Reflectarray Antennas

Contents

List of Figures

1 Introduction

As its name reflectarray inherits its features from both phased arrays and reflectors. Reflectarray consists of an array of radiating elements on a flat reflecting surface and a primary radiator, illuminating feed, that illuminates the elements, as shown in Figure 1 [24]. The elements on the reflecting surface are designed to re-radiate the incident field from radiating feed or multi-feeding radiators, located in free space to form planar phase front. This is similar to the concept of parabolic reflector operation when its feed located at focal point. Constituent elements of reflectarray antennas (e.g. waveguides, dipoles, microstrip patches or rings) are placed in certain lattice to imitate the operation of phased array. Phased array employ feeding

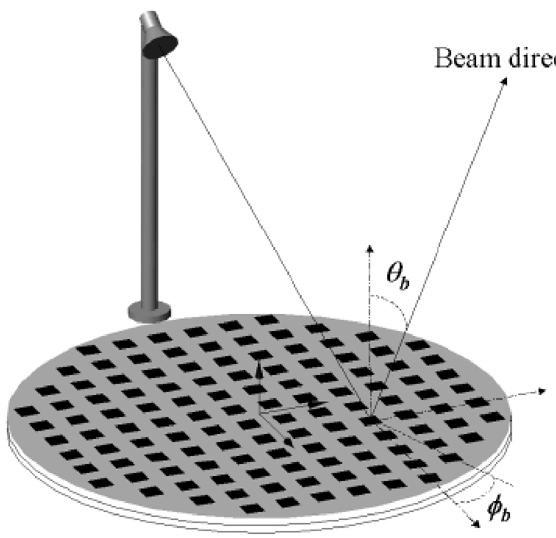
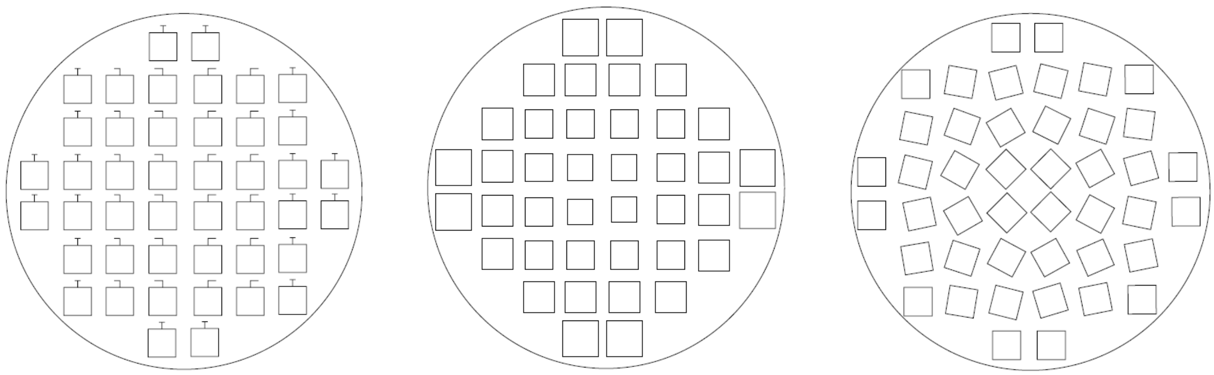


Figure 1: Reflectarray Antennas

network to excite the elements but in reflectarray free space used as transmission line between the source, or feed, and the elements. The planar wave-front can be achieved by adjusting geometrical parameters of reflectarray elements. Phase transformation is the vital function of a reflectarray. Analogous to center fed-parabolic reflector, reflectarray antenna performs spherical to planar phase transformation. In fact, there are different methods to achieve the desired transformation.

One method is to load microstrip patches with different length phase delay stubs, as shown in Figure 2a. These delay lines are used to compensate the phases due to different path lengths from the feed [17][6]. The phase shift produced by delay lines is proportional to the double of its length.One of drawbacks of this method that delay lines require accommodation for those stubs with length up to $\lambda/2$,[23]. Hence, The tuning stubs are bent produce spurious radiation and contribute dissipative losses[9]. Another method is by changing element's dimensions, e.g. patches of variable-sizes, rings, or dipoles of variable lengths, Figure 2b. So, elements will have different impedances and will produce different phases [22]. Analogous to spiraphase array, the third method is arisen by rotating patches[7][11], as shown in Figure 2c.



(a) Variable-length stubs (b) Variable-size patches (c) Rotating

Figure 2: Phasing unit cell methods

Now, let's summarize the most advantages of reflectarray vs reflectors and phased array antennas. Firstly, the absence of feeding network, as in phased array, reduces the losses and complexity of the design of reflectarray. In addition, reflectarray could be made to be active by connecting amplifiers to radiating elements[13]. Secondly, due to rapid development of microstrip antenna technology, the reflectarray replaced reflectors. The low-profile reflectarray make it alternative he bulky and curvy surface of reflectors. Thirdly, Reflectarray is a good candidate for beam-scanning application.

1.1 Development History of Reflectarray antenna

In this section we briefly state the development history of reflectarray.

1.1.1 Waveguide Reflectarray

The concept of reflectarray was firstly conceived in 1963 by D Berry, R Malech and W Kennedy [3]. Authors in [3] proposed that radiation characteristics can easily achieved by synthesized the surface impedance. Figure 3 shows the first reflectarray experiment. They constructed 4×26 waveguides array illuminated by an offset feed radiators, with a separation from center to center by 0.6λ. Different radiation patterns can be obtained by adjusting the length of either Short-ended or open-ended waveguide. Wireless systems were working at low microwave frequencies resulted in heavy and bulky waveguides. Thus, reflectarray concept was not continued until a long period.

