A 3D-printed broadband millimeter wave absorber

Matthew Petroff,1, a) John Appel,1 Karwan Rostem,2 Charles L. Bennett,1 Joseph Eimer,1 Tobias Marriage,1 Joshua Ramirez,3 and Edward J. Wollack2

1) Department of Physics & Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA
2) Code 665, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
3) Johns Hopkins Applied Physics Laboratory, Laurel, Maryland 20723, USA

We present the design, manufacturing technique, and characterization of a 3D-printed broadband graded index millimeter wave absorber. The absorber is additively manufactured using a fused filament fabrication (FFF) 3D printer out of a carbon-loaded high impact polystyrene (HIPS) filament and is designed using a space-filling curve to optimize manufacturability using said process. The absorber’s reflectivity is measured from 63 GHz to 215 GHz and is compared to electromagnetic simulations. The intended application is for terminating stray light in Cosmic Microwave Background (CMB) telescopes, and the absorber has been shown to survive cryogenic thermal cycling.

I. INTRODUCTION

The ongoing development of increasingly sensitive cosmic microwave background (CMB) telescopes requires commensurate improvements in the control of systematic errors. One such source of error is from stray light, which needs to be controlled and terminated through the use of millimeter wave absorbers, both under ambient conditions and within cryogenic receivers.1,2 Since the field is moving towards the use of multichroic detectors with wide frequency bands in a shared optical path,3 broadband absorbers are required. Per this application, the frequency range from 30 GHz to 230 GHz is of interest, since it covers the CMB emission peak as well as synchrotron and thermal dust foregrounds; the frequencies from 70 GHz to 110 GHz are of particular importance as they lie near the CMB foreground minimum. Broadband millimeter wave absorbers should also prove useful in W band radar applications or, more generically, as terminations or glint reduction media in an optical bench.

In recent years, additive manufacturing in the form of 3D printing has become increasingly common, in particular fused filament fabrication (FFF). [This is also referred to by the phrase “fused deposition modeling” and trademarked acronym FDM.] FFF-based printing works by extruding a plastic filament through a heated nozzle mounted on a CNC stage such that an object is built up layer-by-layer. This allows for rapid prototyping and allows for manufacturing easily customized designs and one-off parts. In this work, this ease of customization is applied to the fabrication of millimeter wave absorbers.

Graded index absorbers generally take the form of an array of pyramidal structures.5 In the limit where the wavelength is similar to or greater than the feature size, the pyramids form a smooth gradient in effective permittivity, greatly reducing reflections. In the limit where the wavelength is smaller than the feature size, the pyramids cause the incident light to reflect off the absorber structure multiple times, with some radiation absorbed at each interaction. Since these two limits are governed by the feature pitch and the wavelength, it can be helpful to use the parameterization \( p/\lambda_g \), where \( p \) is the pitch and \( \lambda_g = \lambda_0/\sqrt{\epsilon_r} \) is the wavelength in the absorber material as a function of the free space wavelength, \( \lambda_0 \), and the real component of the absorber material’s dielectric function, \( \epsilon_r \); this parameterization can be derived from the antenna theory analogue of a graded index absorber.6

While a periodic pyramidal structure makes for an effective absorber, it is not well suited for FFF-based printing. When sliced into layers for FFF-based printing, each pyramid slice is disconnected from the others in a given layer. Thus, the filament extrusion process must be stopped and the filament retracted for each and every pyramid slice; this procedure prevents the creation of sharp points, since small amounts of plastic can be drawn back into the nozzle, and possibly causes stringing—thin strands of plastic stretched over gaps—that must be manually removed after the print is finished. Furthermore, prints are generally weakest along their layer lines, making points liable to break off. To avoid these issues, a geometric approximation of a space-filling curve is used, which fills the plane with a continuous wedge.

In this paper, we demonstrate that 3D printing allows for the rapid production of broadband millimeter wave absorbers. These easily customizable absorbers can achieve adequate performance for stray light termination at low cost and as a thermal plastic—not a foam—they can be used cryogenically.

II. SPACE-FILLING CURVES

A space-filling curve is a curve that passes through every point of a two-dimensional region with positive Jordan measure, in this case area.7 For such a curve, the Lebesgue covering (topological) dimension is equal to the Hausdorff (fractal) dimension. Thus, a space-filling curve is not a fractal in the purest sense, since a fractal requires the Hausdorff dimension to be strictly greater than the geometric dimension.5,8 This type of mathematical monster was first described by Peano.9 Shortly thereafter, Hilbert described another such curve but also described an iterative sequence of geometric approximations to his curve.10 Importantly, this type of geometric approximation can be physically realized.

