

Printed leaky-wave antenna with aperture control using width-modulated microstrip lines and TM surface-wave feeding by SIW technology

*Original*

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(Article begins on next page)

**Printed Leaky-Wave Antenna with Aperture Control using  
Width-Modulated Microstrip Lines and TM Surface-Wave  
Feeding by SIW Technology**

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Thank you for suggesting to us to submit a revised version of our paper “Printed Leaky-Wave Antenna with Aperture Control using Width-Modulated Microstrip Lines and TM Surface-Wave Feeding by SIW Technology” We also thank the Associate Editor and Reviewers for their time and helpful comments (shown in **bold and italic font** below). Our responses to the Reviewers detailing the revisions made to the manuscript are provided below in blue while explicit changes from the manuscript are highlighted in red.

**ASSOCIATE EDITOR'S COMMENTS:**

***1) The quality of figures in this paper should be improved. The words in Fig. 1 are too large. The format of this paper is not correct. No footnote in the first page. Authors should use the temple to revise this paper.***

We thank the Associate Editor for their comments to improve the quality and readability of the figures within the manuscript as well as the helpful suggestions on formatting. To further address these points, we would like to mention the following:

- i. The text within Fig. 1 and its images have been reduced in size and re-arranged.
- ii. Several other figures were also updated and combined to improve readability and to address some of the Reviewer’s comments. It should also be mentioned that Fig. 11 from the original manuscript (which compared the co-pol. beam pattern with the cross-pol. levels) has been removed to include the important comments by the Reviews while also keeping within the page limitations required for the submission.
- iii. A footnote has now been included by following the template requirements for IEEE AWPL manuscripts.

***2) A comparison of the performance and size of different works is necessary.***

We thank the Associate Editor for their helpful comment to improve the quality of the contribution. The First Reviewer had a similar comment, please see our detailed response below where a comparison table is provided of different works.

**Reviewer: 1**

***Comments for Transmittal to Author:***

***Comments to the Author In this paper, the Authors provide a planar LWA with width-modulated microstrip lines. The Reviewer thinks this is an interesting idea. However, some issues should be addressed before publish.***

We thank the Reviewer for their comments and hope that we have satisfactorily addressed the relevant issues and that the paper can be now be published.

***The authors are requested to address the following comments:***

- 1) The Reviewer found a number of conferences are cited in this paper. It is not necessary to cite the conferences without measured results, whereas, the papers showing the***

*state-of-the art designs in the literature should be given. For instance --The antenna adopting the same technique: [R.1] Broadside Radiation in Leaky-Wave Antenna Using Multiperiodic Width-Modulated Microstrip Lines --The antenna designing for the similar purpose: [R.2] Low-Sidelobe-Level Short Leaky-Wave Antenna Based on Single-Layer PCB-Based Substrate-Integrated Image Guide [R.3] Ka-Band Low-Sidelobe-Level Slot Array Leaky-Wave Antenna Based on Substrate Integrated Nonradiative Dielectric Waveguide --The leaky-wave antennas using microstrip line as the feed line: [R.4] All-Metal Endfire Antenna with High Gain and Stable Radiation Pattern for the Platform-Embedded Application [R.5] Microstrip-Fed Surface Wave Antenna for Endfire Radiation [R.6] Narrow-Width Periodic Leaky-Wave Antenna Array for Endfire Radiation Based on Hansen-Woodyard Condition --The modulated reactance surface leaky-wave antennas [R.7] Tapered Unit Cell Control of a Sinusoidally Modulated Reactance Surface Antenna [R.8] Design of Wideband Leaky-Wave Antenna Using Sinusoidally Modulated Impedance Surface Based on the Holography Theory [R.9] Axially Modulated Cylindrical Metasurface Leaky-Wave Antennas The Authors should at least cite these works in the introduction.*

We thank the Reviewer for their comments and providing this extensive reference list to ensure that our paper has included a complete citation listing of the state-of-the-art. These important works have been referenced in the introduction section and throughout the paper where relevant. We hope this revised journal and conference paper citation listing in the revised manuscript is now more appropriate.

**2) The novelty and advantages of the antenna are not clear, thus, the Authors should make a comparison about the performance and size..**

The Reviewer has brought up a very good point and has made an important suggestion to better highlight the novelty of our contribution. The further address this point, as well as the second comment of the Associate Editor, we have prepared a comparison table (see RTable 1) of some recent works found in the literature in terms of antenna performance and size.

The most important comparison for the proposed LWA are with works [19], [20], and [24]. Regardless, from RTable 1 it can be identified that our proposed antenna is the first to offer a very high radiation efficiency (by excitation of the  $n = -1$  spatial harmonic) for operation at about 23.5 GHz, and, implemented within a very compact size. This is mainly related to the employed GDS which had a dielectric constant of about 10 which supports a very high SW excitation for antenna leakage and radiation. Previous LWAs operated with lower dielectric constant values for the GDS, operated well below 20 GHz, and/or do not offer any controlled aperture distribution.

We hope RTable 1 now better identifies the novelty of our work and we have also included a condensed version of this table in the revised manuscript and updated the relevant text accordingly.

