American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

UWB Reflectarray Antenna for Chipless RFID Reader Gain Enhancement

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Abstract

The main limitation of chipless Radio Frequency Identification (RFID) systems is its short reading range which is generally less than $40cm$ as the amplitude of the back scattered tag signal is inversely proportional to the fourth root of the reading distance. In this paper, a design of reflectarray (RA) antenna consisting of unified unit cell. Five different unit cells structures centered at 6GHz for chipless RFID reader applications is introduced. The proposed RA has a narrow half power beam width (HPBW) and high gain which significantly enhance the reader sensitivity, maximize the reader reading range, reduce the multipath effects, and improve the tag localization. The proposed RA is realized on a rectangular single layer Rogers RT5880 lossy substrate of thickness$h = 1.57mm$ and relative permittivity $\varepsilon_r = 2.2$. $N = 100$ radiating cells or elements with uniform element spacing $d_c = \lambda/2$ are arranged on the rectangular substrate of dimensions $(250 \times 250)mm^2$and fed by a pyramidal horn antenna with gain of $12.3dBi$, $-18.4dB$ SLL and HPBW equals 46.7°and 42.8° at E-plane and H-plane respectively. The simulation results showed that the proposed RA gives high gain up to 16.3 dBi which is greater than the feeder gain by $4dBi$ and three times narrower HPBW of about 14.9°.It operates over frequency range from $4.7GHz$ to $7.3GHz$ with 43% fractional bandwidth (FBW) and has side lobe level, $SLL = -7.4dB$, which can't be achieved by the conventional antenna arrays.

Keywords: Radio Frequency Identification(RFID); Reflectarray antenna(RA); Side lobe level (SLL).

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1. Introduction

A printed reflectarray antennas or flat reflectors can be considered as a new type of antennas. A reflectarray antenna is made up of an array of radiating elements that provides a focused pencil beam at a certain direction when illuminated by a feed. The horn antenna is the most commonly used feeder in reflectarray feeding due to its very low losses. Reflectarray antennas have the advantages of both phased antenna arrays and parabolic antennas. Compared to the phased array, it has the possibility of beam steering. On the other hand, it has a feeding mechanism as that of the parabolic antenna which decreases the design complexity and losses of phased array feeding network and avoids the manufacturing complexity of parabolic antennas [1].The main idea of reflectarray is generating a directive reflected beam from the reflectarray planar surface when it is illuminated in a certain direction by varying each element phase shift to collimate a pencil beam at the desired direction. That can be achieved by choosing a proper radiating element (unit cell) which satisfies two main conditions; first, it must span 360° at least to satisfy all required phase shifts. Second, the unit cell must have a linear phase curve with the cell phase controlled parameter, cell radius R, to reduce the phase errors which leads to high gain performance. The circular rings are better than the square ones as the square unit cell gives less phase response in terms of linearity [1,2]. While, the circular ring phase response is independent on the azimuth angle which results in less phase error and high efficiency. To get an overall collimated reflected beam from a reflectarray antenna at a certain direction with high gain and efficiency, the plane wave from a feeder when illuminates its planar surface elements, each element should reflect a beam with a certain phase shift depends on the element size and position on the array surface[2]. However, there is a main drawback with the RA antennas which is its narrow bandwidth behavior. Reflectarray bandwidth is limited mainly by two main factors. The first is the narrow band of the radiating elements and the second is the differential spatial phase delay resulting from the different paths from the feeder to each point on the wave front of the radiated beam[3]. In this paper, a single layer substrate based reflectarray antenna (RA) design with high gain, high efficiency, and ultra-wide bandwidth is proposed for reading range extension of chipless RFID readers. To ensure the phase linearity characteristic of the array, five different circular unit cell (UC)designs that satisfy all the frequency, polarization, bandwidth, gain, and efficiency requirements are introduced. The proposed RAs are composed of a unified cell from each of the five different circular unit cells arranged on a rectangular plane. Each RA is build up with $N = 100$, (10×10), elements or UCs with UC dimensions $(\lambda/2 \times \lambda/2)$ centered at $f_o = 6GHz$ .The RAs aperture profiles are limited to$(250 \times 250 \times 1.57)mm^3$. The RAs are fed with a center feeding rectangular horn antenna with focal length $F = 5\lambda$.

2. Chipless RFID System Limitations

Chipless RFID system is the further cheaper solution which emerges from the difficulties of achieving low cost chipped RFID system. It is expected to replace the bar code technology at 2020 [4].That results in the need for new efficient RFID readers with high gain, high sensitivity, and large reading range. A Chipless tag can't generate a signal without the reader sending an interrogation signal to the tag itself. Therefore, the reader acts as a Master and the tag as a Slave[5].The main drawback of Chipless RFID system is its limited reading range where the back scattered tag signal is subjected to the fourth power reduction in magnitude with the reading distance as in Eq.(1). Besides, they also suffer from the reader low sensitivity, multipath effects, and low efficient tag localization [6]. So, Chipless RFID reader must generate a high gain direct beam over a wide band of frequencies to accommodate multiple bits, reduce the effects of multipath propagation, and enhance the reader sensitivity which in turn leads to increasing the reader reading range which can't be achieved using the conventional antenna arrays [4].

$$R_{range} = \sqrt[4]{\frac{G_T G_R \lambda^2 P_T}{4\pi^3 P_{min}} \sigma} \quad (1)$$

where R_{range} is the RFID reading range, G_T is the reader transmitting antenna gain, G_R is the reader receiving antenna gain, λ is the wavelength, σ is the tag radar cross section (RCS), P_T is the transmitted power, and P_{min} is the reader sensitivity.

