

Mechanically Reconfigurable Slot Array Using Accordion-Like Microactuators

Jack Eichenberger[✉] and Nima Ghalichechian[✉], *Senior Member, IEEE*

Abstract—A novel mechanically reconfigurable 8×11 slot array using accordion-like microactuators as an alternative to conventional electronically steered arrays is reported. The array scans 0° to -30° in elevation by simultaneously varying the inter-element spacing between sliding slot elements. To maintain low sidelobe levels, the radiating slots are designed to have nonuniform width. The array is fed by a single slotted waveguide from one side. The actuator provides continuous motion with a precision of $30 \mu\text{m}$ ($\lambda_0/625$) and is controlled via a printed circuit board (PCB) circuit. The accordion-like structure provides a uniform yet tunable spacing between each slot column, eliminating the need for costly and complex electronic scanning. This high precision approach reduces the system footprint, ensures high power handling capability, and ensures ease of integration in future applications. The structure, operating at 16 GHz, is fabricated using a laser-etching process and in-house additive manufacturing. Measurement results are congruent with simulations.

Index Terms—Actuator, beam scanning, mechanically reconfigurable, slot array.

I. INTRODUCTION

ANTENNA arrays are ubiquitous, whether the need be beam steering, gain enhancement, or small half-power beamwidth. The traditional approach for beam steering is electrical reconfiguration in which each element or group of elements has its own feed [1]. By changing the phase difference between successive elements, beam control is achieved. However, individually controlling the phase of each element creates a need for an expansive feeding system [2], [3]. Unfortunately, the increasing complexity of the feeding system increases the number of possible failure points. One way to avoid complex feeding structures is to use a frequency scanning array, such as a slotted waveguide [4]. As the frequency of operation changes, the interelement spacing has a different electrical length, which allows for scanning. This leaves a choice between a complex and possibly bulky feeding structure, operating at a fixed frequency, or a simple feeding structure, operating over a range of frequencies.

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Jack Eichenberger is with the ElectroScience Laboratory, Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43212 USA (e-mail: eichenberger.9@osu.edu).

Nima Ghalichechian was with the ElectroScience Laboratory, Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43212 USA. He is currently with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30038 USA (e-mail: nima.1@gatech.edu).

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Mechanical reconfiguration permits the use of both complex and simple feeding structures, with an increase in reconfiguration time being the only drawback of this scheme.

Previously, various methods have been used for the mechanical reconfiguration of antennas. For example, Euler and Fusco [5] used a frequency selective surface with individually rotatable elements to demonstrate beam scanning. Although the structure did exhibit steering, this design was impractical for use in larger scale arrays. Indeed, the increase in array size makes control of the individual elements a daunting task. Moreover, the scheme requires a complex feeding structure that must address each element. The physical rotation of an antenna is an obvious alternative, as demonstrated by [6]. Here, a slotted waveguide array is covered by a rotating metal jacket. This one-dimensional (1-D) array configuration does not resolve the problem of multiple points of control if extended to 2-D, however. The insertion of tuning screws into waveguide power dividers has also been used successfully for scanning [7], [8]. Unfortunately, the multiple inputs required for this approach only achieves a discrete tunability. PIN diodes and varactor diodes are widely and successfully used for beam steering [9], [10], though these elements can exhibit nonlinear behavior on top of this approach requiring multiple points of control. Another possible avenue is feeding only a single element in an array while the others are excited via mutual coupling. Scanning is then possible by loading the passive elements with capacitors and changing the reactance [11]. However, this approach is difficult to expand to large-scale arrays if narrow beam patterns are needed, such as in radar applications. As an alternative to electronic tuning, Zandvakili *et al.* [12] constructed a dipole array partially reflective surface on a stretchable polymer. This approach is interesting in that there is a single input, which is the application of the force applied to the polymer, but it suffers from nonuniform expansion, thus limiting predictability.

We propose a mechanically reconfigurable 8×11 linearly polarized slot array operating at 16 GHz that is controlled by a linear microactuator with a single input port. The microactuator, controlled by a printed circuit board (PCB), is connected to columns of slot antennas via an accordion-like structure that changes the interelement slot spacing equally across the array. The proposed design allows for a robust single input system, with minimal possible points of failure, that can be scaled to an array of arbitrary size without any negative impact on performance. The elegant simplicity of this structure is highly reliable while providing continuous scanning up to -30° . Additionally, it has high power handling capability and does not suffer from nonlinear effects. To the best of our knowledge, ours is the first such linear microactuator-controlled slot array of this nature to be reported.

