Quasi-optical components for the THz-regime: Fabrication and characterization

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We discuss the fabrication, and the characterization of a series of quasi-optical terahertz components required to construct a shear-interferometer. Lenses with different focal length and Ronchi phase gratings with different period and height are demonstrated. Optimal components with best performance regarding signal-to-noise ratio at the camera and diffraction efficiency of the gratings were selected.

1 Introduction

Terahertz (THz) radiation provides numerous advantages, which include: i) The capability to penetrate materials, which are opaque to visible light providing information about the inner structures, ii) a non-ionizing nature as compared to X-rays, which makes them safe for humans and biological tissues, and iii) a convenient spectral range where many materials, such as drugs and explosives, have unique spectral fingerprints. Consequently, THz sensing has found several applications such as non-destructive testing [1] and quality control of food [2]. This, in turn, led to developments in various directions including new and unique approaches for sources, detectors, and optical components.

A convenient approach for interferometry in the THz domain, is shear-interferometry, which can be realized by means of a simple Ronchi phase grating (RPG). In the future, this could lead to THz wave front sensing without the need of an external reference wave, as it is required by current approaches like THz time-domain spectroscopy [3] and THz digital holography. Here, we discuss the fabrication, and characterization of a series of quasi-optical THz components required to construct a shear-interferometer (SI). Based on this survey, components which give the optimum performance in terms of imaging quality and diffraction efficiency of the gratings were selected to construct a THz SI.

2 Fabrication of the optical components

Since the required THz optical components are not commercially available, they had to be designed and fabricated in house. Many polymers such as polypropylene or polystyrene are used for the fabrication of THz quasi-optical components since they are transparent in the THz regime. Optical components made of plastics are usually manufactured using a 3D printer, and thus the material chosen must allow for high-quality printing. Since it has a high transparency for THz-radiation and can be printed with high quality, Cyclic olefin copolymers or TOPAS was chosen to print the lenses [4]. Plano-convex lenses were printed from TOPAS with a focal length of $f = 140$ mm. A different process was used for the RPG due to the high precision required. The grating was mechanically milled from an HDPE block using a computer numerical control (CNC) machine. The nominal value of the grating period is $a = 6.44$ mm. Photographs of two examples of the optical components are shown in Fig. 1.

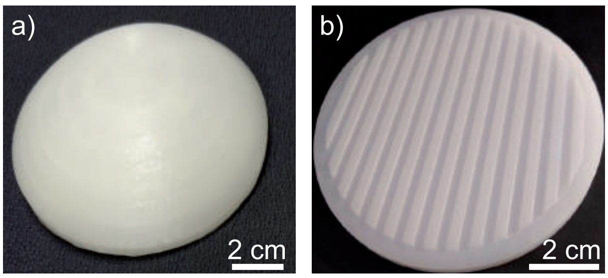

Fig. 1 *Examples of fabricated optical components for the 280 GHz. In a) a plano-convex lens with $f = 140$ mm and in b) a RPG with a grating period of $a = 6.44$ mm and grooves depth of $d = 955$ mm are shown.*

3 Characterization and evaluation

The lens was measured using a 3D tactile measurement system (Mitutoyo Crysta Apex V7106) to obtain accurate information about its radius of curvature. For a plano-convex lens the radius R and the focal length f are related by

$$\frac{1}{f} = (n-1)\frac{1}{R}\,, \tag{1}$$

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where $n = 1.5197$ is the refractive index of TOPAS at 280 GHz. For the design parameters, the radius is $R = 72.75$ mm. From 6 tactile measurements, the mean value for the radius was determined to $R = 73.83 \pm 0.18$ mm. The focal length calculated from the mean value is $f = 142.07 \pm 0.34$ mm, which corresponds to a deviation of approx. 1.4% from the desired value. We used a simple scalar diffraction model to calculate the properties of the RPG. For a desired shear of 23 mm (46 pixels of the camera), we obtained a grating period of $a = 6.44$ mm. The RPG needs to provide a periodic phase shift of π, which is achieved by a depth of the grooves of $d = 955\,\mu$m.

