

Reflectarray as plane wave generator for Compact Antenna Test Range in millimetre frequency band

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Abstract- In this work, a reflectarray is proposed to be used as a plane wave generator (PWG). The reflectarray works at 28 GHz and produces a uniform plane wave in a certain region of the Fresnel region of the antenna, reaching an ultra-compact structure. In a first approach, a far-field focused reflectarray is analyzed to create the plane wave. However, the size where the plane wave is considered uniform is not large enough for its use in compact antenna test ranges (CATR). The desired wave must satisfy tight requirements, both in amplitude and phase, to be considered as a uniform plane wave. The generalized Intersection Approach is used to improve the plane wave performances by doing a Phase-Only synthesis (POS) on the phase of the reflectarray elements. Simulations of the plane wave generated by the antenna before and after the optimization process are compared, showing an important enhancement on the uniformity of the wave. The obtained phase distribution is used to design and manufacture a reflectarray based on a three-parallel-dipoles cell. The prototype is measured in a planar range facility to evaluate the quality of the radiated plane wave. Measurements show a low ripple in both amplitude and phase, thus promising results are obtained.

I. INTRODUCTION

The rise of the interest on the applications at (sub)millimeter frequencies has led to new technological requirements, particularly the development of efficient 5G communications at 28, 39 or 60 GHz [1,2], satellite communications at Ka-band [3] or automotive radars at 70 GHz [4]. Therefore, antenna measurements systems need to evolve and satisfy the new requirements that demand these applications. In this line, Compact Antenna Test Ranges (CATRs) are widely known in the measurement of radiation patterns or Radar Cross Sections (RCS). These systems present a significant advantage regarding near-field scanning or far-field measurement systems. CATR enables to measure in far-field conditions but in the near-field region of the probe, avoiding the use of NF-FF transformations or large distances. The main working principle is based on a parabolic reflector that transforms a spherical wave front, provided by a horn, into a plane wave. This plane wave is created in the Fresnel region of the reflector and is used to measure the radiation pattern of the device under test (DUT) [5].

However, CATRs present some drawbacks that should be considered. Firstly, the size of the generated uniform plane wave is proportional to the equivalent aperture of the antenna, thus electrical large reflectors are typically required, dealing with bulky antennas or structures. The amplitude of the plane wave is highly influenced by the illumination taper over the reflector surface. Additionally, the manufacturing process at (sub)millimeter frequencies requires really low surface errors,

increasing the cost and the complexity of the process. Previous literature has studied some alternatives like lenses [6] or holograms [7]. Another potential candidate is reflectarray antennas [8]. These antennas have demonstrated their potential in many far-field applications such space communications, where extremely tight specifications must be fulfilled.

In this work, a reflectarray antenna is proposed to be used as a plane wave generator (PWG). The reflectarray is designed to generate the required uniform plane wave in the Fresnel region of the antenna to measure devices, replacing the traditional parabolic reflector. In this case, a small reflectarray of 188 mm × 188mm is proposed to create the plane wave at a distance of 500 mm at 28 GHz. This antenna provides an ultra-compact structure that can be potentially used in the measurement of 5G devices. The desired plane wave must satisfy tight requirements both in amplitude and phase within an area of diameter 100 mm. The proposed reflectarray is manufactured and measured in a planar range facility to evaluate the plane wave performance.

II. REFLECTARRAY AND PLANE WAVE CHARACTERISTICS

A. Antenna optics and unit cell definition

A squared reflectarray made up of 44 × 44 elements, distributed in a regular grid of periodicity $\lambda/2 \times \lambda/2$ ($a \times b$) is proposed to demonstrate its use as a PWG antenna at 28 GHz. The reflectarray is fed in an offset configuration and the phase center of the feed is placed at $(x_f, y_f, z_f) = (-79.3, 0, 200)$ mm using the coordinate system depicted in Fig. 1. The feed is a pyramidal standard horn gain of 20 dBi (Narda 665-20) that generates an illumination taper of -15.80 dB at the edge of the reflectarray. The reflectarray is tilted an angle 20° around the y_r -axis, obtaining an equivalent aperture (D) of

$$D = D_x \times D_y = 188 \cos \gamma \times 188 = 177 \times 188 \text{ mm}^2 \quad (1)$$

