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Terahertz Sieves

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***Abstract*— Imaging at terahertz (THz) frequencies offers a great potential for applications including: security screening, telecommunications biodetection, and spectroscopy. Some of these applications need specially designed lenses with customized characteristics that are not commercially available. In this work we present the THz sieves as a new kind of THz lenses. We demonstrate that these lenses improve the resolution of conventional zone plates constructed with the same level of detail. Amplitude and phase THz sieves were 3-D printed and tested experimentally. Excellent agreement was obtained between the experimental and calculated results.**

***Index Terms*—Terahertz materials, Photon sieves, Terahertz focusing, and imaging.**

I. INTRODUCTION

NUMEROUS applications of THz an sub-THz radiation such as imaging or spectroscopy require passive devices like lenses [1], filters [2], and waveguides [3]. Focusing lenses allow improving the sensitivity of terahertz setups, which is a crucial issue in this range of electromagnetic radiation, where there is a lack of high-power sources and high-sensitive detectors.

The optical properties of different polymers [4] have been exploited to fabricate a variety of THz lenses that are commercially available. However, many applications require custom-made THz lenses with a special design. Refractive lenses with different geometries have been manufactured from bulk polymers by lathe turning, compression molding [1], and recently, by 3D printing [5,6]. On the other hand diffractive THz optical elements have been proposed and tested [7,8]. In spite of their lower light throughput and chromatic aberration, diffractive lenses can have high numerical aperture [9], and permit beam shaping [10,11], working in linear and compact setups. Therefore, in many applications, the performance of diffractive THz lenses is better than that of their refractive homologous. Additionally, 3D printing technology has also been used recently to construct special designs of diffractive lenses [10-12].

Photon sieves (PSs) are diffractive optical elements, originally conceived to improve X-rays focusing [13]. The first PSs where basically amplitude Fresnel zone plates (FZPs) in which the transparent rings were substituted by non-overlapping holes of different sizes. Special features of PSs in the visible range were investigated in several works [14–17], from which different applications emerged [18,19]. The main features that characterize PSs are the following: (1) They can be fabricated on a single sheet without any substrate, (2) PS allow a better resolution than a Fresnel zone plate (FZP), with the same dimensions[13], (3) they allow improved focusing by the suppression of secondary maxima and higher orders of diffraction[16,17].

In this work, we introduce the THz sieves (TS). We study the TS axial and transverse resolution in comparison with those provided by a conventional FZP constructed with the same level of detail. The focusing properties of both, amplitude and phase TS are experimentally demonstrated.

II. TERAHERTZ SIEVES. DESIGN AND FOCUSING PROPERTIES

The construction procedure of a TS starts from a conventional FZP designed for a given THz frequency. As it is well known, an amplitude FZP of focal length f at wavelength λ, consists of alternate transparent and opaque zones, where the radius of the n-th zone is given by $r_n^2=2nf\lambda+n^2\lambda^2$.

The width of outermost ring of a zone plate with N zones, $w=r_N-r_{N-1}$ (see Fig. 1a), imposes a limit on the maximum resolution achievable with the FZP: $w=\lambda f/2r_N$. It was shown [13] that a PS can overcome this limitation because the pinhole diameter can be bigger than the width of the underlying zone. Thus a PS can have a higher numerical aperture than a FZP constructed with the same level of detail. This property is of particular interest in THz applications, where low-cost diffractive lenses can be 3D printed.

A TS is constructed by replacing the transparent rings of width w in the Fresnel zone plate by non-overlapping circular holes of diameter d distributed about the rings (see Fig. 1b). Thus, the transmittance function $t(x,y)$ of a TS can be expressed as a binary function that takes the values $t(x,y)=1$ if $(x - x_{i,j})^2 + (y - y_{i,j})^2 \le d_{i,j}{}^2$; and either $t(x,y)=0$ or $t(x,y)=-1$, otherwise; depending on if the TS is of amplitude or phase, respectively. In the transmittance function, $x_{i,j}$ and $y_{i,j}$ are the center coordinates of the holes, with $i=1,2,\ldots N$ and $j=1,2,\ldots m$; being m the number of holes in each zone.

