Gain and Bandwidth Limitations of Reflectarrays

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***Abstract* -** In reflectarray antenna designs, it is important to find the gain and bandwidth for a desired application. In this paper, two analysis methods are illustrated, which can provide quick estimations on the reflectarray gain and bandwidth. A quantitative comparison on these two different approaches is made in terms of accuracy and computation time. Parametric studies are performed to provide design guidelines for selecting appropriate f/D ratio and feed pattern of a center-fed reflectarray in order to optimize the antenna gain and bandwidth. A gain and bandwidth comparison between the broadside and offset fed reflectarray antennas is presented. Furthermore, the effect of element bandwidth on the performance of an X-band reflectarray is given both numerically and experimentally.

***Index Terms* ─** Bandwidth, directivity, efficiency, gain, reflectarray.

I. INTRODUCTION

Reflectarray antenna combines the advantages of both traditional reflectors and conventional phased array antennas. It has a high gain like parabolic reflectors. But, unlike the reflector that has a theoretically infinite bandwidth due to its curved surface, the reflectarray has a narrow bandwidth due to its phase compensation mechanism.

In the last decades, it has been shown that there are mainly two factors which limit the bandwidth performance of a reflectarray antenna [1-2]. One is the narrow bandwidth of the microstrip patch element [3] and the other is the differential spatial path delay. The second bandwidth limitation factor depends on system parameters like aperture diameter (D), focal length to diameter ratio (f/D), and power factor (q) of the feed pattern. In this paper, the gain and bandwidth of reflectarrays are studied in details, and the focus is on the effects of the system parameters. Note that the frequency bandwidth in this paper, if not explicitly defined, is calculated at -1 dB from the maximum gain.

Section II of this paper describes two different methods to quickly estimate the reflectarray gain and bandwidth. A comparison is made in terms of accuracy and computation time. Focusing on the differential spatial delay effect, Section III presents the bandwidth study of a broadside center-fed reflectarray antenna. Parametric studies are performed in order to optimize the antenna gain and bandwidth. In Section IV, a comparison between broadside and offset reflectarray antenna in terms of gain and bandwidth is given. In Section V, an X-band reflectarray with identical circularly polarized elements but different rotation angles is investigated. Both the effect of differential spatial path delay and the effect of element bandwidth on the performance of reflectarray are studied. The simulated gain of this reflectarray antenna is compared with the measured result.

II. GAIN COMPUTATION METHODS

To analyze the radiation performance of reflectarray antennas, several approaches have been developed with different levels of accuracy and complexity. The most accurate method is to perform a full wave simulation on the entire reflectarray aperture and the feed horn. However, this method requires prohibitively large memory storage and computational time, especially for large-size reflectarrays. An infinite array approach is widely used by assuming local periodicity, where each reflectarray element is analyzed within

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a periodic environment to obtain its reflection magnitude and phase. The frequency variation, polarization status, and the actual incident angle can be considered in the simulation. Once the element property is determined, the aperture field distribution can be calculated and the radiation performance of the reflectarray can be obtained. This method is proved to be accurate; however, the algorithm is relatively complex and simulation time is relatively long.

In some engineering designs, it is necessary to provide quick estimations on the reflectarray performance such as the gain and bandwidth. In light of this, two simple and quick approaches are presented here for such estimations, which are based on the array theory and the aperture efficiency. Their accuracy and computational time are compared quantitatively in this paper. Combined with specific element phasing techniques, these approaches can be used to calculate the gain and bandwidth of reflectarray antennas.

The gain (G) calculation of a reflectarray antenna is defined as a product of the directivity (D_a) and aperture efficiency (η_a) [4] such that

$$G = D_a \times \eta_a, \tag{1}$$

where D_a of the aperture with an area A is

$$D_a = \frac{4\pi A}{\lambda^2}. \tag{2}$$

The η_a is the product of spillover efficiency (η_s), illumination efficiency (η_i) and other efficiency (η_o) factors. Other efficiencies include the feed loss, feed blockage, reflectarray element loss, polarization loss, mismatch loss, etc. Thus,

$$\eta_a = \eta_s \times \eta_i \times \eta_o. \tag{3}$$

In some gain computation methods, the directivity is calculated from the aperture field distribution [5-7]. Thus, the gain already includes the illumination efficiency which can then be represented by the following equation,

