Evaluation of a Dual-Circularly-Polarized Reflective Metasurface as a Plane Wave Generator in Ka-Band

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***Abstract*—In this work, a reflective metasurface is designed to generate a dual-circularly-polarized uniform plane wave at Ka-band (31 GHz). The metasurface is designed using a Phase-Only Synthesis with the generalized Intersection Approach. The design considers tight constraints in both amplitude and phase of the radiated near field. The synthesized phase-shift distribution is also used to convert the dual-linearly polarized incident field into a dual-circularly polarized reflected field. The unit-cell of the metasurface is based on two stacked layers of three parallel dipoles, adjusted cell by cell to provide the synthesized phase distributions with less than ±1° of phase error. Preliminary results show the generation of a uniform plane wave in an area equivalent to 82.8% of the metasurface aperture size, revealing the possibility of generating dual-circularly-polarized uniform plane waves using metasurfaces with a simple design process.**

***Index Terms*— metasurface antennas, electromagnetics, propagation, measurements.**

I. INTRODUCTION

Mm-wave frequencies have increased its popularity throughout the last years due to their use in applications such as satellite and 5G communications, or automotive radars. The characterization of the radiating elements (antennas) at those frequencies is commonly performed by using conventional measurement systems. Mainly, spherical compact ranges or near field acquisition ranges. However, a novel approach has recently been proposed based on alternative systems with the capability of carrying out a fast evaluation of the antennas without using fixed systems. This leads to a reduction in costs, as well as to less complex and bulky facilities. The idea is to develop portable systems that can be used *in-situ*, thus in an area of interest, such as labs or manufacturing lines, or directly evaluating radiating elements that are working on. These portable systems are not a replacement for conventional systems but an alternative with a tradeoff between cost, accuracy, and flexibility.

These portable systems can characterize the antenna performance using the standard Over-The-Air (OTA). These standard states that the antenna should be characterized at infinity distance without a direct connection between the probe and the Device-Under-Test (DUT), similar to the measurement of the DUT under far field condition. Besides, the DUT should be as close as possible to capture as much radiated power as possible. When dealing with devices at FR2 (Frequency Range 2 reserved for 5G communications to operate in Ka-band), such as user terminals or base stations, reaching far field conditions implies a large distance between DUT and probe, thus the free-space attenuation is quite high, decreasing the received signal.

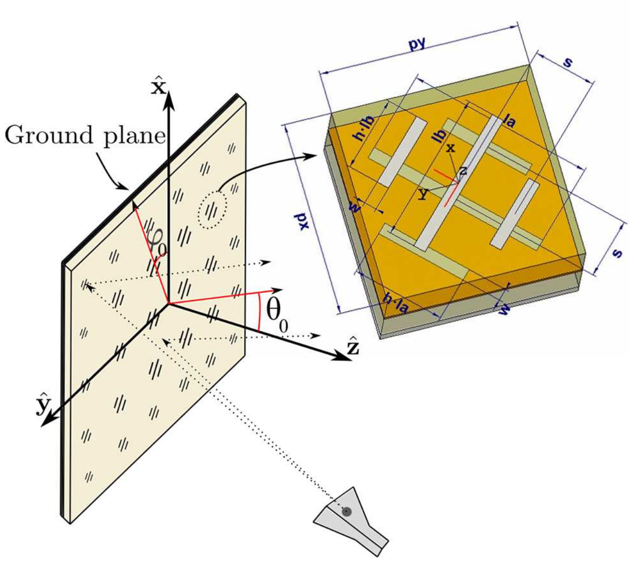


Fig. 1. Sketch of the antenna optics.

An alternative to overcome that, which has been proposed in the last years, is the use of plane wave generators (PWG). A PWG can generate a uniform plane wave (UPW) within the near field of the antenna. Therefore, a PWG reaches far field condition in a short distance. These antennas are typically based on an array that radiates the UPW over a volume in a close distance to the aperture. The generation of the UPW allows emulating far field conditions to test the DUT at a reduced distance, decreasing the free-space attenuation and improving the received signal.