The focusing properties of our proposal were assessed in comparison with a FZP by means of the irradiance at different planes for a point object at infinity i.e.; the point spread function (PSF). This function was computed numerically by using the nonparaxial scalar diffraction theory:

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$$I(x,y;z)=1/\lambda^2 \times \left| \iint t(x_0,y_0) \frac{\exp\left\{ i\frac{2\pi}{\lambda}\sqrt{(x-x_0)^2+(y-y_0)^2+z^2} \right\}}{\sqrt{(x-x_0)^2+(y-y_0)^2+z^2}} dx_0\, dy_0 \right|^2, \quad (1)$$

We employed Eq. (1) to compare the focusing properties of phase TS and FZP. In particular we analyzed two lenses of the same focal distance: f =122 mm, at the same design frequency: ν_0=0.625 THz. For the lens material we considered polyamide PA6, which has a refractive index n=1.59 at this frequency[10]. The radius of the FZP (r_N = 18.8 mm), and its outermost width (w=1.63 mm), were both selected to be compatible with an experimental verification in our lab. For the TS the minimum hole diameter was fixed to be d_{min}=1.65mm; i.e.; approximately of the same size of w. The maximum hole diameter was d_{max}=4.11 mm. The hole density in each zone was selected such as the transparent area in each TS zone must be at least a 75% of the whole Fresnel zone. With these parameters we used Eq. (1) to compute the axial irradiance provided by the TS for different values of d, in the range $1w \leq d \leq 2w$, obtaining that the value d = 1.33 w provided the best apodization of the third diffraction order focus. Thus, we found that with the same width of the outermost ring, the numerical aperture of the TS is 1.33 times higher than the FZP, being the TS radius r_N=25 mm. The axial irradiances and transverse intensities at the focal plane, provided by both lenses are shown in Fig. 1c) and Fig. 1d), respectively. As can be seen in Figs. 1c) and 1d) both the axial and transverse resolution are better for the TS. The full width at half maximum (FWHM) of the axial irradiance peak provided by the TS is 18.8 mm, which is 52% lower than FWHM of the FZP. For the transverse resolution the FWHM at the focus of the TS is 1.31 mm, and 1.77 for the FZP. The apodization of the third order focus at z=40mm can be clearly seen in Fig. 1c). The physical reason for this apodization is that the axial irradiance only depends on the angular average of the effective pupil along the radial coordinate [20], which in the case of TS is smoothed by effect of the holes.

In order to investigate the effect of a finite bandwidth on TS performance, we have computed the axial PSF for the TS at two other frequencies. The result is shown in Fig. 2). In this case in addition to the focal shift produced by the chromatic aberration of the TS, the peak intensity is lower for the other two frequencies because for these frequencies the phase difference between the holes and the plate is not exactly π.

