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Ka-Band Circularly Polarized High Efficiency Wide Band Reflectarray Using Cross Bow-Tie Elements

Muhammad M. Tahseen* and Ahmed A. Kishk

Abstract—A Circularly Polarized (CP) high efficiency wide band Reflectarray (RA) antenna is designed for Ka-band using cross bow-tie elements. The reflected wave phase curve is obtained by anti-clockwise bow-tie rotation. The linear phase curve with complete 360° degree is obtained when left-hand circularly polarized (LHCP) is incident normally in unit cell environment. The proposed method provides high gain, high aperture efficiency, wideband axial ratio (AR), in circularly polarized bow-tie RA using multiple copies of unit cell to form $25 * 25$ antenna array. Before designing RA, the unitcell is analyzed, for oblique incidence to predict its bandwidth. The proposed antenna provided good performance in terms of Half Power Beam width (HPBW), Side Love Level (SLL), cross polarization, gain bandwidth and AR bandwidth. A $25 * 25$ bow-tie RA antenna provides the highest aperture efficiency of 57%, HPBW of 9.0 degrees, SLL −19 dB, cross polarization −27 dB. A 1-dB gain bandwidth of 32.5%, 3-dB gain bandwidth of 51.4% and 1.5-dB AR bandwidth of 32.9% while 3-dB AR bandwidth of 48.7% is achieved in simulation. These results are validated through fabricated cross bow-tie RA, and the measurements make good agreement with simulation results.

1. INTRODUCTION

For long distance communication, e.g., satellites, radars, remote sensing, radio astronomy etc., high gain antennas with narrow HPBW are desired. Traditional arrays, with array theory method or parabolic antennas with geometrical optics principle, are normally designed for these requirements. These traditional arrays require complex feeding network, which are difficult to design for large arrays operating at high frequencies. The feeding network designed for the array elements uses transmission lines which increase the antenna losses through the long path for the RF signal. In addition, the network bends and discontinuities affect the antenna performance by creating losses in terms of undesired network radiations. On the other hand, parabolic reflectors meet with the requirement but have non-planar curved reflector surface that makes it bulky and increases fabrication complexity. Recently, planar surface RA has been proposed as an alternative to parabolic reflectors, which are in low cost, light weight and easier to design and provide the advantages of both reflector and arrays [1].

Reflectarray converts incident wave with spherical wave front, transmitted from feed at focal point, to planar wave front at RA surface in transmit mode while converting back the planar wave front to spherical wave front in receiving mode working on the principle of focusing energy to a focal point of reflector using geometrical optics. The traveling distance of the wave, from focal point to each location at parabolic reflecting surface, is the same due to curved parabolic surface while this distance is not the same in RA due to planar surface. This extra path length difference, which waves travel before hitting to RA surface, creates phase errors which needs to be compensated to get constant planar wavefront in the scattered field phase. Several methods have been proposed to fulfill this job, such as varying patch size [2], circular and square rings size variation, slot in ground plane variation, using multi-layer unit

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* Corresponding author: Muhammad M. Tahseen (m_tahse@encs.concordia.ca).
The authors are with the ECE Department, Concordia University, Montreal, Canada.

cell with slot and patch, multi-layer cells with air gap layer used in between to increase phase range and bandwidth, changing effective dielectric constant of the substrate by drilling holes in it and many other methods [2–5].

Bandwidth of RA is controlled by two major factors: the element bandwidth and non-constant path delay between RA elements [6, 7]. The narrow band elements used in RA designing will end up in decreasing the RA bandwidth by introducing phase errors. Narrow band elements such as patch antenna with (3–5%) bandwidth, if used as a radiating element, will further reduce the overall achieved antenna bandwidth. Several methods, such as stacked patches with variable patch length [3], multi-resonant dipoles [8], disk elements attached with phase-delay lines [9], have been proposed to widen RA bandwidth, which has reached providing 10–20% of RA bandwidth using different structures. All these methods try to achieve a linear curve for the reflected wave phase and minimum amplitude loss, which further provides wider bandwidth by reducing amplitude and phase errors and ease in fabrication tolerance. It is effective to get wide RA bandwidth, and array elements should have wide bandwidth.

