Analysis of Comparison Between a Non-tapered Reference Array (4x4) and An Amplitude Tapered Array (6x6) With Similar Beam-width

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Abstract

Aim of this project was to compare the 4x4 non-tapered array with a 6x6 amplitude tapered array and analyze the difference between SLL, gain and EIRP for tapered and non-tapered configurations. Array unit cell was a DRA with center frequency 6.5 GHz, it was designed using Antenna Magus. CST was used to design antenna arrays. Matlab was employed to generate the array definition file. Effects of steering the beam were also analyzed. It was found that, the gain is slightly changed when moving from non-tapered to tapered. EIRP and SLL change significantly. Steering plays an important role in gain and directivity computation and it is affected by the number of elements in the array.

I. Introduction

This project was aimed towards comparing the performance of a 4x4 non-tapered array with a 6x6 amplitude tapered array for broadside beam and for $\theta = 60deg$ and $\phi = 45deg$ beam. An important condition was to keep the beam-width of the tapered array similar to that of non-tapered array. The unit cell of the array was a dielectric resonator antenna with center frequency of 6.5 GHz, 10% bandwidth and ε_r of 10.

A Dielectric Resonator Antenna (DRA) has multiple advantages of its own. It is an antenna used at microwave frequencies and consists of a ceramic block mounted on a metal plate. DRA has high efficiency, low loss and small size. DRAs can be easily integrated into other planar technologies. Performance of the DRAs can be optimized without much efforts. These antennas also provide a wider range of bandwidth and have multiple resonating modes.

The DRA was designed using Antenna Magus. The design process and the impedance matching of the DRA is described in the section II. Designed antenna was then exported to CST and using CST's far-field array pattern tool, the far field was computed for 4x4 non tapered and 6x6 tapered array. The array definition file used to provide element spacing and phase-shift was designed using Matlab. Antenna design is described in section III, the subsequent sections discuss the different array configurations.

To satisfy the condition of the having similar beam-width for the non-tapered and the tapered array, Chebyshev window was used for amplitude tapering. It was observed that the suppressing the side-love levels increases the beam-width and reduces the directivity. Detailed observations for different configurations are described in subsequent sections. It was also observed that the directivity reduces for non-broadside beam.

II. Design and Analysis of Dielectric Resonator Antenna

Dielectric Resonator Antenna (DRA) is used at microwave and millimeter wave frequencies. The antenna consists of a resonator of different shapes mounted on a metal plate. The wave is introduced into the resonator by a transmitter feed. Then the wave forms a standing wave inside the resonator by bouncing off the walls however, the walls of the resonator are partially transparent and allow the radio waves to radiate to the space.[1]

DRA has high efficiency and low losses as the resonator is a dielectric and not metal. DRAs can be very small in size as their relative permittivity can vary from 10 to 100 allowing the size to be smaller. Coupling of DRAs is easy allowing them to be integrated in different planar structures. Optimizing the performance is also easy in case of DRAs compared to other structures such as dipole. DRAs can provide wider range of bandwidth ranging from a fraction of the center frequency to up to 20%.

The project deals with two different arrays of DRAs, one 4x4 non-tapered and another 6x6 amplitude-tapered array. The unit cell of these arrays was designed in Antenna Magus. Rectangular DRA was designed, the resonator of this antenna is a cuboid. The length, width and the height of the cuboid decides the center frequency and the performance of the antenna. Apart from the resonator dimensions, the position of the feed is also important. The DRA was designed to adhere to the parameters as mentioned in table 1

No.	Parameter	Value
1	ε_r	10
2	Center Frequency(Fc)	6.5 GHz
3	Bandwidth	650 MHz (10% of Fc)
4	Input Impedance	50 Ω

Table 1. Design parameters of the DRA

Figure 1 shows the designed unit cell with its dimensions.

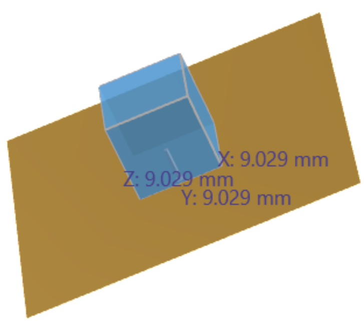

Figure 1. DRA unit cell

Tweaking the dimensions of the DRA changes its performance. This DRA was optimized to obtain parameters as mentioned in table 1. Table 2 shows the dimensions of the DRA after the optimization was done. Figure 2 and 3 represent the impedance and the reflection coefficient of the unit cell. It can be seen that the resonant frequency is close to 6.5 GHz (around 6.52 GHz). The bandwidth is around 9.95% and the impedance is 50 Ω.