1.1.2 Spiralphase Reflectarray

Spiralphase reflectarray was firstly introduced in the mid of 1970s, [19]. It used 4-arm spiral elements and switching, as shown in Figure 4. this enabled the reflectarray to scan its main beam electronically[26]. This is possible since spiral arms are circularly polarized. And by rotating the radiating elements by

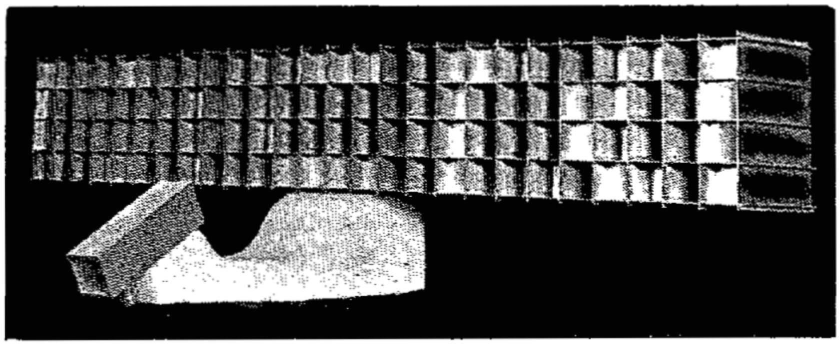


Figure 3: Wave-guide reflectarray model [3]

certain amount, its propagating electrical phase will also change proportional the amount of rotation. However,the spiralphase reflectarray model was relatively bulky and heavy due large electronic components and the thickness of spiral cavity, $\lambda/4$ depth. In addition, its aperture efficiency was poor.Thus, this work was not continued.

Figure 4: 4-arm spiral elements reflectarray[26]

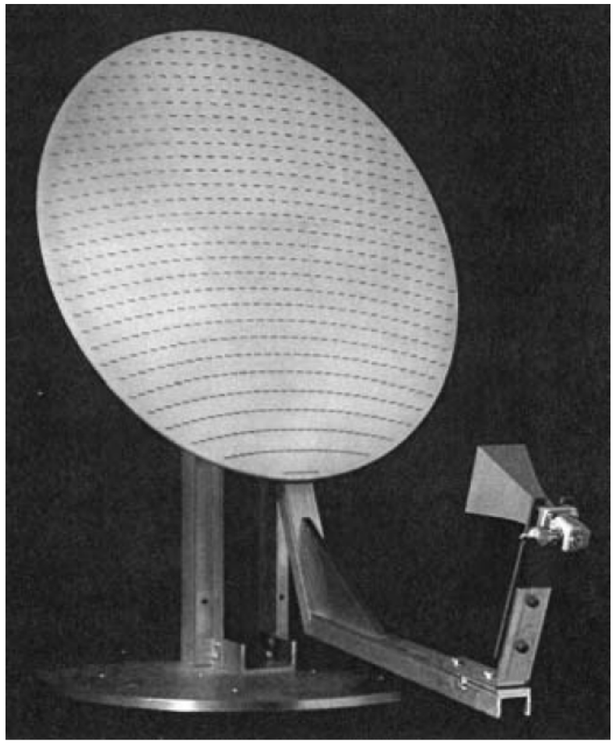


Figure 5: Printed dipoles reflectarray

1.1.3 Microstrip Reflectarray

Printable microstrip antennas technology allow reflectarray to develop. The first implementation of microstrip elements for reflectarray was In 1978 [26]. Infinite array approach was used to design microstrip reflectarray in purpose to achieve light-weight and small-size antenna. One form of printed reflectarray used identical patches with variable-length delay lines [27, 10]. These phase delay lines were used to compensate for the phase due to different paths.Length of the lines are on the order of half-wavelength long or less. Another form of printed reflectarray used different dipole lengths which resulted in different scattering impedances, which then provide the different phases needed to compensate for the different path-length delays. This method used to form a frequency scanned grating-reflector antenna with an offset feed. Similarly, microstrip patches with variable patch sizes were used.

2 Design Guidelines of Reflectarray

Reflectarray antennas consists a quasi-periodic set of unit cell elements in a regular lattice. The operation of reflectarray antenna can be explained by considering it in transmitting mode illuminated by feed horn antenna radiator. And assuming radiating elements in the far-field region of the feed. Elements are printed on a substrate, thickness h and relative permittivity ϵ_r. As we mentioned, the function of reflectarray, in its most basic form, is phase-front transformation, from spherical to planar phase front, by adjusting dimensions of elements, Figure 6a. For example, the generated phase of element located at A, ϕ_A must satisfy [24] :

$$k_\circ \times (FA - FO) - \phi_A = 2n\pi \tag{1}$$

where, $k_\circ$ is the propagation constant , n an integer.

Satisfying (1) ensure that the phase difference between any element and the element located at O is $2n\pi$. n is used to keep the phase generated by the patch between 0° and 360°.

The same procedure used in designing scanned beam reflectarray, as shown in Figure 6b. The required phase contribution at each element to direct the main beam in r_{out} direction is given by [24] :

$$k_\circ \times (FA - \vec{FO}.\hat{r}_{out}) - \phi_A = 2n\pi \tag{2}$$

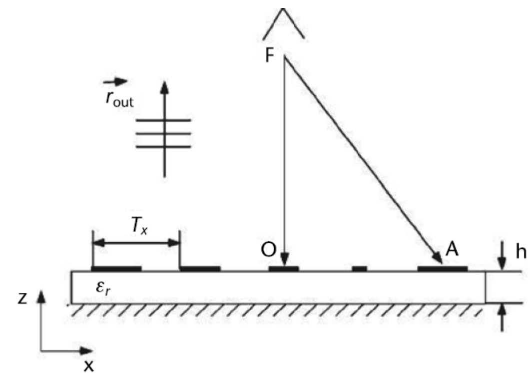
Eq.s (1) and (2) contain k_o which corresponds to the design operating frequency of reflectarray. Thus, the desired phase shift is constrained by the design frequency. Therefore, any deviation from the design operating frequency leads to a phase error. This error contribute loss in gain performance. Figure 6d shows the variation of phase as function of patch length. The shape of phase-length curve add restrictions on reflectarray design [4]. For instance, as the S-shape has steeper slope means any fabrication error leads to phase error and changing in radiation characteristics.