The reflectarray is designed using cells based on a set of three parallel dipoles oriented to the polarization axes as Fig. 1 shows. The dipoles width is $W=0.5$ mm and the separation among the three dipoles is $S = 1.43$ mm. The length of the lateral dipoles (L_1) depends on the central dipole length and is defined as $L_1 = 0.7L_2$. the variation of the length L_2 allows to adjust the phase-shift of the cell. In Fig. 2 both amplitude and phase response are shown for normal incident, obtaining a phase-shift range larger than 360° and an amplitude in the

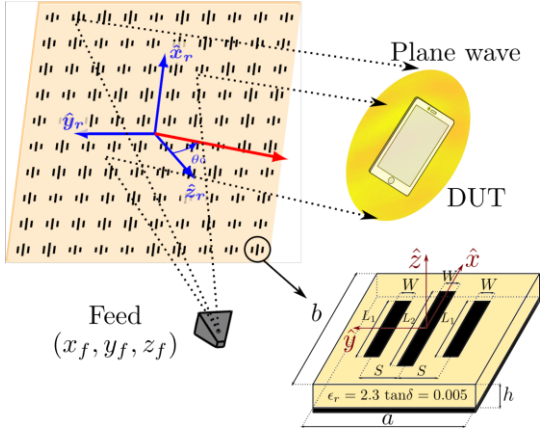


Fig. 1. Scheme of a plane wave generator (PWG) with a reflectarray to measure the device under test (DUT).

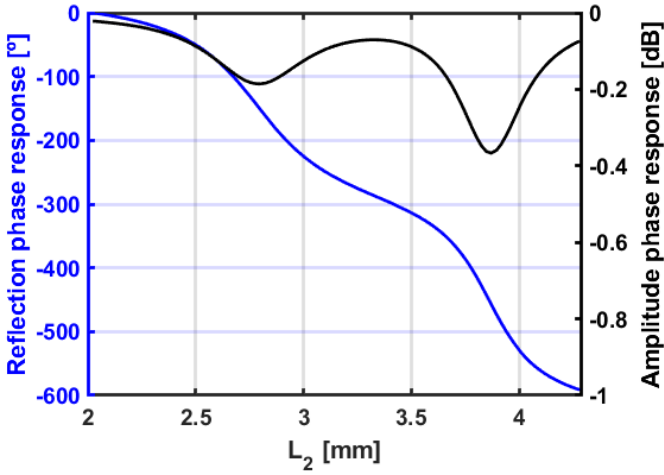


Fig. 2. Response of the three parallel dipoles cell for normal incident at 28 GHz.

worst case better than -0.40 dB. The dipoles are printed on a single layer of Duclad 880 substrate ($h = 0.762$ mm, $\epsilon_r = 2.3$, $\tan\delta = 0.005$).

B. Uniform plane wave requirements

The plane wave should be generated on a plane perpendicular to the propagating direction, 500 mm (46.66λ) far from the center of the reflectarray. This configuration provides an ultra-compact structure considering that the far-field region starts at 12.52 m (1170λ). The typical tight specifications of 1 dB and 10° for these applications are imposed on an area of diameter 100 mm (9.33λ), equivalent to more than the 50% of the antenna aperture width in both x - and y - axes.