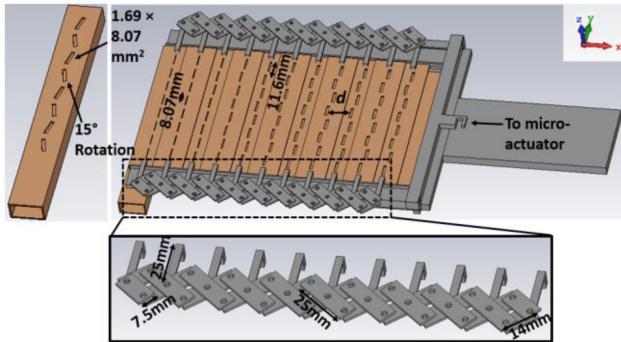


Fig. 1. Array model designed in CST with dimensions shown. Interelement spacing *d* is varied to achieve scanning. Enlarged images of accordion structure and feeding waveguide are shown to display details.

The letter is organized as follows. Section II involves a discussion of the design and full-wave simulation of the array, followed by fabrication and measurement results in Section III, and reviews and conclusions in Section IV.

II. DESIGN AND SIMULATION

The array factor (AF) for a *K*-element antenna is given by

$$\text{AF}(\theta) = \sum_{i=1}^K a_i \cdot e^{j[k_0(K-i) \cdot d \cdot \sin(\theta) + \beta]} \quad (1)$$

where *d* is the distance between elements, β is the interelement phase shift, θ is the scanning angle, and a_i are the amplitude taper coefficients [13]. Unlike conventional electronically scanned arrays, in which β is varied to achieve scanning, in our proposed structure, we instead vary *d*. The design is a Ku-band 8×11 slot array that operates at 16 GHz. The interelement slot spacing can be continuously varied from 12 to 16.5 mm, which is 0.33 λ_0 of movement between each element. For the entire array, this movement corresponds to 2.31 λ_0 . The structure consists of eleven aluminum plates, alternatingly stacked, each with eight laser-etched slots and a thickness of 0.76 mm (0.04 λ_0). This unique configuration allows the plates to easily slide past each other when an external force is applied. A model is shown in Fig. 1. By changing the width and offset of the radiating slots on each plate, the amplitude and phase of the exciting electric field for each slot are altered. The array performance was further optimized in CST based on this concept. Two nonradiating square slots are located at the top and bottom of each plate to mechanically connect to the accordion structure. A WR-62 slotted waveguide with eight slots, corresponding to the eight rows, is used to excite the array via aperture coupled feeding slots. The array acts as a traveling wave antenna with the electromagnetic radiation travelling in the +*x* direction and being radiated at each column of slots. A side view of an *xz* cut-plane (axis visible on Fig. 1) is shown in Fig. 2 to illustrate how energy is coupled from the feeding waveguide to the traveling-wave array. To ensure that the interelement slot spacing remains constant throughout the array, an accordion structure is connected to each of the 11 plates on the top and the bottom. These are then connected to a microactuator. The accordion structure enables equal and uniform spacing (*d*) between slot columns. The array was designed to maximize scanning while allowing for a highly reliable and robust reconfiguration mechanism. One primary challenge in

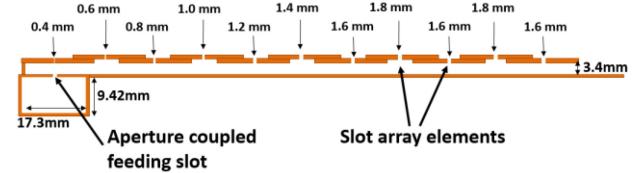


Fig. 2. *xz* cut-plane of proposed traveling wave antenna array with a nonuniform slot width.

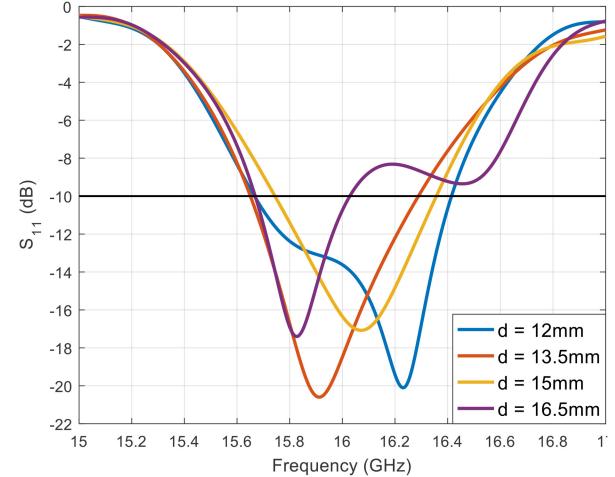


Fig. 3. Simulated reflection coefficient for four slot spacings.

this process was designing the support and accordion structures in such a way to keep the slotted plates stable in both the *y* and *z* axis while allowing fluid movement on the *x* axis. Stability in the *z* axis is crucial because the performance rapidly degrades if the plates do not lie completely flat.

