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A Half-Mode Groove Gap Waveguide for Single-Layer Antennas in the Millimeter-Wave Band

Miguel Ferrando-Rocher, *Member, IEEE,* Jose I. Herranz-Herruzo, *Member, IEEE,*
Alejandro Valero-Nogueira, *Senior Member, IEEE,* Mariano Baquero-Escudero, *Senior Member, IEEE*

***Abstract*—This paper presents an alternative to significantly reduce the time and difficulty in designing and fabricating antennas in Gap Waveguide technology (GW) by using a novel half-mode groove gap waveguide. GW is often criticized within the subtractive manufacturing field for the high fabrication time required to mill many pins with the waveguides in the same piece. To demonstrate the possibilities of this new approach, two different antennas have been designed, fabricated, and measured. Both antennas, formed by only two pieces with no contact, operate from 29 GHz to 31 GHz and present reflection coefficients below -10 dB and high antenna efficiency above 90%. In addition, both prototypes can reuse the bed of nails, which favors shorter manufacturing times and lower costs in the development phase.**

***Index Terms*—Antenna, Array, Bed of nails, Fabrication, Gap Waveguide, Half-Mode Waveguide, Ka-Band.**

I. INTRODUCTION

GAP Waveguide technology, proposed 15 years ago, set a new paradigm in the field of guided media in the millimeter-wave band [1]. Professor Kildal's idea of integrating soft and hard surfaces [2]- [4] crystallized in a technology that allows that even if different metal plates are not in contact, the field remains confined with practically no leakage, even with an air gap present. Metallic pins are used to achieve this competitive advantage. These quarter-wavelength pins create a PMC on their surface, preventing propagation over them for a given frequency range. However, of course, GW has some drawbacks and should be highlighted. For example, it is always more expensive, at least in subtractive fabrication, to make a groove surrounded by many pins than to mill a simple groove in a metal plate. But, it has been demonstrated that this trade-off is often worthwhile. Devices as diverse as transitions [5], resonators [6], coaxial cavities [7], diplexers [8], power distribution networks [9] and of course as an integral part of antennas [10]- [12] are some of the examples usually of interest. Recent research has attempted to achieve similar performance to the GW but to alleviate the problem of pin fabrication. In particular, the concept of Glide-Symmetric Holes (GS), inspired by the GW, should be mentioned [13]- [14].

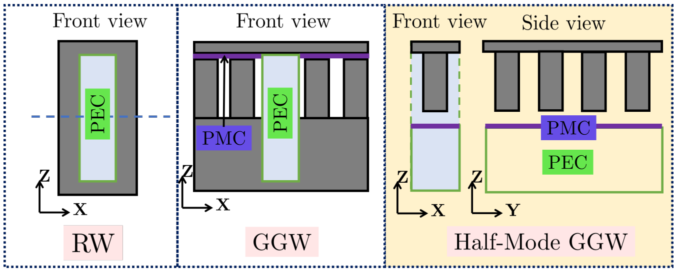

Fig. 1. Schematic comparison of horizontally polarized conventional rectangular waveguide (left) with groove gap waveguide (middle) and the half-mode groove gap waveguide (right).

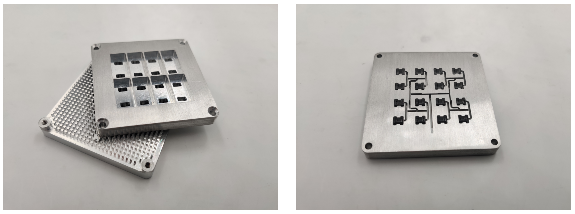
(a) (b)

Fig. 2. Antenna 1. (a) Top view. (b) Bottom view of the upper piece.

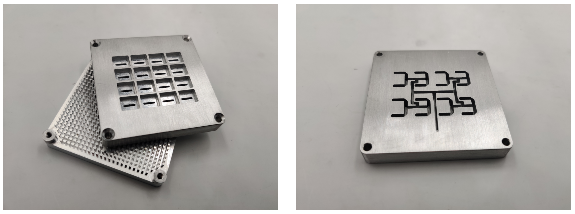
(a) (b)

Fig. 3. Antenna 2. (a) Top view. (b) Bottom view of the upper piece.

