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Bandwidth Enhancement of a Metal-Only Reflectarray Based on the Phoenix Cell

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Abstract— This paper presents a detailed analysis of the effect of the height of the 3D Phoenix Cell on the performance of Metal-Only Reflectarray Antennas. An improved design approach is proposed and a 18% bandwidth (for gain variations less than 1 dB) is obtained after the optimization.

I. INTRODUCTION

Reflectarray antennas (RAs) can be seen as a combination of planar arrays and parabolic reflectors with the advantages of high gain, low profile, low cost and easy manufacturing. Normally, RAs are designed using planar structures which have fixed height, such as microstrip cells. Recently, a 3D unit cell was proposed by some of the authors, the so-called 3D Phoenix Cell (PC) and it was fabricated using Selective Laser Melting technology [1]. This new cell is a Metal-Only (MO) structure, which avoids the use of dielectric materials and their associated drawbacks (such as the insertion losses, possible outgassing in vacuum, etc). In [2], the 3D PC has been used to design a Metal-Only Reflectarray Antenna (MORA). The phase variation of the cells was obtained by changing only one geometrical parameter, namely the cross-section of the internal metallic waveguide within the cell. However, the height of all cells in the designed MORA was identical.

The present contribution aims at improving the performance of the previous MORA by exploiting another degree of freedom in the 3D PC, its height. This paper offers a detailed analysis of the effect of the height of the 3D PC on the performance of MORAs. Part II introduces the 3D PC. Part III describes the initial and improved RA design approaches and analyzed 5 different MORAs. Finally, a conclusion is made in part IV.

II. 3D PHOENIX CELL

A RA unit cell named as 3D Phoenix cell was recently proposed by some of the authors of this paper in [1], its main features are shown in Fig.1. It consists of two concentric square metallic waveguides and a square metallic block at the center. The performance of such 3D PC has been explained in [1], and it will not be revisited here for the sake of conciseness. The detailed parameters of the 3D PC used in this paper are tabulated in Table I. The center frequency is 20GHz. Note that a database is established by varying both the height of the 3D PC (h) and the cross section of the internal waveguide (L_r). In comparison to the design proposed in [2], here the variable h is used as an additional degree of freedom and varied in a large range to improve the performance of the MORA. The 3D PC is simulated using HFSS[®]. During the simulations, perfect

electric conductor boundaries are assigned on the metallic surfaces. A Floquet port is used at the input and master/slave boundary conditions are assigned on the lateral faces to mimic a cell in a periodic infinite environment.

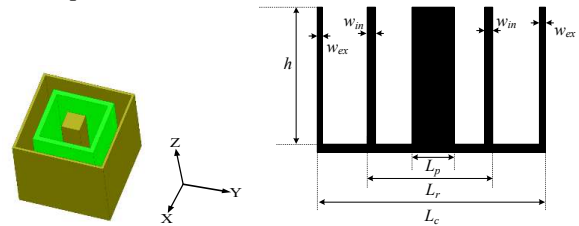


Figure 1. The 3D view of the PC (left) and the sectional view (right).

TABLE I. THE DETAILED PARAMETERS OF 3D PC.

Parameter	L_c	L_r (step 0.1)	L_p	h (step 0.1)	w_{in}	w_{ex}
Value(mm)	7.5	1-7.5	1	4-10	0.2	0.2

III. REFLECTARRAY DESIGN AND ANALYSIS

Five RAs are designed in this paper. The radiating aperture of each RA is $13\lambda_0 \times 13\lambda_0$ (λ_0 being the wavelength in free space at central frequency, $f_0 = 20\text{GHz}$) while the spacing is $0.5\lambda_0$. The RA is illuminated by a horn antenna with an offset angle of 25° with respect to the normal of the panel. The f/d ratio is 1.183. The direction of the main beam has a tilt angle of 25° (opposite to the offset). Each designed RA is simulated in HFSS[®] together with the illuminating horn antenna.

A. Initial design approach and analysis

All the designs in this paper were done based on the phase-only synthesis approach presented in [3], which minimizes the total phase error at two frequencies by selecting an appropriate reference phase for each frequency. The cumulative phase error over all $N \times N$ cells at both frequencies is based on the equation below:

$$Er_{cum} = \sum_{n=1}^N \sum_{m=1}^N [I_{mn_up} \times Er_{mn_up} + I_{mn_low} \times Er_{mn_low}] \quad (1)$$

where I_{mn_up} and I_{mn_low} represent the normalized illumination intensity of mn^{th} element at upper frequency and lower frequency respectively. Er_{mn_low} and Er_{mn_up} are the phase errors of the mn^{th} element at both frequencies. Here, f_{low} and f_{up} are set to 19.5GHz and 20.5GHz respectively in order to enlarge the bandwidth around $f_0 = 20\text{GHz}$.

