Broadband High Efficiency Single-Layer Reflectarray Antenna Based on Spiral Crosses

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Abstract **─** This paper presents the design and analysis of a broadband high gain reflectarray antenna based on a novel radiating element, named spiral cross, that has been investigated showing high performance capabilities. The unit cell and the reflectarray antenna have been analyzed by using a full-wave Moment Method code. The proposed antenna exhibits excellent polarization purity, an aperture efficiency of 43.5 %, and a 25.3% bandwidth for 3-dB gain reduction operating at 20 GHz.

Index Terms - Broadband antenna, cross polarization, and reflectarrays.

I. INTRODUCTION

During the last few years, microstrip reflectarray antennas have received the interest of the research community because of its well-known multiple advantages. They have several attractive applications such as remote sensing, radar, satellite communications, and direct broadcast satellite services. Reflectarray antennas combine the benefits of parabolic reflectors and phased arrays antennas, which are low weight, low profile, low cost, compatibility with active devices, beam scanning capabilities, and short manufacturing time. On the other hand, their main disadvantage is the narrow-band behavior, which is due to the inherent narrow-band nature of the microstrip radiating elements and to the different spatial phase delays between the feed and each element. The second factor is more dominant in the case of large size reflectarrays, and depends on system parameters like aperture diameter, *f/D* ratio, and power factor of the feed pattern [1]. To overcome this limitation, some proposals based on multilayer configurations [2-4], single-layer multi-resonant structures [5], aperture coupled lines [6], sub-wavelength unit cells [7], and rectangular dielectric resonators [8] have been reported.

In this case, the adopted solution to increase the bandwidth is based on a single substrate layer of spiral crosses that provides a wide phase range with varying the size of the crosses. The analyzed single-layer spiral cross is cost effective and easy to fabricate, and shows good response in term of bandwidth. A reflectarray antenna has been designed and analyzed to evaluate the benefits of the proposed unit cell. Results show a notable improvement in terms of bandwidth, cross-polarization levels, and aperture efficiency when comparing with conventional single-layer reflectarrays.

II. UNIT CELL DESIGN

The design of the unit cell is a tedious task, since it must provide an appropriate reflection phase curve with a phase range wider than 360º and a linear curve slope. If both requirements are fulfilled, a wide bandwidth can be achieved and manufacturing errors can be reduced. Since the behavior of the reflectarray antenna strongly depends on the unit cell response, the optimization of its geometrical parameters is a mandatory pre-process that must be carried out before generating the whole reflectarray antenna layout.

The proposed elementary cell is a spiral cross composed of a conventional metallic cross and two little stubs perpendicularly located at the end of its four arms. We have found that the effects of adding these two little stubs are: 1) an important

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increase in the aperture efficiency and 2) a notable bandwidth enhancement.

A single-layer configuration has been used to design the unit cell to simplify the manufacturing process and reduce the cost of the antenna. Figure 1 shows the top view of the spiral cross. The dielectric substrate located between the spiral cross and the ground plane is a 3 mm thick interface of relative permittivity $\varepsilon_r = 1.05$ and low loss tangent. It is commonly named as foam.

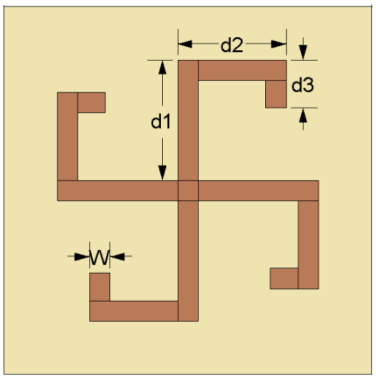

Fig. 1. Top view of the unit cell.

A parallelized Moment Method code [9-10] has been used to analyze the behavior of the unit cell. The phase curve is computed by analyzing a periodic array of identical unit cells that scatter a normal incidence plane wave. Figure 2 depicts the reflection coefficient phase versus the length of the spiral cross in the band from 18 GHz to 22 GHz. It can be seen that the phase range is slightly wider than 360º and the phase variation is quite smooth. The first condition ensures high directivity levels and the second avoids manufacturing errors due to minimum manufacturing tolerances. Note that the frequency curves remain quite linear, with no changes in the slope at extreme frequencies.

It is important to highlight that the size variation is affected to the parameters d1, d2 = 0.9d1, and d3 = 0.4d1. The variation range of parameter d1 is set from 1.763 mm to 4.249 mm, and the cross width is set to 0.5 mm in every cell.