From figure 3 one can see that, the reflection coefficient of the antenna at 6.5 GHz is below -30 dB. This shows that the antenna is properly matched. Also, the imaginary part of impedance is zero at 6.52 GHz, showing that the

No.	Dimension	Value
1	Resonator height	9.029 mm
2	Resonator width	9.029 mm
3	Resonator length	9.029 mm
4	Probe inset	0.9029 mm
5	Probe height	3.751 mm
6	Probe diameter	0.451 mm
7	Coax length	1.354 mm
8	Coax diameter	1.040 mm

Table 2. Dimensions of the DRA

resonant frequency is around 6.52 GHz, which is close to 6.5 GHz.

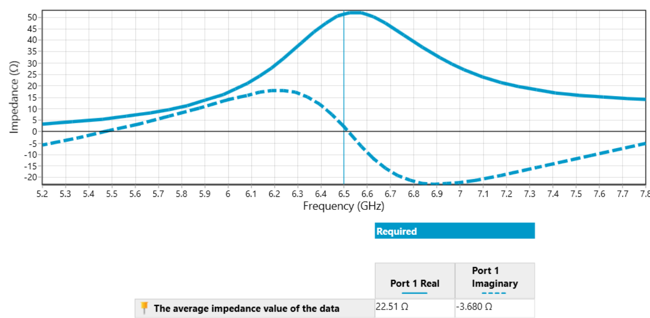

Figure 2. Input impedance of the antenna

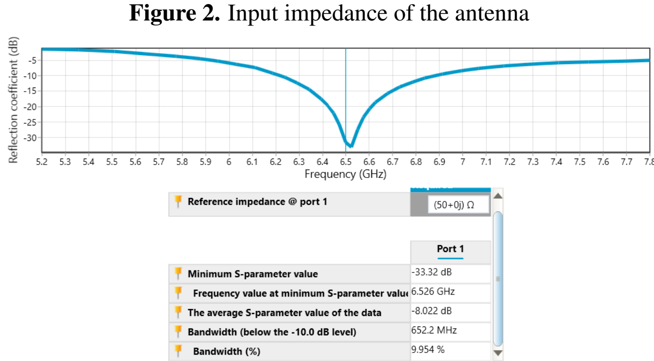

Figure 3. Reflection coefficient of the antenna

The single element radiation pattern can be seen in figure 4. Different properties of this pattern are mentioned in table 3. Maximum directivity and gain are listed.

EIRP was calculated using equation 1

$$EIRP(dBW) = G(dBi) + P_{in}(dBw) \qquad \textbf{Equation } 1.$$

III. Array Design

Array design is one of the most crucial parts of this project. The DRA designed in Antenna Magus was exported to CST. CST has an inbuilt antenna array far-field calculation tool. Using the antenna array tool, the far-field patterns for the array were computed.

