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Reconfigurable SIW Antenna for Fixed Frequency Beam Scanning and 5G Applications

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ABSTRACT A novel reconfigurable slotted leaky-wave antenna (LWA) based on a substrate integrated waveguide (SIW) with a fixed-frequency beam-steering capability is presented in this paper. For improved compactness, the structure is based on a SIW technology with rectangular slots fed by associated coupling with plated-through holes (PTH). This represents a new feeding method for etched slots in SIW antennas. Each via is loaded with a pin diode on both sides front end of the waveguide. The pin diodes are tunable by adjusting the DC bias voltage, which results in beam scanning at a fixed frequency of around 27 GHz. Thus an electronically controlled steerable SIW antenna has been designed and experimentally verified that the radiation angle varies from -33° to $+33^\circ$.

INDEX TERMS Active antenna, Beam-scanning, feeding slots, reconfigurable antenna, slotted SIW, 5G applications.

I. INTRODUCTION

With the development of 5G communication, the 24.25–27.5 GHz is one of the most promising bands for 5G deployment. This is because SIW antennas and RF components are very easy to design and integrate at these frequencies due to their compact size. Also, they are suitable for array design for beam-scanning and other beam-forming systems in PCBs, without requiring a complex feeding network [1]–[4].

Beam steering is frequently needed in communication systems. For this reason, beam scanning antennas are proposed to decrease the problems associated with multipath fading and to increase energy efficiency in crowded environments [5].

To enhance the scanning range of planar phased arrays, multiple slotted beam-scanning SIW antennas have been proposed [6], [7], however they require feeding networks and phase shifters.

Recently many works on reconfigurable antennas and beam switching arrays [8], [9] for 5G mobile applications have been published. The 3D radiation pattern reconfigurable antenna (RPRA) [10] has the advantage of 3D spatial coverage at 28GHz, and it's suitable for the use as a sensor for

mobile terminals to automatically detect and connect with 5G base stations. Another suggestion, is a linearly polarized 6×6 element transmit-array [11] providing a beam steering range of 100° at 24.6 GHz. It's based on unit-cells providing a continuous electronically reconfigurable phase range of 360° by using varactor diodes as tunable elements. Fixed-frequency beam-steering can be achieved by using varactor diodes to realize an electronically controlled antenna [12]. Pin diodes are also used as binary switches, to change electronically the effective width of the SIW antenna. Then the propagation constant and the beam direction of the structure can be altered accordingly as presented in [13].

To suppress the open stop band for continuous beam scanning, an introduction of inductive post along with longitudinal slot is proposed in [14]. Otherwise, the plated-through holes are used differently, they are positioned beside the centered slots which can radiate the electromagnetic energy through the field disturbance caused by the PTH [15]. However, to our knowledge, there are few research works carried out about reconfigurable SIW antenna for fixed-frequency beam-scanning.

In this paper, a new radiation pattern reconfigurable SIW antenna is presented, which uses pin diodes as binary switches to control the phase shifts and position of

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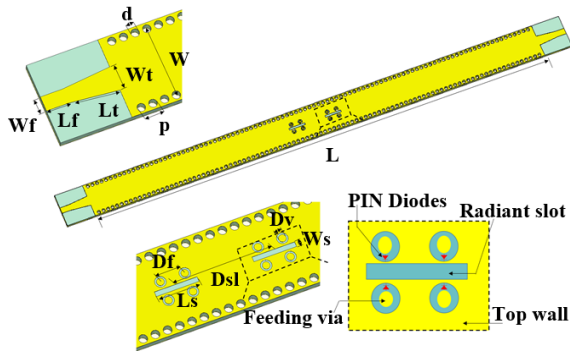


FIGURE 1. Details of the proposed SIW antenna array. $L = 100$ mm, $W = 6$ mm, $W_t = 2.1$ mm, $L_t = 4.2$ mm, $W_f = 1.27$ mm, $L_f = 1.9$ mm, $d = 0.7$ mm, $p = 1$ mm, $D_{sl} = 8$ mm, $L_s = 3.5$ mm, $W_s = 0.4$ mm, $D_f = 2$ mm, $D_v = 0.6$ mm.

feeding slots. This design is realized by introducing a new method for centered slots excitation, based on four coupling plated-through holes, which are inserted on each side of the slots. Each hole is directly connected to the ground plane and top wall as done in conventional SIW. This feeding method consists of connecting or disconnecting holes to the ground plane and top wall by pin diodes whose states can be changed between “ON” and “OFF” by bias voltage. Therefore, the phase shifts are controlled by altering the switches states, and the beam direction of the SIW antenna can be electronically steered by associating different slot configurations.