Circular polarization is preferred in many applications due to its potential against environment interference. For this purpose, multiple CP reflectarray antennas are implemented in the literature. In [10, 11], element rotation technique has been used for obtaining the required phase delay. The aperture efficiency and 3-dB bandwidth achieved by these techniques are less than 42% and 18%, respectively. In [12], circular polarized reflectarray is designed using crossed slots rotation, which provides high efficiency, but bandwidth is still the trade-off. A variety of elements are analyzed for phase enhancement in [13, 14], for reflectarray designing. For obtaining wide range of reflected phase, U-shaped transmission line length variation in aperture coupled element is analyzed in [15, 16]. A CP reflectarray is designed [17], using microstrip patch attached with variable-length phase delay lines, which provides over 650° degrees reflected phase range. This design provides 1-dB gain bandwidth of 10% and the measured aperture efficiency of 45%. In spite of narrowband, reflectarray is still a good candidate for dual-band operation where communication systems require two widely separated frequency bands, and same RA aperture can be used for two interested bands. A broadband double square element with dual-band capability is designed in [18], with frequency selective surface (FSS), but the design provides low aperture efficiency of 40%. A novel CP reflectarray antenna is proposed in [19], transforming incident linearly polarized (LP) fields from the feed to CP radiation fields using multi-layer size varying rectangular patch elements. To achieve polarization diversity with wider AR bandwidth using LP feed is used in [20], the small grid multi-layered varying size rectangular patch elements are used, resulting over 30% AR bandwidth.

A broadband Ka-band circularly polarized printed cross bow-tie RA antenna is designed here. The single element in RA is simulated in CST unit cell periodic environment. The reflected wave phase curve with linear variation is obtained by anti-clockwise bow-tie rotation. The unitcell has a size of $0.25\lambda * 0.25\lambda$. The proposed unitcell is analyzed for different parameters, e.g., oblique incidence and expected RA bandwidth. The proposed method has upper hand over previous published methods in case of providing higher aperture efficiency, wider gain bandwidth and wider AR bandwidth in CP reflectarray.

The paper outline is as follow: Section 2 provides the detailed analysis of RA design with simulation and measurement results while Section 3 provides conclusion.

2. REFLECTARRAY DESIGN

2.1. Reflectarray Principle

The field is incident on each element in RA at certain angle, e.g., normal and oblique incidence. The constant scattered field phase can only be obtained from RA, if proper phase compensation is done to individual elements. The basic schematic of RA is shown in Figure 1, where it can be seen that the elements are arranged on flat RA surface and excited only from the horn placed away at some distance (focal point).

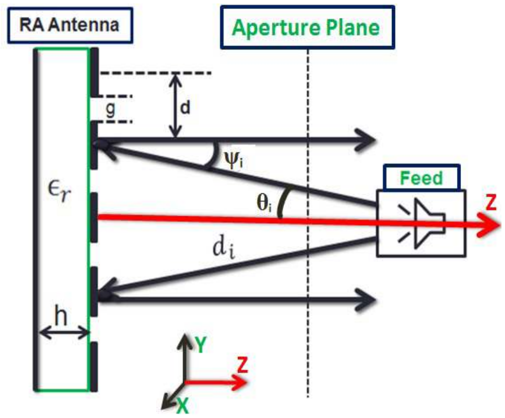

Figure 1. RA antenna basic structure.

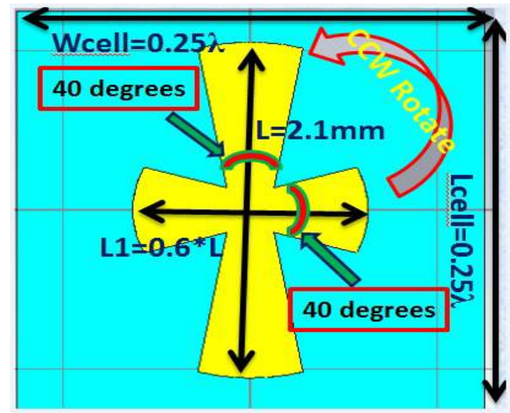

Figure 2. RA unit cell of the crossed bowtie.

2.2. Unitcell Design

2.2.1. Reflected Phase Curve with Bow-Tie Size Variation

Single element with electrical size $0.25\lambda * 0.25\lambda$ is designed in CST microwave studio as shown in Figure 2, at 30 GHz. The vertical and horizontal bowtie slant angles are also shown, which are optimized here to obtain wider bandwidth and these slant angles are critical. It is recommended to use the minimum possible size unitcell in RA design for better antenna performance. In order to achieve smooth variations for the phase on the reflectarray aperture, the cell size should as small as possible. Here, a unitcell size of 0.25λ is used, instead of the conventional 0.5λ size elements. A cheap FR-4 material that is not usually recommended for this frequency band is used, with dielectric constant of 4.5, loss tangent of 0.02 and thickness 'h' of 0.8128 mm. For obtaining the reflection phase characteristic, the unit cell is simulated in periodic environment along x and y directions and left-hand circularly polarized (LHCP) plane wave normal incidence is used. The reflected wave is RHCP. Therefore, the LHCP wave component is the cross polarization component, which needs to be reduced or eliminated while the right-hand CP (RHCP) component is the co-polar, which should be maximum in this situation. The cross-polar component is reduced to be less than 10-dB within the whole operating band to overcome the RA losses. The bow-tie length ratio of the shorter to the longer is chosen optimum at 0.6. Before rotation, the co-polar and cross-polar wave component magnitudes with frequency are shown in Figure 3. It is clear from

