# Design and Measurements of a 480 GHz Metamaterial Flat Lens

Cassandra N. Whitton, Daniel Lu, Adhitya B. Sriram, Philip D. Mauskopf, Christopher E. Groppi, Michael Marrs, Paul F. Goldsmith, Georgios C. Trichopoulos

***Abstract*—There exist scientifically interesting molecular lines, such as the ground state transitions of water, that cannot be observed except from space. Observations of these lines can be made more cost-effective by lightweighting observation components, such as the primary optical aperture. This is particularly important for SmallSats and CubeSats which have highly limited weight budgets. Here we present a flat lightweight metamaterial lens which operates at 480 GHz, close to the 557 GHz ground state transition of ortho–$H_2O$. The lens is composed of alternating layers of spin-coated polyimide and patterned aluminum. The aluminum patterning was generated by optimization to a specific phase pattern. We have manufactured and tested the lens. The lens has an optical diameter of 124 mm. It weighs 3 grams and is less than 150 microns thick. It is also flexible. We have demonstrated using a near-field scan that the optical performance of the lens is nearly diffraction- limited. We have found the loss of the lens using radiometric techniques to be 2.5dB. This loss is roughly 1.5dB higher than expected, and we investigate possible reasons for this discrepancy.**

***Index Terms*—Terahertz, cubesat, metamaterial, lens, optics.**

## I. Introduction

THIS work focuses primarily on the development of lightweight terahertz optics enabled by the use of metamaterial design. This is of particular interest for Smallsat applications where SWaP restrictions are of paramount importance. ASTRO 2020 recommends the expansion of Smallsat based astrophysics through NASA's Astrophysics Research and Analysis (APRA), Pioneer and Explorer opportunities [1]. For this development to include THz applications, low mass, large aperture antennas are essential. The metamaterial method used in this paper is one possible path to this goal.

The main characteristic of this lens that results in dramatic improvements in SWaP resource requirements is the thin geometry of the metamaterial structure. In a traditional bulk lens, focusing is achieved through the transformation of a planar wavefront to a spherical wavefront with a dielectric of varying thickness. In the sub-mm and THz, this thickness is at a minimum several mm and increases when a lens with a small f/D ratio is required. For example, the state-of-the-art low focal ratio, f/D=0.27, silicon lens in [2] is more than 10 mm thick for a lens diameter of 74 mm.

There have also been lenses and reflectors created that use metamaterials and metasurfaces to generate the same phase shift as a conventional optic [3]–[8]. The lens presented here is based on techniques developed in [3]. Using metamaterials consisting of metal layers embedded in dielectric layers, this group has developed lenses up to 300 GHz in frequency [4]. Here we present a 124mm-diameter lens which performs at 480 GHz, an operation frequency which is close to the 557 GHz line of water without being close enough to incur significant atmospheric losses in a lab environment. In addition, we here use a different fabrication method from previous works; while most previous work utilized polypropylene or polyethylene sheets that were first patterned and then were pressed together [3], our design builds up polyimide using spin-casting followed by patterned aluminum in alternating layers, allowing for very precise top-to-bottom alignment. Our lens has also reached a larger diameter or higher operation frequency than most comparable alternatives lenses.

C. Whitton, D. Lu, A. Sriram, P. Mauskopf, C. Groppi, M. Marrs, and G. Trichopoulous are with Arizona State University, Tempe, AZ, United States.
P. Goldsmith is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States.

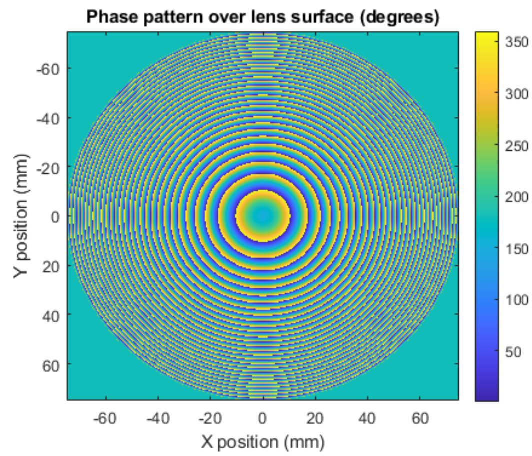


Fig. 1. The ideal phase pattern of the lens.

