Metasurface-based lens with application to horn beam squinting

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***Abstract*—This contribution presents the design and synthesis of a three-layer metasurface lens capable of deflecting an impinging beam of a desired angle with negligible reflections. The design is validated by applying the lens at the mouth of a conical horn, with the objective to obtain a squinted beam feed, that is advantageous in multibeam antenna applications.**

***Keywords*—Metasurface, lens, horn.**

I. INTRODUCTION

Gradient metasurfaces (MTSs) are two-dimensional structures capable of manipulating an impinging electromagnetic wave by imparting to it local, space-variant phase changes [1]-[5]. They can operate either in reflection or transmission mode. Recently, it has been shown that a symmetric stack of three MTSs provides the necessary degrees of freedom to achieve perfect transmission and complete phase coverage [2]-[3].

This paper applies this approach for designing a deflecting lens based on a gradient MTS (metalens). The innovative feature of the design consists in the synthesis of the metallic layers. In fact, in previously published works, this latter is performed by choosing the constitutive elements among a limited number of unit cells (typically, 5). On the other hand, in this work the geometry and size of the unit cell at a generic lens position are chosen according to proper maps, which provide the equivalent sheet impedance of the locally periodic structure as a *continuous* function of a specific geometrical parameter. The unit cell is electrically small, and the element shape is chosen so as to obtain a seamless transition from small inductive reactances to small capacitive reactances passing through high reactance resonating elements. This allows the realization of an arbitrary insertion phase distribution with a smooth variation of the geometrical parameters of the metalens constituent elements, thus, ensuring the validity of the local periodicity approximation.

This contribution is organized as follows. Section II describes the general design procedure for a generic gradient MTS. Section III illustrates the application of this procedure to the synthesis of the squinted-beam horn. Finally, Section IV draws the conclusions.

II. METALENS DESIGN

The proposed metalens consists of three patterned metallic layers separated by two thin dielectric slabs and it operates according to the principle described in [2]-[3]. Accordingly, the first and third layer are equal. The central layer is sandwiched between two dielectric layers with relative permittivity $\varepsilon_r = 2.2$ and thickness $d = \lambda/8$ at $f = 12GHz$.

Each metallic layer can be modeled as a shunt admittance between two transmission line segments, as shown in Fig. 1. By solving the transmission line model in Fig. 1, we obtain the following conditions on the three surface admittances to achieve $S_{11} = 0$ (perfect transmission) and $S_{12} = e^{j\phi}$, where ϕ is the desired phase-shift [2]

$$\begin{aligned} Y_1 &= \frac{j}{Z_d \tan(k_d d)} + \frac{j}{Z_0 \tan\left(\frac{\phi}{2}\right)} \\ Y_2 &= \frac{j\left[Z_0 \sin\left(\frac{\phi}{2}\right) + Z_0 \sin\left(\frac{3\phi}{2}\right) + 2Z_d \sin(2k_d d)\cos\left(\frac{\phi}{2}\right)\right]}{2Z_d^2 \cos\left(\frac{\phi}{2}\right)\sin^2(k_d d)} \end{aligned} \tag{1}$$

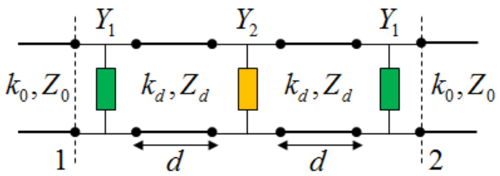

Fig. 1. Transmission line model of a stack of three MTSs separated by dielectric spacers of thickness *d*, under normal incidence. Vertical dashed lines indicate the reference planes.

In general, both capacitive and inductive sheet admittances are require to obtain a complete phase coverage. For this reason, MTSs made by both slot-type (inductive) and patch-type (capacitive) elements are needed.

The choice of the unit cell geometry represents an important aspect in order to go with continuity from inductive to capacitive admittance, while maintaining a gradual variation of the elements. The proposed geometry, allows to go from slot-type to patch-type elements with continuity. Fig. 2 shows the admittance map as a function of a geometrical parameter for the proposed unit cell; three different regions, characterized by the variation of different parameters, are highlighted with different colors. The corresponding unit cell geometry are shown in the insets. The first two regions are relevant to slot-type elements, while the last one corresponds to patch-type elements. The transition is realized by making a small cut in a thin strip that connects adjacent cells.