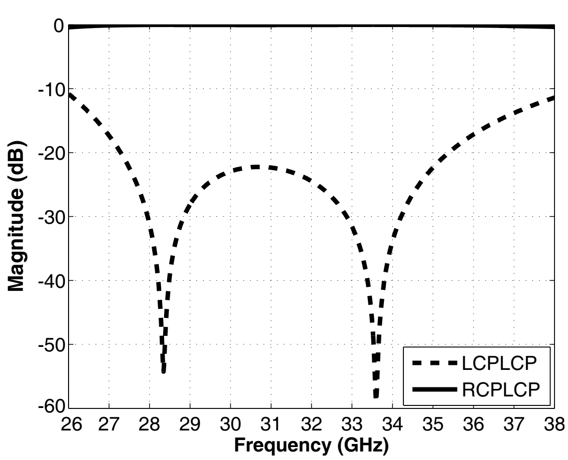

Figure 3. Copolar and cross polar components versus frequency.

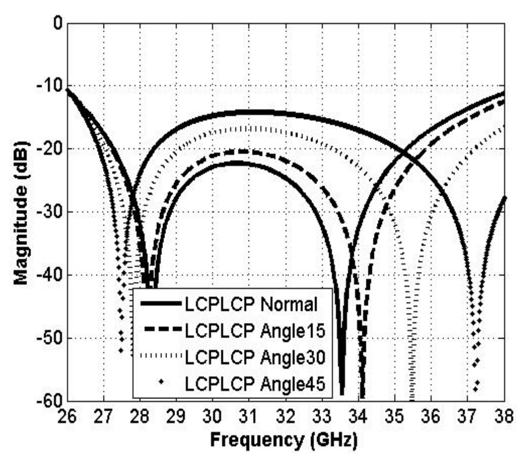

Figure 4. Cross polar components versus frequency for multiple incidence angles.

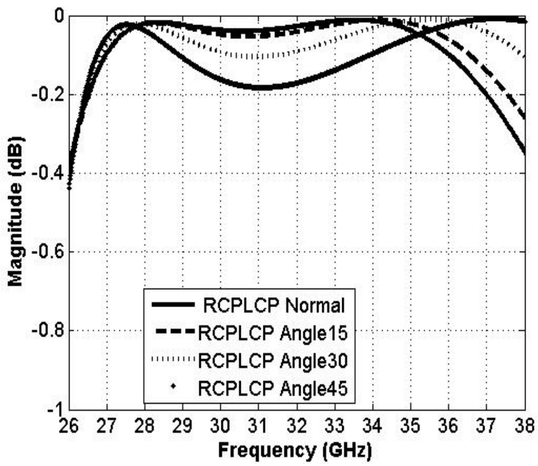

Figure 5. Copolar components versus frequency for multiple incidence angles.

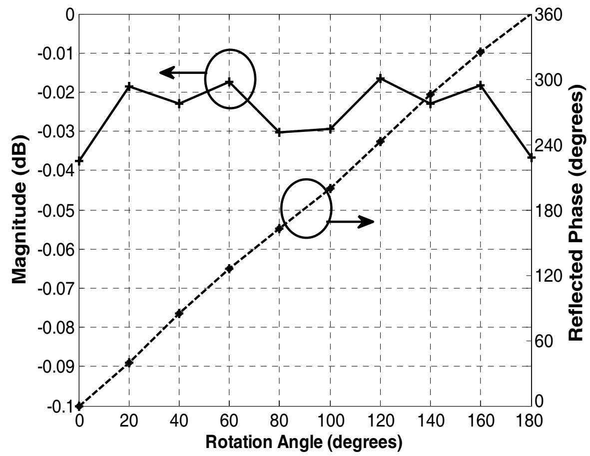

Figure 6. Reflected wave amplitude vs bowtie rotation at 30 GHz.