To avoid grating lobes in design of reflectarray, the element spacing, center-to-center) should be less than half wave length. For example, in Figure 6c to avoid emergence of grating lobes, T_x and T_y are set to be less than ($\lambda/2$).

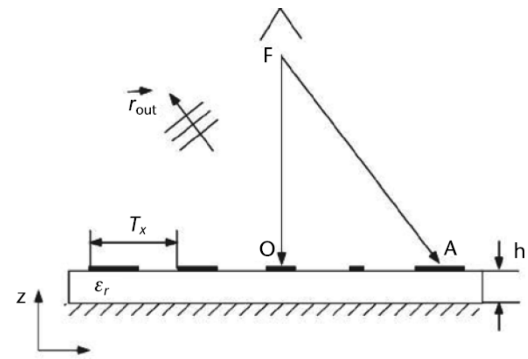
Design Procedures

Reflectarray design can be summarized in the following steps:

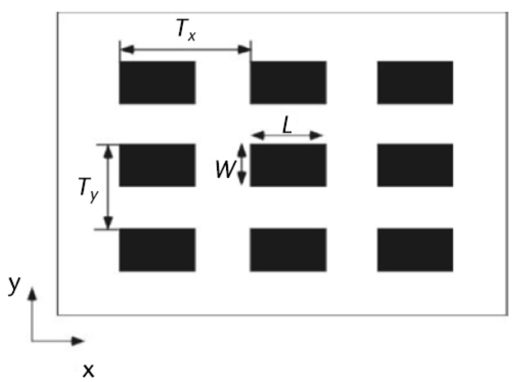
1. Select the substrate, ϵ_r based on many factors, e.g. frequency, cost, bandwidth.
2. Then numerical method utilized to calculate the amplitude and phase of scattered field from that specific region, the method of moment (MOM).
3. Element's dimensions are calculated from Eq.s (1) and (2) in interpolation of data from step 2.
4. The pattern of reflectarray is calculated using antenna theory.
5. Efficiencies, directivity and the gain are computed.



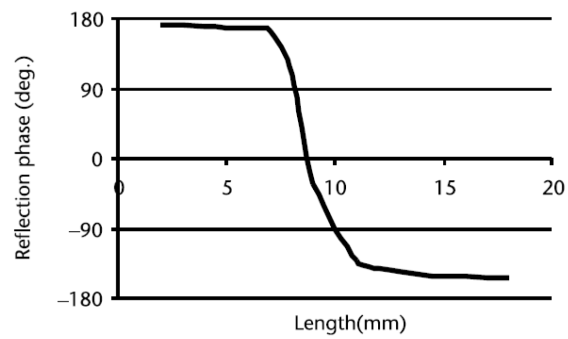
(a) Broadside beam



(b) Scanned-beam



(c) top view of 2D patch reflectarray



(d) Typical S-shape of phase-length relation in designing reflectarray

Figure 6: Center-fed reflectarray antenna and phase -length curve

3 Literature Review

3.1 Types of Reflectarray

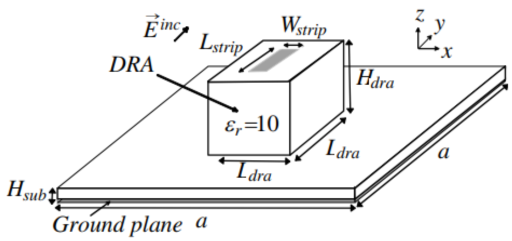
The nature and type of reflectarray elements determine the performance of the array. In general, we can classify reflectarray, based on the materials used, into four groups: Metallic, Dielectric, Waveguide and microstrip reflectarray. Authors in [12] proposed array configuration for low-loss applications. The unit cell is based on Dielectric Resonator antenna (DRA) Figure 7a.A thin film of silver is printed on DRA as a tuning element to control the phase. A 24×24 DRA elements reflectarray was designed to operate on 30GHz. This model provides high radiation efficiency, improve bandwidth, and small mutual coupling. The maximum gain obtained is about 28 dBi and 5.6% bandwidth. However, DRA antennas have shortcomings. For example, at mm-wave, the mechanical process to locate the unit cell elements at the exact location is relatively complicated. In addition, it's also difficult to shape the element[1].

Authors in [1] new approach to reduce these drawbacks of DRA. The idea is to use single-layer perforated substrate. Control the required phase by drilling a fixed number of holes on each unit cell. The over all dielectric constant was changed due to air-hole substrate. So, the phase be adjusted by changing the number of holes per cell and the distribution of holes. 29×29 elements reflectarray provides a maximum gain of 35dBi.

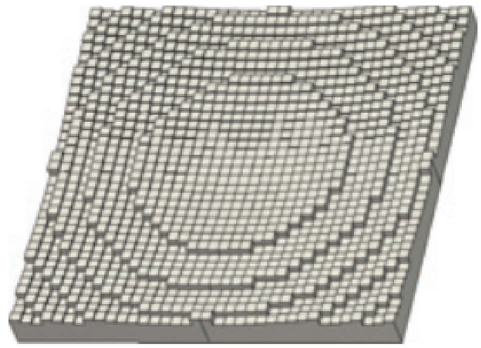
To design a reflectarray of efficiency more than 40% at higher frequency is considered a severe problem [14]. The reason is backed to the resonance phenomenon. Since, phase nonlinearly change against the element size. Coupling multiple resonant elements, or changing the substrate material help reducing the sensitivity to the phase variation. The proposed unit cell is a variable-height square conductor, Figure 7b. Unlike other unit cell elements, The reflection phase vs element size curve is linear. A maximum gain of 36×36 reflectarray was 36dBi its efficiency was 50%.

