2-D Steerable Submillimeter-Wave Antenna for Planetary Wind Measurements

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Objective:

The objective is to develop a novel beam scanning antenna system at submillimeter-waves enabling wind measurement on planetary atmospheres, specifically on Mars. This innovative antenna system will replace conventional 2D scanning of primary (30-cm or larger) reflector systems. The scanning system will consist of a novel lens array antenna system with integrated piezo-electric actuator based translation stage, accomplishing beam scanning of ±20° both in horizontal and vertical directions.

Our proposed antenna will address the shortcomings of existing systems where 2-D scanning is accomplished by articulating the primary reflector with power hungry motors and associated mechanisms. We will design, fabricate, and evaluate a lens array based antenna system. The challenging risk is the performance of this beam scanning antenna system relies on compromise between the scanning angle range and gain reduction in the system resulting from aperture phase error and power spillover due to the translation of the sub-reflector. We will show that this antenna system meets the performance requirements for such instruments.

Approach:

Electronic beam scanning antennas have not, up to now, been available at submillimeter-wave frequencies. The primary reason for that has been the non-availability of low-loss phase-shifters at these frequencies. Under this task, we have developed a technology that can be directly integrated in the feeding system of the antenna elements enabling beam scanning capabilities. The technology we developed achieved scanning capability by using small piezo-electric actuators to displace silicon micro-lenses in an antenna array. We are using a three-dimensional stacked silicon micromachined architecture, developed under a MatISSE program, to accomplish fabrication and assembly.

Phased Array Scanning Antenna using Piezo-Electric Actuators: Implementing a submillimeter-wave antenna system that possesses the field of view required for limb sounding, all within a low mass design, is a significant challenge. One common approach to perform scanning on submillimeter wave space instruments is to rotate the whole antenna optics system to focus the beam at the desired spot. For our proposed work, the amount of power and mass required for this rotation approach is not practical. Another approach is the scanning of a secondary reflector in a Gregorian or Cassegrain system. However, this approach is limited by the narrow field of view (FoV) constrained by the antenna magnification factor, mass of the secondary reflector, and power required for the mechanical rotor. In this work, we plan to use small piezo-electric actuators to generate linear phase shift over a micro-lens array antenna for scanning the beam. This flight-heritage piezo-electric actuator based movement achieves higher speeds and provides more compact solution compared to gimbal-based bulky solutions done at the reflector level.

Under this task, we implemented a new quasi-optical beam scanning architecture where the scanning capabilities are integrated in the antenna feed. Fig. 1 (left) shows the basic architecture of the warry. The array is composed of a sparse array of active RF array elements distributed over the whole array aperture coupled to a layer of actuated lenses (one per array element). The single layer of lenses can be translated mechanically relative to the ground plane, to achieve element pattern scanning, while the active RF phase shifters cause array factor (AF) scanning. The grating lobes resulting from the array's sparsity are attenuated by the directive element patterns of the lenses. For this implementation we used a multi-mode leaky-wave (LW) feed to illuminate the antenna. The LW feed uses a quarter wavelength layer of a certain permittivity, added in-between the lens and the air cavity, to generate multiple leaky modes in this cavity, which helps to enhance the aperture efficiency. Simulated results of the lens antenna array show aperture efficiencies greater than 80% for a bandwidth of 35%. Scanning angles of ±20° can be achieved with a scan loss lower than 2 dB. We have fabricated a prototype at 550 GHz and measured the steerable element array embedded pattern, showing good agreement with the simulations, and thus validating the concept. Fig. 1 (center) shows the broadside array factor and elements patterns of the 19-element hexagonal array shown in the inset of Fig. 1 (left). Fig. 1 (right) shows the array pattern of the antenna. However, for this task we fabricated a 7-element antenna array (shown in inset of Fig. 1, shaded).

Fabrication, Assembly, and Results:

First, we designed and fabricated a single-lens element at 550 GHz. The broadside and steering properties of a single lens element at 550 GHz have been analyzed using the FO approach. The broadside patterns radiated by a single lens element with the LW feed (i.e., the secondary patterns) are shown in Fig. 2 (a). The pattern displays good symmetry at broadside. This results in a scan angle in the secondary pattern of 19.2°. The scanned secondary radiation pattern is shown in Fig. 2 (b) in UV-coordinates. The scan loss (i.e., the gain relative to broadside) of the single lens is shown in Fig. 2 (c).