3. Proposed Unit Cells Structures

The basic building element of a reflectarray antenna is the reflecting $\mathbf{UC}$.All $\mathbf{UCs}$ must give high reflection coefficients equal or close to $\mathbf{0}\boldsymbol{dB}$ at the center frequency $\boldsymbol{f_0}$. It must span 360° at least to satisfy all the required phase shifts and must have a linear phase curve with the cell radius to reduce the phase errors which leads to high gain and wide bandwidth. According to Chipless RFID system applications operating at a center frequency $\boldsymbol{f_0 = 6\ GHz}$, a five circular $\mathbf{UCs}$ are proposed and designed with ground plane of thickness $\boldsymbol{w_g} = \mathbf{0.07mm}$ and fixed substrate dimensions of $(\boldsymbol{\lambda/2 \times \lambda/2})$.The Rogers RT5880(lossy) substrate of thickness $\boldsymbol{h} = \mathbf{1.57mm}$ and relative permittivity $\boldsymbol{\varepsilon_r} = \mathbf{2.2}$ is utilized to reduce the material loss as shown in figure 1(a) shows the general side view of the UC layers. While the other sub-figures show the front views of the proposed circular ring based unit cells, $\mathbf{UC_1}, \mathbf{UC_2}, \mathbf{UC_3}, \mathbf{UC_4}, \boldsymbol{and}\ \mathbf{UC_5}$.The unit cell dimensions are listed in Table 1. With resonator boundary conditions, the cells reflection loss curves against the frequency are plotted as shown in figure 2. All the unit cells give high reflection co-efficient near to $\mathbf{0}\boldsymbol{dB}$ over the entire operating frequency range from $\mathbf{4.7}\boldsymbol{GHz}$ to $\mathbf{7.3}\ \boldsymbol{GHz}$. At the center frequency $\boldsymbol{f_0 = 6GHz}$, the calculated reflection coefficients are very close to $\mathbf{0}\boldsymbol{dB}$ as summarized in Table 2. Also, applying resonator boundary conditions introduced in[1], the cells reflection phase curves against the cell phase control parameter $\boldsymbol{R}$ are plotted as shown in figure 3. Figure 3 (a) shows that $\mathbf{UC_1}$ gives the most linear phase curve but with phase span less than $\mathbf{360}°$ almost equals $\mathbf{342}°$. In this case, the $\mathbf{UC_1}$ can't be separately used in full RA design although its linearity. Figure 3(b) and figure 3(c) show that both $\mathbf{UC_2}$ and $\mathbf{UC_3}$ give acceptable linear phase curves with phase span more than one cycle which equals $\mathbf{544}°$ and $\mathbf{692}°$ respectively. So, they can be used individually in full RA design. Figure 3(d) and figure 3(e) show that both $\mathbf{UC_4}$ and $\mathbf{UC_5}$ give more than two cycles span with different linear parts of phase curves which makes them efficient choices for reflectarray design. A comparison between the phase curves of the proposed five UCs at the center frequency $\boldsymbol{f_0 = 6\ GHz}$ is summarized in figure 4. The slow phase variations provides immunity against manufacturing tolerance and truncation errors [7]. None of the unit cells has a perfect linear phase characteristic. But, each has limited linear regions over the radius span $\boldsymbol{R < \lambda/4}$ where the substrate dimensions are $\boldsymbol{\lambda/2 \times \lambda/2}$. With the aid of the second derivative phase curves shown in figure 5, the most linear regions of each curve can be identified by its closeness to zero. From this point of view, a RA can be designed using different UCs utilizing their linear regions to achieve the desired phase shifts that maximize the array gain.