$$G = D_0 \times \eta_s \times \eta_o. \tag{4}$$

A. Directivity Calculations: Method 1

The directivity of an array with isotropic elements whose main beam is pointing in the $\theta = \theta_0$ and $\varphi=\varphi_0$ direction is given as,

$$D_0 = \frac{\left|AF(\theta_0, \varphi_0)\right|^2}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left|AF(\theta,\varphi)\right|^2 \sin\theta d\theta d\varphi}. \tag{5}$$

where,

$$AF(\theta,\varphi) = \sum_{n=0}^{N-1} A_n \cdot e^{j\phi_n} \cdot e^{j\beta\left(\hat{r}\cdot\vec{r}_n\right)}. \tag{6}$$

Here, A_n and ϕ_n are the amplitude and phase of the n^{th} array element, and

$$\hat{r}\cdot\vec{r}_n = p_{x_n}\sin\theta\cos\varphi + p_{y_n}\sin\theta\sin\varphi. \tag{7}$$

The position of the n^{th} element in an N-element planar array in the xy-plane is denoted by $\left(p_{x_n}, p_{y_n}\right)$. The array can have arbitrary configuration in the xy-plane and each element is indexed with a single index n. Note that N is the total number of elements and would equal to the product of the number of elements in x and y directions ($N_x \times N_y$) for a rectangular array.

The denominator in Eq. (5) referred to as '*DEN*' can be written as,

$$DEN \overset{\Delta}{=} \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left[AF(\theta,\varphi)\right]\left[AF(\theta,\varphi)\right]^* \sin\theta d\theta d\varphi. \tag{8}$$

When substituting equation (6) into equation (8), one obtains,

$$DEN = \sum_{n=0}^{N-1}\sum_{m=0}^{N-1} w_n w_m^* \int_0^{\pi}\frac{1}{2}\sin\theta d\theta \int_0^{2\pi}\frac{1}{2\pi}\exp\left(j\frac{2\pi}{\lambda}\left(\Delta p_{x_{nm}}\sin\theta\cos\varphi + \Delta p_{y_{nm}}\sin\theta\sin\varphi\right)\right)d\varphi, \tag{9}$$

where,

$$w_n = A_n \cdot e^{j\phi_n}, \tag{10}$$

$$\Delta p_{x_{nm}} \overset{\Delta}{=} p_{x_n} - p_{x_m} = \rho_{nm}\cos\varphi_{nm}, \quad \Delta p_{y_{nm}} \overset{\Delta}{=} p_{y_n} - p_{y_m} = \rho_{nm}\sin\varphi_{nm}, \tag{11}$$

$$\rho_{nm} = \left(\left(\Delta p_{x_{nm}}\right)^2 + \left(\Delta p_{y_{nm}}\right)^2\right)^{\frac{1}{2}} = \left\|\Delta p_{nm}\right\|, \quad \varphi_{nm} = \arctan\left(\frac{\Delta p_{y_{nm}}}{\Delta p_{x_{nm}}}\right). \tag{12}$$

Using Eqs. (11) and (12) in the inner integral in Eq. (9) gives

$$\int_0^{2\pi}\frac{1}{2\pi}\exp\left(j\frac{2\pi}{\lambda}\rho_{nm}\sin\theta\left(\cos\left(\varphi-\varphi_{nm}\right)\right)\right)d\varphi = J_0\left(\frac{2\pi}{\lambda}\rho_{nm}\sin\theta\right), \tag{13}$$

where $J_0(.)$ is a Bessel function of order zero. Substituting Eq. (13) into Eq. (9) gives

$$DEN = \sum_{n=0}^{N-1}\sum_{m=0}^{N-1} w_n w_m^* \int_0^{\pi} \frac{1}{2}\sin\theta . J_0\left(\frac{2\pi}{\lambda}\rho_{nm}\sin\theta\right)d\theta \qquad (14)$$
$$= \sum_{n=0}^{N-1}\sum_{m=0}^{N-1} w_n w_m^* sinc\left(\frac{2\pi}{\lambda}\rho_{nm}\right).$$

Thus, the directivity in Eq. (5) can be calculated analytically, and the computational time of equation (14) is in the order of N^2.