To evaluate the steering properties of the 19-element lens-phased array, we multiply the obtained single lens patterns with the corresponding array factor. For broadside, Fig. 2 (d), the grating lobe level is −17 dB with a gain of 48.2 dB. When scanning to 19.2°, shown in Fig. 2 (e), the highest grating lobe is in the E-plane and is −13.2 dB. The gain when scanning the array toward 19.2° is 46.7 dB. The E-plane radiation pattern is shown in Fig. 2 (f) for scan angles up to 30°.

Prototype Leaky-Wave Lens Array at 550 GHz: A prototype at 550 GHz has been developed to validate the radiation properties of the LW feed and demonstrate the dynamic steering capabilities of the proposed lens antenna. The prototype, is shown in Fig. 3 (a), the number of elements fabricated for this prototype is 7, marked in gray in the inset of Fig. 1 and the equivalent f–number of the lens is $f_{\#}$ = 1.6. A piezoelectric actuator that sits on the side of this metal fixture achieves displacement of ±1.25 mm, i.e., a scan angle of around ±24°. The lens array is shown in Fig. 3 (b). A photograph of the perforated silicon layer and its dimensions is shown in Fig. 3 (c). First, the reflection coefficient of the antenna was measured and is shown in Fig. 4 (a). Displacement vs. scan angle result is shown in Fig. 4(b). Fig. 5 shows the array patterns of the broadside case, 10° and 20° of scan angle. The 2-D array patterns show the multiple grating lobes from the array factor but as a result of the multiplication with the element pattern. The E, H-, and 60° planes of the radiation pattern normalized to 0° are shown for these scan angles and plotted against the array pattern using the FO simulation. The maximum grating lobe level for broadside, 10° and 19.2° scan angle is −12, −11, and −9 dB, values that are considerably lower than other sparse arrays. The results obtained with this prototype show higher grating lobes due to the limited lens diameter, which leads to a near field illumination of the lens.

Background:

We are developing an electronically steerable antenna at submillimeter-wave frequencies that does not require motors or gimbals. This development will noticeably reduce mass, volume, and power requirements and will have significant impact on the way submillimeter-wave instruments are built for planetary, Earth-science, and astrophysics applications.

Global, vertically resolved measurements of wind co-located with atmospheric temperature, water vapor and, perhaps, other species is a high-priority outstanding need for the Mars atmospheric science community, as identified in the Science Analysis Group for NASA's next Mars-orbiting mission. This group also identified a submillimeter limb sounder as an ideal instrument for obtaining such measurements. Instrument requirements are significantly different from other (e.g., Earth sounding) microwave sensors, requiring a new implementation approach to reduce mass, power and volume. Further, there is a strong need for such an instrument to be able to steer its view in two dimensions. This is driven by (i) the scientific desire to measure 2D vector winds (north-south and east-west), (ii) the desire to view as wide a range of latitudes as possible for important polar measurements, and to mitigate against science loss induced by the intent for the next orbiter to switch between sun-synchronous and precessing, lower inclination orbits roughly halfway through the mission, and (iii) the desire to avoid potential, frequent interruption in observation resulting from spacecraft maneuvers needed to point the planned high-resolution camera instrument.

Implementing a submillimeter-wave antenna system that possesses the narrow field of view required for limb sounding (which demands an antenna of order 30-cm across), yet is steerable across a large (±20°) 2D range with minimal distortions in beam shape at extreme angles, all within a low mass design, is a significant challenge. The current state-of-the-art would be a single 30-cm reflector scanned in two-axes, using high motor power and having a complex mechanical design. As submillimeter-wave instrument development is within JPLs core business, investment in improvements is clearly relevant and further increases JPL's ability to successfully win competitions. The intended outcome is to determine if 2D scanning of a sub-reflector retains appropriate science and risk postures, while reducing mass and complexity; a significant outcome would be the ability to propose a scanning sub-reflector sub-mm instrument for the Next Mars orbiter call.