RTable 1 – Antenna Comparison

	Center Frequency	Antenna Size	Beam Angle Range	Realized Gain Max	Aperture Control	SLL	Efficiency	Radiating Harmonic
[4]	29.4 GHz	n/a	-25° to -22°	12.7 dBi	No	-18.1 dB	Not given	n = -1
[5]	5 GHz	5.5 $\lambda_0$ by 0.33 $\lambda_0$ by 0.217 $\lambda_0$	88° to 92°	12.9 dBi	No	-9 dB	n/a	n = -1
[6]	4.75 GHz	5.76 $\lambda_0$ by 1.15 $\lambda_0$ by 0.18 $\lambda_0$	3° to 11°	13.3 dBi	No	-10 dB	n/a	n = 0
[8]	13.6 GHz	n/a	108° to 112°	14.4 dBi	No	-19.2 dB	84.5 %	n = -1
[11]	4 GHz	4 $\lambda_0$ by 0.43 $\lambda_0$ by 0.26 $\lambda_0$	71° to 77°	11.8 dBi	No	< -10 dB	n/a	n = -1
[19]	10 GHz	11 $\lambda_0$	-25° to -35°	16.6 dBi	Yes	-14.33 dB	n/a	n = 0
[20]	15 GHz	n/a	22° to 60°	17.8 dBi	No	< -10 dB	>95%	n = -1
[24]	14 GHz	n/a	-58° to 35°	21.3 dBi	No	< -10 dB	88%	n = -1
This work	23.5 GHz	1.1 $\lambda_0$ by 9.8 $\lambda_0$	-25° to -16°	14.9 dBi	Yes	< -10 dB	>85%	n = -1

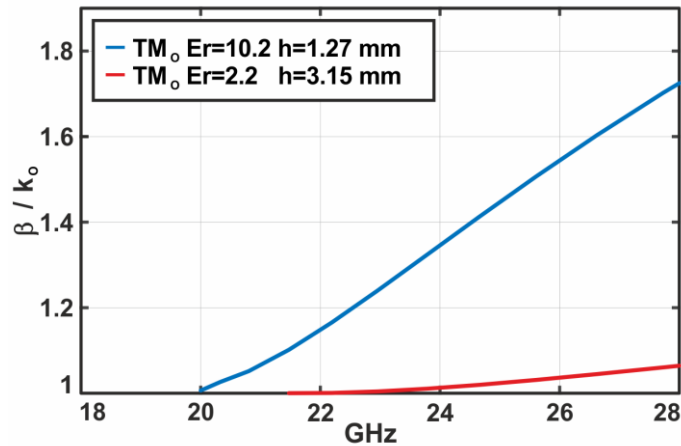
**3) The bandwidth of the antenna is relatively narrow. The Authors should give some analyses or parameter studies to show how to enlarge the bandwidth.**

We thank the Reviewer for their interesting comment which has given us some motivation to improve the operating bandwidth of the proposed antenna. In particular, we have designed a new SIW-SWL to illustrate that the bandwidth can be enlarged, and some results are highlighted below. Also, to further address this helpful comment, we would like to mention the following:

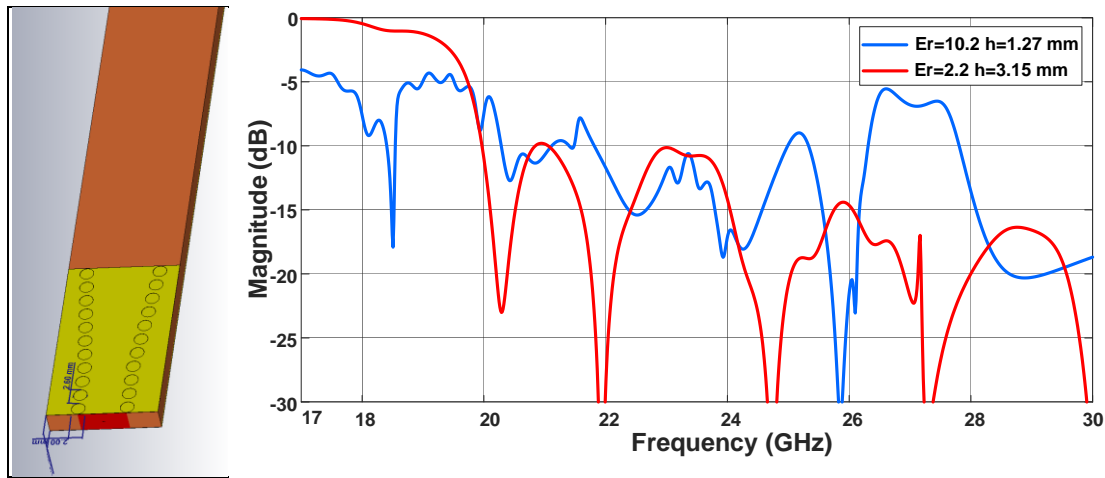
- The Reviewer has correctly mentioned that the proposed antenna has a somewhat narrow operating bandwidth from about 22 GHz to 24 GHz. This is due to the high dielectric constant; i.e. the  $TM_0$  mode is somewhat dispersive.
- This relatively distinct dispersion can be observed in RFig. 1 when the normalized SW propagation constant for the  $TM_0$  mode on the ground dielectric slab (GDS) is compared considering  $\epsilon_r = 10.2$  and 2.2. For example,  $\beta/k_0$  varies between about 1.0 and 1.7 [1.0 and 1.07] for  $\epsilon_r = 10.2$  [ $\epsilon_r = 2.2$ ] from about 18 GHz to 28 GHz.
- Given that we are exploiting the  $TM_0$  SW mode on GDS for the proposed LWA, the radiated beam pattern will follow this dispersive nature in that the main beam angle will scan more with frequency when compared to a LWA which uses  $\epsilon_r = 2.2$ .

