Huygens' Metasurface Leaky-Wave Antenna with GAP Waveguide Technology

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***Abstract*—The development of a Leaky-Wave Antenna based on Bianisotropic Huygens' Metasurfaces and using GAP waveguide technology is presented in this work. The waveguide is designed with horizontal polarization of the mode at 20 GHz, different than the conventional vertical polarization. Additionally, a uniform leaky-wave antenna designed just slotting the top surface of the waveguide is compared with the same structure but combining the slot with the Huygens' metasurface which change the radiation angle of the LWA to the desired broadside radiation pattern.**

***Index Terms*—Bianisotropic, Huygens' Metasurface, GAP waveguide, Leaky-wave antenna.**

I. Introduction

Huygens' Metasurfaces have been highly developed in the last decade, allowing the possibility of designing antennas that control both the direction of the beam and its shape through the transformation of the electromagnetic fields which interact on the metasurface [1]. The versatility of this technology allows the implementation in several topologies, such as transmitarrays, lens antennas and Leaky-Wave Antennas (LWAs) [2].

In particular, the interest to implement low-profile and high-gain antennas for applications such as automotive radar and satellite communications has been one of the main challenges in antenna design [3]. Therefore, one of the main topologies that is attractive to satisfy such characteristics are LWAs [4]. They operate by transforming guided waves inside a waveguide or transmission lines into leaky waves through the incorporation of a perturbation in the design. The properties of the leaky wave determine the radiation pattern generated. On the one hand, the phase constant β controls the radiation angle, while the attenuation constant α controls the beamwidth and hence the radiation rate across the aperture [5].

The property of controlling independently both the directivity and direction of the radiated wave constitutes the main reason for combining both technologies. Traditionally, LWAs have suffered form important limitations [6]. First, due to the phase constant, when located in the stop-band domain, it cannot generate a broadside radiation pattern since the waves are reflected back to the source, on the other hand, the radiation angle is also limited by the phase constant and generating a broad scan-angle of the wave +/- 90° is a challenge that uniform and periodic 1D-structures are normally not able to achieve.

Even though the study of LWA in recent years has focused on overcoming such limitations and achieving a better control of the beam [7], [8], there are still challenges to be tackled. That is the reason for combining Huygens' metasurfaces with the LWA design, since by knowing the direction and amplitude of the leaky wave it is possible to design metasurfaces that transform the incident wave into a transmitted wave with the desired characteristics. Nevertheless, there are also limitations, since isotropic Huygens' metasurfaces cannot allow complete control of both the reflection and transmission coefficient, which is essential to achieve an optimal design of the structure.

New advances in this technology have allowed to control both the reflection coefficient and the transmission coefficient by introducing a new degree of freedom called the magnetoelectric coupling coefficient [9], [10], provided by Bianisotropic Huygens' Metasurfaces (BHMSs) of the Omega type. The application to the design of a LWA with arbitrary control of the radiation parameters has been demonstrated by implementing BHMS with a parallel-plate waveguide to develop a low-profile antenna with a broadside radiation pattern and high directivity presented in [11].

In this work, we demonstrate the same physical principle but with a different waveguide, using a GAP waveguide technology. The idea is the introduction of the BHMSs into the cover with no electrical contact of the structure, so that the desired characteristics of the antenna are achieved. Particularly, this kind of topology, when designed as LWA, cannot radiate in broadside due to the effect of the open stop-band, therefore, once the phase constant of the leaky wave is determined, it is possible to generate a new transmitted wave pointing at broadside through the metasurface properties. Initially, the design and operation of the GAP waveguide will be described, then, the initial structure designed as LWA is presented and finally, the design of the BHMS and its respective implementation are detailed, both behaviours are compared with each other in order to demonstrate the proposed structure.

II. GAP waveguide design

In this section, the design of the GAP waveguide is presented. First, the configuration of the structure implemented inside the guide composed by a bed of pins is studied through the analysis of the irreducible Brillouin zone; then, the scheme of the structure with its respective dimensions is presented. It should be noted that, for the BHMS used in this work, a different configuration to the conventional design for a GAP waveguide has been considered.