Significant Benefit to JPL and NASA:

We developed an electronically steerable antenna at submillimeter-wave frequencies that does not require motors or gimbals. This development will noticeably reduce mass, volume, and power requirements and will have significant impact on the way submillimeter-wave instruments are built for planetary, Earth-science, and astrophysics applications. Implementing a submillimeter-wave antenna system that possesses the narrow field of view required for limb sounding yet is steerable across a large (±20°) 2D range with minimal distortions in beam shape at extreme angles, all within a low mass design, is a significant challenge. The current state-of-the-art would be a single 30-cm reflector scanned in two-axes, using high motor power and having a complex mechanical design. As submillimeter-wave instrument development is within JPLs core business, investment in improvements is clearly relevant and further increases JPL's ability to successfully win competitions. This work will save mass and power for future planetary missions. An electronically steerable antenna at submillimeter-wave frequencies that does not require motors or gimbals will noticeably reduce mass, volume, and power requirements and will have significant impact on the way submillimeter-wave instruments are built for planetary, Earth-science, and astrophysics applications. The idea is to determine if 2D scanning of a sub-reflector retains appropriate science and risk, while reducing mass and complexity; a significant outcome would be the ability to propose a scanning sub-reflector sub-mm instrument for the Next Mars orbiter call.

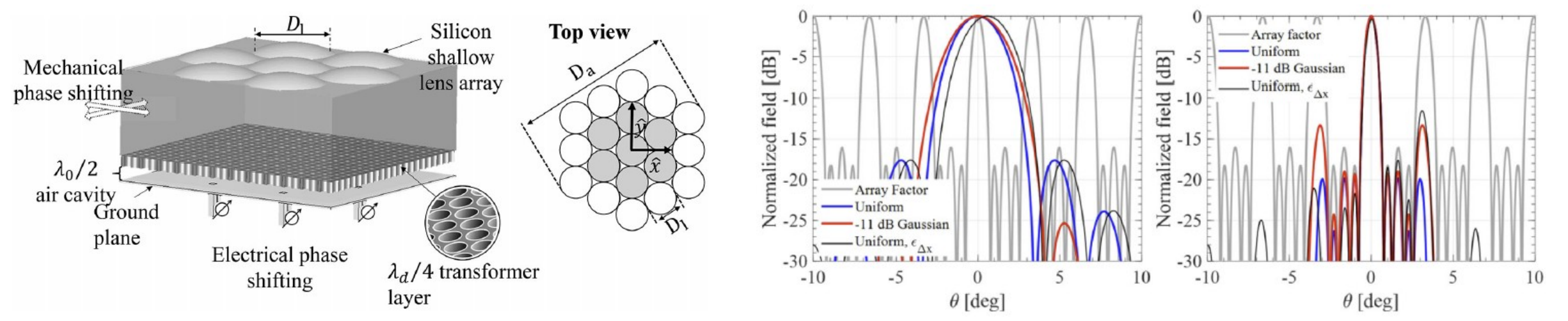
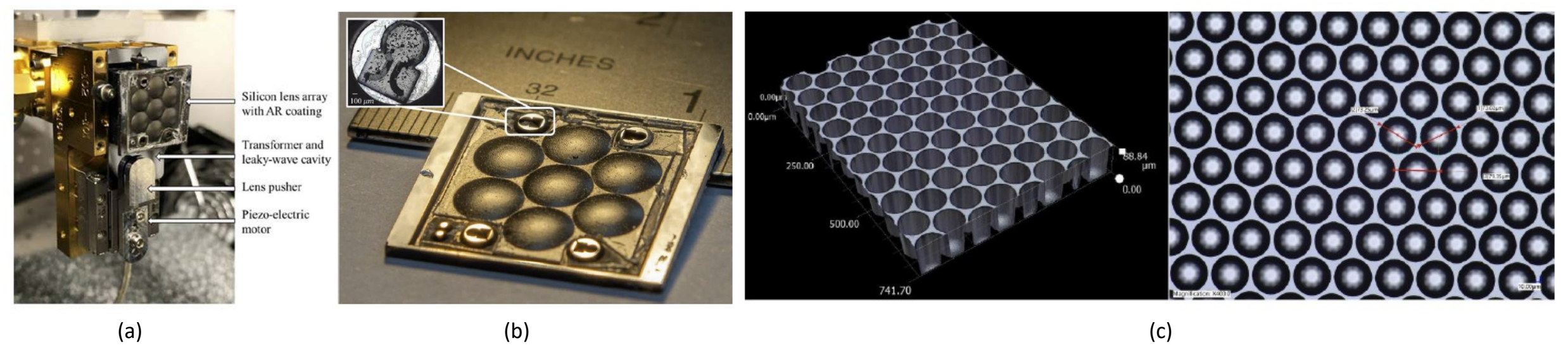
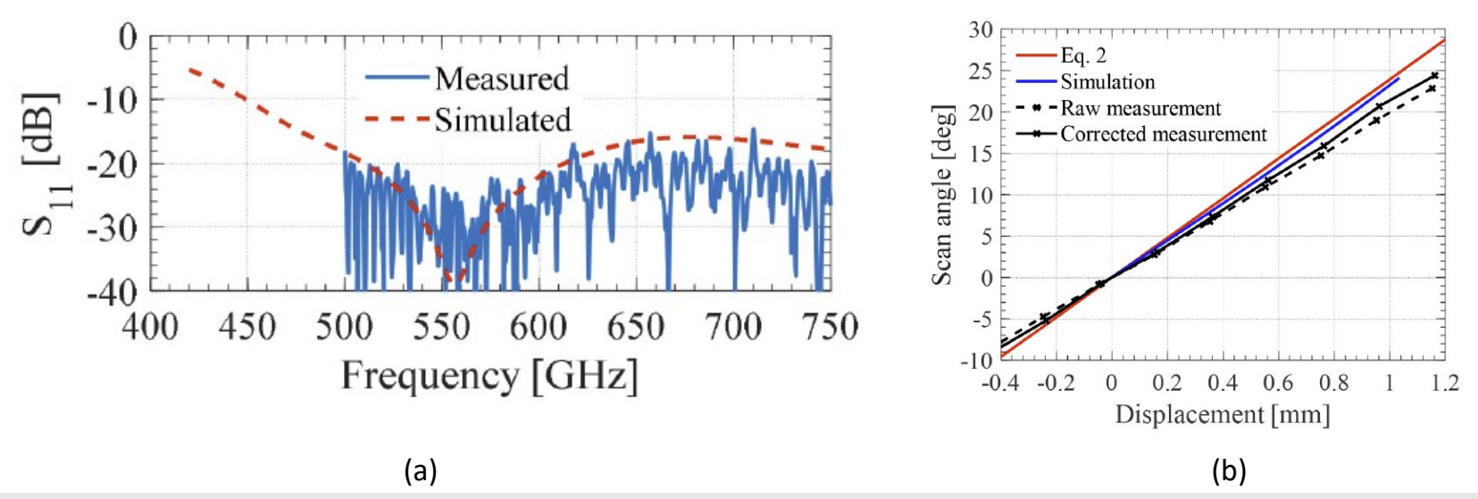