B. Directivity Calculations: Method 2

Another simple approximation formula to calculate the directivity of a large planar array is,

$$D_0 = D_a \times \eta_i . \qquad (15)$$

The illumination efficiency (η_i), due to the non-uniform amplitude and phase distribution on the aperture plane [8], is given as,

$$\eta_i = \eta_t \times \eta_{ph} , \qquad (16)$$

where η_t and η_{ph} are the taper and phase efficiencies. The η_t accounts for the aperture illumination taper due to the feed and the reflector geometry and is given by,

$$\eta_t = \frac{1}{A}\frac{\left[\sum_{n=0}^{N-1}\left|E_n\right|\Delta x\Delta y\right]^2}{\sum_{n=0}^{N-1}\left|E_n\right|^2\Delta x\Delta y}. \qquad (17)$$

The η_{ph} accounts for the phase-error over the aperture due to various causes such as, frequency change, displacement of the feed-horn from the on-axis focus, distortion of the optical surfaces, or it may be caused by phase-error in the field of the feed-horn. This η_{ph} is given by,

$$\eta_{ph} = \frac{\left|\sum_{n=0}^{N-1} E_n \Delta x\Delta y\right|^2}{\left[\sum_{n=0}^{N-1}\left|E_n\right|\Delta x\Delta y\right]^2}\times\cos\theta_0 . \qquad (18)$$

Finally, the illumination efficiency is given as,

$$\eta_i = \frac{1}{A}\frac{\left|\sum_{n=0}^{N-1} E_n \Delta x\Delta y\right|^2}{\sum_{n=0}^{N-1}\left|E_n\right|^2\Delta x\Delta y}\times\cos\theta_0 , \qquad (19)$$

where,

$$E_n = A_n \cdot e^{j\phi_n}\cdot e^{j\beta\left(\hat{r}_0\cdot\vec{r}_n\right)}. \qquad (20)$$

The term $\beta(\hat{r}_0\cdot\vec{r}_n)$ is the phase due to the change in the main beam direction. For a broadside beam, this term will disappear. The parameters Δx and Δy represent the spacing between the elements along x and y axes, respectively. It is worthwhile to point out that the computational time in the denominator of Eq. (19) is only an order of N.

In summary, from Method 1 to Method 2, the computational time of the directivity is reduced from a $O(N^2)$ to $O(N)$.

C. Spillover Efficiency

The spillover efficiency (η_s) is defined as the ratio of the power intercepted by the reflecting elements to the total power [9],

$$\eta_s = \frac{\int_A \vec{p}.d\vec{s}}{\int_\Sigma \vec{p}.d\vec{s}}. \qquad (21)$$

Both integrals are the fluxes of the Poynting vector $\vec{P}$ through some certain surface areas. The integral of the denominator is performed over the entire spherical surface centered at the feed, denoted by Σ. The integral in the numerator is evaluated on the array aperture A. Once the spillover efficiency is determined, the reflectarray gain can be calculated using equation (4).

D. Comparison of Results

By assuming the efficiency factor η_o = 1 in equation (4), a comparison between Method 1 and Method 2 for gain calculations was performed for a rectangular aperture reflectarray antenna which has a center feed and a broadside main beam (frequency = 32 GHz; spacing between elements = λ/2; f/D = 0.5; feed pattern power factor, q = 3). Ideal phasing elements are used in these comparisons. These comparisons are performed using Matlab on an Intel duo-core 3.2 GHz CPU and 2 GB of RAM and the results are reported in Table 1. Note that Method 1 always gives accurate results for any aperture size, whereas the approximation error in Method 2 decreases when the aperture size increases. Figure 1 illustrates the percentage error of Method 2 with respect to Method 1. The error is calculated using the following equation:

$$Error(\%) = \frac{\left|G(M2)-G(M1)\right|}{G(M1)}\times 100\%. \qquad (22)$$

Of the two methods, the time taken for gain calculation is much less using Method 2. From Fig. 2, a clear agreement of the two methods at off-center frequencies can be seen for a broadside reflectarray. For 21 frequency points the Method

1 takes about 8 minutes whereas the Method 2 only takes around 30 seconds. The bandwidth obtained using either of the methods is about 5 %.