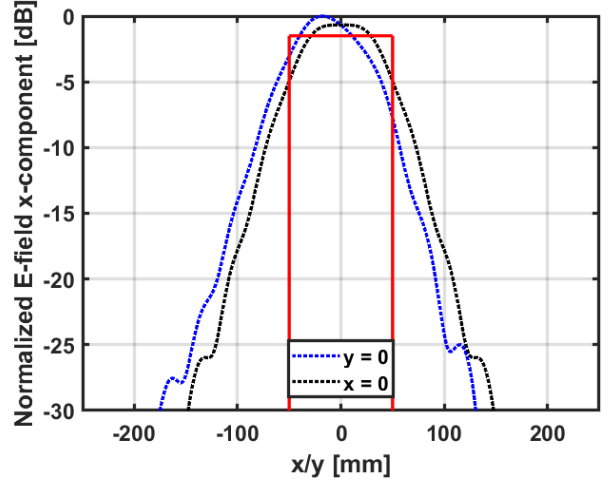
III. REFLECTARRAY STUDY

A. Far-field focused reflectarray

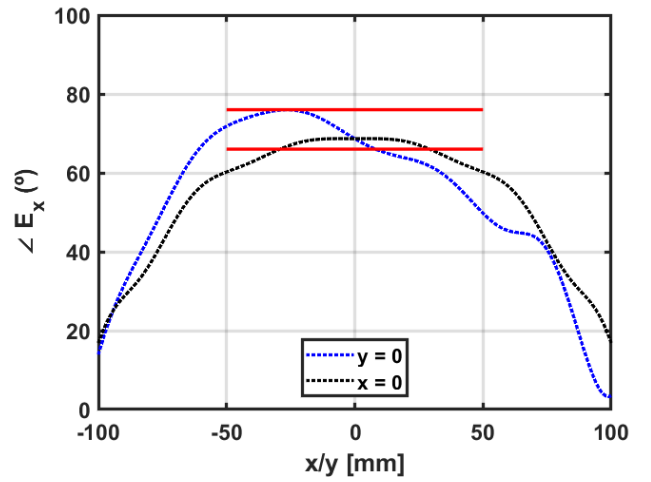
In a first approach, a far-field focused reflectarray is considered, whereby the radiation pattern is a pencil beam focused in a certain (θ_0, φ_0) direction. Assuming $\varphi_0 = 0^\circ$, the phase of the reflectarray elements can be computed as

$$\phi^{mn} = \phi_{in}^{mn} - k_0 x_i \sin\theta_0 \quad (2)$$

where ϕ_{in}^{mn} is the phase of the incident field at the mn -th element; k_0 is the vacuum wavenumber and θ_0 is the focusing direction. This equation provides the reflection coefficient



(a)



(b)

Fig. 3. Plane wave generated by a far-field focused reflectarray (a) Normalized amplitude (b) Phase. Red lines show the area where the plane wave must be uniform.

phase distribution for either the X or Y polarization. In this case, according to the system depicted in Fig. 1, they agree with the X polarization.

The plane wave created by this phase distribution is shown in Fig. 3. The phase is almost flat because of the wave is generated in the collimating direction whilst the amplitude barely satisfies the 1 dB ripple. The illumination taper of the feed is remarkably limiting the uniformity of the wave, especially on the non-symmetry plane ($y = 0$).

B. Optimized reflectarray design

The generalized Intersection Approach (IA) [9] with NF formulation is used to carry out a Phase-Only Synthesis (POS) of the reflectarray elements. The phase distribution of the reflectarray elements after the synthesis is shown in Fig. 4. This phase variation along the reflectarray surface is smooth enough for a proper design.

The main cuts of the synthesized phase distribution are shown in Fig. 5, while Table I outlines a comparison of maximum ripples and specification compliance before and after the optimization. Both amplitude and phase show a significant improvement, highlighting an increment from the 25% to a nearly 90% of compliance in the amplitude and a ripple reduction of 7 dB. Despite having a markedly better

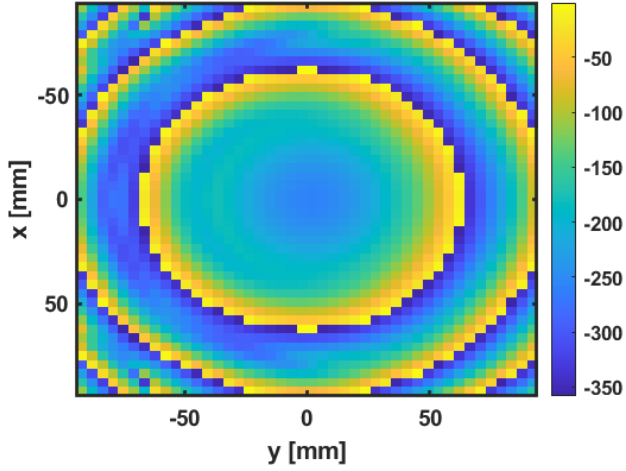


Fig. 4. Reflection phase coefficients of the reflectarray elements obtained after the optimization process.

