Compact diffractive optical components for terahertz beam manipulation

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***Abstract*— Zone plates of the conventional design and the complex with integrated band-pass filter apertures were fabricated on the metal film and highly resistive silicon substrate using the direct laser writing. The focusing performance of the diffractive components was studied measuring the 0.6 THz frequency beam profiles along the optical axis. The compact lenses with the focal length of 5 and 10 mm and the numerical aperture up to 0.5 was experimentally demonstrated with the preference for the silicon components due to less pronounced standing waves effect between the detector and the zone plate.**

I. INTRODUCTION

OVER the past few years number of applications with compact THz sources [1] and detectors [2] significantly increased taking a particular attention on development of the spectroscopic THz imaging systems [3]. However, system dimensions are still limited by commercially available large size components like mirrors, beam splitters, waveguides, and lenses used to manipulate the THz radiation. The Fresnel zone plates being thinner, lighter and in some cases more effective in comparison to identical diameter and focal length THz lenses and mirrors made of traditional materials can be used to scale down size of imaging systems. New type optical component – the THz zone plate with integrated resonant filter apertures (TZP) – on an optically-thin metal foil was recently developed [4-5]. Such a composite TZP components can more efficient in terms of individual frequencies selection and tiny beam focusing in one device.

In this work the performance of the compact diffractive optic components designed for 0.6 THz frequency beam focusing was investigated. Normal and inverted design conventional zone plates as well as the TZPs were processed on thin metal foil and highly resistive silicon (HR-Si) wafer. In this way, a set of nine optical components of 16.5 mm diameter and focal length of 5 and 10 mm were processed. The performance was obtained measuring two-dimensional THz beam profiles along an optical axis.

II. RESULTS

The samples were processed on the molybdenum foil and on the HR-Si using the laser direct writing (LDW) as described elsewhere [4-5]. Scanning electron microscope (SEM) images of fabricated conventional zone plates on 30 μm thick metal film are shown in Figs. 1a, d. The TZPs were designed by replacing open area of the Fresnel zones with the array of cross apertures where the cross center was fitted in (Figs. 1 b, e). The zones radii of the phase zone plate (Fig. 1 c) was the same as for the conventional zone plate but the opaque rings (metal) were replaced with the low absorption material which thickness was altered by the DLW to introduce the phase change of π. Therefore, the grooves of up to 80 μm in depth on the 500 μm thick HR-Si wafer (Fig. 1f) were laser ablated.

Three-dimensional finite-difference time-domain modeling was used to foresee the focusing performance of the zone plates and analyze the distribution of electric fields in free space. Modeling results were experimentally confirmed via profiling of the 0.6 THz frequency beam obtained from the commercial THz electronic source.

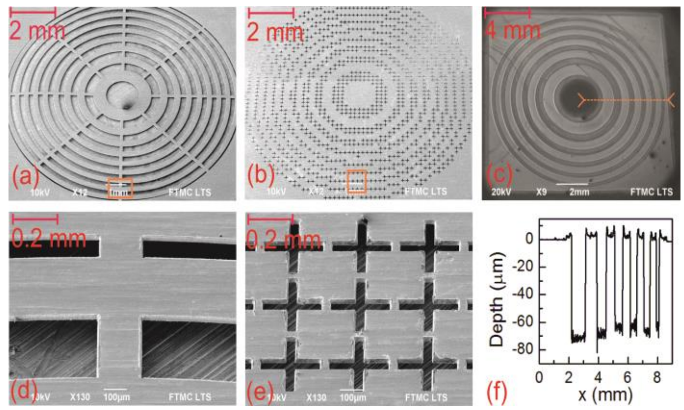

Fig. 1. The SEM images of the diffractive optic components with the focal length of 5 mm and the diameter of 16.5 mm: (a) the Fresnel zone plate and (b) the TZP both processed on metal film; (c) phase zone plate processed on HR-Si substrate; (d) zoomed zone plate and (e) zoomed TZP; (f) depth profile along the line shown in figure (c).

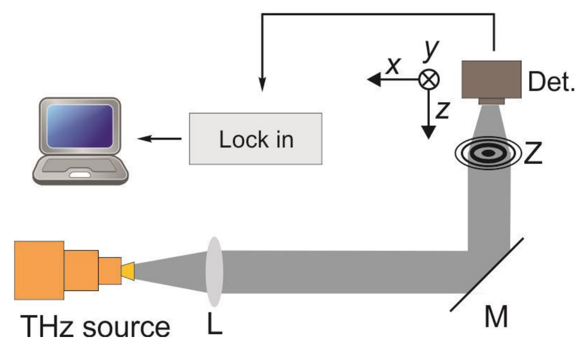

Fig. 2. Scheme of the THz beam profile profiling, where L – the Teflon lens with the focal distance of 12 cm; M – the mirror; Z – the investigated sample; Det. – the THz detector with small active area.

Fig.2 shows a schematic diagram of the experimental setup used. Radiation from the THz source was electrically modulated at 2 kHz frequency. The beam was collimated with f = 12 cm focal length and 5 cm diameter Teflon lens. The collimated beam was angled by the flat 5 cm diameter mirror to the THz detector through the zone plate. The antenna-coupled CMOS field-effect transistor was taken for the THz radiation measurements as such the detector provided small enough pixel size [6].