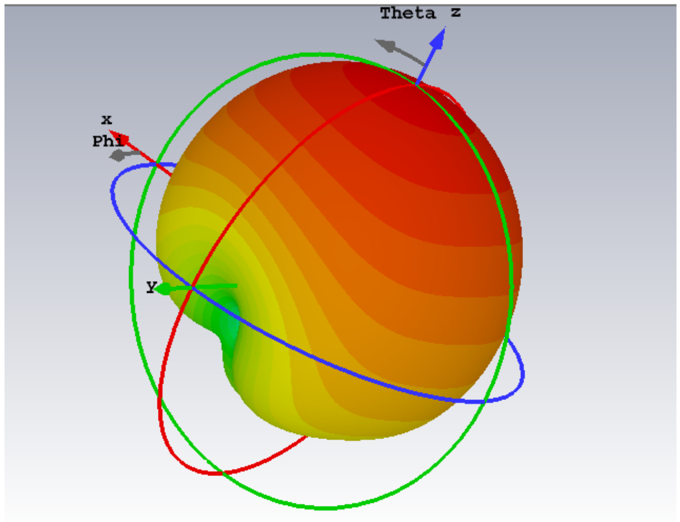

Figure 4. Radiation pattern of standalone DRA

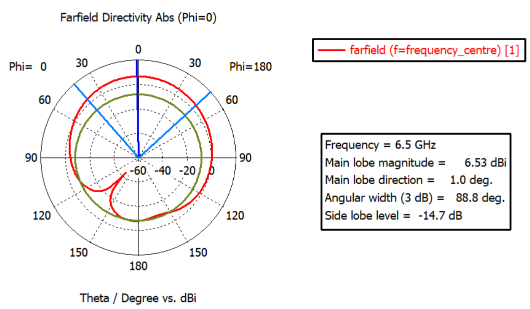

Figure 5. Radiation pattern for single element (vs. θ), cut angle $\phi = 0$ deg

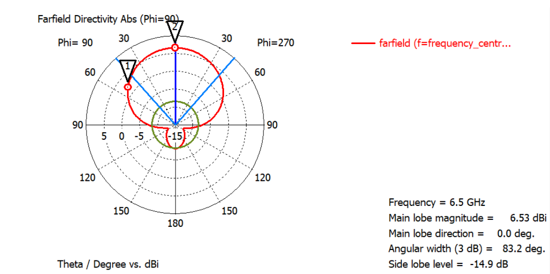

Figure 6. Radiation pattern for single element (vs. θ), cut angle $\phi = 90$ deg

No.	Parameter	Value
1	Directivity	6.53 dBi
2	Gain	6.64 dBi
3	Side-Lobe Level	-14.7 dB
4	Beam-width (E-plane)	88.8 deg
5	Beam-width (H-plane)	83.2 deg
5	EIRP	19.67 dBm

Table 3. Observed values of different parameters for DRA

The tool requires specifying the position of the antennas, the phase-shifts and the input amplitude to each of the antenna. Non-tapered array can be easily created using the tool's rectangular array function, requires specifying the space-shift (distance between the two elements). However, creating the tapered array, requires to specify the amplitude of each element. This can be tedious task, Matlab was employed to create the antenna array definition file, which was then imported in CST to design the required arrays.

Equations 2, 3, 4 were used to calculate the phase-shift[2] between elements of the planar array. The spacing between the elements were taken to be half-wavelength i.e. $\lambda/2 = 23.1mm$.

$$\beta_x = -k_0 d_x cos(\alpha_x) = -\frac{2\pi}{\lambda} d_x sin(\theta_0) cos(\phi_0) \quad \textbf{Equation } 2.$$

$$\beta_y = -k_0 d_y cos(\alpha_y) = -\frac{2\pi}{\lambda} d_y sin(\theta_0) sin(\phi_0) \quad \textbf{Equation } 3.$$

$$\beta_{m,n} = m\beta_x + n\beta_y \quad \textbf{Equation } 4.$$

Here, θ_0 and ϕ_0 are the angles where the beam has to be steered, $\beta_{m,n}$ is the phase shift of m^{th} element along x and n^{th} element along y.

IV. Analysis of 4x4 non-tapered array

Last section described the procedure to design antenna array from given unit cell. A 4x4 array using the DRA that was designed using the aforementioned procedure. Two different array far-field patterns were analyzed, in first case, the array was designed to point in the broadside direction, the array is oriented in XY plane so, $\theta_0 = 0\,deg$ and $\phi_0 = 0\,deg$ is a broadside direction. And in another case, the main beam was pointing towards $\theta_0 = 60\,deg$ and $\phi_0 = 45\,deg$.

Analysis of broadside beam

Figure 7 shows the radiation pattern of the broadside beam. Table 4 represents different parameters observed for this configuration.