In the literature there are extensive studies and experiments about the implementations and design methods of this kind of technology, being the usual practice to use a vertical polarization of the electric field, as shown in Fig. 1(a), but, since the

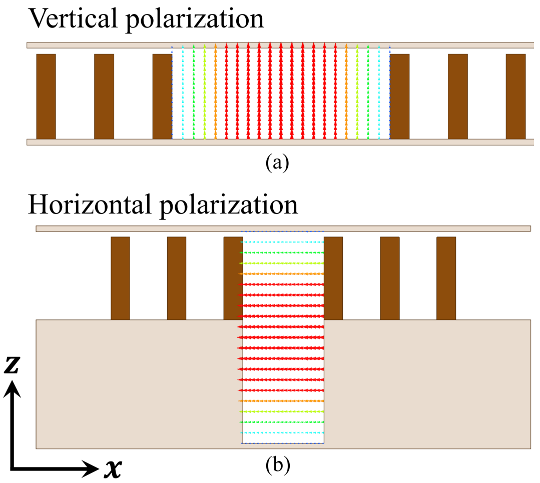

Fig. 1. GAP waveguide setup for different electric field polarization (a) Vertical polarization (b) Horizontal polarization.

BHMS is designed for a horizontal TE-mode, a variant of the traditional gap-waveguide that allows a horizontal polarization of the electric field has been used, as shown in Fig. 1(b), so that it excites the desired E-field for the BHMS [12].

A. Irreducible Brillouin zone

As shown in Fig. 1, the periodic bed of pins must be designed to achieve a range of the stop-band to work in the K-band, since the antenna presented is designed to operate at 20 GHz. In Fig. 2 the Irreducible Brillouin zone diagram is plotted, which shows that the stop-band is located between 15 and 30 GHz, being the expected range for the desired band. In addition, the same figure shows the schematic of the metasurface design corresponding to one period together with its respective design parameters. The dimensions are the period $P_m = 3mm$, the GAP between the pin and the top cover $H_{gap} = 0.3mm$, height and width of the pin $H_{pin} = 4.4mm$ and $w_{pin} = 1mm$, respectively.

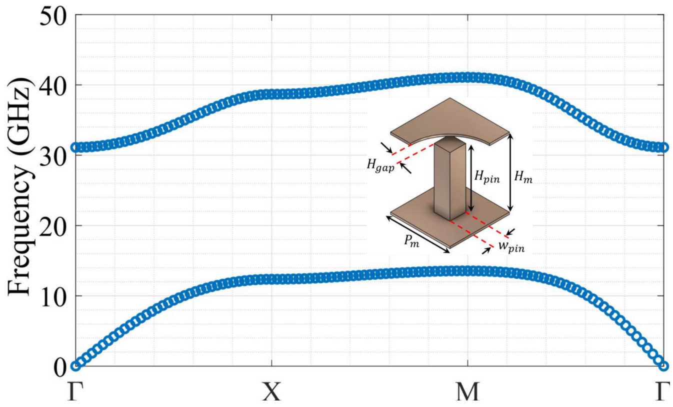

Fig. 2. Irreducible Brillouin zone diagram for the UC implemented into the GAP waveguide.

B. Design parameters

Once the bed of pins is designed and the propagation of the guided wave inside the paralel plates is not allowed in any of the directions of the irreducible Brillouin zone, it is possible to design the GAP waveguide with horizontal polarization of the electric field, since the height of the pin is greater than the width of the BHMS, the implementation into the pin face for a vertical polarization implies design a new bed of pins and it is possible to add undesired leakage using a short pin, to ensure that the energy radiation is produced only by the BHMS and not to have to design another metasurface, it was preferred to use horizontal polarization and implement the BHMS in the top-cover without electrical contact. Therefore, in Fig. 3(a) the structure layout is presented, which consists of the top cover without electrical contact and the respective bed of pins. In this case, the dimensions of the inner guide correspond to the height calculated in [11]. The overall dimensions of the waveguide are the height and width of the inner rectangular waveguide (RWG) $H_{RWG} = 11.25mm$ and $W_{RWG} = 4.3mm$ respectively, and the total width of the structure is approximately 1.8λ.

