Design of Reflecarray With Cosecant Squared Radiation Pattern in X-band

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***Abstract*— In this work, an X-band center-fed microstrip reflectarray antenna with cosecant squared beam is designed in 10 GHz using circular patch with an annular ring on a single-layer substrate. The required phase shift in X-band is obtained by varying the radii of annular ring and circular patch. A uniform amplitude and non-linear phase distribution is used in synthesis technique. About 19.4 dBi gain is obtained.**

Keywords- reflectarray; non-linear phase; shaped beam; cosecant squared

I. INTRODUCTION

Microstrip reflectarray antennas are flat reflectors made of one or multiple layers of microstrip patch arrays. They combine the numerous of both printed phase array and parabolic reflector to create a new generation of high-gain antennas [1]. Comparing to phased arrays, the reflectarray eliminates the complexity and losses of the feeding network and exhibits a higher efficiency [2]. The flat surface, low weight, capability of beam shaping and scanning, and low manufacturing cost make microstrip reflectarray antennas a suitable replacement for the conventional parabolic reflector antennas in wireless communication and satellite systems. They present less distortion and cross-polarization at the cost of narrower bandwidth [3]. A reflectarray antennas are made up of array of unit cells which affected on general characteristics of reflectarray. The broadband unit cell is more and more linear behavior improves general characteristics of the reflectarray antennas. There are several ways to increasing the linear-phase response and the bandwidth of unit cell. With increasing range of linear-phase response, sensitivity to fabrication tolerance will reduce [4]. Multilayer structures can improve linear phase response [5]. Other alternatives have been proposed to control and improve the phase distribution on a reflectarray, such as using phase delay lines [6], [7], tapering the resonant length of the patches [8], [9], using phase shifters [10], or diode as variable capacitors [11]. Another type of reflectarray is active reflectarray [10] that includes amplifiers, circulators, phase shifters, and diode varactor. By using active devices, Pattern is similar to the desired result more easily but the manufacture of the reflectarray is more complicated. For millimeter wave applications in which the phase control is achieved by varying the capacity of diodes connected to the radiating patches, a reflectarray in monolithic technology was proposed in [11]. Nowadays, the monolithic technology is limited to very special applications such as small size antennas for very high frequencies [2]. By varying the resonant length of the patches a progressive phase-shift of the reflected field is obtained simply [8], [9]. This technique allows simple manufacture based on photo-etch procedures. It can be used for large reflectors at microwave and millimeter-wave frequencies and it produces lower cross-polarization levels than the stubs of different length attached to the radiating patches [2]. Using very low loss materials, such as foam or honeycomb, the efficiency of the reflectarray can be similar to that of reflector [2]. Two basic methods for analysis of the reflectarray antenna are studied here. In the first method, the reflectarray antenna radiation pattern is obtained using conventional array summation with proper element excitation. In the second method, the radiation pattern of the antenna is obtained using the tangential fields on the reflectarray's aperture. The first method is array-theory. Conventional array theory can be implemented to obtain the far-field radiation pattern of the reflectarray antenna. The radiation pattern of a two-dimensional planner array with $M \times N$ elements can be calculated as [1]

$$\vec{\mathrm{E}}(\hat{u}) = \sum_{m=1}^{\mathrm{M}} \sum_{n=1}^{\mathrm{N}} \vec{\mathrm{A}}_{mn}(\hat{u}).\vec{\mathrm{I}}(\vec{r}_{mn}), \qquad (1)$$
$$\hat{u} = \hat{x}\sin\theta\cos\phi + \hat{y}\sin\theta\sin\Phi + \hat{z}\cos\theta,$$

Where $\vec{\mathrm{A}}$ is the element-pattern vector function, $\vec{\mathrm{I}}$ is the element-excitation vector function, and $\vec{r}_{mn}$ is the position vector of the mnth element [12]. In Fig. 1 the geometry of the reflectarray system is shown. Simplicity of the formulation and program development and shorter computational time are advantages of the former method and limitation of the former method is ignoring cross-polarization. The second method is aperture-field. In this method the radiation pattern of the reflectarray is calculated from the aperture fields using the equivalent principle. First of all, the incident fields on the aperture's surface are obtained while considering the polarization of the feed horn. The radiation pattern of an ideal feed horn [13] with a fixed phase center is given by

$$\mathrm{E}^{Fx}(\theta,\phi)=\mathrm{A}_0\left[\hat{\theta}C_{\mathrm{E}}(\theta)\cos\phi-\hat{\phi}C_H(\theta)\sin\phi\right]\frac{e^{-jkr}}{r} \quad (2)$$

For x polarization, and

$$\mathrm{E}^{Fy}(\theta,\phi)=\mathrm{A}_0\left[\hat{\theta}C_{\mathrm{E}}(\theta)\sin\phi+\hat{\phi}C_H(\theta)\cos\phi\right]\frac{e^{-jkr}}{r} \quad (3)$$

For y polarization.

