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David Rene-Loxq, Olivier Lafond, Mohamed Himdi, Langis Roy, Farhan Ghaffar. Reconfigurable half-mode SIW antenna using uniaxial field programmable microwave substrate structure. *IEEE Transactions on Antennas and Propagation*, 2022, 70 (11), pp.11103 - 11108. 10.1109/TAP.2022.3195559 . hal-03841048

**HAL Id: hal-03841048**

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Submitted on 15 Dec 2022

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# Communication

## Reconfigurable half-mode SIW antenna using uniaxial field programmable microwave substrate structure

David René--Loxq, Olivier Lafond, Mohamed Himdi, Langis Roy, Farhan Ghaffar

**Abstract**—This paper presents the design and implementation of a beam steerable leaky wave antenna based on integrated electronic devices (varactor diodes). The design uses a half-mode substrate integrated waveguide (HMSIW) where the short circuited wall or PEC boundary is realized with field programmable microwave substrate (FPMS) based unit cells. By virtue of placing integrated varactor diodes in these unit cells, the wave number and the phase shift of the propagating signal can be controlled. This allows a beam steering of  $25^\circ$  for a fixed center frequency. Furthermore, control of the varactor bias voltages allows a fixed beam direction over a wide frequency bandwidth. Excellent agreement can be observed between the simulated and measured results, validating the first ever FPMS based reconfigurable antenna design.

**Index Terms**—Beam steering, Leaky wave antennas, varactors, HMSIW technology

### I. INTRODUCTION

Leaky wave antennas (LWAs) have long been used for applications where the radiated beam is steered with frequency [1]. Such antennas can be a low-cost alternative to traditional phased arrays. A broad overview of LWAs operating principles, including the incorporation of active circuits, is given in [2]. Since LWAs belong to the class of traveling wave antennas, a convenient and popular approach to their implementation is via modified waveguides [3]. With the introduction of substrate integrated waveguide (SIW) technology [4], a new platform for the design of such antennas has become available. SIW is well suited to the realization of LWAs [5] due to its ease of integration with active devices. Recently, a novel LWA having radiating slots along its length and integrated PIN diodes, has been reported for 5G applications [6]. Such a design provides proof-of-concept for efficient smart antenna systems that can meet the needs of modern wireless applications.

The advent of half-mode substrate integrated waveguide (HMSIW) has opened new avenues for the implementation of LWAs [7], [8]. The HMSIW employs only one half of the SIW structure, yet provides the same performance for frequencies above the cut-off frequency of the waveguide. Moreover, as the HMSIW is open on one side, it can be designed to radiate

close to the cut-off frequency, as demonstrated in [9] for a millimeter-wave application. This gives HMSIW an advantage over conventional SIW, which is the basis for its use in this work.

As is well known, the beam direction of a LWA varies with signal frequency and many designs exploit this property to achieve beam scanning. For a LWA, the main beam direction  $\theta_m$  is given by [3]:

$$\theta_m = \sin^{-1} \frac{\beta}{k_0} \quad (1)$$

Where  $k_0$  is the free space wave number, and  $\beta$  is the phase constant. As  $\beta/k_0$  changes with frequency, the direction of the main beam also varies. To overcome this dependency on frequency, some solutions have been proposed to obtain a main beam in the broadside direction regardless of frequency, as in [10]. Such a solution provides wideband performance LWA with a fixed beam direction. This may be useful in certain wireless applications, but the main advantage of a LWA is its ability to scan the beam. Thus, it is desirable to preserve LWA beam steering while operating at only one frequency. To achieve this capability, the phase constant  $\beta$  needs to be controlled by other means than changing the frequency. In [11], it has been shown that by loading the free edge of HMSIW with lumped capacitors, the phase constant can be adjusted in a defined manner, thereby providing control of the direction of maximum radiation. More recently, in [12], by loading the free radiating edge with patches and by opening/shorting the patch to ground with a PIN diode switch, the LWA design achieves beam steering at a single frequency. The work of [12] was furthered in [13], where the HMSIW structure is excited on each port, yielding a wider angular scan range at the center frequency. Thus, a few single-frequency LWA designs with beam steering capability have been reported; however, relatively little work has been done on the topic.