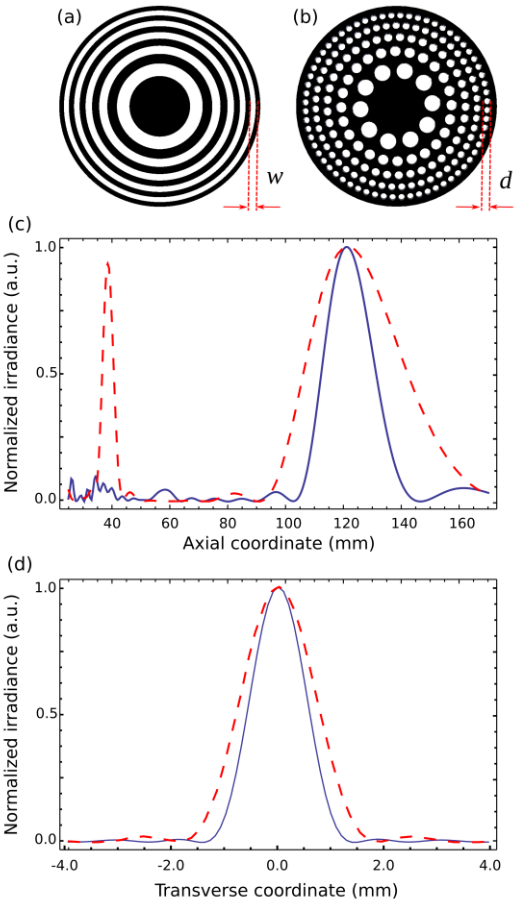

Fig. 1. a) Binary Fresnel zone plate, w is the width of the outermost zone, which determines its transverse resolution. b) THz sieve with the same number of Fresnel zones, d is the diameter of the holes at the Fresnel zone corresponding to w. c) Numerical axial point spread function; and d) Transverse Intensity at the focal plane, computed for a FZP (dashed line) and a TS (continuous line) of the same focal distance (f=122 mm; ν_0=0.625 THz). In Fig. 1c) and Fig. 1d) each plot was normalized to its maximum value

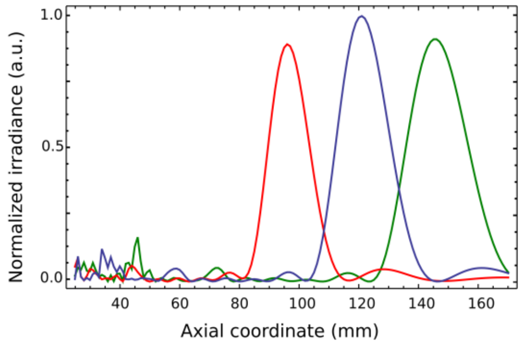

Fig.2. d) TS performance at 3 different frequencies: ν_0=0.625 THz (blue line); ν_1=0.496 THz (red line) and ν_2=0.741 THz (green line). The maximum value of the irradiance for the design frequency was used for normalization.

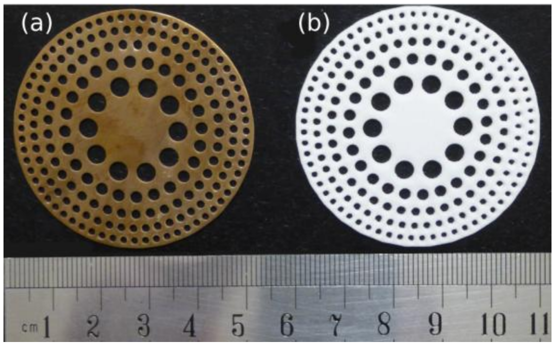

Fig.3. 3D printed THz sieves. a) Is an amplitude lens made in bronze. b) Is a phase lens made in PA6 polyamide. The holes are located in the even zones of a Fresnel zone plate (focal distance *f*= 122 mm).

III. EXPERIMENTAL RESULTS

Fig. 4 shows the setup we employed for the experimental characterization of the TSs. A VDI frequency multiplier (Virginia Diodes, Inc. Charlottesville, VA. USA) provided the 0.625 THz beam. The source of microwave radiation for the VDI frequency multiplier was an electromagnetic YIG-tuned oscillator MLXB-1768PA. It generates radiation in frequency range 13-15 GHz. The base frequency was multiplied 48 times. The divergent beam, emerging from the horn antenna, was collimated by a high density polyethylene (HDPE) lens and directed to the investigated TS. The detector: a Schottky diode, was mounted on a 3D motorized stage. The focal spot was scanned with a horn antenna, having a 2.4 mm aperture diameter. A lock-in system, based on modulation at 187 Hz, and a mechanical chopper, was employed to measure the signal from the detector. The inset in Fig 4 shows the intensity recorded at the transverse plane (x,y) just before the lens plane.