To validate the fundamental principle, a study of passive 2-element arrays is investigated. Then, the reconfigurable array is designed to achieve the electronic beam scanning ability. Measurements and simulations around 27 GHz of both passive and active antenna arrays will be presented and discussed. This solution is a promising candidate for 5G communications due to its merits of compact structure and convenient integration with differential integrated circuits.

II. ANTENNA DESIGN AND ANALYSIS

A. ANTENNA GEOMETRY

The scheme of the proposed slotted SIW structure is shown in Fig. 1. On the top surface, two centered slots are etched as radiation elements, the length of the slots L_s is about $0.44\lambda_g$ and the distance D_{sl} that separates the slots is equal to λ_g . At the outer corners of each slot are linked with four 0.9mm diameter-isolated plated-through holes, which are used as the feeding system. They are arranged to connect the top conductor and the ground as in conventional SIW, in order to separately control the switching of the slot feeds.

As shown in Fig. 1, four pin diodes are connected on each PTH for radiation pattern reconfigurability. The pin diodes are MA4AGBL912 from Macom with low series resistance of 4Ω , low capacitance of 28 fF, and an extremely fast switching speed of 5ns.

A microstrip to SIW transition with a length of $L_t + L_f$ and a width being linearly tapered from W_t to W_f was also designed to feed this antenna as illustrated in Fig. 1. Simulations are performed using CST microwave studio time

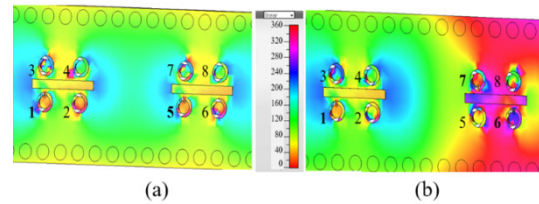


FIGURE 2. Two different slot array configurations with single and double excitation with their phase distribution at 26.75 GHz, for: (a) $\Delta\phi = 0^\circ$, (b) $\Delta\phi = 225^\circ$.

domain solver. The proposed leaky-wave antenna (LWA) is designed on a Roger 3003 substrate with a thickness of $h = 0.5$ mm, dielectric constant of $\epsilon_r = 3$ and a loss tangent of $\tan \delta = 0.0013$ at 27 GHz.

B. SLOT FEEDING: PLATED-THROUGH HOLES METHOD

This method of excitation using plated-through holes is inspired essentially from the classic feeding method based on probes inserted in the middle of the slots. The only difference is the number and location of the metalized via holes. The arrangement proposed in this article allows different slot excitations to control the EM wave. It is also an approach for introducing a fixed amount of phase shift in an SIW structure [16]. As shown in Fig. 1, each slot is fed by four metalized vias holes which disturb the incident signal flow, the spacing between these feeding vias was fixed at $\lambda_g/4$, and each vias position is used to feed the central slot with a given phase shift. In this design, the adjacent PTH are controlled by pin diodes, which in turn achieves the ability of switching in the SIW technology [17], by connecting or isolating the holes simultaneously from the ground plane and top wall of the waveguide by changing the states of the pin diodes. When the all diodes are turned OFF, there is no effect on the impedance of the SIW and the incident signal is transmitted. But in case of turning ON the diodes, the incident signal is reflected back by the PTH inside the waveguide channel. Thus, this allows a new feeding method for the centered slots by controlling the electrical phase shifts.

To control the electrical phase shifts $\Delta\phi$, different slot configurations fed by single or double excitation are studied. The electrical phase shifts 0° , 90° , 180° and 270° require a single PTH excitation slot, however, to reach $\Delta\phi = -45^\circ$, $+45^\circ$ and 225° two PTH excitations are required. As described in Fig. 2(a), the two centered slots have the same phase distribution with single PTH excitations (1 and 5), which mean no phase shift is introduced $\Delta\phi = 0^\circ$. While in Fig. 2(b), the first slot is excited by only the PTH number 1, but the second one is fed by double excitation (6 and 7). The phase distribution at each slot is different (represented by different colors), thus resulting in an overall $\Delta\phi$ of 225° . Therefore, by changing the vias feeding position we can control the phase of the elements of the array.