A metal-only reflectarray antenna using slot-type elements is presented. The design consists of two properly separated stainless sheets without any dielectric substrate. First, the performances of a conventional microstrip patch element and its complementary slot design are studied and compared. Next, a new kind of slot element for metal-only reflectarrays is proposed, and its radiation characteristics are investigated. Finally, a prototype operated at 12.5 GHz is designed, fabricated, and tested for verification purpose.

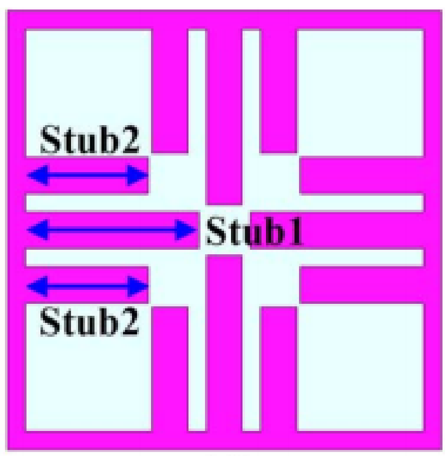
The dielectric substrate is eliminated in[2]. Unit cell is a metal-only slot element. A piece of steel sheet is used as the ground plane and element is etched on another stainless sheet. Elements are printed on a circular aperture od diameter 516 mm. the total number of elements is 1380 slot elements. The incident angle of $25°$ was set to avoid feed blockage and optimize the aperture efficiency. The maximum gain achieved is 32.5dB. The advantage of using metal-only reflectarray is reducing substrate cost.



(a) 3D model of DRA unit cell



(b) Non-resonant conductor reflectarray



(c) metal-only slot element

Figure 7: Types of Unit cell elements

3.2 Bandwidth issues

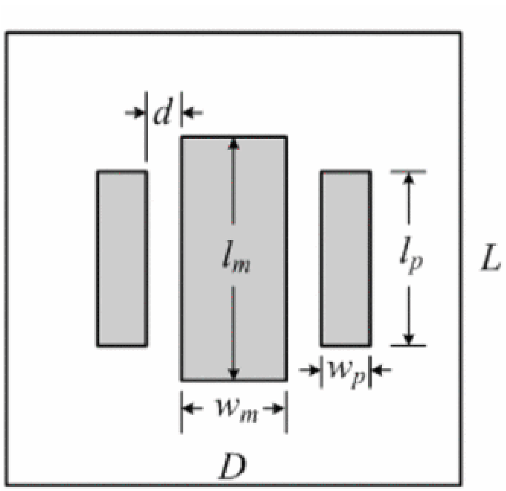
The bandwidth of reflectarray can be seen as two parts: unit cell bandwidth and full reflectarray bandwidth[20]. In general, reflectarray antennas are considered a narrow bandwidth.There are two factors that govern the limitation of reflectarray bandwidth. Firstly, the narrow bandwidth performance of the unit cell, or radiating elements.This is a dominant factor on moderate size reflectarray ($< 20\lambda$) and ($f/D > 0.5$).the The second factor is arise from the variety of path lengths between elements and feed radiator. This is called the differential phase delay [24]. the effect of no-constant phase delay is severe for large arrays f/D is very small[20]. Different techniques are used to encounter bandwidth issue of reflectarray.

Authors in [15] address a solution for narrow bandwidth of the unit cell. The unit cell microstrip reflectarray consists of main dipole and two parasitic dipoles, Figure 8a. This introduce two degrees of freedom: the ratio of lengths of main to parasitic dipoles and the distance between dipoles. Parasitics dipoles are used to modify scattering impedance of the element. But the design of the reflectarray become more complex greatly.

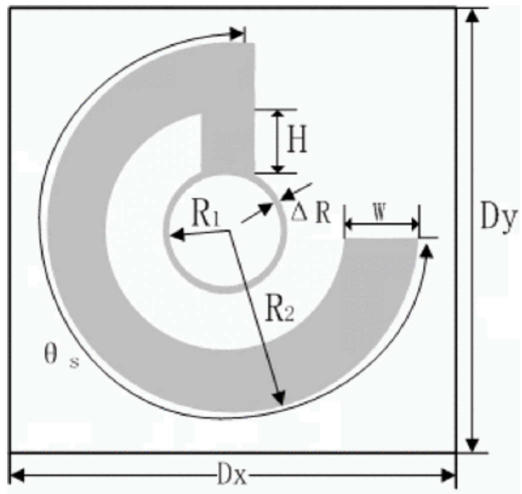
An open-circuited stub attached to circular ring was used to obtain linear phase characteristics Figure 8b, [16]. The introduced delay for the reflected field results in a smooth curve and increase bandwidth. A conical horn feed is used in this design. They manually optimized the horn dimensions to obtain constant gain and radiation.

Author in [21] proposed reflectarray bandwidth improvement method by using artificial impedance. This technique shows bandwidth improvement by 20% for reflectarray of 10λ in diameter. The enhancement of bandwidth is achieved by using small electrically grid spacing, reduce the period of antenna $< \lambda/2$. And using element size less than resonant size, unlike conventional microstrip reflectarray. Differential phase delays effect vanished with no complexity added to array design.

