Phase-only Shaped Beam Transmit-Array

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***Abstract*— A new analytical formulation is presented in this paper to obtain the phase correction function for planar transmit-arrays, to produce a prescribed amplitude template. This phase-only design enables using high transmission unit cells to favor maximum gain. Here, a transmit-array transforms the known power radiation pattern of the primary source into a desired output power pattern. As a proof of concept, two different output power radiation patterns are presented, namely, a sec^2 with a roll-off at 45º and a flat-top with 20º of roll-off, at the 30 GHz Ka-band. The transmit-array aperture is 180 mm × 180 mm, with 60 mm focal length. It is illuminated by a 10.8 dBi feed radiation pattern, with circular polarization.**

Keywords*— Transmit-arrays, planar lens antennas, radiation pattern shaping, Geometrical Optics, secant squared power pattern.

I. Introduction

Beam shaping has been implemented traditionally by three different antenna technologies, namely, arrays, reflectors and lenses. However, each of those technologies present some disadvantages. The technology based on arrays requires a complex, expensive and lossy beam-forming network, especially at mm-waves. The main drawback of shaped reflectors is related to the limit on the performance and flexibility of this solution, due to its natural configuration. On the other side, dielectric lenses and namely integrated lenses tend to be bulky [1], with non-negligible insertion losses. Reflect-arrays [2] and transmit-arrays [3]-[7] are special cases of reflectors and lenses, respectively. Both are thin, planar, light-weight, low-cost structures. The challenge of using transmit-arrays for beam-shaping is that the operation principle is normally based uniquely on the local phase shifts introduced by the unit cells when the incident wave passes through. Reports on amplitude shaping produced by transmit-arrays are very rare in the literature. In [6] and [7] the authors use, both, phase and amplitude shifting surface (PASS) to match the defined target template. Because they deliberately use transmission loss at the unit cells (up to 4 dB) to control the amplitude distribution over the aperture, this solution seriously penalizes the antenna efficiency.

In this paper, a new analytical formulation is developed to produce a power radiation pattern complying with a given input power pattern, using only phase correction over the aperture.. The formulation's underlying assumption is that, in the GO limit, the shape of the outgoing phase front radiated by the transmit-array is mostly sufficient to determine the shape of the far-field magnitude radiation pattern. A mathematical formulation is presented and validated by simulation, meeting different target power-pattern templates. A transmit-array with 180 mm of diameter and a focal distance of 60 mm is considered, operating at 30 GHz with circular polarization.

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II. Transmit-Array Design Formulation

The formulation developed in this work is, in some way, related with some assumptions of the previous analytical formulations presented in [1] for dielectric lens, but here with the necessary adaptation. In Fig.1, a transmit-array with diameter D is represented with the primary feed phase center at distance F from the transmit-array.

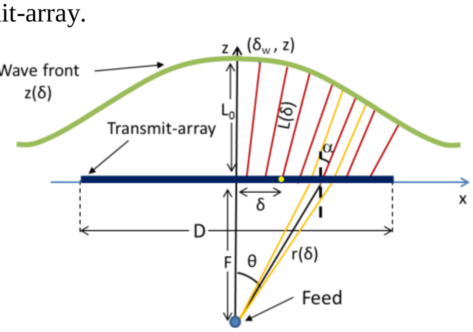

Fig. 1 – Geometry for the transmit-array design, showing the tranmit-array, the feed, the output rays and the output wave-front.

Two main steps are defined during the design process. First, it is necessary to determine the direction $\alpha(\delta)$ that each ray must follow when exiting each point δ of the transmit-array to synthesize the desired $G(\alpha)$ function. Considering an elementary ray tube marked yellow in Fig 1, it defines an elementary solid angle $\sin\theta\ d\theta\ d\varphi$. After crossing the transmit-array, the ray tube is assumed to propagate along an angle α, defining the elementary solid angle $\sin\alpha\ d\alpha\ d\varphi$. For an axial-symmetric problem, power conservation across this elementary ray tube on both sides of the transmit-array can be expressed, as (1); T represents the power transmissivity across the intersected part of the transmit-array:

$$U(\theta)\ T\ sin(\theta)\ d\theta = K\ G(\alpha)\ sin(\alpha)\ d\alpha \qquad (1)$$

K is a normalization constant to be determined from the power balance between the incident and transmitted waves and is described by (2), where α_{max} is the roll-off angle of the target radiation pattern.

$$K = \frac{\int_0^{\theta_{max}} \left(U_{\parallel} t_{\parallel}^2 + U_{\perp} t_{\perp}^2\right)\ tan(\theta)\ d\theta}{\int_0^{\alpha_{max}} G(\alpha)\ tan(\alpha)\ d\alpha} \qquad (2)$$

