Synthesis Algorithm for “Quasi-Planar” Dielectric Lenses

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Abstract—**In this work a phase-only synthesis algorithm based on a planar aperture model is proposed to design “quasi-planar” dielectric lenses with different radiation characteristics, either with a one-beam or two-beam pattern. The model is initially validated with both GO and full-wave simulations, and then with the measurement of a manufactured prototype in anechoic chamber. Both simulations and measurement show good agreement with the model results.**

Index Terms—**radiation pattern shaping, transmitarrays, dielectric antennas, three-dimensional (3D) printing, measurement.**

I. INTRODUCTION

Transmitarrays, also known as planar array lenses, have been extensively investigated in recent years [1]-[3] and have been postulated as appropriate candidates for 5G multibeam antennas [4]. They are characterized by being quasi-periodic, planar, lightweight and low-cost structures that transform the incoming phase front radiated by one (or several) feed antenna(s) into a certain outgoing phase front. If the radiation pattern of the transmitarray must be shaped to meet a given template, then a phase synthesis method must be used to find the necessary outgoing phase distribution [5], [6]. The transmission phase through the structure is then achieved by changing some parameter of the quasi-periodic element from cell to cell.

Additionally, dielectric lenses based on 3D printing technology have also been recently proposed as low-loss and low-cost solutions for millimeter-wave and terahertz antennas [7]. They are in fact dielectric transmitarrays, where the unit cell element is a dielectric slab and the necessary transmission phase through the lens is accomplished depending on the slab height [6], [7].

In this contribution, which is a continuation and an improvement of the work presented in [6], the use of a transmitarray synthesis algorithm to design “quasi-planar” pixelated dielectric lenses will be validated. The adequacy of the planar model for this purpose will be proved with both simulations and measurements.

II. METHODOLOGY

A. Synthesis of Transmitarrays

In [6] a synthesis algorithm based on a planar aperture model [8] and the iterative application of the Fourier transform [9] was presented for the synthesis of transmitarrays. In that model the amplitude of the transmission coefficient of the lens is assumed to be unity. Then the synthesis algorithm finds the necessary transmission phase to obtain, from the field generated by the feed, the required field in the aperture in order to achieve the desired radiation pattern. The spillover effect is taken into account in the synthesis process.

The feed in the mentioned model is a horn, modelled as a punctual source. However, unlike [6], where a $cos^q \theta$ model was used, in this contribution the NFPC (Near Field Plane Cuts) model presented in [8] will be used to find the field generated by the horn on the plane of the lens. Thus some of the near-field effects of the feed are taken into account. The use of this model implies the measurement or simulation of the main cuts of the electric field generated by the horn at the lens distance, from which the field on the lens surface is obtained. As a first approximation, the feeding horn will be simulated using the full-wave simulator HFSS [10].

B. Design of the Dielectric Lens and Simulation

The necessary phases obtained in the synthesis algorithm can be used to design a pixelated dielectric lens, which can be seen as an array of dielectric slabs with different heights. Then, in order to minimize the shadowing effects, the highest slabs should be placed at the center of the lens, being often necessary to add a phase constant to the original phase given by the algorithm. In [6] this process was applied to synthesize two different pixelated dielectric lenses at the frequency of 10 GHz, yielding a flat-top beam pattern and an isoflux pattern respectively. In both cases, a good agreement was observed between the algorithm results and the simulation of the dielectric lenses using Geometrical Optics (GO) approximation.