Table 1: Gain and CPU time comparison

Array size	Gain (dB)		Time (s)	
	Method 1	Method 2	Method 1	Method 2
11×11	24.3142	24.3855	0.6180	0.6060
21×21	30.0432	30.0834	0.6660	0.6420
41×41	35.9062	35.9307	2.2680	1.0140
81×81	41.8450	41.8622	22.2960	2.4840

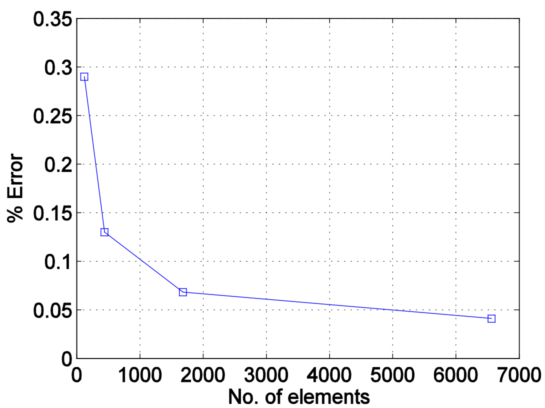

Fig. 1. Gain error of Method 2 vs. number of elements.

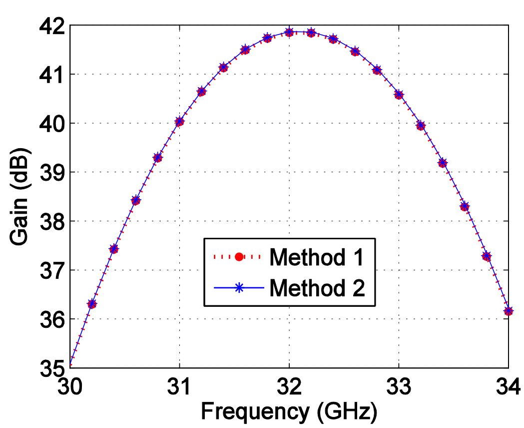

Fig. 2. Gain comparison of two methods for an 81×81 element reflectarray.

III. BANDWIDTH OF BROADSIDE FED REFLECTARRAY

Bandwidth of reflectarrays is determined by two factors: the system configuration and the element performance. In Sections III and IV, we focus on the effects of the system configuration, namely, the aperture size, the feed property, and the feed location. During this investigation, an ideal element phase is used, that is, as frequency varies the relative element reflection phase does not change. The reason for this assumption is to study only the effects of the system parameters. This assumption is valid also because in the element rotation technique, to be discussed in Section V, the relative reflection phase of the co-polarized CP wave (normalized to a reference element, e.g., the element located at the center of the aperture) only depends on the rotation angle and is therefore a constant over the frequency range of interest.

Considering the accuracy and computation time, Method 2 is used here to conduct a parametric study on the reflectarray gain and bandwidth performance.

A. Gain and Bandwidth vs. (f/D, q)

First, a parametric study has been done for a circular aperture (frequency = 32 GHz; spacing between elements = $\lambda/2$; diameter = 0.5 m (D/λ = 53.4); number of elements = 8937) with a gain around 43 dB. As the gain and bandwidth of a reflectarray varies with q and f/D ratio, an appropriate selection of these parameters is required. For a given q value, the gain versus f/D increases to a certain value and then decreases as shown in Fig. 3. The larger the q value, the narrower the horn beam. Thus, we need to choose a larger f/D in such cases in order to have a more uniform field distribution on the array.

It has been noticed that for a particular f/D and q value where we get maximum gain, the bandwidth may not be maximum. In Fig. 4, a gain of 43 dB is obtained for different combinations of f/D and q, but the bandwidth is wider for larger f/D and q values. The phase efficiencies at f/D = 0.5 and 0.75 are shown in Fig. 5 with q = 3. At off-center frequencies, the phase efficiency is high for large f/D ratio. This phase efficiency contributes to the increased bandwidth when we increase the f/D ratio. The bandwidth increases with an increase in the two parameters f/D and q as shown in Fig. 6.

