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Fabrication of high-effective silicon diffractive optics for the terahertz range by femtosecond laser ablation

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Abstract

Comparison of the two laser sources (UV nanosecond and IR femtosecond) used for the formation of micro-relief at the silicon surface showed the advantage of the second one. A four-level silicon diffractive THz Fresnel lens has been fabricated by laser ablation at high repetition rate (f = 200 kHz) of femtosecond Yb:YAG laser. Features of the lens were investigated in the beam of the Novosibirsk free electron laser at the wavelength of 141 µm. Detailed results of investigation of fabricated lens micro-relief are presented. The measured diffractive efficiency of the lens is in good agreement with the theoretical prediction.

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Keywords: multilevel diffractive optics; femtosecond laser ablation; diffractive microrelief; diffraction efficiency.

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1. Introduction

The development of coherent, high power sources of THz radiation (see Kulipanov et al. (2015)) has formed a need for optical elements to control this radiation. It is known that high-power THz beams can be controlled by silicon diffractive optical elements (DOEs). The widespread lithographic etching of a silicon substrate , used in fabrication of binary elements (Agafonov (2013, 2015), Knyazev et al. (2015)), has disadvantages in the case of multilevel ones. Formation of multilevel microrelief by lithographic etching requires an expensive and complicated procedure of photomask alignment, and binary (two-level) elements, in turn, have limited energy efficiency. A principal possibility of the microfabrication of high-effective power silicon diffractive optics for terahertz range by laser ablation was shown by Komlenok et al. (2015). We present here results of investigation of the fabricated lens in the beam of a free electron laser at the wavelength of 141 μm. Comparison of application of nanosecond UV and femtosecond IR laser ablation for forming THz micro-relief at the silicon substrate is also reported, and the advantage of the application of femtosecond laser source is demonstrated.

2. Experiment

A high-resistance silicon sample was irradiated with an excimer KrF laser (Optosystems Ltd., CL 7100, τ = 20 ns, λ = 248 nm, f = 50 Hz) or a disk Yb : YAG laser (Dausinger and Giessen, λ = 1030 nm, τ =400 fs, f = 200 kHz) in normal ambient conditions. For irradiation with the excimer laser, the projection optical setup (fig.1a) was used to illuminate the surface of the sample uniformly (demagnification factor of 20×). Square mask with the size of 4 mm was used for irradiation, so size of laser spot on a surface was 200 μm. Laser fluence on the surface was controlled with filters mounted before the mask. The sample was moved by the translation stage. In the experiments with the Yb : YAG laser, the beam was focused onto the silicon surface in a spot with a diameter of 10 μm (1/e intensity level). The sample was mounted on a rotating platform on the translation stage (fig. 1b). The rotating platform was used to obtain radial symmetry for lens formation. The depth of a surface structure was controlled by moving the axis of rotation with different velocity of the translation stage.

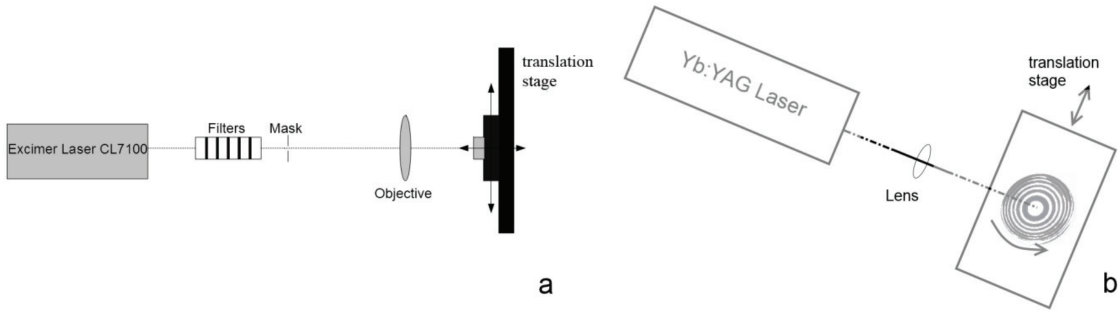

Fig. 1. Optical systems for sample irradiation with the excimer laser (a) and the Yb:YAG laser (b).

3. Results and discussion

Since wavelengths and pulse durations of the lasers used were different, the optical absorption lengths were also drastically different. For the IR radiation, the optical absorption coefficient α is 125 cm^{-1} (optical absorption length l_a = 80 μm), and for UV – α = 1.8 10^6 cm^{-1} ($l_a \approx$ 6 nm) (see Green and Keevers (1995)). Tested structure consisted of three different depth levels of 14.5, 29.1 and 43.6 μm was chosen to compare two laser sources. In the case of the UV irradiation, the laser fluence was 4 J/cm^2 and slightly exceeded the threshold of silicon ablation, which was about 1 J/cm^2. The sample was mounted on the translation stage and was shifted with different steps: 20 and 200 μm, corresponded to the 0.1 and 1 of the size of laser spot on the surface. To reach required depth of structure, the