New Technique to Design Fresnel Zone Plate Antennas

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Abstract **—** A new method to design Fresnel Zone Plate Antennas (FZPA) is presented in this paper. The proposed method is based on deforming a flat metallic surface in order to achieve the desired phase distribution required to point the main beam to a certain direction. The resulting shaped reflector is modeled by using parametric surfaces, since they allow fitting the real shape of the antenna accurately providing smooth variations. Therefore, the diffraction effect that appears in the transition region between Fresnel zones can be reduced. Unlike bulky parabolic reflectors, FZPAs are much smaller and easy to transport and support, being a promising candidate for satellite communication applications due to its high gain, high polarization purity and minimum volume.

Index Terms **—** Electromagnetic radiation, reflector antennas, satellite communication.

I. INTRODUCTION

Shaped reflector antennas have been typically used to radiate contoured beams in applications where a certain geographical coverage is required [1]. Although contoured beams can also be obtained using array feeds, parabolic shaped reflectors are becoming more popular mainly because they have smaller volume and lower losses, and because array feeds require a complex feeding network. Moreover, the shaping technique is cheaper, since it only needs a single feed element. Parabolic reflectors have been also deformed to improve the antenna performance [2]. For instance, the shaping technique has been applied to increase the aperture efficiency, to improve the beam scanning capabilities, to enhance the polarization purity or to minimize side lobes. These reflectors have been particularly useful in satellite communications because they require simple feeds. However, in practical applications, parabolic reflectors are too bulky and difficult to place due to mechanical constraints. To overcome this limitation, membrane and mesh reflectors have been deployed for space applications. Although these reflectors outperform Fresnel Zone Plate Antennas (FZPA) due to its broad bandwidth, FZPAs have been also studied over a period of many years due to its low profile and low weight. The concept of the zone plate for optical wavelengths was developed by Wood in 1898 [3]. The first millimeter wave usage was reported in 1960 [4]. There are two types of zone plates: one where alternative concentric zones are made opaque or reflecting [5], and the second where phase correction is introduced in successive zones [6]. The latter can be fabricated by cutting grooves in a slab of dielectric material and depositing a thin metal film on the substrate. Thus, each zone is composed of a number of terraces or steps that are used to compensate the phase shifts. Starting from the idea that the bandwidth of the FZPA increases as the number of steps increases, the proposed antenna has been designed considering that the number of steps in the correcting zones tends to infinity. Figure 1 illustrates this concept. It shows the profile of a conventional FZPA with 5 zones and 4 steps per zone and the equivalent profile of the proposed FZPA, where it can be seen that the steps in each zone have been replaced by a NURBS (Non-Uniform Rational B-Splines) surface [7]. Also, note that the shadow regions, which are the transition areas between Fresnel zones, are not completely abrupt.

Hence, the novelty of the proposed antenna is that it is designed by smoothly deforming a flat metallic surface and that it is not composed of

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correcting zones. The modified FZPA present neither terraces nor grooves, and it is defined by continuous parametric surfaces that accurately model the deformations of the metallic surface.

Fig. 1. Schematic profile of a conventional FZPA with 5 zones and 4 steps and schematic profile of the proposed FZPA.

Compared to reflectarray antennas [8, 9], FZPA are easier to manufacture since they do not need any complex layout to reflect the incident field, and FZPA are cheaper since they are made of aluminum and do not require any layer of dielectric substrate. A 60cm x 60cm prototype operating at 10 GHz has been designed and analyzed to validate the benefits of the proposed technology. Although the proposed antenna has not been measured, the full wave Moment Method code that has been used to perform the simulations provides reliable results. The code has been validated with many experimental results.

II. THEORY OF OPERATION

The FZPA operation consists of converting a spherical wave front into a desired scattered wave front by means of an appropriate phase distribution. To achieve this, according to Fig. 2, each point of the original flat surface must introduce a phase shift that is obtained as follows:

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

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 reflector plane to the i_{th} point of the surface, d_i is the distance from the feed to the i_{th} point and N is an integer number. We obtain the value of N in each $\vec{r_i}$ by imposing that ϕ_i is in the (0, 2π) range.