The classical implementation of PWG is based on array antennas, finding some preliminary published works that proposed different configurations to obtain the plane wave [1]-[2]. However, these array-based PWG require beam-forming feeding networks with complex designs to properly control the excitation of the array elements. An alternative to avoid the use of feeding networks was introduced in [3], proposing a reflectarray antenna to generate the UPW. The first demonstrator of a reflectarray-based PWG was presented in [4], and it was extended to a dual-polarized UPW in [5], considering independent phase distributions in both linear polarizations. Both works take advantage of phase-only synthesis (POS) and the generalized Intersection Approach [6] to obtain the phase-shift distribution on the reflectarray surface that radiates the UPW using a simple technique to address a quite challenging near field synthesis with constraints in both amplitude and phase of the radiated field.

In this work, the technique presented in [5] is used to synthesize a reflective metasurface to obtain a dual-circularly-polarized UPW. Following the nature of PWGs as providing simple and low-cost solutions, the metasurface is designed to generate a dual-CP UPW when it is spatially fed by a dual-linearly-polarized radiating source, leading to a simplification of the feeding subsystem. A POS is carried out to obtain the required phase-shift distributions of the elements of the metasurface. To the best knowledge of the authors, this is the first time that a near field synthesis is carried out for circular polarization, moreover, considering amplitude and phase constraints in the radiated field. These preliminary results enhance the results obtained with previous reflectarrays in terms of the UPW size, reaching an UPW in an area equivalent to 82.8% of the aperture size.

II. METASURFACE-BASED PLANE WAVE GENERATOR DEFINITION

A. System optics

The metasurface is divided into 62×62 cells, with a period of $\lambda_0/3$ at 31 GHz (3.2 mm) in the x- and y- direction, according to Fig. 1. The metasurface is fed in off-set configuration placing the phase center of the feed at $\boldsymbol{r}_{HA} = (-100, 0, 300)$ mm. The linearly-polarized feed is a horn antenna modelled as a $\cos^q \theta$ function with a q-factor of 12, obtaining an illumination taper of -6 dB at the edge of the metasurface. The antenna generates a plane wave in the specular direction $(\theta_0, \varphi_0) = (18.43°, 0°)$, thus the equivalent aperture D is

$$D = \sqrt{(D_x \cdot \cos\theta_0) \cdot D_y} = 193.2 \text{ mm} \tag{1}$$

where D_x and D_y are the physical aperture of the reflective surface in the x- and y-direction, respectively (198.4 mm).

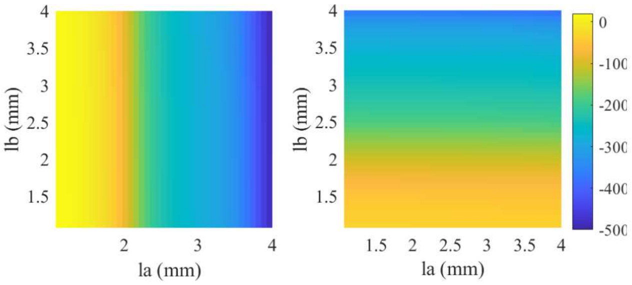
For this study, the UPW is generated at $\sim 73\lambda_0$ (700 mm) at 31 GHz from the center of the antenna. Note that this distance is significantly short considering that the far-field region starts at $\sim 1514\lambda_0$ at 31 GHz ($\sim$15 m). The radiated near field should behave as a UPW in a circular area of diameter 160 mm, equivalent to 82.8% of the aperture size. Within this area the near field should have a ripple lower than 1 dB (peak-to-peak) in amplitude and a maximum deviation in phase of 10°, which is the theoretical definition of a UPW for these systems [7].

B. Definition of the Unit-Cell

Each cell comprises two orthogonal sets of three parallel dipoles in a staked configuration, as depicted in Fig. 1. The dipoles are rotated 45° to decompose the incident field into two linear and orthogonal components, thus making it possible to provide a dual-linear to dual-circular polarization conversion at the antenna surface [8]. The dielectric configuration of the cell contains two sheets of 0.508 mm thick Kappa 438 ($\epsilon_r = 4.38, \tan\delta = 0.005$) bonded by 76-$\mu$m thick CuClad 6250 film ($\epsilon_r = 2.32, \tan\delta = 0.0013$). The dipoles would be printed on both sides of the upper dielectric sheet. The geometrical parameters of the cell, defined after a parametric study, are listed in Table I.

