Dual-Polarized Plane Wave Generator based on Reflectarray for its Application to Portable CATR Systems

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***Abstract*- In this work, a reflectarray antenna is introduced to act as a plane wave generator (PWG) to evaluate devices in mm-Wave frequencies. The reflectarray is designed to radiate a uniform plane wave close to the aperture to reduce the size of the system. The Intersection Approach is used to design the reflectarray carrying out two phase-only synthesis for the two linear polarizations. The synthesis significantly improves the results obtained by an analytical approach obtaining a dual-polarized PWG. The result of the synthesis is used to carry out a design. The unit cell is a double set of orthogonal coplanar dipoles printed on a single-dielectric layer. The designed reflectarray shows significantly good performance in terms of the uniform plane wave obtained. Finally, the reflectarray-based PWG is used for the first time to evaluate the radiation pattern of an antenna. This compact measuring system presents quite good results evaluating the radiation pattern.**

I. INTRODUCTION

Several applications such as 5G communications, or automotive radars operate at mm-Wave frequencies. The characterization of devices or antennas at those frequencies is an easy task using conventional measurement systems. However, a true interest arises in the development of alternative measurement systems with the capability of performing a fast evaluation of the antenna without needing a fixed, expensive, and bulky facility. This means having portable systems that can be deployed in the area of interest, such as labs or manufacturing lines, and obtaining an accurate characterization of the antennas or devices. The characterization can be performed following the standard Over-The-Air (OTA). OTA aims to characterize an antenna at infinity distance without a direct connection between the device-under-test (DUT) and probe. To reach this condition the DUT and probe should be located at the far-field distance each of them. Performing OTA on devices such as base stations or user terminals at FR2 implies significant electrical distance that leads to high free-space attenuation and decreases the received signal.

The interest in plane wave generators (PWG) has increased their popularity throughout the last years since they are presented as a potential alternative to radiate a uniform plane wave at short distances. A PWG is typically defined as an array antenna that radiates a uniform plane wave over a volume at a close distance to the antenna aperture. Hence, it emulates far-field conditions to test devices at a reduced distance, minimizing the free-space attenuation and enhancing the received signal from the DUT. Preliminary studies use different arrays configurations to obtain the plane wave [1], [2]. However, the solutions based on arrays require the design of complex beam-forming feeding networks to properly control the excitation of the elements.

In [3] a reflectarray was presented as a PWG to generate a uniform plane wave at a close distance to the aperture, showing the possibility of controlling the amplitude and phase of the radiated near-field. In this work, the technique presented in [3] is used to enhance the reflectarray performance by generating two uniform plane waves in orthogonal polarization using a single-layer unit cell topology. Besides, not only the performance of both uniform plane waves are evaluated, but also, the radiation pattern of an array is evaluated using a reflectarray antenna for the first time.

II. REFLECTARRAY-BASED PLANE WAVE GENERATOR

A. System definition and antenna optics

The proposed PWG is based on a single-layer dual-polarized reflectarray. The reflectarray consists of a grounded single dielectric layer of RO4003C ($\epsilon_r = 3.65, \tan\delta = 0.0027, \text{thickness} = 32\text{ mil}$) of 36×36 elements for the X-polarization, and 35×35 elements for the Y-polarization. The elements are distributed in a regular square grid of periodicity $5.3 \times 5.3\text{ mm}^2$ $(a \times b)$ in both polarizations. The grid of the Y-polarization is displaced half of a period in the orthogonal direction of the lattice. The total size of the reflectarray is $191 \times 191\text{ mm}^2$.

The feed is in an offset configuration at $(x_f, y_f, z_f) = (-79{,}0{,}200)$ mm, see Fig. 1. The feed is a horn antenna of 15 dBi gain with an illumination taper of -16 dB at the edges of the reflectarray. The antenna operates in double linear polarization at a central frequency of 28 GHz.