In this paper, the authors propose a novel active HMSIW LWA design that provides beam steering at a fixed frequency. The proposed design has the additional feature of operating over a wide frequency range (7.5 to 9.25 GHz) with a fixed direction of radiation. This effectively combines two antenna functions in a single design. To achieve such results, the radiating free edge is not disturbed; rather, the PEC via walls are loaded by varactor diodes to modulate the antenna characteristics (each via hole is integrated within a unit cell structure). The design of the unit cell structure is inspired from the field programmable microwave substrate (FPMS) first presented in [14]. Through adjustment of the varactor bias

This work was supported by the French/Canadian (ANR/NSERC) project RWC-FPMS between 2019 and 2022. It was also supported in part by the European Union through the European Regional Development Fund.

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voltages, the effective width of the HMSIW - and hence its propagation constant - is artificially modified. The prototype is realized using a single-layer PCB (Rogers 5880 substrate). Simulated and measured results at X-band are in good agreement, validating the design concept.

## II. PRINCIPLE

The operating principle of an SIW antenna is explained eloquently in [15] where the effective width of the guide is used to steer the antenna beam at a fixed center frequency. To be able to control the effective width, the authors used two rows of via holes on each side of the waveguide. One row is directly connected to the ground and the other row (the inner row) is connected to ground through PIN diodes. Thus, by controlling the on and off states of the diode, the authors have shown control of the effective width of the SIW structure. The antenna presented here will follow essentially the same principle to electronically modulate the effective width of the waveguide. However, the principle employed in this work is different from the one reported in [15]. Despite using multiple via rows and PIN diodes, the proposed antenna design uses only one via row where each via is connected to the ground through a varactor diode. In fact, the idea of using varactor diode comes from a novel technology known as the field programmable microwave substrate (FPMS) [14], where the artificial substrate consists of unit cells that can be reconfigured to have a range of positive or negative dielectric constant. The unit cell itself can be viewed as a metal parallel plate structure where the two plates are connected through a via hole and a varactor diode. By virtue of these varactor diodes, the dielectric constant of the material can be varied to control the propagating wave.

The HMSIW with integrated FPMS unit cells proposed in this work is shown in Fig. 1. The simulated results show the magnitude of the propagating E-field inside the guide. In the unbiased state (0V) at 8GHz (Fig. 1(a)), the via wall loaded by varactor diodes acts as a quasi-normal metallic wall, thus allowing the propagation of  $TE_{0.5,0}$  mode. This state corresponds to the case of a waveguide with the maximum effective width. By changing the voltage the distance between two maxima of the electric field in the waveguide is modified, which means that the propagation constant is changed and the effective width of the waveguide is reduced (Fig. 1(b)). In the extreme case of varactor bias (12V) (Fig. 1(c)), the effective size of the waveguide becomes too small for the  $TE_{0.5,0}$  mode to propagate at 8GHz, and most of the power is reflected. This physical explanation of the waveguide performance is evident from the simulated S-parameters shown in Fig. 2. Depending on the state of the varactor diodes, the cut off frequency of the waveguide structure can be controlled, as is clear from  $S_{21}$  plot in Fig. 2. These results validate the operating principle of the waveguide structure loaded with FPMS unit cells.

## III. DESIGN AND RESULTS

The antenna is a half-mode substrate integrated waveguide (HMSIW) structure of 79.5 mm length ( $l$ ) and 7.25 mm width (a). It is realized on Rogers RT5880 substrate with a thickness