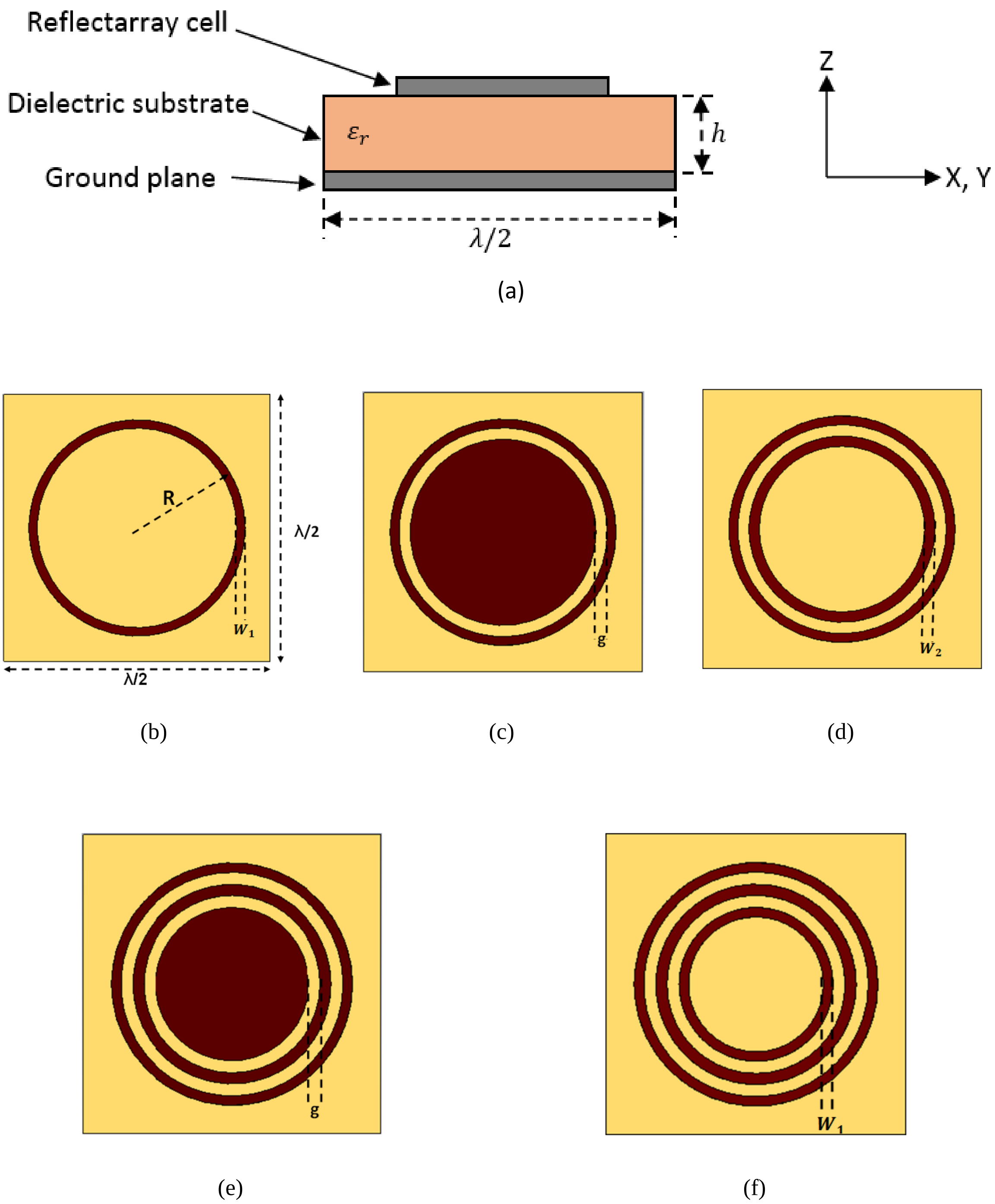


Figure 1: Unit cell structure (a) cell side view,(b)UC_1 front view,(c) UC_2 front view,(d) UC_3 front view, (e) UC_4 front view, and (f) UC_5 front view.

Table 1: Unit cells parameters

Parameter	w_1	w_2	g	h	w_g
Dimensions in mm	0.8158	0.952	1.0186	1.57	0.07

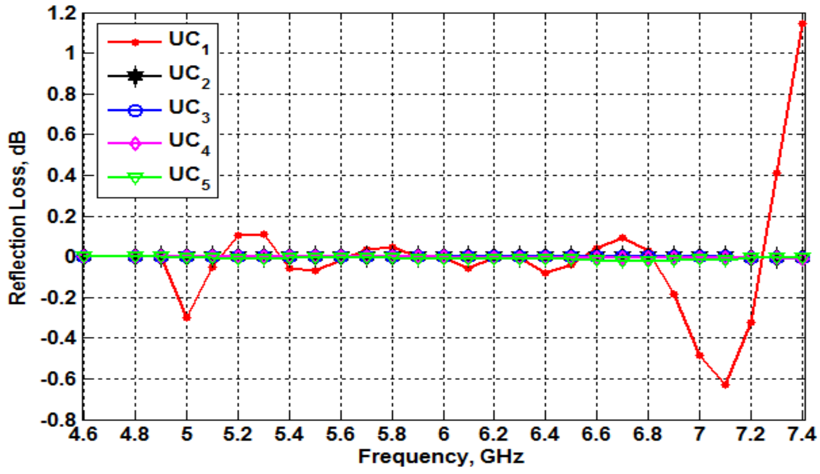
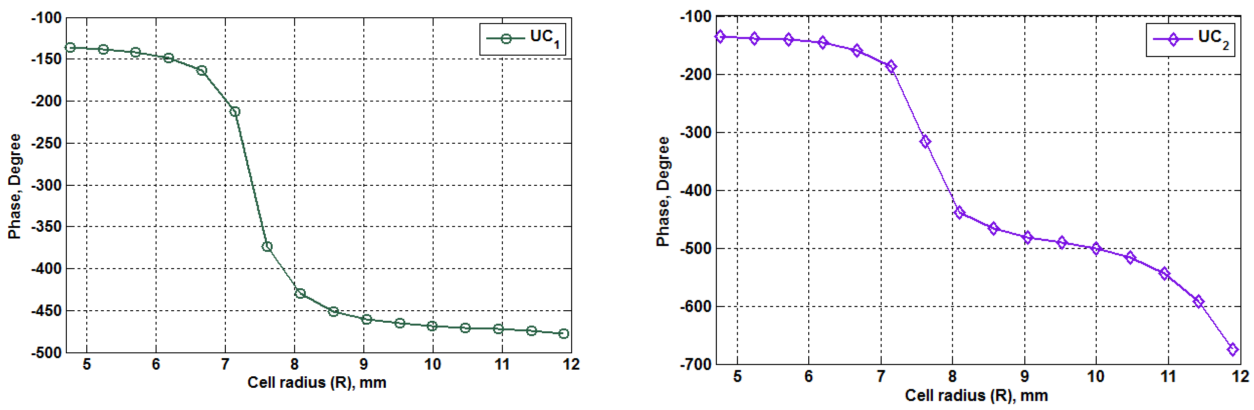


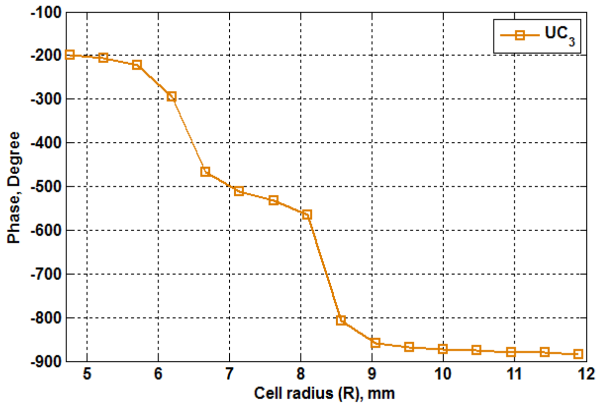
Figure 2: Reflection loss versus frequency for the five unit cells.

