Physical Implementation of Leaky-Wave Antenna with Engineered Aperture Distribution Based on Bianisotropic Huygens Metasurfaces

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***Abstract*—A methodology based on omega-type bianisotropic Huygens' metasurfaces is presented to control the aperture field distribution of leaky-wave antennas. The studied structure is a parallel-plate waveguide with the top plate replaced by a metasurface. Previous works achieved independent control of the phase constant and the leakage factor, but they were constrained to be constant. The required theoretical extensions to overcome this limitation are presented in this work, thus enabling the design of arbitrary radiation patterns. A slowly varying amplitude approximation approach is employed to satisfy Maxwell's wave equation and obtain the relation between the horizontal and vertical wavenumbers. In addition, a semianalytical algorithm able to predict near-field coupling effects is applied in the microscopic design of the metasurface unit cells. Two designs are carried out with real unit cells, presenting different aperture configurations. Finally, electromagnetic simulations validate the methodology with an excellent agreement without any further full-wave optimization.**

***Index Terms*—leaky-wave antennas, metasurfaces, aperture control, synthesis algorithm.**

I. Introduction

Planar Leaky-Wave Antennas (LWAs) are a promising alternative for new communication systems with requirements such as low profile, reduced cost and high directivity. They are travelling-wave structures that gradually leak power along its length [1], which facilitates simple feeding networks, reducing complexity with respect to phased arrays. LWAs are characterized by their wavenumber k, composed of a phase constant β and a leakage factor α, which control the output angle and the rate of the radiation, respectively. The design of arbitrary radiation patters requires independent control of both parameters and the ability to modulate the leakage rate along the antenna length.

On the other hand, Huygens' metasurfaces [2] have recently become a very popular tool to manipulate the electromagnetic field at will [3]–[5]. They consist of subwavelength electrically- and magnetically-polarizable particles able to satisfy the boundary conditions required for a desired field transformation. In [6] it was demonstrated that omega-type bianisotropic Huygens' metasurfaces (BHMSs) only need to satisfy a local power conservation condition between the fields on both sides of the metasurface to achieve arbitrary transformations. In this sense, the use of this type of BHMSs

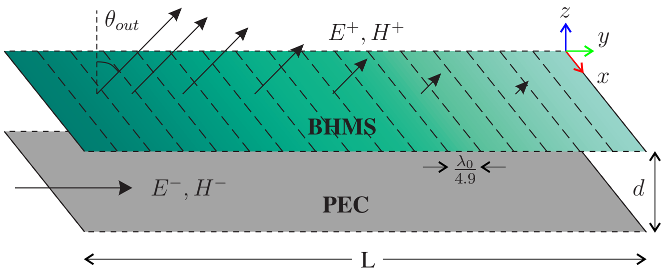

Fig. 1. Diagram of the considered LWA with a BHMS on top.

has been studied in previous works from some of the authors in order to transform a guided field into a leaky-wave radiated one [7], [8]. This way, the independent control of both wavenumber components was achieved, along with several degrees of freedom in the LWA parameters selection.

Although traditional LWAs allow the use of variable leakage factors, they normally have constraints in the choice of the β once the leakage factor is fixed. This limitation is overcome in BHMS-based LWAs; however, so far, only the case of constant leakage factor has been studied. This contribution expands on the previous works in an attempt to enable the design of arbitrary aperture distributions with these antennas.

Moreover, a semianalytical approach adapted from [9], [10] is used to design the metasurface particles (or *meta-atoms*) as it takes into account the intra-cell near-field coupling effects, avoiding time-consuming full-wave simulations of the individual meta-atoms.

II. Theory

The studied structure is a parallel-plate waveguide with an omega-type BHMS as its top plate, presenting a 2-D configuration ($\partial/\partial x = 0$), a length L and a separation d between both plates, as shown in Fig. 1. The macroscopic design of a metasurface consists of stipulating the fields on each of its sides and then obtaining the parameters that synthesize the required boundary conditions. Thus, in accordance with the structure, a guided-wave mode and a leaky mode are stipulated below and above the BHMS, respectively [7].

