Gain Limits of Phase Compensated Conformal Antenna Arrays on Non-Conducting Spherical Surfaces using the Projection Method

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***Abstract*—Previously, it has been shown that the projection method can be used as an effective tool to compute the appropriate phase compensation of a conformal antenna array on a spherical surface. In this paper, the projection method is used to study the gain limitations of a phase-compensated six-element conformal microstrip antenna array on non-conducting spherical surfaces. As a metric for comparison, the computed gain of the phase-compensated conformal array is compared to the gain of a six-element reference antenna on a flat surface with the same inter-element spacing and operating frequency. To validate these computations, a conformal phased-array antenna consisting of six individual microstrip patches, voltage controlled phase shifters and a power divider was assembled and tested at 2.22 GHz. Overall, it is shown how much less the gain of the phase-compensated antenna is than the reference antenna for various radius values of the sphere.**

***Index Terms*—conformal antenna array, phase compensation.**

I. Introduction

Conformal antenna arrays are used extensively in a wide variety of applications such as antennas on an aircraft [1], satellite arrays [2] and wearable networks [3]-[4]. One of the main advantages of a conformal antenna is the ability to place them on curved surfaces. This can be very useful because this removes the requirement of defining a flat surface, which may not be practical in some designs. On the other hand, these curved surfaces may be subjected to forces, such as vibrations, that alter the shape of the conformal surface (as shown in Fig. 1). If the shape of the conformal surface is changed significantly, this can have a negative impact on the radiation pattern of the conformal antenna array [5]-[9].

Fortunately, various methods have been proposed to improve the radiation pattern of a conformal array on a changing surface [10]-[19]. Among these methods is the projection method [20]. For illustration of the projection method, consider the conformal antenna on the curved surface in Fig. 2. This problem consists of six antenna elements placed on a cross-section of a sphere with radius r. A reference plane is also defined to be orthogonal to the z-axis (i.e., in the x-y plane) above the sphere. The reference plane is defined above the sphere for illustration purposes only. The antenna elements on the sphere are denoted as black dots and the elements in the reference plane are denoted as grey dots. One application of the projection method is to project the elements on the sphere onto the reference plane and consider the radiation from the projected array. This consideration assumes that the desired radiation of the array on the sphere is in the z-direction and that appropriate phase compensation has been utilized to ensure that the radiated field from each antenna element on the sphere arrives at the reference plane with the same phase. This will ensure a broadside radiation to the reference plane.

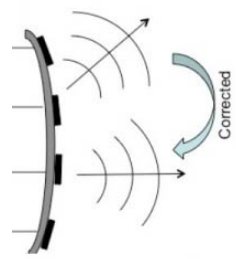

Fig. 1. Array on a conformal surface.

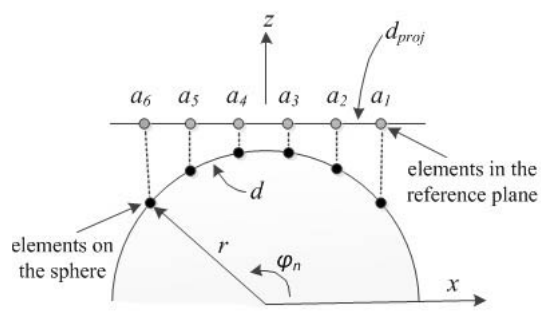

Fig. 2. Conformal antenna illustration of the projection method on a spherical surface.

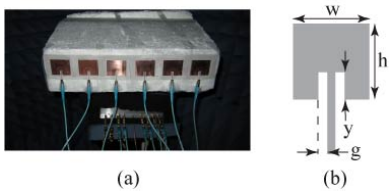

Fig. 3. (a) 1×6 fabricated array mounted on a flat surface and (b) layout of each individual patch (w = 48.0 mm, h = 39.64 mm, g = 2.0 mm and y = 11.0 mm).

The objective of this work is to use the projection method to study the gain limitations of a phase-compensated array on the non-conducting spherical surface in Fig. 2. The specific array considered for this work is the six-element conformal array shown in Fig. 3 (on a flat surface) with a spacing of $\lambda/2$ at an operating frequency of 2.22 GHz.

Related work of a conformal array on a wedge-shaped surface has been conducted and reported in [21]. In particular, this work presented analytical expressions that can be used to compute the gain of the phase-compensated array with respect to a flat array. The research reported in this paper differs in two ways. Namely, spherical surfaces are considered and the projected array has non-linear spacing.