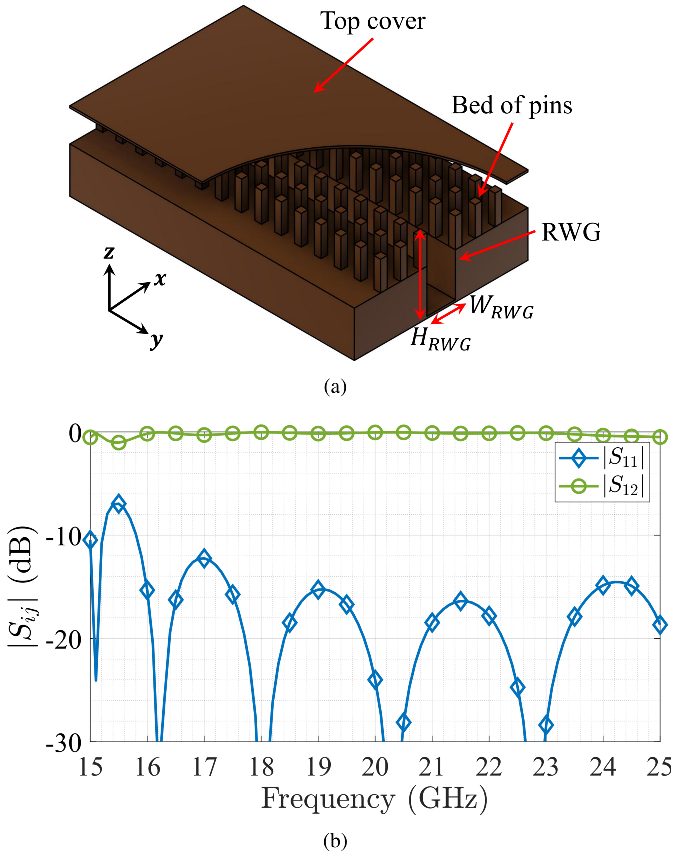

Fig. 3. Schematic of the GAP waveguide designed and simulation results. (a) GAP waveguide (b) S-Parameters.

The simulated reflection and transmission parameters of the structure are shown in Fig. 3(b). It can be observed that the $|S_{11}|$ parameter is correctly matched and the $|S_{12}|$ parameter is approximately 0 dB along the desired band.

III. Antenna Design

Once the GAP waveguide is designed through the analysis of the irreducible Brillouin diagram and the analysis of the simulation results, in this section the presented structure will be used to design two different antennas using the same waveguide. The first antenna is a LWA with a radiation angle of 45°, while, the second antenna is the same LWA with

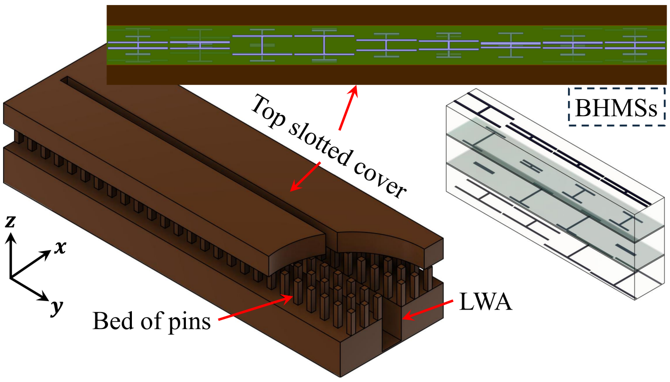

Fig. 4. GAP waveguide LWA schematic and BHMSs implemented into the top slotted cover.

the integration of the BHMS to generate a radiation pattern with high directivity at broadside. Below, both designs and the operation of the metasurface implemented to achieve the transformation of the initial fields of the leaky wave in order to modify their respective radiation angle will be detailed, finally both antennas will be compared through their characteristics calculated using HFSS. Both antennas are designed to operate at 20GHz.

A. LWA design

The same dimensions of the gap waveguide specified in the previous section to perform the leakage of energy and transform the guided wave into a leaky wave are used. Unlike the conventional LWA designed with GAP technology, by using a horizontal polarization of the electric field, the aperture that is introduced into the structure is located in the cover without electrical contact. Fig. 4 shows the layout of the proposed LWA. It can be observed that the aperture is located in the top slotted cover, while, the bed of pins, the internal rectangular waveguide and the width used are those presented above with the length configured of 10λ.