Measurements were performed in *xy*-plane along the optical axis (see Fig. 1). Typical results obtained focusing the THz beam with the conventional zone plates and TZPs are shown in Fig 3. The THz beam focusing performance was described by the Gaussian beam propagation model (Fig. 3 a). The distance along which the focused beam waist ω increases by factor of $\sqrt{2}$ is known as Rayleigh length z_R that also demonstrates the beam divergence Θ angle.

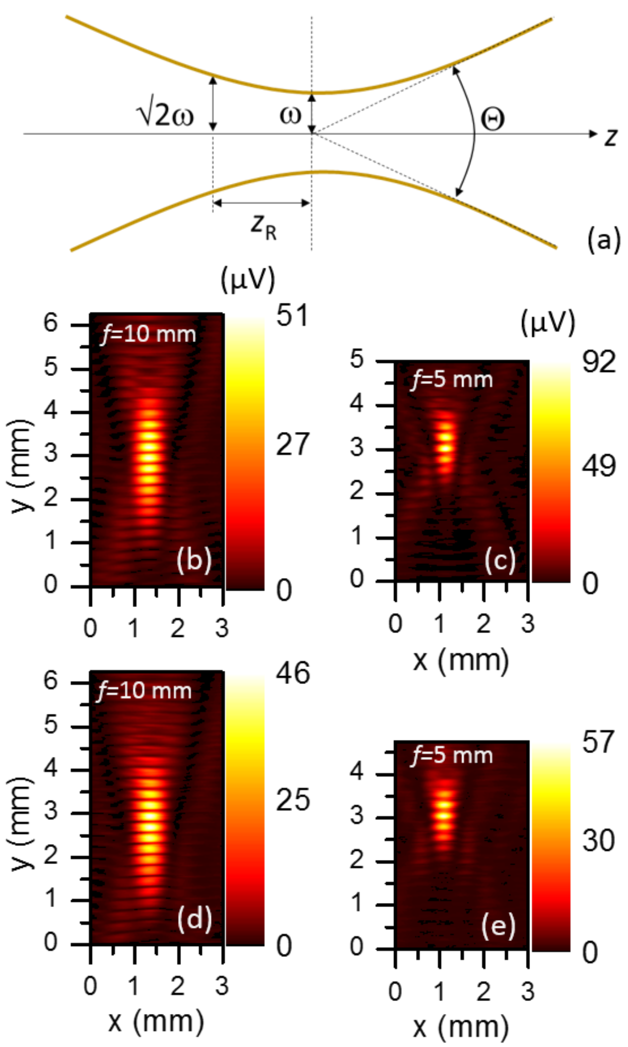

Fig. 3. Focusing parameters of the Gaussian beam (a): ω – beam waist; z_R – Rayleigh range; θ – total angular spread. Images of the THz beam focused with the conventional zone plate (b, c) and the TZP (d, e) with the focal length of 10 mm (b, d) and 5 mm (c, e). Pixel size 25×25 μm^2.

It was obtained within the accuracy of the experiment that the integrated resonant apertures did not contribute to the size of focused beam waist (compare Fig. 3b with d, and Fig. 3c with d). The waist values of the THz beam focused with the $f = 10$ mm conventional zone plate and the TZP was of 0.40 mm and 0.42 mm, respectively. The results obtained with the 5 mm focal length diffractive optics demonstrated the beam waist values of about 0.38 mm independently on the lens type. The Rayleigh length was in the range of 1.4 mm and 0.7 mm for the components with the longest and the shortest focal length, respectively.

The maximum intensity of focused THz beam was found dependent on the particular diffractive component used and that it is seen from the intensity scale of Fig. b-e. The biggest difference was found measuring the $f = 5$ mm components. The intensity of focused THz beam with the Fresnel zone plate was almost two times higher in comparison to the same size TZP (see Fig.3 c, e). In this case the dimensions of the THz resonant apertures were close to the measures of the outside zones of the TZP what caused a staircase-like modification of the circle (see Fig.1 a, b) which in turn deteriorated the transmittance performance of the lens. In all experiments, the signal amplitude oscillations along z-axis were observed due to standing waves formation between the zone plate and the detector mounted on the gold patterned chip holder. However the standing waves were not observed in the simulation data where the metal plane behind the detector was removed. In addition, the phase sensitive zone plate was designed in order to reduce the standing waves effect using smaller reflection coefficient of the HR-Si material. And indeed, a less pronounced standing waves were obtained measuring the focusing performance of the HR-Si components which the results will be presented elsewhere.

To conclude, the compact diffractive optic components with the focal length of 5 and 10 mm and the numerical aperture up to 0.5 at frequency of 0.6 THz have been experimentally demonstrated. The beam waist and the Rayleigh range were obtained smallest focusing the beam with the shortest focal length samples, which the transmittance performance was found to be very sensitive to the THz resonant apertures integration creating the composite TZP components.

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