The main advantage proposed by GS is that it is much easier drilling holes than milling pins, which is true. However, the significant disadvantage of the GS is the large size of these holes, which rules it out for compact metallic antenna designs with few layers. In this context, it is clear that the challenge remains to find a solution that is not as laborious to fabricate as a bed of nails embedded between the waveguides (GW) while being compact enough to allow compact devices with few layers instead of large holes in multiple layers (GS). In this framework, at least as a first step, this paper tries to provide an alternative. Two Ka-band antenna arrays fed by a novel half-mode Groove Gap Waveguide (HM-GGW) are presented here. Both antennas have identical dimensions, but their feed network and element spacing differ. Thanks to the use of an HM-GGW, first proposed in [15] as a proof of concept in a power divider, the complexity of working with pins is substantially alleviated without losing the inherent GW

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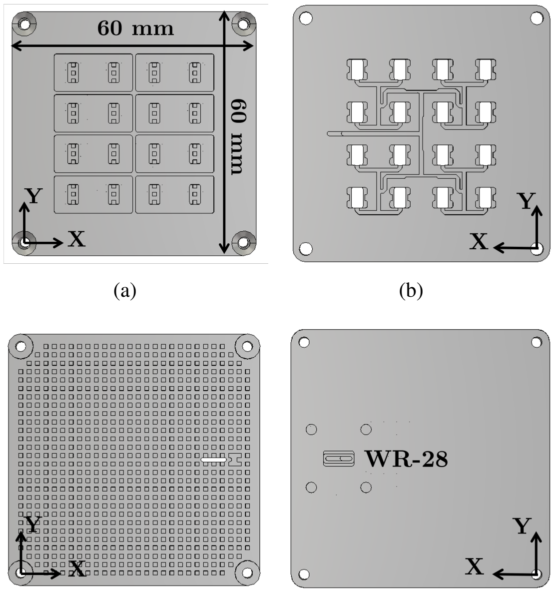
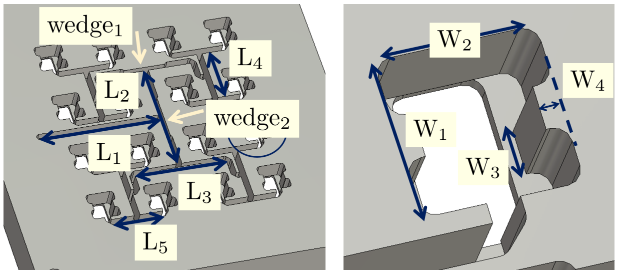


(a) (b) (c) (d)

Fig. 4. Prototype 1: subfigures (a) and (b) correspond to the front and rear side of the upper piece; (c) and (d) correspond to the front and rear side of the lower piece.



(a) (b)

Fig. 5. (a) Perspective detail of the distribution network. The variables of the relevant dimensions are marked. (b) Detail of the cavity that back feeds the aperture.

advantages.

In Fig. 1 front and side views of the half-mode waveguide and its analogy with a conventional rectangular waveguide (RW) and a groove gap waveguide (GGW) are shown. Thus, the following sections are structured as follows. Section II describes each antenna in detail in two separate subsections. The experimental validation of the proposed concept is presented for both manufactured prototypes in Section III and a brief discussion of the HM-GGW usefulness within the GW technology in Section IV. Finally, Section V draws the main conclusions.

II. HALF-MODE GROOVE GAP WAVEGUIDE FED ANTENNA

This section presents the design of two similar-looking antennas composed of 4×4 radiating elements (Figs. 2 and 3). Each of the two antennas is composed of only two aluminum pieces. The bottom layer of the two prototypes is identical and it was used on both antennas. First, the dimensions and characteristics of the bed of nails used for both prototypes are provided. The design criteria followed to obtain the desired band-gap have been thoroughly studied in the past [16]. Typically, the band-gap created by a bed of nails is an octave. In this case, one can get a band gap from 20 GHz to 40 GHz with the following dimensions: pin height of 2.5 mm, pin periodicity of 2 mm, pin width of 1 mm, and air gap of 200μm. It should be emphasized, of course, that it is an entirely uniform bed of nails, and the only modification made to the piece is a slot used to bottom feed the antenna. This bed of nails, free of other alterations, favors a faster CNC manufacturing since it is enough to mill the metal part in rows and columns.