C. ANGULAR BEAM TILT PRINCIPLE

A detailed study of 2-element array configurations is carried out in order to study and validate this angular beam-tilting approach. Each centered slot is fed by at least one metalized

Configuration	Electrical phase shift
	$\downarrow + \downarrow + \lambda_g = 0^\circ$ $0^\circ + 0^\circ + 360^\circ = 0^\circ$
	$\downarrow + \downarrow + 0^\circ + 90^\circ = -45^\circ$ $0^\circ + 0^\circ + 0^\circ + -45^\circ = -45^\circ$
	$\downarrow + \downarrow + 45^\circ + 90^\circ = 45^\circ$ $0^\circ + 0^\circ + 45^\circ + 0^\circ = 45^\circ$
	$\downarrow + \downarrow + \lambda_g/2 = 90^\circ$ $0^\circ + 0^\circ + 180^\circ = 90^\circ$
	$\downarrow + \uparrow = 180^\circ$ $0^\circ + 180^\circ = 180^\circ$
	$\downarrow + \downarrow + 180^\circ + 225^\circ = 225^\circ$ $0^\circ + 180^\circ + 180^\circ + -90^\circ = 225^\circ$
	$\downarrow + \downarrow + 5\lambda_g/4 = 270^\circ$ $0^\circ + 0^\circ + 90^\circ \text{ in phase opposition} = 270^\circ$

FIGURE 3. Slot configurations and associated phase shifts.

via hole located directly on its edge. For controlling the desired angular beam tilts, the distance between central slots and feeding vias are kept constant, and the slot associations are determined based on the appropriate slot configurations as explained previously. To validate theoretical beam tilts, which can be approximately expressed by:

$$\theta_0 = -\arcsin(\Delta\phi * \lambda_0 \div 2\pi d) \quad (1)$$

where θ_0 refers to the theoretical beam tilt, $\Delta\phi$ is the electrical phase shift and d is the distance between the slots. Fig. 3 shows different association of slots, with all configurations fed by single or double excitation, to control the electrical phase shifts with an offset of 45° .

For $\Delta\phi = 180^\circ$, an association of two slots are fed differently and spaced by λ_g (i.e. corresponding to $\Delta\phi = 360^\circ$); the first one is fed from below, and the second from the top, to get the physical phase opposition which corresponds to $\Delta\phi = 180^\circ$. Furthermore, $\Delta\phi = 0^\circ$ is the association of two slots fed by the same way, from the bottom right side and always spaced by λ_g .

To obtain $\Delta\phi = 0^\circ, 90^\circ, 180^\circ$ and 270° , only one excitation per slot is required. To obtain $\Delta\phi = 45^\circ, -45^\circ$ and 225° , different associations based on double excitations are described in Fig. 3.

In designing a two slot array, the positions, number of excitations per slot, and the distance between feeding vias, changes the current distribution, and the resulting electrical phase shift. A single excitation allows a single electric field, against the field radiated by a double excitation which is a field resulting from the two excitations as depicted in Fig. 3. This proposal validates the principle of getting different beam-tilts, by essentially switching the slot associations, without using millimeter waves phase shifters. A recent study

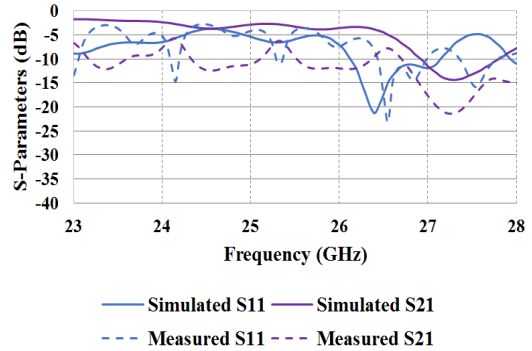


FIGURE 4. Simulated and measured S-Parameters of passive array with phase shift $+45^\circ$.

using the same fixed frequency beam scanning principle applied to a 2×6 array antenna operating in C-band was reported in [18], which demonstrates a beam-scanning range of 25° (from 34° to 59°). The main advantage of this work is that it's based on fewer radiating elements, and has a wider beam scanning range of 66° (from -33° to $+33^\circ$).

III. PASSIVE SIW ANTENNAS

Seven passive SIW antenna arrays (2×1) operating around 27 GHz are designed and fabricated, based on physical short circuit without using active components such as pin diodes or varactors, to test and validate the principle of design. S-parameters and radiation patterns are presented and discussed in detail.

