Rapid Prototyping of Simple Optical Elements for the Terahertz Domain

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Introduction

The long wavelength of terahertz (THz) radiation lowers the requirements for surface roughness and shape in optical components very significantly. This allows for highly accessible and customizable optical components that can be manufactured in conventional manual milling machines and simple fused filament fabrication (FFF) 3D printers. Recently, work on reflective optics, especially off-axis parabolic mirrors, have emerged[1]. We evaluate well-known methods for manual machining of spherical elements, and provides qualification of a simple methodology for finishing of FFF printed optical elements.

Fabrication of Spherical Lenses

Setup of blank High-density polyethylene (HDPE) is chosen for its low absorption ($< 2\mathrm{cm}^{-1}$ from 100 GHz-2.5 THz[2]) and machinability. A single point milling tool (colloq. fly-cutter) is set with a rotational axis off vertical (blue line in fig. 1), while a HDPE blank is rotated continuously around an offset axis (red line in fig. 1).

Design The curvature of the plano-convex lens is defined by the angle of the cutter's axis of rotation and the diameter of the single-point cutter, according to the following formulas:

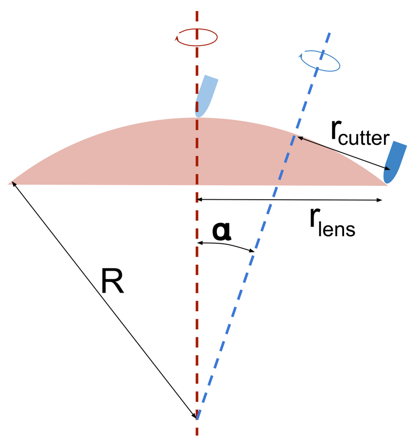

Fig. 1: Specification of angles and rotation axes for manual milling of spherical lenses.

$$r_{cutter} = \frac{\sqrt{r_{lens}^2 + S^2}}{2}, \qquad \alpha = \tan^{-1}\left(\frac{r_{lens}/2}{R - S/2}\right)$$

Where $S = R - \sqrt{R^2 - 2r_{lens}^2}$ is the sagitta, R is the lens curvature, r_{lens} is the radius of the desired lens, r_{cutter} is the cutting point diameter and α is the angle between the rotation axis of the polymer blank and the cutting tool.

Fabrication of Off-Axis Parabolic Mirrors

Design Off-axis parabolic mirrors (OAPMs) are modeled as revolved solids from parabolas in Autodesk Fusion 360 and files for the 3D FFF printer (Ultimaker 3 Extended) are prepared with the software Cura.

Slicing and printing Solids are oriented in the Cura slicer workspace, so every optical surface of the OAPM has an angle $> 15°$ from horizontal, to avoid discretization errors at local minima. A layer height of 0.1mm was sufficient with subsequent polishing. 2.85mm Poly-lactic acid polymer was used (3DE PLA max, Grey).

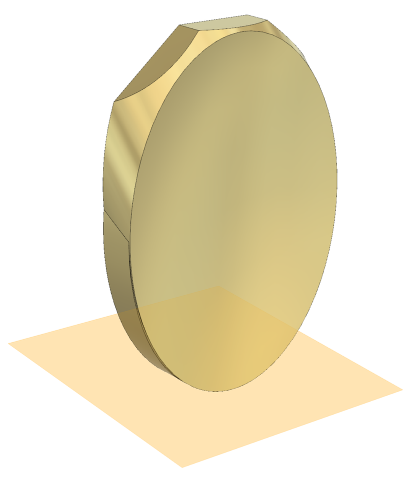

Fig. 2: Suggested mirror orientation in the printer space. The mirror surface should not be parallel to the extrusion axes or the z-plane.

Polishing Polishing was performed manually, from grit 220 to grit 4000, wet sanding with water and silicone-free detergent.

Metallization The metallization of Ti/Au (50nm/300nm) was done in a sputter coater after thorough cleaning of the optical surface with detergent, distilled water and ethanol.

Acknowledgements

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The author has regretfully failed to include reference number 4 in the submitted abstract. The correct and crucial reference should be made to the paper by Fullager et al.[1].