## II. Lens Design

The design of the lens proceeds in stages. First, an ideal lens phase pattern is created depending on the operation frequency, focal length, and diameter of the lens. The phase pattern is based on gaussian quasioptics [9], and is shown in figure 1. This phase pattern is then subdivided into pixels sized according to the metamaterial structure employed in the lens. A library of meta-atoms is then created and simulated: each meta-atom in this structure is a single metal square. Then, using this simulated library of meta-atoms, optimizations are performed to create pixels in the lens structure which approximate the ideal phase pattern as closely as possible. Each pixel then consists of alternating layers of dielectric and meta-atom,

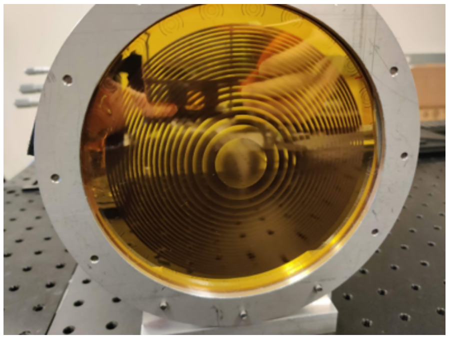

Fig. 2. The lens mounted in its aluminum ring holder. The phase-wrap boundaries can be seen quite clearly.

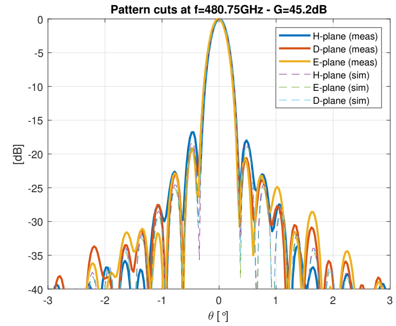


Fig. 3. The measured far-field beam pattern of the lens-horn system, compared to simulation

and the entire lens structure is alternating layers of dielectric and metal patterned grids. This lens structure is then converted into manufacturing files, and the metamaterial lens is created by building up alternating layers of solid polyimide dielectric and patterned metal using photolithography. An image of the complete lens in a ringholder is shown in 2.

## III. Lens Characterization

Theoretical simulations of the lens were performed in order to provide a baseline of comparison. These simulations were based on the as-optimized model of the lens, and thus included the phase errors, reflection losses, and material losses of the optimized pixels.

Two primary methods of measurement were used to characterize the lens performance: a 2d near-field scan and a radiometric loss measurement.

To perform the near-field scan, the lens was mounted one focal distance from a near-field probe, acting as the lens feed. The near-field probe illuminated the lens nearly uniformly. A second near-field probe acted as a receiver. The receiver was scanned through the x-y plane in the lens's nearfield, obtaining both frequency and phase information.

The radiometric loss measurement used a diagonal horn connected to a 1100K receiver designed and built at JPL that operates in the frequency range of our lens. A horn feeding the receiver was placed at approximately the focus of the lens. A Y-factor measurement was then performed, alternating between a room-temperature absorber and an absorber submersed in liquid nitrogen on the side of the lens opposite the horn [10]. This Y-factor measurement was then repeated with the lens removed. Given both of these measurements, the loss of the lens alone could be deembedded from the loss of the horn-receiver system.

### A. Results

The data obtained from the near-field scan were processed to obtain a far-field beam pattern using standard complex near-to-farfield transformations. The resulting far-field pattern at 480 GHz can be seen in Figure 3, which compares the measured near-field-to-farfield transformed pattern to the theoretically modeled results. It is clear that the far-field beam pattern measured in the lab very closely matches the theoretical expectation. The largest discrepancies are deviations of a few dB in the sidelobe levels.

The results of the radiometric loss measurements were analyzed as well. The combined reflective and transmissive loss is roughly 2.5 dB at the design frequency and only varies by about $\pm 0.2$ dB over the measured band. This is significantly higher than the expected loss of the lens, which our simulations predicted to be 1.0. Of this 1.0 dB of simulated loss, approximately 0.2 dB is reflective loss, 0.5 dB is conductive loss, and 0.3 dB is dielectric loss.