The phase curve of a conventional cross has been also analyzed in order to evaluate the benefits of the spiral cross. The same parameter variation has been carried out at the same frequencies. In Fig. 3 it can be observed that the phase range is less than 360º for every frequency.

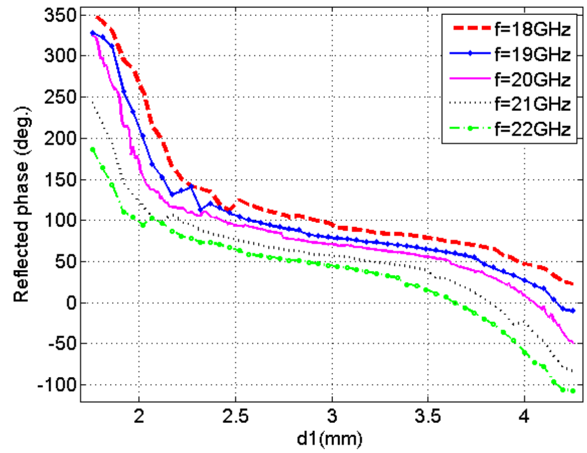

Fig. 2. Phase curve of the spiral cross in the band from 18 GHz to 22 GHz.

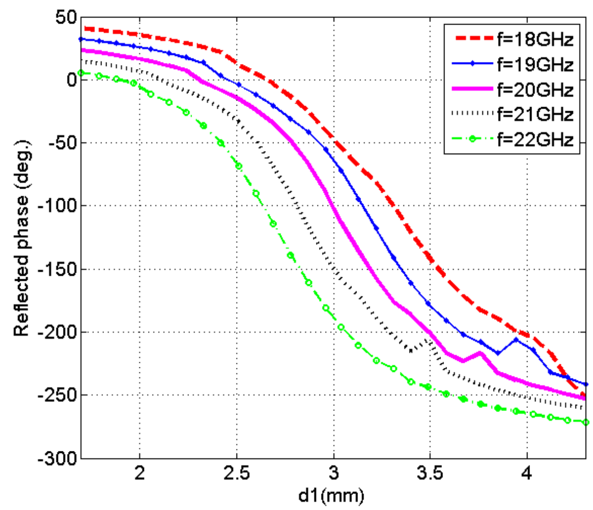

Fig. 3. Phase curve of the conventional cross in the band from 18 GHz to 22 GHz.

The reflected phase of both crosses has been also studied versus the thickness of the substrate. The results are shown in Figs. 4 and 5. It can be seen that the curve slope is too abrupt for thinner substrates in both cases. Again, the phase range is less than 360º in the case of the conventional cross for every thickness.

III. REFLECTARRAY ANTENNA DESIGN

Two center-fed reflectarray antennas have been designed and analyzed to validate the performance of the proposed unit cell. Once the phase curves are obtained, the layouts of the reflectarray antennas are generated taking into account the phase shift introduced by each radiating element, which can be computed as follows,

$$\phi_i = k_0(d_i - \vec{r_i} \cdot \hat{r_0}) + 2\pi N \quad N = 0, 1, 2, \ldots \tag{1}$$

where k_0 is the propagation constant in vacuum, $\hat{r_0}$ is the unit vector in the desired direction of the main beam, $\vec{r_i}$ is the position vector from the center of the reflectarray plane to the i_{th} radiating element, and d_i is the distance from the feed to the i_{th} element.

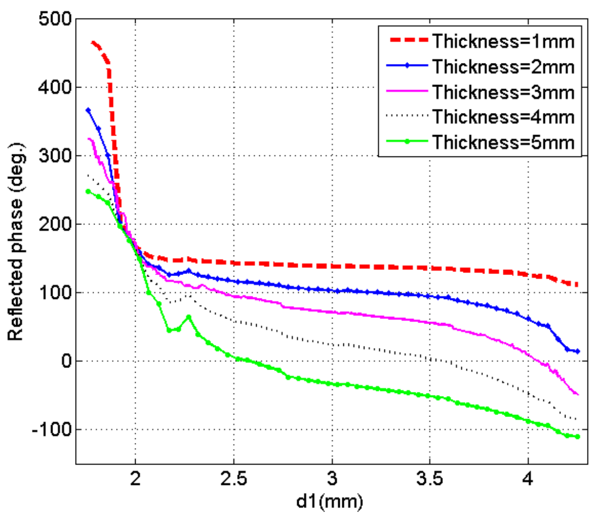

Fig. 4. Phase curve of the spiral cross versus the thickness of the substrate.