- Following this discussion, it is possible to re-design the SIW-SWL considering a relative dielectric constant of 2.2 and a thicker substrate. Basically to enhance the possible operating bandwidth. This would likely allow for an improved operating bandwidth of the LWA; i.e. less beam scanning with frequency since  $\beta$  for the  $TM_0$  SW mode with  $\epsilon_r = 2.2$ , exhibits less variation (or dispersion) versus frequency.
- To further illustrate this point, an SIW-SWL was newly redesigned in CST (see RFig. 2). It can be observed that the impedance matching is improved for the structure which employs  $\epsilon_r = 2.2$ ; i.e.  $|S_{11}| < -10$  dB from 20 GHz to 30 GHz (while the design with  $\epsilon_r = 10.2$  is only matched to about 26 GHz).
- We would like to stress that these new findings are preliminary – but can inspire future research – and that including these results within the revised manuscript would deviate from the reported findings of the paper. In addition, it would also increase the document length which is not possible due to the 4-page limit for AWPL submissions. Moreover, including these findings is not possible since we need to address the other comments from the Reviewers directly in the manuscript.
- Regardless, we provided the following discussions in the revised manuscript text which summarizes the important points inspired by the Reviewer while also further describing our design approach for possible future work (page 4, left column):

“It should be mentioned that the measured LWA has a somewhat narrow operating bandwidth from about 23 GHz to 24 GHz. This is due to the employed design approach where a specific center frequency for radiation was chosen and the unit cells were selected to achieve the required aperture distribution. This is also related to the relatively high dielectric constant ... for the employed GDS to ensure good coupling efficiencies into the dominant  $TM_0$  SW mode. These design constraints can be alleviated in future work, for example, by considering a lower dielectric constant for the GDS and with an increased thickness. Mainly because the  $TM_0$  SW mode can be less dispersive when using a lower dielectric constant ... . This however would require the redesign of the SIW-SWL and aperture distribution. Such an approach would present similar limitations in the beam scanning angle range. In our work we have adopted a LWA structure that exhibits a good compromise between these two main constraints; i.e. very good SW coupling efficiency [2], [20] whilst respecting the dispersion of the  $TM_0$  SW mode.”



RFig. 1 – Surface wave propagation constant for a GDS considering  $\epsilon_r = 10.2$  and  $2.2$ .



RFig. 2 – Simulation results for a new SIW-SWL using  $\epsilon_r = 2.2$  (left) and the resulting reflection coefficient (right). Results are also compared to the proposed SIW-SWL for  $\epsilon_r = 10.2$ . The impedance matching is improved for the new structure which employs  $\epsilon_r = 2.2$ ; i.e.  $|S_{11}| < -10$  dB from 20 GHz to 30 GHz.

**Reviewer: 2**

*The paper presents the design and the experimental validation of an original printed leaky-wave antenna (LWA) tapered for pattern synthesis and efficiently excited by a SIW waveguide with a proper matched horn. The paper is well written, clear, and correct.*

We thank the Reviewer for their encouraging comments as well as their deep scientific understanding and appreciation of our paper.

- 1) At row 42, column II, p. 1:  $L$  is declared as unit-cell length; however the period  $D_u$  is also defined as unit-cell length. Please, clarify

The Reviewer is correct. To avoid confusion and to be consistent with Fig. 1 and 2, we have revised that sentence to the following "...the control of the unit cell parameters; i.e. the width  $W$  and periodicity  $D_u$  provided high flexibility for the printed design...".

- 2) *In Section II.B, the control of  $\alpha$  has been related to the variation of  $W_{max}$ . A reference to [14] can be made in this context, by indicating the modulation index as the main parameter related to  $W_{max}$*

We thank the Reviewer for their helpful comment. Indeed  $\alpha$  is related to the width of the unit-cell and with this it is possible to change the modulation index. This is part of the main design approach. We should also mention that reference [14] is now [17] in the revised manuscript.

The revised text is as follows (see Section IIB, right column, page 2): " $D_u$  was varied to change  $\beta$ , ... and  $W_{max}$  was varied to control  $\alpha$  [28] since the modulation index is related to  $W_{max}$  of the unit-cell [17]."

- 3) *In Section II.B, the normalized phase constant of the radiating space harmonic has been fixed to -0.292. The behavior of the normalized  $\beta$  as function of the antenna length has been shown in Fig. 3. However, a second y axes (on the right) can be added to the plot in order to indicate the values of the normalized  $\beta$ . At the moment, the values on the left y axes are for the normalized attenuation constant, I guess, that ranges between 0.03 and 0.065.*

We thank reviewer for their input. We have revised this figure and made a better illustrative connection with the attenuation constant over the structure. This defines a new Fig. 2 and a revised caption. We hope that this clarifies more the proposed geometry and its tailored attenuation (which changes over the aperture) and its propagation constant (which remains constant).

- 4) *In Section II.B, could the Authors, please, explain better how the leakage constant has been obtained? It is not fully clear to me. What I understand, however, is that a structure that is periodic (it extends to infinity) along y, and has a finite length along x has been excited with an ideal  $TM_0$  SW and simulated by CST. Then, from the properties of the FF pattern in the zx plane, values of  $\alpha$  have been obtained. The sentence "by simulating each unit cell independently in an infinite aperture environment" could be misleading; i.e., which kind of infinite aperture environment is considered?*

The Reviewer's summary of the design process is accurate. It is important to keep in mind that, while the placement of unit cells influences the LW attenuation constant along the direction of propagation, the phase constant does not depend on such positioning. This means that, in general, the LW phase and attenuation constants can be determined independently.

In our design we prepared a detailed study for different unit cell dimensions; i.e.  $W_{max}$  and the periodicity  $D_u$  and repeated 20 unit-cells with 9 rows. Then illuminated the structure with a uniform  $TM_0$  SW and observed the radiated beam pattern in the far-



field considering the design frequency of 23.5 GHz. Then by changing these unit cell parameters, we were able to construct a design table (an example is shown below) with the important LWA parameters such as the 3dB beam width and direction of the main beam. This provided indication of the LW attenuation and phase constants.