Fig. 1 depicts two adjacent unit cells. Each set of dipoles is in a different grid, and the displacement between them is half of a period. The coplanar dipoles oriented in the x-axis control the phase of the copolar reflection coefficient (ρ_{xx}) of the X-polarization, while the other orthogonal set controls the phase of the copolar reflection coefficient (ρ_{yy}) of the Y-polarization. The phase shift of each polarization is related to the length of the central dipole. To ensure good isolation between polarizations the symmetry of the unit cell is preserved, which are edge coupled to the central dipole [4].

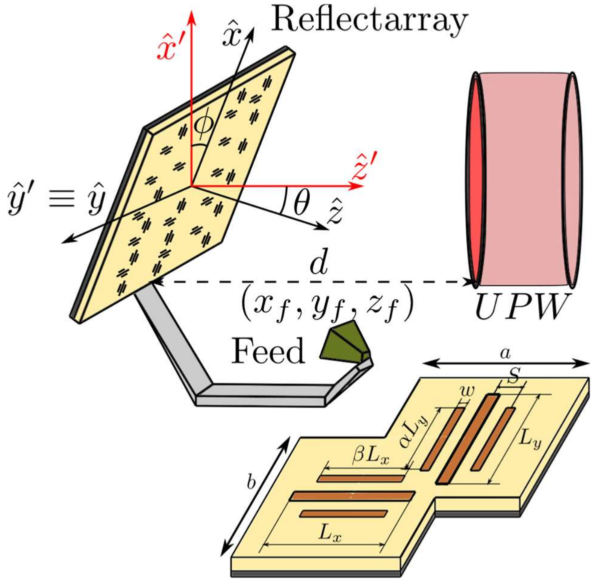


Fig. 1 Sketch of the propose reflectarray-based plane wave generator to measure antennas and the unit cell.

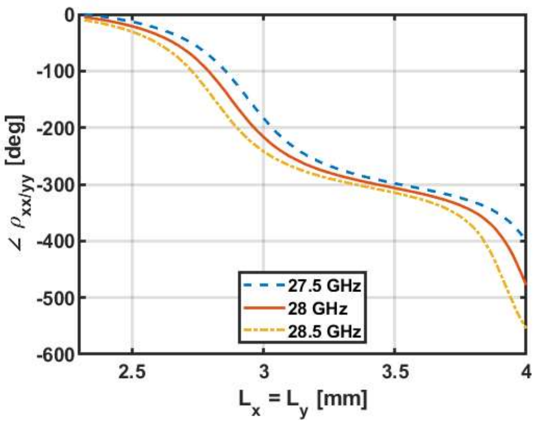


Fig. 2 Phase response of the proposed unit cell based on two sets of coplanar parallel dipoles at different frequencies,normal incidence, and both linear polarizations.

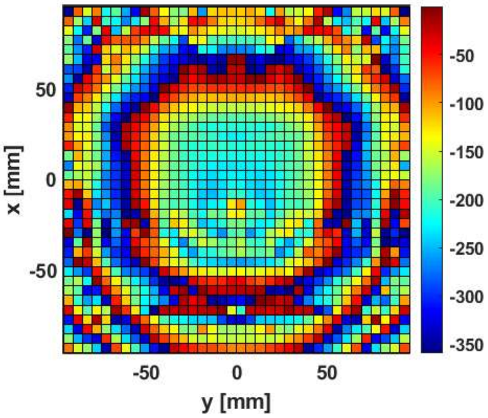


Fig. 3 Phase distribution obtained after the synthesis process based on the Intersection Approach for the X-polarization.

The separation between dipoles (S) is 0.8 mm, the thickness of the dipoles (w) is 0.3 mm and α and β are 0.75. With this configuration, the unit cell provides a phase-shift range larger than 360°, which is enough to cover a full phase cycle.

According to the scheme of Fig. 1, the reflectarray must generate a dual-polarized uniform plane wave at 500 mm (d). The reflectarray is tilted 20° and the uniform plane wave is radiated in $\hat{z}'$ direction. The radiated near-field at d must present a low ripple. Ideally, to consider the radiated field as a uniform plane wave the ripple should be lower than ± 0.5 dB and $\pm 5°$ in amplitude and phase, respectively. These specifications are established within a circular area of diameter 100 mm, which is equivalent to 56% of the antenna aperture.