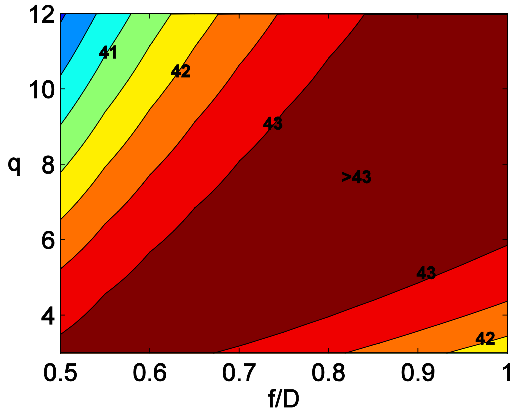

Fig. 3. Gain (dB) vs. (f/D, q) for a center-fed reflectarray at 32 GHz.

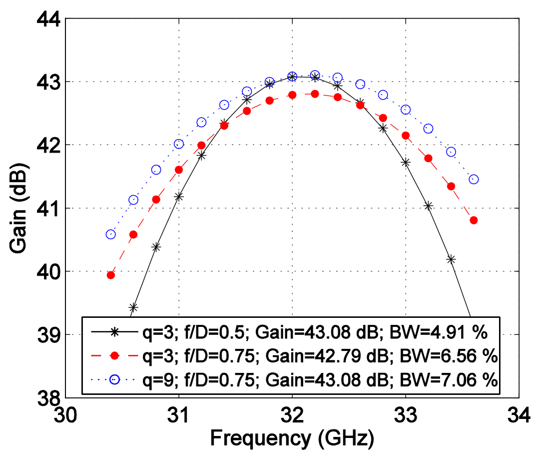

Fig. 4. Gain of center-fed reflectarrays with different q and f/D.

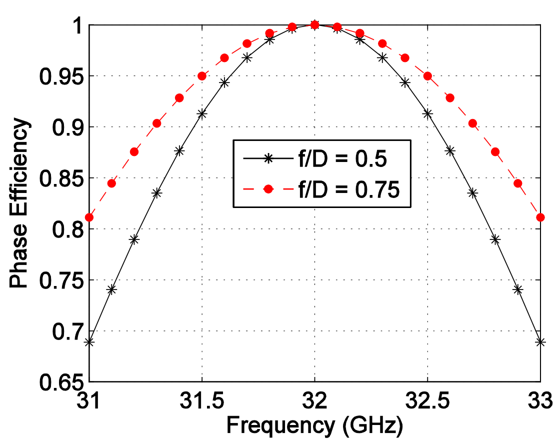

Fig. 5. Phase efficiency vs. frequency for a center-fed reflectarray with q = 3.

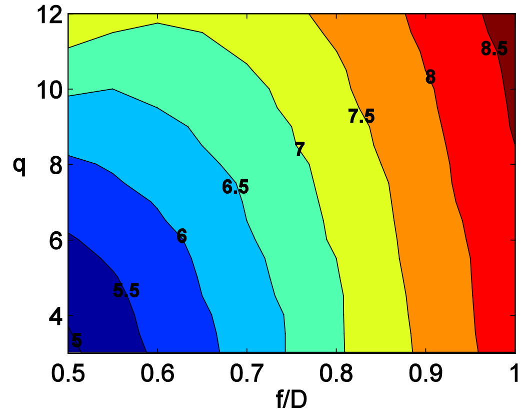

Fig. 6. Percentage bandwidth vs. (f/D, q) for a center-fed reflectarray.

B. Gain and Bandwidth Relation

A relation between gain and bandwidth of a large size (43 dB; $D/\lambda = 53.4$) and middle size (32 dB; $D/\lambda = 16$) reflectarray is shown in Figs. 7 and 8, respectively. It can be observed that for a fixed q value, the variation in gain is small (< 0.4 dB) when the f/D is increased. Meanwhile, the increase in bandwidth is high for a middle size reflectarray when compared to that of a large size reflectarray. At q = 3 and f/D from 0.5 - 0.74, the bandwidth of a large size reflectarray is varying from 4.91 % to 6.5 %, whereas the bandwidth of middle size reflectarray is varying from 16.37 % to 21.22 %. Figures 7 and 8 also illustrate that the gain and bandwidth are high for large f/D and q.