B. BHMS design

The bianisotropic Huygens metasurface used in this work was designed and analyzed theoretically in [11]. In the scheme of Fig. 4, half period of the metasurface used is shown. It is composed of dog bone type metal strips printed on 3 layers of substrate. The substrate used is Rogers 3010 with a relative permittivity of 10.2. Therefore, the BHMS is introduced in the slotted layer with a width of $\lambda/6$. When the irradiated leakage mode with a radiation angle at 45° interacts with the metasurface in the bottom layer, the new transmitted wave is transformed by the Huygens metasurface to change its radiation angle and obtain the desired radiation pattern at broadside. At the same time, due to its bianisotropic property, it is possible to control the reflected wave, which continues to travel inside the guide, leaking its energy along the structure. In this case, if it is not possible to control the reflections, it would not be possible to radiate energy along the structure, since, if the reflection coefficient is low, all the energy would be concentrated at the beginning of the guide, while, if the reflection coefficient is high, it would behave as a non-radiating waveguide and would not generate radiation pattern in far field. Both antennas will be compared below.

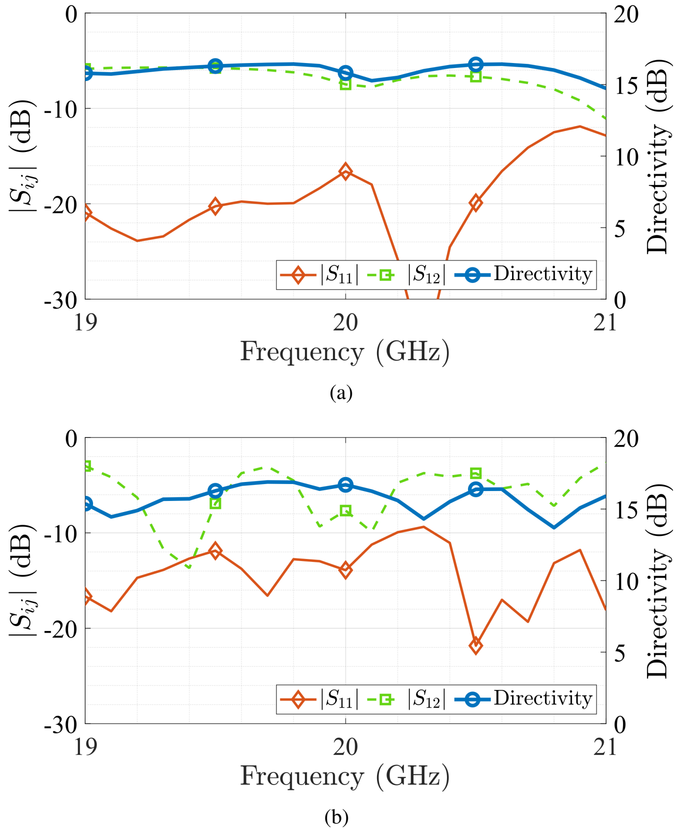

Fig. 5. Simulation results of both presented antennas, S-Parameters and Directivity. (a) GAP waveguide LWA (b) LWA with BHMS.

C. Simulation results comparison

The simulation results obtained in HFSS are compared to demonstrate that the implementation of the BHMS inside the guide achieves the desired functionality and generates the expected characteristics. The parameters to be compared are S-parameters, directivity, directivity radiation pattern and finally the radiated fields of the antenna.

The $|S_{11}|$, $|S_{12}|$ parameters and directivity as a function of the frequency of both antennas in from 19 to 21 GHz range are shown in Fig. 5. The GAP LWA is presented in Fig. 5(a), it can be observed that the antenna is well matched while the $|S_{12}|$ parameter shows losses with respect to the closed waveguide, due to the radiation of the energy while it propagates inside the structure; the directivity remains stable with a magnitude close to 15 dB. On the other hand, the GAP LWA implemented with the BHMS is presented in Fig. 5(b), where the $|S_{11}|$ parameter shows good matching as well and the $|S_{12}|$ highlights the energy leakage in the studied frequency range; the directivity magnitude is about 15 dB, similar to that without the BHMS . Both results show good agreement with the expected phenomenon.

Regarding the directivity radiation pattern, which can be observed in Fig. 6 in polar plane for both antennas, the GAP LWA has a radiation angle at 45° and a Side-Lobe Level (SLL) of -10 dB, on the other hand, the antenna with BHMS generates a radiation pattern at broadside with a SLL of -10 dB. Therefore, it is verified through the far-field radiation pattern that the desired transformation of the incident wave to the metasurface is achieved.

