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New Phase Realization Approach for Implementation of Braodband Reflectarrays

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Abstract—**We present a new phase realization approach applied to design the broadband single-layer reflectarray antennas. Such an optimization technique minimizes the adverse effects of frequency dispersion which limit the bandwidth of reflectarray antenna designed by traditional methods. Using this new approach leads to obtaining a wideband reflectarray by finding the optimum element arrangement on the antenna aperture. The excellence of such an approach in comparison with its counterparts is to decrease the dependency of wideband reflectarray design to the element phase behavior. For really assessment this phase synthesis approach, a single-layer reflectarray compromising of square patches loaded with split rings is designed with the help of this optimization technique. It is analytically and numerically shown that the simulated reflectarray can be a broadband antenna in which Side Lobe Level (SLL) value is reduced. To validate the obtained numerical results, a designed 29×29cm^2 reflectarray is fabricated and measured. Measurements demonstrate 1.5dB gain bandwidth of about 28% covering 12-16GHz frequency band. Its |SLL| is also less than -17dB (<-13.5dB for uniform excitation arrays). Such a design technique is applicable for approximately all reflectarray elements and relieves the designer from complex elements and multilayer structures.**

Keywords- Reflectarray Antenna, Broadband, Phase Realization Technique, Optimization.

I. INTRODUCTION

In various applications such as military communication, space telecommunications, and remote sensing, reflectarray antennas are used as a competitive alternative in respect to conventional reflector ones [1]. It is due to their high gain radiation patterns and other desirable properties such as low-weight, low-cost, low-profile, flexibility of radiation patterns controlling and conformability to a given surface shape [2-5]. However, the main drawback of such antennas is their narrow performance bandwidth which arises from differential spatial phase delay factor and narrowband unit cells [6, 7]. Recently, extensive efforts have been devoted to decrease the effect of narrowband radiating elements by stacked patches/-multilayered elements [8-10], periodic/-artificial substrates [11, 12], and using complex unit cells [13-18]. Moreover, there have been proposed two approaches in the literature to ameliorate the effect of differential spatial phase delay on reflectarrays frequency performance. The first approach is based on designing wide phase range elements having parallel phase response diagrams at different frequencies. This technique imposes a tedious and time-consuming trial-and-error procedure that finally leads to a multilayer, and complex structure [8-10]. As another technique, an optimization approach has been reported in [14] for

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minimizing the summed error of each element's phase realization at central frequency and two extreme ones instead of reflectarray designing at central frequency. Although, such a method is an advantageous one, but error function values of various elements have not a clear relationship. In the optimization procedure, a local minimum is thus yielded and thereby a suboptimal frequency performance for resultant antenna is obtained.

This paper offers an optimization technique is presented to minimize the frequency dispersion's adverse effects to obtain the most appropriate element arrangement on the aperture of reflectarray to achieve wider bandwidth. This technique is investigated thoroughly with experimental demonstration that shows a 1.5dB gain bandwidth of about 4GHz (28% with center frequency of 14 GHz) which has not been reported in reflectarray antenna literature [19-21]. Using this new design approach leads to achieving a lower Side Lobe Level (SLL) with respect to the reported traditional approach in [14]. As mentioned, the designed reflectarray using this approach are finally fabricated and measured. The measurements have a good agreement with the numerical results.

II. Approach Phase Synthesis and Selection of Optimum Element

The key in designing reflectarray is to realize a most proper distribution of phase shifts on the reflectarray aperture in such a way that meets the design requirements. In the case of a reflectarray with a single pencil-beam in (θ_b, φ_b) direction, the needed phase shift of the (m, n)th cell is calculated as [1]:

$$\phi_R = k_0\left(d_i - \left(x_i \cos\varphi_b + y_i \sin\varphi_b\right)\sin\theta_b\right) \qquad (1)$$