$w_{max}$ [mm]	$D_u$ [mm]	$\theta_p$ [deg]	$\theta_p$ [rad]	$\Delta\theta_p$ [deg]	$\Delta\theta_p$ [rad]	$\alpha$ [Np m <sup>-1</sup> ]	$\beta$ [m <sup>-1</sup> ]
0.7	4.00	-21	-0.3665	12.2260	0.2134	1.9462	-176.3738
<b>0.7</b>	<b>4.05</b>	<b>-18</b>	<b>-0.3142</b>	<b>11.7290</b>	<b>0.2047</b>	<b>1.9346</b>	<b>-152.1119</b>
0.7	4.10	-16	-0.2793	11.4297	0.1995	1.9271	-135.6864
0.9	4.00	-20	-0.3491	12.6540	0.2209	1.9666	-168.3522
<b>0.9</b>	<b>4.05</b>	<b>-18</b>	<b>-0.3142</b>	<b>12.3391</b>	<b>0.2154</b>	<b>1.9600</b>	<b>-152.1119</b>
0.9	4.10	-16	-0.2793	12.0948	0.2111	1.9553	-135.6864
1.1	4.00	-20	-0.3491	13.2516	0.2313	2.0208	-168.3522
<b>1.1</b>	<b>4.03</b>	<b>-18</b>	<b>-0.3142</b>	<b>13.1553</b>	<b>0.2296</b>	<b>1.9920</b>	<b>-152.1119</b>
1.1	4.05	-17	-0.2967	12.9928	0.2268	1.9886	-143.8975
1.1	4.10	-15	-0.2618	12.8039	0.2235	1.9863	-127.3866

In summary the key process for designing the aperture is as follows:

- (1) Define the mean beam angle and the operating frequency (23.5 GHz);
- (2) Select the possible range in which the unit cell modulation parameter  $w_{max}$  and the periodicity  $D_u$  can vary;
- (3) Then simulate the larger aperture (see Fig. 3 inset) and observe the radiated fields considering a uniform unit cell arrangement; i.e. the unit cells have consistent dimensions;
- (4) The next step is a proper choice of the unit cells along the guiding surface to synthesize or define the aperture distribution; i.e.  $\alpha(x)$ , assuming propagation along the x-direction.
- (5) From the above look-up table and based on this parametric study completed, we selected a binomial-like aperture distribution offering low side lobe levels. The results are reported in Figs. 2 and 3 of the revised manuscript.

To further address this important point by the Reviewer we have revised the following text in the manuscript (Section IIB, page 3, left column):

“It should be mentioned that the LW attenuation constants were computed by simulating each unit cell independently using an aperture with a large number of unit cells representing an almost infinite structure (180 unit cells) as illustrated in Fig. 3 (see inset). This aperture was illuminated with a uniform TM0 SW field distribution originating from the edge of the guiding surface. ... This procedure allowed us to acquire the relationship between the parameters of the unit cells and the generated LW field. Mainly, by changing Wmax and Du whilst considering a 23.5 GHz design frequency, we were able to construct a design table. Based on this parametric study we were able to synthesize  $\alpha(x)$  for a constant  $\beta$ .”

5) Please, correct the values of the normalized attenuation constant in the caption of Fig. 4 (they should be 0.03 and 0.05).

The Reviewer is correct, and the figure caption has been updated.

- 6) ***In Section III, the predicted pointing angle from the tapering procedure illustrated in Fig. 3 at 23.5GHz can be provided and then compared with those obtained by full-wave simulations and measurements. The leaky theoretical pointing angle (i.e., obtained by the normalized phase constant equal to -0.292) should be almost equal to -17°.***

The Reviewer has correctly identified that the designed angle of radiation is -17° from broadside. We have revised the relevant figure caption and clarified this in the text (see Section IIB, page 3, right column): "The predicted beam maximum of the examined structures is -17° at 23.5 GHz (see Fig. 3)."

- 7) ***It is not clear if a modified value of the relative permittivity of the dielectric substrate has been used only in Fig. 9 (where it is clearly declared in the legend) or in all the full-wave simulations of Figs. 7-11. The Authors could specify.***

The Reviewer has mentioned that there might have been some misunderstandings with the figure captions when describing the simulated value for dielectric substrate. Simulations of the beam pattern (see Fig. 6 caption) took into consideration  $\epsilon_r = 10.6$  and the effects of the practical connector. We also updated the labels for Figs. 7, 8, and 9 and added additional explanations within the relevant captions and the text.

- 8) ***In the Conclusion, III sentence, "existing" has been used two times in the same sentence. It could be eliminated before the word "literature".***

Corrected. We thank the Reviewer for this suggestion to improve document readability.

# Printed Leaky-Wave Antenna with Aperture Control using Width-Modulated Microstrip Lines and TM Surface-Wave Feeding by SIW Technology

Maksim V. Kuznetsov, *Student Member, IEEE*, Victoria Gómez-Guillamón Buendía, *Student Member, IEEE*, Zain Shafiq, *Student Member, IEEE*, Ladislau Matekovits, *Senior Member, IEEE*, Dimitris E. Anagnostou, *Senior Member, IEEE*, Symon K. Podilchak, *Member, IEEE*

**Abstract**—The article presents a width-modulated microstrip line leaky-wave antenna (LWA) with substrate integrated waveguide and microstrip feeding. In particular, the planar antenna system consists of an integrated surface-wave launcher and three identical rows of quasi-periodic width-modulated microstrip lines for TM leaky-wave excitation which produces a tailored binomial-like aperture distribution on the guiding surface. The behavior of the antenna when changing the width-modulated lines for different aperture distributions is also analysed and presented. The measured LWA demonstrates a fan beam pattern in the far-field with realized gain values greater than 10 dBi and with a beam direction of about  $-20^\circ$  from broadside at 23 GHz. Also, far-field measurements and near-field data indicate that the half-power beamwidth is below  $10^\circ$  and the position of the main beam maximum is relatively stable; i.e. ranging from about  $-23^\circ$  to  $-15^\circ$  between 23 to 24 GHz. The measured prototype is also well matched over these frequencies and  $|S_{11}| < -20$  dB at 23.5 GHz.