A. S-PARAMETERS

Both measured and simulated S-parameters of passive array with a phase shift of $+45^\circ$ are reported in Fig. 4. It indicates that the slot arrays present a good matching with a measured $|S_{11}|$ over the frequency range from 26.25 GHz to 27.2 GHz.

The measured magnitude of S_{21} parameter was close to -11 dB at 26.75 GHz, while the simulated value is around -7.5 dB. This S_{21} difference can be due to the use of two Ka connectors, 1092-01A-6 [Southwest Microwave], with insertion losses around 0.8dB/connector around 27 GHz, and also measurement uncertainty (e.g. misconnection) that were not included in the simulation.

B. RADIATION PATTERNS

The simulated and measured radiation patterns of the seven passive arrays (2×1) configuration are shown in Fig. 5. All results have been verified at a fixed frequency of 26.75 GHz.

Figs. from 5(a) to 5(g) show the simulated and measured H plane (xz plane) far-field radiation patterns of the SIW antenna at 26.75 GHz. These patterns show that the beam can scan from -33° to $+33^\circ$ with a discrete offset of 8° , when the slot configurations are changed by isolating or bypassing the slot excitations. However, the LWA cannot radiate effectively when all PTH are isolated, because of the centered slots being not excited. Therefore, only the far-field patterns of the LWA fed with double excitations are provided in Fig. 5(b), 5(c) and 5(g) for directing the beam to $-8^\circ, +8^\circ$ and $+23^\circ$, respectively. Figs. 5(a), 5(d) to 5(f) show the