In which, k_0 is the free space wave number, and d_i is the length of path from phase center of feed antenna to (x_i, y_i) point which is the location of ith cell on the array. It is quite easy to fulfil the requirement of Eq. (1) in a single frequency reflectarray. However, as the antenna bandwidth increases, realization of this requirement at each frequency point of this bandwidth become more and more difficult and the designer is encountered with phase realization errors. As it is known, this error is mainly due to the differential spatial phase delay factor that has been extensively investigated in [1]. A procedure for selecting the reflectarray's cells dimensions is reported in [14], which is based on decreasing the following error function:

$$e(m,n) = \sum_{i=l,c,u}\left|\Phi_{fi}^{\text{desired}}(m,n) - \Phi_{fi}^{\text{achieved}}(m,n)\right| \qquad (2)$$

where (m, n) points to an element location on the surface of reflectarray lattice, lower, center and upper frequency samples within operating bandwidth are represented by l, c and u. In these extreme frequencies, the achieved and desired phase shifts are also represented by $\Phi_{fi}^{\text{desired}}$, and $\Phi_{fi}^{\text{achieved}}$, respectively. Such a procedure selects an appropriate phase shift for each cell at the mentioned extreme frequencies in such a way that the mask requirements are fulfilled. Therefore, the particular element is chosen to decrease the error function of Eq. (2) at each cell of a reflectarray lattice regardless of the other cells. However, no relation exists among error values of various reflectarray elements, which leads to a local minimum in this procedure. In other words, the computed error function value of an element by this procedure may be close to zero while the computed one for the adjacent element becomes a large value. Such a large difference between error function values leads to a non-optimal reflectarray performance. For this issue, we propose an optimization procedure for minimizing the average of error function values which computed for reflectarray elements. In addition to, such an optimization procedure considers the principle that the computed phase shifts at each frequency on reflectarray antenna aperture for attaining a desired radiation pattern is not unique. we also consider a weighting function that assigns greater weights to more influential elements on reflectarray radiation pattern. This technique is based upon two principles:

- The calculated phase distribution on reflectarray aperture is not the only one that yields to the intended radiation pattern. In the other words, if " $[\Phi]$ " were the calculated phase distribution on reflectarray surface in each of the center or two extreme frequencies, then " $[\Phi]+\theta$ ", in which " θ " is a constant and an arbitrary phase, would also lead to the same radiation pattern.

- As the elements located nearer to reflectarray center are illuminated with more power, they have greater impact on the form of the radiation pattern. Accordingly, to attain a radiation pattern with maximum likelihood to the predefined mask, a weighting function can be allocated to the elements based on their position on reflectarray surface.

Using these principles, the error function of Eq. (2) is amended considering the total phase error of the whole reflectarray and can be mathematically expressed as follows:

$$e(\theta_l,\theta_u) = \min\left\{\sum_{m,n}\left[\begin{array}{l}\left|\Phi_{f_l}^{\text{desired}}(m,n)-\Phi_{f_l}^{\text{achieved}}(m,n)+\theta_l\right| \\ +\left|\Phi_{f_c}^{\text{desired}}(m,n)-\Phi_{f_c}^{\text{Achieved}}(m,n)\right| \\ +\left|\Phi_{f_u}^{\text{desired}}(m,n)-\Phi_{f_u}^{\text{Achieved}}(m,n)+\theta_u\right|\end{array}\right]\times w(m,n)\right\}$$

$$\text{for all members of the search space}$$

$$\text{and for } \theta_l = -180:\text{step}:180 \text{ and } \theta_u = -180:\text{step}:180 \qquad (3)$$

To calculate $e(\theta_l,\theta_u)$, the above objective function is calculated for all members of the search space which are composed of different classes of the prescribe reflectarray element. The particular element arrangement that minimizes the right-hand side of (3) is selected as the optimum choice and is named as $e(\theta_l,\theta_u)$. In this regard, the arrangement of elements that eventuates to the minimum value of the error matrix, $[e]$, is selected as the most appropriate element arrangement. It is obvious that by selecting the optimum element arrangement, the structural data of all reflectarray constitutive elements would be determined automatically. In addition, despite of considering the desired phase distribution at center frequency as reference in (3), this can be allocated to each of the desired phase distributions interchangeably. Moreover, although smaller steps in (3) result in less error, but the steps smaller than one degree have no significant impact on the antenna performance. At the other hand, the second principle is embedded into (3) as a weighting function, $w(m,n)$, allocating higher weights to the elements that are located nearer to the center of reflectarray surface and lower weights to the elements located nearer to its edges.