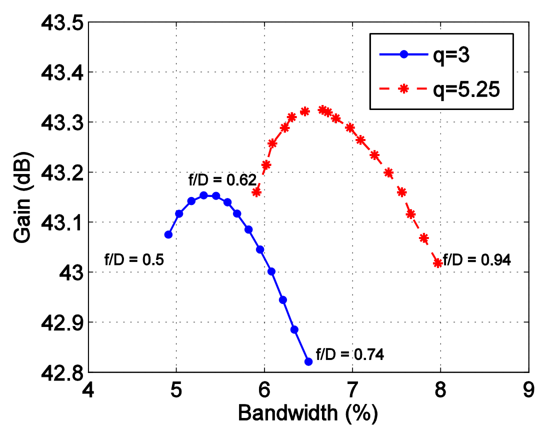

Fig. 7. Gain vs. bandwidth for a large size center-fed reflectarray with $D/\lambda = 53.4$.

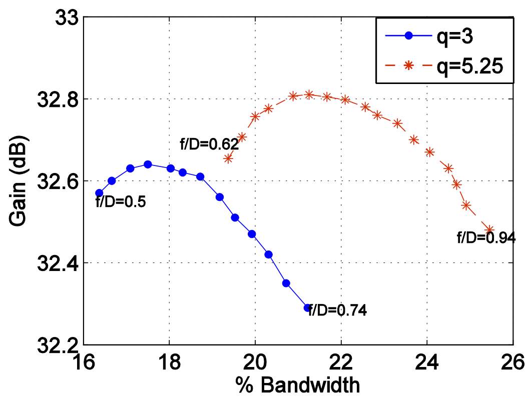

Fig. 8. Gain vs. bandwidth for a middle size center-fed reflectarray with D/λ = 16.

IV. BROADSIDE AND OFFSET FED REFLECTARRAY

For a circular aperture (frequency = 32 GHz; spacing between elements = λ/2; diameter = 0.5 m; number of elements = 8937), a comparison is done between broadside and offset reflectarrays. Here, the incident and main beam of the offset reflectarray is making an angle of 25° with respect to the broadside direction. In doing so, the reflected energy and the reradiated energy of each reflectarray element can be collocated in the same direction and not wasted [10]. At fixed f/D and q values, an offset reflectarray has lower gain but wider bandwidth (gain = 42.48 dB, bandwidth = 5.31%) when compared to that of a broadside reflectarray (gain = 43.08 dB, bandwidth = 4.95%), as shown in Fig. 9.

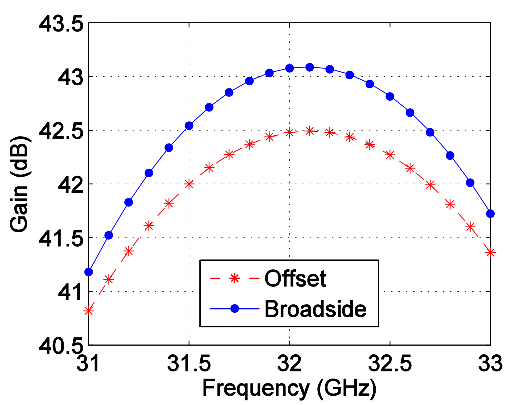

Fig. 9. Gain vs. frequency, for broadside and offset reflectarrays at q = 3 and f/D = 0.5.

The gain and bandwidth characteristics of both reflectarray antennas are shown in Fig. 10. At q = 3 and f/D = 0.4 - 0.74, for a broadside fed reflectarray, the maximum gain of 43.15 dB is achieved when f/D = 0.56, while the largest bandwidth of 6.5% is obtained when f/D = 0.74. Yet for an offset reflectarray antenna, the maximum gain of 42.5 dB is achieved when f/D = 0.52, while the largest bandwidth of 7.25% is obtained when f/D = 0.74.

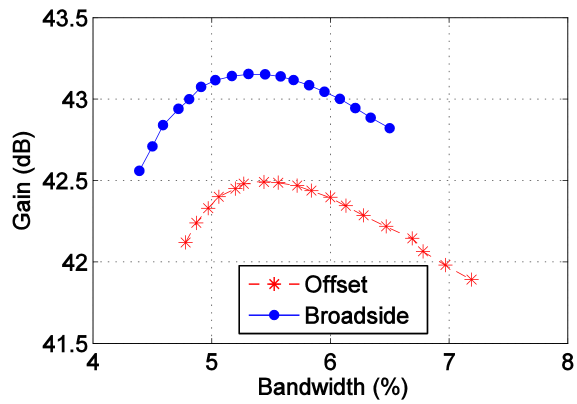

Fig. 10. Gain vs. bandwidth, for broadside and offset reflectarrays at q = 3 and f/D = 0.4 - 0.74.