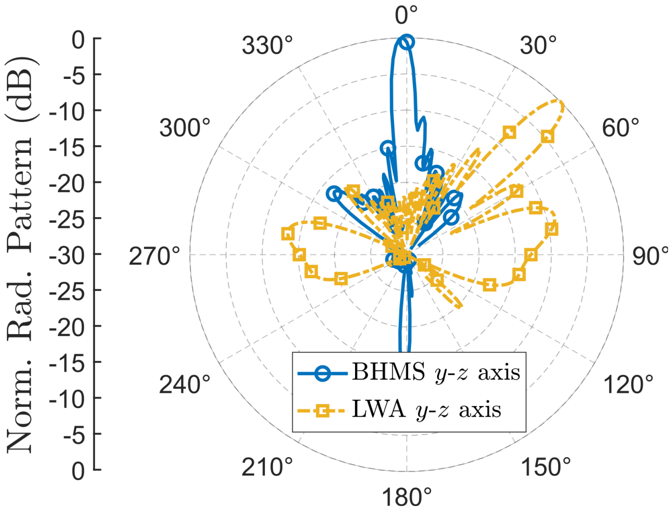

Fig. 6. Normalized directivity radiation pattern for the comparison between both antennas at 20 GHz.

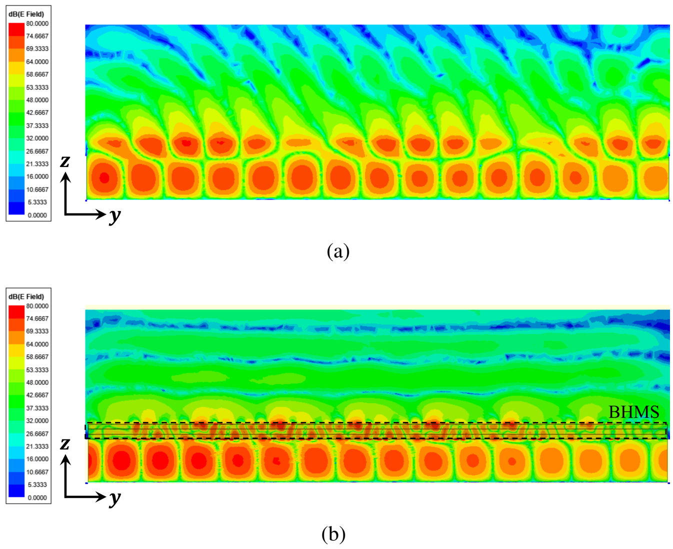

Fig. 7. Radiated electric field (dBV/m) in the aperture of the antenna at 20 GHz. (a) Gap-waveguide LWA (b) BHMS implemented into gap-waveguide LWA.

Finally, electric fields (dBV/m) inside the gap-waveguide and in the radiation aperture of both antennas are shown in Fig. 7, drawn in the y-z plane. Furthermore, the radiated electric field of the LWA is plotted in Fig. 7(a) while the radiated electric field of the BHMS implemented into the gap-waveguide LWA is shown in Fig. 7(b). From both electric fields, it can be observed how the antenna with BHMS generates the transmitted wave at 0° with a flat wavefront. As shown, the leaky wave has a propagation direction of 45°. Under this analysis the transformation of the wave which interacts with the metasurface can be observed in a more graphic way, proving that the antenna can operate with the proposed topology.

IV. Conclusions

In this paper, a leaky-wave antenna based on a gap waveguide with horizontal polarization of the electric field that uses a bianisotropic Huygens' metasurface as the top cover has been presented at 20 GHz. The BHMS transforms the guided wave in the gap-waveguide into a leaky wave radiating at the desired direction, particularly for this case, a radiated angle of 45° achieved for only the gap-waveguide LWA has been transformed into a radiated angle of 0° (broadside) when the BHMS was implemented without generating significant changes in the S-parameters and the directivity. It is proved that the gap waveguide technology can be an alternative technology to the already used conventional waveguide for this metasurface-based leaky-wave antennas. It should be noted that the work presented is a first study of this topology for BHMS that proves it is possible to excite the correct polarization of the electric field necessary for the desired field transformation. This paves the way to develop this class of antennas using gap waveguide techonology with different bianisotropic Huygens' metasurfaces to control both the reflection and the transmission of the wave and radiate the energy in an arbitrary manner.

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