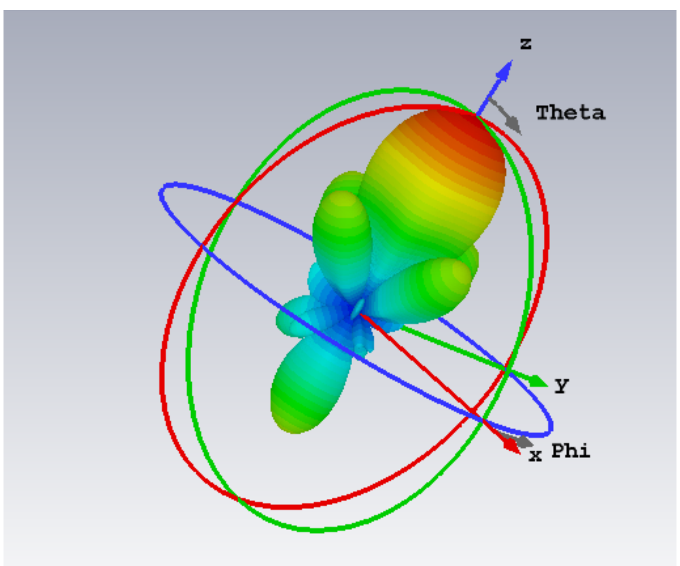

Figure 7. Radiation pattern of standalone DRA

From table 2 and 4, we can see that, array has much improved directivity and gain compared to single element. Also, array pattern has a lower beam-width.

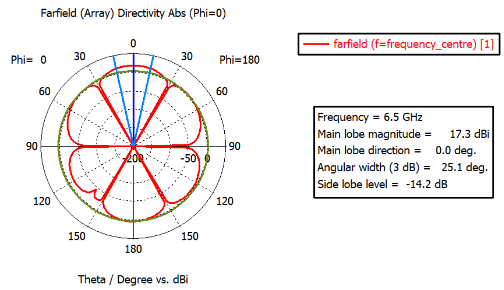

Figure 8. Radiation pattern of broadside beam (vs. θ), cut angle $\phi = 0$ deg

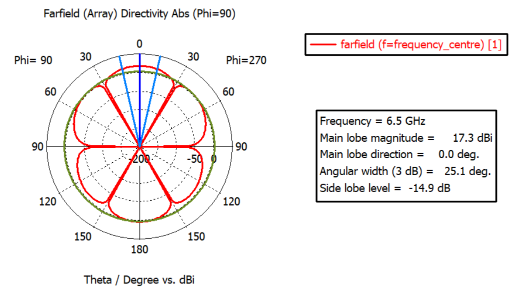

Figure 9. Radiation pattern of 4x4 broadside beam (vs. θ), cut angle $\phi = 90$ deg

No.	Parameter	Value
1	Directivity	17.3 dBi
2	Gain	17.4 dBi
3	Side-Lobe Level	-14.2 dB
4	Beam-width (E-plane)	25.1 deg
5	Beam-width (H-plane)	25.1 deg
5	EIRP	42.45 dBm

Table 4. Observed values of different parameters for 4x4 non-tapered broadside beam

Analysis of beam steered towards $\theta = 60\,deg$, $\phi = 45\,deg$

If the number of elements in an array is less it becomes difficult to steer the beam. Beam steering depends on the spacing between the elements, the number of elements and the wavelength.

For smaller number of elements, as the steer angle increases the beam becomes less directive, the side-lobe levels start increasing and the performance decreases overall.

For this case, 4x4 array, with equation 2 and 3 we get a value of phase-shift. Theoretically this value should steer the beam to the needed angles, however, due to less number of elements, the beam gets wider and wider as we reach the required angle. This leads to main beam at $\theta = 49deg$ instead of 60 deg. An offset of 20 deg was added to the phase-shift obtained from aforementioned equations. The beam was then steered towards $\theta = 59deg$ however, the performance decrease was observed also, this lead to $\phi = 44deg$ instead of $\phi = 45deg$.

Figure 10 and 11 shows the radiation pattern of the array in $\phi = 45\,$deg and $\theta = 60\,$deg plane. Table 5 shows the observed parameters for this configuration.

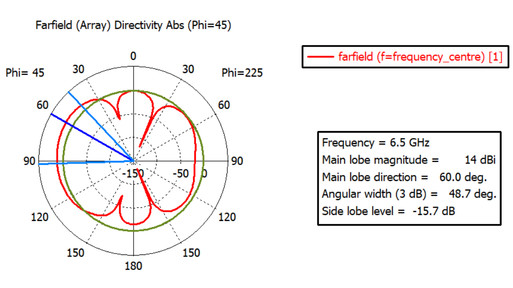

Figure 10. Radiation pattern of $\theta = 60\,$deg and $\phi = 45\,$deg beam (vs. θ), cut angle $\phi = 45$ deg