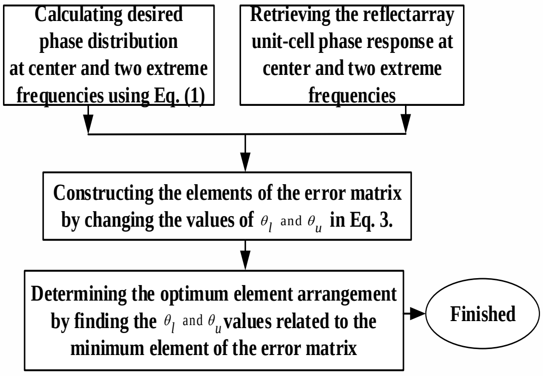


Figure 1. Block diagram of the proposed optimization procedure.

Therefore, $e(\theta_l,\theta_u)$ is an optimum arrangement of elements minimizing Eq. (2). Such an arrangement, which decreases the error matrix [e], is then chosen and the structural information of the reflectarray's optimum elements is automatically determined. In order to implement the proposed approach, it is initially needed to compute the desired phase distribution on the reflecarray aperture at extreme frequency samples using (1).

It is clear that the unit-cell of reflectarray antenna should be firstly analyzed using an EM-solver at extreme frequencies and a database of returning phase responses is then generated. Using database of unit cell's phase responses as the input, the proposed optimization method is deployed to determine the optimum element arrangement of reflectarray antenna lattice. The block diagram of our optimization approach is depicted in Fig. 1.

In the next section, this approach is used for the design of a center-fed reflectarray antenna. It is numerically and experimentally demonstrated that using such an optimization approach leads to broadening the performing reflectarray bandwidth and reduction its |SLL|.

III. Reflectarray Design and Experimental Verification

For practicality validation of the described approach in the previous section, a wideband reflectarray is implemented in Ku band. To do so, various classes of a multi-resonance unit -cell is used for the design of such a reflectarray. The schematic of unit cell and its design parameters are depicted in Fig. 2. By full-wave analysis of this unit-cell, its phase diagram is calculated at two extreme and center frequencies once $g_1=g_2=0.3$mm, and $w_1=w_2=w_3=0.5$mm. Fig. 3 shows the obtained phase diagram for normally incident plane-wave. As shown in the same figure, such a single-layer unit-cell has low slope phase variations as well as wide phase range. Such properties of unit-cell lead to designing a wideband reflectarray in which susceptibility to fabricating errors, complexity and cost of manufacturing are reduced.

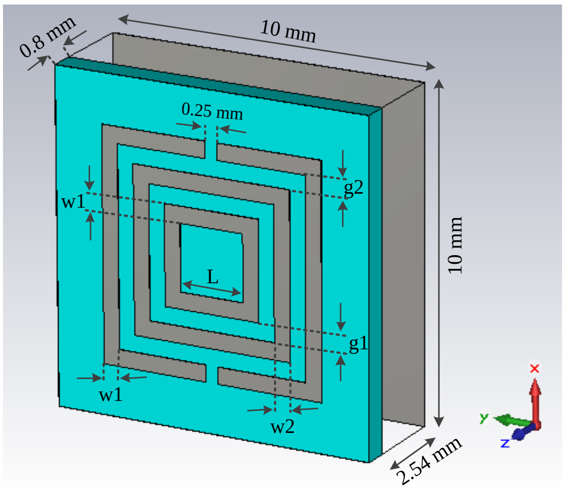


Figure 2. Reflectarray unit cell.