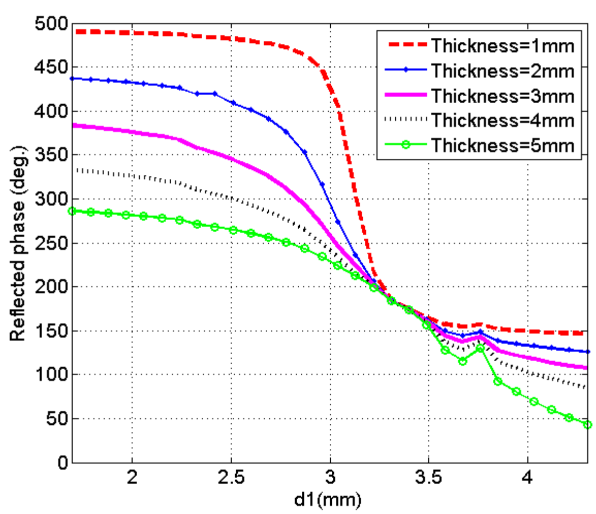

Fig. 5. Phase curve of the conventional cross versus the thickness of the substrate.

Figures 6 and 7 depict the top view of the obtained layouts. The feed location ($x_f = 0$, $y_f = 0$, $z_f = 120$ mm) is the same for both cases and has been calculated to maximize the antenna efficiency. The periodicity has been set to 0.6 λ to avoid grating lobes. The radiating elements are symmetrically located in a 15 × 15 square lattice, so the total size of the reflectarrays is 135 × 135 mm (9λ × 9λ at 20 GHz).

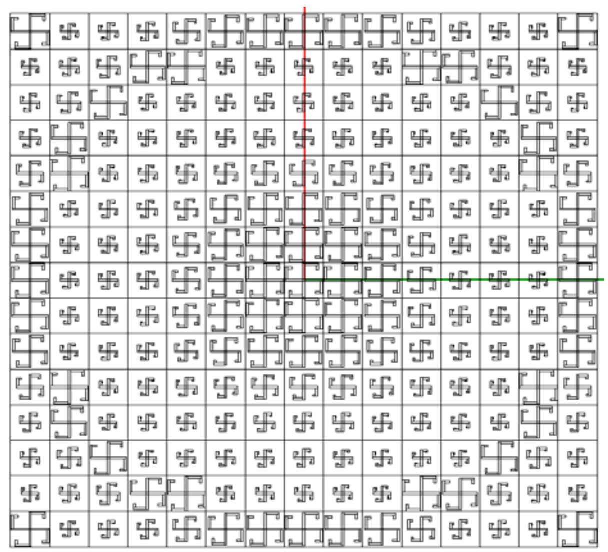

Fig. 6. Layout of the reflectarray antenna composed of spiral crosses.

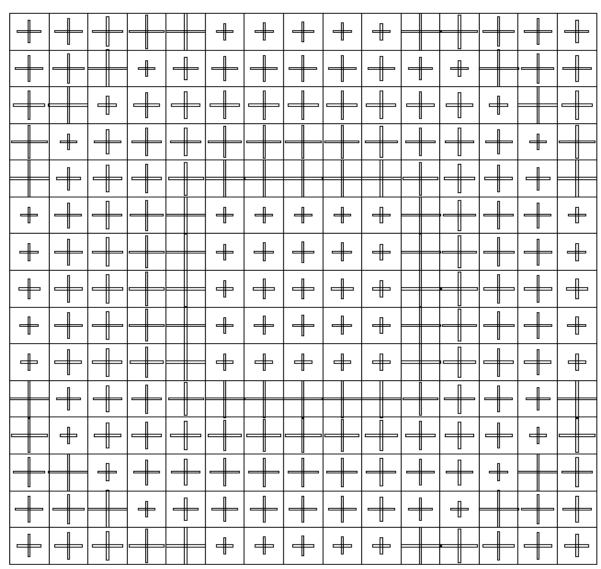

Fig. 7. Layout of the reflectarray antenna composed of conventional crosses.

IV. RESULTS

The designed reflectarray antennas have been analyzed by applying a full-wave Moment Method code [9-10]. Hence, the formulation takes into account the incidence angle of the waves that are reflected by each radiating element. This code has been validated in many benchmark experiments to check its reliability [11-13], showing high accuracy when comparing to measurements. The same linearly polarized antenna has been used to feed the reflectarrays. Figure 8 depicts the normalized radiation pattern of the feed antenna that is used in the numerical simulations.