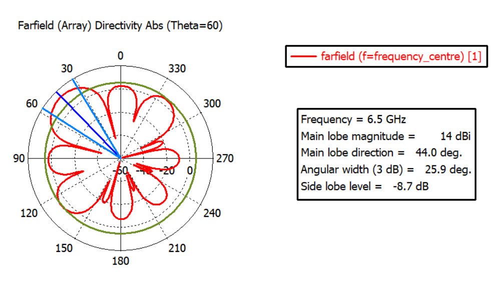

Figure 11. Radiation pattern of 4x4 $\theta = 60\,$deg and $\phi = 45\,$deg beam (vs. ϕ), cut angle $\theta = 60$ deg

No.	Parameter	Value
1	Directivity	14 dBi
2	Gain	14.1 dBi
3	Side-Lobe Level	-15.7 dB
4	Beam-width (E-plane)	31 deg
5	Beam-width (H-plane)	30.3 deg
5	EIRP	39.15 dBm

Table 5. Observed values of different parameters for 4x4 non-tapered $\theta = 60\,\text{deg}$ and $\phi = 45\,\text{deg}$ beam

V. Analysis of 6x6 amplitude-tapered array

The array definition file was obtained using Matlab, as mentioned before. In this case as well two different arrays were defined similar to previous section. One pointing in broadside direction and the other one pointing in $\theta = 60\,\text{deg}$ and $\phi = 45\,\text{deg}$.

Chebyshev window was used to taper the amplitude. It was observed that the lower the side-lobe levels the wider the beam-width. For 6x6 non-tapered array, the main beam is more directional than for 4x4 non-tapered array. More directionality results in narrower beam. To widen the beam, the side-lobe levels were suppressed.

Analysis of broadside beam

Figure 12,13 and 14 represent the radiation pattern for the 6x6 amplitude tapered array. Comparing with figure 7,8 and 9 one can see that beam width in E-plane and H-plane is same for both the arrays. However, the pattern is significantly changed, the side-lobe levels are much lower in case of 6x6 array even though the first side lobe level is comparable. Apart from that 6x6 array is more directional than 4x4. Also, the gain is higher in 6x6 array but the EIRP is lower. Table 6 shows the observed parameters for this configuration.

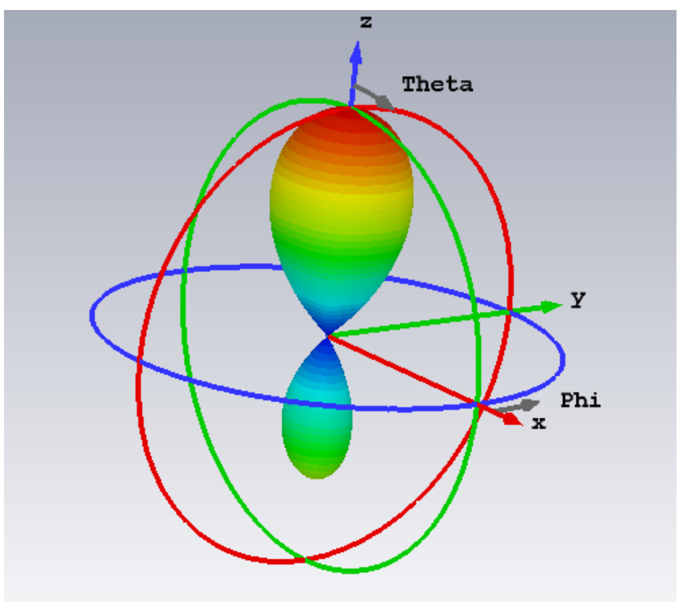

Figure 12. Radiation pattern of broadside 6x6 amplitude tapered array

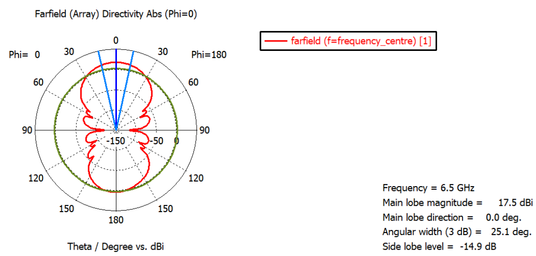

Figure 13. Radiation pattern of broadside beam of 6x6 amplitude tapered array(vs. θ), cut angle $\phi = 0$ deg