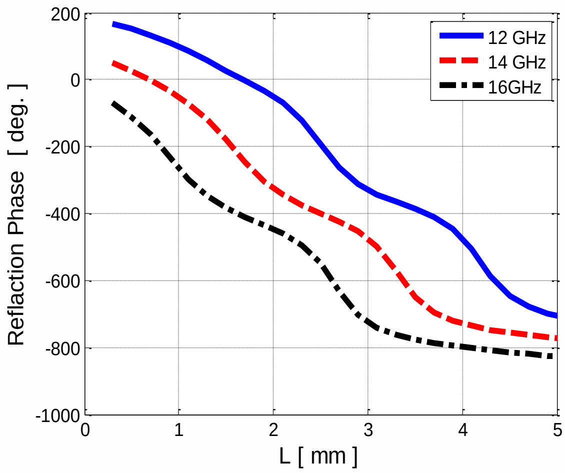


Figure 3. Phase diagram of the depicted unit-cell in Fig. 2.

TABLE I. Parameters of the reflecatarray unit-cell for various configurations

g_1, g_2 (mm)	g_3 (mm)	w_1, w_2, w_3 (mm)	L (mm)
0.2-0.3 step: 0.1	0.25	0.3-0.5 step: 0.2	0.2-5.1 step: 0.05

It is obvious that by tuning the design parameters of unit cell, w_1, w_2, w_3, g_1, g_2 and L in Fig. 2, one can generate various classes of the reflectarray elements. Table I indicates the structural data of the designed unit cell. In this regard, the used substrate is RO4730 LoPro laminate (ε_r=3; tanδ= 0.0033 at 10GHz; thickness=31 mil) backed by an aluminum plane as an air-filled stacked structure using PTFE (ε_r=2.08; tanδ= 0.0004 at 10GHz; height=10 mil) spacers. Note that the copper on the back side of the mentioned laminate is etched. In order to attain the best performance of reflectarray with the help of described method, a database of phase diagrams of elements corresponding to all the permutations of Table I values is generated at main frequencies. The location of feed antenna (focal length) in the reflectarray design is also calculated such a way that the efficiency of the entire system to be maximum, and its value is 25cm.

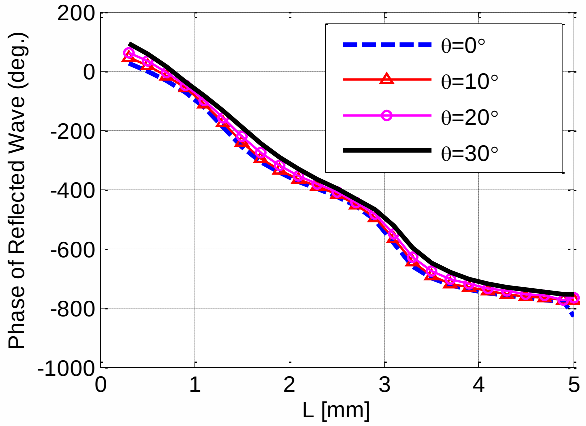


Figure 4. Variations of the phase response of the unit-cell for diffrenet incident angles once it is less than θ_e at central frequency (=14GHz).

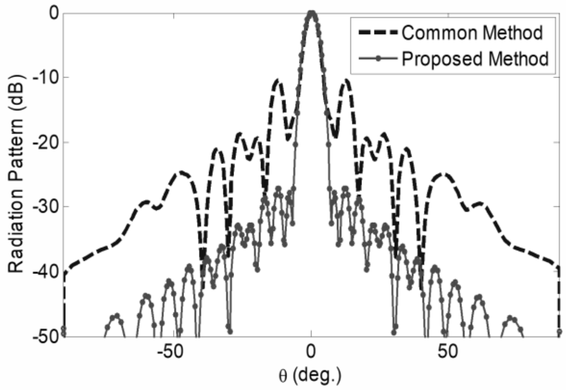
TABLE II. PARAMETERS OF THE DESIGNED REFLECATARRAY

Substrate type	RO4730 LoPro
No. of Elements	29×29
Dimension	29×29cm^2
F/D	0.85
Operating Freq.	Ku-band (12~16GHz)
***q*-Horn antenna**	8.5

