

Piezoelectric Actuators Enhanced Low-Cost Reconfigurable mmWave Metasurfaces

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Abstract—This article demonstrates an ultra-precise low-cost reconfigurability technique for millimeter-wave (mmWave) metasurfaces. Typically, varactors or diodes are required to achieve phase shift at unit-cell level, translating proportionally to higher cost, complex biasing, limited availability of off-the-shelf components, high performance controller to name a few. Our proposed technique rely on achieving beamforming using only four piezoelectric actuators housed in an RF transparent housing. A metal plane at the back side of the substrate is mechanically displaced using actuators in the Z-direction, creating a thin air-cavity between substrate and the ground plane, leading to the change in phase-coding. Full-wave EM response of the panel is presented, demonstrating up to 15 dBi of array gain at 28 GHz with 15 GHz of wide operational bandwidth using a 10 cm² panel.

I. INTRODUCTION

The focus of upcoming technologies is on energy efficiency and sustainability, hence, technologies like reconfigurable metasurfaces have gained momentum as they are mostly passive and require minimal power consumption [1]–[4]. The recently reported RIS architectures use either PIN diodes or varactors to electronically achieve the reconfigurability in phase. There are several shortcomings of such approaches not limited to high RF losses, parasitic effects at mmWave frequencies, limited reconfigurability, limited tuning states, high cost, availability concerns, soldering, biasing, complex signal processing circuitry to name a few [5]. Piezoelectric actuators excel notably in terms of their precision and dependability, particularly for tasks requiring nano-positioning. These benefits, coupled with their affordability and ultra-fast response time in the microsecond range, make them ideally suited for this application. Furthermore, they offer a resolution below one nanometer, display a high degree of energy conversion efficiency, operate on low voltage, generate substantial force, and are not subject to electromagnetic interference.

A novel technique to achieve reconfigurability in periodic electromagnetic reflective surfaces is discussed in this paper. The structure consists of an air cavity created between periodic metallic surface on a dielectric substrate and a ground plane as shown in Fig. 1. Four piezoelectric actuators are employed to support the ground plane and move it vertically. The concept is based on the displacement produced by the actuators under DC bias, which changes the air cavity thickness and results in significant tuning of the reflection phase response for operation at 28 GHz with 15 GHz wide operational bandwidth.

II. DESIGN DETAILS

A reconfigurable mmWave reflective surface has been proposed using piezoelectric actuators to achieve the dynamic

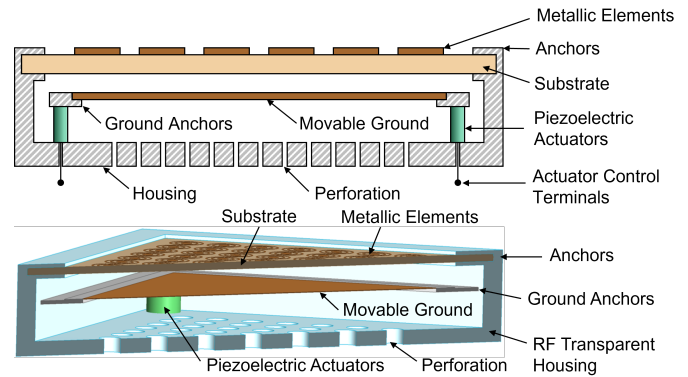


Fig. 1. A cross-sectional view and a 3D cut-plane view of the proposed mechanically tunable metasurface highlighting metallic resonating elements on the substrate, a movable ground plane, piezoelectric actuators, and the RF transparent housing with the perforated back.

tuning of the reflection phase. The reflective surface is formed by a two-dimensional periodic array of unit cells. Metallic concentric circular loops are printed on a 1 mm thick FR4 substrate. The FR4 substrate is placed over a ground plane forming an air cavity. The reflection phase response of the structure is strongly dependent on the cavity thickness, which leads to a significant tuning range. The unit cells are arranged in a two-dimensional array forming a periodic structure as shown in Fig. 2.

The surface is held over a ground plane separated by an air cavity as highlighted in Fig. 1. For any incident beam, the reflected beam from the surface can be redirected in a desired direction by changing the thickness of the air cavity. A plastic housing is used to support the ground plane and keep the FR4 substrate in place. If the plastic base is a straight plane, the air cavity under all the unit cells can be changed equally if all the piezoelectric actuators provide equal displacement. Air cavity under different sections of the 2D surface can be adjusted by individually controlling the displacement from each piezoelectric actuator, or in other words, using a tilting action of the ground plane. Using a movable copper plane controlled by piezoelectric actuators provides a mechanical like beam steering without making the overall system bulky. The bottom surface of the plastic housing is perforated to reduce the air damping effects.

