Progress In Electromagnetics Research Letters, Vol. 50, 67–72, 2014

A Broadband Reflectarray Using Phoenix Unit Cell

Chao Tian*, **Yong-Chang Jiao, and Weilong Liang**

Abstract—In this letter, a novel broadband single-layer reflectarray element composed of a circular patch and double circular ring is presented. The element in the reflectarray provides a nearly 360° linear phase range and has rebirth capability. The broadband characteristic of this reflectarray is obtained due to the sub-wavelength of the element space and the combination of two resonators of complementary size on a single layer. Then, a prime-focus 225-element microstrip reflectarray with this Phoenix cell has been designed and implemented. The measured gain is 22 dBi with 1 dB drop within 29% bandwidth at the center frequency of 10 GHz.

1. INTRODUCTION

The microstrip reflectarray is rapidly used in both terrestrial and satellite communication systems because of its advantages such as low profile, ease of manufacture, and possibilities offered for beam shaping and electronic beam control [1–4]. These characteristics make the reflectarray technology a suitable choice for satellite and wireless communication systems. However, the most severe drawback of the microstrip reflectarray is its limited bandwidth performance. Therefore, intense efforts have been made in recent years to overcome this shortcoming. The bandwidth performance of a microstrip reflectarray is limited primarily by two factors. The first is inherent narrow bandwidth behavior of microstrip elements themselves. The second is the differential spatial phase delay resulting from the different paths from the feed to each reflectarray element. However, this letter presents the elements with linear phase response which can be used to improve the bandwidth of reflectarrays with moderate sizes.

In order to extend the range of linear phase frequency response as wide as possible, different approaches such as multilayer stacked patches [5, 6], multiresonant broadband elements [7], phase-delay lines [8], and circular rings with open-circuited stubs [9] have been proposed. However, these methods will introduce more complexity, higher cost in the fabrication process and higher power loss.

Recently, single-layer elements have attracted more attention. Several novel structure including double-petal loop element [10], square cross element [11], and rectangular-patch/ring combination element [12] have been proposed for broaden the single-layer reflectarray bandwidth. In [13], the single-layer with rectangular-patch/double-loop combination element called Phoenix cell is presented. Phoenix cell is designed to overcome the limited antenna bandwidth, which is a common issue faced by most microstrip reflectarray cells. The design is based on the idea of employing multiresonators to each cell which in turn improves the bandwidth characteristics. Another different technique for designing broadband reflectarray is using sub-wavelength coupled-resonant elements [14] instead of conventional $\lambda/2$ ones. In most applications, the characteristics of sub-wavelength resonance are important, but it is not reported in [13].

In this letter, we propose a novel reflectarray cell, consisting of a circular-patch and a double-ring, whose geometry exhibits a cycle evolution. More precisely, it comes back to its initial shape after a

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Received 30 September 2014, Accepted 13 November 2014, Scheduled 28 November 2014

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whole theoretically 360° phase cycle has been achieved. Several important parameters of the element are investigated using the Ansoft HFSS software. Compared to the Phoenix cell in [13] and single-layer element in [12], the novel element can obtain larger 1-dB gain bandwidth.

2. THE STRUCTURE AND PHASE CHARACTERISTICS OF THE PROPOSED CELL

The Phoenix cell operates around resonance with grid spacing of the order of 12 mm, which is equivalent to 0.4 wavelengths at 10 GHz. Periodic boundary conditions are introduced to take into account interactions with identical neighbor elements.

The proposed element is shown in Figure 1. The element is built from a circular ring slot with radius r_4 and width w_d. A metallic ring (radius r_3 and width w_r) and circular patch (radius r_1) are inserted into the slot. The phase shift reflected by the element is defined by changing the radius r_3 of the metallic ring. When the radius of r_3 varies from $r_{3\min} = r_1$ to $r_{3\max} = r_4 + 2w_d$ (from step 1 to 5 shown in the Figure 2), the phase shifts from 0° to 360°, thus the rebirth capability can achieve. The complete cycle is described in Figure 2.

The configurations discussed in the previous literature [12, 13] operate around resonance with grid spacing of the order of 17 mm and 35 mm, which are equivalent to 0.56 and 0.5 wavelengths. The