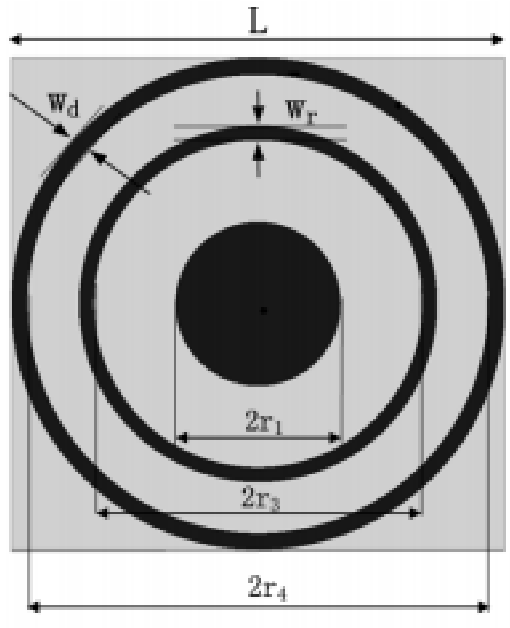
Phoenix unit cell was proposed in [25] to achieve $360°$ swing and enhance bandwidth. The unit cell is composed of circular patch with concentric circular rings, Figure 8c. 25×25 Phoenix reflectarray provides up to 29% improvement in bandwidth. The main reason behind this performance was thick substrate gap air filled. One of the drawbacks of this techniques is their complexity design at high frequency.



(a) Parasitic dipoles



(b) Element with open-end stub



(c) Phoenix unit cell [25]

Figure 8: Wide band reflectarray elements

4 Design Examples

4.1 Reflectarray with variable slots on ground plane [5]:

A configuration of reflectarray based on planar coupled is presented in [5]. A multilayer of printed patches are implemented in this proposed configuration. The radiating elements are patches of identical size on the top layer and a slot of variable length in the ground plane, as shown in Figure 9. The element phasing is determined by Eq.s (1) and (2). To obtain the required phase-shift the length of ground slots is adjusting. The slots on the ground plane act as an inductive load and its inductance depend on the length. Design parameters are summarized in the table1:

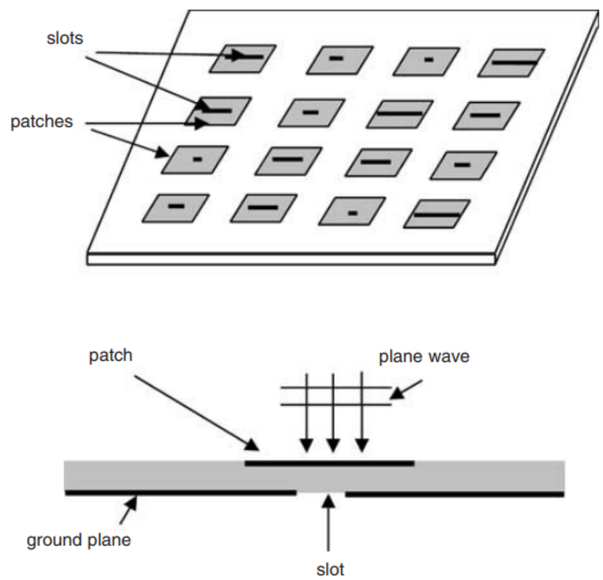
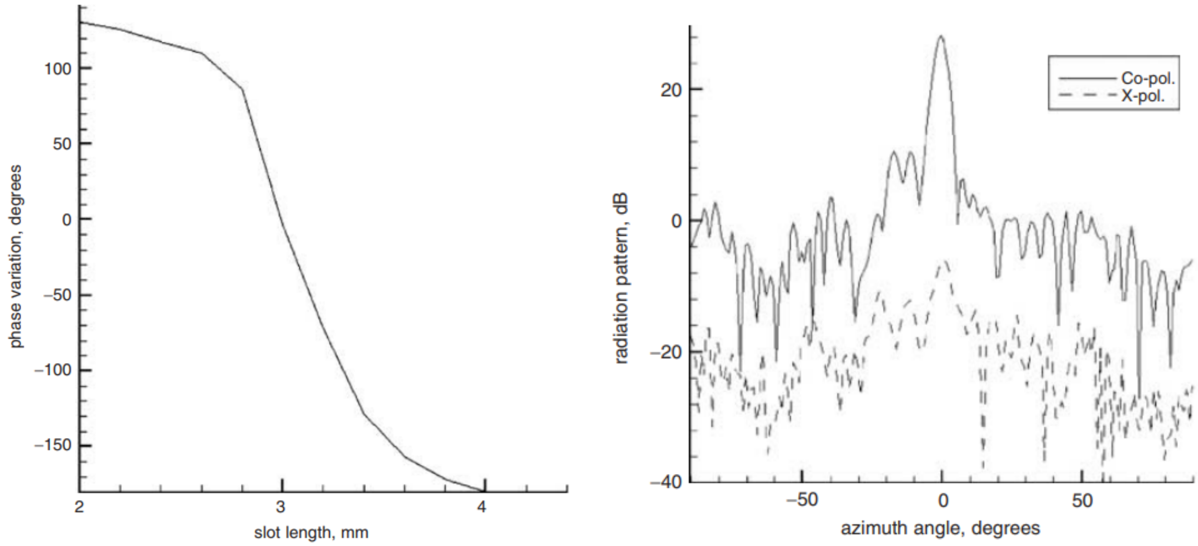


Figure 9: Microstrip reflectarray of identical patches and variable ground slots

Table 1: Design Parameters

Prameter	Value
Operating frequency	26 GHz
Unit cell size	6mm $\times$ 6mm
substrate thickness	0.02
ϵ_r	3
Patch size	3.2 mm $\times$ 2.3 mm
f/D	0.9
Slot width	$\lambda/20$
Feed	Center