Space-filling curves are self-similar.7,8 Thus, absorbers

a) Electronic mail: petroff@jhu.edu
created from different order geometric approximations of space-fillings curves will exhibit similar behavior. In this work, a Hilbert curve, which fills a square, is primarily used. However, other shapes are possible. For example, an absorber designed around a generalized Gosper curve,\textsuperscript{11,12} which roughly fills a regular hexagon, was also prototyped, since it allows one to more easily cover a circle with absorber tiles. For \( n > 2 \), all electromagnetic absorbers with \( n \)-fold rotational symmetry have no net polarization response.\textsuperscript{13} Although a Hilbert curve has only 1-fold symmetry—or 2-fold symmetry in the case of the loop variant, the Moore curve—geometric approximations of the Hilbert curve have asymptotically equal numbers of uniformly distributed horizontal and vertical line segments;\textsuperscript{14} thus, they should not show a net polarization response in reflectivity, unlike 2-fold symmetric absorbers created from sets of parallel wedges.

To create an absorber, a wedge was modeled such that the peak of the wedge follows the centerline of a geometric approximation of the Hilbert curve. The wedge then extends down such that the halfway point between segments of the curve form troughs. Furthermore, only a shell is printed, leaving the inside hollow, to reduce printing time and save on material use. A rendering of a second order Hilbert curve absorber model can be seen in Fig. 1.

### III. MATERIAL SELECTION

Two different material candidates were tested, a commercially available carbon-loaded conductive PLA filament\textsuperscript{15} and a high impact polystyrene (HIPS) filament custom extruded\textsuperscript{16} from a commercially available carbon-loaded conductive HIPS pellet.\textsuperscript{17} The PLA has the advantage of being an off-the-shelf filament, and PLA is generally easier to print than HIPS. However, since the carbon-loaded HIPS comes in pellet form, it can easily be mixed with normal HIPS pellets during filament extrusion to control the conductivity and dielectric properties of the resulting filament. It may thus be desirable to find a source of carbon-loaded PLA pellets—or pulverized PLA to mix with a powdered additive—to maintain this advantage and combine it with the ease of use of PLA.

The complex relative dielectric functions of the carbon-loaded PLA filament, the carbon-loaded HIPS, plain PLA,\textsuperscript{18} and plain HIPS\textsuperscript{19} plastics were characterized using a pair of filled rectangular waveguide sections [WR28.0; broad-wall 0.280", guide height 0.140"] for each material, which each form a Fabry-Pérot resonator; the waveguide section thicknesses were nominally chosen such that the thinner and thicker sections would constrain the real, \( \varepsilon_r \), and imaginary, \( \varepsilon'' \), components of the dielectric function, respectively. To fill the waveguide sections, the plastic samples were heated until soft and then compressed, eliminating air bubbles; excess material was then removed, and the sections were lapped flat. Using a modeling approach described in existing literature,\textsuperscript{20} the dielectric functions were extracted from scattering parameters measured from 22\,GHz to 40\,GHz using a vector network analyzer (VNA),\textsuperscript{21} sampled at 801 points. The results of these measurements are summarized in Table I.

| Material                | \( \varepsilon'_r \) | \( \varepsilon''_r \) |
|-------------------------|-----------------------|-----------------------|
| Avantra 8130 HIPS       | 2.49                  | 0.003                 |
| Ingeo 4043D PLA         | 2.80                  | 0.03                  |
| PS-715 Conductive HIPS  | 7.7                   | 2.1                   |
| Proto-pasta Conductive PLA 15        | 15.                   |

Of the materials tested, the carbon-loaded HIPS is the best candidate for an absorber, since it is an absorptive dielectric that is not too reflective. The carbon-loaded PLA is much more conductive and behaves like a poor metal, making it too reflective for this application. Without carbon loading, the HIPS is a low-loss dielectric, which makes it potentially useful in millimeter wave optics applications, while the PLA is a relatively lossy dielectric, with properties similar to that of nylon.

### IV. ELECTROMAGNETIC MODELING

A small unit cell of the absorber was modeled in the ANSYS HFSS software package,\textsuperscript{22} which performs an electromagnetic finite element analysis (FEA). Periodic boundary conditions were implemented using a pair of perfect electric conductor (PEC) planes and a pair of perfect magnetic conductor (PMC) planes around the unit cell. A second order Hilbert curve was used as a unit cell for the absorber, since it has greater symmetry than a first order curve—and thus should have lower residual polarization response—while having reduced simulation complexity when compared to higher order curves. The simulation setup is shown in Fig. 1. Reflectivity at normal incidence was simulated.

