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Millimeter Wave Beam Steering Reflectarray Antenna Based on Mechanical Rotation of Array

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ABSTRACT This work provides design and analysis of a beam steering reflectarray antenna, designed at 26 GHz, based on the mechanical rotation of the array. Unit cells based on circular ring elements are designed, and scattering parameter measurements have been carried out for obtaining progressive phase distribution. The unit cell measurements demonstrated a maximum reflection loss of 4 dB with a total phase range of almost 360°. Symmetricity of the array and the resonant elements has been exposed to steer the main beam by tilting the reflectarray at different angles. A beam steering range of more than ±60° has been demonstrated by varying the tilt angle from +30° to −30°. The designed 20×20 element array provided a maximum gain of 26.47 dB at 0° which reduced to 19.8 dB at 61.9° in the elevation plane. On the other hand, the reflectarray antenna demonstrated a maximum bandwidth of 13.1% with a minimum side lobe level of −25.9 dB.

INDEX TERMS Reflectarray antenna, scattering parameters, radiation patterns, mechanical rotation, beam steering.

I. INTRODUCTION

The advantageous nature of reflectarray antennas in many aspects over parabolic reflectors and phased arrays have made it suitable in advanced high gain antenna applications including 5G communication systems. These systems require wide bandwidth, high gain, high efficiency, polarization diversity and adaptive beam steering capabilities in order to meet the core challenge of dealing with data up to 1000 times faster than the currently used systems [1]. Therefore, massive improvements in the performance of each of the components of these systems are required, including the antennas [2], [3].

As an ancestor of parabolic reflectors and phased array antennas, reflectarrays have inherited some of the best features of these antennas, such as high gain, high efficiency and beam steering capabilities. Versatile radiation performance can be achieved, in the case of reflectarray antennas, by controlling the phase response of individual elements mechanically or electronically [4].

Reconfigurable reflectarrays has been demonstrated in a number of research works based on the electronic beam scanning. Controlling the phase of individual elements by using RF MEMS [5], [6], using PIN diodes as switches [7] and employing varactor diodes to vary the capacitance of the resonant elements [8], [9] are some of the most commonly demonstrated techniques for electronic beam steering. Another way to employ electronic beam steering in reflectarray is demonstrated using liquid crystal and varying the material properties by an external voltage, as discussed in [10] and [11].

Even though electronically reconfigurable reflectarrays have successfully demonstrated the beam steering capability, but the losses associated with such techniques are its significant drawbacks. Adding the electronic components for controlling the phase of individual elements of reflectarray, causes high element loss which is mainly attributed to the fact

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that these devices are directly involved in element radiation, causing high insertion loss. Moreover, the switch type devices introduce quantization loss as this configuration can only provide a limited number of discretized phase states, resulting in high phase errors [12]. On the other hand, liquid crystals also carry high material losses, which degrade the reflection performance of individual elements and hence reduce the gain as well as the efficiency of the reflectarray antenna.

In order to rectify the losses associated with electronic beam scanning techniques, mechanical control of individual reflectarray elements using micro motors and actuators has been proposed in [12]–[19]. In these techniques, micro motors are connected to the resonant elements which are continuously rotated up to 180°, providing a phase shift range of 360° without any quantization loss. These motors are usually attached at the backside of reflectarray without having any effect on element radiation. Therefore, these motors do not significantly elevate element loss. However, because of the large number of motors, the efficient control and design complexity become a significant issue that limits the large scale implementation of such reflectarrays. Moreover, most of these designs are also prone to poor axial ratio, limited bandwidth, high reflection loss and inefficient beam steering. The details about the various issues and potential future 5G applications of reflectarrays have been reviewed by the authors in [20]–[23].

This work provides the design and practical validation of a beam steering reflectarray antenna based on mechanical movement of array designed at 26GHz. The unit cell design has been validated by scattering parameter measurements using vector network analyzer, while periodic reflectarrays are used for the radiation pattern measurements.

The paper is organized as follows. Section II describes the design and fabrication of the proposed reflectarray unit cell configuration. Verification of simulated results by scattering parameter measurements is explained in this section. A periodic reflectarray design consisting of 20 × 20 elements is explained in Section III, where a fixed beam is produced at $\theta = 40°$, $\varphi = 0$. The simulated results are compared with the far-field measurements of the designed reflectarray. Section V provides the detailed procedure opted to steer the beam in one plane while keeping it fixed in the other plane. Finally, the conclusion of this research work is provided in Section VI.