Fig. 1:(left): Geometry of the proposed scanning lens-phased array. The prototype array consists of seven elements (shaded). (Center) Broadside array factor and elements patterns of the 19-element l array, and array pattern of the antenna (right).



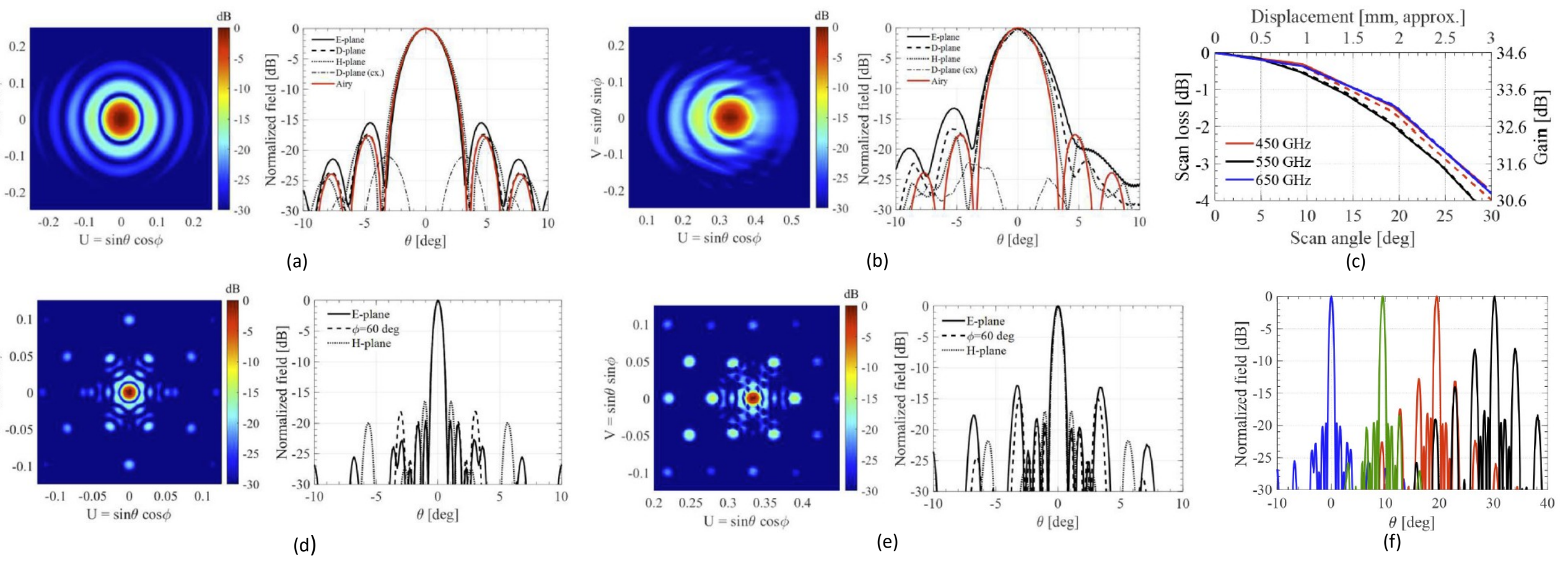
(a) (b) (c)

Fig. 3: Photo of the array (a and b) and the 3-D top view of the fabricated artificial dielectric taken under a microscope.



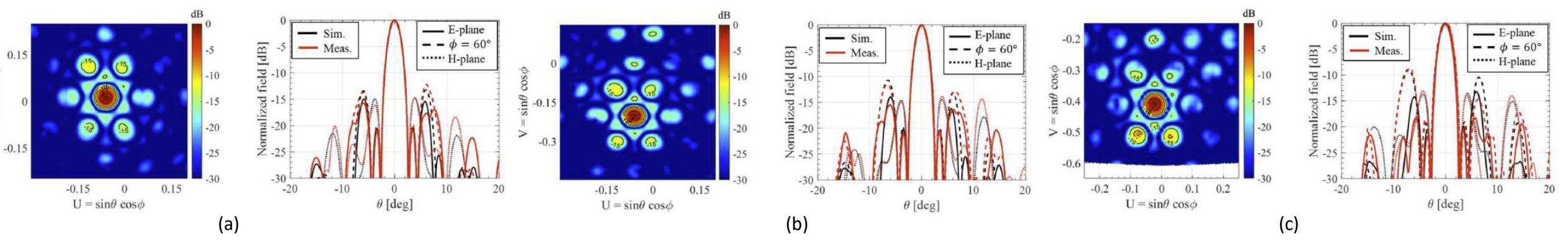
(a) (b)

Fig. 4: Measured and simulated reflection coefficient of the embedded lens antenna array prototype (a). Scan angle as a function of the displacement of the antenna array of the measured radiation patterns (b). The red line represents the scan angle obtained from displacing the feed of a quasi-optical system of an $f_{\#}$ = 1.6.



(a) (b) (c) (d) (e) (f)

Fig. 2: Radiation pattern of a single lens at 550 GHz, for broadside (a) and scanned to 20° (b). The scan loss and gain of the lens element pattern is shown in (c) as a function of scan angle and approximate displacement. The bottom row shows the radiation pattern for the 19-element array for broadside, 20° and E-plane pattern up to 30° scan angle.



(a) (b) (c)

Fig. 5: Measured 2-D radiation pattern of the array at 550 GHz for (a) broadside, (b) 10° scan angle and (c) 19.2° scan angle in the Hplane. E/H/D-Plane cuts of the measured and simulated pattern at the aforementioned scanned positions in (a), (b), and (c).

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