However, the design of arbitrary aperture field distributions requires the ability to specify a non-constant leaky wavenumber. This can be accounted for by integrating the longitudinal

(y-axis) wavenumber along the waveguide length. Assuming a Transverse Electric (TE) polarized excitation at $y = 0$ ($E_y = E_z = H_x = 0$), the electromagnetic fields are stipulated as follows:

$$\begin{aligned} E_x^- &= |E_{in}| \left(e^{jk_z^-(z+d)} - e^{-jk_z^-(z+d)} \right) e^{-j\int_0^y k_y^-(\tau)\, d\tau} \\ &= 2j|E_{in}| \sin(k_z^-(z+d))\, e^{-j\int_0^y k_y^-(\tau)\, d\tau} \end{aligned} \tag{1}$$

and

$$E_x^+ = |E_{out}|\, e^{-jk_z^+ z} e^{-j\int_0^y k_y^+(\tau)\, d\tau}. \tag{2}$$

In order to let the structure radiate, the wavenumbers are complex, with a phase constant β and a variable α along y:

$$\begin{aligned} k_y^- &= \beta^- - j\alpha^-; \quad k_z^- = \beta_z^- - j\alpha_z^-, \\ k_y^+ &= \beta^+ - j\alpha^+; \quad k_z^+ = \beta_z^+ - j\alpha_z^+. \end{aligned} \tag{3}$$

Field expressions (1) and (2) must satisfy Maxwell's wave equations, but the non-constant k_y poses a difficulty when trying to solve them, as the relation between the vertical and longitudinal wavenumbers depends on their first- and second-order partial derivatives. In order to lower the complexity of the wavenumbers relation, a Slowly Varying Amplitude Approximation (SVAA) approach is adopted for α, allowing the derivatives to be ignored. This way, the typical leaky-wave relation is restored:

$$\begin{aligned} {k^-}^2 &\simeq {k_y^-}^2 + {k_z^-}^2, \\ {k^+}^2 &\simeq {k_y^+}^2 + {k_z^+}^2, \end{aligned} \tag{4}$$

where ${k^-}^2$ and ${k^+}^2$ are the wavenumbers of the media below and above the metasurface, respectively.

The bianisotropic sheet transition conditions [11] relate the transverse field components above (E_x^+, H_y^+) and below (E_x^-, H_y^-) the BHMS. Thus, the electric surface impedance Z_{se}, the magnetic surface admittance Y_{sm} and the magnetoelectric coupling coefficient K_{em} of the metasurface can be calculated from (1) and (2). Furthermore, the boundary conditions imposed by the metasurface will allow the fields to adequately propagate regardless of the waveguide height. Finally, the leakage factor is $\alpha(y) = \alpha^- = \alpha^+$ to satisfy the local power conservation condition imposed by the BHMS, which also relates the amplitude of the fields above and under the metasurface, $|E_{out}|$ and $|E_{in}|$ respectively.

III. Design Methodology

First, the metasurface must be discretized along the y-axis into its so-called *meta-atoms*, which are the sub-wavelength unit cells that implement the required boundary conditions. In this work, the discretization step is $\lambda_0/4.9$. The metasurface parameters can be related to a 2×2 Z-matrix that characterizes the tangential fields below and above a given meta-atom, as follows [6]:

$$\begin{aligned} Z_{11} &= Z_{se} + \frac{(1+2K_{em})^2}{4Y_{sm}}, \\ Z_{12} &= Z_{21} = Z_{se} - \frac{(1-2K_{em})(1+2K_{em})}{4Y_{sm}}, \\ Z_{22} &= Z_{se} + \frac{(1-2K_{em})^2}{4Y_{sm}}. \end{aligned} \tag{5}$$

The obtained Z-matrices must then be implemented by a given unit cell structure able to provide the three degrees of freedom needed.

On the other hand, the arbitrary aperture illumination control requires a precise control of the leakage factor along y. From [1], a well-known LWA approximate expression can be used to obtain the leakage factor required to synthesize a given aperture field distribution:

$$\alpha(y) = \frac{|A(y)|^2}{\frac{1}{\eta_{rad}} \int_0^L |A(\xi)|^2\, d\xi - \int_0^y |A(\xi)|^2\, d\xi}, \tag{6}$$

where η_{rad} is the required radiation efficiency which, if chosen very high, could invalidate the SVAA approach due to a more rapidly varying $\alpha(y)$.