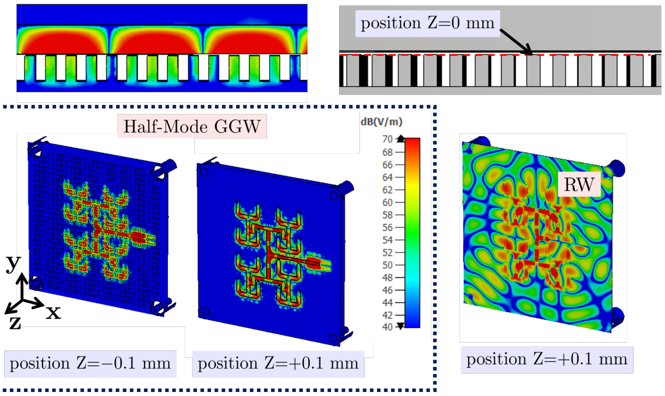


Fig. 6. Simulated electric field at 30 GHz in the antenna distribution network. Field confinement is observed. The figure on the right shows the noticeable field leakage that a conventional waveguide would produce for the same air gap.

TABLE I
FEATURED DIMENSIONS (IN MM) OF THE PROTOTYPE 1

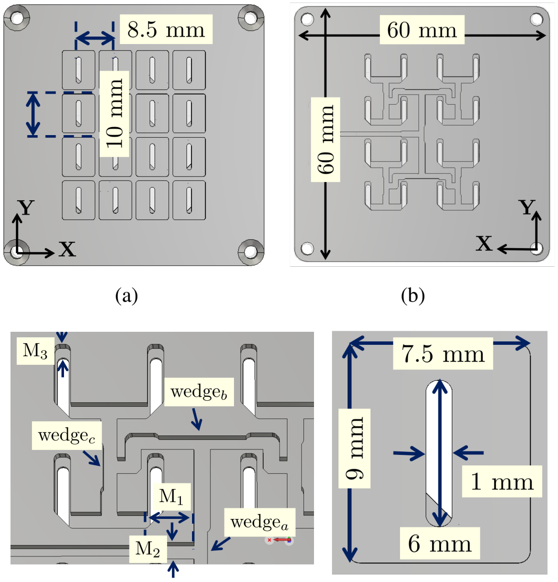
L$_1$	L$_2$	L$_3$	L$_4$	L$_5$	W$_1$	W$_2$	W$_3$	W$_4$
22	19	16	9	9	4.8	4.8	1.3	0.8

TABLE II
DIMENSIONS (IN MM) OF THE WEDGES IN THE POWER DIVIDERS.

Antenna	Prototype 1		Prototype 2		
	wedge$_1$	wedge$_2$	wedge$_a$	wedge$_b$	wedge$_c$
Width	0.35	0.25	0.27	0.25	0.2
Length	7.20	7.60	3.5	7.9	3.9

A. *Prototype 1*

The key point of interest and useful feature of this antenna for the community is its corporate feed network with a half-mode waveguide in GW. This is an all-metal structure with a competitive advantage in radiation efficiency. The chandelier-shaped corporate distribution network provides a wideband uniform power distribution within a wide impedance bandwidth and low transmission losses. The groove dimensions are 3.5 mm in depth and 1 mm in width. The cut-off frequency of a conventional waveguide with these dimensions would be 42 GHz. Now, the cut-off frequency of this groove with the high impedance surface (HIS) produced by the pins, is 22 GHz,



(a) (b)

(c) (d)

Fig. 7. Prototype 2: subfigures (a) and (b) correspond to the front and rear side of the upper piece; (c) and (d) corresponds to antenna details to indicate the relevant dimensions.

TABLE III

MEASURED GAIN (DBI) AND ANTENNA EFFICIENCY (%) FOR BOTH PROTOTYPES.

Frequency (GHz)	29	29.5	30.0	30.5	31
Gain (Prototype 1)	21.72	21.89	22.05	22.12	21.85
Antenna Eff. (Proto. 1)	93.15	93.18	96.92	98.49	96.01
Gain (Prototype 2)	20.98	21.20	21.43	21.41	21.28
Antenna Eff. (Proto. 2)	91.71	95.62	98.30	95.49	93.13

which is close to the cut-off frequency of a full waveguide twice the groove depth. Additionally, this design allows the lower layer structure to be reused in different models. The upper layer is very quickly machinable in CNC fabrication since it is sufficient to make a groove on a solid metal piece.

