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Design of a Shape Optimized Printed-circuit Beamformer

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***Abstract*—This work presents the experimental realization of a printed-circuit beamformer designed using shape optimization. Shape optimization of the printed-circuit beamformer is enabled through the use of a circuit network solver that utilizes reduced-order models of printed-circuit unit cells to rapidly evaluate device responses, and the adjoint variable method to evaluate gradients. The designed beamformer is patterned on a microwave substrate and interfaces with a 3-D printed tapered aperture antenna. It produces nine orthogonal beams and has isolated input ports that are impedance matched. Experimental results for the performance of the 3-D printed antenna and the beamformer will be presented at the conference.**

I. Introduction

In recent years, computational inverse design has proven to be a powerful design paradigm for realizing high-performance metastructured devices, [1]–[4]. Here, an experimental realization of a microstrip beamformer designed using the computational inverse design framework provided in [5] is demonstrated. The beamformer is designed to interface with a 3-D printed, exponentially-tapered aperture antenna. It has nine inputs that correspond to nine orthogonal radiation patterns.

Previously, several design methods have been proposed to realize metastructured beamformers using heuristic, [6], and computational inverse design methods [7]. Due to inherent errors associated with heuristic design methods computational inverse design is a more promising option to realize high performance devices. However, if full-wave solvers are used, as in [7], the forward problem can become computationally prohibitive when designing electrically-large aperiodic metastructures. The design method provided in [5] utilizes a database of printed-circuit unit cells and circuit theory to reduce the computational cost of the forward problem. This allows for the patterns of complex printed-circuit structures, like metastructured beamformers, to be optimized directly.

II. Design Procedure

The shape optimization procedure in [5] for multi-input multi-output (MIMO) metastructures is used to design the beamformer and is summarized in this section. The advantage of this computational inverse design method is its computational efficiency. For computational efficiency, the design method uses: (1) a fast, forward problem solver based on microwave network theory for the rapid evaluation of device responses (2) the adjoint variable method to evaluate gradients in a computationally efficient manner.

To design MIMO metastructures, a cost function is defined to determine the device's performance on all of the desired outputs at each iteration as follows,

$$g(\mathbf{p}) = \sum_{k=1}^{K} g_k(\mathbf{p}), \tag{1}$$

where K is the number of inputs (input ports) and outputs (output beams) and,

$$g_k(\mathbf{p}) = \frac{1}{2}(\mathbf{v}^k(\mathbf{p}) - \mathbf{v}^k_{\text{out}})^H \overline{\overline{G}}(\mathbf{v}^k(\mathbf{p}) - \mathbf{v}^k_{\text{out}}) \tag{2}$$

In (2), $\mathbf{p}$ is a vector containing all of the design variables in the metastructure, the vector $\mathbf{v}^k(\mathbf{p})$ represents the solution to the forward problem (subject to the design variables) when it is excited by $\mathbf{v}^k_{\text{in}}$, and the superscript H indicates the conjugate transpose. The matrix $\overline{\overline{G}}$ is used as a mask to select and scale the elements of $\mathbf{v}^k(\mathbf{p}) - \mathbf{v}^k_{\text{out}}$ depending on their importance in the design. Using (1) the design problem can be posed as an optimization problem

$$\begin{aligned} &\arg\min_{\mathbf{p}} g(\mathbf{p}) \\ &\text{subject to :} \quad \mathbf{p}_{\text{lb}} \preceq \mathbf{p} \preceq \mathbf{p}_{\text{ub}}, \end{aligned} \tag{3}$$

where $\mathbf{p}_{\text{lb}}$ and $\mathbf{p}_{\text{ub}}$ are vectors containing the lower and upper bounds of the design variables, respectively. To design metastructures using (3), local solutions are solved for that satisfy the design requirements. This is done using the adjoint variable method and a gradient-based optimization routine such as MATLAB's fmincon(), [8].

III. Beamformer design

The beamformer is designed to operate at 10 GHz and produces nine orthogonal beams that correspond to excitations at 50 Ω input ports. It feeds a 3-D printed tapered aperture antenna, see Fig. 1 (a). The beamformer is patterned on a Roger's RT/Duroid RO5880 substrate, $\varepsilon_r = 2.2$, with a height of $h = 0.787$ mm. The width of the beamformer is $W_{ap} = 24$ cm , and it's depth is $D = 6$ cm to provide sufficient space to spread the power over the aperture without utilizing cavity effects. The input ports are impedance matched to 50 Ω