II. REFLECTARRAY ELEMENT DESIGN AND MEASUREMENTS

The proposed circular ring element design configuration is shown in Fig. 1(a). A circular ring element has been used in this work because of the symmetricity of this configuration which provides freedom of tilting as demonstrated in Section IV. The reflectarray unit cell was designed at 26 GHz on a standard 0.254 mm thick substrate of Rogers Rt/Duroid 5880. 3D EM simulation software of CST MWS and HFSS were used for the simulations of unit cells, representing infinite arrays, using the proper boundary conditions.

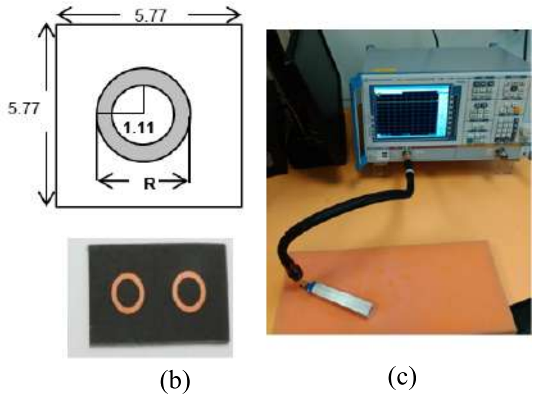


FIGURE 1. Proposed reflectarray unit cell (a) Design configuration (b) Fabricated two patch element unit cell (c) Scattering parameter measurement setup.

The inter-element spacing was kept at half wavelength while varying the radius of the outer ring from 1.51 mm to1.71 mm. This variation in the radius of the outer ring provides progressive phase distribution which is required for the array design. Fig. 1(b) shows the fabricated two patch element unit cell. Although λ/2 inter-element spacing is considered optimal in this design for minimizing the mutual coupling between the neighbouring elements, still two resonant elements were fabricated for each unit cells to observe the mutual coupling effect. A waveguide simulator was also fabricated for the scattering parameter measurements with one aperture having standard dimensions of WR34 (4.31 mm × 8.36 mm). The other aperture of the waveguide was designed to fit the two patch element unit cell with dimensions of 5.77 mm × 11.54 mm. The length of the fabricated waveguide was 116.4 mm (10λ) which provided an angle of 0.714° and 1.429° between the two apertures. These small angles have a negligible effect on the linearity of the incident wave even at millimeter wave frequencies. Hence the waveguide acts as a standard straight rectangular waveguide without generating unwanted propagation modes. The waveguide was connected with the network analyzer through a coaxial cable and an adapter while the reflectarray unit cell was inserted into the other aperture of the waveguide. Fig. 1 (c) shows the complete measurement setup.

A comparison between simulated and measured results of scattering parameters is shown in Fig. 2. Unit cells with a different element radius were used for amplitude and phase measurements. In order to verify the authenticity of the results, two most commonly used computer models of CST MWS and HFSS were used for simulations. It can be observed from Fig. 2 that, the measured and simulated results demonstrated a very close agreement. Although the proposed circular ring element acquired a maximum measured loss of 4dB, however, the element does not show very high phase sensitivity and covers almost the whole 360° phase range. Therefore, in this case, the phase errors are considered to be negligible because of the wide reflection phase range of the resonant element. The phases obtained from the results of different reflectarray

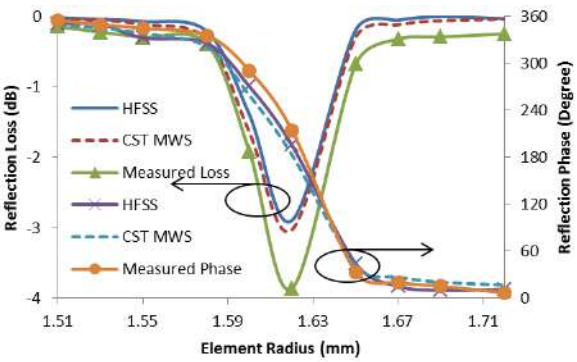


FIGURE 2. Measured and simulated scattering parameters of reflectarray unit cells.