However, the phase constant applied to the lens elements in order to implement the dielectric lens cannot be applied to the elements that model the spillover effect. Then the relative phase between the lens and the spillover elements changes and this may alter the radiation pattern of the lens, which may worsen with respect to the given specifications. To improve the results, the synthesis algorithm has now been implemented in two stages, as illustrated in Fig. 1: after the first stage, as described in [6], the matrix of necessary phases $[\phi_{mn}]^1$ on the aperture is obtained, which comprises the matrix of phases in the transmitarray $[\phi_{mn}^{TA}]^1$ and the matrix of phases in the spillover elements $[\phi_{mn}^{sp}]^1$. After applying the necessary phase constant, two new matrixes are obtained, $[\phi_{mn}^{TA}]_{adj}^1$ and $[\phi_{mn}]_{adj}^1$, for the phases on the transmitarray and the whole aperture respectively. This latter constitutes the initial aperture for the second stage of the algorithm, from which the phases on the transmitarray, $[\phi_{mn}^{TA}]_{adj}^2$, are obtained and the corresponding heights of the dielectric slabs are calculated.

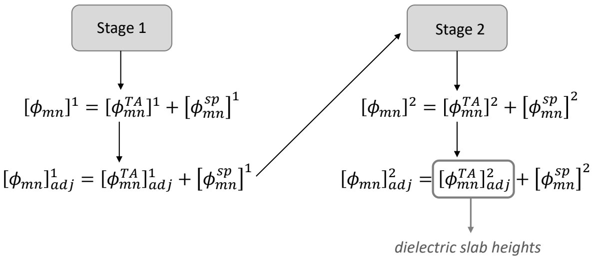


Fig. 1. Scheme of the two-stage synthesis algorithm.

The process described in Fig. 1 has been used to design a dielectric lens with a fan-beam radiation pattern and another one with a two-beam pattern, both at the frequency of 28 GHz. This frequency has been chosen because it is one of the frequency bands of interest for 5G wireless communications. Both lenses consisted of 36 × 36 elements, being the periodicity of the unit-cell $0.3\lambda \times 0.3\lambda$, resulting in a size of $11.6 \times 11.6\ cm^2$. Furthermore, in order to get a lens as planar as possible the phase range has been limited to 240 degrees instead of 360 degrees so that the values of $[\phi_{mn}^{TA}]^i$ higher than 240 degrees approach either to 240 or 0 degrees. The study carried out for the two analyzed lenses showed that the convergence of the algorithm worsened significantly if the thickness was further reduced.

The designed fan-beam lens was firstly simulated with FEKO software [11] using GO approximation. This allows very fast simulations in a preliminary phase in which it may be necessary to make some adjustments. Afterwards, HFSS [10] was used to carry out a full-wave simulation of the final design and validate the previous results. For the two-beam lens, only some preliminary results have been obtained so far using HFSS.

C. Manufacture and Measurement of the Protoype

The fan-beam lens has been fabricated and measured. A 3D printer was used to fabricate both the lens and the mechanical support to attach it to the horn. The printer had a fundamental resolution of 100 µm. The dielectric material was polylactic acid (PLA) with $\varepsilon_r = 2.5$ and $tan\delta = 0.005$.

Finally, the manufactured prototype was measured in an anechoic chamber equipped with a spherical range measuring system.

III. RESULTS

A. Dielectric Lens with a Fan-Beam Pattern

The transmission phase needed in the lens once the necessary aperture $[\phi_{mn}^{TA}]_{adj}^2$ has been obtained is shown in Fig. 2. With this information, the slab heights were calculated and the dielectric lens was designed and manufactured. Fig. 3(a) shows a picture of the whole system, consisting of the horn, the dielectric lens and the structure joining both elements. The weight of the whole is 260 grams. In Fig. 3(b) the antenna is already placed inside the anechoic chamber, ready for measurement.