## I. INTRODUCTION

IN modern radio frequency technology, the use of directive beam pattern antennas has different sensor and communication applications such as radar and satellite connectivity. In these systems it is often necessary to have controlled-beam antennas to improve the overall performance of the transceiver system. One solution can be to use leaky-wave antennas (LWAs) and surface-wave (SW) driven structures. Examples include microstrip-based planar antennas [1]–[6], substrate integrated waveguide (SIW) antennas [7], [8], or even hybrid types where planar and metallic technologies are combined [9]–[11]. In general, these antennas can also be used in a wide range of applications for machine-to-machine (M2M) systems [12], charging stations [13], or local Internet of Things (IoT) [14] services. Another application for LWAs is in automotive radar [15]–[17].

One important challenge when designing LWAs is to ensure efficient radiation. To achieve high values, appropriate leaky-wave (LW) field distributions should be synthesized. One possible solution is the use of a sinusoidally-modulated reactive surface (SMRS) [18], [19]. Those LWA designs are based on

a printed array of unit cells which consist of metallic strip configurations having different gap-sizes, and by varying the surface reactance as well as the modulation factor and the periodicity, it is feasible to control the LW phase constant ( $\beta$ ) and the leakage attenuation rate ( $\alpha$ ). Another approach to achieve a tailored aperture distribution is by holographic principles [20], where radiation can be controlled by altering the unit-cell dimensions. Expanding on these methodologies the antenna engineer can synthesize any desired aperture distribution for LW radiation. Another solution, introduced in the literature, is the use of width modulated microstrip lines within the unit cell [21]–[23]. In contrast with the SMRS from [18] where the fundamental mode (harmonic) radiates, in width-modulated microstrip LWAs, the  $n = -1$  spatial harmonic is employed for Bragg radiation [21]–[24].

Following these developments, planar LWAs using Cartesian [21] and Polar [22] aperture arrangements and  $\text{TM}_0$  surface-wave launchers (SWLs) have been reported [2], [25]. Typically the Yagi-Uda-like SWL uses slots which are integrated within the ground plane of a grounded dielectric slab (GDS) and where the main driven slot is connected to a 50- $\Omega$  coplanar transmission line for antenna feeding. A new type of SIW-SWL is developed in this work using a continuous ground plane and no slots for  $\text{TM}_0$  SW excitation and with a 50- $\Omega$  microstrip feed (see Fig. 1). This significantly expands the possible applications for the proposed antenna and simplifies mounting requirements. For example, any antenna which employs the developed SIW-SWL feed system could be easily placed on a car or metallic airplane fuselage.

Also following the earlier work in [21] and [22], a novel width-modulated aperture was reported in [23] that maintained the same LW phase propagation constant over the aperture while also changing  $\alpha$ ; i.e. effectively controlling the leakage while maintaining the same beam angle in the far-field. In these preliminary findings, the control of the unit cell parameters; i.e. the width  $W$  and periodicity  $D_u$  provided high flexibility for the printed design and can also be utilized to achieve different beam patterns as desired, possibly obtaining high efficiency and low side lobes. Having such a quasi-independent control of  $\alpha$  and  $\beta$ , one can properly cascade the unit cells allowing for a local tailoring of the desired leakage rate along the antenna aperture. To the best of the authors' knowledge a design approach with such flexibility has not yet been experimentally verified.

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M.V. Kuznetsov, V.G. Buendia, Z. Shafiq, D.E. Anagnostou, and S.K. Podilchak are with Heriot-Watt University, UK (e-mail: skp@ieee.org).

L. Matekovits is with Politecnico di Torino, Dipartimento di Elettronica, Italy. (e-mail: ladislau.matekovits@polito.it)

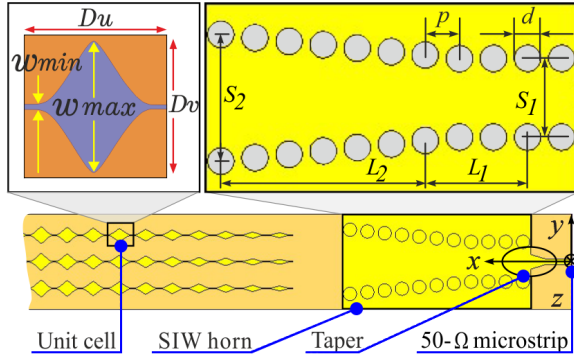


Fig. 1. Proposed 1-D LWA with microstrip feeding and SIW horn antenna for  $TM_0$  SW excitation. The dimensions of the unit cells for the aperture are defined in Fig. 2 (a).

Given these findings, we propose a new LWA. The presented aperture consists of three rows of cascaded unit cells. Within each row, different width-modulated microstrip line geometries are cascaded (see Figs. 1 and 2 (a)) to realize a binomial-like aperture distribution. This has the design motivation to increase radiation efficiency and decrease side-lobe levels whilst employing low-cost printed circuit board technology. Analysis of other types of comparable aperture distributions and their resulting radiation performances are also investigated. Moreover, the proposed binomial-like distribution is simulated and measurement results are close to those of the fabricated prototype. As mentioned, a new type of SIW-SWL is also presented and the design methodology is explained. Measurements and simulations are also presented while taking into account possible manufacturing errors, variation in the dielectric, and minor antenna performance degradation due to the connector. Also, radiation patterns using near-field (NF) and far-field (FF) measurement systems are presented and well compared with these simulations.

## II. DESIGN PROCEDURE

The proposed planar LWA mainly consists of two parts: (1) the width-modulated microstrip unit cells arranged in lines and (2) the SIW horn SWL (see Figs. 1 and 2). The main idea is to excite  $TM_0$  SWs from the aperture of the SIW horn antenna which are perturbed by the width-modulated unit cells aiming to obtain controlled LW radiation.

The considered aperture distribution is a binomial-like one with different unit cells generating a beam with low side-lobes. On that basis, and in a similar manner to LWAs with periodic holes or strips [26], [27], the control of  $\alpha$  dictates the beam pattern features, such as the beam width, the realized gain, and the side lobe levels. For our proposed LWA we will consider an aperture where  $\alpha$  is low at the beginning and at the end, while being high in the middle of the structure (see Fig. 2).