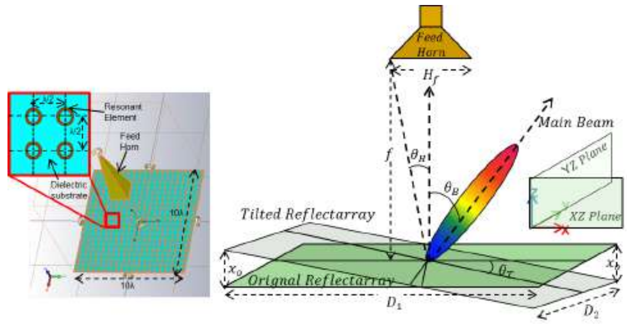


FIGURE 3. Complete assembly of the simulated reflectarray and its schematic diagram.

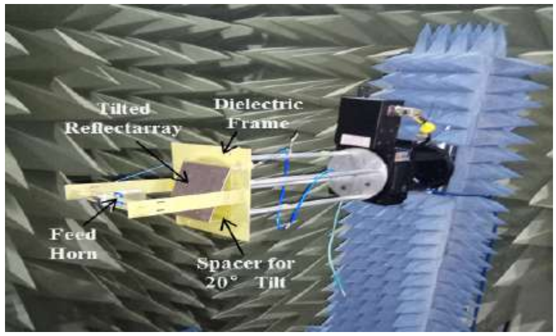


FIGURE 4. Radiation pattern measurement setup in the anechoic chamber.

elements are used to obtain progressive phase distribution required for periodic reflectarray antenna design.

III. 20×20 ELEMENTS REFLECTARRAY DESIGN

In order to construct a periodic reflectarray antenna, 20×20 resonant element array was designed on 0.254 mm thick Rogers Rt/Duroid 5880 dielectric substrate. The inter-element spacing was optimized to be kept constant at 0.5λ, as in the case of unit cells, which made the total size of the array to be 10λ×10λ (115.4 mm×115.4 mm). A center feed horn was placed above the reflectarray at a distance equals to the maximum reflectarray dimension (*f/D=1*). In order to avoid the complexities involved with off-set feed horn, the designed reflectarray was tilted to an angle of $\theta_T = 20°$ in the XZ plane as shown in Fig. 3. The required phase shift for different elements in the array was determined by a very well established ray tracing method. Additional phase delay effects, caused by the array tilt (θ_T), were included in the obtained progressive phase distribution in order to focus the main beam at $\theta_B = 40°$, $\varphi = 0°$ (40° in the azimuth plane). The purpose of focusing the main beam in this direction was to avoid the feed horn blockage, where θ_B had to be larger than θ_H as shown in Fig. 3. θ_H can mathematically be expressed as:

$$\theta_H = \frac{1}{2} HPBW + tan^{-1} \frac{H_f}{2f} \tag{1}$$

where HPBW is the 3 dB beam width of the desired reflected beam, H_f is the maximum aperture dimension of the feed horn and f is the distance between the array and the feed.

The radiation pattern measurements of the designed reflectarray were carried out in a fully anechoic chamber. Fig. 4 shows the measurement setup, where 20×20 element reflectarray was placed at a distance from the feed horn according to $f/D = 1$. The feed horn was connected to a standard WR34 coaxial to waveguide adapter which operates from 22 GHz to 33 GHz. The reflectarray was tilted to 20° using a spacer and all these components were assembled in a dielectric frame.

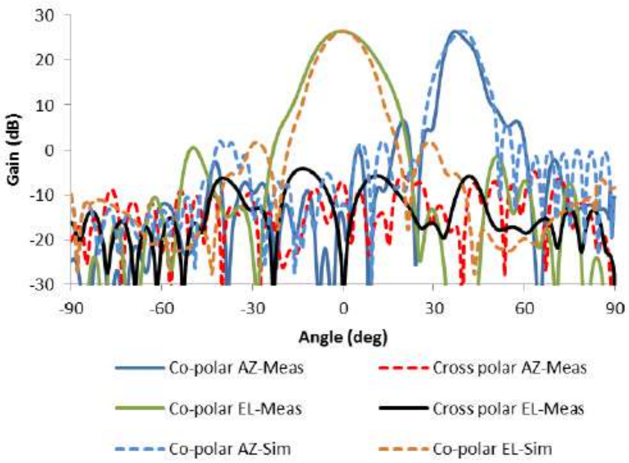
Fig.5 (a) depicts the comparison between the measured and simulated radiation patterns for the fixed beam reflectarray antenna at 26 GHz. A close comparison between measured and simulated results can be observed where a maximum measured gain of 26.45 dB was achieved as compared to a gain of 26.7 dB in simulations. The main beam which was focused in simulations at 40° azimuth (AZ) provided a measured AZ angle of 37°, while in elevation (EL) plane both beams were observed to be at 0°. On the other hand, the measured 3 dB beam widths are 9° and 12° as compared to 8° and 15° simulated 3dB beam widths for AZ and EL planes respectively. The difference between simulated and measured gain can be attributed to the extra losses caused by the measurement setup as well as specular reflections and edge diffractions. While the slight discrepancies between measured and simulated beam directions can be because of the assembling and fabrication tolerance of different components.