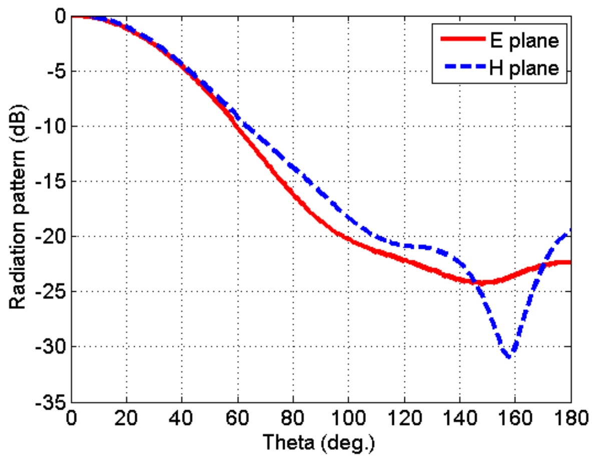

Fig. 8. Radiation pattern of the feed antenna.

The current distribution and the 3D far field radiation pattern of the spiral cross reflectarray at 20 GHz are shown in Fig. 9.

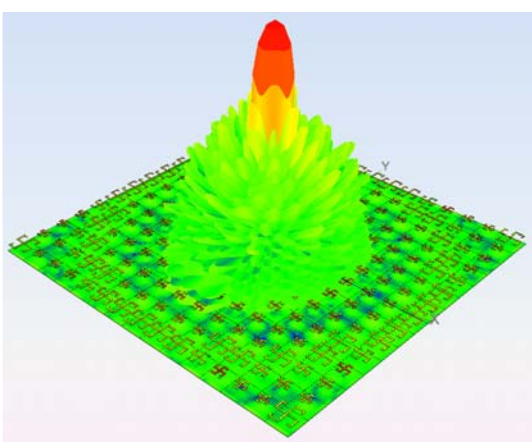

Fig. 9. Current distribution and 3D radiation pattern at 20 GHz.

Figure 10 depicts the E-plane of the normalized radiation pattern at 20 GHz. It can be seen that the simulated cross-polarization is below -30 dB for all directions. The side lobe levels of the co-polarized far field radiation pattern are below 17.6 dB regarding the maximum gain level.

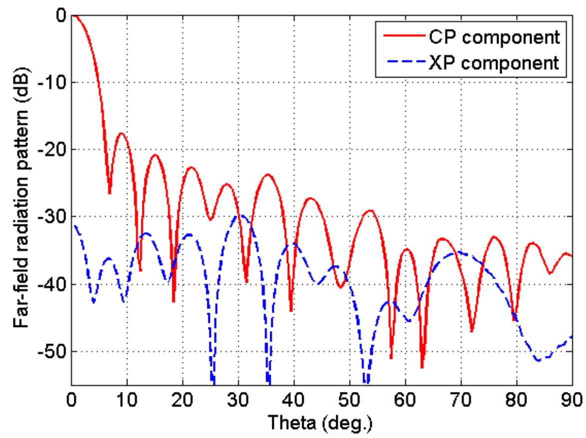

Fig. 10. Far field radiation pattern for the E-plane at 20 GHz.

Figure 11 shows a comparison between the maximum gains provided by each reflectarray. A remarkable difference can be observed. The gain peak of the spiral cross reflectarray is 26.37 dBi, which means an aperture efficiency of 43.35 %, whereas the gain peak of the conventional cross reflectarray is 24.6 dBi, which means an aperture efficiency of 28.25%. Regarding the broadband performance, the proposed reflectarray provides a 1 dB gain bandwidth of 12.41 % and a 3 dB gain bandwidth of 25.3 %. However, the conventional cross reflectarray provides a 1 dB gain bandwidth of 11 % and a 3 dB gain bandwidth of 17.5 %. On the other hand, the maximum cross-polarization level in the diagonal plane (θ = 45º) as a function of the frequency has been also studied to ensure the goodness of the polarization purity. Whereas the level of the cross-polar component is very low in the E- and H-planes, and in some cases could be high in the diagonal plane. Hence, the diagonal plane of the radiation pattern has been computed following the Ludwig's third definition [14].

