Full-wave evaluation of a 40 dBi Transmit-array for Ka-band SoTM

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***Abstract*- Transmit-array (TA) antennas have been shown to be a cost-effective solution for the new generation of satellite communications. These antennas are usually composed by thousands of fine-tuned subwavelength unit-cells. Therefore, full-wave evaluations become quite challenging as the required gain increases, constraining the antenna design and optimization. This is aggravated by the fact that, when beam scanning is required, higher gains cannot be obtained by simply scaling a given design. In fact, for a F/D ratio, the maximum gain of the TA is limited by the scanning aberrations. Recently, we have proposed a new phase compensation law for the TA, designated as the bifocal correction, that allows to overcome the usual gain/scanning tradeoff limit. However, due to the lack of computational resources, we were only able to demonstrate this concept for a 40 dBi TA using PO/GO methods. In this communication we present the full-wave performance of this 40 dBi bifocal TA design using a new efficient numerical evaluation method, properly validated with a smaller 30 dBi TA.**

I. INTRODUCTION

Transmit-arrays (TAs) have been an attractive solution to realize low-cost, low-profile, high-gain steerable pencil beam in many point-to-point and satellite communication applications [1]-[3]. These arrays comprise a collection of unit-cells, which can provide beam collimation for the transmitted radiation coming from a primary feed. The phase shifts of the unit-cells are tuned by a careful design of subwavelength metallic features in each layer. Performing a full-wave analysis of these electrically large antennas, properly accounting the unit-cell fine sub-wavelength details is computationally challenging. On the other hand, PO/GO based methods [4], although extremely fast, have limitations regarding the estimation of gain, scan loss, and side lobe. In this communication, we present an equivalent dielectric description of the TA that emulates the real antenna response. The main advantage is that the obtained model does not contain all the metallic subwavelength details of the original problem, requiring much less computational resources to perform the full-wave evaluation of the equivalent TA. The procedure consists in find a set of homogeneous dielectric materials that mimic the real response of the unit cells. We should stress that although homogenization theory is a mature topic [5]-[6] it is usually employed for the analysis of periodic structures. Herein, we show that we can apply this theory in the broader context of non-periodic structures. The effectiveness of this method is assessed using the 30 dBi TA developed in [1]. We show that the shape of the main beam was kept when compared to the full simulation of the real TA, with antenna gain differences less than 1 dB. With the proposed method, the simulation of the equivalent TA ran more than 3 times faster and the memory was reduced by half. Using an equivalent dielectric model, the bifocal 40 dBi TA array design [7] was then validated using full-wave simulations for the first time, which was not been possible to do due to the large computational resources required to simulate the real TA. The bifocal TA achieves a 39 dBi maximum gain @ 30 GHz with an elevation scanning range up to 56º within a 3dB scan loss and a side lobe level below -15 dB for a $450 \times 650mm$ aperture.

II. EQUIVALENT DIELECTRIC TRANSMIT-ARRAY

A. Equivalent unit cell design

By applying suitable homogenization techniques to a given unit-cell design, we can get an equivalent, and yet simpler description of the original TA. In fact, this procedure can be quite inclusive of a wide range of unit cell designs. The main assumptions are the following:

1) The unit-cell losses can be neglected, as is usually considered for TA design.

2) Subwavelength unit cell size, which is also a typical requirement to avoid grating lobes.

3) The unit cell scattering response can be describe considering only plane-wave normal incidence. In fact, the maximum incident angle of the rays illuminating the TA is usually below 45º, depending on the F/D ratio, which is low enough to make this assumption valid for most unit-cell designs.

4) Isotropic permittivity and permeability constitutive parameters are enough to emulate the unit cell response for normal incidence. This restriction applies to cells that are polarization insensitive which is also a usual specification, especially for satellite applications.

5) The analytical description of the unit cell is done by neglecting the multi-reflections inside the cell, which is also reasonable to do in the context of quasi-transparent unit-cells.