The time domain solver in CST Microwave Studio was used to simulate the structure. Slot size for the feeding waveguide is 1.69×8.07 mm² with an offset of 1 mm from the center. The array slots have a length of 8.07 mm, a width varying from 0.4 to 1.8 mm, and an offset varying from 0 to 1 mm. Vertical slot spacing is 11.6 mm. Feeding waveguide slots were rotated ±15° in alternating fashion to avoid destructive interference from reflected waves. A parametric sweep across spacing (*d*) ranging from 12 to 16.5 mm was performed to demonstrate continuous tunability (scanning).

Four cases are shown in Figs. 3 and 4. For each, the reflection coefficient S_{11} was less than -10 dB at 16 GHz, indicating the system is well matched as can be seen in Fig. 3. The radiation patterns for each case, as presented in Fig. 4, indicate a scanning capacity up to -30°. The array is linearly polarized and maintains a high polarization purity of at least -25 dB at the main beam for each case. Cross-polarization (x-pol) levels are displayed in the measurement section.

III. FABRICATION AND MEASUREMENT

The aluminum slotted plates, ground plane, and feeding waveguide were fabricated via laser-etching. The accordion structure, the micromotor connection, and the support construct were created in-house via additive manufacturing using PLA material. Micro bolts and nuts were used to secure the accordion beams. The Actuonix L12-30-50-6-R micro-actuator was chosen for its reliability and small mass of <50 g. Finally, an Arduino UNO

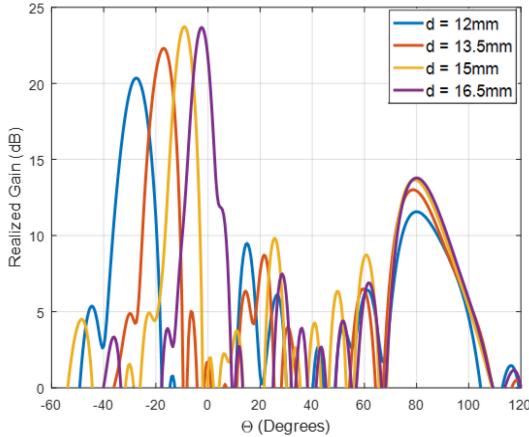


Fig. 4. Simulated *E*-plane radiation patterns at 16 GHz for four slot spacings.

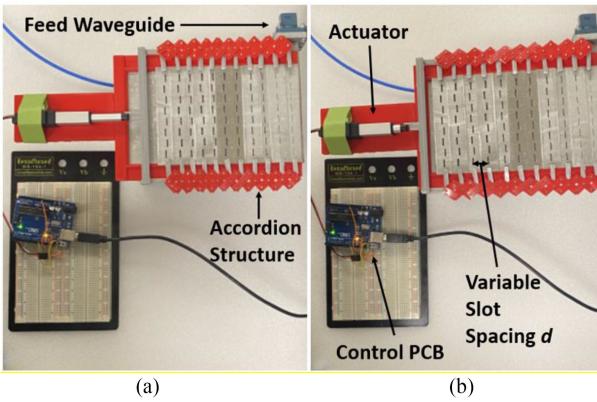


Fig. 5. (a) Fabricated array in a contracted state with $d = 14$ mm. (b) Expanded state with $d = 16.5$ mm.

board was used to control the motor position via a USB port. The system's singular input is a value in $30 \mu\text{m}$ ($\sim \lambda_0/625$ at 16 GHz) steps that defines the actuator's position, yielding an effectively continuously reconfigurable array. The fabricated system in both contracted and expanded states is shown in Fig. 5.

The pattern was measured in an anechoic chamber with the array supported atop a rotating foam column that remains upright during testing. The measured reflection coefficient, detailed in Fig. 6, agrees with the simulation results. The fabricated array had a frequency shift of roughly 150 MHz, though it is still matched at 16 GHz with $S_{11} < -10$ dB. A picture of the measurement setup is shown in Fig. 7. The radiation from a horn antenna is reflected off a parabolic reflector for collimation, where it then impinges on the antenna-under-test.