It is possible that the effective conductivity of the aluminum was lower than estimated due to its thinness, an effect that can arise at high frequencies due to defects in the metal surface [11].

## IV. Conclusion

We have designed, fabricated, and tested a flat metamaterial 480 GHz lens with a diameter of 124 mm. The design employed optimization of 10 layers of meta-atoms to match a desired phase output. The manufacturing process made use of spin-casted polyimide in combination with photolitographically etched aluminum. The lens weighs only 3.0 grams, significantly less than a comparable conventional lens.

Our lens exhibits near diffraction–limited directivity at the design frequency. Future work will focus on increasing the bandwidth through various means, including using a longer focal length, and using broadband optimizations rather than single-frequency optimizations. We also plan to manufacture 300mm diameter lenses in the future using identical techniques with a larger wafer as a base.

The lens did exhibit 1.5 dB more loss than expected, having 2.5 dB of loss as opposed to the 1.0 dB simulated loss. It is unclear what is the source of this loss. Simulations suggest it is highly unlikely that the loss is due to excess dielectric loss, increased dielectric thickness, or skin depth effects due to decreased metal thickness. Our current expectations are that the loss is due to reflections as a result of under- or over-etching the patterned surfaces, or due to decreased conductivity due to the thinness of the metal. Future work will focus on understanding these losses and designing around them.

## Acknowledgments

We would like to thank Alain Maestrini of JPL for conceiving and performing the radiometric loss test of the lens. We would also like to thank Sven van Berkel, also of JPL, for performing the near-field measurement of the lens and for providing critique on this work. This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. 80NSSC20K0650 issued through the APRA Program. This research was conducted in part at the Jet Propulsion Laboratory, which is operated by the California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA).

## References

[1] National Academies of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*. Washington, DC: The National Academies Press, 2021.

[2] S. van Berkel, M. Alonso-delPino, C. Jung-Kubiak, and G. Chattopadhyay, "An f/0.27 high-gain lens antenna for ultrasmall platforms at thz frequencies," *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 5, pp. 549–560, 2023.

[3] G. Pisano, M. W. Ng, F. Ozturk, B. Maffei, and V. Haynes, "Dielectrically embedded flat mesh lens for millimeter waves applications," *Applied optics*, vol. 52, no. 11, pp. 2218–2225, 2013.

[4] G. Pisano, A. Shitvov, P. Moseley, C. Tucker, G. Savini, and P. Ade, "Development of large-diameter flat mesh-lenses for millimetre wave instrumentation," in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708. SPIE, 2018, pp. 16–27.

[5] Z.-W. Miao, Z.-C. Hao, Y. Wang, B.-B. Jin, J.-B. Wu, and W. Hong, "A 400-ghz high-gain quartz-based single layered folded reflectarray antenna for terahertz applications," *IEEE Transactions on Terahertz Science and Technology*, vol. 9, no. 1, pp. 78–88, 2019.

[6] T. S. Nowack, Y. D. Shah, J. P. Grant, I. E. Carranza, M. G. Kenney, D. Faccio, E. Wasige, and D. R. S. Cumming, "Metasurface optics with on-axis polarization control for terahertz sensing applications," *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 4, pp. 373–380, 2023.

[7] B. Nie, H. Lu, T. Skaik, Y. Liu, and Y. Wang, "A 3d-printed subterahertz metallic surface-wave luneburg lens multibeam antenna," *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 3, pp. 297–301, 2023.

[8] Z. Wani, M. P. Abegaonkar, and S. K. Koul, "Thin planar metasurface lens for millimeter-wave mimo applications," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 1, pp. 692–696, 2022.

[9] P. F. Goldsmith, *Quasioptical systems: Gaussian Beam Quasioptical Propagation and Applications*. New York: IEEE Press/Chapman & Hall, 1998.

[10] D. M. Pozar, "Microwave engineering," *Fourth Editions, University of Massachusetts at Amherst, John Wiley & Sons, Inc*, pp. 26–30, 2012.

[11] N. Laman and D. Grischkowsky, "Terahertz conductivity of thin metal films," *Applied Physics Letters*, vol. 93, no. 5, 2008.