The phase constants above and under the metasurface are related to the LWA pointing angle θ_{out} and the angle of incidence inside the waveguide θ_{in}, respectively [1], by:

$$\begin{aligned} \beta^+ &\approx k^+ \sin(\theta_{out}), \\ \beta^- &\approx k^- \sin(\theta_{in}). \end{aligned} \tag{7}$$

Two designs are carried out at 20 GHz in order to present a $\theta_{out} = 20°$: one implements a constant $\alpha = 0.05k_0$ (reference) and the other presents an uniform aperture with $\eta_{rad} = 95\%$ in order to show the capabilities of the proposed methodology. The LWA is filled with air, has a height $d = 0.6\lambda_0$ and a total length $L = 10\lambda_0$.

For the constant α design, the resulting LWA is periodic, whose period relates the phase constants in both regions of the space [7]. In this case, a period $p = 12\lambda_0/4.9$ is chosen, thus giving a $\theta_{in} = 48.62°$. There are two reasons for the selection of this period: 1) a long period better shows how effectively the metasurface allows a single spatial harmonic to radiate, and 2) the obtained θ_{in} in combination with the chosen LWA height results in a waveguide field profile that would not propagate in a conventional waveguide, thus exhibiting another of the metasurface special capabilities.

IV. Physical Implementation

The three degrees of freedom required by the metasurface parameters can be ideally implemented by three cascaded ideal reactance sheets whose values can be derived through a transmission line model from the Z-matrix in (5) [6].

In reality, impedance sheets are synthesized by geometries printed in the copper layer of metalized substrates, which present non-zero resistances and, consequently, losses. The three layers configuration offers a single solution to the reactances selection, so the resistances minimization capability

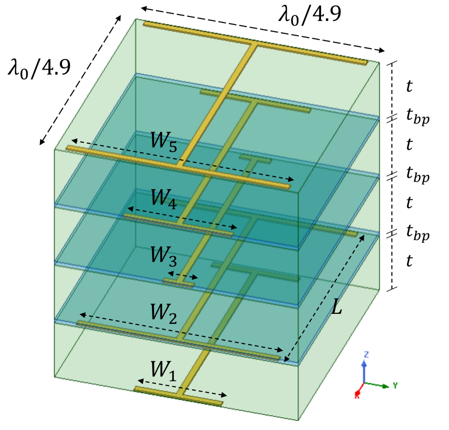

Fig. 2. Unit cell implementation using 5 layers of dogbones.

is limited. Therefore, unit cells with more than three copper layers can be used, which offer more flexibility for selecting impedances which may result in lower total losses. Furthermore, the electromagnetic coupling between the different layers of copper traces can invalidate the transmission line model, especially if the substrates between the layers are not thick enough and/or have a low permittivity.

In this work, a unit cell configuration consisting of five layers of copper strips with dogbone geometries has been used. Rogers RO3003 laminates ($\epsilon_r = 3$, $\tan\delta = 0.0013$) of thickness $t = 30\,\text{mil}$ are used as substrate between each layer, and they are bonded with Rogers Bondply RO2929 adhesive layers ($\epsilon_r = 2.94$, $\tan\delta = 0.003$) of thickness $t_{bp} = 2\,\text{mil}$. The total dimensions of each meta-atom is then $\lambda_0/4.9 \times \lambda_0/4.9 \times \lambda_0/4.7$, and it is shown in Fig. 2. The copper traces are $18\,\mu\text{m}$ thick and $3\,\text{mil}$ wide, and all the dogbones have a fixed $L = \lambda_0/4.9 - 3\,\text{mil} \approx 117.44\,\text{mil} \approx 2.98\,\text{mm}$.

As can be noticed, both aforementioned conditions for having strong near-field coupling between layers are met with this unit cell configuration. Consequently, a semianalytical method is used to take this into account in order to obtain the dimensions W_i of the copper layers that correctly synthesize the required Z parameters of each unit cell. The synthesis methodology and algorithm are based on the works presented in [9], [10], adapting it to the design requirements of the LWAs in study.

For both designs, the S-parameters obtained from the Z-parameters in (5) are fed to the synthesis algorithm, which outputs the layers geometries that give the three different scattering parameters closest to the objective ones (minimizing the RMS of the Euclidean distances). Then, each of the obtained unit cells are simulated in Ansys HFSS with local periodicity conditions to verify how closely their parameters resemble the theoretically required ones. These three steps are shown in Fig. 3 for the uniform aperture design as, unlike the constant α one, every unit cell in the whole antenna length needs to be synthesized due to the lack of a period. A high similarity between the goal and simulation-obtained parameters can be noticed, especially since no further optimization is carried out to the dimensions obtained from the algorithm.