Under these conditions, the cell reflection and transmission coefficient are simply given by

$$T = \frac{2\sqrt{\mu_r}}{\sqrt{\varepsilon_r}+\sqrt{\mu_r}} e^{-jk_0\sqrt{\varepsilon_r\mu_r}H_{cell}}, \quad \Gamma = \frac{\sqrt{\mu_r}-\sqrt{\varepsilon_r}}{\sqrt{\mu_r}+\sqrt{\varepsilon_r}} \tag{1}$$

where H_{cell} is the height of the unit cell, which is considered to be the same for the equivalent and real cell. For the example in [1] the unit-cell family is a set of $N = 63$ cells designed to operate at 30 GHz. The equivalent constitutive parameters for a given unit cell k, with $k = \{1,2,..N\}$ result from the inversions of Equations (1) . Because the working principle of the TA only depends on the relative phase difference between the unit-cells, an arbitrary constant phase φ_0 can added to the transmission coefficient. This degree of freedom allows to impose and additional condition. We defined φ_0 as the minimum value that guarantees for every cell $\mu_k \geq 1$ and $\varepsilon_k \geq 1$, implying that $n_k = \sqrt{\varepsilon_k\mu_k} \geq 1$. Thus, for the lossless and dispersive regime that we assume, we get a causal description of all cells, otherwise we would get superluminal energy velocities. Moreover, for every cell there is an equivalent material description, equally valid, where the permittivity and permeability values are interchanged. In this example we consider that $\varepsilon_{PD}^k \geq \mu_{PD}^k$. Accordingly, the unit-cell constitutive parameters, shown in Fig. 1, are then given by

$$\varepsilon_k = -\frac{arg(T_k)+\varphi_0}{k_0H_{cell}}\frac{1+|\Gamma_k|}{1-|\Gamma_k|} \tag{2}$$

$$\mu_k = -\frac{arg(T_k)+\varphi_0}{k_0H_{cell}}\frac{1-|\Gamma_k|}{1+|\Gamma_k|} \tag{3}$$

Where $\varphi_0 = -333.9°$ implying as intended that $\varepsilon_k \geq \mu_k \geq 1$ for every cell.

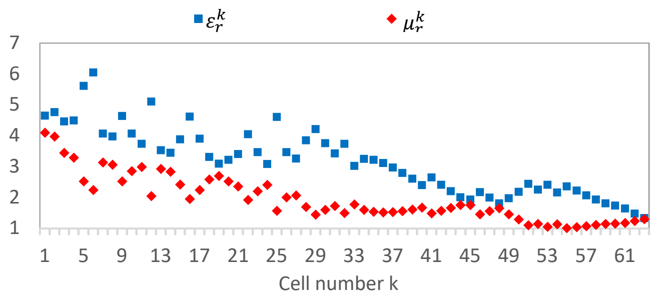

Fig. 1 Equivalent constitutive parameters of the unit-cells [1] for 30 GHz.

B. *Model validation for a 30 dBi TA*

After obtaining the set of equivalent dielectric unit cells, the dielectric model of the TA is assembled by simply replacing each unit-cell by the corresponding isotropic dielectric material with proper permittivity and permeability values. In this section we perform this procedure for the TA design presented in [1], (see Fig. 2). This TA has a rectangular $140mm \times 190mm$ aperture and focal distance of $100mm$. The maximum gain is 30 dBi at 30 GHz and beam-steering is achieved by translating the feed along the longer axis of the TA with constant z. The feed is a 14.5 dBi standard gain Ka-band horn. The simulated radiation patterns of the TA and the equivalent TA are presented in Fig. 3. The radiation patterns are obtained at 30 GHz for different *x*-positions of the horn: a=+30mm, 0mm, and -27mm. It can be seen from this figure that the TA and the equivalent TA direct the beam in the same direction for all the positions of the feed. Moreover, the gain of the two TAs in the beam maximum direction is in great agreement with a maximum difference of only 0.5 dB for $a = 0mm$. Furthermore, the equivalent TA also presents a good estimation of the side lobe levels and even of the back lobe. The Hybrid TLM-FDTD approach, available in the ® CST Microwave Studio, is used for the analysis of the TA. The simulations where performed with a high-end workstation (Dell T7610, 128 GBytes RAM, 2 Processors at 2.5 GHz) using Tesla K20c Graphic process units (GPUs) to accelerate to computing time of this electric large problem. The equivalent TA full-wave simulation required about 43 minutes and 3.84 Gbytes of GPU memory, whereas using the real TA takes more than three times that amount of time and almost twice the memory. We should stress that as the complexity of the problem is further scaled, this method is expected to become even more effective in saving computational resources.