II. Background

As mentioned above, one method of achieving radiation in the z-direction in Fig. 2 is to have each radiated field from the antenna elements on the sphere arrive at the reference plane with the same phase. To compute the amount of phase introduced by the propagation from the elements on the sphere to the reference plane, the following equation can be used [6]:

$$\Delta\phi_n = -kr(1 - \sin\phi_n) \tag{1}$$

where ϕ_n is the angle of the nth element on the sphere measured from the +y-axis. For the expression in (1), the reference plane has been moved to the top of the upper-hemisphere in Fig. 2. Therefore, to cancel this negative phase due to propagation to the reference plane, a phase shifter was used to introduce a positive compensation phase of

$$\Delta\phi_n^c = -\Delta\phi_n \tag{2}$$

at the nth element. Next, the gain of the projected array (i.e. phase compensated array) needs to be computed in the broadside direction. To do this, the spacing d_{proj} of the projected array will be computed in terms of the radius of the sphere r and the angular location of the elements on the sphere ϕ_n. For notation, the projected elements in Fig. 2 will be labeled as a_1, a_2, a_3, a_4, a_5 and a_6 starting from the right. Then, the spacing between the projected elements a_1 and a_2 can be computed as $d_{proj,1} = r(\cos\phi_1 - \cos\phi_2)$, between the projected elements a_2 and a_3 can be computed as $d_{proj,2} = r(\cos\phi_2 - \cos\phi_3)$ and between the projected elements a_3 and a_4 can be computed as $d_{proj,3} = 2r\cos\phi_3$. Due to symmetry, the spacing between elements on the left-hand side are similar. Because of the angles ϕ_n of each element on the sphere, $d_{proj,1} \neq d_{proj,2} \neq d_{proj,3}$. Therefore, the projected array should be considered as an array with a zero inter-element phase shift and a non-uniform spacing. To compute the gain from the array with non-uniform spacing, the following gain expression reported in [22] was used:

$$G = \frac{\left(\sum_{k=0}^{N-1} A_k\right)^2}{\sum_{m=0}^{N-1}\sum_{p=0}^{N-1} A_m A_p e^{j(\alpha_m - \alpha_p)} \frac{\sin[\beta(x_m - x_p)]}{\beta(x_m - x_p)}} \tag{3}$$

where x_n is the location of the nth element projected onto the reference plane, A_n is the amplitude of the nth element, $\alpha_m = \alpha_n$ due to phase compensation and ideal elements were assumed.

For comparison purposes, a six element reference array on a flat surface (i.e., $r = \infty$) with a spacing of $\lambda/2$ will be defined. Then, the gain shift G_s reported in [6] will be computed in the following manner:

$$G_s = G_c - G_r \tag{4}$$

where G_c is the compensated gain in the z-direction and G_r is the gain of the flat reference antenna. G_c can be determined by computing the gain of the non-uniformly spaced flat projected antenna array and G_r can be computed using the gain expressions reported in [22] for a Uniformly Excited, Equally Spaced Linear Array (UE,ESLA).

III. Analytical and Measurement Results

For measurement validation purposes, the prototype conformal phased-array antenna shown in Fig. 3 was developed. More specifically, this prototype was used to experimentally validate the phase compensation expressions in (2) and the gain shift values. The individual patch elements were designed for a center frequency of 2.22 GHz on a Rogers RT/Duroid 6002 grounded substrate [23] with a thickness of 20 mils ($\epsilon_r = 2.94$, $\tan\delta = 0.0012$) and the spacing between adjacent elements in the array was fixed at $\lambda/2$. The six individual elements of the array were connected to individual voltage controlled phase shifters with identical SMA cables. Then, each phase shifter was connected to a single port on the power splitter. The commercially available phase shifters were designed by Hittite Microwave Corporation (part no: HMC928LP5E) [24] on a connectorized board.

A. Flat Surface (Reference Array)

First, the prototype array was connected to the flat surface shown in Fig. 3 and the radiation pattern in the x-z plane was measured in a fully calibrated anechoic chamber. For these radiation pattern measurements all the antenna elements were fed in phase. The measured S_{11} of the array is depicted in Fig. 4 and the pattern measurements are shown in Fig. 5. A good match can be observed at 2.22 GHz. As a further validation, the array was simulated in HFSS [25] at 2.22 GHz. These results are also shown to agree with the measurements in Fig. 5.