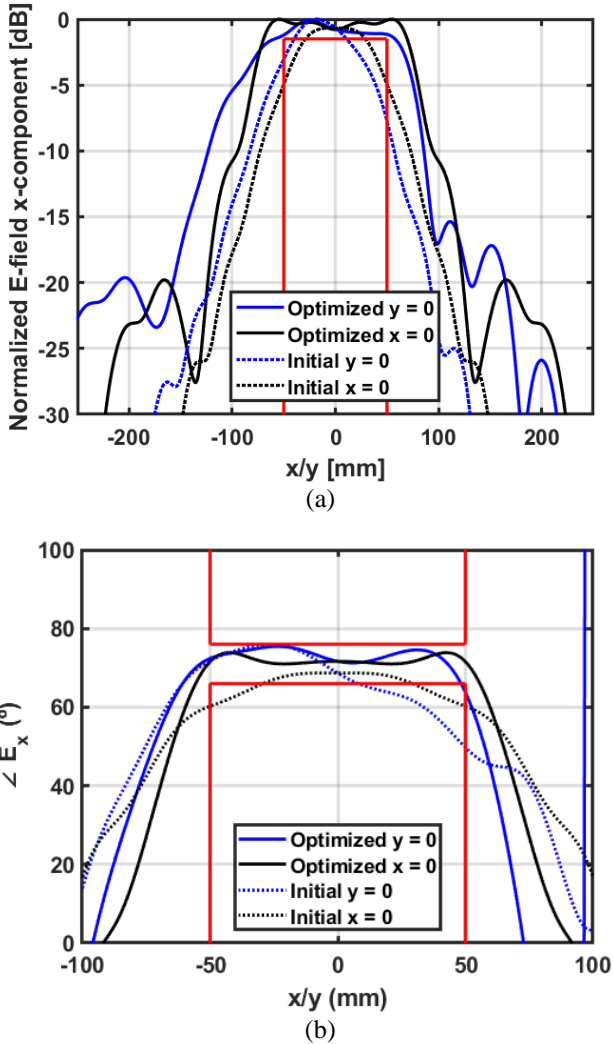


Fig. 5. Comparison between the optimized and initial (a) amplitude and (b) phase. The amplitude is normalized to the maximum and the phase to the central position.

TABLE I
EVALUATION OF THE MAXIMUM RIPPLE (dB and °) AND THE SPECIFICATION COMPLIANCE IN THE DESIRED AREA AND ITS MAIN CUT FOR THE STARTING AND OPTIMIZED POINT.

		Starting point		Optimized point	
		Ripple (dB)	Compliance (%)	Ripple (°)	Compliance (%)
Total area	Ampl.	8.01	25.25	1.33	89.42
	Phase	26.82	46.01	4.30	100
Main cuts	Ampl.	8.01	38.83	1.10	83.49
	Phase	26.82	39.80	4.30	100

starting point on the phase, the optimized phase reduces its ripple to 4.30° in the whole area. The main cuts are of a particular interest since they represent the largest dimensions of the specification area due to its circular shape. After the synthesis, the cut $y = 0$ has been significantly enlarged with an increase of a 262% and 303% in amplitude and phase, respectively. The cut $x = 0$ is also enlarged in a 209% and 135% in amplitude and phase. The current plane wave has the same size in its main cuts.

Once the desired plane wave is obtained, the phase distribution must be physically implemented using the three-parallel-dipole cell. In the designing process, the length of the dipoles is adjusted to produce the required phase-shift. In this case, the design is done element by element, considering local periodicity environment and the real angle of incident of each cell.

IV. EXPERIMENTAL VALIDATION

The squared reflectarray of 44×44 cells has been manufactured. In order to properly evaluate the plane wave performances, the prototype is measured in the planar acquisition range at the University of Oviedo. The reflectarray is placed on an aluminum structure and tilted 20° (see Fig. 6). The plane wave is generated parallel to the probe aperture, an open-ended Ka-band waveguide, at a plane $z = 500$ mm. The plane is measured in a regular squared grid of 150×150 mm² that totally covers the area of interest. The copolar component of the electric field, both amplitude and phase, is obtained and shown in Fig. 7 and the ripple compliance is outlined in Table II. The amplitude ripple is nearly close to 1 dB in the whole area within a maximum peak-to-peak ripple of 1.8 dB. The ripple compliance of 1 dB ripple is a 89.95% and, almost the 100% of the ripple is lower than 1.5 dB. The phase of the plane wave shows a notably flatness through the whole area. The maximum deviation is 19.64° but most of the phase has a ripple between $10^\circ - 15^\circ$, only having short areas out of specifications. It may be highlighted the smoothness along the main cuts, both amplitude and phase. The cut $y = 0$, that typically is the worst case due to the feed position, practically satisfies the specifications, whilst the cut $x = 0$ totally satisfies them. Hence, this plane virtually behaves as a uniform plane wave.