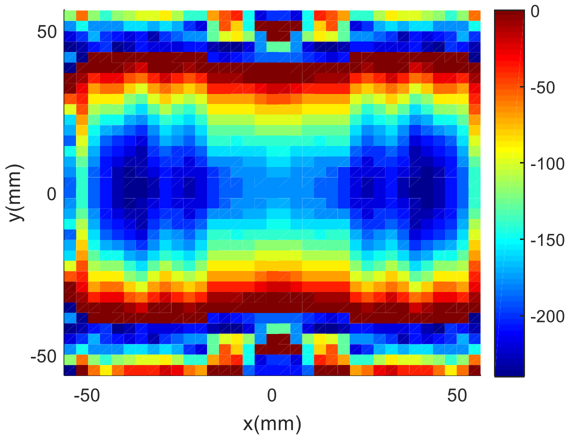


Fig. 2. Transmission phase needed in the lens for a fan-beam pattern.

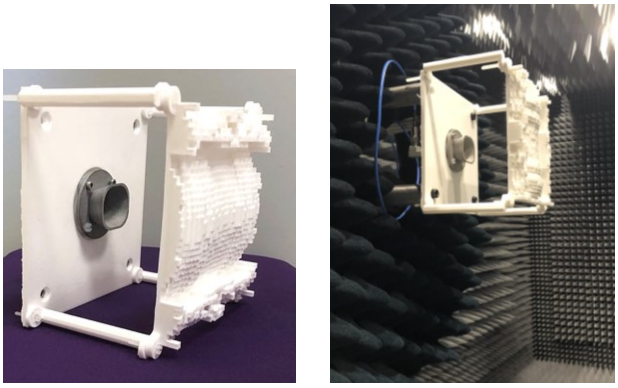
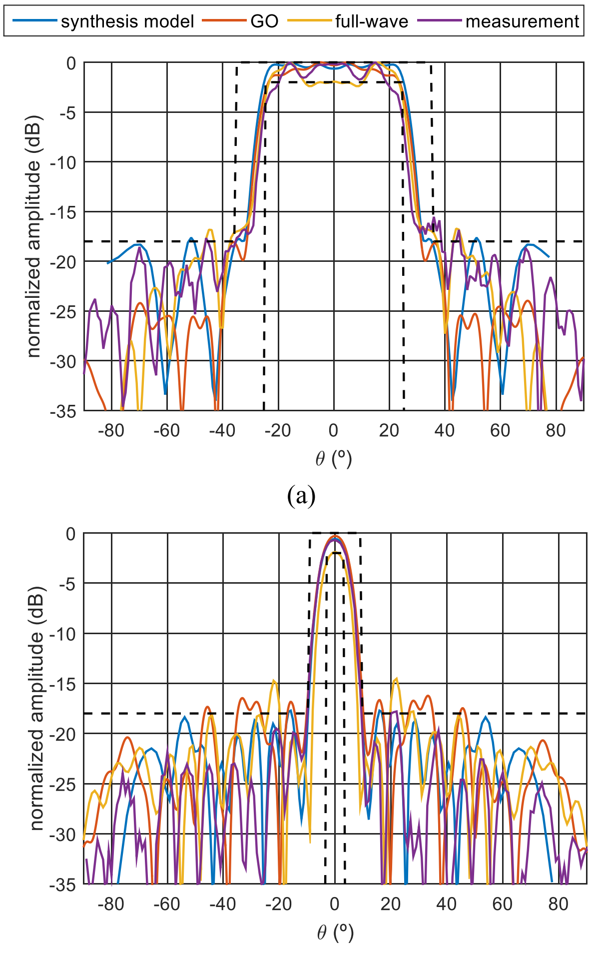

(a)
(b)

Fig. 3. Manufactured prototype: (a) detail, (b) placed in the anechoic chamber (right).

The main cuts of the radiation pattern achieved with the designed lens are shown in Fig. 4. Different curves are compared: the radiation pattern according to the plane aperture model; the simulation result of the designed dielectric lens using GO approximation; the simulation result using a full-wave method; and the measured pattern. The specifications were given by templates, which are included in the figures in black discontinuous line.