Different wall thicknesses, including a solid cross section, were simulated for the conductive HIPS, as were orthogonal polarizations. Additionally, the conductive HIPS was simulated with varying degrees of conductivity. Possible wall thicknesses are quantized by the diameter of the 3D printer’s extrusion nozzle, 0.5 mm in this case. Unless otherwise noted, a double nozzle diameter wall thickness, with a thickness of 1 mm and manufactured with two parallel passes of the printer’s extrusion nozzle, and a 3:1 wedge height to wedge width aspect ratio was used (before truncation due to nozzle diameter). A 2:1 aspect ratio was also tried; since this affects \( p/\lambda_0 \), it should result in a somewhat different frequency response. A cross section of this model, including dimension labels, is shown in Fig. 2; the aspect ratio refers to this wedge cross section, not the unit cell shown in Fig. 1. The single wall width simulation used a 0.5 mm thick wall, while the triple wall width simulation used a 1.5 mm thick wall. To simulate orthogonal polarization, the PEC and PMC boundaries were switched to the opposite walls from what is shown in Fig. 1. The results of these simulations are shown in Fig. 3.

The simulation data show good polarization symmetry,
FIG. 1. The unit cell used in simulations, a second order Hilbert curve, is shown. Periodic boundary conditions were established by using perfect electric conductors (PECs) for the front and back faces of the bounding prism and perfect magnetic conductors (PMCs) for the left and right faces of the bounding prism. The top face of the prism was used as a wave port, and the bottom face was set as a PEC.

V. FABRICATION

To prepare a solid model for an absorber, a script was written to procedurally generate the model to meet specific design parameters using a solid modeling scripting library. With the solid model in hand, G-code instructions for the 3D printer were generated using slicer software. The solid model generation code, the resulting solid models, and the final G-code have been made available.

This G-code instruction file was then used to print the absorber prototype on a LulzBot TAZ 6 FFF 3D printer with a 0.5 mm diameter extrusion nozzle. The tested absorber prototype was manufactured using carbon-loaded HIPS and is a fifth order Hilbert curve with a square footprint of 160 mm by 160 mm and a total height of 14.5 mm; a double wall and 3:1 aspect ratio were used. A cross section of the tested absorber is shown in Fig. 2. The prototype absorber is shown in Fig. 4, and a detailed view of the prototype is shown in Fig. 5.

VI. MEASUREMENT

The fabricated absorber prototype was measured using a VNA coupled to a free space quasi-optical setup. This setup is described in detail in previous literature. Measurements were taken in two waveguide bands, from 63 GHz to 115 GHz and from 140 GHz to 215 GHz. The results are shown in Fig. 6. There is good agreement between the measurements and electromagnetic simulations, providing additional validation of the choice of unit cell used for the simulations. Furthermore, prototypes have been successfully used cryogenically at 60 K for stray light absorption, surviving dozens of thermal cycles, and have been successfully cooled using liquid nitrogen for use as cold loads.

VII. CONCLUSION

A broadband graded index absorber was designed around a geometric approximation of the space-filling Hilbert curve and was 3D-printed using FFF. Its reflectance was then measured in the frequency range 63 GHz to 215 GHz and found to be better than −20 dB. The use of a space-filling curve overcomes the limitations impose by FFF while also providing additional mechanical robustness when compared to a traditional tiled pyramid design. With a single 3D printer, one absorber can be fabricated per day, but this production rate can be easily scaled up by parallelizing fabrication across multiple 3D printers. To extend the concept from stray light absorbers to cryogenic calibration targets, the reflectivity needs to be further reduced, and the thermal gradient caused by plastic’s poor thermal conductivity needs to be addressed, such as through the use of a thermalizing core, which variations were not used for the prototype absorber.
could be made from metal or a plastic designed to have higher thermal conductivity.

The absorber could be further refined by using a smaller extrusion nozzle on the 3D printer, allowing for a sharper peak to the wedge, which should improve performance. Since additive manufacturing allows for rapid prototyping, multiple wedges profiles could be easily tried and their performances compared. The use of a multi-material FFF printer could allow for different amounts of carbon loading to be used for the outer and inner walls of the absorber.

FIG. 3. The results of FEA reflection simulations of absorber variants (solid) are shown against the baseline simulation of the geometry and material used for the fabricated prototype (dashed). Each simulation was performed from 1 GHz to 60 GHz at an interval of 1 GHz. The reflectance is shown as a function of frequency for six absorber variants.

FIG. 4. The prototype carbon-loaded HIPS Hilbert curve absorber is shown. The footprint of the absorber is a 160 mm square.

FIG. 5. A detailed view of the prototype absorber is shown. Layer lines from the 3D printing process are visible.

FIG. 6. Reflectance measurement results (solid) are shown along with reflectance values predicted by electromagnetic simulation (dashed).
to decrease reflection or to potentially create a gradient in the carbon loading, something that would be difficult to accomplish with more traditional manufacturing techniques. Moving away from FFF, a selective laser sintering (SLS) [stereolithography (SLA)] 3D printer could be used with carbon powder or stainless steel powder mixed in with the nylon powder [resin] to further extend the ease of customization of the absorbers, including for covering curved surfaces, by utilizing a more traditional pyramidal absorber structure. The fine resolution of SLA 3D printers is also well suited for the creation of extremely low reflectivity calibration targets.

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