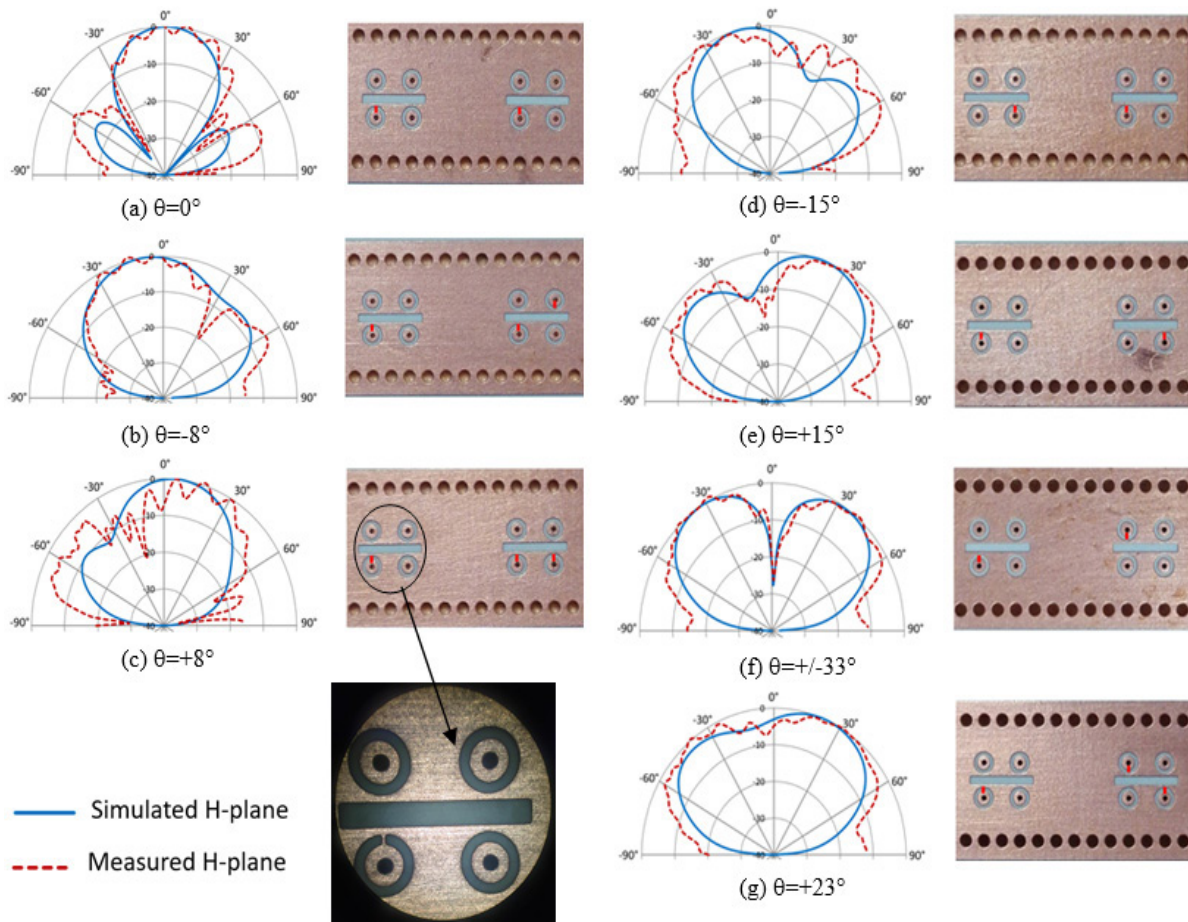


FIGURE 5. Simulated and measured H-plane of passive arrays with associated phase shifts at 26.75 GHz. a) $\Delta\phi = 0^\circ$, b) $\Delta\phi = 45^\circ$, c) $\Delta\phi = -45^\circ$, d) $\Delta\phi = 90^\circ$, e) $\Delta\phi = -90^\circ$, f) $\Delta\phi = 180^\circ$, g) $\Delta\phi = 225^\circ$.

far-field radiation patterns of the H plane at 26.75 GHz fed with single excitation per slot. These patterns show that the beam can shift from 0° to $-/+15^\circ$ and $-/+33^\circ$, which correspond to $\Delta\phi = 0^\circ, +/-90^\circ$, and 180° respectively. As shown in Fig. 6, the directivity level is about 8-9 dBi for almost all configurations, but the gain depends on the adaptation (the maximum gain is 7 dBi).

Due to the delay and the limited number of elements, about half of the energy is lost on port 2 with a radiation efficiency ranging from 30% to 65%.

It worth mentioning that the electric fields of the radiated waves are parallel to y-axis, because the proposed LWA is uniform in geometry and the radiation pattern is mainly generated by the slots fed by PTH. The cross-components are not described in Fig. 5, because of their level (below -14 dBi) for all the configurations, which is acceptable for this type of antenna.

Reasonable agreement is obtained between simulated and measured results although Ka connectors have not been taken into account in the simulation which can cause some additional diffraction.

These passive antennas are designed only to validate the basic principle. This will be the basis of a compact and reconfigurable antenna design solution, which will be proposed in the next section.

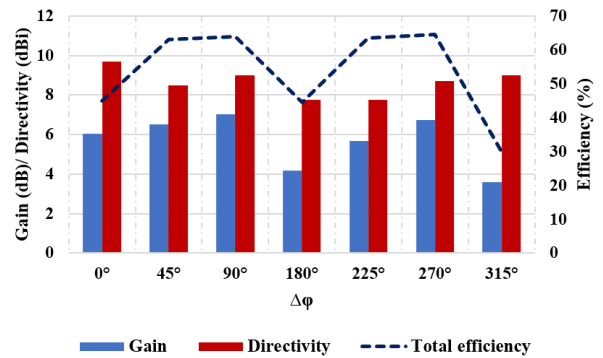


FIGURE 6. Directivity and Gain levels for different passive 2×1 SIW antenna arrays with the radiation efficiency curve at 26.75 GHz.

IV. PROPOSED RECONFIGURABLE SIW ANTENNA

A. BIASING CIRCUIT

As illustrated in Fig. 7, the radiating elements are located on the lateral face, whereas, the biasing circuit is located on the rear face.

The facility of integration of active components is one of the advantages of SIW technology. By using the two faces of the structure, the upper face which contains the radiating elements; each slot has four excitation vias crossing the structure in height. Each PTH is loaded with a pair of pin diodes from the top and bottom, which also means that each

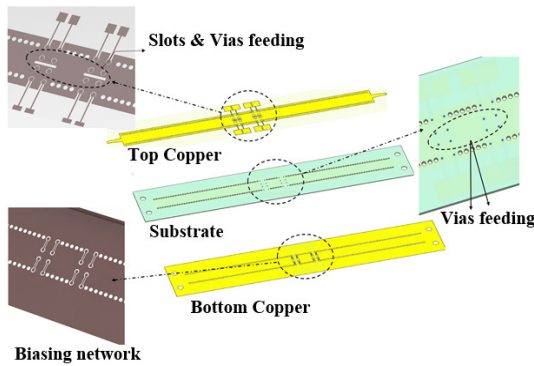


FIGURE 7. Exploded view of the proposed reconfigurable 2 × 1 SIW antenna array.