Table 2: Reflection loss for the five unit cells at the center frequency $f_0 = 6$GHz.

Unit Cells	Reflection Loss in dB at $f_0 = 6GHz$
UC_1	0.053
UC_2	0.00071
UC_3	0.00058
UC_4	0.001
UC_5	0.00664



(a) (b)



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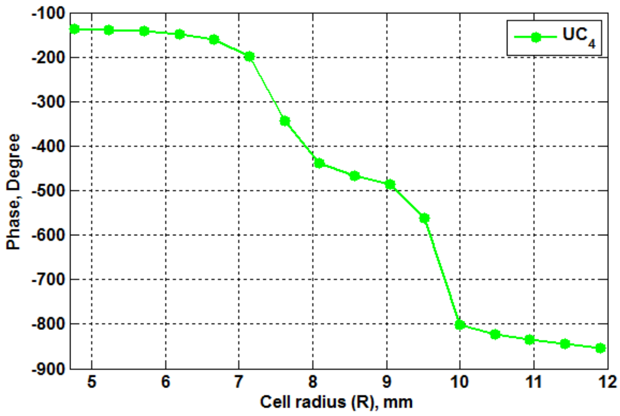

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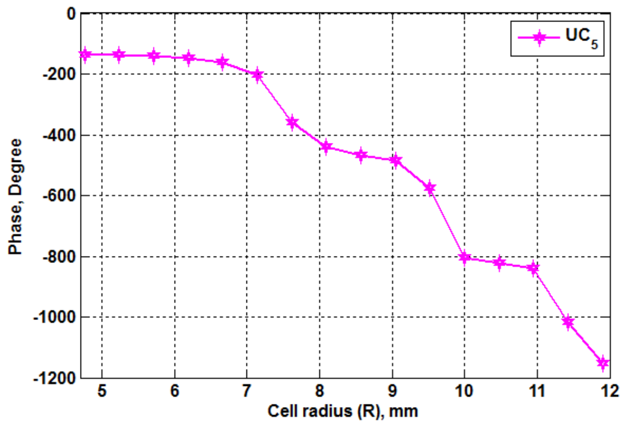


(e)

Figure 3: Phase characteristic curves for each unit cell against its radius at 6GHz (a)UC_1 phase curve, (b)UC_2phase curve, (c)UC_3phase curve, (d)UC_4phase curve,and (e)UC_5phase curve.

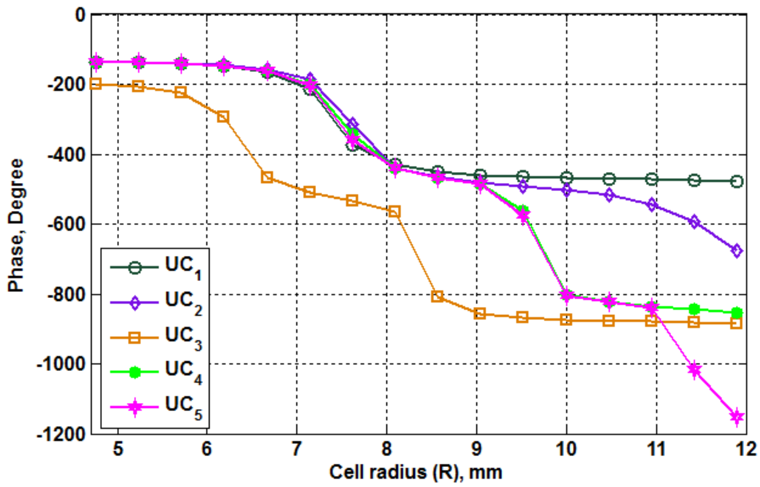


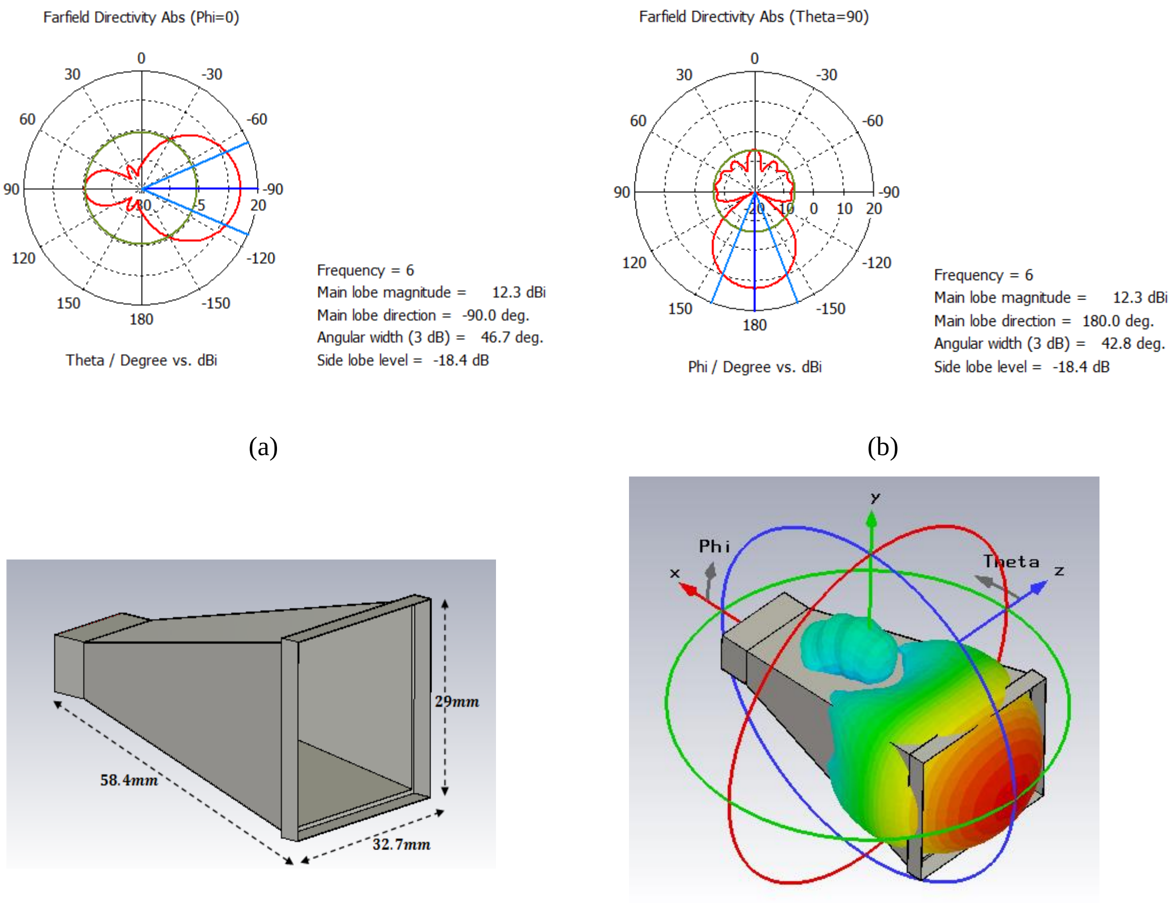
Figure 4: A comparison between the phase curves against the unit cells Radius of the proposed five UCs at the center frequency $f_0 = 6\ GHz$.