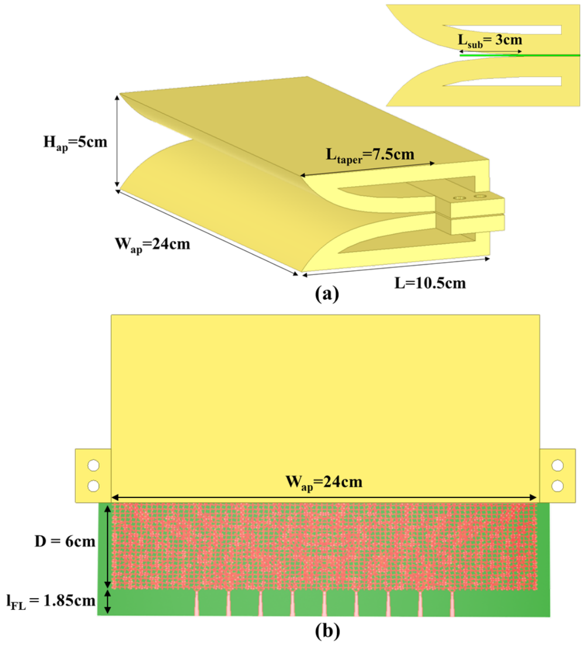

Fig. 1. (a) Rendering of the 3-D printed aperture antenna with an aperture size of $H_{\text{ap}} = 5$ cm and $W_{\text{ap}} = 24$ cm. The antenna is impedance matched to a dielectric filled parallel-plate waveguide using a exponential taper with a length of $L_{\text{taper}} = 7.5$ cm and a piece of substrate with a length of $L_{\text{sub}} = 3$ cm. (b) Depiction of the microstrip beamformer feeding the 3-D printed antenna. The optimized region of the beamformer has dimensions of $D = 6$ cm and $W_{\text{ap}} = 24$ cm. The beamformer is designed to produce nine orthogonal beams and has nine input ports that are isolated and impedance matched to 50 Ω using tapered feed lines with a length of $l_{\text{FL}} = 1.85$ cm.

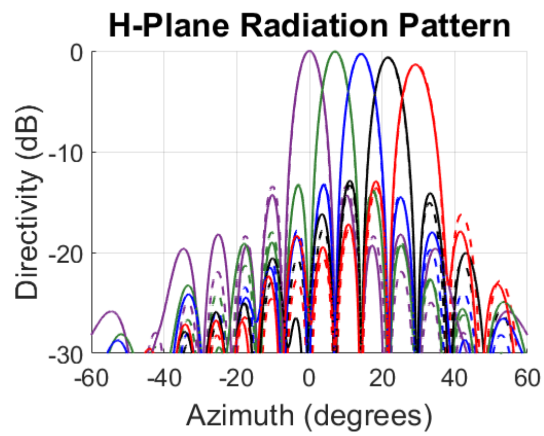

Fig. 2. Predicted radiation pattern from an aperture antenna excited by the beamforming network: dashed lines correspond to the desired and the solid lines correspond to the optimized beamformer. The radiation pattern is computed using MATLAB by assuming the outputs of the beamformer produce a piece-wise uniform electric field across the aperture. For clarity, only beams at positive scan angles are shown since the beams at negative scan angles are identical due to symmetry.

and are isolated from each other. The nine orthogonal beams correspond to uniform aperture illuminations with linear phase gradients that provide main beams at the following angles $\theta_B = 0°, \pm7.18°, \pm14.48°, \pm22.02°, \pm30°$, see Fig. 2. To avoid reflections, the output of the beamformer is impedance matched to the scan impedance of the antenna for each of the scan angles.

The beamforming region is designed by discretrizing it into square unit cells that have a side length of $d = 3$ mm. Each unit cell contains six design variables that represent lengths and widths of microstrip transmission-lines in the unit cell. To enable the use of the circuit network solver, accurate models of the unit cells admittance matrices are generated from a database of full-wave simulations of $15,625$ unit cells. The unit cell models and design goals (form the desired output voltage distributions, minimize return loss, maximize isolation) are then fed into the shape optimization routine presented in Section II to produce the design shown in Fig. 1 (b). The circuit-network solver is then used to simulate its performance. The results are shown in Fig. 2. Good agreement between the desired and simulated radiation patterns is observed.

IV. Conclusion

A computationally efficient shape optimization procedure for MIMO structures was reviewed and applied to the design of printed-circuit beamformers. The shape optimization procedure was used to design a beamformer with control over the amplitude and phase of the electric field across the antenna aperture. The beamformer was designed to feed a 3-D printed tapered aperture antenna and is printed on a single layer printed-circuit board. It supports nine orthogonal beams that correspond to port excitations. Each of the input ports are impedance matched and isolated allowing for simultaneous excitation of the beams. At the conference, experimental results for the beamformer and antenna will be presented.

Acknowledgement

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