Most reflectarray antennas use microstrip radiating elements to compensate the phase shift given by (1). The proposed new solution deforms the flat surface to achieve the desired phase distribution. First, the reflector surface is meshed using rectangular patches. The elements of the mesh have the same area that shall be electrically small (less than a half of wavelength) in order we can assume that in each element the amplitude and phase of the current is constant. Once the desired phase distribution ϕ_i is known, the deformed surface can be completely determined by moving each element a certain distance given by (2) if ϕ_i is in the $(0, \pi)$ range and given by (3) if ϕ_i is in the (π, 2π) range.

$$z_i = \phi_i \frac{\lambda}{4\pi}, \qquad (2)$$

$$z_i = -\phi_i \frac{\lambda}{4\pi}. \qquad (3)$$

As mentioned before, the obtained shaped surface is modeled by NURBS surfaces that exactly fit the deformations that have been conducted on the flat surface. These particular surfaces are able to model accurately any freeform shape, providing an extraordinary realism as they perfectly fit the shape of real objects. Moreover, they are defined as mathematical equations so the computational treatment is not very complicated. NURBS are compatible with several CAD formats and they are invariant under affine transformations.

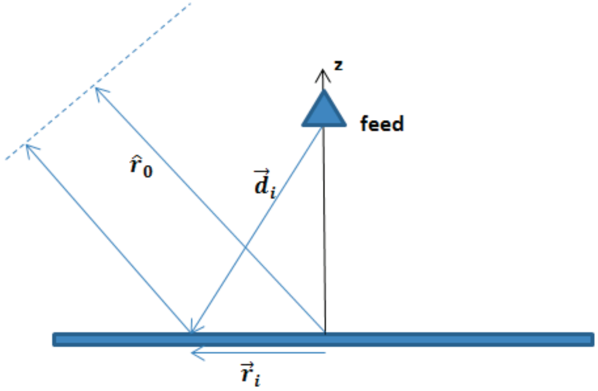

Fig. 2. Diagram of the original flat reflector.

III. VALIDATION AND SIMULATION

A center-fed FZPA has been designed to operate at 10 GHz to radiate a collimated beam in the direction given by θ=10º, ϕ=0º. The total size of the prototype is 20λ x 20λ x 0.5λ. The designed antenna has been fed by using the radiation pattern of a linearly polarized pyramidal horn positioned at x=0, y=0, z=0.45 m. The geometrical model of the proposed antenna is depicted in Fig. 3 and its flat profile can be observed in Fig. 4.

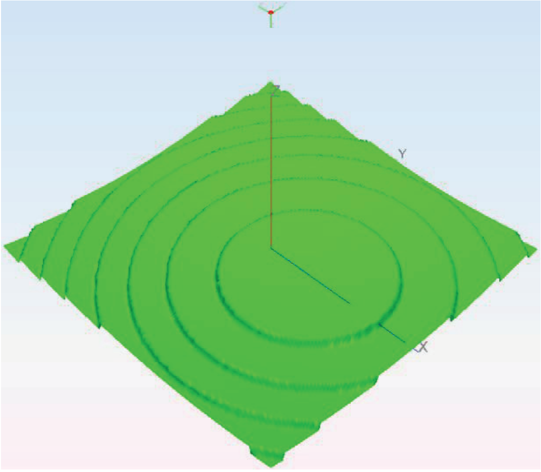

Fig. 3. Geometrical model of the FZPA.

Fig. 4. Side view of the FZPA.

Simulation results based on the Method of Moments (MoM) have been conducted to evaluate the proposed technique. The full wave MoM code Monurbs [10-12] has been used for this purpose. This code has been validated in many benchmark experiments to check its reliability [13-16], showing high accuracy when comparing to measurements. The computed 3D radiation pattern is shown in Fig. 5.

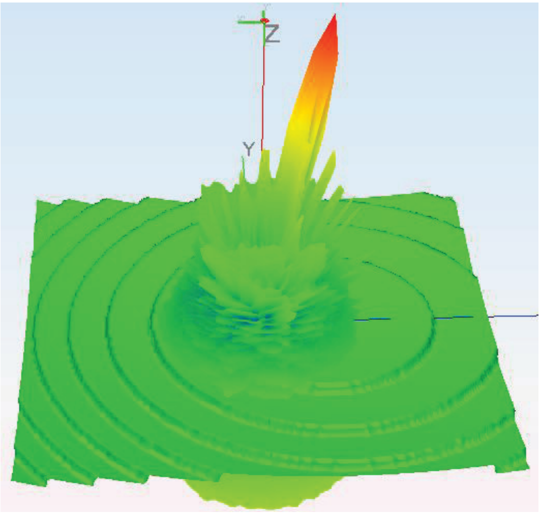

Fig. 5. 3D radiation pattern.

As it can be observed in Fig. 6, the peak gain provided by the FZPA is 33.67 dBi. This implies an aperture efficiency of 46.45%. Figures 7 and 8 depict the E and H planes of the normalized radiation pattern. The side lobe levels of the co-polarized far field radiation pattern are below 18.6 dB regarding the maximum gain level.