The cross-polar components in both AZ and EL planes were observed to be more than 30 dB below the maximum level of co-polar components in the whole angular range. The main beam direction and co/cross-polar components can also be clearly observed by the measured three-dimensional radiation patterns provided in Fig. 5 (b).

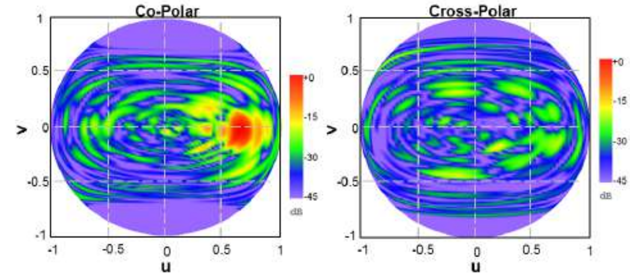
IV. BEAM STEERING REFLECTARRAY

The progressive phase distribution for a reflectarray designed at 26 GHz in this work was calculated using the following equation [4].

$$\Delta\varphi = \varphi - \varphi_i = \frac{2\pi}{\lambda}(f - f_i) \tag{2}$$



(a)



(b)

FIGURE 5. Radiation pattern results for fixed beam reflectarray at 26 GHz (a) Measured and simulated azimuth and elevation planes in cartesian coordinates (b) Three dimensional measured results in UV plane.

where $\Delta\varphi$ is the change in reflection phase, φ is the progressive phase center, φ_i is the phase of i^{th} element, f is the distance between feed and array and f_i is the path delay of the i^{th} element with respect to the array center. According to the above equation, the change in the reflection phase remains constant for the elements placed on a circle with a particular radius in the reflectarray. Keeping in view this theory, the planar reflectarray was tilted in this work from $-30°$ to $30°$ in the YZ plane, in order to steer the reflected beam. It should be noted that the original tilt angle of 20° in the XZ plane was still maintained. The tilting of the reflectarray modified the direction of the phase of surface current distribution as shown in Fig. 6. The red solid arrow shows the direction of surface current phase for the fixed beam reflectarray while the black dotted arrow shows the direction with particular tilt angles. The phase currents travel in a direction (θ_s) which is almost double of the tilt angle. Moreover, according to equation (2), the change in the reflection phase is similar for the red solid arrow as well as black dotted arrows in all the cases because the feed center is kept constant. Therefore, the reflected beam is steered in a direction governed by θ_s.

In order to validate this theory practically, radiation pattern measurements were carried out for reflectarrays tilted at different angles in YZ plane using the same measurement setup as shown in Fig. 4. The tilting of the array can easily be

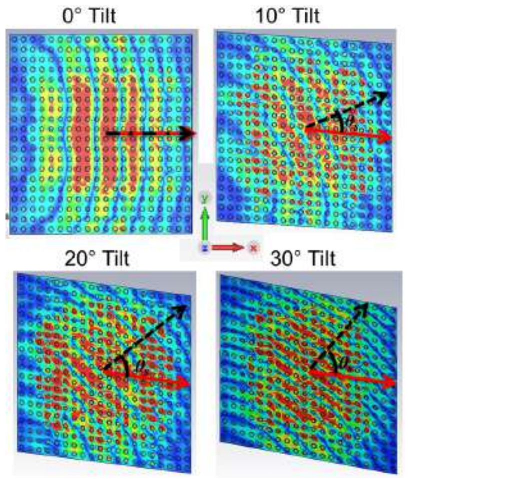
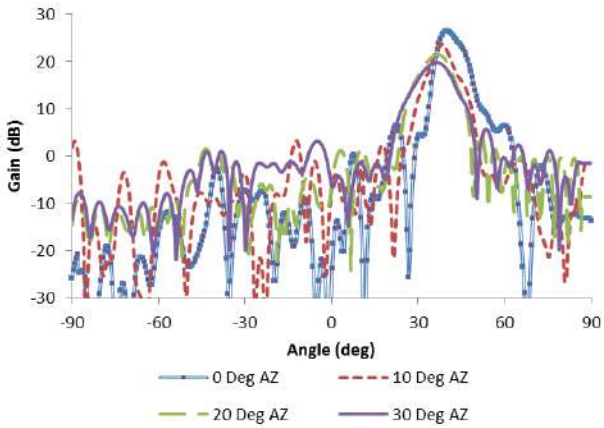
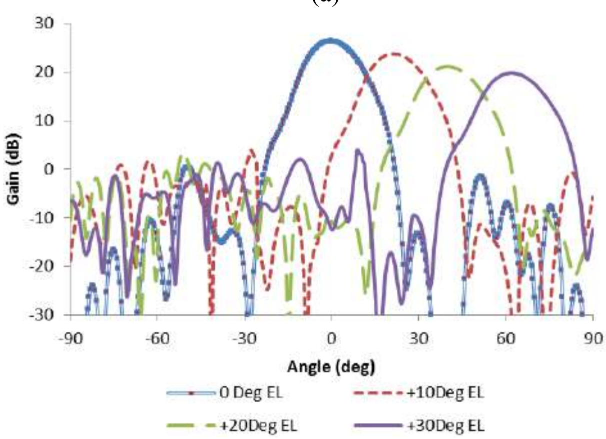


