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Report on Additive Manufacturing of RF Antennas for Phased Array Designs

Abstract

Active radar systems require testing and verification using broadband signals that vary in position and frequency. One solution to create these signals is to develop a phased array, an example of an electronically steered antenna system (ESAs). The RF elements of the array must be designed to meet bandwidth and efficiency specifications, and we present designs created in a brand new technique with fully open-source software. We combine RF elements to form computational models of compact (~1 m) 16-element RF phased arrays capable of steering 45 degrees from boresight. The steering angle and beamwidth depend on frequency, and the achieved bandwidth is [0.5-6] GHz with VSWR values of approximately 1.25. We have begun 3D printing RF elements with a variety of conductive filaments, and have performed our first calibration measurements on printed models. With the appropriate concentration of copper in the 3D printer filament, we will optimize antenna quality and show that the RF phased array is accessible with additive manufacturing.

Introduction

The goal of our engineering research under the Office of Naval Research (ONR) Summer Faculty Research Program is to develop radio-frequency (RF) phased arrays for a variety of anechoic chamber testing and verification applications. Phased arrays were selected as the overall design theme for the ability to electronically steer a broadband test signal. In microwave bands like the L band through the X band, centimeter-wavelength radiators can be modeled with open source computational electromagnetics (CEM) codes. We have applied an open-source solution called the MIT Electromagnetic Equation Propagation (MEEP) package in Python3 to produce suitable RF element designs. The CEM package yields radiation patterns and S-parameters for RF elements and the whole arrays. The arrays can be either *one-dimensional*, as in a row of antennas, or *two-dimensional*, as in a grid of antennas capable of steering in two angular dimensions.

Progress made in 2020

In Summer 2020, we selected the MEEP package [1] and determined how to use this CEM tool for antenna design. Some examples did exist, but not in the appropriate bandwidth [2]. MEEP is usually used to calculate the properties of micrometer-wavelength systems. CEM results scale in frequency in inverse proportion to the length scales involved in the system, and MEEP accounts for this effect. Thus, code meant originally for micrometer wavelengths could be re-purposed for RF element design. We developed theoretical expectations for our phased array designs, given the desired specifications of compactness and bandwidth. We constructed CEM models for four cases: one-dimensional single-frequency, one-dimensional broadband, two-dimensional single frequency, and two-dimensional broadband phased arrays.

We demonstrated that the CEM radiation patterns of each case matched phased array theory at a variety of beam angles and radiation frequencies. Phased array beamwidth was found to be inversely proportional to frequency, as expected, and the steering angle matched theoretical predictions as well. Using the results already obtained, we published a paper that won Top 10 Most Notable Papers in 2020-2021 Electronics Journal [3]. The journal is an open-access engineering journal focusing in part on microwave and wireless communications. We then moved on to assessing the efficiency (S-parameters) of the designs using MEEP, and began plans for 3D-printing test designs.

Progress on Research Activities in 2021

In Summer 2021, we learned how to create CAD files using open-source tools like KLayout that could be imported as structures into MEEP. The designs account for varying dielectric coefficients of real materials, and custom materials can also be defined. Our the shape of our broadband design from Summer 2020 was conveniently expressed in terms of elementary functions in a given coordinate system. This made importing the design into KLayout straightforward, and the CEM routines of MEEP yielded the expected radiation pattern. The goal, however, was to obtain the S-parameters given a coaxial cable attachment.

Along with an undergraduate student, we modeled the coaxial line attachment to the RF element, which is a linearly-polarized horn design. The S11 parameter was derived by transmitting a simple RF pulse down the coaxial line and calculating the flux reflected from the horn antenna relative to the total incident flux. When done versus frequency, this computation shows that the VSWR (from the S11 parameter) is less than 1.5 for a bandwidth of [0.5 – 6] GHz. Thus, a phased-array of such elements would have the steerable beam with desirable properties found in Summer 2020, and it would radiate efficiently.