V. ELEMENT BANDWIDTH EFFECT

In this section, the effect of the element bandwidth is included to investigate the performance of an X band reflectarray operating at 8.4 GHz. A split square loop is designed to reflect the CP wave with the same polarization state at X-band (8.4 GHz). A modified element rotation technique is used to compensate the spatial phase delay [11]. The full wave solver Ansoft Designer is applied in the element designs. Periodic boundary conditions (PBC) are placed around a single element to model an infinite array environment, and a plane wave is launched to illuminate the unit cell. It is worthwhile to point out that the mutual coupling effects between elements are considered in this analysis. The array grid is uniform and square shaped, with a period p = 18.75 mm between adjacent cells, as shown in Fig. 11. Figure 12 shows the magnitudes of the reflected co-polarized (right hand circularly polarized, RHCP) and the cross-polarized (left hand circularly polarized, LHCP) components under normal incidence. The element bandwidth obtained at -1 dB is about 4.29% (8.23-8.59 GHz) centered at 8.4 GHz. By rotating the slots around the perimeter of the square loop, different reflection phases can be obtained to compensate the spatial phase delay of elements at different locations on the reflecting surface.

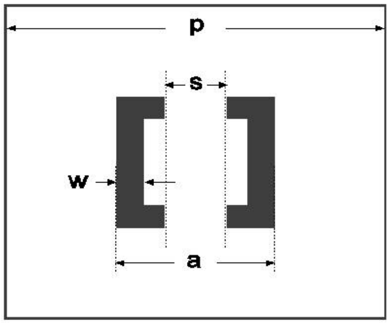

Fig. 11. Element geometry [11]: a = 11.375 mm, w = 2 mm, s = 7.2 mm and P = 18.75 mm, (substrate thickness = 1.57 mm and ε_r= 2.33).

The antenna elements are aligned on a circular aperture with the diameter D = 500 mm (D/λ = 14), f/D = 0.68, q = 6 and an offset feed structure is used with an angle of 25° aside from the normal direction of the reflector plane. Using these configuration parameters, the effect of differential spatial phase delay is studied first, and the results are shown in Fig. 13. Here, the gain is calculated using Method 2. As the aperture directivity (D_a) linearly increases with frequency, it can be observed that the maximum gain is obtained at 9 GHz instead of the design frequency 8.4 GHz. Figure 13 also shows the aperture efficiency over a frequency range of 7.8 GHz – 9 GHz. Note that the spillover and taper efficiencies are constant with frequency, but the phase efficiency varies with frequency. The gain bandwidth due to differential spatial phase delay is 25.83%.

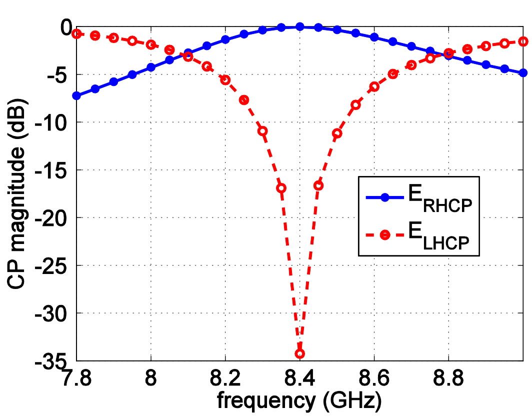

Fig. 12. Performance of the CP element using Ansoft Designer.

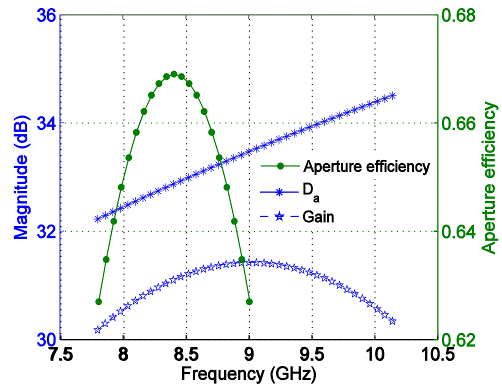

Fig. 13. Reflectarray performance due to spatial phase delay effect.