4. Reflectarray Antenna Design

There are seven steps for an efficient reflectarray (RA) antenna design which can be summarized as follows:

- Design a UC that meets all the aforementioned requirements at the desired center frequency.
- Estimate the UC phase curve against the cell phase controlling radius parameter (R).
- Find the desired phase shift from each array UC according to Eq.(2) introduced in [8].

$$\emptyset_{\mathrm{R}}\ (x_{ij}\ , y_{ij}) = k_0(d_{ij} - (x_{ij} sin\theta_0\ cos\varphi_0 - y_{ij} cos\theta_0 sin\varphi_0) \quad (2)$$



(a) (b)

(c) (d)

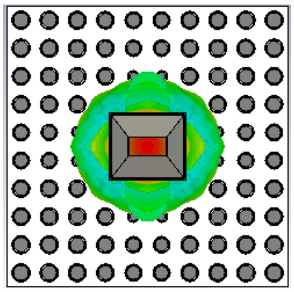
Figure 5: Feeder horn antenna (a) E-field radiation pattern at the center frequency $f_0 = 6$GHz ,(b) H-field radiation pattern at the center frequency $f_0 = 6$GHz, (c) Feeding horn antenna dimensions, and (d) The feeding horn antenna 3-D radiation pattern at the center frequency $f_0 = 6$GHz.

where $\emptyset_R\ (x_{ij}\ , y_{ij})$ is the required phase shift from the $(i, j)^{th}$ unit cell. $k_0 = 2\pi/\lambda_0$ is the free space wave number and λ_0 is the free space wavelength which depends on the resonance frequency f_0. d_{ij} is the distance between the face center of the feed horn antenna and the center of $(i,j)^{th}$ cell. (x_{ij}, y_{ij}) are the (i,j) cell coordinates. θ_0 and φ_0 are the Elevation and Azimuth angles of the incident plane wave.

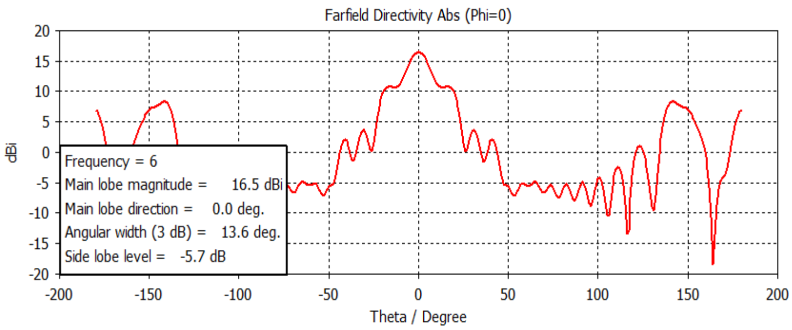
- Determine each cell radius (R) according to the required phase shift from its reflection phase curve.
- Repeat 4 & 5 steps for each element on the array.
- Build the array of cells with different radii that satisfy the required phase shifts according to their positions on the array surface according to Eq. (2).

All the designed RAs are fed with a pyramidal horn antenna. The feeder horn antenna has $12.3dBi$ gain, $-18.4dB$ SLL and HPBW equals 46.7°and 42.8° at the E-plane and H-plane, respectively as shown in figure 5(a) and figure 5(b). The horn dimensions are $(32.7 \times 29 \times 58.4)\text{mm}^3$ using the standard ATH1G18A waveguide (WG) for high gain horn antenna as shown in figure 5(c). Figure 5(d) shows the horn antenna 3-D radiation pattern at the center frequency $\text{f}_0 = 6\text{GHz}$.