Where A_0 is a complex constant, C_E and C_H are the E- and H-plane radiation patterns of the horn antenna, respectively. One important approximation in this approach is that the tangential currents are assumed to be constant within each element, so the integration over the aperture surface is approximated by a double summation. The advantage of this approach is accurate modeling of feed and element polarization and disadvantages of this approach are complicated formulation and program development and increased computational time [1].

In this article the principle plane pattern is designed to be proportional to the squared of the cosecant of the elevation angle, the received signal form a target flying at constant height has a strength independent of range such patterns have obvious application in target-seeking radar systems. For the same basic reason they are also useful in ground-mapping radars and airport beacons [14]. A shaped-beam reflectarray providing a cosecant squared pattern was first reported in 1993[15], [16]. In a recent work [17], a reflectarray antenna has been demonstrated for transmit (TX: 11.4 GHz -12.8 GHz) and received (RX: 13.7GHz- 14.5GHz) frequency bands using a single layer of metallization made of multi open loop elements. In [16] a shaped beam reflectarray antenna with unit cell made up of three parallel dipoles printed on the same side of a dielectric substrate has been designed, manufactured and tested. It is illuminated orthogonally by a plane wave, and provides a 60 sector in azimuth with a squared cosecant shaped in elevation in a 10% bandwidth In the previous works, so as to obtain cosecant squared pattern some approaches have been used such as using the whole surface of structure like shaped reflector antennas, or simultaneously controlling amplitude and phase of unit cells in reflectarray antennas. In this work cosecant squared pattern is obtained just by managing phase of unit cells.

II. II. Unit Cell Design

For the design of the reflectarray, any possible value of phase-shift must be implemented by varying one parameter in the unit cell, such as patch size, stub length, or patch rotation angle. One of the most important parts of the reflectarray analysis and design is the accurate characterization of the reflectarray element, accuracy predict the phase-shift and dissipative losses for each polarization of the field [18]. The unit cell is assumed to be one element of an infinite two-dimensional periodic array. The reflectarray unit cell with dimensions are shown in Fig. 2(a) and Fig. 2(b).

In the design stage, the dimensions of the annular ring and circular patch unit cell are varied until both the linear phase response and the required phase range at least 360° are obtained. The reflectarray unit cell has a single-layer configuration operates in X-band frequency. For a central frequency of 10 GHz, a 20*20 mm^2 ground plane and substrate with a circular patch and annular ring is obtained. As shown in Fig. 2(b) the inner radius of the annular ring (r), the outer radius of the annular ring (5mm) and the radius of the circular patch (r-0.4mm), are adjusted to obtain the reflection phases.

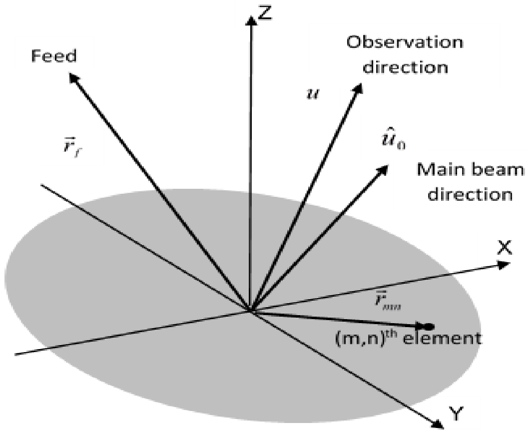
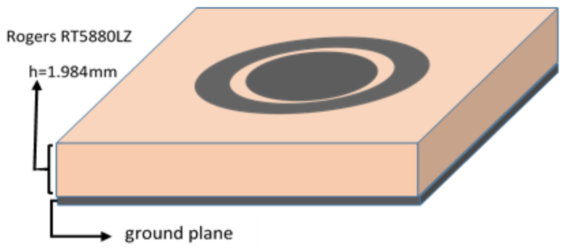
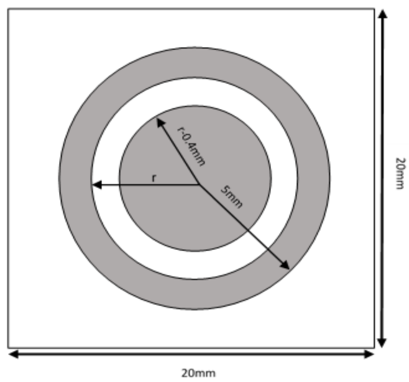


Figure 1. Schematic and geometry of the single layer unit cell



(a)



(b)