To include the element effect, the values of RHCP shown in Fig. 12 are considered as polarization mismatch in the code while doing frequency scan. The effect of element bandwidth on the performance of the reflectarray is shown in Fig. 14. The bandwidth with element effect is about 4.29% (8.25-8.61 GHz). The bandwidth obtained is equal to that of the element bandwidth, but note that the frequency range is slightly higher. It was observed that the bandwidth from element is much narrower than the bandwidth from differential spatial phase delay. Therefore, the element performance has a dominant effect on the reflectarray bandwidth compared to the spatial phase delay.

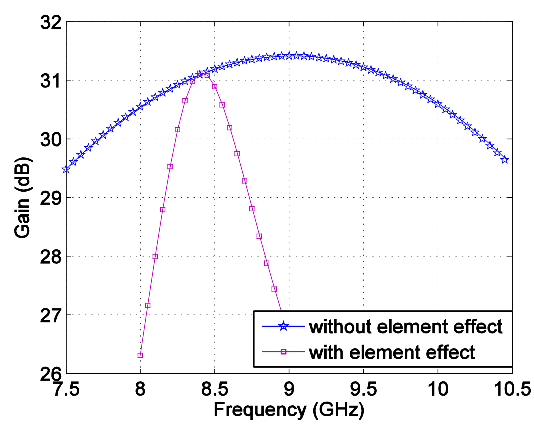

Fig. 14. Effects of spatial phase delay and element bandwidth on the reflectarray gain.

The gain of the reflectarray antenna obtained from simulations is compared with the measured result in Fig. 15. The gain of the prototype was obtained from near field measurements [11].

Table 2 summarizes the gain and bandwidth values. Since the measured result includes other efficiency factors such as the feed loss, which is lower than the simulated results. A major reason for the discrepancy between the simulated and measured results is due to the feed horn antenna effect. The q value, the purity of the RHCP beam, and the return loss of the horn all vary with frequency, which causes gain reduction. In particular at 8.8 GHz, the return loss of the horn is poor, resulting in a low gain. Since we do not have the complete data for the horn, this effect is not calculated in the simulation.

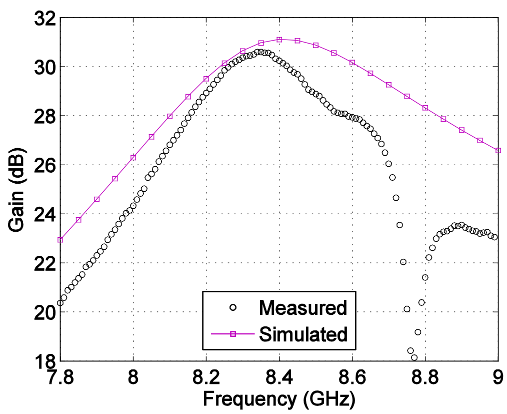

Fig. 15. Measured and simulated results of an offset reflectarray with D = 500 mm, f/D = 0.68, and q = 6.

Table 2: Gain and bandwidth from the measured and simulated results

	Gain at 8.4 GHz (dB)	1 dB Bandwidth (%)	3 dB Bandwidth (%)
Measured	30.25	2.86	6
Simulated	31.12	4.17	8.45

VI. CONCLUSION

Two methods of gain computation have been described, and it is observed that Method 2 has acceptable accuracy and takes less time for calculation. Based on the conducted parametric studies it was observed that the selection of f/D and q will affect both the gain and bandwidth performance of a reflectarray antenna. The tradeoff between gain and bandwidth is revealed to obtain an optimum performance of reflectarrays and it was observed that a reflectarray with large f/D and q can give a high gain and large bandwidth. At a fixed f/D and q value, an offset reflectarray has low gain but large bandwidth when compared to that of a broadside reflectarray. The gain and bandwidth of an X-band reflectarray has been calculated and the results are proved to be in good agreement with the measured results. For reflectarray with small D/λ, the spatial phase delay effect is smaller than the element effect on the performance of reflectarray.

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