Two different TS lenses were fabricated by 3D printing: an amplitude lens, shown in Fig. 3a), constructed in bronze, and a phase lens, shown in Fig 3b), made in PA 6 polyamide. The physical dimensions of both lenses were the same, and coincide with those used to compute Fig. 1c) and Fig. 1d). As the minimum thickness of the phase TS that provides a π phase difference between the lenses material and the holes $t=\lambda/2(n-1)=0.4$ mm, was considered too thin to be handled, we have constructed the lenses with a thickness of 3t=1,2 mm, which produces the same phase shift. Other details of the 3D lens production can be found elsewhere [10].

Fig. 5 shows the experimental results obtained for the axial PSF (dotted lines) corresponding to the lenses shown in Fig. 3. The numerical simulations obtained with Eq. (1) are shown in the same figure for comparison (continuous lines). To obtain the numerical results, the transmittance of the lens was multiplied by the normalized field amplitude recorded of the at the lens plane (x,y) shown in Fig. 4). In addition, we not considered a point-like detector as in Fig. 1c), but integrated the irradiance in the area of detection at the horn antenna. Note that, in spite of that, the surface roughness, and microstructure of the 3D printed lenses have not been considered, we found a very good agreement between theory and experiment.

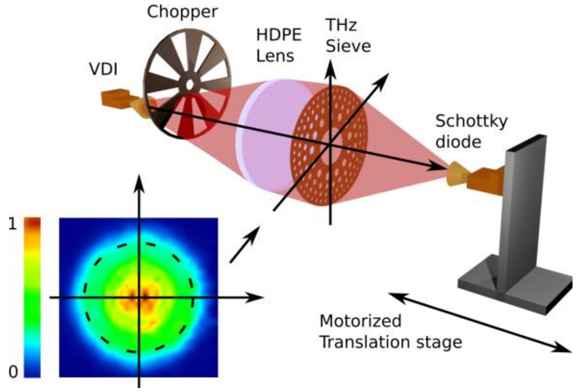

Fig.4. Experimental setup used in axial PSF measurements. The source of THz is a VDI frequency multiplier with a horn antenna. The divergent beam, is collimated by a HDPE refractive lens (focal distance *f* =150 mm). The transverse intensity measured at TS plane (x,y) is shown in the inset. The radius of the dashed line in the inset is r_N = 18.8 mm. The detector: a Schottky diode, with a horn antenna, mounted on a 3D motorized stage, scanned the focal volume. A lock-in system, based on modulation at 187 Hz, and a mechanical chopper, was employed to measure the signal from the detector.

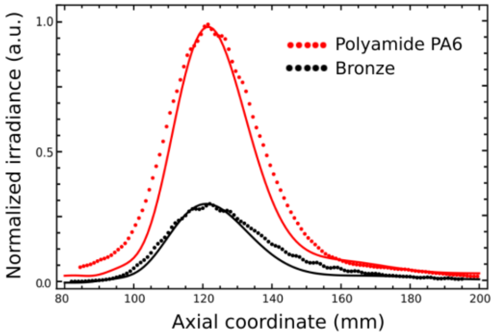

Fig.5 Experimental (dotted lines) and numerical simulation (continuous lines) provided by the 3D printed THz lenses of Fig. 3a) (black lines) and 3b) (red lines). The maximum value of the irradiance for the PA6 lens was used for normalization.

As expected phase polyamide TS is four times more efficient than the amplitude bronze TS of the same dimensions.

IV. CONCLUSION

By using 3D printing technology, we have demonstrated the feasibility of realizing TS diffractive lenses. The focusing properties of both: amplitude and phase TS were tested using 0.625 THz beam. We have shown that TS can achieve better resolution than binary FZP. Further improvements are expected with other exotic sieves distributions [15,16]. So, our proposal opens the possibility to use low cost optics for a wide range of THz applications. Two examples of special interest are THz astronomical telescopes where ultralarge space telescope primaries are necessary, preferably as a single membrane; i.e; with no supporting structure [19, 21] and THz compressive sensing, to achieve the precise focalization needed in a single pixel camera [22].

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