Article

Broadband RF Phased Array Design with MEEP: A 3D-Printed Open-Source RF Horn in the multi-GHz Bandwidth

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Abstract

Radio-frequency (RF) antenna design traditionally proceeds in three phases. First, the design performance is modeled with expensive and proprietary computational electromagnetism (CEM) software. Second, the design is fabricated using intricate metal machining. Third, the fabricated design is characterized using benchtop RF measurement tools. The traditional process can include machine learning algorithms for optimization. We have developed an open-source alternative process that utilizes the MIT Electromagnetic Equation Propagator (MEEP) CEM package for design and simulation, and 3D printing with conductive filament for fabrication. Using this process, we designed and fabricated an exponentially curved RF horn antenna. To characterize our design, we show that the E-plane and H-plane radiation patterns, the VSWR, and the cross-polarization ratios match our CEM calculations. These results indicate that our design is a linearly polarized, broadband RF horn antenna in the [5.5-6] GHz bandwidth. The bandwidth of our instrumenation is limited to 6 GHz, and our CEM calculations predict good performance above 6 GHz. We therefore conclude the bandwidth of our printed design extends above 6 GHz. Future work will include expanding to lower bandwidth by 3D printing larger antennas, and constructing a broadband RF phased array.

Keywords: Computational Electromagnetism (CEM), Additive Manufacturing, MEEP, RF Engineering, Open-Source Design

1. Introduction

Broadband RF antennas are ubiquitous tools within scientific instrumentation and communication applications. Traditionally, RF antennas are designed using expensive, proprietary software packages, like XFDTD and HFSS [1,2]. Designs are fabricated by cutting and shaping metal with precision machine tools. This technique is sometimes called *subtractive manufacturing*, as opposed to *additive manufacturing*. Compared to *additive manufacturing* techniques, subtractive manufacturing can be costly [3,4]. Open-source additive manufacturing boosts cost efficiency in both the design and fabrication of RF antennas, provided that the 3D printing filament has sufficient conductivity.

Development of new RF antenna designs requires exploration of conductor shapes that set the boundary conditions for radiated signals. Developing new conductor shapes that meet design requirements has been aided by machine learning (ML) strategies [5–7]. While mixing new ML algorithms into open CEM code is straightforward, incorporating them into proprietary software is often challenging and time-consuming. Ideally, RF engineers would keep the functionality found in proprietary software to compute standard RF antenna

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metrics, while retaining the flexibility to incorporate new ML techniques. Creating a design process based on open CEM tools achieves this goal.

Previously, J. C. Hanson (2021) demonstrated that the open-source MEEP software package may be used as an RF antenna design tool [8]. MEEP operates via the FDTD algorithm for Maxwell's Equations on a Yee lattice [9]. Specifically, the author of [8] produced RF phased array designs in two and three dimensions using MEEP code. The designs included broadband RF horn elements in the [0.5-5] GHz bandwidth. Further, J. C. Hanson demonstrated that open-source CAD software may be used to create complex designs that can be 3D-printed [10].

In this work, we present the first open-source broadband RF horn designed with MEEP and fabricated entirely from conductive 3D-printer filament. In Sec. 2, we explain the CEM design (Sec. 2.1), open-source CAD (Sec. 2.2), and fabrication technique (Sec. 2.3). In Sec. 3, we show that the E-plane and H-plane radiation patterns (Sec. 3.1), the VSWR (Sec. 3.2), and the cross-polarization ratios (Sec. 3.3) match our CEM calculations. In Sec. 4, we discuss the limitations of our analysis, applications of the results, and future research directions. In Sec. 5, we summarize our key results.

2. Materials and Methods

The goal of this work was to use open CEM tools to design, model, and fabricate a linearly polarized, broadband RF horn antenna in the multi-GHz bandwidth. We selected MEEP for our open CEM tools. Over the past decade, MEEP has most often been used to design and model photonics systems [11,12]. However, due to the scale-invariance of Maxwell's equations, MEEP may be used to model electromagnetic propagation with wavelengths at the cm-scale [8,10]. Further, antenna designs created with open CAD tools like kLayout can be imported into MEEP. Using parametric CAD design, we can specify antenna shapes using analytic functions that are then translated into kLayout and MEEP. Designs in kLayout can also be translated into 3D printer files, ensuring we are simulating the same device we are fabricating.

Our open fabrication technique hinges on the existence of commerically available conductive 3D printer filament. Multi3D[1] has shown that a copper-doped thermoplastic serves as a 3D printer filament with conductivities of $\approx 10^{-1}\ \Omega$ cm, depending on the printing pattern. Using a ruby-tipped 3D printing head and Electrifi filament from Multi3D, we can complete antenna prints on the scale of 16 cm in length in several hours. The printed structures are fitted with RF connectors and tested with a network analyzer, standardized metal antennas, and custom mounts. Figure 1 (left) contains a flow diagram for the design and fabrication process.