Figure 12 shows the comparison between the maximum cross-polar levels in the diagonal plane, which is -26 dB for both reflectarrays. It can be seen that the polarization purity of the spiral cross reflectarray at 18.6 GHz is excellent. The cross-polar level at that frequency is -36.6 dB. From Fig. 11 we can see that the computed gain of the spiral cross reflectarray at 18.6 GHz is 25.19 dBi, which means a decrease of 1.18 dBi regarding the maximum gain achieved at 20 GHz. However, this downgrade can be overcome by increasing the size of the reflectarray. With respect to the conventional cross reflectarray, it can be seen that the cross-polarization level is a bit lower than the levels provided by the reflectarray composed of spiral crosses at the center frequencies.

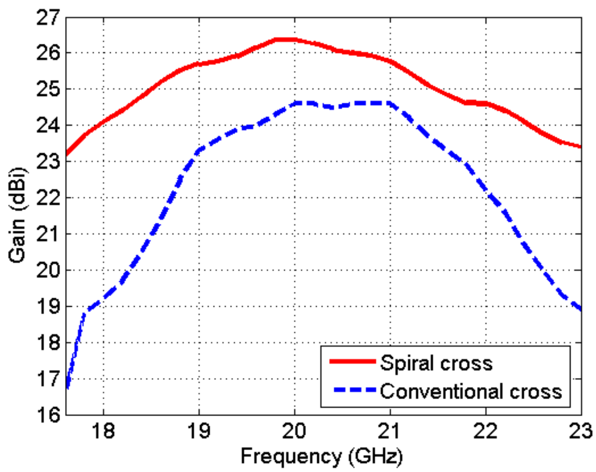

Fig. 11. Gain versus frequency for the spiral and conventional cross.

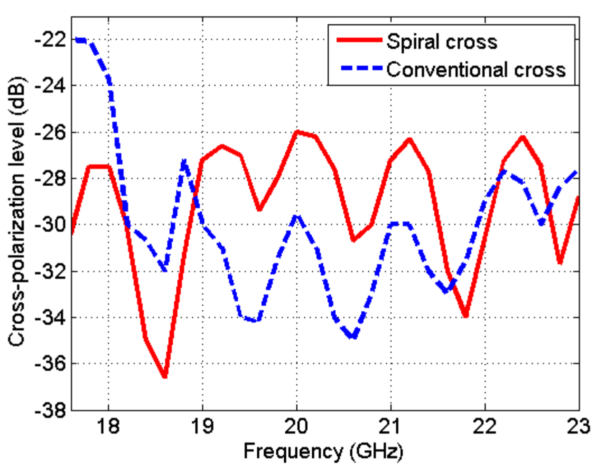

Fig. 12. Comparison of the maximum cross-polarization level in the diagonal plane versus frequency.

The bandwidth limitation due to the effect of non-constant path delay is more significant for large reflectarrays with small *f/D* ratios. Therefore, the prototype presented in this paper, whose electrical size is 9 λ and *f/D* ratio is 0.88, exhibits excellent performance when comparing to other previously published and measured reflectarrays that have similar aperture size and *f/D* ratio. For instance, the 22.8 λ reflectarray with *f/D* = 0.68 presented in [15] provides a 3 dB gain bandwidth of 6 % and cross-polarization levels lower than -16 dB. Three similar reflectarray antennas in term of size (around 9 λ) are proposed and measured in [16-18]. The reflectarray presented in [16] achieves a 3 dB gain bandwidth of 18 %, cross-polarization levels lower than -13 dB and an aperture efficiency of 35 %. Chang in [17] reports a reflectarray with *f/D* = 0.88 that provides a 3 dB gain bandwidth of 7 % and maximum cross-polar level of -25 dB. Finally, the reflectarray analyzed in [18], whose *f/D* ratio is 1.02, shows an aperture efficiency of 39.81 % and a 3 dB gain bandwidth of 17 %.

V. CONCLUSIONS

A novel unit cell named spiral cross has been studied and used to generate the layout of a 9 λ reflectarray antenna operating at 20 GHz. The designed center-fed reflectarray antenna shows good performance in terms of gain, bandwidth, aperture efficiency, and side lobe level. It achieves a 3 dB gain bandwidth of 25.3 %, an aperture efficiency of 43.35 %, maximum cross-polarization level of -26 dB, and secondary lobe level of 17.6 dB. The single-layer reflectarray is cost effective and might be a promising candidate for applications requiring high gain and low profile reflectors.

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