FIGURE 6. Phase of the surface current distribution of different tilt angles.



(a)



(b)

FIGURE 7. Measured radiation patterns for scanned beam reflectarray at different tilt angles (a) Azimuth plane (b) Elevation plane.

managed by using a single stepper motor. However, in this work, for demonstration purpose, the array was tilted manually at different angles from $-30°$ to $30°$. AZ and EL cut radiation patterns were obtained to demonstrate the tilting effect in XZ and YZ planes respectively. For the clear visibility, results of only 0° to 30° tilt in YZ plane are shown in Fig. 7. The tilt of 0° to $-30°$ demonstrated almost identical

TABLE 1. Summary of the measured results.

Tilt angle (°)	Scan Angle (°)		Gain (dB)	SLL (dB)		Bandwidth (%)
	AZ	EL		AZ	EL	
0	40.0	0	26.47	-21.5	-25.9	13.1
10	38.3	21.3	23.83	-21.4	-19.8	9.2
20	36.8	39.8	21.17	-20.6	-17.5	7.6
30	36.3	61.9	19.85	-17.1	-15.8	7.0

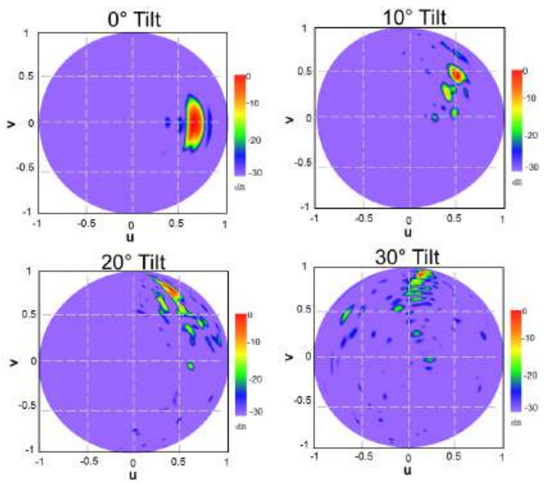


FIGURE 8. Measured 3D Co-polar components in UV plane for different tilt angles of reflectarray.

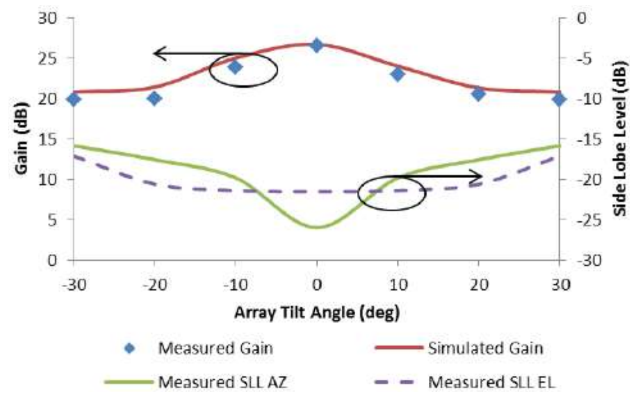


FIGURE 9. Gain and side lobe levels for different reflectarray tilt angles.