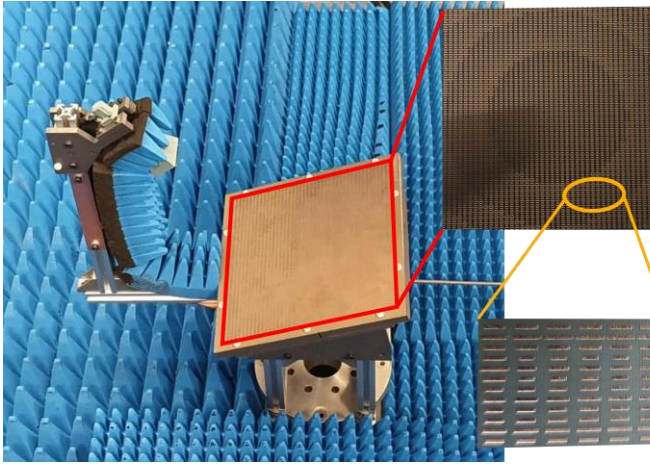


Fig. 6. Plane wave generated by the proposed reflectarray at $z = 500$ mm and measured in the planar facility range at 28 GHz (a) Normalized amplitude (b) Phase.

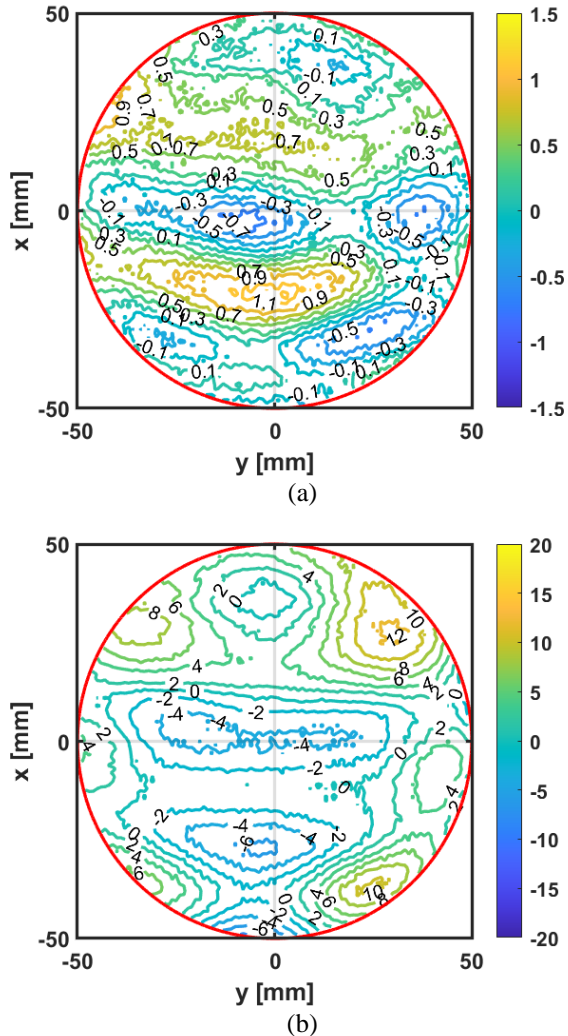


Fig. 7. Plane wave generated by the proposed reflectarray at $z = 500$ mm and measured in the planar facility range at 28 GHz (a) Normalized amplitude (b) Phase.

V. CONCLUSIONS

A reflectarray antenna is analyzed to generate a plane wave to measure the radiation pattern of an antenna. The reflectarray generates the plane wave in an area close to the antenna providing a compact structure. Particularly, the proposed reflectarray is made of 44×44 elements based on three-parallel-printed dipoles cells at 28 GHz. The plane wave satisfies the tight ripple requirements close to 1 dB in amplitude and 10° in phase. The reflectarray is manufactured and evaluated in a planar range facility, where the plane wave at a distance equivalent to 46.6λ , which is suitable to be used for the test of 5G devices at millimeter waves.

TABLE II

EVALUATION OF THE MAXIMUM RIPPLE AND THE SPECIFICATIONS COMPLIANCE IN THE MEASURED PLANE WAVE AND ITS MAIN CUTS.

	Amplitude			Phase		
	Max.	1 dB	1.5 dB	Max	10°	15°
Total area	1.80	89.95 %	97.91 %	19.64	61.60 %	91.24 %
$y = 0$	1.46	79.48 %	100 %	15.93	61.53 %	94.87 %

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