5. Reflectarray Antenna Specifications



(a)



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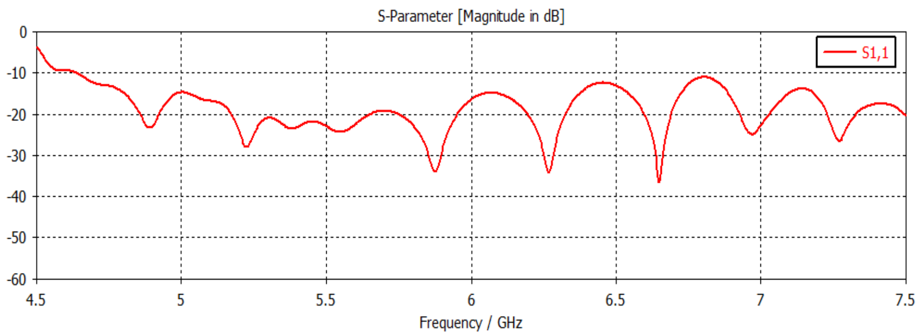


(C)

Figure 6: (a) UC_2 based RA structure , **(b)** radiation pattern of the RA at $f_o = 6GHz$, and **(c)** S- parameter $(S_{1,1})$ over the entire bandwidth from $4.7GHz$ to $7.3GHz$.

The unified reflectarray antenna (URA) is a RA that is based on a single UC to achieve all the required phase shifts.UC_1 is excluded as it doesn't span 360° and it can't give all the required phase shifts to build the RA. Four URAs are designed based on the four unit cellsUC_2, UC_3, UC_4, and $UC_5$where their structures, radiation patterns, and scattering parameters$S_{1,1}$are shown in figure 6, figure 7, figure 8, and figure 9, respectively. The radiation patterns parameters of the RAs at the center frequency $f_o = 6GHz$ are summarized in Table 3 .

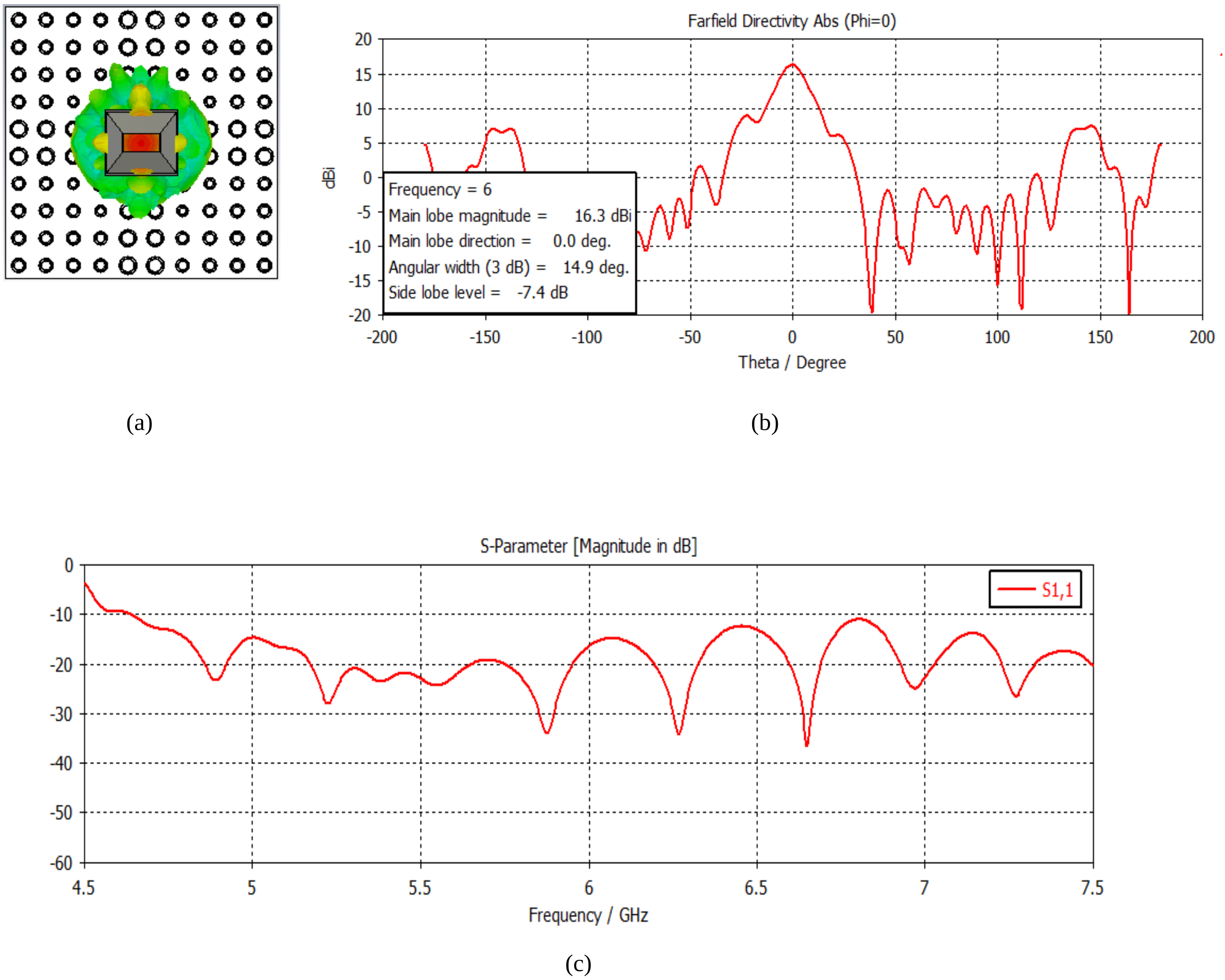
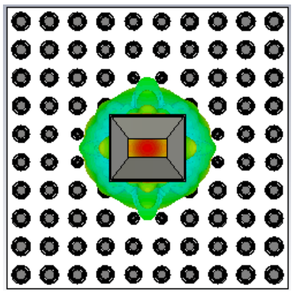
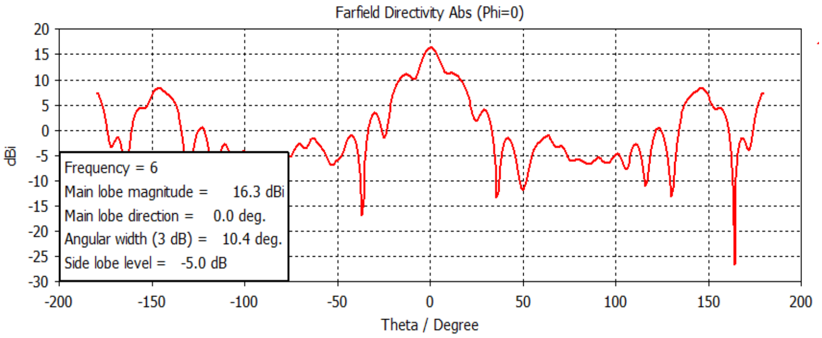
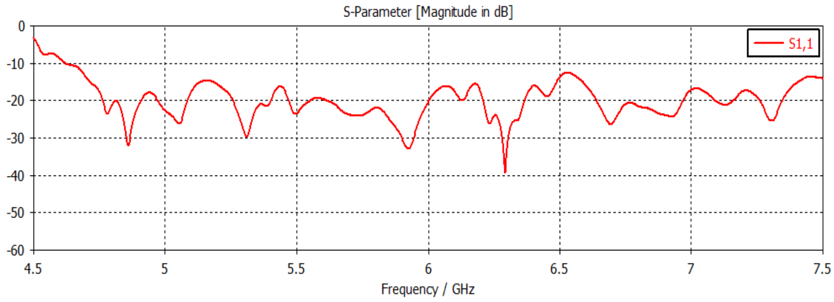