Figure 2. Schematic and geometry of the single layer unit cell

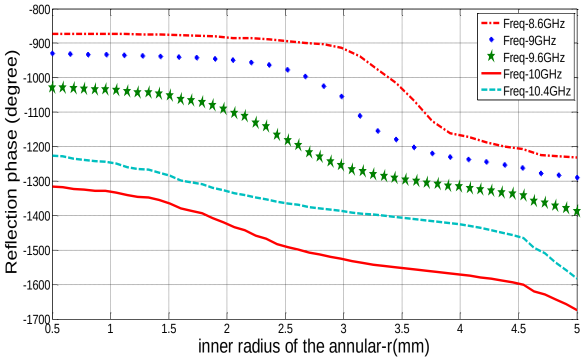


Figure 3. Phase response versus radius for different frequencies

The substrate used for this unit cell was Rogers RT5880LZ with ε_r=1.96, μ=1 and h=1.984mm. This substrate is placed 1.984 mm above the ground plane and circular patch with annular ring is placed above the substrate. The reflection phase responses of the single layer elements as a function of inner radius of the annular ring(r) for different frequencies is shown in Fig. 3. The narrow bandwidth of the reflectarray antennas is their weakness which is due to their narrow bandwidth unit cells. But as it is shown in Fig. 3 the reflected phase of this unit cell in comparision with monolayer unit cell designed in [2] has more linear behavior over wider bandwidth of about 1.8GHz which is compariable with two layer unit cells designed such as [2],[19].

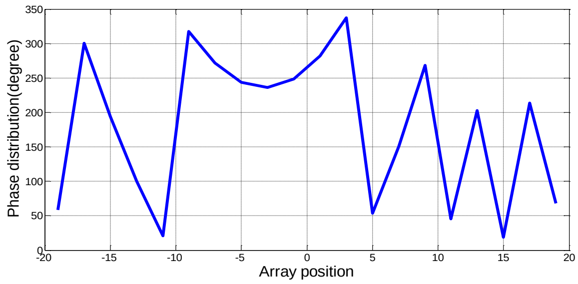


Figure 4. Synthesized phase distribution for X-band 20*1

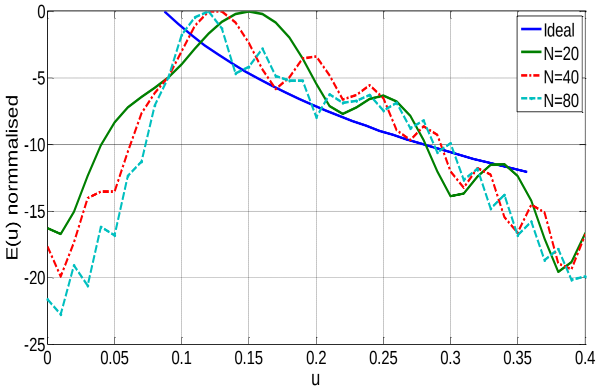


Figure 5. Pattern of linear array for various number of unit cells

III. Beam Synthesis and Array Design

As it mentioned before in the all pervious works, cosecant squared pattern have been obtained either by using the whole surface of structure or simultaneously managing amplitude and phase of unit cells in reflectarray antennas. This work is achieved to cosecant squared pattern with only by controlling the phase of unit cells without caring about amplitudes. Here due to fabrication difficulties, the structure is designed and simulated with 20 unit cells in each column and 21 unit cells in each row. In this section the reflection phase of the reflectarrays are synthesized to fulfill the desired squared cosecant beam pattern in elevation angle. In [20], [21] for the elevation shaped beam a phase-only synthesis technique is applied to obtain the linear phase distributions, for an array with a length of 2L and a wavelength of λ, and the derivative of phase distribution is given as :

$$\Phi'_R = \frac{2\Pi L}{\lambda}\cdot\frac{1}{\frac{1}{u_0}+\left[\frac{1}{u_1}-\frac{1}{u_0}\right]\cdot\frac{\int_{-1}^{x}A^2(x)dx}{\int_{-1}^{1}A^2(x)dx}} \quad (4)$$

Where A(x) is the amplitude distribution, and u_0 , u_1 are used to define the squared cosecant shape. The pattern function can be found by

$$E(u)=\int_{-1}^{1}A(x)\,e^{j(\frac{2\Pi L}{\lambda}ux-\Phi(x))}\,dx \quad (5)$$

Where u=sinθ. To realize shaped beam, a square reflector surface with 400*400mm^2 dimensions is defined. The single layer array has 21*20 elements working at 10 GHz. With predefined u_0=0.0872 and u_1=0.3584 for X-band squared cosecant beam, the sensitized phase distributions is shown in Fig. 4 and the patterns of the linear arrays for different numbers of unit cells are shown in Fig. 5. As it can be seen in Fig.5 by increasing the number of unit cells, error rate will be reduced. After obtaining the linear phase distribution, by applying the following formula, the array phase distribution over the reflectarray surface that is required to produce a collimated beam at broadside direction are computed [18] :

$$\Phi_{mn}=K_0\left(d-\left(x\cos\Phi_b+y\sin\Phi_b\right)\sin\theta_b\right) \quad (6)$$