B. Reflectarray design

An important advantage of the proposed unit cell is the independent control of the phase response of each polarization. The dipoles of one linear polarization are orthogonal to the dipoles of the other one. This unit cell topology minimizes the coupling between both polarizations resulting in a low cross-polarization level [4],[5]. Besides, the physical implementation of the X-polarization does not affect the Y-polarization. Thus, the design of the reflectarray can be split into two independent processes.

Using the antenna optics and specifications given in the previous section, each uniform plane wave is obtained through a Phase-Only Synthesis (POS). In a POS the phase of the reflection coefficients (ρ_{xx} and ρ_{yy}) of the elements of the reflectarray is synthesized until reaching a distribution that radiates the desired field. In this case, the POS is carried out using the generalized Intersection Approach for near-field [3]. This approach is certainly useful since it allows imposing restrictions in both amplitude and phase of the radiated near-field at the same time. The POS process is carried out twice to obtain a phase distribution for the X-polarization and others for the Y-polarization.

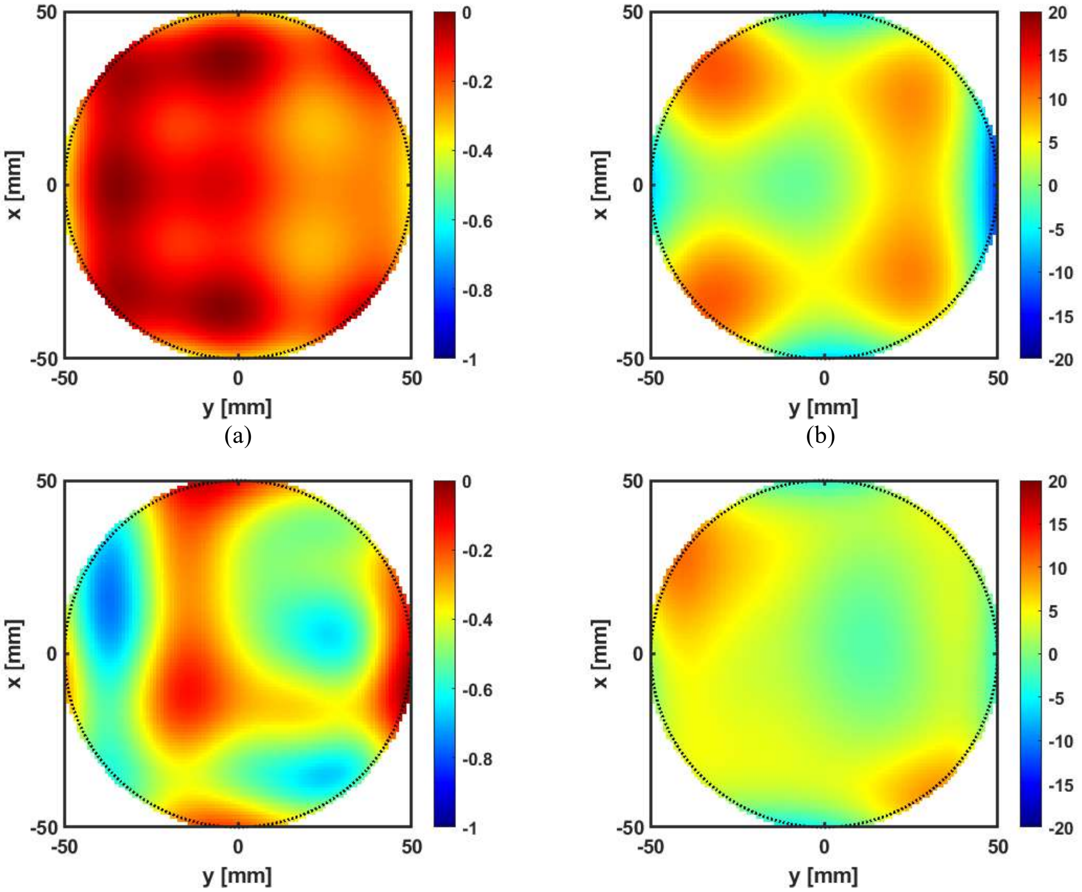
The starting point of the POS of the reflection coefficients (ρ_{xx} and ρ_{yy}) is a pencil beam distribution pointing to ($\theta_0 = 20°, \phi_0 = 0°$). The starting point is the same for both polarizations and it is analytically computed using [6]