Firstly, two different RAs are designed using this approach. The first RA (RA1) has fixed height ($h = 6\text{mm}$) while the second one (RA2) is designed using PCs with

variable height ($h \in [4, 10]$ mm). The detailed parameters of all the designed five RAs are tabulated in Table II. Figure 2 depicts the gain versus frequency in the direction of maximum radiation.

Table II shows that the cumulative phase error of RA2 is much smaller than that of RA1 at both frequencies which demonstrates the ability to better control the phase thanks to this second degree of freedom. However, it can also be seen from Fig.2 that the gain of RA2 is lower than that of RA1 except for a few frequency points. This dysfunction of the design process can be understood by analysing the variation of the cell geometry in both RAs. To do so, Fig.3 (left) presents the optimized values of L_r for RA1 while Fig.3 (middle) and (right) show that of L_r and h in RA2. It appears that the introduction of a new degree of freedom (h) resulted in a more chaotic distribution of the successive geometries. This is particularly visible in Fig.3 (right) where isolated cells with large h (yellow dots) can be observed within the panel. Such abrupt variations in the geometry between two adjacent cells in RA2 may decrease the accuracy of the phase predictions, and subsequently result in a gain drop and a bandwidth reduction.

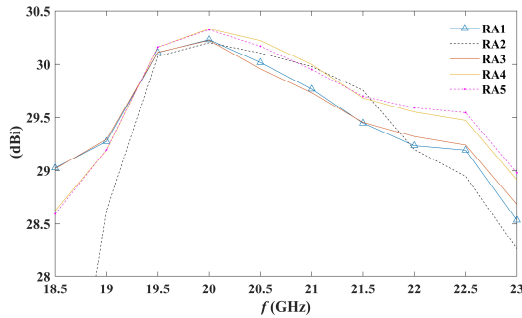


Figure 2. The gain versus frequency of RA1, RA2, RA3, RA4, RA5 in the desired direction.

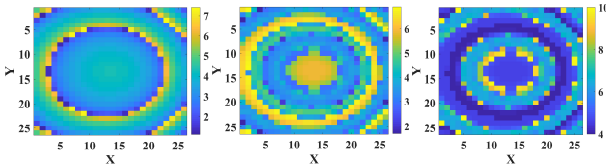


Figure 3. Cells geometry evolution in the array (mm): The L_r of RA1 (left); The L_r of RA2 (middle); The h of RA2 (right).

B. Improved design approach and analysis

The previous section shows that reducing the phase error is not sufficient to enhance the antenna performance. Preserving a smooth geometry evolution in the array remains an imperative factor. This section aims to expand the design process, in order to fully benefit from the capability of the 3D PC with variable height to improve the bandwidth of the RA. The idea relies in finding a method that permits to reduce the total phase error while preserving this smooth geometry variation.

In order to reduce the difference in the geometry between two adjacent cells, a predefined limitation is added to the process to design a RA. There are two variables for each cell: L_r and h . Since a smooth L_r distribution can easily be obtained (as shown in Fig.3 (left) for RA1), the improvement of the

design process focuses on the height h of the cells. More precisely, it is proposed to limit the variation in the value of h between two adjacent cells. The maximum difference between two such cells (dh) is adjusted to find a better balance between the total phase error and the smoothness of the cell geometries over the RA. In this process, L_r and h are derived successively. Also, since the cells in the center have stronger illumination intensity, the geometry of these cells is determined first. As a consequence, for any two adjacent cells, the difference of h is no more than the predefined dh .

TABLE II. THE DETAILED PARAMETERS OF RA1-RA5.

	dh (mm)	h (mm)	Cumulative phase error (°)		
			19.5GHz	20.5GHz	19.5GHz + 20.5GHz
RA1	---	6	6.96	8.30	15.26
RA2	---	4-10	4.14	3.91	8.05
RA3	0.5	5.4-6.4	7.10	7.50	14.60
RA4	1	4.7-6.7	7.50	7.09	14.59
RA5	1.5	4.2-7.1	7.91	6.64	14.55

In order to verify the aforementioned optimization process, three different RAs (RA3, RA4, RA5) are designed. They differ by the used value of dh (0.5, 1 and 1.5 mm respectively). It can be seen from Table II that the cumulative phase error decreases with the increases of dh , which is consistent with the fact free variations in h provide an additional degree of freedom to reduce the error. It can be seen from Fig.2 that there is no obvious change in gain between RA1 and RA3 (when dh is equal to 0.5 mm). On the contrary, the 1-dB bandwidth is increased from 15% to 18% for RA1 and RA5. These results make it possible to validate the proposed optimization process and subsequently the impact of the regularity of the geometries of the cells on the panel.

IV. CONCLUSION

In this work, five different RAs are designed to investigate the effect of the height of the 3D PC on the performance of MORAs. Simulation results show that the gain of MORAs can be optimized by selecting an appropriate height for each cell, provided that geometric variations between adjacent cells are limited. A design methodology is proposed and validated by improving the bandwidth from 15 to 18%. A prototype will be produced to validate these results experimentally.

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