Simplifying Digital Array Architectures with Multifunctional Metasurface Apertures

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ABSTRACT

Holographic metasurfaces, tailored to exhibit a precise electromagnetic response from a low profile, are a powerful platform for wavefront manipulation and present the possibility to substantially simplify the architecture of increasingly popular (and increasingly complex) digital phased arrays. This article describes the work a Johns Hopkins University Applied Physics Laboratory (APL) team is doing in this area.

Electromagnetic manipulation is a focus area for APL's Research and Exploratory Development Department. A natural contribution to this area is the development of a novel antenna platform. A key asset in the electromagnetic manipulation toolbox, metasurfaces have proven to be of interest for antenna design because of their ability to shape wavefronts.[1] Large-array antennas with high directivity and a steerable beam are a particularly ripe target for the application of metasurfaces.

Most often, highly directive and steerable antennas are implemented through phased arrays and digital beamforming because of the flexibility of these techniques; however, these technologies are complex, power hungry, and expensive. These unfavorable cost, size, weight, and power characteristics are acceptable in some applications, but these traditional approaches are often overengineered solutions and may not always be necessary. A dexterous platform based on a metasurface antenna may be able to perform comparably with a reduced cost and form factor, thereby enabling enhanced capabilities in previously unforeseen use cases. Our APL team has targeted the development of a design model, optimization routines, and a fabrication process flow toward this goal.

The multifunctional metasurface aperture under development has a form factor based on simple printed circuit board (PCB) processing and, therefore, is low profile and inexpensive. A waveguide structure is baked into the PCB layers and distributes energy to a collection of resonant metamaterial elements embedded in the top layer. Signals can be injected directly into this waveguide at a series of locations along the back of the PCB, and each feed excites the entire collection of elements. In this way, the various feeds can share the entire aperture and each will enjoy the benefits necessary to create a highly directive beam. For example, if a collection of eight distinct radiation patterns is required for the application, only eight feeds must be used. This is in contrast to phased arrays where the most common approach is to provide enough independent antennas, phase shifters, and amplifiers to fill the entire aperture at the Nyquist limit. The high cost and complexity associated with the components of digital arrays makes the metasurface aperture an enticing alternative.

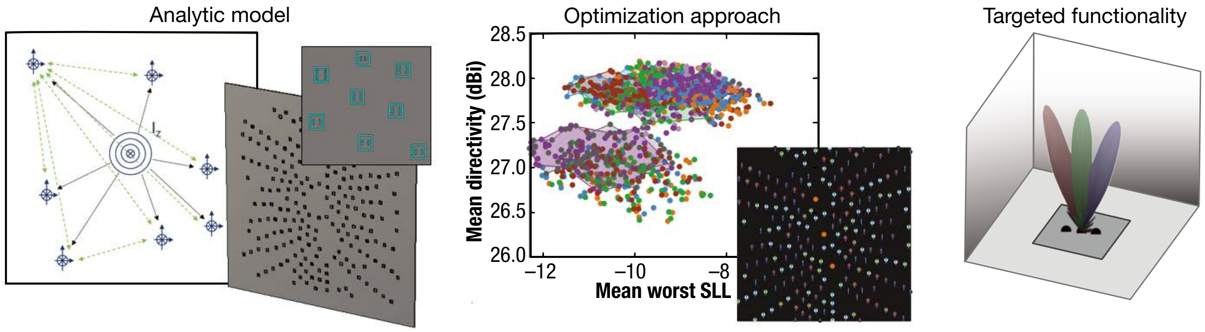

Figure 1. The modeling, optimization, and targeted behavior of our design flow. The backbone of the design process is the analytic model that represents the resonating elements and allows for fast/efficient optimization. A rapid analytic model allows for a vast design space to be explored to achieve the synthesis metrics—mean directivity and mean worst side lobe level (SLL)—across numerous complex patterns.

When targeting the synthesis of multiple patterns produced from a shared aperture, a multi-objective optimization problem must be addressed. With a vast design space (including the many degrees of freedom made available by the usage of metamaterial elements and the aperture) and a series of metrics (sidelobe level, gain, etc.), an intensive optimization procedure must be completed. A central focus has therefore been to generate a high-fidelity analytic model to estimate the behavior of the aperture. Implementing a coupled dipole model allows for simulations to be run on the order of seconds, enabling a rigorous optimization process that can be completed in minutes or hours.[2] This is in contrast to the more common approach of full-wave simulations, which would be prohibitively expensive for such an optimization problem. Figure 1 shows the modeling, optimization, and targeted behavior of our design flow where a metasurface can generate three distinct beams from the same aperture when fed at three different locations.

To validate the proposed analytic model and design procedure, a circularly polarized antenna was fabricated and characterized. Circularly polarized patterns, being composed of two linear polarizations, can effectively be considered two beams pointed at the same direction with a phase shift of 90°. In this sense, we applied the multi-objective optimization procedure to design the two functional patterns. As shown in Figure 2, a full-wave simulation was completed to confirm the analytic model, and a metasurface antenna was subsequently fabricated and characterized. Anechoic chamber measurements confirmed the entire design procedure and showed promising performance for navigating the complex multifunctional optimization space.

The results to date have shown that the complex infrastructure of a digital array can be reproduced from significantly simpler metasurface apertures, where the complexity has been shifted to the modeling/design procedure rather than allowed to burden the hardware development. While the robust flexibility of the phased array is not likely to be entirely captured by such a multifunctional metasurface, the vast cost, size, weight, and power advantages make our platform preferable in many application spaces. Satellite communications and the highly anticipated 5G framework can both take advantage of the multifunctional metasurface platform. Multifunctional metasurface apertures are poised to play a tremendous role in a host of antenna applications and may find broad use in the continuing challenge to establish electromagnetic spectrum dominance.

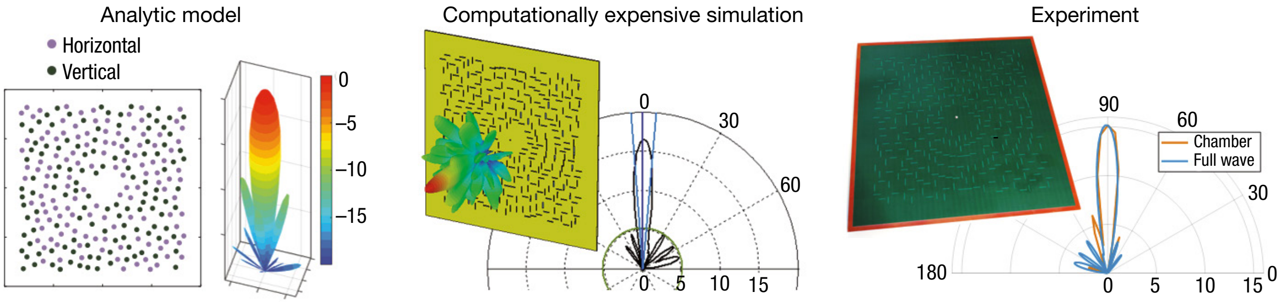

Figure 2. Confirmation of the analytic model. A complete design flow involves optimization through a rapid analytic model, validation through a computationally intensive full-wave simulation, and ultimately an experimental demonstration. As a first study, we designed a circularly polarized beam from a single feed and validated excellent agreement throughout the design process.

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