Aspheric Lenses for Terahertz Imaging

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Abstract: We present novel lens designs for Terahertz imaging. Kirchhoff's diffraction theory and experimental results show that the achievable resolution depends critically on the lens shape, and a resolution of close to λ/2 can be achieved.

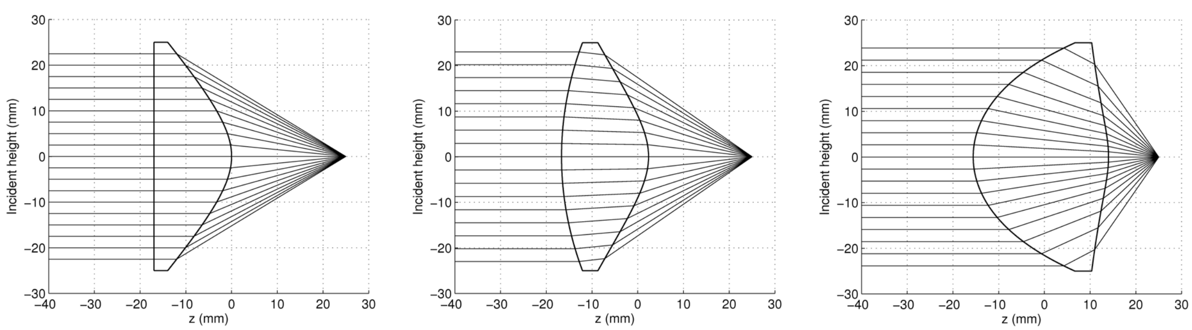
OCIS codes: (110.6795) Terahertz Imaging; (220.1250) Aspherics; (220.3630) Lenses; (260.1960) Diffraction theory.

1. Introduction

In the past, imaging of Terahertz (THz) beams has relied on using off-axis parabolic mirrors (OAPMs) due to the lack of suitable lenses. OAPMs generally provide near diffraction limited performance [1]. On the other hand, they are susceptible to large aberrations like coma and astigmatism with a very small misalignment, therefore affecting imaging resolutions. Lenses, on the other hand, are much less susceptible to aberrations and are much easier to align as they can be inserted in the beam without changing its direction. By placing the lenses on the optical axis without tilt ensures correct alignment. Due to the very long wavelength of the THz beams compared to optics, the paraxial approximation is often violated, and therefore aspherical lenses have to be used. In this paper, we present novel lens designs, and the evaluation of these high numerical aperture lenses shows that a resolution of less than one wavelength can be achieved.

2. Lens design

Our lenses are designed simply by ray tracing with Fermat's principle strictly followed, i.e. all rays from the same wavefront would reach the focal spot traversing the same optical distance. This ensures that spherical aberrations are avoided. Fig 1 shows three different lens designs. Using plane and elliptical profiles as the first surfaces, the second surfaces can be derived analytically. On the other hand, the symmetric lens was designed numerically adjusting the deviation due to refraction to be the same on both surfaces, forming a symmetric pass. This is similar to passing a prism with minimum deviation, which ensures the lowest reflection losses. All the lenses used in this investigation had a focal length of 25mm and a diameter of 50mm. n= 1.52 was used for the simulations as this is the refractive index of our lens material, High Density Polyethylene (HDPE).



(a) (b) (c)

Fig 1. (a) The planar-hyperbolic lens; (b) the elliptical-aspheric lens; (c) the symmetric lens

3. Evaluation

The three main factors that would affect the size of the focal spot, and hence the imaging resolution, are: (i) reflection losses; (ii) absorption losses; and (iii) the cone angle (beam convergence) as a function of the radial distance from the optic axis, δ(r) (see Fig 2 (a)). The first two effects modify the output beam profile slightly, and the third effect is dominant for determining the focal spot size. Numerical simulations using Kirchhoff's scalar