TABLE I. GEOMETRICAL PARAMETERS OF THE UNIT-CELL

Geometrical parameters		
Name	***Description***	***Value***
px	Period along the *x* axis	3.2 mm
py	Period along the *y* axis	3.2 mm
w	Width of the dipoles	0.2 mm
s	Separation between adjacent dipoles	1.0 mm
h	Scale factor of the lateral dipoles	0.5
la	Length of the lower central dipole	[1.0 – 4.0] mm
lb	Length of the upper central dipole	[1.0 – 4.0] mm



(a) (b)

Fig. 2. Phase in degrees introduced at 31 GHz in the (a) x' and (b) y' components of the field when the lower and upper dipoles are independently increased.

The unit-cell has been analyzed by a routine based on the Method of Moments in the spectral domain (SD-MoM) and the local periodicity approach [9]. Fig. 2 shows the phases introduced by the cell in the linear x' and y' components (see Fig. 1) of the field when la and lb are independently increased, under the incidence angles $(\theta_i = 18.5°, \varphi_i = 0°)$. The phase response proves that each orthogonal set of dipoles controls independently the phase in x' and y' component, with a range of phase values close to 400°.

III. SYNTHESIS PROCEDURE

The starting point of the proposed synthesis is the phase-shift distribution required to produce a pencil-beam [10] pointing to the center of the UPW area $(\theta_0 = 18.43°, \varphi = 0°)$. This phase-shift distribution is analytical, and it is computed as

$$\phi_{mn} = k_0(d_{mn} - (x_m \cos\varphi_0 + y_n \sin\varphi_0)\sin\theta_0) \tag{2}$$

where ϕ_{mn} is the phase of the reflection coefficient of the mn-th element of the metasurface, (x_m, y_n) are the

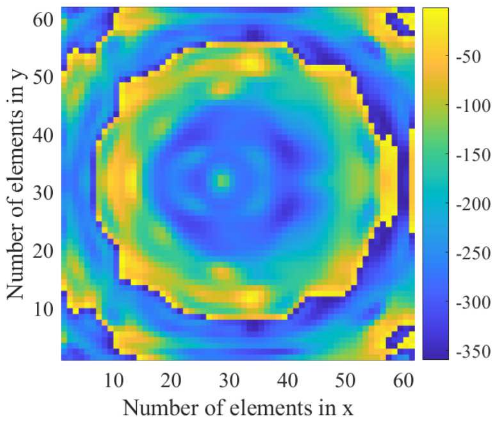


Fig. 3. Phase-shift distribution obtained through the Phase-Only Synthesis to generate a dual-circularly-polarized UPW at 31 GHz.

coordinates of the mn-th element expressed in the antenna system; k_0 is the wavenumber in vacuum; and d_{mn} is the distance between the (m, n)-th element and the phase center of the feed.

A pencil-beam phase-shift distribution generates a plane wave in the desired direction. However, this analytical approach cannot be used to generate a UPW because of two main issues. First, the illumination taper of the incident field has a deep impact on the amplitude of the UPW, requiring using low-directivity feeds. Hence, increasing the field level at the edge of the antenna would cause edge diffraction in a prototype and therefore ripple in the near field of the antenna. Second, the off-set configuration tilts the phase of the radiated field in the off-set cut, requiring correcting this deviation to not limit the size of the UPW.

From this starting point, the POS is carried out using the Intersection Approach for near field, which allows imposing constraint in the amplitude and phase of the radiated field simultaneously. Note that the additional dual-circular to dual-linear polarization conversion constrains the required phase distributions in each orthogonal component of the field: the objective phase-shift distributions in x' and y' components must present a difference of $-90°$. Therefore, applying a single POS it is feasible to obtain the phase-shift distribution of both linear components of the field.