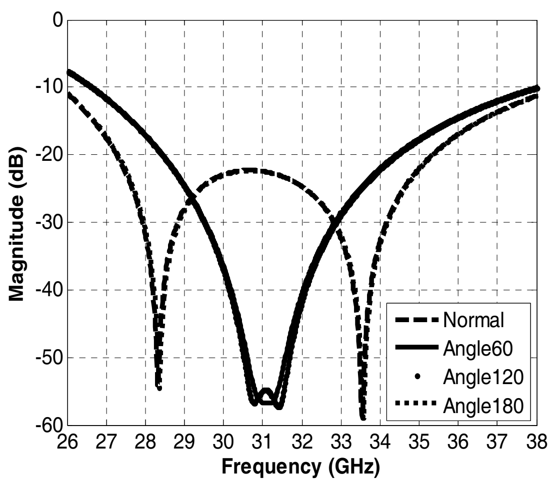

Figure 7. X-polarized wave reflected magnitude suppression.

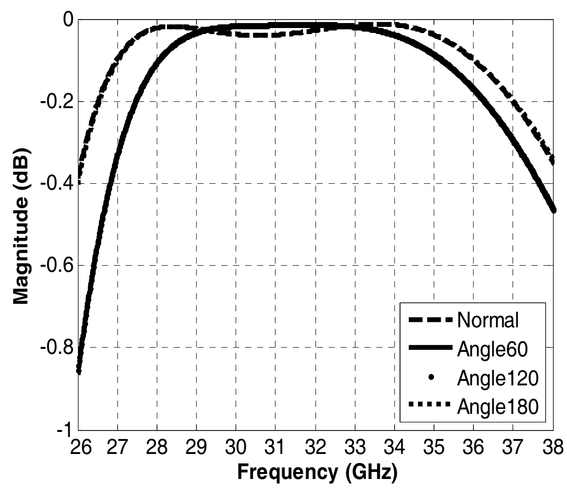

Figure 8. Co-polar wave maximization in operating band.

the plot that the unitcell has tendency to operate in a wideband providing low losses in the whole operating band. For better authentication of the selected unitcell for wideband operation, multiple incidences are also explored. The cross-polar and co-polar wave component magnitudes with frequency at multiple incidence angles are shown in Figures 4 and 5. From these results, it is visible that the cross polarization is still minimum while the amplitude losses are less than 0.4 dB at multiple incidence angles, in the whole operating frequency band. The reflected phase and amplitude versus anti-clockwise bow-tie element rotation angle are shown in Figure 6. The X-polar wave component is suppressed as required to be less than 10 dB in the operating band in all rotating bow-tie angles, as shown in Figure 7 while the co-polar component is also maximized in all rotating angles as shown in Figure 8. The results show that the linear reflected wave phase curve is achieved, which assures providing wider CP reflectarray bandwidth.

2.2.2. Normal and Oblique Incidence

The effect of the angle of incidence on the reflectarray surface is also investigated. Figure 9 shows the effect of the angle of incidence on the reflected phase. Analysis clearly indicates that the accurate results will be accomplished when angle of incidence is taken into account during bow-tie CP RA design. The

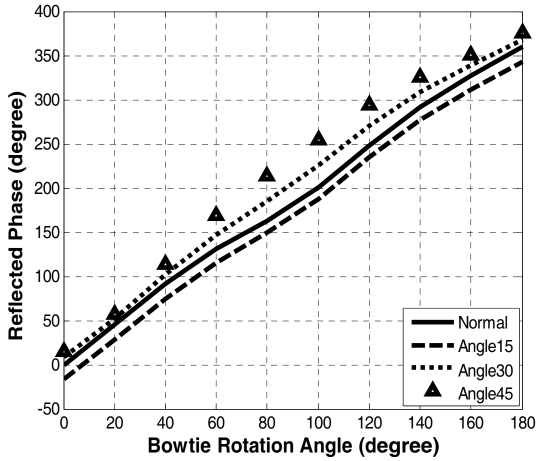

Figure 9. Reflected phase for different incidence angles vs bowtie rotation at 30 GHz.

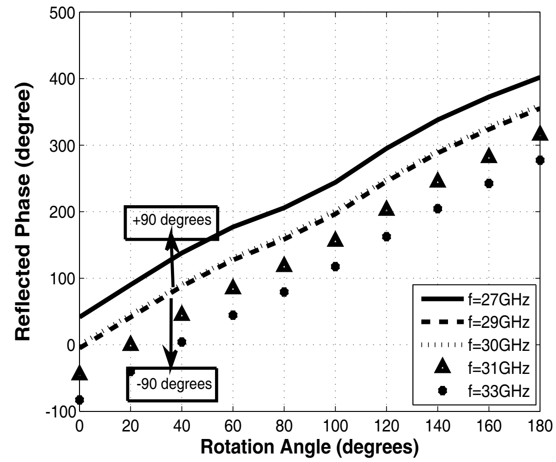

Figure 10. Bandwidth analysis for RA unit cell.

accurate results can be obtained when oblique incidence phase difference is compensated at individual elements.