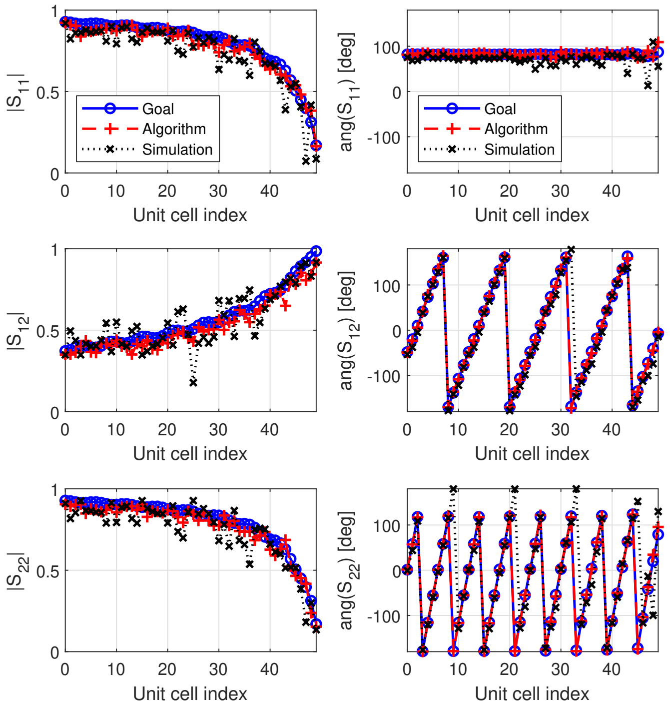

Fig. 3. S-parameters of each unit cell for the Uniform aperture design: theoretically required parameters versus predicted by the semi-analytical algorithm for the chosen geometries versus individual simulation results assuming local periodicity.

V. Simulation Results

Both real LWAs implementations are simulated in Ansys HFSS with an ideal current line source as excitation. These simulations were computationally intensive, converging in around 7 hours using a maximum of almost $110\,\text{GB}$ of RAM each, and all 24 logic cores of a computer running a 2020th $4\,\text{GHz}$ AMD processor. Thus, ideal simulations using the unit cells with three cascaded reactance sheets are also carried out as intermediate steps, which could converged in less than 30 minutes, using maximum $30\,\text{GB}$ of RAM.

Fig. 4 shows a comparison of the electric field magnitude in the yz plane as well as the 2D directivity between the theoretical derivation and the real simulation results for each design. The top figures correspond to the reference design with constant α, where the expected exponential power decay translates into an underutilization of the antenna length, as the power mainly radiates at the beginning, and an inability to shape the radiation pattern at will. On the other hand, the bottom figures show the results for the design with the engineered leakage rate, which achieves a practically uniform aperture even when the field inside the waveguide is clearly decaying, thus better exploiting the available antenna area.

A good agreement between theory and simulations can be seen, with the metasurface successfully allowing the guided field to propagate in both designs even with a slightly cut profile. The uniform aperture design presents a higher directivity than the reference one, as expected, thus obtaining a