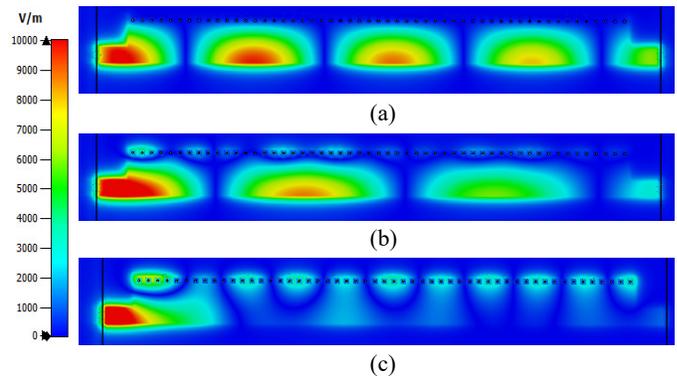


Fig. 1. Electric field distributions along the waveguide ( $z = 0.25$  mm) at 8GHz for three different voltages: (a) 0 V, (b) 4.7 V and (c) 12 V

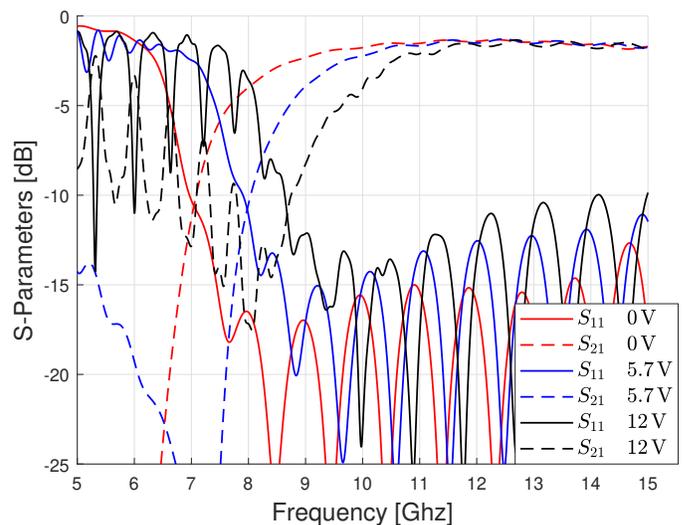


Fig. 2. Simulated S-Parameters for 3 different bias

of 0.787 mm, dielectric constant  $\epsilon_r = 2.2$  and loss tangent of  $\tan\delta = 0.0009$ . The fabricated prototype of the HMSIW antenna is shown in Fig. 3. The conceptual image of the unit cells integrated along the PEC boundary of the antenna is illustrated in Fig. 3 (c) alongside a zoomed photograph of the actual structure. The diameter of each via is 0.3 mm ( $d$ ) and the spacing between vias ( $S$ ) is 1.5mm. Each via is connected to the ground through a MA46580-1209 Macom varactor diode (Beam lead). With the chosen dimensions, this antenna uses a total of 53 diodes, all biased with the same voltage at a time.

The varactor diode has been characterised in [16] and an equivalent RLC circuit (Fig. 4) has been used to explain its RF response. The equivalent circuit consists of a series combination of  $L = 0.105$  nH with an  $R = 2.2 \Omega$  along with a variable capacitor. The value of the capacitor can be ascertained using (2). As can be observed that the applied bias across the varactor controls the capacitance value and its resulting performance. This model is used in this work to carry out the full-wave simulations of the antenna design.

$$C(V) = \frac{C_0}{\left(1 + \frac{V}{V_0}\right)^\psi}, C_0 = 1.56 \text{ pF}, V_0 = 5.755 \text{ V}, \psi = 1.96 \quad (2)$$