### A. SIW Feed Design for TM SW Generation

Classically SIW horn antennas are of interest due to their low-cost and simple fabrication. For the proposed SIW-SWL it is important to properly choose the dielectric material and thickness since the overall response at microwave and

millimeter-wave frequencies can affect the SW excitation efficiency. Thus, our choice of the dielectric substrate was Rogers RT6010 ( $\epsilon_r = 10.2$ ,  $h = 1.27$  mm) as it can ensure suitable TM SW launching [2], [25] at the antenna design frequency.

The SWs will be generated at the output of the horn and will propagate along the air-dielectric interface by the dominant mode of the slab; i.e. the  $TM_0$  SW mode [28]. This is because the  $E_z$  component of the  $TE_{10}$ -like mode of the SIW horn is field matched to that of the  $TM_0$  SW mode of the employed GDS. Also, to improve impedance matching, the flare in the  $H_{(x-y)}$  plane of the TM SW horn was optimized using CST to minimize reflections such that  $|S_{11}| < -20$  dB.

The final part of SIW feed includes a connecting 50- $\Omega$  microstrip line. A taper was included to match the impedances of the microstrip line and the SIW horn. Also, the microstrip line supports a quasi-TEM mode and the SIW line supports a  $TE_{10}$  mode [29], of which have similar field configurations. Further details on SIW tapers can be found in [29] and [30].

### B. Aperture Design by Width-Modulated Microstrip

The next part of the antenna structure is the radiating aperture. It consists of a combination of unit cells based on printed microstrip lines with maximum and minimum width values  $W_{max}$  and  $W_{min}$  (see Fig. 1). Based on holographic antenna principles, the behavior and shape of each unit cell allows the designer to control  $\alpha$  and  $\beta$ . The structure is characterized by the periodicity  $D_u$  and  $D_v$  in the longitudinal and transverse directions, respectively. For the considered geometry, the frequency behavior of the single unit cell was modeled analytically and follows Mathieu's and Hill's functions [31], [32] as applied in [22]. Also by following [21]–[23], a minimum width of  $W_{min} = 0.1$  mm was selected. Therefore,  $D_u$  was varied to change  $\beta$ , while  $D_v$  was kept constant to minimize possible coupling between the transverse unit cells and  $W_{max}$  was varied to control  $\alpha$  [33] since the modulation index is related to  $W_{max}$  of the unit-cell [22].

By selecting the appropriate unit cells the LW field excitation can be controlled in the  $x$ -direction along the length of the antenna [33]. Figure 2(b) plots the LW phase and attenuation constants given the unit cell dimensions from Fig. 2(a). Also, by having the same pointing angle for each unit cell; i.e.  $\hat{\beta} = -0.292$ , (where  $\hat{\cdot}$  refers to a normalization with respect to  $k_0$ ), it is possible to achieve control of the aperture field. In the present proof of concept LWA, as illustrated in Fig. 1, three identical lines (see Fig. 2) have been considered to generate a fan beam pattern in the FF. Each unit cell as defined in Fig. 2 can be represented as an independent radiation element.

Simulations with a larger aperture show that by using only lines with relatively low and a constant leakage rate  $\hat{\alpha} = 0.03$  for comparison (20 unit cells by 9 rows  $W_{max} = 0.7$  mm and  $D_u = 3.97$  mm giving  $\hat{\alpha} = 0.03$ ) a narrow beam width and higher level of side lobes can be observed when compared to an equivalent structure using the designed binomial-like aperture (see Fig. 3). On the other hand, an aperture with a constant but higher leakage rate ( $W_{max} = 1.5$  mm,  $D_u = 4$  mm,  $\hat{\alpha} = 0.05$ ) generated a wider beam but with lower side



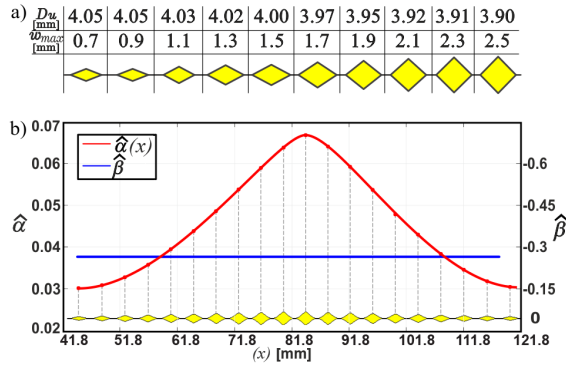


Fig. 2. (a): Dimensions of the width-modulated unit cells for the first half of the aperture. (b): Normalized  $\alpha$  and  $\beta$  versus length for the 20-element binomial like aperture at 23.5 GHz using the unit cells described in (a). With this geometry  $\hat{\alpha}$  is tailored (which changes over the aperture) while the LW propagation constant remains consistent; i.e.  $\hat{\beta} = -0.292$ .

lobe levels. Also, as expected, no distinct side lobes can be observed for the binomial-like aperture and when compared to the apertures defined by a constant leakage rate.

It should be mentioned that the LW attenuation constants were computed by simulating each unit cell independently using an aperture with a large number of unit cells representing an almost infinite structure (180 unit cells) as illustrated in Fig. 3 (see inset). This aperture was illuminated with a uniform TM<sub>0</sub> SW field distribution originating from the edge of the guiding surface. Then by observing the 3dB beamwidth and pointing angle ( $\theta_p = \sin^{-1} \hat{\beta}$ ) for the radiated beam pattern in the FF,  $\hat{\beta}$  could be determined as well as  $\hat{\alpha}$  using  $BW_{3dB} = 2\hat{\alpha} \csc \theta_p$  [34]. This procedure allowed us to acquire the relationship between the parameters of the unit-cells and the generated LW field. Mainly, by changing  $W_{max}$  and  $D_u$  whilst considering a 23.5 GHz design frequency, we were able to construct a design table. Based on this parametric study we were able to synthesize  $\alpha(x)$  for a constant  $\beta$ .