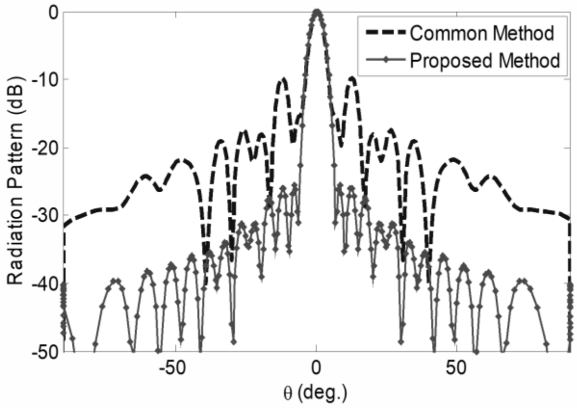
Thus, the half of subtended angle from the feed to the planar array aperture (θ_e) is obtained 30^o. Consequently, the effect of incident angle's variation on phase diagrams is considered to increase antenna design accuracy. To do so, the angular phase response dependence is numerically calculated as visualized in Fig. 4. In this figure, the negligible dependence of phase diagram on angle of incident wave is demonstrated once it is less than θ_e.

With the help of the proposed technique, a 29cm × 29cm center-fed reflectarray antenna is first designed analytically in 12~16GHz. For feeding the designed reflectarray, a pyramidal horn antenna with a linearly polarization is designed. This feed antenna is located 25cm far from the center of the antenna aperture with a feeder/diameter ratio $F/D \approx 0.85$ and $q=8.5$ at center frequency in which q is the feed specification defined by $cos^q\theta$. Table II summarizes the designed reflectarray antenna's parameters.

Analytical radiation patterns in H-plane and E-plane of the designed reflectarray at central frequency 14GHz are shown in Fig. 5(a) and 5(b), respectively. As can be seen in these figures, the calculated radiation patterns in [14] using traditional method are reported for comparison. Such a comparison demonstrates that lower |SLL| is obtained in radiation patters once our procedure is used in the reflectarray design. Using proposed optimization approach, the average of phase realization error is decreased from 40^o in [14] to 5^o on each element of reflectarray. The aforementioned reflectarray antenna is then simulated in FEKO environment and finally fabricated for really assessment of our design approach. Fig. 6 exhibits the structure of the fabricated reflectarray antenna which comprises of 841 elements on a 29cm × 29cm aperture.



(a)



(b)

Figure 5. Calculated radiation patterns in (a) E-plane, and (b) H-plane of the designed reflectarray antenna at 14GHz. Results of [14] using common method are reprted for comparson.

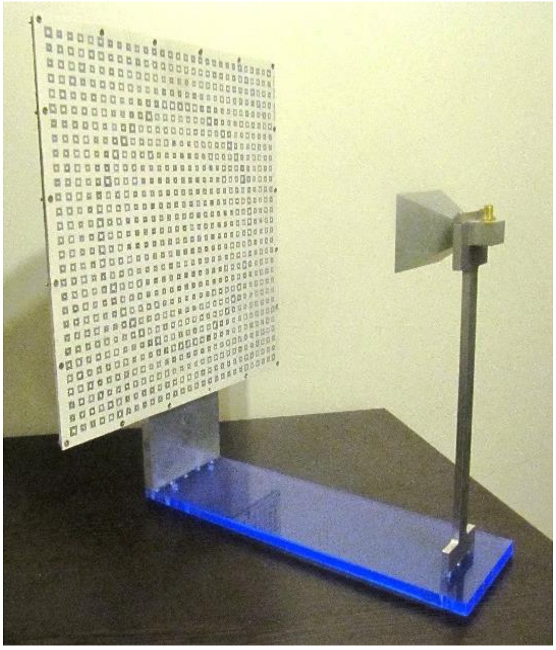
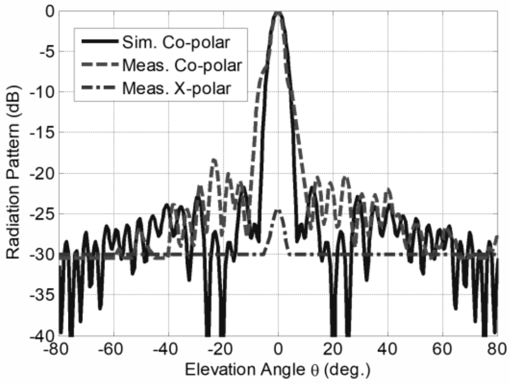
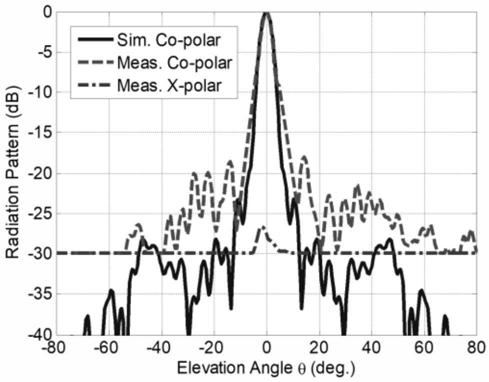