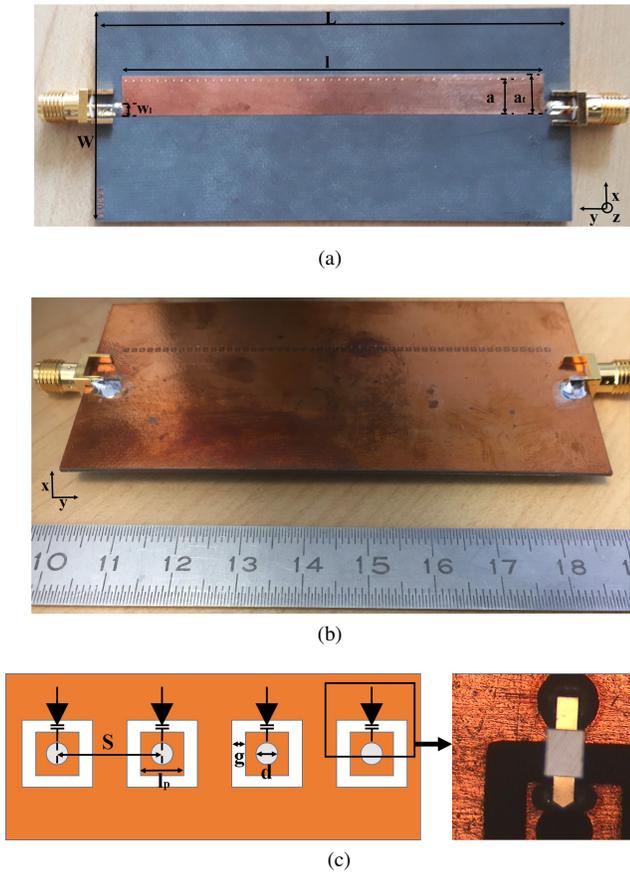


Fig. 3. Antenna prototype: (a) Top view,  $L = 89.5$  mm,  $W = 40$  mm,  $l = 79.5$  mm,  $a = 7.25$  mm,  $a_t = 8$  mm,  $w_l = 2.4$  mm, (b) bottom view and (c) Varactor placement,  $g = 0.2$  mm,  $d = 0.3$  mm,  $l_p = 0.6$  mm,  $S = 1.5$  mm

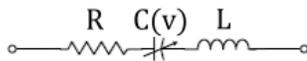


Fig. 4. Varactor diode equivalent RLC circuit

### A. Simulation results

The overall antenna has been simulated in CST Microwave Studio. The varactor diode of the FPMS unit cell is modeled by an RLC lumped element circuit with a variable capacitance. As mentioned above, the cut-off frequency changes with the varactor diodes' DC bias. The radiation pattern of the simulated antenna in H plane at 7.75 GHz is shown in Fig. 5. At this frequency, the antenna achieves a beam steering from  $18^\circ$  to  $45^\circ$  with gain varying from 6.7 dBi to 9 dBi. The maximum gain is obtained with the 5V configuration for an angle of  $32^\circ$ . It is noticeable that the extreme angles ( $18^\circ$  and  $45^\circ$ ) have the lowest gain which is expected. The  $18^\circ$  angle is obtained when the voltage is set at 8V. For this configuration, the return loss is 6 dB reducing the gain of the antenna. In fact, a higher bias voltage could provide a better steering range, however, this would reduce the overall gain of the antenna due to its poor impedance performance. On the other hand, for a steering angle of  $45^\circ$ , the bias voltage is set at 0 V. For this case, the gain of the antenna is still affected but not due to the mismatch of the antenna rather it is due to the transmission

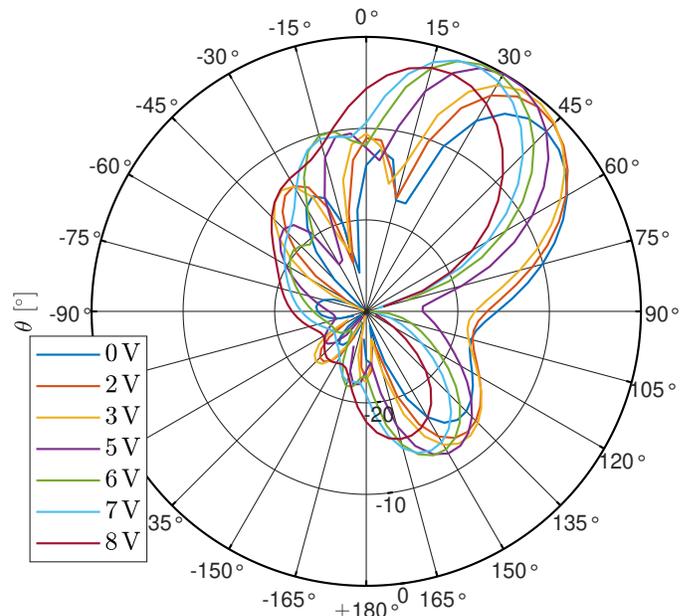


Fig. 5. Realized normalized gain at 7.75GHz in H-plane( $\Phi = 90^\circ$ ) for different bias