2.2.3. Bandwidth Analysis

Usually, the RA is designed at the central frequency, but it is important to find the possible bandwidth before starting the RA design. Therefore, the phase variation of the cell versus the bow-tie rotation angle is studied for different frequencies. The two major factors evolve when frequency varies, affecting the RA performance: the phase variation with frequency and at each element location varies due to different path delay at multiple frequencies while the second factor is the phase curve obtained by rotating bow-tie also varies at each frequency. The bandwidth can be predicted as the frequency band within which the phase varies by about ±90 degrees.

$$\beta = \frac{|f_U - f_L|}{f_0} \tag{1}$$

Equation (1) shows the expected bandwidth from unitcell where f_U, f_L, and f_0 are the upper, lower, and center frequency phase curves where the phase variation is no more than a certain amount, e.g., 45 or 90 degrees, when compared with center frequency 30 GHz at that element rotation. This phase difference remains throughout at any bow-tie rotation angle. It is expected here that the bandwidth will be within a phase variation between ±90 degrees. Figure 10 shows the phase variation as the frequency is changed and the expected bandwidth is 31%.

2.2.4. Amplitude Analysis

The reflected wave magnitude is 0 dB in the whole band, at normal and oblique incidence angles, which is clearly shown in Figure 11. This reflection coefficient magnitude makes the incident voltage equal to reflected voltage, and it will help in minimizing the grating lobes or surface waves, generated from ground plane. The result shows that the element is suitable for designing RA for low losses broadband applications.

2.3. Feed for Reflectarray

After concluding unit cell analysis, the next step is to use these elements in RA environment for overall design investigation. To illuminate RA elements, conical horn shown in Figure 12 is used, which is available in our lab. The horn has 5 steps septum used for canceling different modes excited from coaxial ports, and pure circular radiation pattern is obtained at the horn aperture. The feed circular

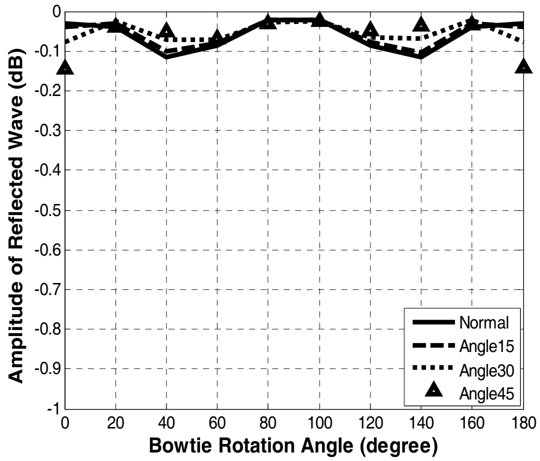

Figure 11. Reflection magnitude with bowtie rotation for multiple incident angles at 30 GHz.

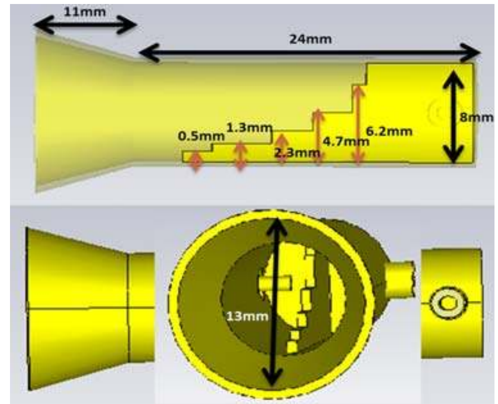

Figure 12. Ka-band CP feed horn.

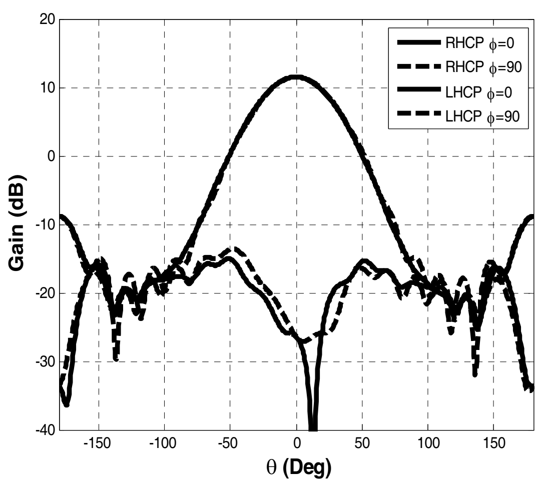

Figure 13. Simulated radiation patterns of the CP feed in two planes at 30 GHz.