The total radiation efficiency for the different distributions investigated (from Fig. 3) were computed in a commercial full wave simulator CST by taking into account conductor and substrate losses while also considering a consistent aperture (20 unit cells by 9 rows). The predicted beam maximum of the examined structures is  $-17^\circ$  at 23.5 GHz (see Fig. 3). As observed, results in Fig. 4 show that the binomial like distribution provides the highest efficiency for all considered apertures with values above 85%.

### III. SIMULATIONS, MEASUREMENTS & DISCUSSION

The proposed LWA was designed, simulated and manufactured. A photograph of the prototype is shown in Fig. 5. As described in Table I, previous LWAs operated well below 20 GHz and do not offer any controlled aperture distribution.

In our work, the pitch and diameter of the vias was  $p = 2.6$  mm and  $d = 2$  mm, the distance between one end of vias to another was  $S_1 = 6$  mm and  $S_2 = 9.5$  mm, while lengths for the SIW horn were  $L_1 = 7.8$  mm and  $L_2 = 18.2$  mm. Moreover,  $W_{min} = 0.1$  mm (see Fig 1). Dimensions of the structure, i.e. width  $W_{max}$  and periodicity  $D_u$  of the different modulated unit cells are tabulated in Fig. 2(a). To verify performance in the NF and the FF, the NSI-5912 Near-Field Scanner and the DAMS 7100 Diamond Engineering Far-field

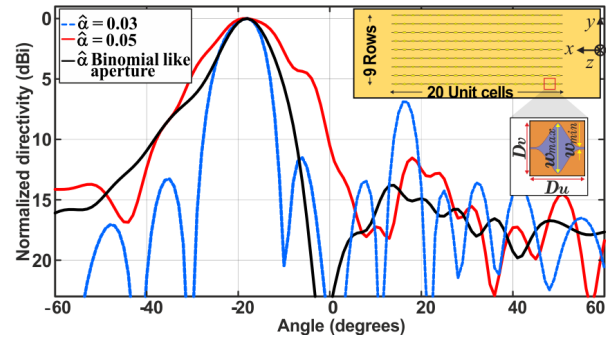


Fig. 3. Normalized directivity for different aperture distributions considering 180 unit-cells at 23.5 GHz for a constant LW aperture with  $\hat{\alpha} = 0.03$  and 0.05. Results are also compared to the arrangement in Fig. 2 and with the same number of unit-cells for the realization of a binomial-like aperture. The designed pointing angle for all the structures is  $-17^\circ$  at 23.5 GHz.

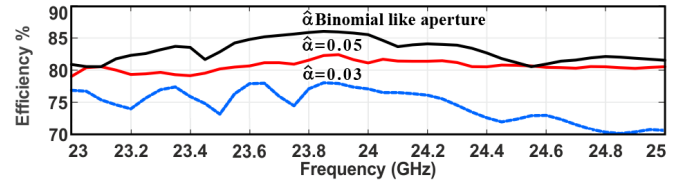


Fig. 4. Simulated radiation efficiency for the LWAs as considered in Fig. 3.



Fig. 5. Fabricated LWA using Rogers RT6010 with a rated relative dielectric constant  $\epsilon_r = 10.2$ , thickness  $h = 1.27$  mm: (a) top view (b) bottom view.

Measurement System were used, respectively. Measurements and simulations are compared in Figs. 6-9.

Simulations showed that at the design frequency of 23.5 GHz, the realized gain is 14.2 dBi with a pointing angle of  $\theta_p = -19^\circ$ . The beam pattern and the pointing angle of the main beam in the FF over a wide frequency range around 23.5 GHz has been experimentally validated and presented in Figs. 7 and 8 demonstrating LWA operation.

The antenna is well matched for the frequency range 22 to 24 GHz with  $|S_{11}|$  values below -10 dB and about -20 dB at the design frequency of 23.5 GHz (see Fig. 9). The employed Southwest end launch SuperSMA (292-04Z-6) type connector was also taken into consideration during simulations, which generated a minor gain drop over frequency and contributed to an angle shift in the main beam position due to electromagnetic coupling between the connector itself and the radiating LW fields. The maximum gain of the antenna with the connector was observed to be 13.4 dBi at 23.2 GHz.

Simulations and measurements shown in Figs. 7, 8, and 9 further take into account all losses and practical variations in the dielectric constant [35]. For the measured structure the maximum realized gain occurs at 23.45 GHz with values of 10.7 dBi as shown in Fig. 8. The reduction in gain is likely related to the connector and a practical change in  $\epsilon_r$  from its rated value. More specifically, simulations showed that practical variations in the relative dielectric constant from 10.2

TABLE I  
COMPARISON TO SIMILAR LWAS FOUND IN THE LITERATURE

Reference	Center Frequency	Beam Angle Range	Realized Gain Max	Aperture Control	Side Lobe Level	Efficiency	Radiating Harmonic
[19]	10 GHz	-25° to -35°	16.6 dBi	Yes	-14.33 dB	-	$n = 0$
[20]	15 GHz	22° to 60°	17.8 dBi	No	<-10 dB	>95%	$n = -1$
[24]	14 GHz	-58° to 35°	21.3 dBi	No	<-10 dB	88%	$n = -1$
This work	23.5 GHz	-25° to -16°	14.9 dBi	Yes	<-10 dB	>85%	$n = -1$