TABLE I  
IMPACT OF THE SIZE OF THE WAVEGUIDE ON THE PERFORMANCE OF THE ANTENNA AT 8 GHz

Size	number of Diodes	Beam steering	Maximum gain
79.5 mm ( $2.12 \lambda$ )	53	$18^\circ$ to $48^\circ$	9.3 dBi
150 mm ( $4 \lambda$ )	100	$28^\circ$ to $54^\circ$	11.9 dBi
225 mm ( $6 \lambda$ )	150	$29^\circ$ to $57^\circ$	13.2 dBi

of the power to the other port. This is evident from  $S_{21}$  of the antenna shown in Fig. 2. To improve the antenna gain and radiation performance, one can increase the size of the antenna. This phenomenon is illustrated in Table I, where longer antennas provide for better gain values. However, this complicates the practical handling of the antenna. Therefore, the authors kept the antenna size to 79.5 mm as it still provides the proof-of-concept. Note that this antenna has two input ports, so if the signal is exited on the second port, it leads to the same results but for beam varying from  $-18^\circ$  to  $-45^\circ$ .

The antenna radiates with a beamwidth of  $30^\circ$  in the H-plane. However, this value varies with the applied voltage. As the antenna beam is steered, its beamwidth is seen to increase in the H-plane. In E-plane the antenna beamwidth is between  $55^\circ$  and  $65^\circ$ . The cross polarization is below -15dB whatever the voltage configuration and the frequency. Thus, these result validate the effect of FPMS unit cell integration on the antenna radiation performance by steering the beam around the maximum gain value with acceptable radiation performance.

### B. Prototype results

The measured S-parameters of the antenna for 3 different bias voltages of the varactor diodes are shown in Fig. 6. The results are in good agreement with the simulated ones (Fig. 2) with two minor deviations. Firstly, a frequency shift