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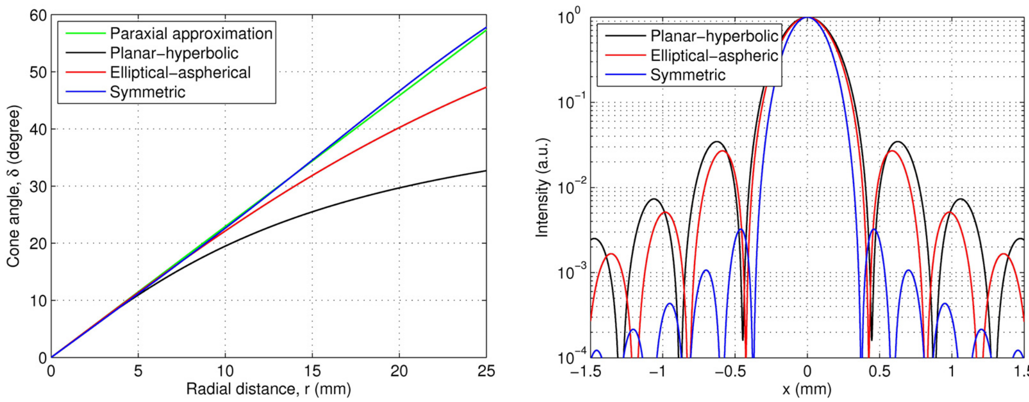
diffraction theory [2] were performed using the intensity distribution at the second lens surface as the input, and the intensity distribution in the focal plane as the output (see Fig 2 (b)). Table 1 shows the simulated focal spot sizes, in comparison with the case where the lens material is lossless. Due to the polarization-dependent reflection losses the focal spot is very slightly elliptical, and material loss only plays little role in affecting the imaging resolution. It is shown that the focal spot sizes are all below one wavelength, and is close to $\lambda/2$ for the symmetric lens.

Table 1. Evaluated focal spot sizes, using Kirchhoff's scalar diffraction, for different lenses at 0.7 THz (λ = 0.429 nm)

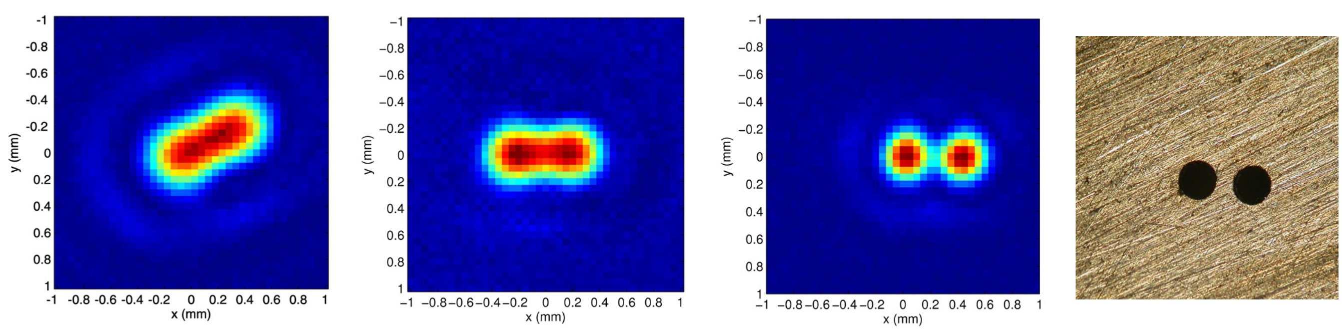
Lens	Focal spot size, FWHM (mm)		
	$\alpha = 0.0135\ mm^{-1}$	$\alpha = 0\ mm^{-1}$	$\alpha = 0.0135\ mm^{-1}$ (TE)
Planar-hyperbolic	0.388	0.391	0.399
Elliptical-aspheric	0.365	0.369	0.375
Symmetric	0.292	0.296	0.302



(a) (b)

Fig 2. (a) Cone angle, $\delta(r)$ curves for different lenses. (b) Intensity profiles at the focus.

The standard planar-hyperbolic and the elliptical-aspheric lenses have similar performances, while the symmetric lens has a much smaller focal spot and less diffraction. This is verified experimentally by imaging a double pinhole with hole diameters of 0.25 mm and a separation of 0.4 mm, as shown in Fig 3. While the planar-hyperbolic and elliptical-aspheric lenses are close to be just resolved, the symmetric lens clearly resolves the pinhole image.



(a) (b) (c) (d)

Fig 3. THz images taken at 0.7 THz (λ = 0.429 mm) for a double pinhole using: (a) the planar-hyperbolic lens; (b) the elliptical-aspheric lens; (c) the symmetric lens; (d) original pinhole, with diameter = 0.25 mm and separation = 0.4 mm.

4. References

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[2] E. Hecht, *Optics*, (Addison Wesley, 1998), Chap 10.