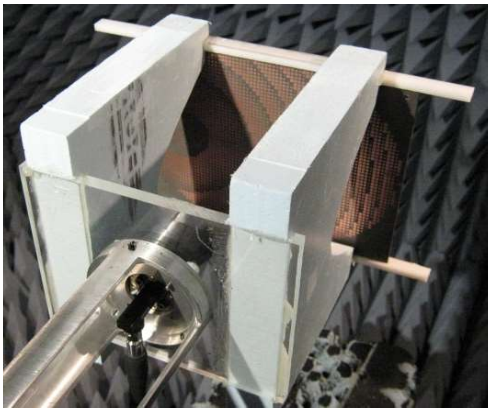

Fig. 2 TA prototype developed in [1].

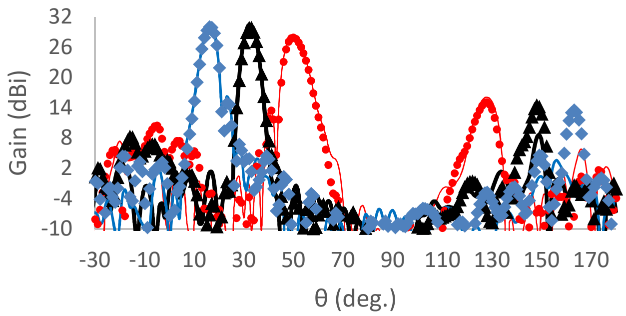

Fig. 3 Full-wave simulated TA (points) and equivalent TA (solid lines) at 30 GHz.

III. 40 dBi BIFOCAL TA

A. *Bifocal design*

The concept of bifocal phase correction was first proposed in [7]. The rationale is to favor a more even distribution of the aberration over all scanned beams. The bifocal function is defined as a weighted average of two unifocal functions, according to

$$\phi_{lens}^{bifocal} = \frac{A_1 \times \phi_1^{uni} + A_2 \times \phi_2^{uni}}{A_1 + A_2} \tag{4}$$

Where A_i, with $i = 1,2$ are the weight functions

$$A_i = e^{-\frac{(x-x_i)^2+y^2}{2\sigma_i^2}} \tag{5}$$

and ϕ_i^{uni} with $i = 1,2$ is the unifocal distributions used to construct the 30 dBi TA [1], given by

$$\phi_i^{uni} = -k_0 x \sin\alpha_i + k_0\sqrt{(x - x_i)^2 + y^2 + F^2} \quad (6)$$

When $A_2 = 0$ or $A_1 = 0$ the lens phase correction reduces to the unifocal case with focus at x_1 or x_2, respectively. The unifocal term ϕ_1^{uni} is dominant in the regions of the lens near x_1 , i.e. $\phi_{lens}^{bifocal} \approx \phi_1^{uni}$, whereas near x_2 the dominant term is $\phi_{lens}^{bifocal} \approx \phi_2^{uni}$. The Gaussian weight functions allows a gradual transition between the two unifocal distributions along the lens. To properly demonstrate the effectiveness of the bifocal method, a 40 dBi TA with a 450×600 mm^2 aperture and focal distance $F = 300\,mm$ is considered. The corresponding scanning performance evaluated using a PO/GO analysis for the bifocal and unifocal phase correction designs are shown in Fig 5. As we have already shown, the bifocal phase correction provides a significant improvement of the overall lens performance.