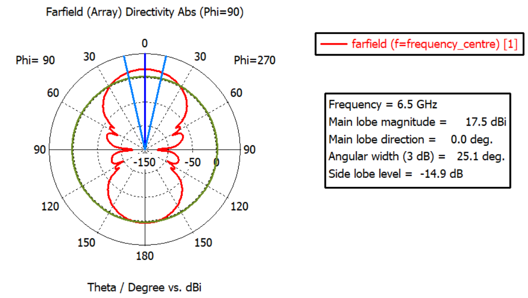

Figure 14. Radiation pattern of broadside beam of 6x6 amplitude tapered array (vs. θ), cut angle $\phi = 90$ deg

No.	Parameter	Value
1	Directivity	17.5 dBi
2	Gain	17.6 dBi
3	Side-Lobe Level	-14.9 dB
4	Beam-width (E-plane)	25.1 deg
5	Beam-width (H-plane)	25.1 deg
5	EIRP	37.85 dBm

Table 6. Observed values of different parameters for 6x6 amplitude-tapered broadside beam

Analysis of beam steered towards $\theta = 60$ deg, $\phi = 45$ deg

This configuration is similar to the beam steered configuration for 4x4 array. And as mentioned before, the theoretical phase shifts gives a different steering than expected. However, in this case, the beam is steered towards $\theta = 54$ deg and $\phi = 45$ deg. The angle is higher than what was obtained for 4x4 array, mainly due to the fact that number of elements are increased. The hypothesis was tested with a 8x8 and a 10x10 array, more the number of elements, more the directivity and more is the maximum steering angle. The amplitude tapering also has an effect beam steering.

An offset was added to the theoretical values to reach the steering of $\theta = 58$ deg and $\phi = 44$ deg. Figure 16 and 17 represent the radiation pattern in $\phi = 45$ deg plane and $\theta = 60$ deg plane.

The Chebyshev window was designed such that the beam-width in E-plane and H-plane is similar to that of the 4x4 non-tapered array, beam directed towards $\theta = 60$ deg and $\phi = 45$ deg. The beam-width obtained in this configuration was 30.4 deg in H-plane and 30.9 deg in E-plane, slightly differing (± 0.1 deg) from that of 4x4 steered configuration. Side-lobe levels are suppressed by 33.8 dB.

It can be seen that, in this case the gain and directivity is better than that of 4x4 array counterpart, however, it is lower when compared to broadside beam for 6x6 array. The EIRP is lower in this case than in 4x4 array case. These parameters indicate a better performance overall.

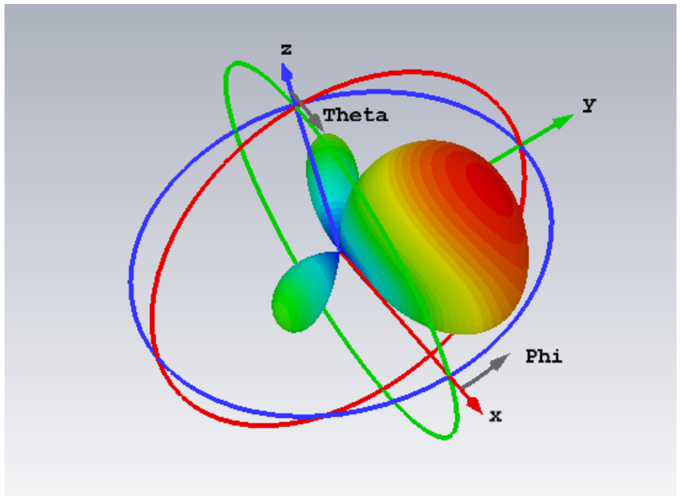

Figure 15. Radiation pattern of $\theta = 60$ deg and $\phi = 45$ deg steered 6x6 amplitude tapered array

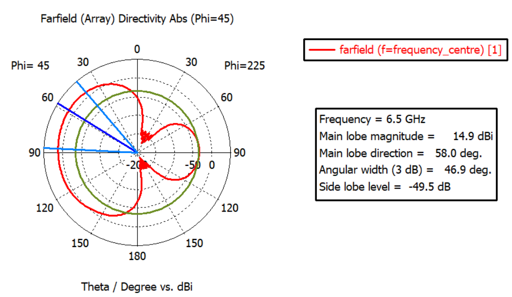

Figure 16. Radiation pattern of $\theta = 60$ deg and $\phi = 45$ deg steered 6x6 amplitude tapered array (vs. θ), cut angle $\phi = 45$ deg