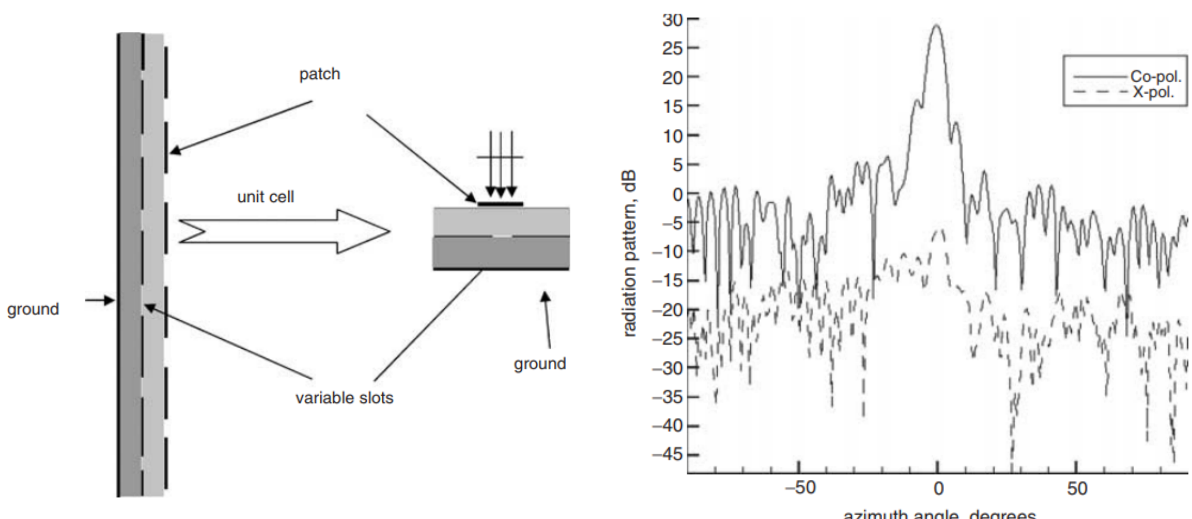
An infinite periodic antenna has been assumed. The maximum gain achieved is 28.65 dB. Figure 10a shows the phase shift versus the slot length curve. Which exhibits 340° swing.



(a) Phase vs slot length

(b) H-plane radiation

Figure 10: single-layer patch-slot reflectarray



(a) Schematic of 2 -layer reflectarray with variable slots

(b) H-plane radiation

Figure 11: 2-layer patch-slot reflectarray

The slot beneath the unit cell, shown in Figure 9, allows leakage of the power. So, A new model of reflectarray is proposed. A reflectarray with 2-layer and variable slot in the middle. The maximum gain is 29 dB and it achieved at 30 GHz.

4.2 A Single-Layer Broadband Reflectarray Antenna by Using Quasi-spiral Phase Delay Line[8]

As mentioned before, reflectarray is a narrow bandwidth antenna. Several methods have been used to improve the its bandwidth performance. Authors proposed a wideband single-layer unit cell, Figure 12. As shown, the element is composed of three coupled circular rings. The outer ring is connected to four quasi-spiral delay lines to provide the required phase shift.

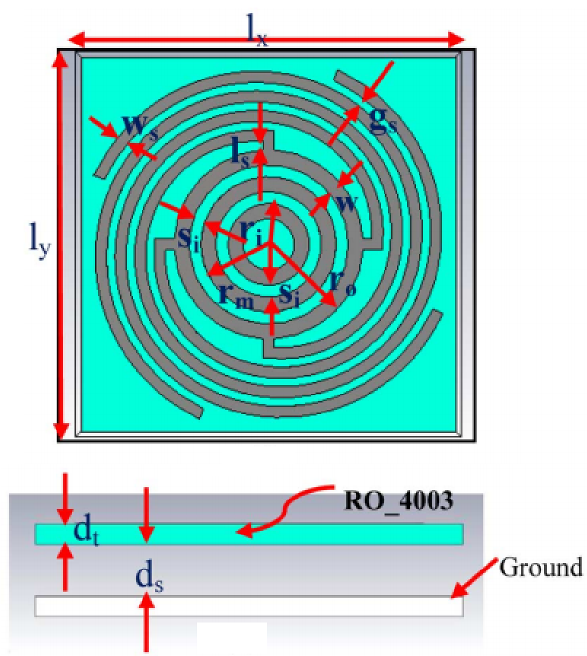
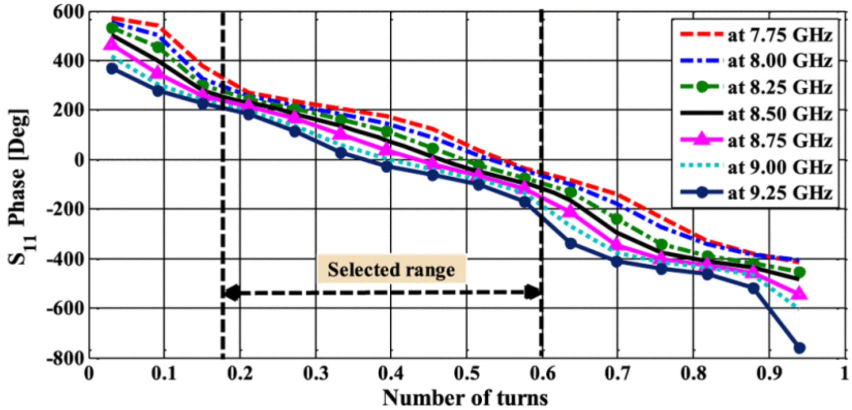