In short, the antenna consists of 16 elements and has total dimensions of 60×60×16.6 mm^3; a general scheme of the prototype with different views can be seen in Fig. 4. The lower part has a thickness of 9 mm and the upper part 7.4 mm, and between the two pieces, there is an air gap of 200 microns. Besides, the groove is 1 mm wide and 3.5 mm deep. It can also be seen, for example, in Fig. 5(b), the large rounding at the inner corners. This has been done precisely to facilitate machining with a cutter 1 mm in diameter, making the piece even easier to fabricate without resorting to different cutters of different radii. The key dimensions of the part are also indicated in Fig. 5 and reported in Table I and II. The radiating elements are spaced precisely 10 mm apart in both plane directions, which means one wavelength at the central operating frequency (30 GHz). In the YZ plane, the null produced in that direction by the slot prevents any grating lobe. Admittedly, in the XZ plane, the omnidirectional slot pattern is more sensitive to the possible appearance of grating lobes when extending this design to higher gain antennas. As a practical solution, as demonstrated in [17], it is sufficient to raise the sidewalls and create a waffle grid, which improves the field's uniformity and sensibly reduces the grating lobes.

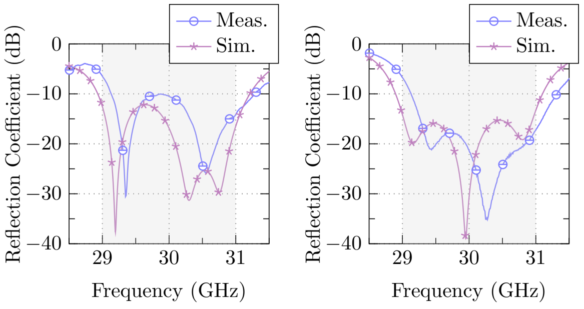
Finally, Fig. 6 shows the mean electric field distribution along with the distribution network in the left subfigure. It is important to underline that despite the air gap, the field is very well confined and propagates through the half-mode waveguide. In fact, the competitive advantage of the half-waveguide design on a bed of nails over, for example, two rectangular half-waveguides facing each other, lies in its capability to ride out an eventual air gap. The figure on the right shows how, for the same air gap, electric field would leak significantly, which would spoil the performance of the same antenna manufactured with conventional waveguides. In fact, very few screws are needed here to assemble the parts since the contact between them is neither necessary nor critical. For instance, in [18] it can be seen how a sub-array of 4×4 elements fed by an E-plane waveguide network to suppress wave leakage requires up to 9 screws instead of the four used here. Also, note that the referred antenna works at a lower frequency, being the assembly less sensitive to any inaccuracy.

B. Prototype 2

A second prototype is presented now to complete the validation of the concept (Fig. 7). This second antenna is also composed of two single pieces of aluminum. The lower part is the same as the one used in antenna 1. In addition, this prototype 2 presents some improvements concerning prototype 1, as it has been made more compact to test the branch-to-branch isolation produced by the bed of nails. The radiating element spacing in the Y-direction is now reduced to a distance of 8.5 mm, i.e., $0.85\lambda_0$ for the central operating frequency. Likewise, the groove is 1.5 mm wide and 4.5 mm deep in this case. To achieve the same phase and amplitude in all elements, the feeding network makes use of a chandelier topology, similar to the previous one, but more compact. The key points of this grid are the transformer (M_1=4 mm and M_2=1.6 mm) in the first divider together with a central wedge (wedge$_a$) and successive wedges in the subsequent power dividers (wedge$_b$ and wedge$_c$). The wedges' dimensions are provided in Table II. Finally, to couple the field from the feeding network to the upper slot, the position of the aperture is adjusted concerning the short of the waveguide (M_3=0.9 mm). In this way, it is no longer necessary to use a cavity as in case 1, and a more compact network is achieved. Even more important than the consideration of bringing closer the elements in a single layer grid is the validation of the idea of the semi-mode waveguide in GW. The distribution networks are different, the bends and splitters are located at different points on the pins grid, and despite using the same bed of nails, the assembly works correctly. All this will be verified in the following section dedicated to experimental results.

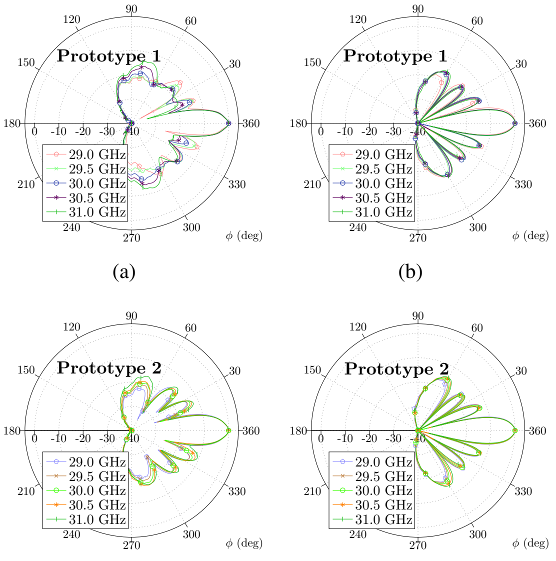
III. EXPERIMENTAL VALIDATION

The results of the measurement campaign carried out on the manufactured prototypes are shown below. First, Fig. **??** shows different images showing various views of the manufactured pieces. The total manufacturing cost of all the parts has been



(a) (b)

Fig. 8. Measured reflection coefficient of the prototypes 1 (left) and 2 (right).