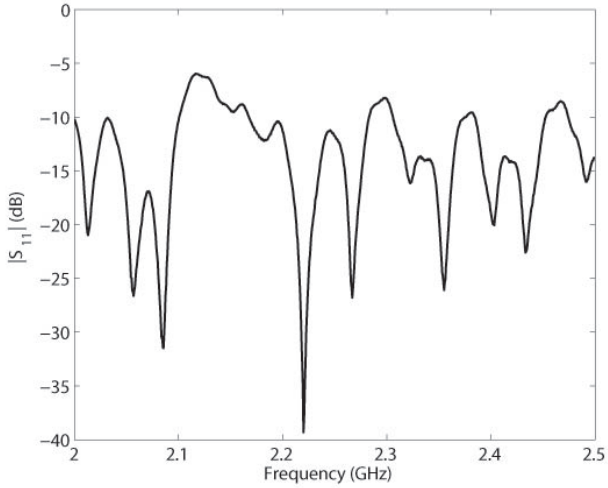

Fig. 4. Measured S_{11} of 1×6 Antenna platform

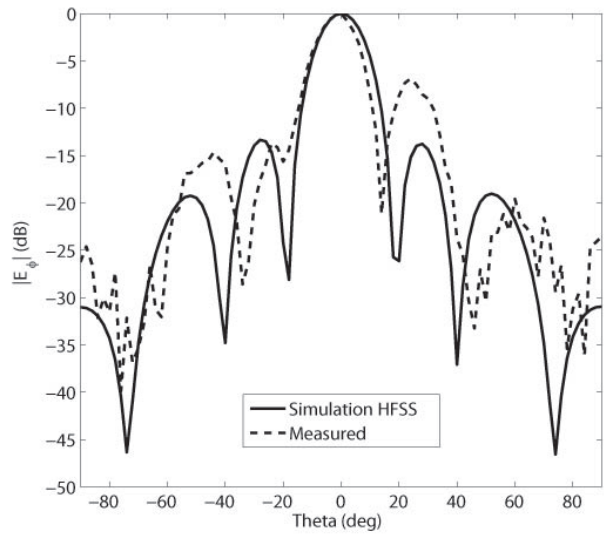

Fig. 5. Simulated and Measured Radiation Pattern in the x-z plane for the 1×6 array on a flat surface.

TABLE I
PHASE COMPENSATION

Surface	Patch 1	Patch 2	Patch 3	Patch 4	Patch 5	Patch 6
20.32 cm	177°	66°	7.5^o	7.5^o	66°	177°
27.94 cm	133°	48°	5°	5°	48°	133°

TABLE II
GAIN SHIFT VALUES AS COMPARED TO FLAT ARRAY

Surface	uncorrected	corrected
20.32 cm	-11.5 dBi	-2 dBi
27.94 cm	-6.5 dBi	-2 dBi

B. Spherical Surface with r = 20.32 cm

Next, the prototype antenna was placed on the spherical surface with a radius of r = 20.32 cm shown in Fig. 6. The phase compensation was then computed using (2) and the voltage controlled phase shifters were used to implement that phase correction in Table I. The measurement results for this case are shown in Figs. 7 and 8. For the uncompensated results, the voltage on each phase shifter was set to the same values. This meant that the fields radiated from the elements on the sphere arrived at the reference plane with different phases. Furthermore, for validation, the analytical expressions developed in [8] were used to plot the analytical array factor for both the uncompensated and compensated results in Figs. 7 and 8, respectively. Overall good agreement can be observed indicating that the phase-compensated array is working for spherical surfaces with r = 20.32 cm.

Finally, the radiation pattern for the flat and two spherical surfaces are compared in Fig. 12. The results shown here illustrate that the phase-compensated array pattern is very similar to the array of the reference antenna.

C. Spherical Surface with r = 27.94 cm

The prototype antenna was then placed on a non-conducting sphere (i.e., styrofoam) with a radius of 27.94 cm and the sphere was placed in the anechoic chamber for measurements. This is shown in Fig. 9. The uncorrected and corrected radiation patterns are shown in Figs. 10 and 11. The plot in Fig. 10 shows that the main beam moves from broadside and results in a wider radiation pattern with increased half power beam-width and decreased gain towards broadside. Now using the phase compensation values given in Table I, the main lobe was successfully recovered towards broadside.

D. Gain Shift

Next, the gain shift versus radius of curvature of the sphere was explored. The gain of the reference antenna was computed to be 7.7 dBi using the UE,ESLA equation in [22]. Then, the gain of the non-uniformly spaced projected array was computed using the expressions in [22] versus radius of curvature. The computations for the non-uniformly spaced array assumed that phase compensation was being used in the array on the spherical surface to ensure that each field radiated from each element arrived at the reference plane with the same phase. The results from these computations are shown in Figs. 13 and 14. The difference of these curves is defined to be the gain shift G_s and is shown in Fig. 14. The analytical difference in gain between flat array and conformal array for r = 20.32 cm and 27.94 cm is -0.5981 and -0.3205 dB respectively which are similar to the measured gain shift values in Table II.