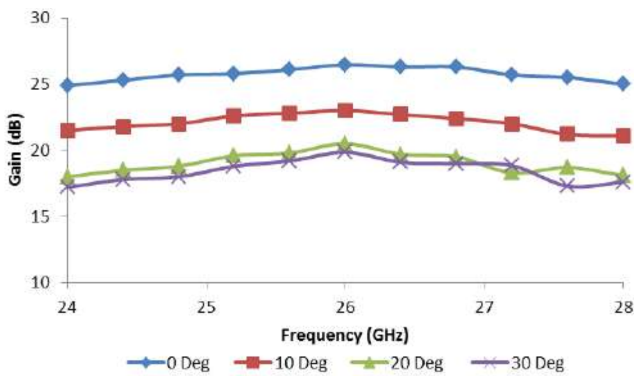


FIGURE 10. Measured gain vs frequency plots for different tilt angles.

results because of symmetricity. Ideally, all the beams were expected to be at 40° in the AZ plane. However, due to tilting in the YZ plane, the beam direction was slightly disturbed as shown in Fig. 7 (a). The focus of the beam in the AZ plane varied from 40° to 36.3° when the reflectarray was tilted from 0° to 30° in the YZ plane. On the other hand, in the elevation plane, the beam steered from 0° to ±61.9° at different tilt angles of the reflectarray as depicted in Fig. 7 (b).

In order to highlight the focus of the beam, three-dimensional measured radiation pattern results are shown in Fig. 8 where main beams can be seen at different positions in UV plane for different tilt angles. Note that, the scale in Fig.8 is more refined as compared to Fig. 5 in order to highlight only the main beam. The sidelobe levels (SLL) and gains obtained for each tilt angle from 0 to ±30° are shown in Fig. 9. As per expectations, the maximum gain and minimum sidelobe levels were obtained for 0° tilt in the YZ plane because the initial progressive phase distribution was optimized for this particular case. The gain reduced from 26.47dB to 19.85dB, while the SLL increased from −25.9dB to −15.85dB, as the tilt angle was increased from 0° to 30° respectively.

TABLE 2. Performance comparison between the proposed design and previously reported reconfigurable reflectarray designs.

Reference	Technique Applied for Scanning	Design Frequency (GHz)	Max. Unit Cell Loss (dB)	No. of Array Elements	Array Size (mm)	Max. Measured Gain (dB)	Scan Range (°)
[24]	Electronic (Varactor Diodes)	60.25	5.3 (Measured)	160×160	560×560	41	±25
[8]	Electronic (PIN Diodes)	5.8	7.4 (Measured)	10×7	300×210	12.9	±50
[12]	Mechanical (Multiple Micro Motors)	8.3	0.2 (Simulated)	15×15	270×270	25.6	0-60°
This work	Mechanical (Single Motor)	26	4.0 (Measured)	20×20	115×115	26.47	±60

1 dB gain drop bandwidth has also been calculated for all the cases by doing radiation pattern measurements in the frequency range of 24 GHz to 28 GHz. Fig. 10 shows the frequency Vs gain plots for different tilt angles. A maximum 1 dB gain drop bandwidth of 13.1% was obtained in the case of 0° tilt, which reduced to 7.0% when the tilt angle was increased up to 30°. The summary of all the measured results is provided in Table 1.

Finally, the performance of the proposed reflectarray design is compared to some of the works presented in the past as shown in Table 2. It can be observed from the comparison that the proposed design provides a simple technique with a single motor and less unit cell loss as compared to electronic techniques, where the element loss is significantly increased because of the lumped components attached to the unit cells. Higher DC power dissipation is also a disadvantage in the case of electronically scanned reflectarrays or designs that require multiple motors. Moreover, the mechanical rotation of the reflectarray provides wide beam scanning, but the scanning speed has to be compromised. Hence, the proposed reflectarray antenna has demonstrated a great potential for future high gain beam steering antenna applications.

V. CONCLUSION

A simple technique for the development of beam steering reflectarray antenna, with a mechanically rotatable array, is presented for the millimeter wave applications. Symmetricity of the circular ring elements and low phase sensitivity has been exploited to produce a constant progressive phase distribution despite different tilt angles of the planar reflectarray. The required tilt angles can be obtained by using a single stepper motor with the whole array instead of using motors with each individual element of the array as presented in previous research works. This helps to reduce the complexity as well as minimizes the power dissipation required for the reconfigurable antennas.

The measured reflection parameters and radiation patterns for the focused and scanned beams were in good agreement with those that were predicted. As a final remark, it can be said that the proposed beam steering reflectarray antenna design is suitable for the applications where wide beam scanning is required and scanning speed is not a major concern.

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