The resulting pattern measurements are compared to the simulations in Fig. 8 at 16 GHz. It can be seen the main lobe occurs at the proper angles and has a magnitude close to that predicted by the full-wave simulations. Cross-polarization (x-pol) levels (25 dB) are similarly shown to be unproblematic. We conclude from our impedance and pattern measurements that the fabricated structure agrees well with expected behavior.

IV. DISCUSSION

In this letter, a novel mechanically reconfigurable linearly polarized slot array based on a linear microactuator was proposed. The array was designed at 16 GHz, simulated in the

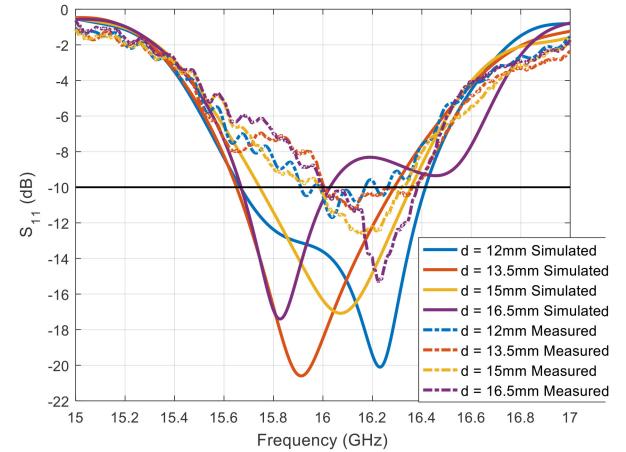


Fig. 6. Simulated and measured reflection coefficient as function of frequency and slot spacing.

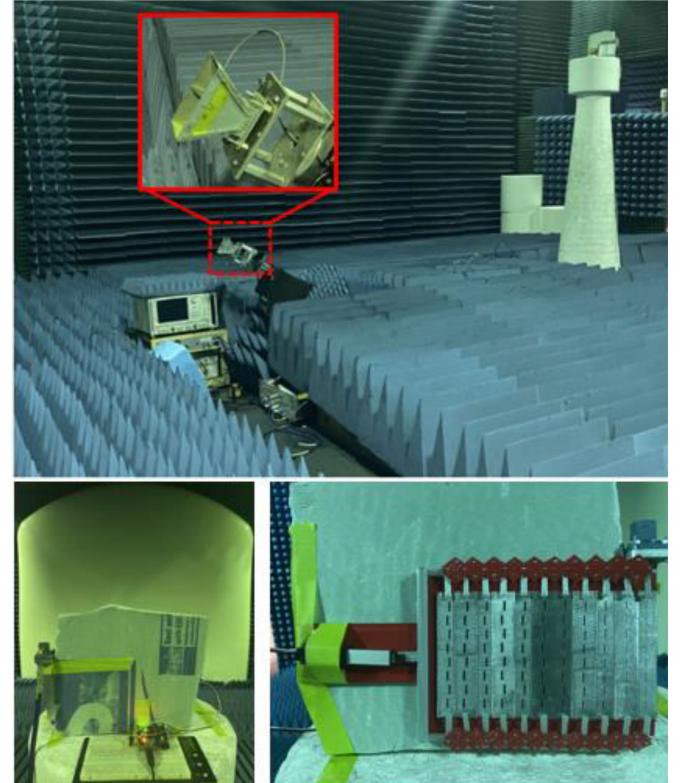


Fig. 7. Measurement set-up in electroscience laboratory anechoic chamber. Array is shown atop a rotating foam column. Feed horn is directed at parabolic reflector. The array is fed by a coaxial cable and mechanically manipulated with the PCB-controlled actuator.

CST Microwave Studio, fabricated via laser etching and additive manufacturing, and characterized. Measurement results were in good agreement with simulations. The structure is well matched (S_{11} below -10 dB) and achieved -30° of continuous scanning with polarization purity better than 25 dB. There was a minor frequency shift of about 150 MHz present in the fabricated array, likely due to machining tolerances. The laser etching process has a tolerance of 0.025 mm, which is significant when compared to the ideal slot geometry of 1.69×8.07 mm. Changes to the slot dimensions within these tolerances impact the gain and resonant