E. Discussion on Phase Compensation

The following useful comments can be made about this research:

1) The results in Figs. 7, 8, 10, 11, 12 and Table I show that with appropriate phase compensation based on the projection method, the radiation pattern and gain broadside to the reference plane can be improved.

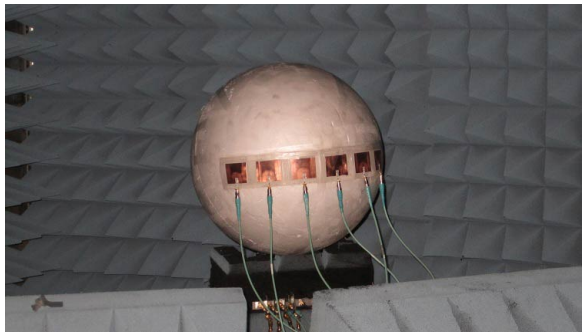

Fig. 6. 1×6 antenna array mounted on a sphere with a 20.32 cm radius.

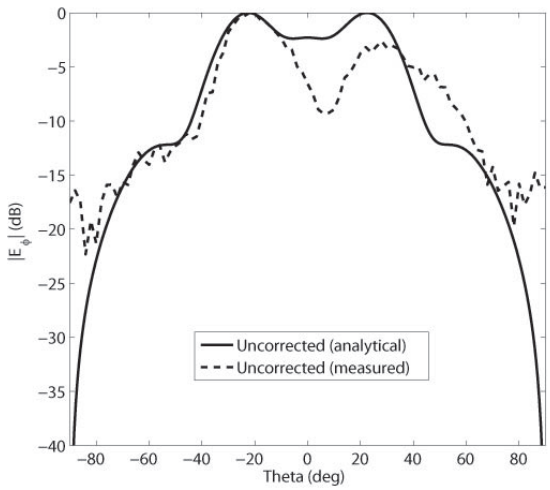

Fig. 7. Uncorrected radiation pattern for a sphere with a 20.32 cm radius.

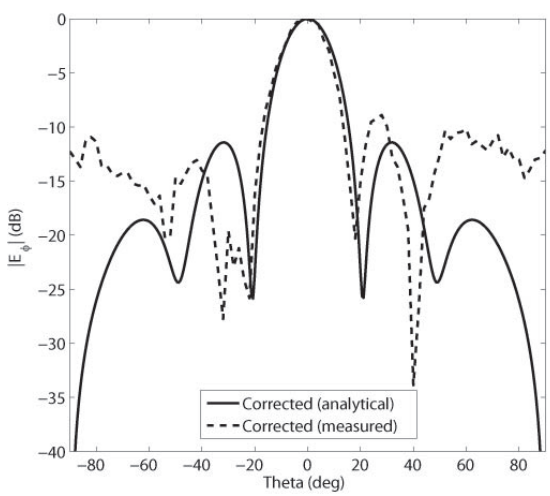

Fig. 8. Corrected radiation pattern for a sphere with a 20.32 cm radius.

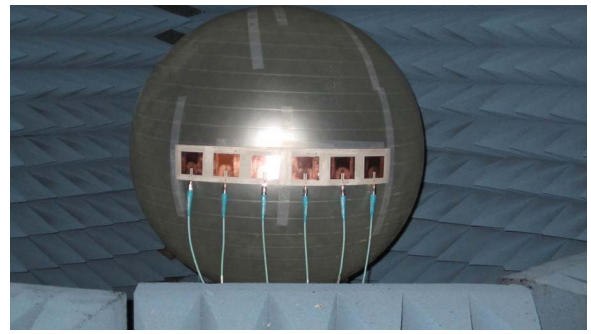

Fig. 9. 1×6 antenna array mounted on a sphere with a 27.94 cm radius.