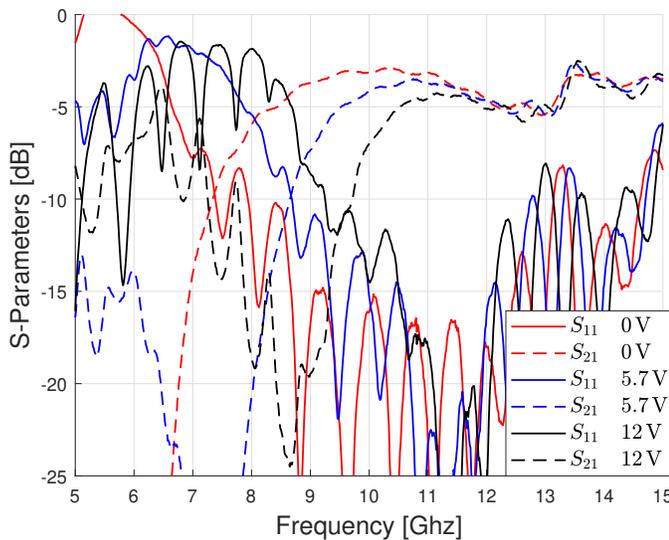


Fig. 6. Measured S-Parameters for 3 different bias

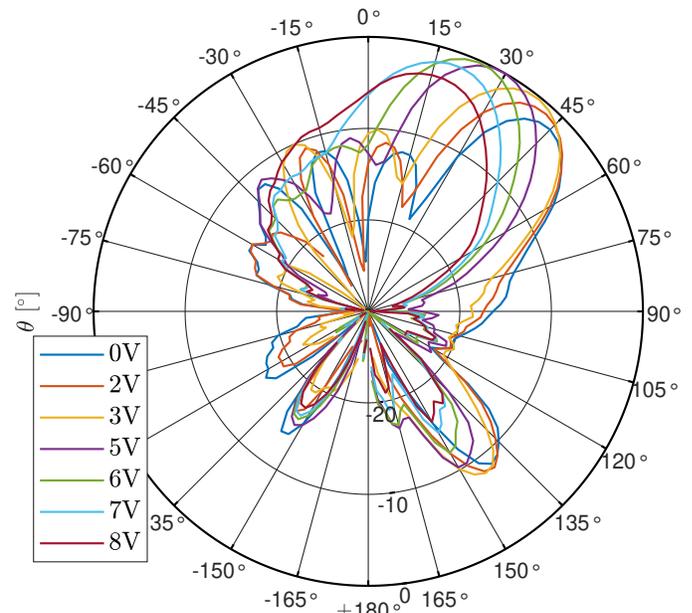


Fig. 8. Measured normalized gain at 8 GHz in H-plane ( $\Phi = 90^\circ$ ) for different bias

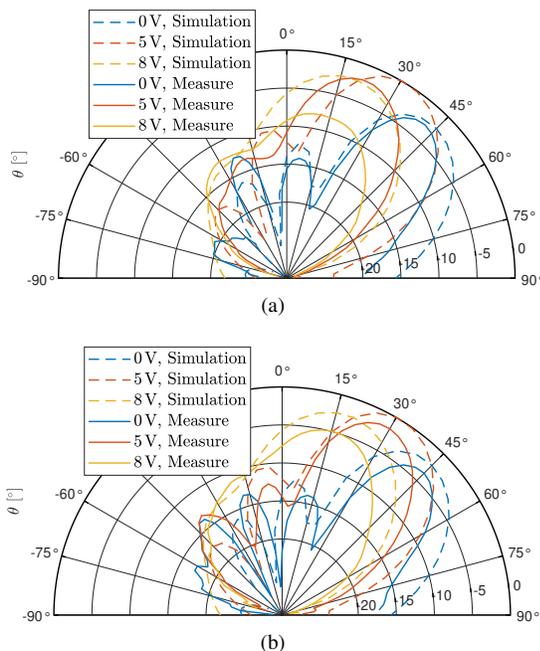


Fig. 7. Comparison between simulated and measured gain in H-plane for different bias: (a) both at 7.75 GHz and (b) simulated results are at 7.75 GHz and measured result are at 8 GHz taking into account the frequency shift

is observed between the simulated and measured results that changes with the applied bias. The range of this shift in the frequency is from 0.25 GHz to 0.5 GHz. This difference could come from multiple factors, like the connector used and the feeding with the DC bias tee, but also the fabrication process and the imperfect varactor model. It can also be observed that there is some discrepancy between simulated and measured results at higher frequency (above 12 GHz), but for these frequencies, the antenna is not designed to radiate well, thus it is not of any concern.

An important issue in the measured reflection coefficient ( $S_{11}$ ) of the antenna is that the antenna matching at 8 GHz is affected due to the biasing of the varactor diodes. This

is an anticipated response from a waveguide based LWA structure. Such a design radiates well close to the cut off frequency of the guide, which is the rationale for choosing 8 GHz as the frequency of interest. However, due to biasing of the varactor diodes this frequency shifts towards the higher bands as explained in section II. The resulting deterioration in the reflection coefficient has an effect on the overall gain of the antenna. Nonetheless, in this case the antenna did not incur a significant change in maximum gain due to the mismatch. Thus, as the first ever design using FPMS technology and delivering acceptable radiation performance, these results are presented without further optimization. In future antenna designs, a key objective will be to improve the impedance matching as a refinement to the design concept.