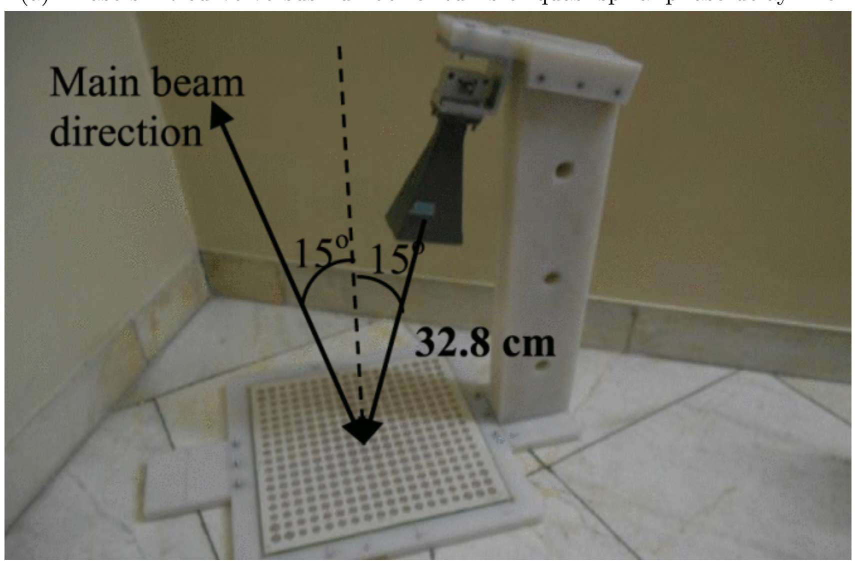
Figure 12: Proposed Unit Cell

The wider phase range is obtained by increasing the length of the delay line. Thus, the smaller outer ring resonance dimension the wider the phase. The value of g_s, w_s and l_s govern matching between outer circular ring and the delay lines. They are optimized to get the best matching. w and s_i are optimized to obtain linear phase variation. The design parameters are: $l_x = l_y = 15$mm, w_s=0.45 mm, g_s =0.34 mm, l_s =0.32 mm, w=0.6 mm, r_o=3.78 mm, r_m=2.7 mm, r_i=1.62 mm, g_r=0.48 mm, d_t=0.8 mm, d_s=2 mm, operation frequency is 28GHz, $f/D = 1.21$ and the unit cell size is $0.425\lambda \times 0.425\lambda$. The phase vs number of quasi-spiral turns is shown in 13a. The phase range can be up to 1000°.

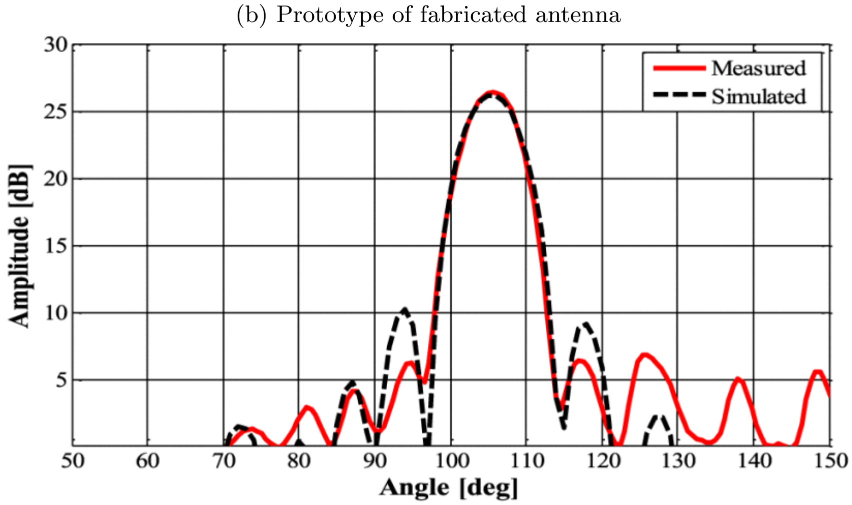
This design shows a similar phase response for all polarizations of incident wave; TE, TM, and circularly polarized (CP). The main beam is at 15°from the broadside, as shown in fi The maximum gain is 26.4 dB at 8.5 GHz. The measured cross-polarization −25 dB and SLL is −20 dB.



(a) Phase-shift curve versus number of turns of quasi-spiral phase delay line



(b) Prototype of fabricated antenna



(c) Radiation Pattern

Figure 13: Reflectarray using Quasi-spiral Phase Delay Line

4.3 Single-feed multi-beam reflectarray antennas [18]

Recently reflectarray arrays have received an attention in satellite communications, contoured beam space antennas, radars and commercial applications. In general, the conventional parabolic reflectors are bulky and expensive due to the curved reflecting surfaces[1]. In contrast, adjusting the phase shift of individual element in the reflectarray gives advantages. Contoured beam can be achieved in the reflectarray without any additional cost. Similarly multi-beam performance can be realized directly by correcting the phase shift of the elements. In this work, Authors proposed multi-beam reflectarray, single-feed designs.

Beam Superposition Method: To generate multiple beams, let say N beams, the tangential E_{filed} on the array surface can be written as:

$$E_R(x_i, y_i) = \sum_{n=1}^{N} \mathrm{A}_n(x_i, y_i) e^{j\phi_n(x_i,y_i)} = \mathrm{A}(x_i, y_i) \sum_{n=1}^{N} e^{j\phi_n(x_i,y_i)} \tag{3}$$

where: θ_n and φ_n correspond to the direction of n^{th} Beam. (x_i, y_i) is the position of each element on surface the reflectarray. A_n and ϕ_n are the amplitude and phase on each element. the required phase for each element is:

$$\phi_n(x_i, y_i) = -k_0 \sin\theta_n (\cos\varphi_n x_i + \sin\varphi_n y_i) \tag{4}$$

The required field distribution on the reflectarray surface can be obtained by direct superposition of the aperture fields associated with each individual beam. The phase distribution which corresponds to the multi-beam phasing elements mentioned above. Drawback of this method is mismatching between the amplitude distribution by the feed and the amplitude required on multi-beam performance.This will increase the side lobe level and reduce antenna efficiency.