Figure 7: **(a)** UC_3 based RA structure , **(b)** radiation pattern of the RA at $f_o = 6GHz$, and **(c)** S- parameter ($S_{1,1}$) over the entire bandwidth from $4.7GHz$ to $7.3GHz$.



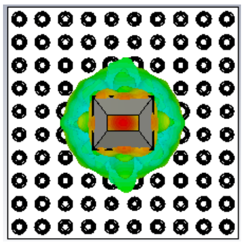


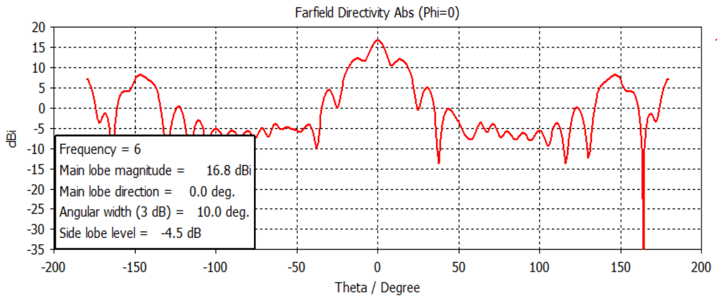
(a) (b)



(c)

Figure 8: (a) UC_4 based RA structure and **(b)** radiation pattern of the RA at $f_o = 6GHz$, and **(c)** S- parameter $(S_{1,1})$ over the entire bandwidth from $4.7GHz$ to $7.3GHz$.





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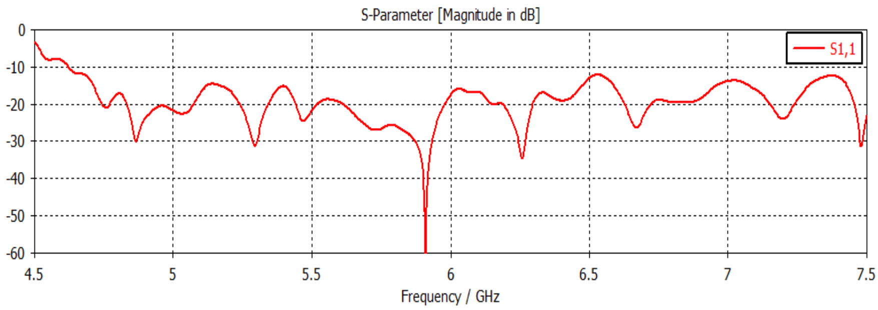

(c)

Figure 9: (a) UC_5 based RA structure and **(b)** radiation pattern of the RA at $f_o = 6GHz$, and **(c)** S- parameter $(S_{1,1})$ over the entire bandwidth from $4.7GHz$ to $7.3GHz$.

Table 3: Comparison between the four unified UC based RAs at the center frequency $f_o = 6$GHz.

RA	RA Antenna Parameters		
	Gain (dBi)	HPBW	SLL (dB)
UC_2 based RA	16.5	13.6°	-5.7
UC_3 based RA	16.3	14.9°	-7.4
UC_4 based RA	16.3	10.4°	-5
UC_5 based RA	16.8	10°	-4.5

It is clear that the unified RAs have higher gains around $16.8dB$ for UC_5based RA with acceptable SLL equals $-4.5dB$. While the lower SLL of the unified RAs is $-7.4dB$ with high gain which reaches $16.3dBi$ for UC_3 based RA. That is because the unified UC based RA has to use the non linear portions of the utilized UC phase curve to meet the required phase shifts. The far field gain against frequency for all proposed RAs are shown in figure 10. ensures that all the RAs give the maximum gain at the designed frequency.