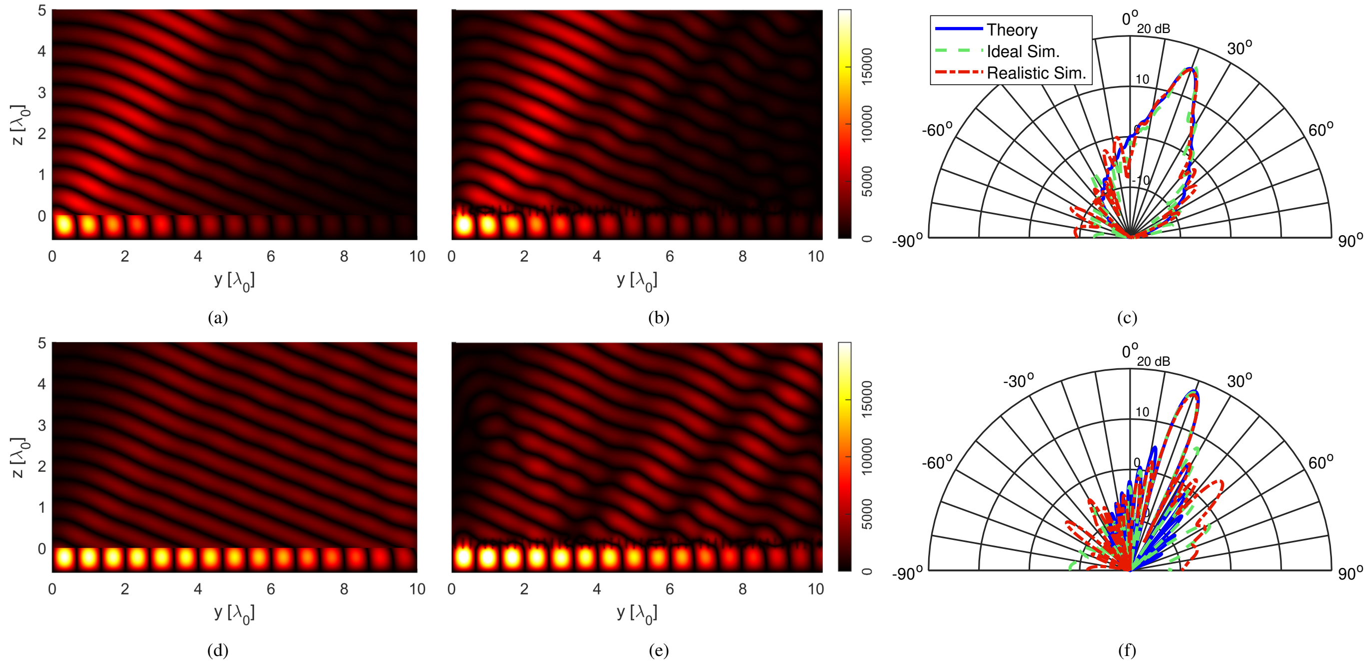

Fig. 4. Field distributions $|\mathrm{Re}(E_x(y,z))|$ (V/m) from (a,d) theoretical prediction and (b,e) electromagnetic simulation, and (c,f) associated 2-D directivity diagrams for (a)-(c) $\alpha = 0.05k_0$ and (d)-(f) uniform aperture.

TABLE I
FIGURES OF MERIT OF BOTH STUDIED DESIGNS.

Design	θ_{out} (°)	D_{max} (dBi)	η_{ap} (%)	SLL (dB)
Constant (Theory)	20	15.6	57.9	-
Constant (Ideal Sim.)	20.2	16.4	69.9	-9.5
Constant (Real. Sim.)	20.3	15.4	55.4	-15.4
Uniform (Theory)	20	17.8	95.8	-12.8
Uniform (Ideal Sim.)	19.9	17.5	88.9	-9.8
Uniform (Real. Sim.)	20.1	17.0	79.9	-12.8

greater aperture efficiency at the expense of higher sidelobes, as known from aperture antennas theory. This proves that the SVAA approach is useful for implementing the desired aperture distribution, even for the considerably high radiation efficiency. Table I summarizes some relevant figures of merit for both designs, including the results from the ideal simulations.

It can be noticed that the simulation presents some deviation from the theory with a secondary lobe not entirely suppressed (Figs. 4e and 4f). However, it must be considered that no full-wave optimizations of the unit cells nor the whole antenna have been carried out after the semianalytical algorithm synthesis. So, taking into account all the approximations, the discrepancies in the figures of merit are within the expectations.

VI. CONCLUSIONS

Previous work from some of the authors has been expanded with the ability of controlling the aperture of LWAs using Huygens' metasurfaces. The theoretical derivation has been modified to account for the insertion of non-constant leakage factors in the antenna designs. Furthermore, a meta-atom synthesis algorithm, which overcomes the limitations of typical simplified transmission line models, has been adapted to the requirements of these metasurfaces. This algorithm systematically provides unit cells suitable for implementation, which consist of five copper layers with dogbone geometries.

Two designs are studied, a reference one with constant α and another with an uniform aperture. Very good agreement is observed between the theoretical predictions and the simulation results, obtaining the desired aperture distributions and associated directivity patterns. The latter design proves that the SVAA approach is valid even when the leakage factor does not necessarily vary slowly, satisfactorily enabling the engineering of arbitrary aperture distributions using BHMSs. Furthermore, both designs demonstrate that the design methodology is capable to predict the inter-layer near-field coupling effects in the unit cells parameters extraction, thus obtaining fabrication-ready metasurfaces, even when they could be further improved.

As future steps, the different LWAs should be fabricated in order to obtain experimental results that match the simulations and, consequently, validate the proposed methodology. Furthermore, reconfigurability mechanisms could be explored, enabling several functionalities grouped in a single design.

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