We learned to translate our KLayout designs into Fusion 360, another CAD program capable of producing STL files for a 3D printing system. We selected an inexpensive conductive 3D printing filament made by ProtoPasta for our test runs, and went through the trial-and-error process of printing full-scale 3D RF horns. Though advertised as conductive filament, the ProtoPasta filament turned out to have a resistivity of ~6 Ohm cm, so we had to perform more research into more conductive filament. The horn antennas printed with the ProtoPasta did receive RF radiation from 1-4 GHz, albeit with a low signal-to-noise ratio (SNR). We have located and purchased another filament type with a measured conductivity of 0.012 Ohm cm, a factor of 500 improvement. We have seen one example of this filament type used to create a horn antenna [4]. Once we repeat our print run with the new filament, we can compare measured antenna properties to CEM results.

Progress on Course Design in 2021

As part of our Summer Faculty Research Program work in 2021, we decided to create an RF Field Engineer Course. This course is designed to introduce Navy personnel to RF field engineering in a practical and thorough manner. The syllabus includes ten weeks of topics, and the material is presented in pre-recorded video form. The course videos include step-by-step examples, example computer code, project ideas, and derivations of key equations and concepts.

The course begins with an introduction to radio waves, including appropriate units and unit conversions, decibels, and properties of electromagnetic waves. Week two introduces complex numbers and phasors, complex impedance, Fourier series and transforms, the concept of a power spectrum, and applications of statistics and probability to the topic of noise. Week 3 covers antenna properties. Week 4 is a applications of lessons learned, to the topic of ESAs. Week 5 is a cumulative review of the first half of the course. Week 6 covers the range equation and radar cross-section. Week 7 covers pulsed-doppler radar with connections to telemetry, and Week 8 adds the subtleties of clutter and attenuation. Week 9 is an application week to the topic of link budgets. Week 10 is a final review.

We produced about 20 hours of course lectures in video format, covering the first half of the course. Although we would have liked to finish off this deliverable, we were also focused on the research work and ran low on time. We plan to resume finishing this course through the program next summer. The end user for this course will be any Navy personnel with access to the right course database, for applications in the field. The relevant textbook for further reading is Introduction to

Airborne Radar, 3rd edition, by Stimson, also known as *Stimson3* (originally the Hughes Radar Handbook). The course will be divided into sub-sections to make it more manageable for the typical user.

Future Goals in Research Activity

Our future goals in CEM and 3D printing include finishing the basic phased-array design, thereby showing that phased-arrays in the [0.5-6] GHz bandwidth can be manufactured through an open-source process. Once we measure the RF element properties with the new filament, we will observe how quickly and efficiently phased array components can be created. With the phased-array prototype in hand, we will test the steering capability, beam pattern, and S-parameters. These parameters should match our CEM results.

From there, many possibilities unfold. Our CEM capability can be mixed with machine learning and further phased-array analysis to develop unique antenna designs with military and commercial, and scientific applications. One example is to boost the sensitivity of the IceCube Generation 2 neutrino detector design, which is connected to our research at Whittier College [5]. For that project, the challenge is to design a phased array with optimized properties that fits inside an ice borehole drilled in Antarctica. Other applications include boosting near-field capabilities of active radar calibration.

We are developing a research program that has begun to involve undergraduate researchers, collaborations with engineers affiliated with ONR, and we have begun to share RF testing equipment. Because the Navy needs future young researchers with the right skills and experience, we have discussed creating a pipeline program between the Naval Surface Warfare Center (NAVSEA) in Corona, California and Whittier College. We hope to form a mutually beneficial partnership that will produce grant proposals, scientific papers, student research experiences, and ultimately new and interesting radar designs.

Future Goals in Course Design

The RF Field Engineering course will continue to be developed over time in the form of recorded lectures. The course must be sub-divided and branded for the appropriate service within NAVSEA. We have organized all content into a downloadable format that can be recompiled and remixed by other instructors. Once complete, the course should be a valuable resource for future service members and civilian contractors serving in field engineering roles for the Navy.

Bibliography

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