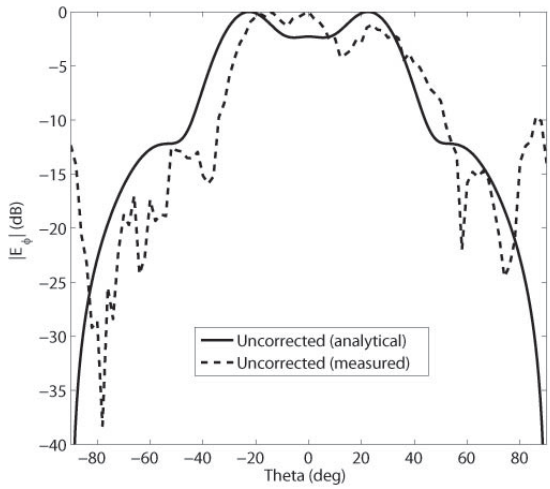

Fig. 10. Uncorrected radiation pattern for a sphere with a 27.94 cm radius.

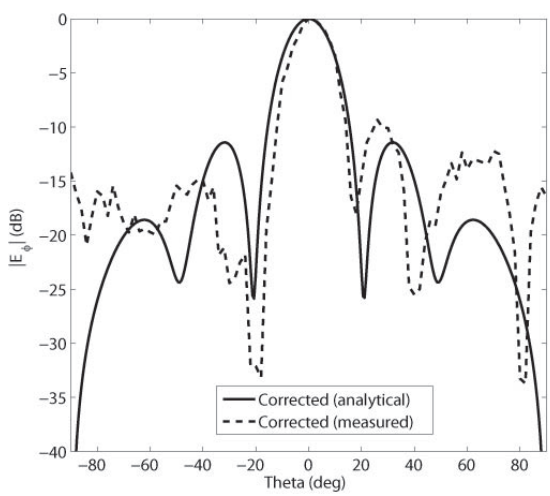

Fig. 11. Corrected radiation pattern for a sphere with a 27.94 cm radius.

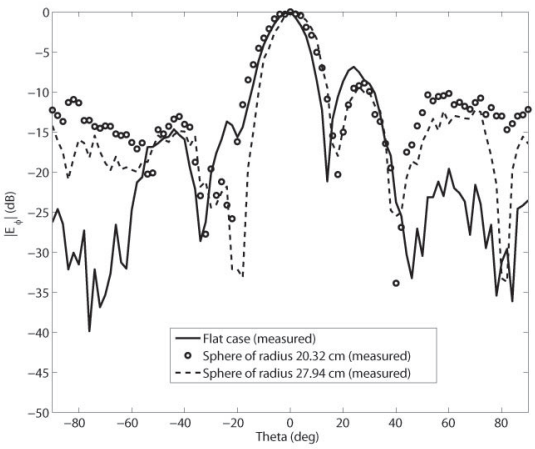

Fig. 12. Comparison between flat and conformal array radiation pattern.

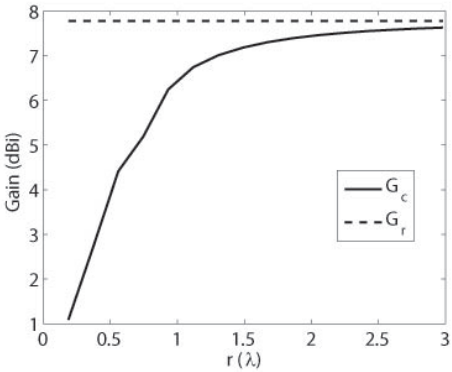

Fig. 13. Gain of the projected array with non-uniform spacing as the radius of the sphere changes.

2) The gain-shift results in Figs. 13 and 14 illustrate the maximum gain that can be achieved using the compensation methods described here versus the radius of the spherical surface. This will be helpful for designers when choosing a compensation technique.

IV. Conclusion

The restrictions of a phase-compensation conformal array on a spherical surface have been investigated here. More specifically, the maximum gain of a spherical array using a phase-compensation method based on the projection method has been explored using simulations, analytical expressions and a prototype antenna. In summary, this research has shown the manner in which the gain of the compensated array degrades as the radius of the sphere is reduced.

Acknowledgment

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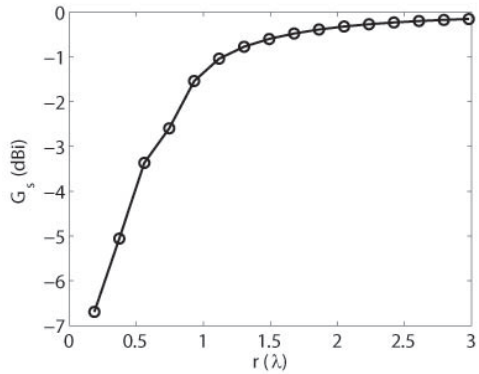

Fig. 14. Gain shift of the phase-compensated array as the radius of the sphere changes.

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