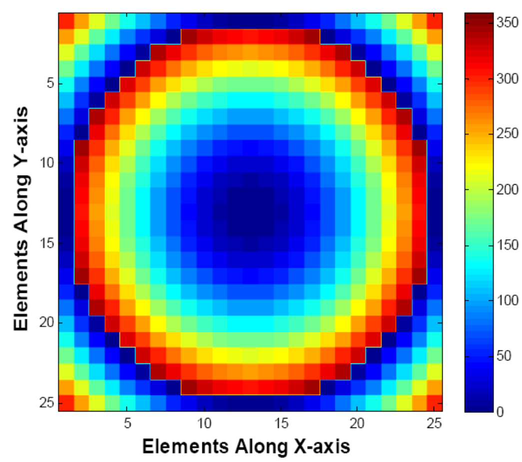

Figure 14. The required phase distribution for elements at RA to compensate spatial delay at 30 GHz.

horn aperture diameter is 1.2λ while length of the horn is 3.2λ. The two coaxial feed points are used for LHCP and RHCP, separately, for transmission and reception. The isolation between right- and left-hand circular waves from two ports in the feed is at good required level. The overall gain in both planes is 10.5 dB, reflection coefficient -15 dB below threshold in the whole band, and SLL is -21 dB. The far-field radiation pattern is symmetric up to -25 dB down. The maximum cross-polar component is around -25 dB below the co-polar peak. These parameters make it suitable to be used in RA design. The edge tapering is considered -10 dB, a position making suspended angle of 90 degrees, which is equivalent to optimized $F/D = 0.59$. This feed is placed at focal point of reflector, and aperture of the horn creates blockage and standing waves between feed and RA causing the reflection at the feed port to increase. The radiation patterns of the CP feed with septums are shown in Figure 13.

2.4. Reflectarray Model

An array of $25 * 25$ reflectarray is designed for analysis with antenna size $6.25\lambda * 6.25\lambda$, and element spacing 0.25λ is considered. The simulated RA contains 625 elements, and the computation is performed on the server present in our lab with "Intel (R) Xenon (R) CPU E5-2670 @ 2.60 GHz (2 processors) and 128 GB of RAM". The resulting CPU time was near 1 hour and this limitation of the number of elements in RA depends on the computational power availability to the designer. The ground plane, with the same size as antenna size, is used at the bottom of RA. The RA elements are excited with a conical horn with symmetric CP radiation patterns as shown in the previous section. The feed is placed at focal point away at a distance 3.7λ to attain broadside radiation from antenna.

2.4.1. Required Phase Distribution and CST Design

To compensate the required phase shift from each element, cross bow-tie rotation technique is used. The spherical waves from the feed at focal distance has different path lengths toward RA elements, so, elements need compensation for these delays, which in return collimate the energy in the desired direction (broadside in this paper). Equations (2) and (3) are used to get the required phase distribution $\phi(x_i, y_i)$ for the RA located in X-Y plane, where the required beam is directed towards (θ_0, ϕ_0). The propagation constant in free space is k_0, and d_i is the distance from feed to individual element location (x_i, y_i) [1]. The total phase delay from feed to a fixed plane in front of the aperture must be constant.

$$\phi(x_i, y_i) - k_0(d_i - \sin\theta_0(x_i \cos\phi_0 + y_i \sin\phi_0)) = 2\pi N \tag{2}$$

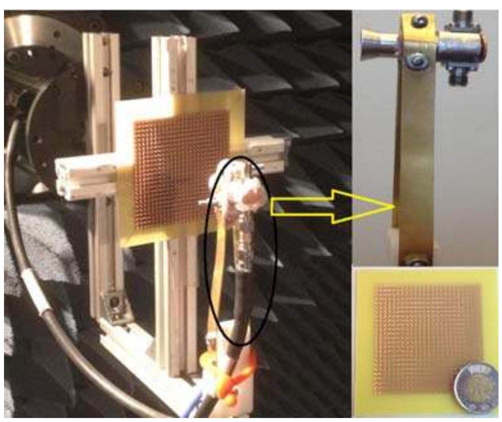

Figure 15. Fabricated bow-tie CP RA antenna.

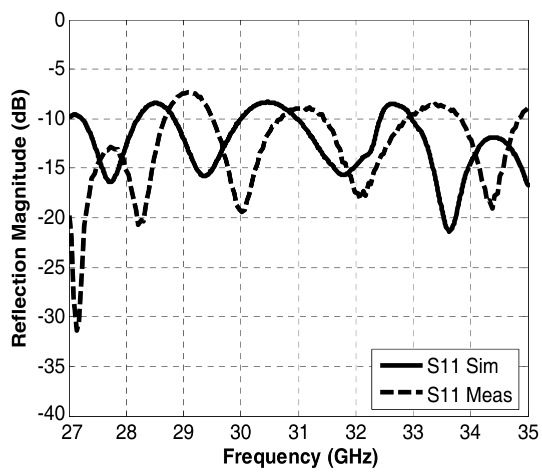

Figure 16. Reflection at input ports of feed after RA simulation.