References

[1] Daniel B. Fullager, Serang Park, Clark Hovis, Yanzeng Li, Jesse Reese, Erin Sharma, Susanne Lee, Christopher Evans, Glenn D. Boreman, and Tino Hofmann. Metalized Poly-methacrylate Off-Axis Parabolic Mirrors for Terahertz Imaging Fabricated by Additive Manufacturing. *Journal of Infrared, Millimeter, and Terahertz Waves*, 40(3):269–275, March 2019. doi: 10.1007/s10762-019-0568-9.

[2] Mira Naftaly and Robert E. Miles. Terahertz time-domain spectroscopy for material characterization. *Proceedings of the IEEE*, 95(8):1658–1665, 2007.

[3] James E. Harvey, Narak Choi, Sven Schroeder, and Angela Duparré. Total integrated scatter from surfaces with arbitrary roughness, correlation widths, and incident angles. *Optical Engineering*, 51(1):013402, 2012.

Surface roughness

To support electromagnetic radiation without excessive scattering, the surface must be sufficiently smooth. Harvey et al.[3] developed an expression for the total integrated scattered radiation (abbreviated TIS), which is helpful in evaluating the roughness requirements that THz radiation poses on the optics:

$$TIS(\sigma, \theta_i, \lambda) = 1 - \exp^{-\left(4\pi \cos\theta_i \frac{\sigma}{\lambda}\right)^2}$$

where σ is the RMS surface roughness, θ_i is the incident angle and λ is the wavelength. For the case of the lenses, the incident angle is roughly normal, and the mirrors have a mean angle of $45°$. Fig. 3 shows the ratio of scattered light to incoming light, for the various manufacturing methods, within a relevant wavelength range of 100GHz to 10THz.

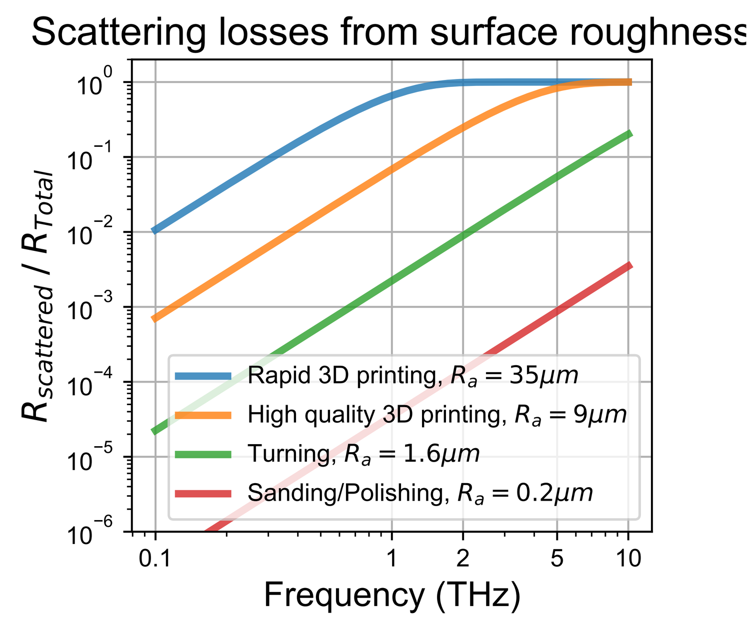

Fig. 3: Total integrated scattering upon reflection, for a selection of machining processes, as a function of frequency.

Profilometric measurements shows Ra values of $2.3\mu\mathrm{m}$ and $0.12\mu\mathrm{m}$ for the machined lens and mirror respectively. This enables support of radiation up to 1.6 and 30THz, with 1% allowable integrated scattering.

Dimensional accuracy of handpolished parts

Using a 2D profile line scanner (wenglor sensoric GmbH MLWL131) mounted on a conventional 6-axis industrial robot (Kuka KR-60), the surface of the mirror has been scanned to assess the gross-scale error from the defined surface. Fig. 4 shows the induced wavefront error across the central 50mm strip along the parabolic direction of the mirror.