The restrictions of the POS have been defined according to the theoretical definition of a UPW given by a maximum ripple of 1 dB in amplitude and 10° of maximum deviation in phase. These requirements are imposed in the area within the UPW should be generated. Outside of this area, the field must have a relative difference of 12 dB regarding the area of the UPW to ensure that there is no radiation in undesired directions. Controlling both amplitude and phase is not a tricky matter, thus the synthesis is carried out following a multi-stage process [11]. The synthesis is divided into several stages, in each stage the requirements are gradually tightened from one to the next stage until finally reaching the requirements of the UPW. The output of this process is the phase-shift distribution shown in Fig. 3, which would be associated to the phase distribution in the x' component of the field. The phase distribution for the orthogonal linear component is obtained by adding a phase constant of $-90°$. Figure 4 shows the main cuts of the resulting circularly polarized UPW when considering ideal phase shifting cells that provide the required phase distribution without phase errors and dielectric losses. The amplitude presents a quite flat-top response within the area of interest while the phase is almost plane within the same range.

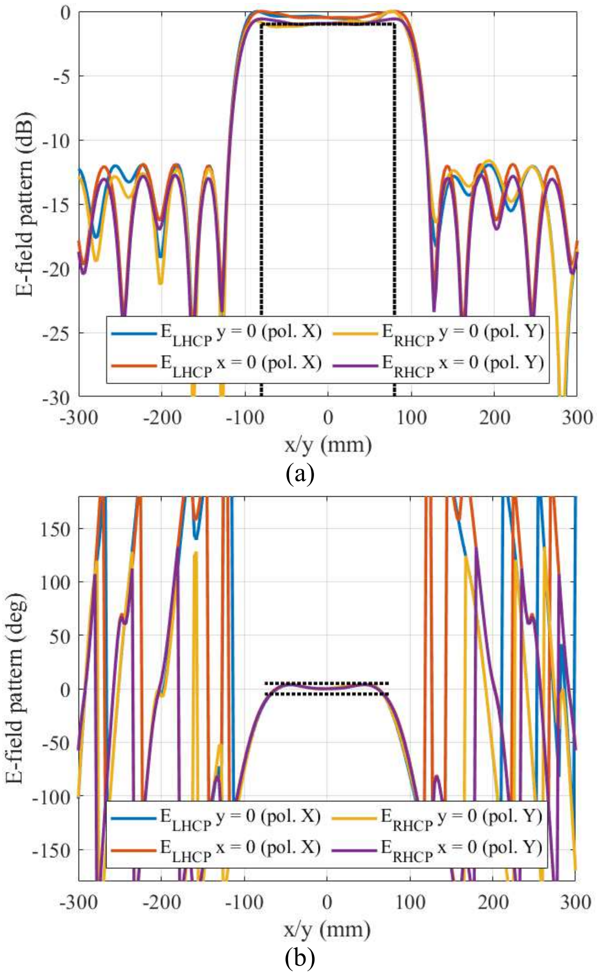


Fig. 4. Main cuts of the uniform plane wave generated by the synthesized phase-shift distribution at 31 GHz considering ideal phase shifting cells. Black line shows the specifications.