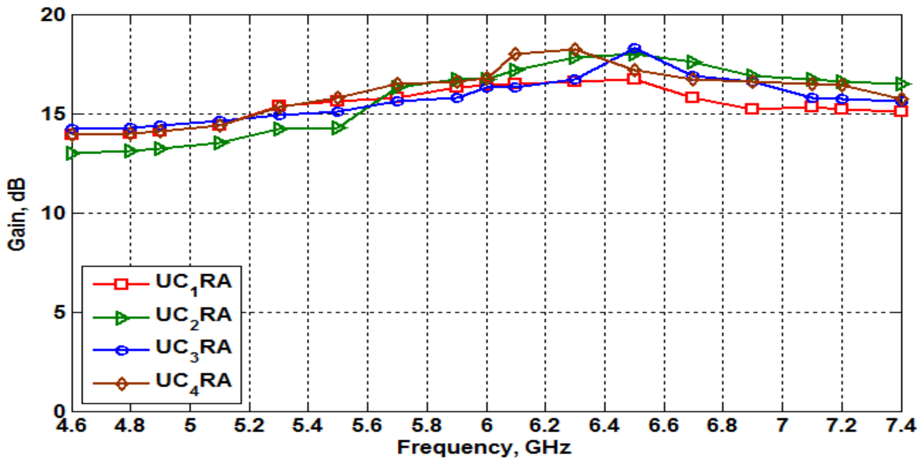

Figure 10: Far field gain versus frequency for all proposed RAs.

6. Reflectarray Performance

There are three factors should be taken into consideration for RA efficient design:

6.1. Feeder Blockage

Can be described as the shadowing with the feed in the path of rays arriving at or departing from the aperture of the antenna or interfering with the radiation.

To avoid feeder blockage UC_2 based RA offset feed, offset beam, and center feed are designed and compared as shown in Table 4 .

Table 4: Comparison between offset beam, center beam center feed, and offset feed UC_2 based RAs.

ARRAYS	**RA Antenna Parameters**		
	Gain(dBi)	**HPBW**	**SLL(dB)**
Offset beam RA withUC_2	16.5	13°	-3.5
Center feed center beam RA withUC_2	16.5	13.6°	-5.7
Offset feed RA with UC_2	15.5	14.9°	-2.4

Table 4 shows that the UC_2 based RA center feeding center beam gives the lowest SLL which is -5.7dB. Where the offset beam UC_2 based RA SLL equals -3.5dB and the offset feed UC_2 based RA gives -2.4dB SLL. And, on the other hand the UC_2 based RA gives also the highest gain up to 16.5dB.

6.2. Element Spacing d_c

Efficient element spacing must be used to enhance gain, BW and minimize the SLL according to Eq.(3).

$$\frac{d_c}{\lambda} \leq \frac{1}{1+\sin\theta} \qquad (3)$$

where, d_c is the element spacing, λ is the wavelength, and θ is the incident angle from the feeder. Table 5 shows that $\lambda/2$ is the sufficient element spacing that gives a high gain and minimum SLL [7]. Three different element spacing UC_2 based RAs are designed and compared as shown in Table 5. The first RA is designed with d_c= 0.3λ, the second is designed with d_c=0.5λ, and the third RA is designed with d_c= λ.

Table 5: Comparison between the three UC_2 based RAs with different element spacing 0.3λ, 0.5λ, and λ.

Array	**RA Antenna Parameters**		
	Gain	**HPBW**	**SLL**
UC_2 RA with d_c= 0.3λ	15.5	13.9°	-3.6
UC_2 RA with d_c= 0.5λ	16.5	13.6°	-5.7
UC_2 RA with $d_c = \lambda$	11.6	9.4°	-0.4

From Table 5, it is clear that the RA with d_c= 0.5λ gives the best SLL and the highest gain which is 5dB greater than that of the UC_2 based RA with d_c= λ and 1dB greater than that of the UC_2 based RA with $d_c = 0.3\lambda$.

6.3. F/D Ratio

The feeder position and orientation are analytically calculated to produce a 10dB taper of the RA panel [3], maximizing the focal length leads to maximize the array BW and minimizes the SLL with trading of spill over and tapper efficiency. Where F is the focal length (the distance between the center of the feeder to the center of the array surface) and D is the RA surface diameter[2].UC_2 based RA is designed at $F/D = 0.8$, $F/D = 1$, and $F/D = 1.5$. Table 6 shows that $F/D = 1$ gives the highest performance in gain and SLL with at least $1dB$ increase in both gain and SLL compared to the other F/D ratios.

Table 7: Comparison of $F/D = 0.8$, $F/D = 1$, and $F/D = 1.5$ UC_2 based RA.

Array	**RA Antenna Parameters**		
	Gain	**HPBW**	**SLL**
UC_2 RA with F/D=0.8	15.2	19.1°	-4
UC_2RA with F/D=1	16.5	13.6°	-5.7
UC_2 RA with F/D=1.5	14	13.1°	-3.7

8. Comparison With Related Work

Related work in RA antenna design (NSL: Number of substrate Layers, FBW: Fractional Bandwidth).

Table 8

Ref	**Related RA Work Results**				
	Type of element	**NSL**	**Element size(λ)**	**Freq.(GHz)**	**FBW**
[5]	Double circular rings	2	0.5	5	37%
[7]	Stacked patches	2	0.56	12	16.7%(1.5dB drop)
[8]	Stacked patches	3	0.56	12	10% (0.5dB drop)
[9]	Patch Loaded With Slot	1	0.7	12.5	4%
[10]	Coupled Structures	1	0.55	35	4.8% (3dB drop)
[11]	3 Parallel Dipoles	1	0.5	300	13%
[12]	Double Cross Rings	1	0.44	22	10% (1dB drop)
[13]	split-slotted-dipole	2	0.45	5.4	21%
This Work	Unified unit cell RA	1	0.5	6	43%

9. Conclusion

In this paper, a RA antenna is introduced for Chipless RFID readers. A high gain pencil beam proposed RA antenna is used to increase the reading range and improve the tag detection. Some considerations are exploited to enhance the operating BW , minimize losses and simplify the design. The simulation results shows a FBW of the UWB RA antenna equals 43% satisfies Chipless RFID reader applications. The radiated beam is 14.9° HPBW three time narrower the feeder beam and covers all the feeder W , 16.3dBi gain and -7.4dB SLL.

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