(a) (b) (c) (d)

Fig. 9. Measured normalized radiation pattern. Prototype 1: (a) XZ-plane and (b) YZ-plane. Prototype 2: (c) XZ-plane and (d) YZ-plane.

500€. This remarkable low manufacturing cost is primarily due to the low fabrication difficulty, already detailed above.

Fig. 8 shows the measured reflection coefficient for both prototypes. The antenna matching meets the expected requirements. It can be seen how there has been a slight shift of the working band to the right. The same behavior is observed for both antennas. Since both antennas share the same bed of nails, which is the one containing the input port, the most consistent reason is due to some slight manufacturing deviation in the input port. Despite that, both antennas show good measured matching, below −10 dB over almost the entire bandwidth of interest (29 GHz to 31 GHz). The two main radiation pattern cuts of both antennas are shown in polar coordinates in Fig. 9. The measurements obtained show excellent stability of the patterns over the whole band, with symmetrical patterns and side lobe levels consistent with uniform illumination. Finally, the measured values of gain and radiation efficiency for both prototypes are presented in Table III. High radiation efficiency values stand out thanks to the low loss provided by the all-aluminum antenna structure. In short, these prototypes validate the HM-GGW as a novel and simple way to feed all-metal arrays, and are perfectly scalable to higher gain antennas just by concatenating successive subarrays in a stepwise manner.

TABLE IV
QUALITATIVE COMPARISON OF ANTENNAS USING AN RW, SUBSTRATE-BASED GW, GGW, OR HM-GGW FEED NETWORK.

-	Complexity	Fab. Cost	Assembly	Losses
RW	low	low	hard	low
μstrip-GW	low	low	medium-low	medium
GGW	medium	medium	low	low
HM-GGW	low	medium-low	low	low

TABLE V
COMPARISON PERFORMANCE OF CORPORATE-FEED KA-BAND ARRAYS

Ref.	Tech.	Layers	Elements	BW	Antenna eff.
[18]	RW	3	8×8	36%	≈60%
[19]	SIW-GW	6	4×4	35%	≈25%
[20]	Printed-RGW	4	8×8	16%	≈42%
This work	HM-GGW	2	4×4	7%	≈90%

IV. DISCUSSION ON THE ADVANTAGES OF HM-GGW OVER GGW

Countless successful examples of distribution networks for GW array antennas have been reported in the literature. Still, in single-layer arrays, the pursuit of very compact networks for very low-profile antennas, only composed of a couple of pieces, involves dealing with network branches that are very close to each other. This is clearly shown in Fig. 7(c). Since the bed of nails follows a regular grid, the groove forming the distribution network does not necessarily fit that grid. As a result, some nails can lose their square shape, becoming wedges or even turn into fragile corners. Being able to separate the network construction from the bed of nails achieves at least two relevant goals. Firstly, the network design is tremendously simplified since it is enough to design it separately as a conventional waveguide, disregarding the nail design. In addition, if two branches are very close to each other, it is not necessary to place tiny pins between them to isolate those two branches. The HIS in the opposite side will play that role with a uniform grid free from further complexity. Finally, Table IV provides a qualitative comparison of technology characteristics when dealing with RW, substrate-based GW, GGW, or HM-GGW feeding networks. Table V compares the performance of recent corporate fed antenna arrays. Few layers required along with its low difficulty of assembly and the high radiation efficiency achieved, is what stands out of the proposed design.

V. CONCLUSIONS

A straightforward method that greatly facilitates the antenna design and fabrication in Gap Waveguide technology is presented by using half-mode GGW. GW's strength in the mm-wave band has always been its ability to confine the field within non-contacting pieces, but it is penalized for its long machining time due to its bed of nails. Here it is demonstrated, by fabricating two Ka-band prototypes with satisfactory experimental results, how this fact can be alleviated thanks to the use of HM-GGW and it opens a new horizon for cheaper and easier fabrication in GW.

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