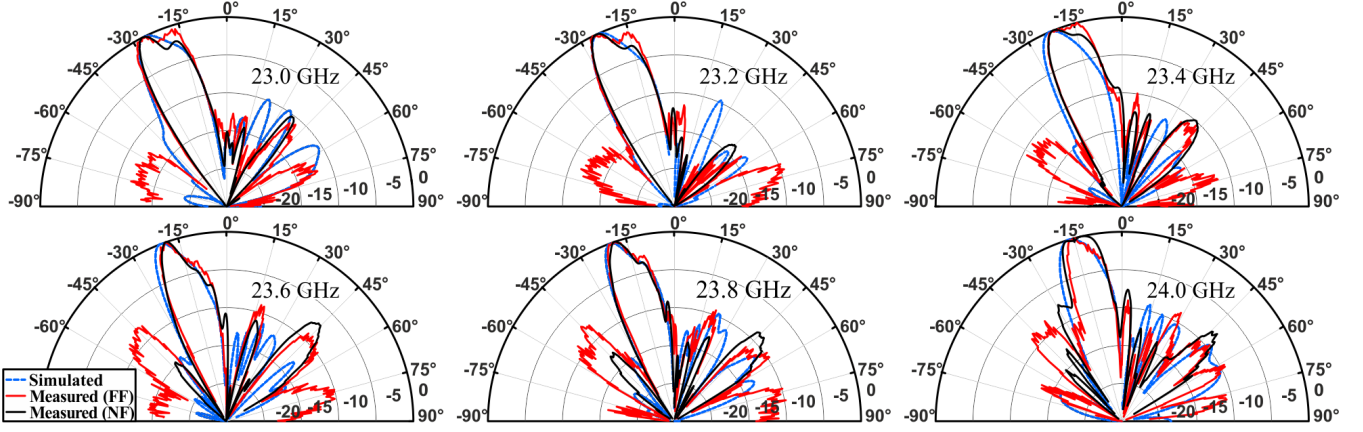


Fig. 6. Measured and simulated radiation patterns for different frequencies from 23 GHz to 24 GHz in the  $x$ - $z$  plane, demonstrating beam scanning from -25° to -15°. It should be mentioned that the simulations consider a relative dielectric constant of 10.6 and connector for consistency with Figs. 7-9.

to 10.6 caused the gain to drop by about 2 dB (see Fig. 8) and the pointing angle at the design frequency is -20° and slightly shifted by about 2° at other frequencies (see Fig. 6).

The minor discrepancy between the simulations and measurements can also be related to manufacturing tolerances e.g. drilling and metalization of the vias. Despite these practicalities, the measurement results are in good agreement with simulations, showing the expected performance, and demonstrating proof of concept. The beam patterns are also plotted in Fig. 7 using both NF and FF measurement approaches and results are in agreement. Also, the measured cross-polarization levels are 10 dB below from the main co-polarized maximum.

It should also be mentioned that the measured LWA has a somewhat narrow operating bandwidth from about 23 GHz to 24 GHz. This is due to the employed design approach where a specific center frequency for radiation was chosen and the unit cells were selected to achieve the required aperture distribution. This is also related to the relatively high dielectric constant ( $\epsilon_r \approx 10$ ) for the employed GDS to ensure good coupling efficiencies into the dominant  $TM_0$  SW mode. These design constraints can be alleviated in future work, for example, by considering a lower dielectric constant for the GDS and with an increased thickness. Mainly because the  $TM_0$  SW mode can be less dispersive when using a lower dielectric constant (for example,  $\epsilon_r \approx 2$ ). This however would require the redesign of the SIW-SWL and aperture distribution. Such an approach would present similar limitations in the beam scanning angle range. In our work we have adopted a LWA structure that exhibits a good compromise between these two main constraints; i.e. good SW coupling efficiency [2], [25] whilst respecting the dispersion of the  $TM_0$  SW mode.

#### IV. CONCLUSION

We introduced a new type of planar LWA with a new SWL and with 50- $\Omega$  microstrip feeding. The proposed SIW-SWL

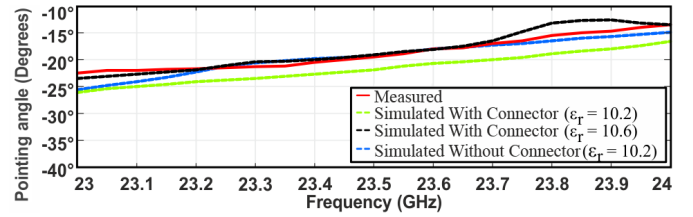


Fig. 7. Beam pointing angle for the proposed LWA (see Fig. 5). A comparison is also provided with and without the connector and  $\epsilon_r = 10.2$  and 10.6. Note: Figs. 8 and 9 have the same legend as this figure.

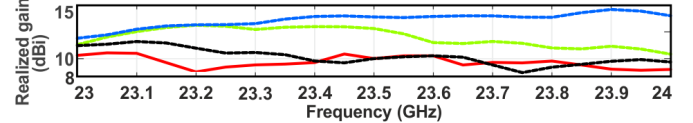


Fig. 8. Measured and simulated maximum realized gain in the  $x$ - $z$  plane.

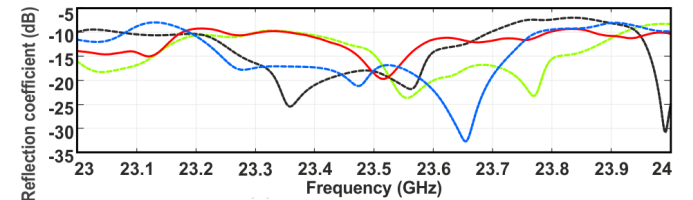


Fig. 9.  $|S_{11}|$  for the proposed planar LWA prototype.

can be used in other types of LWAs where  $TM$  SW excitation is required while also allowing for good efficiency and low-cost implementation. The developed binomial-like distribution represents an alternative to existing approaches found in the literature. The maximum measured realized gain was 10.7 dBi at 23.45 GHz with the main beam direction at about -20°. The experimental radiation patterns are presented and compared with simulations where changes in the dielectric constant and the employed connector were taken into account. The proposed LWA can be used in communication applications such as radar systems where the advantage of having a continuous ground plane allows for placement on cars or airplane fuselages.

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