Figure 6. Fabricated reflectarray along with its horn antenna.

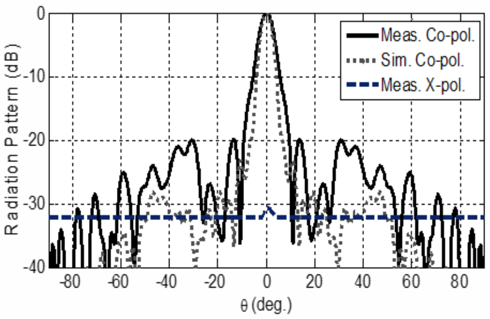
The aperture dimension of the pyramidal feed horn is designed to be 6.5cm × 4.8cm to have an approximately symmetric radiation pattern.



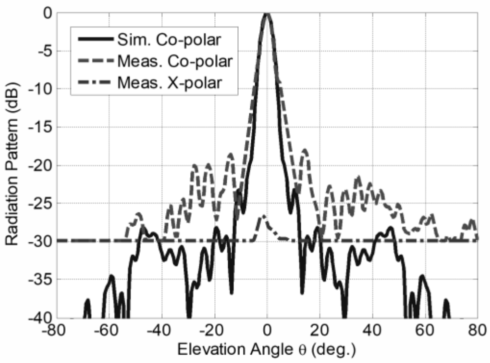
(a)



(b)



(c)



(d)

Figure 7. Normlized E-palne radiation patterns of the designed broadband reflectarray antenna at (a) 12GHz, (b) 14GHz, (c) 15GHz, and (d) 16GHz.

The simulated and measured normalized radiation patterns in E-plane within operating bandwidth of designed reflectarray at 12GHz, 14GHz, 15GHz, and 16GHz are shown in Fig. 7.

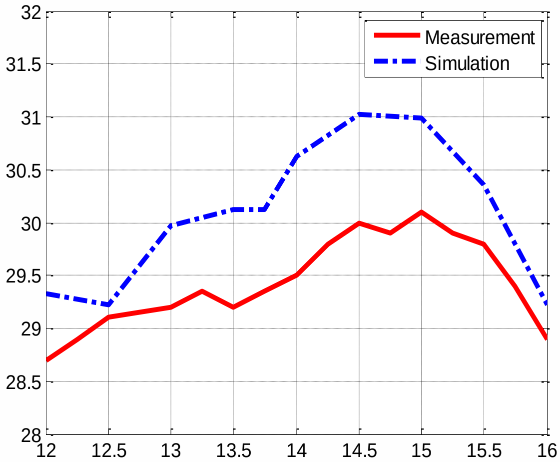


Figure 8. Measured and simulated peak gain values of the implemented reflectarray in frequency range 12~16GHz.

TABLE III. COMPARISON OF THE SINGLE-LAYER REFLECTARRAY ANTENNAS

Ref.	Dim. of array (cm)	No. of cells	Freq. range (GHz)	G_{max} @ f_c (dB)	BW (%)	Max. phase range (deg.)	|SLL| (dB) @ f_c
[24]	40 ×40	1225	12.5 ~14.5	34.0	16.7	360	<-14
[25]	D=32	480	12.5 ~14.5	30.8	17	500	<-20
[26]	27 ×19	650	10.7 ~12.5	25.3	9.7	480	<-14
[14]	120 ×120	10^4	11.4 ~12.8	40.6	11.6	400	<-20
[14]	120 ×120	10^4	13.7 ~14.5	41.5	5	500	<-20
[11]	27×27	729	8.95 ~12.1	26.57	29.5	400	<-14
[18]	15.6 ×15.6	145	13.2 ~19.4	23.4	24.8	520	<-13
This Work	29×29	841	12~16	30.1	28	800	<-20