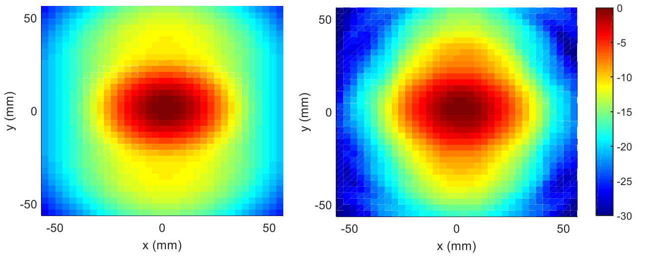
With regard to the plane aperture model, only 1.36% of the whole far-field directions do not-fulfill the specifications, and the mean error of the radiation pattern at those directions, relative to the templates, is 0.49 dB. As far as simulations are concerned, both offer similar results with the exception of the flat central area of the pattern, which is slightly different in the full-wave simulation. Finally the measurement agrees well both with the model and with the simulations except at the ends of the flat central area, where the lower template is not met. The feed model has been investigated as a possible cause of this discrepancy. With that aim, Fig. 5(a) shows the result of the NFPC model applied, which uses the simulation of the feed horn, whereas Fig 5(b) shows the measure of the field generated by the horn on a plane at the focal distance. Some differences can be observed between both graphs that have an effect on the radiation pattern, as shown in Fig. 6. In this figure the radiation pattern given by the plane aperture model when the field distribution of Fig. 5(b) is used for the feed illumination instead of that of Fig. 5(a) is represented and compared to the measured pattern. A better agreement is now found between the measurement and the model. Then, the origin of the discrepancy in Fig. 4 has been identified.



(a)

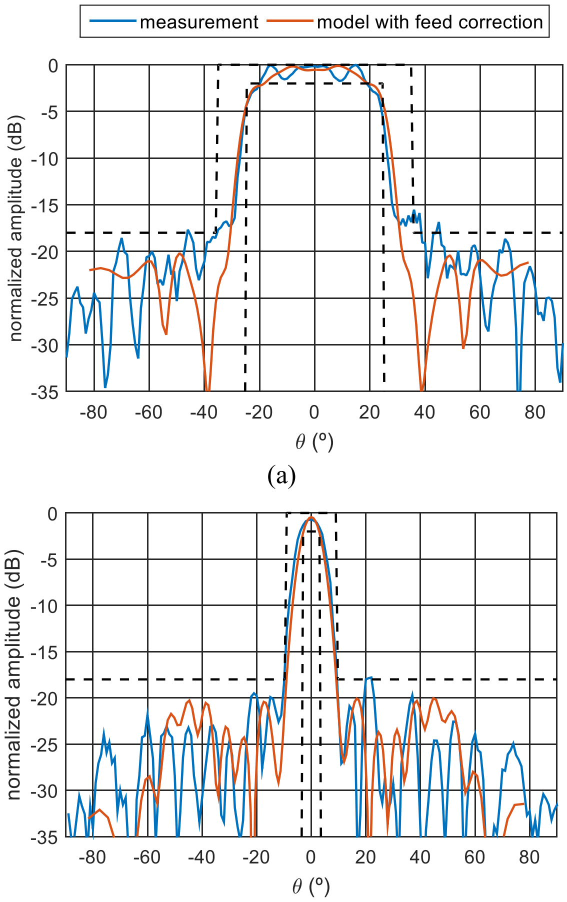
(b)

Fig. 4. Main cuts of the fan-beam radiation pattern: (a) $\phi = 0°$, (b) $\phi = 90°$.



(a) (b)

Fig. 5. E-field (dB) generated by the feed on the plane of the lens: (a) simulating the horn and appliying NFPC model; (b) measuring the horn..



(a)

(b)

Fig. 6. Main cuts of the fan-beam radiation pattern after correcting the feed model: (a) $\phi = 0°$, (b) $\phi = 90°$.