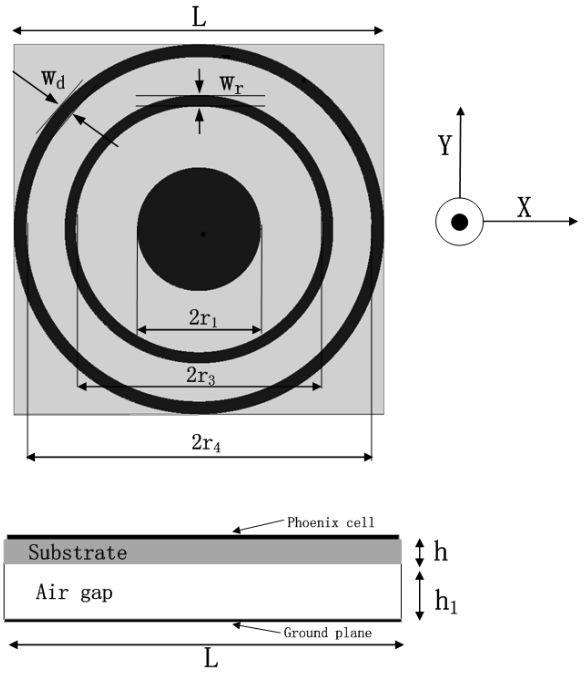


Figure 1. Geometry of the proposed element.

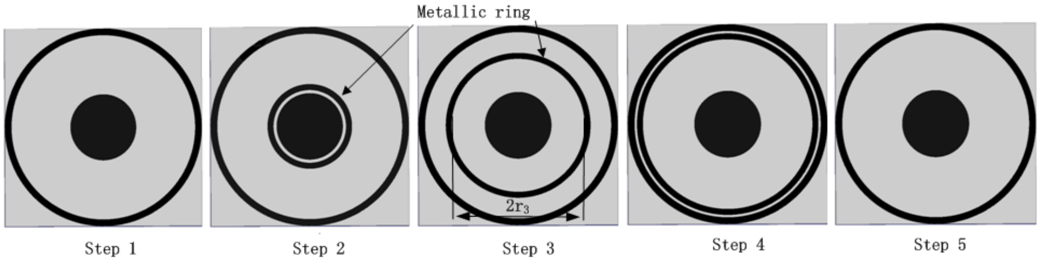
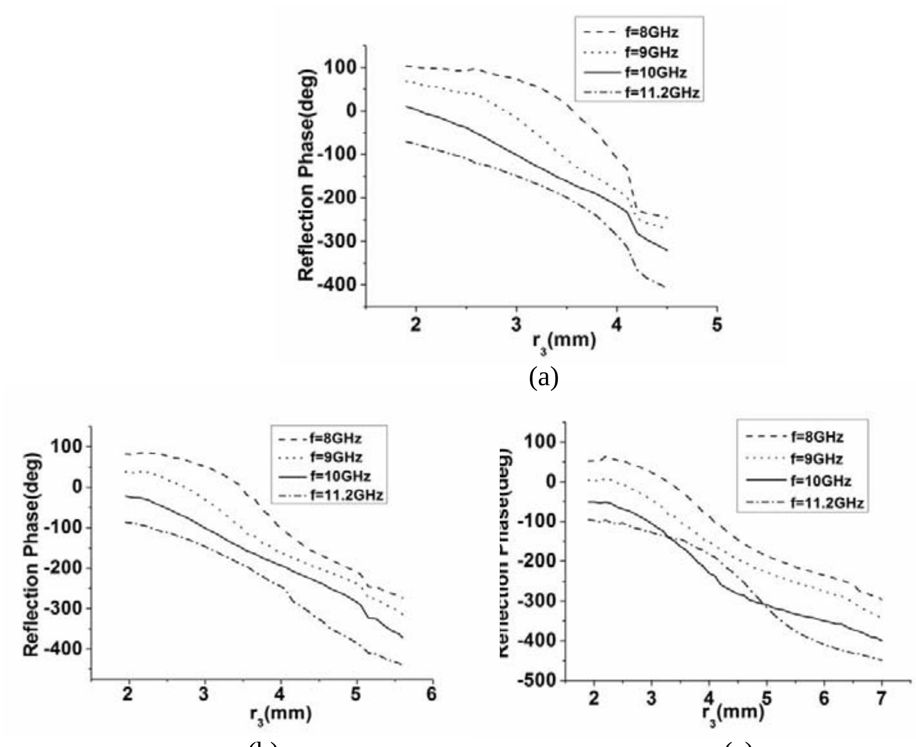


Figure 2. The unit cycle: evolution of the cell geometry over a complete 360° cycle.

proposed structure in this letter is revised slightly. In this case, the reflectarray is assumed to be formed by identical elements arranged in a square lattice with periodicity of $L = 12\,\mathrm{mm}$, which is equivalent to 0.4 wavelengths at 10 GHz. And the circular/double ring structure can get better results on bandwidth.

To validate the proposed design, we study the phase characteristics for the patch element with different grid spacings. Figure 3 shows the phase variation corresponding to the inter-element space. Firstly, it shows that the sub-wavelength unit cells can almost achieve the same phase range as half wavelength unit cell which is typically around 360° for this Phoenix cell. Secondly, by using a proper grid spacing it can yield a set of phase curves which have better parallelism over a large frequency range. It is well known that this can result in an improved antenna bandwidth. In this letter, grid spacing is chosen as 0.4λ.