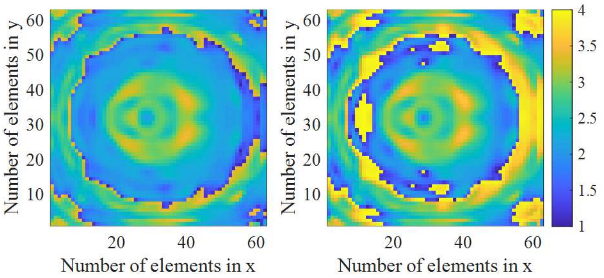
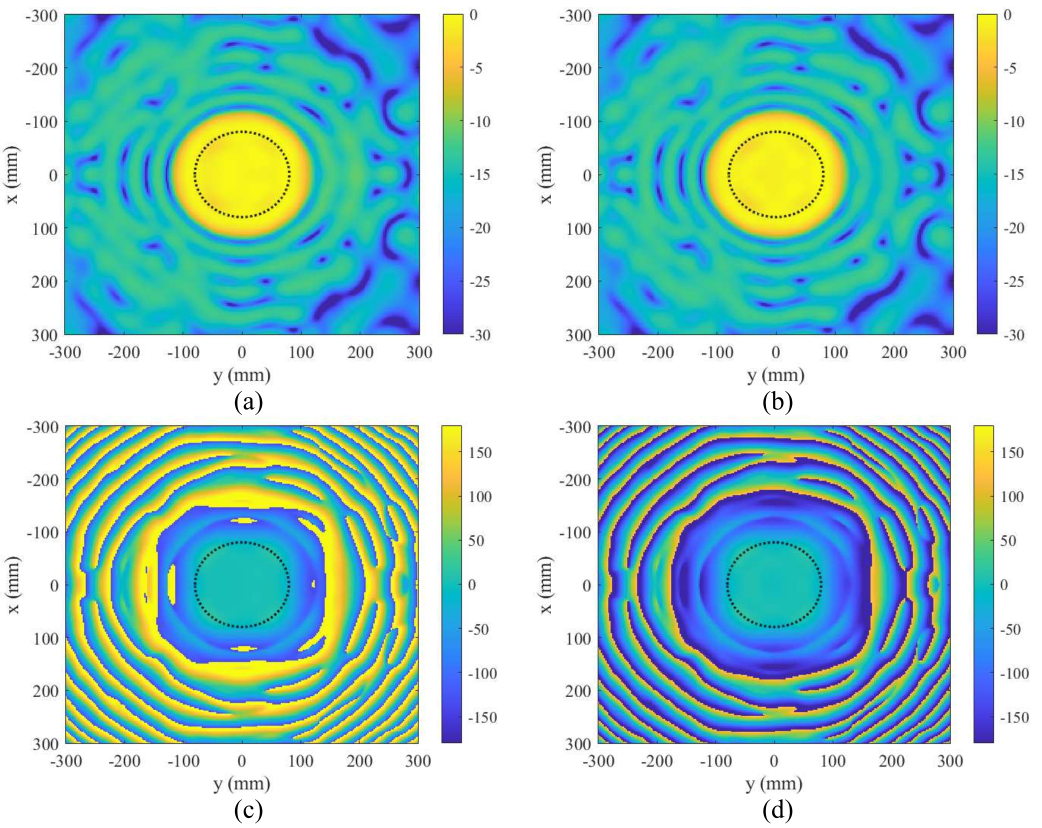


Fig. 5. Length in mm of the central dipoles in (a) the lower and (b) upper metallization layer.



(a) (b)

(c) (d)

Fig. 6. Uniform plane wave generated by the designed metasurface at 31 GHz: (a) amplitude (dB) of the LHCP, (b) amplitude (dB) of the RHCP, (c) phase (deg) of the LHCP, and (d) phase (deg) of the RHCP. The amplitude is normalized to the maximum of the UPW and the phase to the center of the UPW. Black dotted line shows the UPW limits.

IV. CIRCULAR-POLARIZED METASURFACE

The synthesized phase distributions are used to carried out the design of the metasurface. In the design process, the lengths of the dipoles are adjusted to obtain the same response as the synthesized phase distributions. The design process is based on the SD-MoM analysis tool to adjust the lengths of the dipoles, cell-by-cell, considering the real angles of incidence in each cell. The lengths of the designed dipoles are shown in Fig. 5, referred to the lower and upper central dipoles (la, lb). The output of this process is the layout of 62×62 elements of the metasurface. In this case, the maximum phase error provided by the adjusted dipoles is less than $\pm 1°$.

The near field radiated by the designed metasurface is computed to evaluate the performance of the UPW. Figure 6 shows the LHCP and RHCP UPW at 700 mm and 31 GHz. All the results, either amplitude or phase, show significant uniform field distribution within the desired circular area of diameter 160 mm. The amplitude presents that a 100% and 86.98% of the area is within the desired ripple of 1 dB, for the LHCP and RHCP, respectively. However, the maximum peak-to-peak ripple is 1.15 dB, showing that most of the UPW satisfies the specifications or is near to it. In the case of the phase, those percentages are very similar, being a 100% of compliance for the LHCP and a 85% for the RHCP. Increasing the maximum deviation allowed to 14° the compliance increases up to 100%. Figure 7 shows the main cut $y = 0$ for both co-polar and cross-polar components of the UPW, obtaining a CP/XP higher than 24 dB, which is associated with an axial ratio lower than 1.1 dB.