B. Dielectric Lens with a Two-Beam Pattern

A preliminary study has been carried out to investigate the suitability of the algorithm to synthesize a dielectric lens whose radiation pattern has two beams pointing at different directions in space, with only one feeding horn. The templates were then defined with two narrow beams in the plane *uv*, and a secondary lobe level of -15 dB. Fig. 7 shows the radiation pattern provided by the plane aperture model once the necessary phases have been synthesized according to the scheme given in Fig. 1. Next, Fig. 8 represents the lens geometry obtained from the transmission phases found for the lens, and finally Fig. 9 shows the dielectric lens radiation pattern when it is simulated with HFSS.

Although the study is not yet finished and must be completed, these initial results, together with the previous results obtained so far, allow us to be optimistic about the viability of the model to implement this type of lenses.

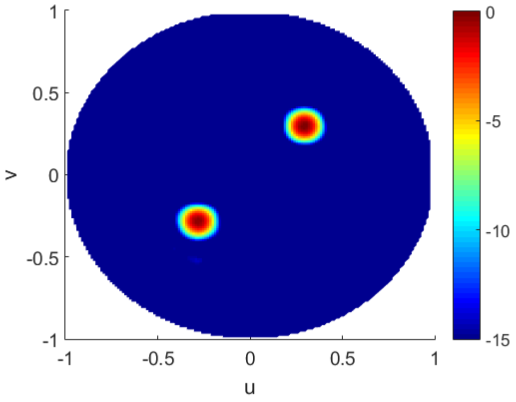


Fig. 7. Radiation pattern obtained from the syntehsis algorithm and plane aperture model.

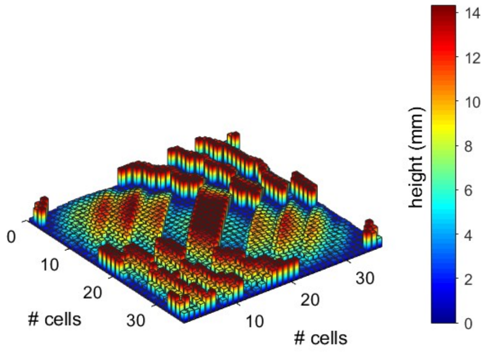


Fig. 8. Geometry of the two-beam dielectric lens.

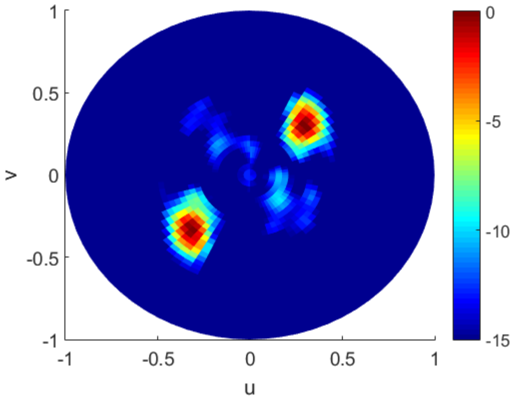


Fig. 9. Radiation pattern simulated for the two-beam dielectric lens.

IV. CONCLUSIONS

An algorithm to synthesize planar array lenses or transmitarrays yielding given shaped radiation patterns has been applied with satisfactory results to the design of pixelated dielectric lenses or dielectric transmitarrays. Furthermore, in order to get a lens as planar as possible, the range of the transmission phase has been reduced from 360 to 240 degrees. This way, the radiation pattern given by the planar model still meets reasonably well the specifications, with a very small error with respect to the template, while the dielectric lens simulation resembles more the result of the planar model, which is way it can be considered as a “quasi-planar” lens.

In relation to the simulations, the consistency between the results provided by the GO approach and the full-wave method makes it possible to validate the GO model for the simulation of this type of lens. Furthermore, the measurement of the manufactured prototype has enabled both the synthesis algorithm and the simulation tools to be validated.

Finally, the synthesis algorithm has been also applied to the design of a dielectric lens with one feed and a two-beam radiation pattern.

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