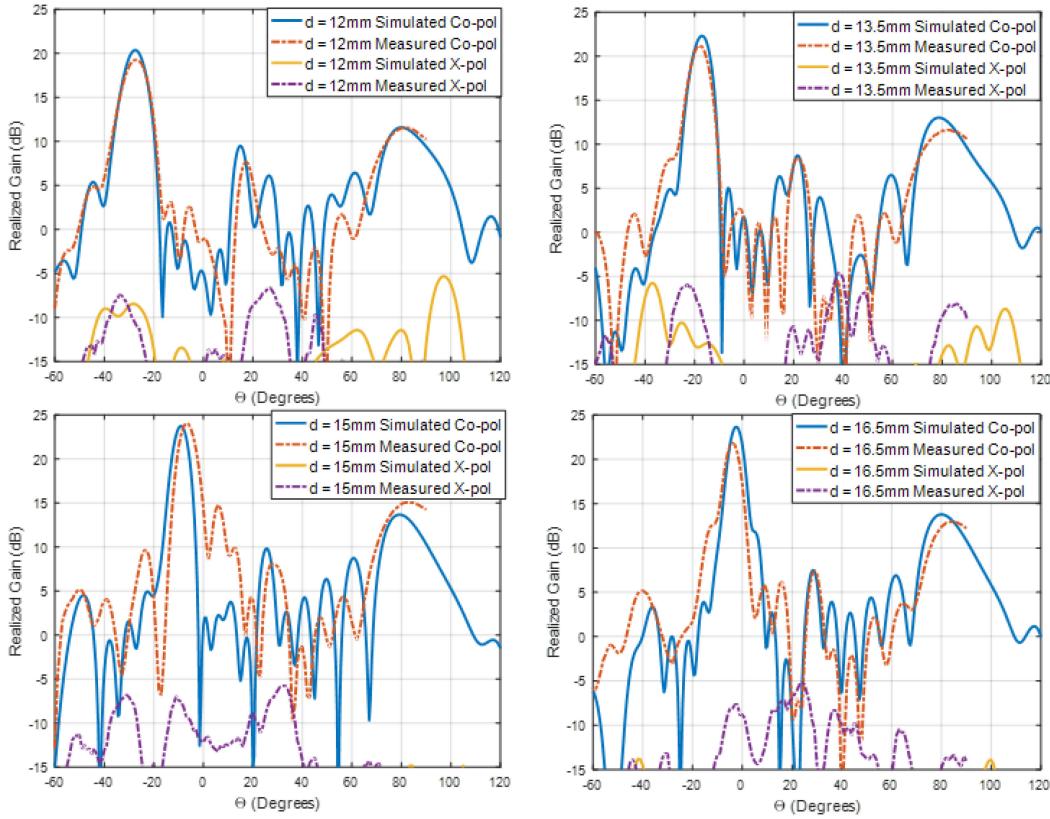


Fig. 8. Simulated and measured realized gain for interelement slot spacings (a) 12, (b) 13.5, (c) 15, and (d) 16.5 mm. Figures corresponds to the scanning angles of roughly -30° , -20° , -10° , and 0° , respectively, at 16 GHz.

frequency. Side lobe levels are at least 10 dB for scan angles up to 20° , and at least 8 dB across all angles.

If symmetric scanning from -30° to $+30^\circ$ is desired in future, it is possible to effectively mirror this structure and have a switching mechanism controlling which side is fed. Scanning beyond -30° is possible in theory, though in practice the scanning range is limited due to the geometry of the slotted plates. If they are too wide, slots will be covered by adjacent plates for smaller element spacings. At our maximum scanning angle of -30° , there is a slot separation of 12 mm. If scanning past -30° is desired, the slot separation must decrease. However, each plate has a width of 19.5 mm and slots have a width of up to 1.8 mm with center offset of up to 1 mm. Once spacing d is less than the sum of half the plate width, offset, and half the slot width, plates will begin to cover slots on adjacent plates. In our case, this places a lower bound of 11.7 mm on d .

This design provides an alternative to bulky and complex feeding structures present in many contemporary electronically scanned arrays. The primary drawback is the increase in reconfiguration time from microseconds to a few milliseconds up to the order of a second depending on actuator choice and size of the array. The linear actuator used in the proposed design has a speed of 25 mm/s. While this would exclude our proposed design from usages for certain defense or space applications, it has many commercial applications including automotive radar, ground penetrating radar, and imaging. Unlike the established concepts for mechanical reconfiguration that are detailed in the literature, this novel scheme requires only a single input for system control: the position of the actuator. This simple yet

robust slot array design makes this device a strong candidate for next generation satellite communications and automotive radar applications. Specifically, this array is highly reliable in that there are few possible points of failure in the design, it is characterized by an absence of nonlinear effects, possesses high power handling capabilities, and is scalable to arbitrary array sizes.

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