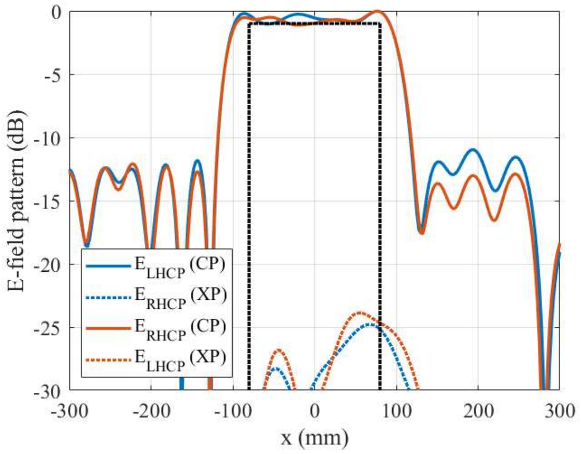
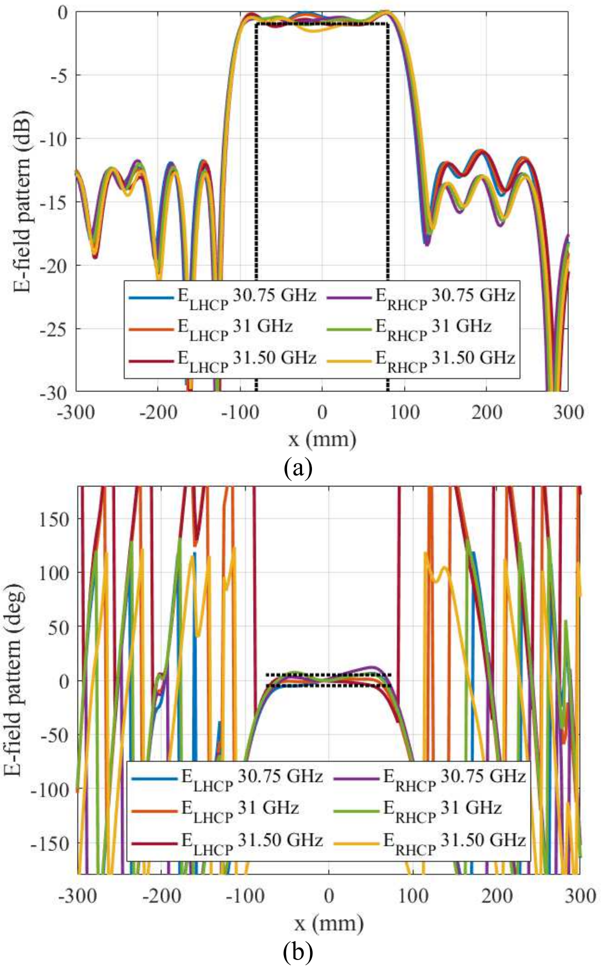


Fig. 7. Main cut $y = 0$ of the copolar and cross-polar components of the UPW at 31 GHz.

The in-band response of the uniform plane wave is analyzed from 30.75 to 31.25 GHz, thus in a 0.5 GHz bandwidth. Figure 8 shows the main cut $y = 0$ for the amplitude and phase within this bandwidth. The response at the lowest frequency in amplitude is nearly the same as the



(a)

(b)

Fig. 8. In-band response from 30.75 to 31.50 GHz of the UPW for the main cut $y = 0$.

result obtained at 31 GHz. Therefore, the behavior at the operational frequency is extended within this bandwidth. Note that the proposed synthesis has been carried out at a single frequency. The design can be enhanced by implementing an in-band optimization, taking advantage of the additional degree of freedom given by the lengths of the lateral dipoles in the cells.

V. CONCLUSION

In this work, a metasurface is designed to produce a dual-circularly-polarized uniform plane wave. The design of the metasurface is based on a Phase-Only Synthesis using the generalized Intersection Approach, which is introduced for metasurfaces antennas for the first time. The synthesis is used to reach the phase-shift distribution that should introduce the elements of the metasurface to radiate a uniform plane wave while converting the incident linearly polarized field into a dual circularly polarized reflected field. Then, the design is carried out using a dipole-based unit-cell that allows the conversion from dual-linear to dual-circular polarization, while generating the uniform plane wave in circular polarization. The numerical analysis of the design shows excellent results in terms of the uniform plane wave generated by the antenna, being the first time, as the authors are aware, that a metasurface controls both amplitude and phase of the radiated near field with such complex and tight requirements. The design is carried out a single frequency, though the in-band response is also analyzed. These results show the possibility of using metasurface antennas as plane wave generators applying a POS in the design process.

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