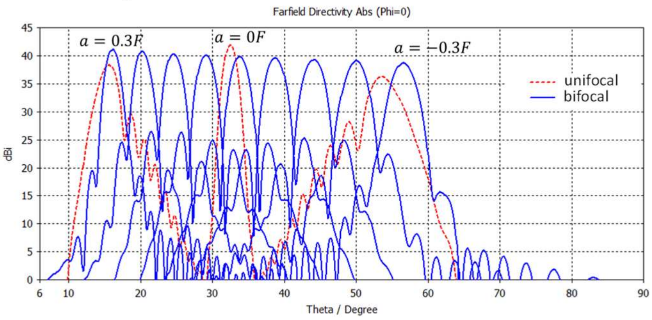

Fig. 4 PO/GO simulation of a 450×600 mm^2 bifocal radiation patterns versus the unifocal case obtained for the feed position $a \in [-0.3F, 0.3F]$ with a $\Delta a = 0.075F$ step. We defined $\sigma_1 = \sigma_2 = 121\ mm$, $\alpha_1 = 15.6°$, $x_1 = 0.1F$, $\alpha_2 = 58°$, $x_2 = -0.3F$ and $F = 300\ mm$

B. Full-wave evaluation of the 40 dBi bifocal TA

The 40 dBi bifocal TA was assembled using the equivalent dielectric unit cells validated in Section II.B. In Fig. 5 we present the radiation patterns for three feed positions superimposing the full-wave and the PO/GO results. As expected, the PO/GO analysis overestimate the TA gain (~more 3 dB), confirming that full-wave simulations are indeed required to evaluate the real TA performance. Only with full-wave simulations it is possible to quantify all physical effects occurring in the aperture which cannot be capture using PO/GO based methods. Such effects include the mutual coupling between adjacent unit cells, that can be quite damaging when 360 cell phase jump occurs. Further details on this comparison can be found in Table 1.

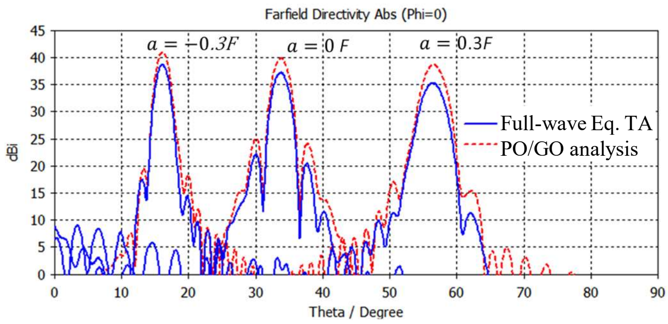

Fig. 5 Radiation patterns of a 450×600 mm^2 bifocal TA using a PO/GO and Full-wave equivalent dieletric analyis. We defined $\sigma_1 = \sigma_2 = 121\ mm$, $\alpha_1 = 15.6°$, $x_1 = 0.1F$, $\alpha_2 = 58°$ and , $x_2 = -0.3F$ and $a = \{-0.3F, 0, 0.3F\}$ with $F = 300$ mm.

TABLE 1 – Assessment of the 40 dBi TA performance using full-wave and PO/GO analyses.

Feed position	$a = -0.3F$		$a = 0F$		$a = 0.3F$	
	FW	PO/GO	FW	PO/GO	FW	PO/GO
Directivity (dBi)	35.3	38.7	37.2	39.8	38.7	41.1
SLL (dB)	23.0	21.6	15.1	14.7	18.9	-21.5
Direction (º)	56.4	56.5	33.7	33.8	16.1	16.1

IV. CONCLUSIONS

We have shown that an equivalent dielectric description of a TA can reduce the intrinsic numeric complexity of the corresponding full-wave analysis without sacrificing the accuracy of the main figures of merit of the antenna. Using this new tool, it was possible to perform the full-wave evaluation of a 40 dBi TA bifocal design, which was been analyzed using only a PO/GO. The concept of bifocal TA design is then further attested by this work, paving the way for the prototyping stage.

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