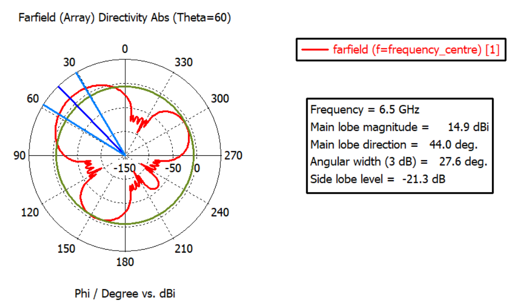

Figure 17. Radiation pattern of $\theta = 60$ deg and $\phi = 45$ deg steered 6x6 amplitude tapered array (vs. ϕ), cut angle $\theta = 60$ deg

No.	Parameter	Value
1	Directivity	14.9 dBi
2	Gain	15 dBi
3	Side-Lobe Level	-49.5 dB
4	Beam-width (E-plane)	30.9 deg
5	Beam-width (H-plane)	30.4 deg
5	EIRP	36.189 dBm

Table 7. Observed values of different parameters for $\theta = 60$ deg and $\phi = 45$ deg steered 6x6 amplitude tapered array

VI. Summary

We find that, moving from 4x4 non-tapered to 6x6 tapered array maintaining the same beam-width in E- and H-plane, for a broadside beam results in slight increase in directivity and gain. Directivity increases by 0.2 dBi, gain by 0.2 dBi, whereas the EIRP decreases by 4.6 dBm. Increasing the beam-width using tapering reduces the maximum gain/directivity, that one can could achieve with 6x6 non-tapered array. Side-lobe was increased by 0.8 dB in this case, however, most of the side-lobes were suppressed apart from the first side-lobe.

Similarly, for beam directed towards $\theta = 60$ deg and $\phi = 45$ deg the difference in gain and directivity is 0.9 dB, these parameters increase in 6x6 tapered array when compared with 4x4 non-tapred. The EIRP decreases by 2.96 dBm.

The side-lobe level was suppressed by 33.8 dB in 6x6 array compared to that of 4x4 array.

Table 8 summarizes all the necessary parameters for different configurations.

No.	Parameter	Standalone DRA	4x4 broadside	4x4 steered	6x6 broadside	6x6 steered
1	Directivity	6.53 dBi	17.3 dBi	14 dBi	17.5 dBi	14.9 dBi
2	Gain	6.64 dBi	17.4 dBi	14.1 dBi	17.6 dBi	15 dBi
3	Side-Lobe Level	-14.7 dB	-15.7 dB	-14.9 dBi	-14.9 dBi	-49.5 dBi
4	Beam-width (E-plane)	88.8 deg	25.1 deg	31.0 deg	25.1 deg	30.9 deg
5	Beam-width (H-plane)	83.2 deg	25.1 deg	30.3 deg	25.1 deg	30.4 deg
5	EIRP	19.67 dBm	42.45 dBm	39.15 dBm	37.85 dBm	36.189 dBm

Table 8. Observed values of different parameters for $\theta = 60\,\text{deg}$ and $\phi = 45\,\text{deg}$ steered 6x6 amplitude tapered array

VII. Conclusions

Effect of amplitude tapering to achieve designated beam-width on directivity, sidelobe level and EIRP was understood. The gain, directivity and side-lobe levels change slightly from that 4x4 array after employing taper on 6x6 array. Gain and direcitity increases, side-lobes are suppressed The EIRP reduces.

Tapering also has an effect on beam-steering. Beam-steering depends on the distance between the elements, the wavelength and the number of elements. Higher the number of elements better the steering.

The project was interesting, fun to do and informative. The mechanism of beam steering, the importance of phase-shifts and space-shifts in arrays, tapering, windowing functions (specifically Chebyshev) and EIRP calculations were the theoretical aspects whose understanding was consolidated. Practically, designing using Antenna Magus, CST array tool, windowing in matlab and designing array definition files were the things that were learned. Dielectric Resonator Antenna was understood and designed.

References

1. Dielectric resonator antenna, *https://en.wikipedia.org/wiki/Dielectric_resonator_antenna* (accessed April 2020)

2. Balanis, C. A. (2005) Arrays: Linear, Planar and Circular, in *Antenna Theory: Analysis and Design* 3nd ed., 283–371, Wiley-Interscience, New Jersey.