# Compact diffractive optics for THz imaging

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**Abstract— we presented a compact diffractive silicon-based multilevel phase Fresnel lens (MPFL) with up to 50 mm in diameter and numerical aperture (NA) up to 0.86 designed and fabricated for compact terahertz imaging systems. The laser direct writing (LDW) technology based on picosecond laser was used to fabricate the diffractive optics on silicon with different number of phase quantization levels *P* reaching almost kinoform spherical surface needed for efficient THz beam focusing. Focusing performance was investigated by measuring Gaussian beam intensity distribution in the focal plane and along the optical axis of lens. The influence of phase quantization number to the focused beam amplitude was estimated, and power transmission efficiency reaching more than 90 % was demonstrated. THz imaging resolution less than 1 mm using robust 50 mm diameter multilevel THz lens was achieved and demonstrated at frequency 580 GHz.**

## INTRODUCTION

Suitability of terahertz (THz) imaging for nondestructive testing [1], biomedical research [2] or food and pharmaceutical industry [3] stimulates a search for compact practically convenient solutions. As a particular important issue can be assumed development of compact THz diffractive optic components, which enable to replace massive parabolic mirrors into much more attractive flat compact optics elements[4], [5].

In this letter, multilevel phase Fresnel lens (MPFL) designs, fabrication and focusing performance are studied. The design of MPFLs starts from two-phase quantization levels *P* and extends up to continuous kinoform shape. Samples were developed for the focusing of 580 GHz frequency beam.

Silicon wafer of 0.46 mm thickness was patterned using industrial-scale-compatible LDW system based on 1064 nm wavelength 13 ps pulse duration, 1 MHz repetition rate, 60 µJ peak energy laser (Atlantic 60 from Ekspla LTd.) [6]. The LDW technology enabled us to manufacture different complexity multilevel zone-phase elements in the same process with the opportunity to modify parameters in time.

Two groups of the MPFL samples with outside diameter of 17.5 mm with the focal distances of 10 mm and 5 mm and one sample with 50 mm diameter and the focal distance of 30 mm were designed and fabricated. The group of 17.5 mm diameter MPFL contained five samples with different number of phase quantization levels for each focal distance allowing to figure out the optimal phase quantization level [5]. The radii and depths of the subzones were calculated according to methodology presented in [7].

The SEM images of the 5 mm focal length MPFL with 4 subzones are shown in Fig. 1 a-b. The step-profile scanned across the center of each sample is given in Fig. 1c. The photo of flat 50 mm diameter MPFL with P=16 quantization levels is depicted in Fig. 1d. As one can see, step-like structure of individual zones start to merge into a continuous kinoform shape for the case of 8 phase quantization levels. Such transition from step like to kinoform shape occurred due to the limited size of the ablation spot of 44 µm. Fig. 1b shows the SEM picture of the surface microstructure at each area of 4 steps MPFL. The laser-processed surface of the silicon contained randomly distributed columnar structures the scale of whose was increased with higher material exposure by laser. Such increase of surface roughness and growth of columnar morphology with number of laser pulses was well known phenomena in materials laser processing [8], [9].

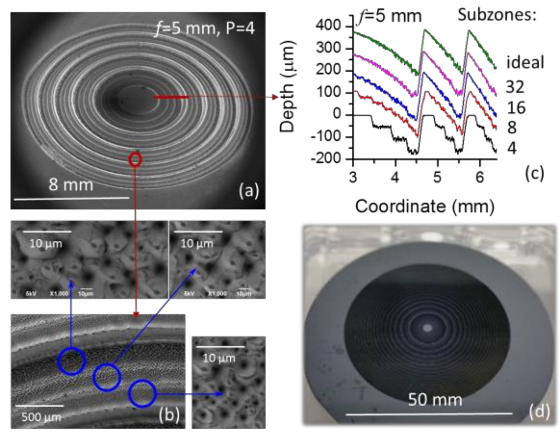


Fig. 1. SEM image of the MPFL of focal distance f=5 mm consisting of 4 phase quantization levels (a), zoomed area of each subzone (b). The cross section of 5 mm focal length MPFL measured with a step profiler (c). Each following profile line was moved by 100 µm [5]. Photo of the 50 mm diameter, 16 subzones MPFL with the focal lengths *f*=30 mm (d).

The multilevel phase Fresnel lens focusing performance was investigated by measuring Gaussian beam intensity distribution in the focal plane and along the optical axis at the 0.58 THz frequency. The peak signal dependency on phase quantization number for 5 mm and 10 mm focal length MPFLs is shown in Fig. 2. It is clearly seen that peak signal saturates at 8 phase quantization levels. This result is in a good agreement with theoretical diffraction efficiency distribution [10]. Detailed investigation was performed aiming to explain the signal deviation in case of 16 and >1000 phase quantization levels. Absolute value of the focused beam intensity was found to be depended of the THz reflection and absorption losses in the laser affected silicon. It is worth noting that laser ablation changes silicon transmittance [11], [12].

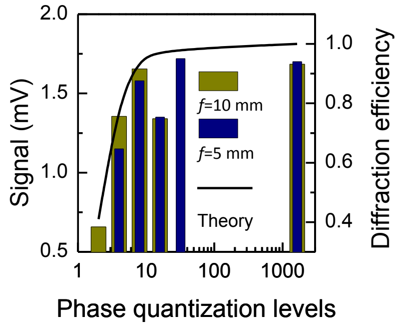


Fig.3. Peak signal of the THz detector dependence on phase quantization number *P*. Theory - diffractive efficiency of the Si-lens depending on the number of phase quantization levels [5].

The comparison of metal zone plate and commercial parabolic mirror focusing performance was presented in [4]. It was shown that the imaging system with the 5 mm focal length zone plate improves the special resolution up to 25% in comparison with that of commercial parabolic mirror. Using the same experimental set up, presented in [4], the resolution target imaging using 50 mm diameter THz MPFL is recorded. Imaging result of the resolution target is shown in Fig. 7. As one can see, periodic stripes were distinguishable if the period was not smaller than 1 mm. Such result is comparable with the parabolic mirror performance, but at the same time it has an advantage of compact size and absence of Fabry-Perrot oscillations as it was observed in the case with metal zone plate [13], [14].

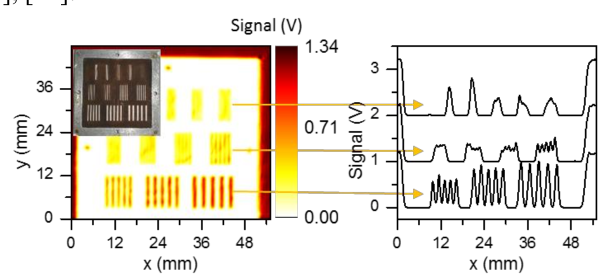


Fig. 7. THz image of the resolution target at 580 GHz frequency obtained by 3 cm focal length diffractive lens (left). Dark color in the THz images corresponds to the transmittance maxima. The cross-section of resolution target different period stripes line (right). Vertical scale is shifted by 1 V. The photo of resolution target is shown in the inset. Detailed target parameters are described in [4].

## Conclusions

The laser direct writing technology was found to be powerful and convenient tool to fabricate diffractive optics for THz frequencies. The multilevel phase Fresnel lenses for 580 GHz reaching 0.86 numerical apertures have been fabricated with a different number of phase quantization levels. The effect of phase quantization number to the focused beam amplitude was determined, and radiation power transmission efficiency reaching more than 90 % was demonstrated. It was shown that imaging resolution less than 1 mm can be obtained employing robust 50 mm diameter multilevel THz lens at 580 GHz frequency.

## Acknowledgment

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