, with periods equal to 1.9, 1.25 and 1 mm, respectively. The orifices were electro-drilled in a 4.5 mm thick stainless steel plate, yielding a diameter to length aspect ratio of 1:9. The black arrows indicate the direction of modulation, called later the modulation vector.

2.2. Experimental setup for EUV backlighting

The characterization measurements of pulsed gas jet or gas puff targets can be performed using various diagnostic methods [21–28]. The most common method is laser interferometry that was used in the characterization measurements of various target systems [29]. In this study we have applied radiography technique (shadowgraphy) in which the gas targets are backlighted with EUV pulses at 13.5 nm. The EUV pulses have been obtained by spectral selection of emission from a laser plasma source. The spectral narrowing was performed using a Mo/Si multilayer mirror. Similar technique has been previously applied for characterization of gas-jet xenon targets [30] and elongated geometry gas targets [31].

The scheme, used in EUV shadowgraphy experiment, is depicted in Fig. 2. Pulses of EUV radiation were produced with a compact laser plasma EUV source based on a double-stream gas puff target [32]. Emission in the 13.5 nm wavelength band with the bandwidth of about 1 nm was selected using a flat mirror with Mo/Si multilayers. The mirror peak reflectivity at 13.5 nm was about 38% for 45° incidence angle. To eliminate the visible light from the plasma source a 200 nm thick Zr filter deposited on a 200 nm thick Si_3N_4 membrane was used. The spectral measurements were performed employing a transmission grating spectrometer (TGS). The TGS was composed of 4 μm period, free-standing grating located 720 mm from the plasma. An entrance slit, 33 μm in width, was positioned ~4 mm from the grating. A normalized Xe plasma spectrum, transmission curves of thin-film filters and the reflectivity curve of the EUV mirror are depicted in Fig. 3(a). The EUV spectrum after spectral filtration is depicted in Fig. 3(b).

Assuming isotropic emission from the source the conversion efficiency of the laser energy into EUV energy in this band of about 1.6% was measured with the use the absolutely calibrated AXUV-HS1 (IRD) detectors [32]. EUV shadowgrams of the characterized multi-jet gas puff targets were registered using a CCD camera, X-vision M-25 (Reflex), equipped with 512 × 512 pixels CCD chip, 0.5 × 0.5 in.^{2} in size. The distances between the source, the characterized target and the CCD camera were 960 and 157 mm, respectively. The CCD chip was cooled down to −20 °C to decrease its thermal, intrinsic noise.

3. EUV characterization measurements

The characterization measurements have been performed for the targets produced using nozzles with various numbers of orifices and supplied with argon gas at different backing pressures (2–10 bars). Typical EUV shadowgrams of the multi-jet gas puff targets produced with 5, 7, and 9 orifice nozzles at low (2 bar), medium (6 bar) and high (10 bar) backing pressures are shown in Fig. 4.

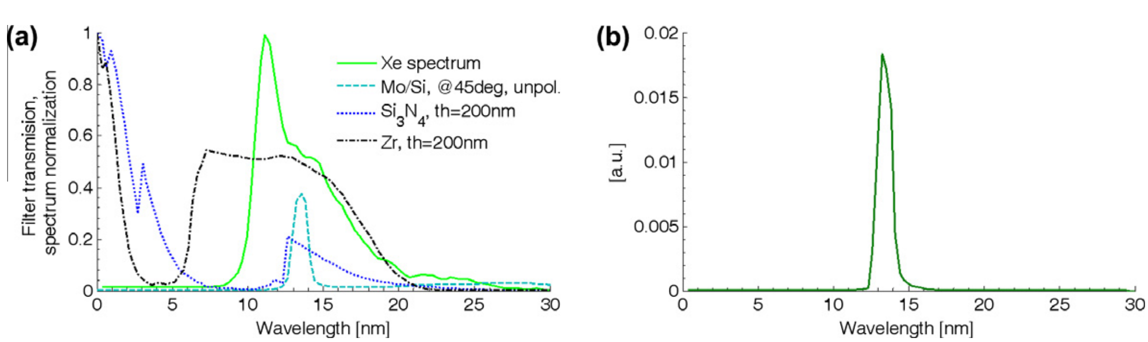

Fig. 3. Spectrum obtained using TGS. The emission in the EUV from Xe plasma and transmission curves for all filters (a). Transmission curves of the filters are based on data available from [33]. EUV spectrum of radiation used in the experiment after spectral narrowing (b).

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