Where (x,y) are the coordinates of the element m,n to the central point of the feed aperture. The desired beam direction is defined by Φ_b, θ_b which are the spherical coordinates with origins at the center of the array. Here we are interested in the surface phase distribution for broadside radiation, so

$$\Phi_b=\theta_b=0 \quad (7)$$

Once the linear phase distribution for the shaped beam and the surface distribution of the circular array for a broadside beam have been determined, the actual reflectarray phase distribution to shaped squared cosecant beam can be obtained by adding the linear phase distribution onto each row of the array phase distribution. Thus Total phase distribution that required to radiate squared cosecant beam is

$$\Phi_t = \Phi_R + \Phi_{mn} \quad (8)$$

In equation (8), Φ_R is integral of Φ'_R and Φ_t is sum of Φ_R and Φ_{mn}. After the reflection phase required at each reflectarray element has been determined the dimensions of each element have to be adjusted accordingly based on the phase-size relation. The top view of the reflectarray is shown in Fig. 6. The result of the single-layer reflectarray are shown in Fig. 7(a) and Fig. 7(b). It is found that reflectarray can generate a better squared cosecant shaped beam at X-band with increasing the number of elements, which more accurate phase distribution is obtained and requires more computation time and computer memory.

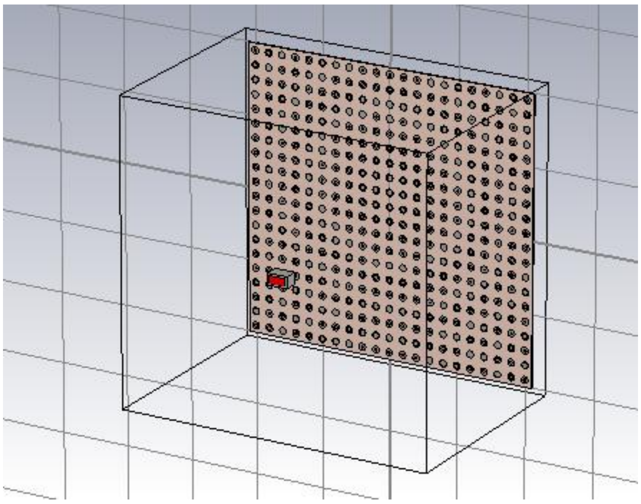
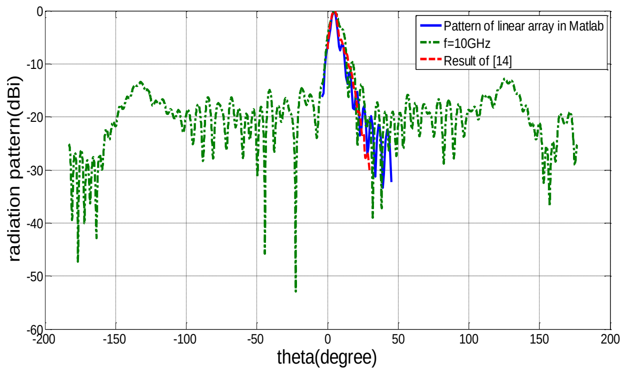
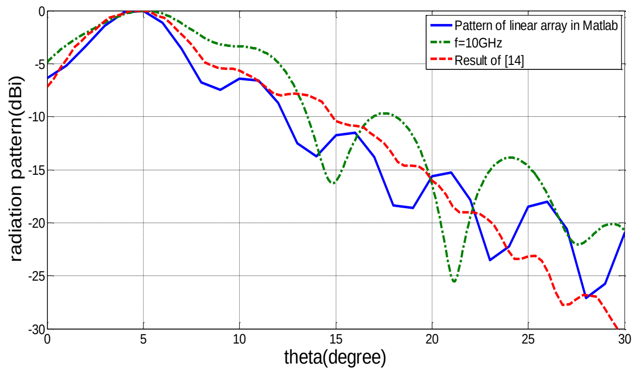


Figure 6. Single layer reflectarray topology.



(a)



(b)

Figure 7. (a)Simulated radiation pattern of the single layerreflect array in X-band(b)Simulated radiation pattern of the single layerreflect array in X-band is just zoom

IV. Conclusion

In this paper, a single layer reflectarray antenna with cosecant squared shaped beam is designed using the phase-only beam synthesis technique. For more accurate phase distribution it is necessary to increase the number of elements; however, it requires more computation time and memory. A square aperture reflectarray with 400*400mm^2 dimensions with 400 elements was designed in 10GHz. A linearly polarized standard horn was used as the feed. This reflectarray has about 19.4 dBi gain.

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