A comparison between the simulated and measured radiation patterns is presented in Fig. 7(a) at 7.75 GHz. However, as discussed in Fig. 6 that there is a slight frequency shift in the impedance measurements of the antenna prototype. Therefore, some deviation can be observed between the simulated and measured radiation patterns of Fig. 7(a). To present a better comparison, the simulated results at 7.75 GHz are plotted with the measured results at 8 GHz in Fig. 7(b). A much better correlation can be seen in this plot between the two sets of results. To provide the complete picture, measured radiation patterns at more bias points are included in Fig. 8. This prototype achieves a measured beam steering from  $18^\circ$  to  $45^\circ$  with the gain variation from 5.95 dBi to 7.55 dBi.

Generally, a good agreement can be observed between the two sets of results with some difference in the gain values. One observation is that the tilt angle  $18^\circ$  is achieved for the 7V configuration and not for the 8V configuration, like in simulation. This is due to the frequency shift that increases with the bias voltage. For the 8V configuration, the antenna prototype achieves a tilt angle of around  $15^\circ$  but the gain falls

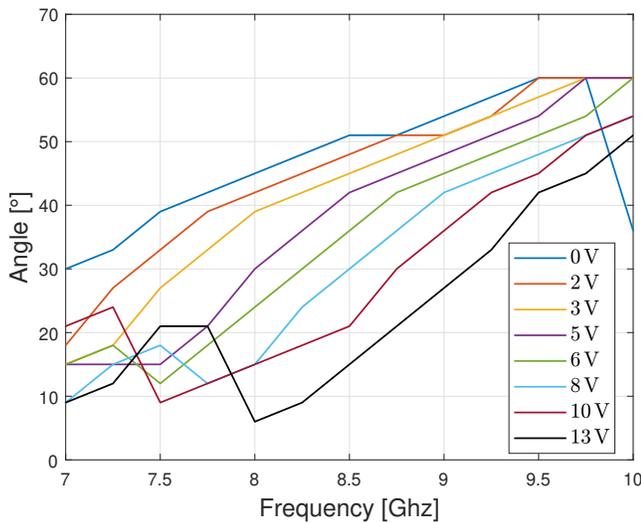


Fig. 9. Main beam angle for different configurations

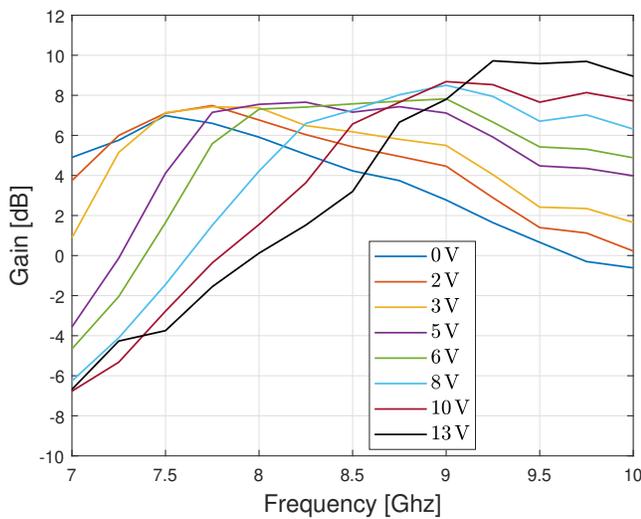


Fig. 10. Maximum measured gain for different configurations

to 4.22 dBi which is quite low as compared to the maximum antenna gain. Only a finite number of configurations are shown in the measurement, but as this antenna uses varactor diodes, it allows for continuous beam steering. Thus, the simulated and measured results clearly validate the effectiveness of this LWA design to provide beam steering at a fixed center frequency of the antenna.

### C. Fixed Beam over frequency

Another investigation carried out on this design is to achieve constant beam direction for different signal frequencies. This can be accomplished by properly modulating the antenna guide with the varactor diodes biased in a particular fashion. For this purpose, the antenna is characterized over a wide frequency bandwidth for different bias voltage. These result are illustrated in Fig. 9 and Fig. 10. The first of these two figures explains the variation of the main beam direction vs. bias voltage while the latter one shows the gain variation. By combining these two results appropriately, one can obtain a