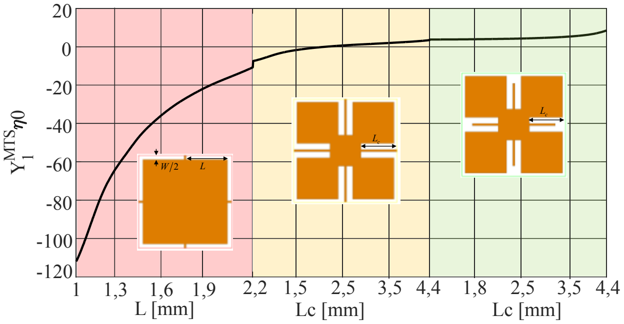

Fig. 2. Sheet admittance for a MTS printed on a dielectric slab as a function of the geometrical parameters of the unit cell geometry. The insets show the geometries of the unit cell for each area.

The admittance values reported in Fig. 2 have been obtained by analyzing, for each unit cell geometry, the corresponding periodic sheet with period equal to $\lambda/5$. The validity of the local periodicity assumption is guarantee by the gradual variation of the elements geometry. Furthermore, it has been verified that for a MTS separation distance of $\lambda/8$, the interactions through higher order modes can be neglected, and, therefore, each metalization can be characterized independently

III. NUMERICAL RESULTS

The proposed design approach is applied to the synthesis of a lens to be placed on the mouth of a horn, so as to obtain a squinted beam feed. This solution can be used to improve the compactness and ease the manufacturing of multiple feeds for multibeam reflector antennas, while optimising the performance of off-axis beams.

In the proposed design, a beam squint of 15° is obtained by locating a deflecting metalens on the mouth of a conical horn with aperture radius of approximately 3.7λ at the operational frequency of $12\,\mathrm{GHz}$. In particular, a low-cross hybrid mode conical horn is considered. This latter is designed by means of the approach presented in [6]. The phase shift distribution required at the horn mouth to convert the impinging phase front into a squinted beam is calculated according to a holographic principle, i.e. by taking the difference between the phase of the horn's aperture field and the one of the desired aperture field. Then, the profiles of outer and inner admittances are found by using Eq. (1) with two dielectric layers of relative permittivity $\varepsilon_r = 2.2$ and thickness $d = \lambda/8$. Finally, the sheets admittances are synthesized through maps similar to the one reported in Fig. 2 by matching the local admittance values.

A full wave analysis of the metalens has been performed with ADF [7] by using the conical horn aperture field as excitation. The results are shown in Fig 3. As expected, the radiated beam is squinted of approximately 15° with respect to the horn axis. Cross-polar patterns are not visible in the plot because their value is below -30dB.

The directivity of the squinted beam is 0.84dB lower than the one of the broadside beam. This is partly due to the scan losses and partly to screen reflections (the simulated back lobe is 18dB below the maximum). This latter aspect could be improved by means of an optimization of the horn in the presence of the metalens.

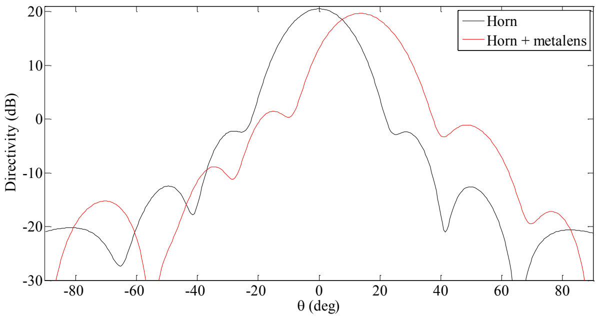

Fig. 3. Simulated co-polar radiation pattern of the conical horn (black line) and conical horn plus metalens (red line).

IV. CONCLUSIONS

The design procedure of a gradient MTS has been presented and applied to the synthesis of a metalens providing a desired beam squint to the field radiated by a conical horn. Full wave results have shown good performances in terms of transmission efficiency and beam integrity.

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