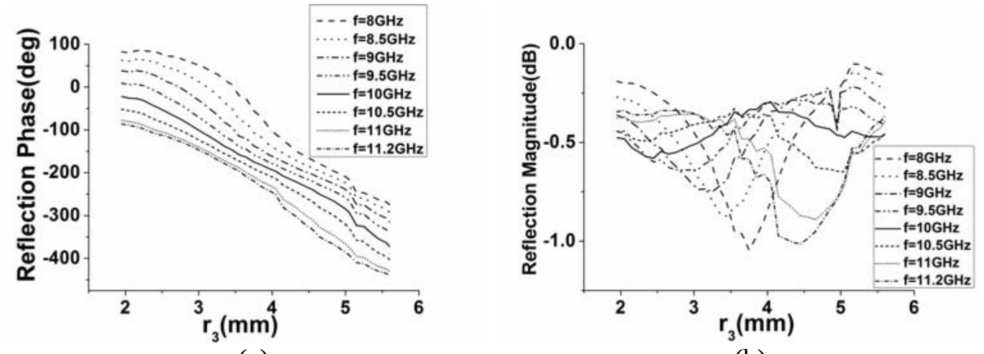


(a)

(b)

(c)

Figure 3. Phase responses of the Phoenix cell for different sub-wavelength element. (a) $L = \lambda/3$, (b) $L = 0.4\lambda$, (c) $L = \lambda/2$.



(a)

(b)

Figure 4. Phase and magnitude responses of the Phoenix cell versus r_3 for different frequencies (8.0–11.2 GHz). (a) Reflection phase. (b) Reflection magnitude.

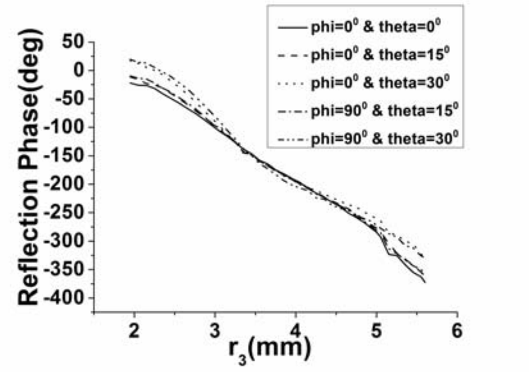


Figure 5. Phase responses of the Phoenix cell versus r_3 for different incident angle at the center frequency of 10 GHz.

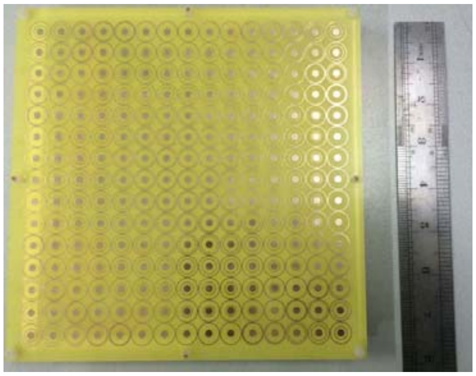


Figure 6. Photograph of the designed 225-element linear reflectarray.

The phase and magnitude of the reflected wave against r_3 are plotted for different frequencies (8.0–11.2 GHz) in the Figure 4. It can be noticed from Figure 4(a) that the several phase curves are approximately parallel. This property leads to the differential phase shift being approximately constant as a function of frequency in the 8.0–11.2 GHz band. This is the required property of the phase characteristic for the broadband reflectarrays. Figure 4(b) shows the reflection magnitude of the unit cell. The loss is mainly due to the dielectric loss, and the performance of the reflection magnitude is acceptable.

Figure 5 depicts the variations in the reflection phase at different oblique incidence angles and for x-polarized incidence signal. The parameters Φ (phi) and θ (theta) are the azimuth and elevation angles, respectively, of the incidence wave. For both TE mode (phi $= 0°$) and TM mode (phi $= 90°$), there are almost no variations in the reflection phase, except small changes at element dimensions ($r_3 < 2.5$ mm and $r_3 > 5$ mm) and with oblique incidence as high as $\theta = 30°$. So the influence of the different incident angles is acceptable.