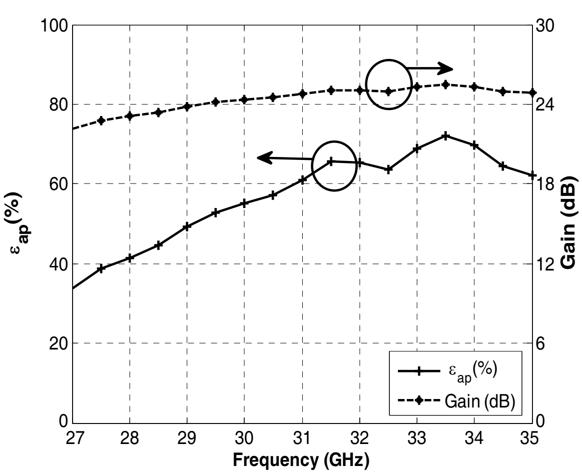

Figure 17. Gain variation with frequency of simulated RA.

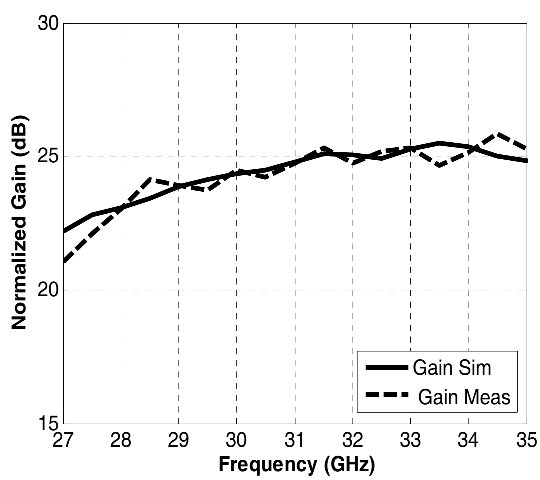

Figure 18. Simulated and measured gain curves.

$$d_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + (z_f)^2} \quad (3)$$

The required phase distribution for the RA is shown in Figure 14, where each element contributes to converging reflected field towards a particular direction.

2.4.2. Simulated Results

A $25 * 25$ CP RA is designed in CST for full wave analysis and fabricated as shown in Figure 15. The simulated and measured reflection coefficients at the input port are compared, as shown in Figure 16. At some frequencies in the operating band, the reflection coefficients magnitudes cross over the threshold level, which can be reduced by making a circular hole cut at the center of RA, but it will reduce overall antenna gain due to RA size reduction. The measured gain of 24.4 dB is realized at center frequency 30 GHz, with 1-dB gain bandwidth of 32.5% and 1.5-dB axial ratio bandwidth of 32.9%. The side lobe level (SLL) is at −19 dB in both planes while the cross polarization is near −27 dB. There are certain factors hinder on high aperture efficiency of reflectarray e.g., feed blockage, feed loss, element loss,

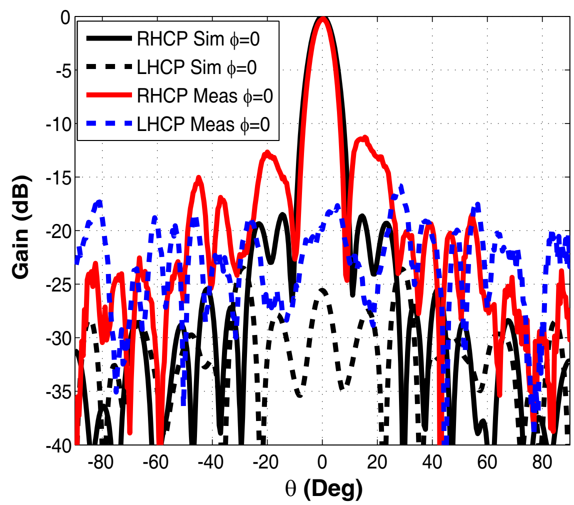

Figure 19. Simulated and measured RHCP and LHCP radiation patterns in XZ plane at 30 GHz.