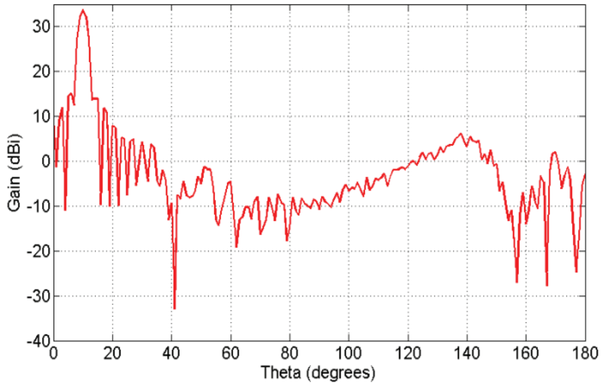

Fig. 6. Gain of the FZPA.

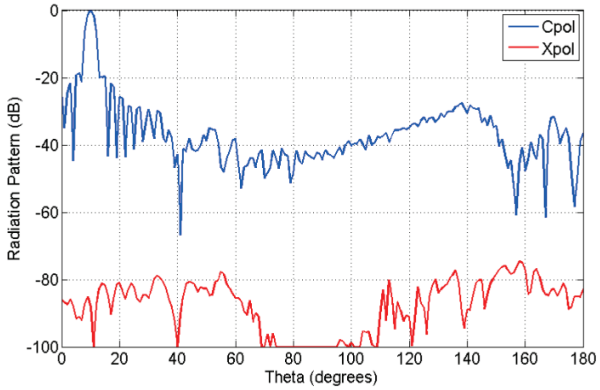

Fig. 7. Normalized far-field radiation pattern. Cut ϕ=0º.

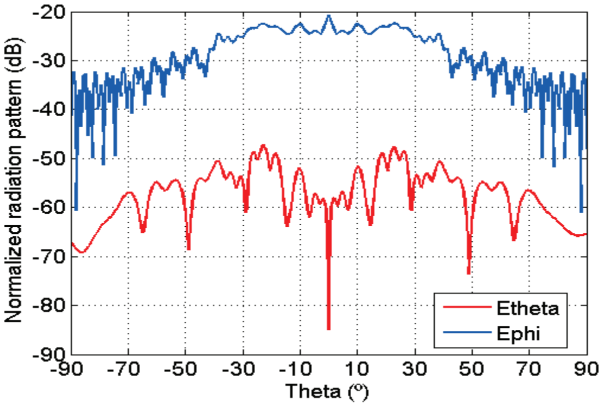

Fig. 8. Normalized far-field radiation pattern. Cut ϕ=90º.

The technique used to design the FZPA has been validated by comparing a previously published similar antenna [17] with a second design. The reference antenna operates at 62.1 GHz, is 150 mm in diameter, 132 mm in focal length, and has an edge illumination level of −12 dB. This design has been analyzed according to the parameters of the reference conventional FZPA antenna. Figure 9 shows the computed gain of the designed antenna. According to Figs. 9 and 10, it can be seen that for the same antenna dimensions and design parameters, the presented antenna with a peak gain of 37.4 dBi and an efficiency of 59.4% surpasses 0.8 dB in gain and 7.7% in efficiency the FZP reported in [17]. Therefore the 3 dB bandwidth of the proposed antenna is also a bit higher than the 22% achieved by the reference antenna.

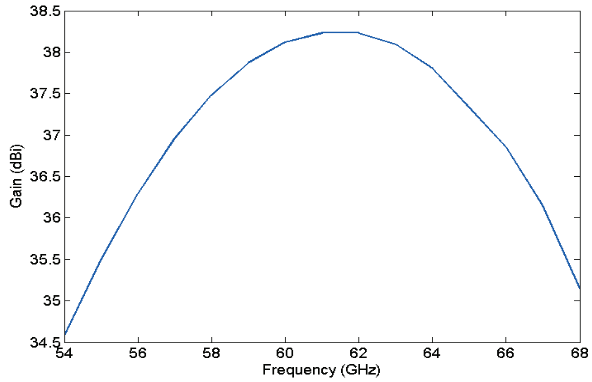

Fig. 9. Computed directive gain against frequency of the FZPA designed using the parameters reported in [17].

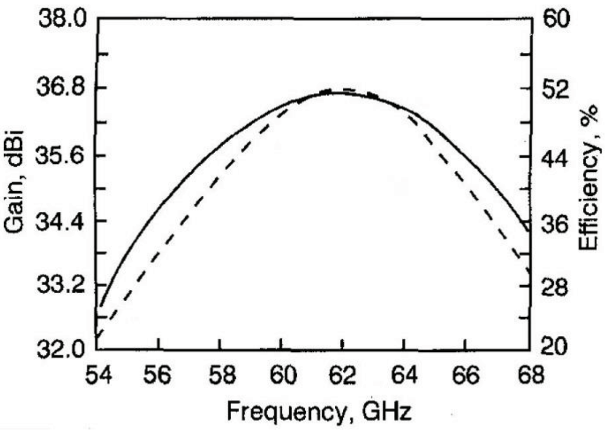

Fig. 10. Directive gain (solid line) and antenna efficiency (dashed line) against frequency of the FZPA reported in [17].