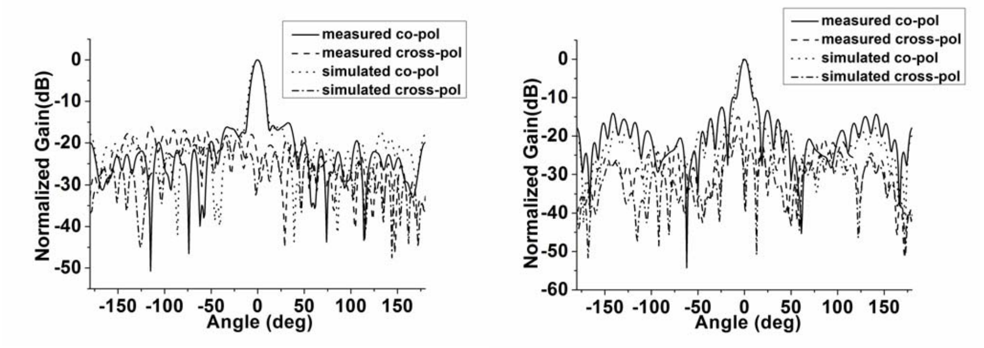
According to the analysis of the proposed reflectarray element, it can be concluded that this novel Phoenix element, consisting of a circular patch and a double ring, can improve the bandwidth characteristics for a moderate size microstrip reflectarrays very well, especially for the single-layer reflectarrays. By simply inserting air layer with a proper thickness between the substrate and the ground plane and properly choosing the grid spacing, the broadband performance can be achieved.

3. EXPERIMENTAL VALIDATION

The Phoenix cell reflectarray using proposed radiating elements has been designed and fabricated. A photograph of the reflectarray prototype is given in Figure 6. The reflectarray consists of 15 × 15 elements printed on a grounded substrate with thickness $h = 1.6$ mm and relative permittivity $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$. The element spacing is $h_1 = 8$ mm so that the size of the reflectarray is $180 \times 180\,\mathrm{mm}^2$. The width of metallic rings are $w_r = 0.35$ mm and $w_d = 0.4$ mm, respectively. The dimension of circular patch is $r_1 = 2$ mm.

In order to validate the effectiveness of the Phoenix cell, a prime-focus 225-element reflectarray is designed and measured. Since the horn will seriously block the reflected wave from the reflectarray, a linearly polarized Vivaldi antenna is chosen as the feed, located 145 mm above the center of the reflectarray, thus giving an F/D ratio equal to 0.8. Considering the radiation pattern of the feed and the configuration of the reflectarray, the illumination levels near the centers of four borders are all about -9 dB. The reflectarray is measured in the Microwave Anechoic Chamber. Moreover, the spillover efficiency is calculated, and its value is 47%, and the taper efficiency is 88%.

Figure 7 presents the measured and simulated radiation patterns of both co-polarization and cross-polarization in E-plane and H-plane for the designed reflectarray at 10 GHz. The measured half-power beamwidths in E-plane and H-plane are 10° and 8°, respectively. The measured and simulated



(a) (b)

Figure 7. The measured radiation patterns for the designed 225-element linear reflectarray. (a) *E*-plane. (b) *H*-plane.

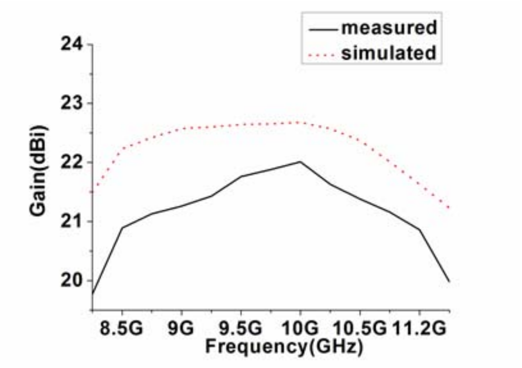


Figure 8. Measured and simulated gains of the designed 225-element linear reflectarray.

directivities are 22.7 dB and 23.2 dB. In Figure 7, the measured and simulated isolations between the two orthogonal polarizations are about 20 dB and 25 dB in the broadside direction. The measured and simulated gains against frequencies from 8 to 11.5 GHz of the proposed reflectarray are shown in Figure 8. It can be seen that the measured and simulated bandwidths, found from the obtained gain variation with frequency (1 dB drop is considered here), are 29% (from 8.3 to 11.2 GHz) and 31% (from 8.1 to 11.2 GHz), respectively. And the measured and simulated peak gains are 22 dBi and 22.6 dBi, at the center frequency of 10 GHz. The antenna efficiency, calculated by comparing the measured copolarized gain to the directivity based on the physical aperture area, is 35% at 10 GHz.

4. CONCLUSION

A novel Phoenix element has been analyzed to design a broadband reflectarray antenna. Element phase response shows a nearly 360° linear phase range and rebirth capability. By using these elements with proper grid spacing and taking into account the oblique incidence, a prime-focus 225-element reflectarray operating at 10 GHz has achieved a 1-dB gain bandwidth of 29%, which is larger than conventional single-layer element.

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