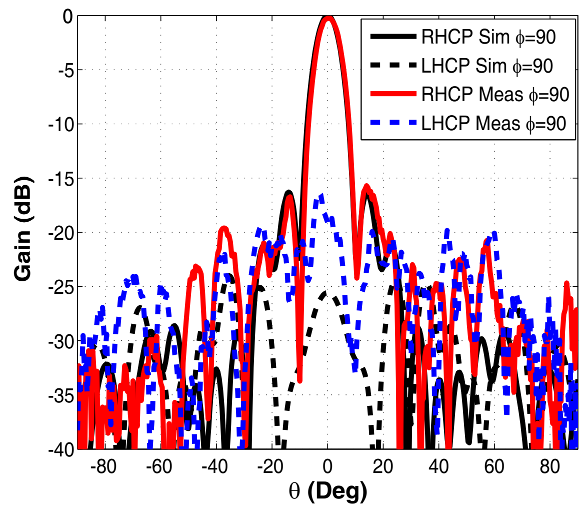

Figure 20. Simulated and measured RHCP and LHCP radiation patterns in YZ plane at 30 GHz.

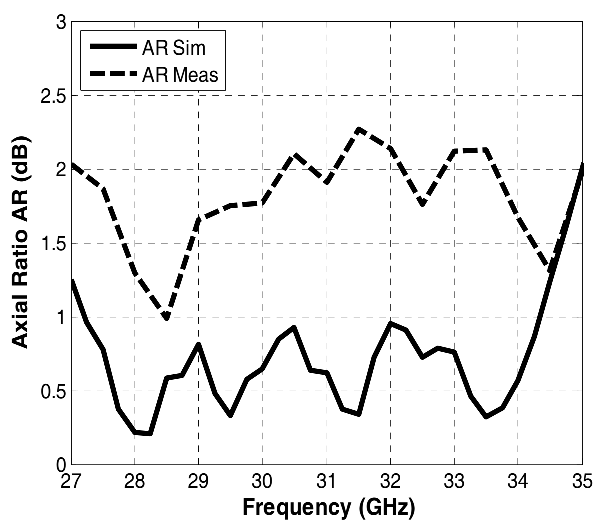

Figure 21. Axial ratio variation with frequency of simulated and measured RA for broadside radiations.

dielectric loss, polarization mismatch loss, and aperture loss. The gain variation versus frequency is shown in Figure 17. The radiation patterns in XZ plane for RHCP and LHCP are shown in Figure 19. High SLL, when compared to simulation, is observed in this plane. This is due to the RF cable and metallic rods supporting feed blockage as shown in the photo in Figure 15. The radiation pattern in YZ plane is shown in Figure 20, which depicts good agreement. The simulated and measured gain plots are shown in Figure 18. The measured 1-dB gain bandwidth is more than 32.3% while the measured aperture efficiency is 57.5% at 30 GHz. The simulated and measured axial ratio variation with frequency plot is shown in Figure 21. The measured 3-dB AR bandwidth for broadside radiations is more than 45%. Although there is about 1-dB difference between measured and computed ARs, it is considered a good agreement as the difference could be due to the tolerance in the manufactured unit as well as in the alignment of the feed with the reflector and the supporting structures. The measured performance of our fabricated cross-bow-tie CP antenna is compared with previous [11], and [17] reflectarray work, as summarized in Table 1.

Table 1. Comparison B/W previous RA performance with proposed.

	RA in [11]	RA in [17]	Prototype Meas.
Freq. Band (GHz)	30–34	9–12	26–38
Central Freq. (GHz)	31.75	10.3	30
Aperture Size D (mm)	506	230	62.5
Meas. Gain (dB)	41.5	25.4	24.45
Meas. Gain BW 3-dB (%)	> 10	15.5	51.4
Meas. AR BW 3-dB (%)	6.5	14.6	48.8
XP (dB)	< 40.7	< 20	< 20
ε_{ap} (%)	50	45	57.5

3. CONCLUSIONS

This paper has presented design and analysis of circularly polarized Ka-band RA using wide-band cross bow-tie radiating elements. The reflected phase range of 360° degrees with linear slope variation has been achieved by rotating the cross bowtie element in counterclockwise direction. The required phase compensation has been calculated and then used in design circularly polarized reflectarray wave towards a particular direction. Using CST microwave studio, a reflectarray antenna with array size $25 * 25$ has been designed with $0.25 * \lambda$ elements. A conical CP feed horn with septums has been used for excitation, which has symmetrical radiation pattern. The feed has been placed for center feeding at focal point of reflector to get radiation fields in broadside direction. The antenna performance has been assessed at 30 GHz. The measurements from fabricated CP bow-tie reflectarray antenna are 1-dB gain bandwidth of more than 32.3%, 3-dB AR bandwidth of more than 45%, a measured gain of 24.45 dB, SLL −18 dB down, cross polarization −19 dB below co-polarization peak and the highest aperture efficiency of 57.5% (at 30 GHz).

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