$$\varphi_{mn}(x_m, y_n) = k_0(d_{mn} - (x_m \cos\phi_0 + y_n \sin\phi_0)\sin\theta_0) \qquad (1)$$

where φ_{mn} is the phase of the reflection coefficient of the mn-th element, (x_m, y_n) are the coordinates of the mn-th element; k_0 is the wavenumber in vacuum; d_{mn} is the distance between the phase center of the feed and the mn-th element; and (θ_0, ϕ_0) the pointing direction of the beam.

Due to the tight requirements to consider the near-field as a uniform plane wave, as well as dealing with the amplitude and phase of the near-field at the same time, both syntheses have been carried out following a multi-stage process [7]. The POS process is divided into several concatenated syntheses in which the requirements are gradually tightened until reaching the goal. Fig. 3 shows the phase distribution obtained after the entire POS process for the X-polarization. The obtained phase variation along the surface on both results (X- and Y-polarization) is smooth enough to carry out a design.

The elements of the reflectarray are designed to produce a phase shift similar to the solution of the POS for each polarization. In the design, the length of the central dipoles (L_x and L_y) are adjusted to produce the required phase shift, while



(a) (b)

(c) (d)

Fig. 4 Normalized amplitude (dB) (a) X-polarization (c) Y-polarization; and normalized phase (deg) (b) X-polarization and (d) Y-polarization of the uniform plane wave generated by the layout analyzed with a MoM-SD analysis.

TABLE I. PERFORMANCE OF THE DUAL-POLARIZED UNIFORM PLANE WAVE BEFORE AND AFTER THE SYNTHESIS

	X-polarization		Y-polarization	
	Starting point	Design	Starting point	Design
Amplitude (≤ 1 dB)	18.91%	100%	16.72%	100%
Phase (≤ 10°)	58.48%	80.14%	69.42%	93.45%
Max. Ripple (dB)	9.56	0.42	7.94	0.75
Max. Ripple (deg)	22.45	27	17.69	16.58

the other geometrical parameters remain constant. The design is carried out element-by-element, considering local periodicity, the real angle of incidence, and the complex permittivity of the dielectric. The response of the elements is obtained using a homemade electromagnetic code based on the Method of Moments in Spectral Domain (MoM-SD) [8]. The output of this process is the layout of the printed elements whose response minimizes the phase error to the required phase shift. The maximum error in a single element and both polarizations is lower than 0.8°.

C. *Uniform Plane Wave performance*

The layout is analyzed with the homemade MoM-SD to evaluate the performance of the reflectarray. Fig. 4 shows the uniform plane wave obtained for the X- and Y-polarization. Both uniform plane wave presents a similar and they mostly satisfy the requirements of ±0.5 dB in amplitude and ±5° in phase. Table II further details the comparison between the starting point (pencil beam distribution) and the design. Both amplitude and phase are significantly improved after the POS process. The ripple is reduced more than 9 dB in the X-polarization and 7 dB in the Y-polarization. The 1 dB specification is satisfy obtaining a very uniform field distribution within the desired area. An 80% of the phase (X-polarization) is within a ±5° ripple. Moreover, this percentage goes up to a 92% for a ripple of ±7.5°. The phase increases the maximum deviation due to the areas close to the boundaries, presenting a strong decay of the phase. However, the reflectarray presents a considerably plane wave in the central area wherein the DUT will be placed.