As shown in these figures, the measured Cross-polar radiation patterns is less than -25dB, moreover, the measured |SLL|<-17dB. Based on Fig. 7(c), the measured X-polar and |SLL| stay below -30dB, and -20dB, respectively. Simulated and measured peak gain variations in frequency range 12~16GHz is visualized in Fig. 8. As seen in the same figure, the maximum gain is 30.1dB at 15 GHz and its 1.5dB bandwidth of about 28% is obtained. Note that our goal in this study is not to propose a new unit cell for increasing the bandwidth of reflectarray. However, an optimization technique is proposed as a phase synthesis approach to broaden the reflectarray bandwidth and reduce its |SLL|. It is clear that using the reported unit cell in [18] and our proposed phase synthesis technique leads to the reflectarray's bandwidth is increased more than the mentioned one. The comparison results of Table III confirm that a satisfactorily trade-off between bandwidth and |SLL| is obtained by our proposed design method.

TABLE IV. ESTIMATED EFFECIENCY OF THE IMPLEMENTED REFLECTARRAY ANTENNA

Type of Efficiencies	Efficiency (%)	Loss (dB)
Illumination (η_I)	82	0.92
Spillover (η_s)	91	0.41
Unit cell (Simulation)	66	1.8
Cross-pol [22]	95	0.22
Feed antenna [23]	91	0.41
Total (η_{total})	**42**	**3.76**

The maximum efficiency for such a system can be given by [23]:

$$\eta_{total} = \lambda_0^2 \frac{G_{\max}}{4\pi A} \times 100, \tag{4}$$

where $G_{\max}$ is the measured maximum gain (= 30.1dB) at 15GHz, A is the reflectarray's aperture area (=0.29×0.29m^2) and λ_0 is the free-space wavelength. Thus, the total efficiency is approximately obtained 42%. This efficiency value can be estimated by [23]:

$$\eta_a = \eta_I \times \eta_s \tag{5}$$

in which, the illumination (η_I) and spill-over (η_s) efficiencies are respectively given as follows [1]:

$$\eta_I = \frac{\left[\left(\left(1+\cos^{q+1}\theta_e\right)\Big/(q+1)\right)+\left(\left(1-\cos^{q}\theta_e\right)\Big/q\right)\right]^2}{2\tan^2\theta_e\left[\left(1-\cos^{2q+1}\theta_e\right)\Big/(2q+1)\right]}, \tag{6}$$

and,

$$\eta_S = 1-\cos^{2q+1}\theta_e \tag{7}$$

in which, q=8.5, and θ_e= 30º. However, other available losses must be considered in total efficiency of the final system. In Table IV, its estimated efficiencies are summarized. In this table, the loss of unit cell is approximately obtained by simulation of the unit cell and calculating its amplitude of the reflected power once it is illuminated by a plane-wave in the central-frequency. As shown in this table, the blockage of horn (feed antenna) is in the order of spillover loss. Therefore, one can obviously use an offset-fed design for increasing the reflectarray efficiency.

IV. CONCLUSION

Based on a new phase realization technique, a single-layer broadband reflectarray is designed and fabricated in Ku-band (12~16GHz). In presented technique, a large database of reflectarray elements is used. Benefits of this design procedure are minimizing the adverse effects of dispersion, broadening the reflectarray bandwidth in comparison with the traditional methods, reduction the |SLL|. Using such a design technique, a broadband reflectarray with 29×29 elements and 25cm focal point is implemented in 12~16GHz. Experimental results demonstrate that the maximum gain of the fabricated reflectarray is 30.1dB at 15GHz and its peak gain variation is less than 1.5dB within a relative bandwidth of 28%. The measured co- and cross-polar radiation patterns are quite stable for all frequencies within operating bandwidth. It is experimentally obtained at 15GHz that the measured |SLL| and cross-polar radiation pattern are below <-20dB and -30dB, respectively.

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