Manipulating the previous equations and given the Fig.1, the direction $\alpha(\delta)$ is calculated by integrating the equation (3); Here, $t_{\parallel}$ and $t_{\perp}$ are the transmission coefficients and are very close to 1 in properly designed transmit-array unit cells.

$$\begin{cases} \dfrac{d\alpha}{d\delta} = \dfrac{\left(U_{\parallel}t_{\parallel}^2 + U_{\perp}t_{\perp}^2\right)}{K\ G(\alpha)\ tan(\alpha)} \dfrac{\delta}{F^2+\delta^2} \\ \alpha(0) = 0 \end{cases} \quad (3)$$

Second, it is necessary to determine the relation between the obtained $\alpha(\delta)$ and the required phase distribution $\varphi_{lens}(\delta)$ over the transmit-array. The output wave-front shape $z(\delta)$ is immediately defined by knowing $\alpha(\delta)$, since it is everywhere normal to the rays output direction, see the green curve in Fig. 1. Consequently, the wave-front is determined from $z(\delta)$. $L(\delta)$ represents the path lengths defined from the transmit-array surface to the wave-front (red lines in Fig. 1) and is determined by (4).

$$L(\delta) = \frac{z(\delta)}{cos(\alpha)} \quad (4)$$

By definition, the phase at the wave-front is constant, and given by (5)

$$k_0 r(\delta) + k_0 L(\delta) + \varphi_{lens}(\delta) = C \quad (5)$$

After some manipulations, the wave-front shape is obtained by integration of (6).

$$\begin{cases} \dfrac{dz}{d\delta} = -z\dfrac{d\alpha}{d\delta}tan(\alpha) - \dfrac{sin(2\alpha)}{2} \\ z(0) = L_0 \end{cases} \quad (6)$$

III. Validation of the Method

The formulation developed in this work was validated, by simulation, using a Physical Optics tool. Two different target patterns are considered, namely, a secant-square with a roll-off of 45º and a flat-top with a roll-off of 20º, see Fig. 2 and Fig. 3. The focal distance in both cases is F = 60 mm, and the transmit-array diameter is D = 180 mm. A 10.8 dBi gaussian radiation pattern with circular polarization is used to illuminate the transmit-array.

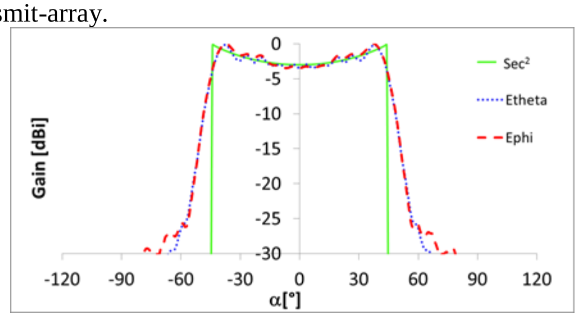

Fig. 2 – PO radiation pattern result for a secant-squared power radiation pattern target with a roll-off of 45º.

The PO results in both cases comply very well with the the two desired power radiation patterns. This analysis confirms that the phase-only formulation developed in this paper for transmit-arrays to produce arbitrary amplitude shaped beams is effective.

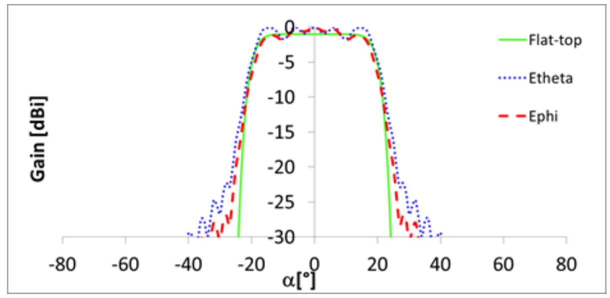

Fig. 3 – PO radiation pattern result for for a flat-top power radiation pattern target with a roll-off of 20º.

IV. Conclusions

Transmit-arrays are thin, low weight and its flexibility to accommodate different radiation pattern requirements, making them attractive aperture antennas. In transmit-arrays, to comply with a power pattern template, it is necessary to find the right correspondence between the output power pattern and the phase distribution over the transmit-array surface. This paper shows that, under certain conditions, this relation is possible. From this work, the transmit-array design can be obtained by directly solving two first-order differential equations. The analytical formulation was validated through Physical Optics analysis, for two demsnding output power radiation pattern templates. This demonstrates the usefulness of the presented formulation. The implementation of a transmit-array using real cells is the next work to complete the study presented in this paper.

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