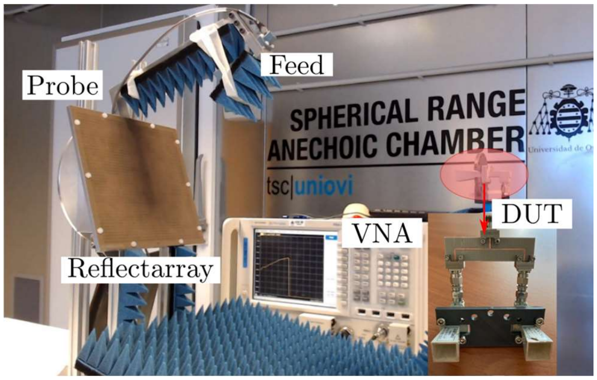


Fig. 5 Setup of the reflectarray-based PWG to measure the radiation pattern of an array of two horn antennas.

III. Evaluation of the radiation pattern of an antenna

This work does not only aim to design a reflectarray-based PWG but also to evaluate it by measuring the radiation pattern of an antenna. The designed reflectarray is integrated into a homemade Compact Antenna Test Range. Fig. 5 shows the setup using the reflectarray as probe and the DUT, which is an array of two horn antennas (A-INFOMW LB-28-10-C-KF) of 10 dBi gain. Both reflectarray and DUT are connected to the vector network analyzer, which measures the radiation pattern in real-time. In this first approach, only the azimuth is scanned, measuring the H-plane of the antenna. An Arduino board and a laptop are used to control the motor and move the DUT to perform the scan between $[-90^\circ, 90^\circ]$ and trigger the measure of the VNA at each scan angle. The separation between the two horn antennas is 50 mm so that the far-field begins at 782 mm. Both DUT and probe are placed within each near-field region. Besides, the array is designed to radiate the main lobe in boresight and several nulls within the scan range. This array aims to evaluate the performance of the systems measuring a complex radiation pattern.

The measured H-plane at 28 GHz is compared to the radiation pattern obtained through a full-wave simulation. The measurement shows a high agreement with the simulations resulting in a quite good concordance in the lobes and nulls within a scan range of 150°.

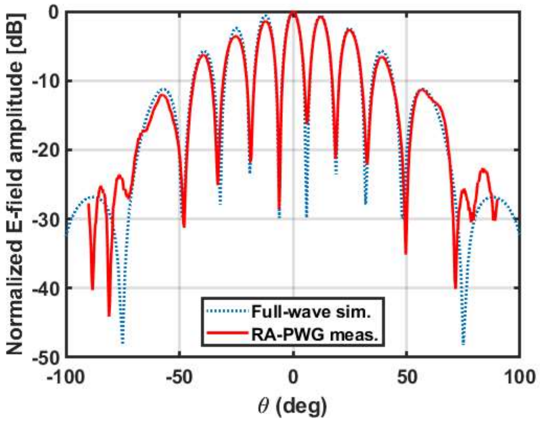


Fig. 6 Comparison of the measured and simulated radiation pattern at 28 GHz.

IV. Conclusions

In this work, the Intersection Approach is used to design a reflectarray that radiates a dual-polarized uniform plane wave. The reflectarray operates in two orthogonal linear polarizations using a single-dielectric layer by means of using orthogonal sets of coplanar dipoles. The design process is carried out with two independent phase-only syntheses, one for each polarization. Then, the elements of the reflectarray are designed to produce the required phase distribution. The layout is analyzed using a homemade MoM-SD obtaining a nearly dual-polarized uniform plane wave. Besides, once again the Intersection Approach shows his potential in improving the performance of reflectarray antennas, considering the starting point. Finally, the reflectarray is evaluated in a homemade CATR to evaluate the radiation pattern of an antenna. An array of two horn antennas is designed to radiate a complex radiation pattern to evaluate the capabilities of the reflectarray-based PWG. For the first time, a radiation pattern is evaluated using a reflectarray, obtaining a significant-good agreement between the measurement and the full-wave simulation. In the light of these results, reflectarray antennas are a suitable candidate to generate uniform plane waves to use in compact measurement systems at mm-Wave frequencies.

Acknowledgements

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