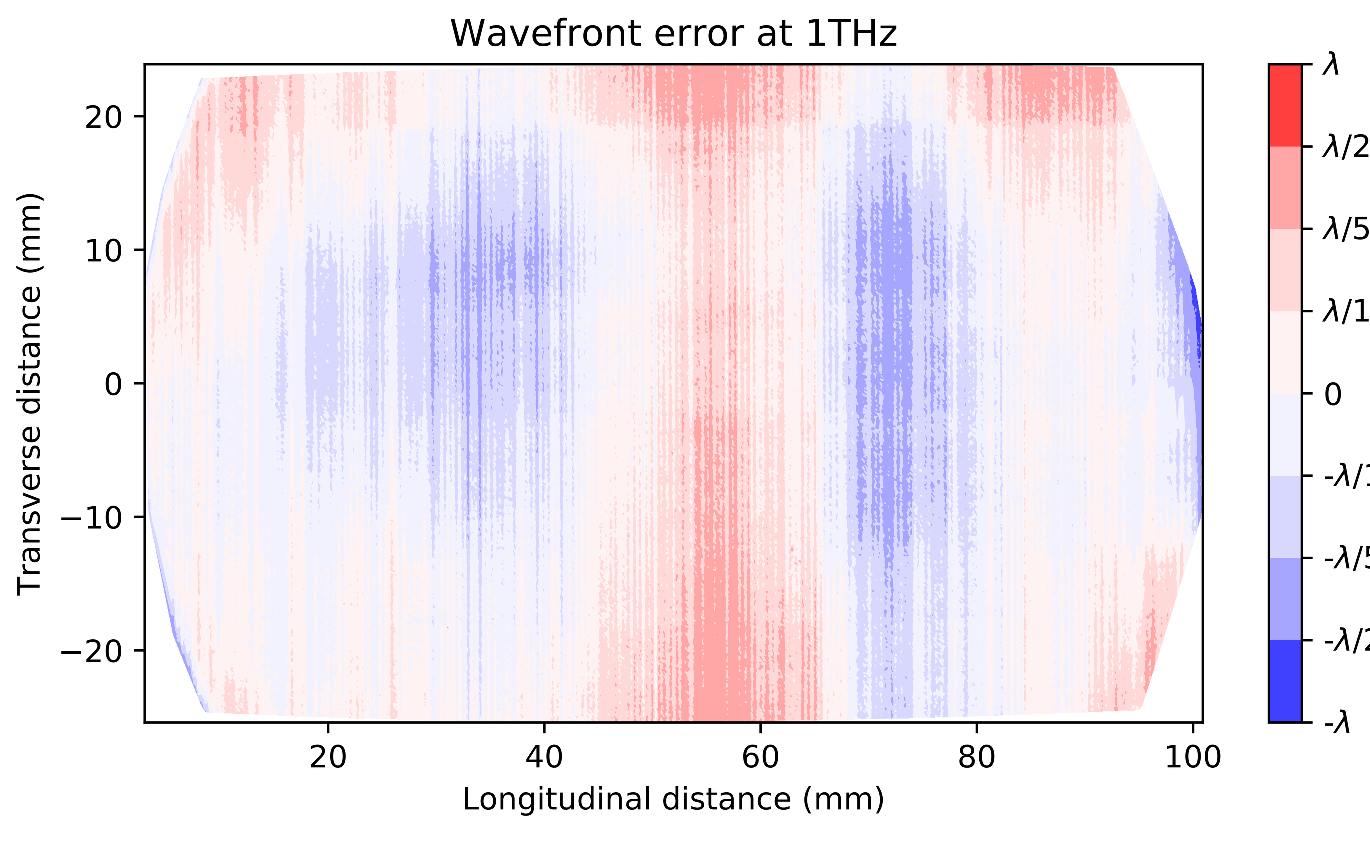

Fig. 4: The induced wavefront error through reflection, at 1THz. Note the non-linear color scale. The section scanned is the central 50mm strip along the longitudinal axis of the mirror. The measurement resolution is stated to be $\lambda/20$, while the measurement scan axis accuracy is within $\lambda/5$.

The 3D scan shows maximum deviations from the parabolic surface of around $\pm\lambda/2$ with larger errors on the very tip, due to edge-rounding. Note also the too-shallow grind in the central band. Mirrors are predominantly polished along the longitudinal direction to remove the layer ridges from the 3D print.

Conclusion

The surface roughness measurements of the lens indicates that further post-processing is advised. The surface roughness of the mirror is however entirely sufficient for work below 10THz. It should however be noted that much greater care is required in the grind to suppress wavefront errors for higher frequency radiation. The mirror as polished is however fully qualified for work up to 1THz.

The performance-to-price ratio is sufficiently high to consider manual post-processing as a viable option for prototype optics for THz applications.