Alternating Projection Method: This approach address the amplitude error effect in the direct superposition method. It is considered as a general array synthesis problem. Radiation synthesis of reflectarray is restricted since the amplitude of each reflectarray element is determined by the feed properties and element location. Thus, Radiation synthesis of multi-beam reflectarray performance is seen as a phase only synthesis approach. The alternating projection method has been applied successfully to the phase synthesis of reflectarrays. This approach is an iterative process to search for the intersection between two sets, i.e. the required pattern mask and the phase of the reflectarray elements. Although, this method can be applied for large arrays but it requires time for the computations. This approach adjust elemet phase to satisfy required mask pattern. The general mask can be described as:

$$M \equiv \{F : M_L(u, v) \leq |F(u, v)| \leq M_U(u, v)\} \tag{5}$$

where F is the far-field radiation, M_l and M_U is the lower and the upper bound of radiation. u, v angular positions. the radiation is modified in each iteration to meet Eq(5). **The Design of quad-beam**:

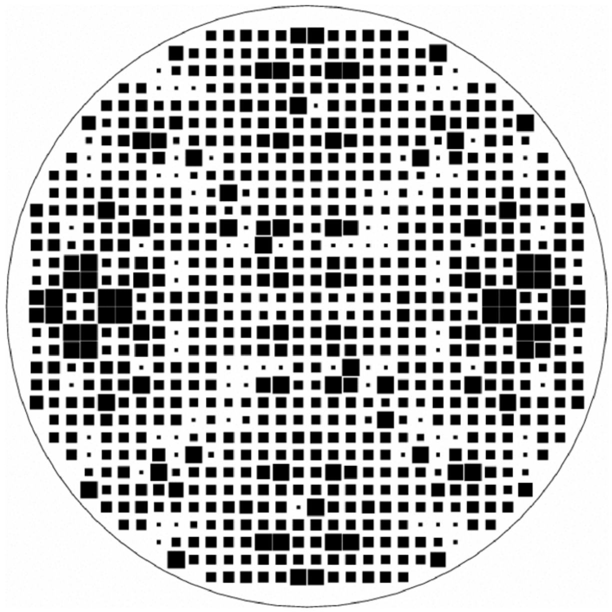
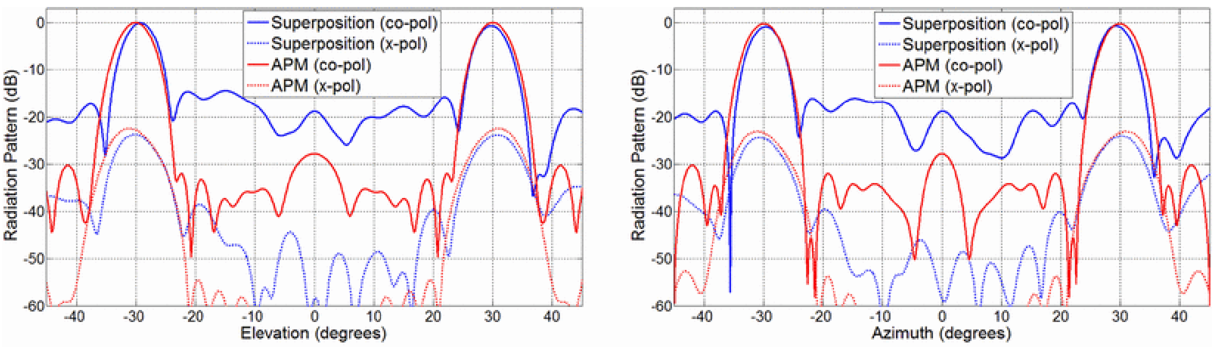
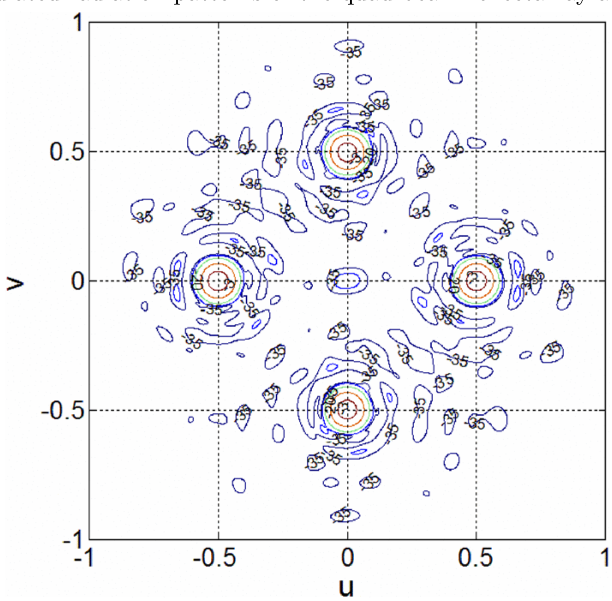


Figure 14: Quad-beam reflectarray.

Authors designed a quad-beam Ka-band reflectarray. The aperture of the array is circular with diameter of 17λ. The phasing elements used in the design are variable-size patches, as shown in Figure 14. The design of each element phase to give four beams at $\theta = 30°$ and $\phi_1 = 0$, $\phi_2 = 90$, $\phi_2 = 180$ and $\phi_1 = 270$, Figure 15b. The calculated radiations using both methods are plotted in Figure 15a. Radiation using superposition method provides high SLL and the main beam direction is shifted.



(a) Calculated radiation patterns of the quad-beam reflectarray at 32 GHz



(b) Co-polarized radiation pattern of the quad-beam reflectarray

Figure 15

5 Conclusion

Reflectarray antennas combine features of phased arrays and reflectors. The direction of the main beam of the antenna is directed by adjusting the phase of each radiating elements. Different methods are applied to control the radiation characteristics. Reflectarray has advantages over reflectors and phased array. The main drawback of reflectarray is limited bandwidth. Several approaches applied to enhance the bandwidth performance. Reflectarray can be used to generate multi-beam similar to multi-fed reflector.

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