While numerous varieties of piezoelectric actuators could be utilized in this design, the most feasible and effective is likely a stacked ceramic disk piezoelectric actuator made of lead (Pb)

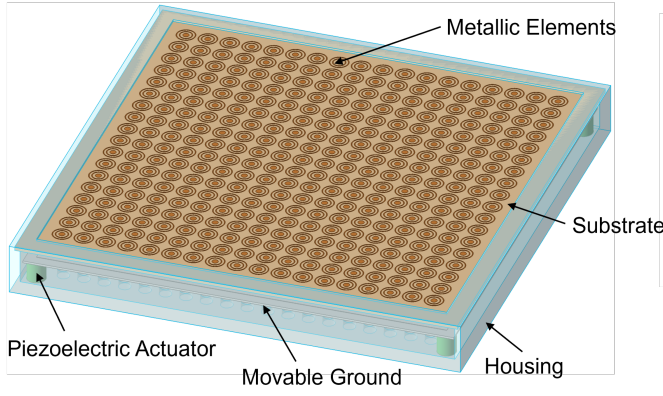


Fig. 2. Isometric view of a fully integrated metasurface

zirconate (Zr) titanate (Ti), also known as PZT. Each disk in the stack exhibits the characteristic of vertical expansion when an electric potential is applied, a property attributed to the piezoelectric effect. The disks in the stack are divided by slim metallic electrodes which apply the voltage. As a result, a substantial cumulative expansion is possible, equal to the sum of the expansions of each individual disk.

The 3D cut plane view of the metasurface highlights the ground plane below the FR4 substrate is supported by a piezoelectric actuator. The piezoelectric actuator is controlled using the voltage terminals taken out from the bottom of the plastic housing. Using this approach, instead of actuating $m \times n$ elements, only four piezoelectric actuators need biasing for beam tuning.

III. RESULTS AND VALIDATION

When the electromagnetic beam is incident from the nearby access point or base station, the beam steering is achieved by changing the vertical gap between the FR4 substrate and the ground plane. In simulations, the electromagnetic beam is generated from a horn antenna placed at a certain angle and distance away from the center of the panel. Full wave EM analysis performed using Ansys HFSS to extract the reflection characteristics of the unit cell and then the complete panel is simulated to extract the beam performance. Periodic boundary conditions are used during simulation of the cell which assume an infinite structure. A parametric simulation is done for the changing air cavity thickness as shown in Fig. 3. For the 28 GHz cell, the air cavity thickness was initially set at $0 \mu\text{m}$ and then gradually increased in steps of $20 \mu\text{m}$ gradually reaching up to $100 \mu\text{m}$. The reflection phase and magnitude tuned by changing the air cavity thickness is shown in Fig. 3. It can be observed that a significant phase shift is obtained with this design ($\Delta\theta = 300^\circ$ for $\Delta t = 100 \mu\text{m}$).

The simulated response of the reconfigurable metasurface for two different scenarios is presented in Fig. 4. In the first case, the reflected beam is in direction $\theta = 0^\circ$ and $\phi = 0^\circ$, while in the second case, the reflected beam is in the direction $\theta = 30^\circ$ and $\phi = 15^\circ$. This tuning approach offers up to 15 dBi of total array gain with a prominent main lobe.

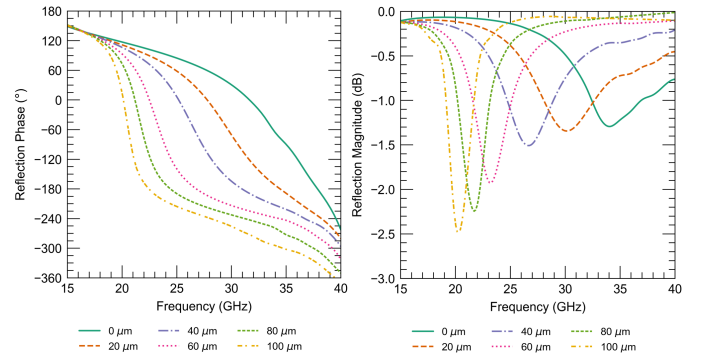


Fig. 3. Full wave EM simulated (left) reflection phase and (right) magnitude of a unit cell at 28 GHz for different air cavity thickness ranging from $0 \mu\text{m}$ to $100 \mu\text{m}$.

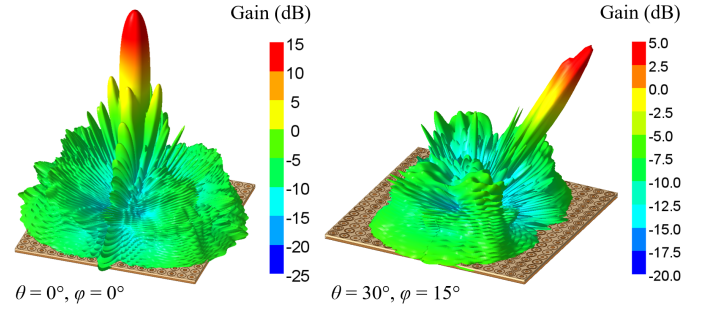


Fig. 4. Simulated total gain (dBi) for two different tuning states.

IV. CONCLUSION

A mechanically tunable approach for mmWave metasurface is presented utilizing only four piezoelectric actuators. A thin air cavity is tweaked using the actuators for beam steering. This low-cost approach doesn't require any off-the-shelf components such as varactors or PIN diodes on each unit-cell and rather rely only on four actuators to precisely control the under-substrate air gap to change the reflection coefficient. This approach is useful to develop ultra-precise low-cost and energy efficient metasurfaces for future wireless communications.

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