The period and the depth of the grooves of the RPG were measured using a Keyence laser scanning confocal microscope (VK-X3000). In Fig. 2 different visualizations of the measurement of the depth of the lattice can be seen.

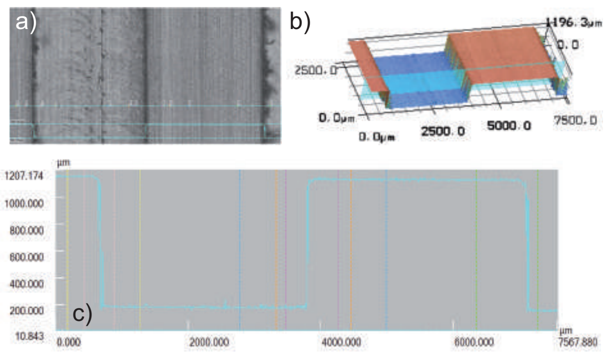

***Fig. 2** a) and b) show 2D and 3D maps of the measured part the RPG. In c) the groove depth was determined by averaging several color-marked segments of the section.*

A measured groove depth of $d = 964 \pm 9\,\mu$m can be determined via the average value. The period is also determined resulting in a value of $a = 6438 \pm 84\,\mu$m. Thus, the measured values agree well with the design parameters.

Finally, the diffraction efficiency η_N across the Nth diffraction order was measured using the setup shown in Fig. 3(a). It can be theoretically determined from the shape using [5]

$$\eta_N = |T(f_x)|^2 = \text{sinc}^2\left(\frac{N}{2}\right)\cos^2\left(\frac{\phi}{2} + N\frac{\pi}{2}\right) \quad (2)$$

Here, the spatial frequency is given by $f_x = N/a$, and $\phi = 2\pi(n-1)h/\lambda$ denotes the phase changes introduced by the groove depth h. From Eq. (2), the 0-th and all even diffraction orders have zero efficiency, i.e. the diffraction orders are suppressed. The recorded intensities are shown in Fig. 3. We found that the diffraction efficiency of the 0-th order and the 1-st order are $\eta_0 = 4.15\%$ and $\eta_1 = 39.5\%$. The deviation from the theoretical value of 40.5% can be explained by the non-ideal groove depth.

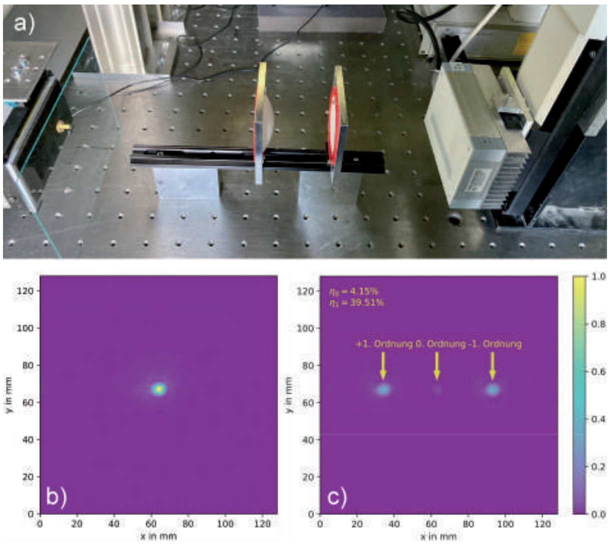

***Fig. 3** a) Photo of the setup used for measuring the diffraction efficiency. b) and c) shows the captured images with and without grating to study diffraction efficiency.*

4 Conclusions

We have demonstrated the fabrication and characterization of lenses and Ronchi phase gratings for THz-SI using various fabrication processes and measurement methods. We determined components with the best performance in terms of image quality and diffraction efficiency and constructed a THz shear-interferometer.

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