IV. CONCLUSION

A new type of FZPA has been introduced in this paper. This new methodology allows designing low profile reflector antennas with the same advantages as the traditional parabolic reflectors, while remaining a minimum volume. Simulated results reveal that the proposed antenna is very attractive for applications in broadcasting and satellite communications due to their good polarization purity and high gain.

ACKNOWLEDGMENT

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REFERENCES

[1] R. Cherrette, S-W. Lee, and R. J. Acosta, “A method for producing a shaped contour radiation pattern using a single shaped reflector and a single feed,” *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 6, pp. 698-706, 1989.

[2] H-H. Viskum and S. B. Sorensen, “A shaped dual reflector optimized for gain, sidelobe performance and low return loss,” *Ninth International Conference on Antennas and Propagation*, (Conf. Publ. No. 407), vol. 1, no. 4-7, pp. 183-186, 1995.

[3] R. W. Wood, “Phase-reversal zone plates and diffraction-telescopes,” *Philosophical Magazine*, series 5, 45, 511, pp. 511-523, 1898.

[4] M. King, J. Rodgers, F. Sobel, F. Wentworth, and J. C. Wiltse, “Quasi-optical components and surface waveguides for the 100 to 300 GHz frequency range,” *Electronic Communications, Inc.*, Report no. 2 on Contract AF19 (604)-5475, Nov. 1960.

[5] H. A. Malliot, “Zone plate reflector antennas for applications in space,” *Proceedings of the Aerospace Applications Conference*, Vail, Colorado, USA, pp. 295-311, Feb. 1994.

[6] J. E. Garrett and J. C. Wiltse, “Antenna pattern characteristics of phase-correcting Fresnel zone plates,” *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, AP-S. Merging Technologies for the 90’s. Digest, Dallas, Texas, USA, pp. 1906-1909, May 1990.

[7] G. Farin, *Curves and Surfaces for Computer Aided Geometric Design*, Academic Press, 1988.

[8] A. Tayebi, J. Gómez, J. R. Almagro, and F. Cátedra, “Broadband high efficiency single-layer reflectarray antenna based on spiral crosses,” *Applied Computational Electromagnetics Society Journal*,

vol. 28, no. 1, pp. 1-7, Jan. 2013.

[9] J. Gómez, A. Tayebi, and F. Cátedra, "Cross-polarization suppression in monolayer reflectarray antennas," *Frequenz*, vol. 67, no. 5-6, pp. 139-143, Apr. 2013.

[10] I. González, E. Garcia, F. Saez de Adana, and M. F. Cátedra, "MONURBS: a parallelized multipole multilevel code for analyzing complex bodies modeled by NURBS surfaces," *Applied Computational Electromagnetics Society Journal*, vol. 23, no. 2, Jun. 2008.

[11] http://www.fasant.com

[12] A. Tayebi, J. Gómez, I. González, L. Lozano, M. J. Algar, E. García, I. Etayo, and F. Cátedra, "Performance comparison between rigorous and asymptotic techniques applied to the analysis of wind turbines," *Applied Computational Electromagnetics Society Journal*, vol. 26, no. 2, Feb. 2011.

[13] I. González, A. Tayebi, J. Gómez, C. Delgado, and F. Cátedra, "Fast analysis of a dual-band reflectarray using two different numerical approaches based on the moment method," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 2333-2336, 2013.

[14] J. Gómez, A. Tayebi, I. González, and F. Cátedra, "Design of a compact circular waveguide antenna of low polarization level using EBG structures," *Applied Computational Electromagnetics Society Journal*, vol. 26, no. 5, 2011.

[15] I. González, J. Gómez, A. Tayebi, and F. Cátedra, "Optimization of a dual-band helical antenna for TTC applications at S band," *IEEE Antennas and Propagation Magazine*, vol. 54, no. 4, pp. 63-77, 2012.

[16] J. Gómez, A. Tayebi, J. R. Almagro, I. González, and F. Cátedra, "Design and optimization of an EBG antenna with an efficient electromagnetic solver," *International Journal of Antennas and Propagation*, pp. 1-8, 2012.

[17] H. D. Hristov and M. H. A. J. Herben, "Millimeter-wave Fresnel-zone plate lens and antenna," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 12, pp. 2779-2785, 1995.

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