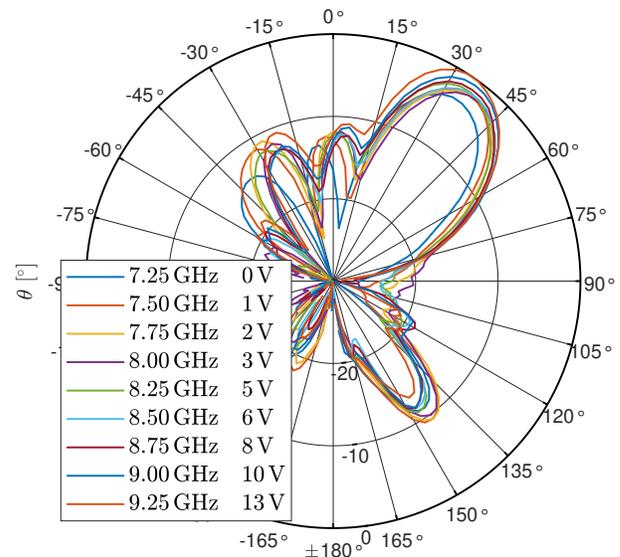


Fig. 11. Measured normalized gain for a fixed beam in H-plane ( $\Phi = 90^\circ$ ) at  $35^\circ \pm 2^\circ$  over frequency

constant direction of radiation over a frequency band. The proposed antenna is able to provide these results by carefully selecting the bias voltages for different center frequencies. The results are shown in Fig. 11 where a fixed beam at  $35^\circ \pm 2^\circ$  is radiated from the antenna at each frequency. The antenna gain varies from 7.13 dBi to 9.7 dBi, over 1.75 GHz of bandwidth between 7.5 GHz and 9.25 GHz. Different fixed angles between  $20^\circ$  and  $40^\circ$  can be achieved, but not always for exactly the same frequency bandwidth.

This is an interesting result which is derived from the proposed LWA design. The state-of-the art of LWAs usually shows one characteristic at a time. That is, either beam steering is achieved by varying the signal frequency or it is obtained at a single frequency.

Table II shows a comparison between this work and other papers reporting closely related antenna types. The main merits of this design are: 1) the first ever use of FPMS technology in an antenna design to provide the required tunability, 2) demonstration of dual purpose from a single design, where the antenna can be used to radiate in a single direction over a large bandwidth, or it can be employed at a single frequency to steer the beam over a considerable angular range, and 3) the length of the antenna reported in this paper is quite small compared to others with comparable gain.

## IV. CONCLUSION

In this paper, an electronic fixed-frequency beam-scanning LWA based on a HMSIW structure is presented. The beam-scanning property is achieved by electronically changing the effective width of the waveguide thanks to the addition of varactor diodes that are connected the ground plane to the wall of via holes. By changing the bias voltage of all the varactor diodes between 0 V and 13 V, the beam direction can be controlled. A continuous beam steering can be achieved at one fixed frequency, with the best case exhibiting beam steering from  $18^\circ$  to  $45^\circ$ . This antenna can also overcome the

TABLE II  
COMPARISON OF THE PRESENTED AND REPORTED FIXED-FREQUENCY BEAM-SCANNING LWAS

Ref.	Structure type	Operating frequencies (GHz)	Antenna length ( $\lambda$ )	Beam scanning range	Maximum gain (dBi)	Gain variation (dB)
[15]	SIW	5.2	6.1	23°	5.5	< 3
[17]	Corrugated microstrip line	5.5-5.8	6.2	45°	8	4.2
[18]	Groove Gap Waveguide	30-33	17	~85°	17	< 3
[19]	Slotted SIW and patches	5	4.6	125°	11.8	< 3
This work	Half mode SIW	8	2.12	27° (54° with 2 ports)	7.55	< 3

natural beam steering of a LWA with frequency to achieve a fixed beam angle over a wide frequency bandwidth up to 1.75 GHz band for an angle of 35°.

#### ACKNOWLEDGMENT

The authors warmly thank J. Sol (IETR) for his technical assistance for microwave measurements, and T. Batte (Photon) for his assistance in diodes mounting process.

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