2.1. CEM Design

The open-source CEM design begins with choosing parametric design parameters for the exponential RF horn. The horn *cavity* is the rectangular volume where the coaxial cable attaches. The horn *surfaces* are the curved structures that connect the cavity to open space. The *opening* is the area where the *surfaces* stop and radiation exits the horn. Let the origin of an xy coordinate system refer to the center of the outside of the cavity. The kLayout design of the RF horn is shown in Figure 1. Let c_l refer to the cavity length in the x-direction, c_w refer to the cavity width in the y-direction, s_l refer to the surface length in the x-direction, and w refer to the opening width in the y-direction. Using these variables, Equations 1 and 2 specify the shape of the RF horn surfaces in the xy-plane:

[1] See https://www.multi3dllc.com

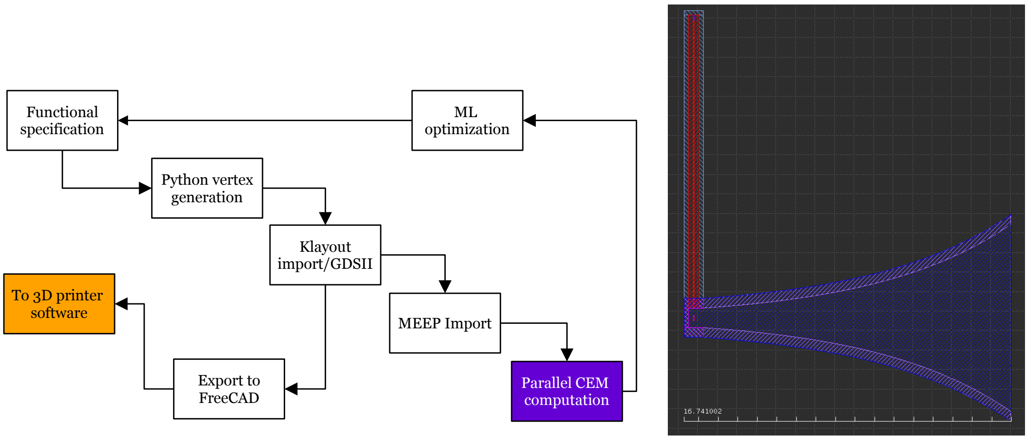

Figure 1. (Left) Flow diagram for the open-source design and fabrication process. (Right) The kLayout CAD design for the RF horn (top view), with a coaxial cable attached. The x-direction is to the right, the y-direction is up, and the z-direction is out of the page.

Table 1. Design parameters for the RF horn antenna.

Parameter	Value [cm]	Variable Name
Cavity Length	0.77	c_l
Cavity Width	1.00	c_w
Surface Length	16.52	s_l
Opening Width	9.59	w

$$f(x) = \frac{c_w}{2}\exp(k(x - c_l)) \tag{1}$$

$$k = (s_l - c_l)^{-1}\ln\left(\frac{w}{c_w}\right) \tag{2}$$

The function $f(x)$ in Equation 1 describes the upper surface in Figure 2, while $-f(x)$ describes the lower surface. Table 1 contains the values for c_l, c_w, s_l, and w corresponding to our first 3D printed RF horn. Manipulating the parameters in Table 1 to determine the effect on simulated and measured antenna performance is a form of *parametric design*.

2.2. Open-Source CAD

things.

2.3. Fabrication Technique

things.

3. Results

This section gives results

3.1. Radiation Patterns

The text continues here.

3.2. The VSWR

The text continues here.

3.3. Cross-Polarization Ratios

The text continues here.

3.4. Figures, Tables and Schemes

All figures and tables should be cited in the main text as Figure 2, Table 2, etc.

Figure 2. This is a figure. Schemes follow the same formatting.

Table 2. This is a table caption. Tables should be placed in the main text near to the first time they are cited.

Title 1	Title 2	Title 3
Entry 1	Data	Data
Entry 2	Data	Data [1]

[1] Tables may have a footer.

The text continues here (Figure **??** and Table **??**).

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses.

5. Conclusions

This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

Author Contributions: J. C. Hanson conceived of the open-source design process and produced the initial MEEP calculations that led to the RF horn design, including a previous publication in *Electronics Journal*. J. C. Hanson also identified the conductive 3D printer filament with sufficient conductivity to fabricate RF antennas. J. C. Hanson also demonstrated that open-source CAD can be incorporated into the process. Finally, J. C. Hanson produced fully three-dimensional CEM models using MEEP to compute the VSWR and radiation patterns for the fabricated designs. A. Wildanger sourced materials, and imported CAD designs into 3D printing format. A. Wildanger successfully completed 3D prints to produce the designs. Together, J. C. Hanson and A. Wildanger collected data using the RF measurement tools. J. C. Hanson used the data to show that the MEEP calculations match the lab measurements.

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Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section “MDPI Research Data Policies” at https://www.mdpi.com/ethics.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data are shown in the main text can be added here if brief, or as Supplementary Data. Mathematical proofs of results not central to the paper can be added as an appendix.

Table A1. This is a table caption.

Title 1	Title 2	Title 3
Entry 1	Data	Data
Entry 2	Data	Data

Appendix B

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled, starting with "A"—e.g., Figure A1, Figure A2, etc.

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