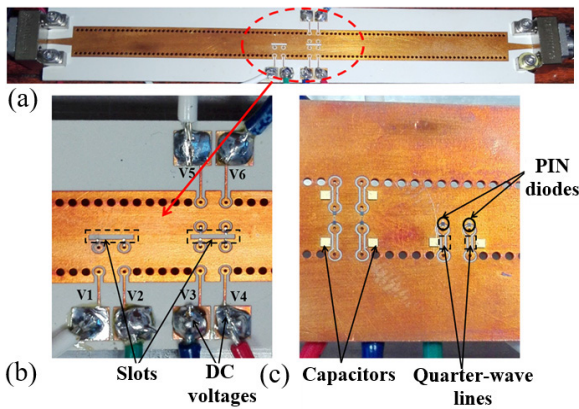


FIGURE 8. Photograph of the fabricated array antenna. (a) Prototype overview. (b) Front view. (c) Back view.

pin diode located in the lower face is polarized by a bias voltage V_i ($i = 1, 2 \dots 6$) as depicted in Fig. 8. The DC supply is connected directly through the conventional holes of the SIW structure. They are connected to the feeding vias by quarter wave-lines on the lower face to feed the pin diodes by coupling on both layers. The ground is taken directly from the lower face which contains the biasing circuit with one coupling capacitor SLC “single layer capacitor” and quarter wave line for each pair of pin diodes, these lines are short-circuited via the grounded capacitors, and return an open circuit to isolate the RF signal from the biasing circuit. This solution aims to ensure the compactness and minimizing the influence of the active components on the antenna radiation. To validate the presented design strategy, as depicted in Fig. 8, an LWA based on SIW technology for beam scanning at fixed frequency is fabricated and measured. The S-parameters of the proposed 2 × 1 array are simulated using CST Microwave studio and measured by the vector network analyzer “Keysight technologies N5222A”.

B. S-PARAMETERS

The measured and simulated S-parameters are shown in Fig. 9. Simulated and measured reflection coefficients magnitude are lower than -12 dB from 26.2 GHz to 27.3 GHz. The radiation efficiency of this antenna varies between 60% and 94%, depending on the chosen excitation configurations. For the case of the slotted array with $\Delta\phi = 270^\circ$ as shown in

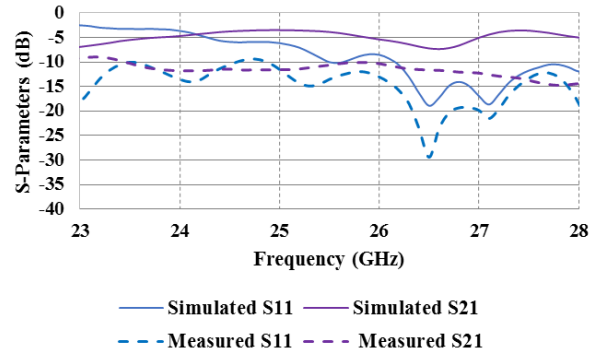


FIGURE 9. Simulated and measured S-Parameters of array configuration with phase shift 270°.

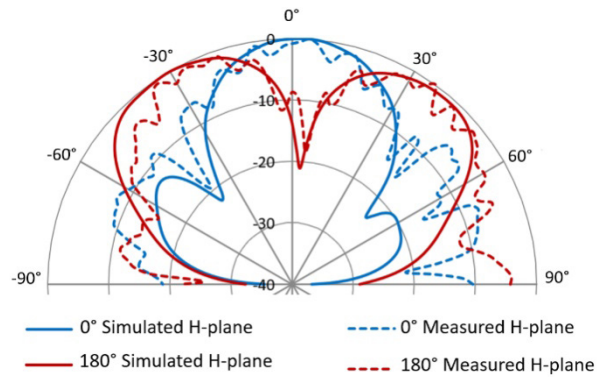


FIGURE 10. Simulated and measured radiation patterns of reconfigurable SIW antenna arrays at 27.25 GHz for $\Delta\phi = 0^\circ$ and $\Delta\phi = 180^\circ$.

Fig. 9, the measured radiation efficiency exceeds 90% with $|S21| = -12.86$ dB at 27.25 GHz.

The measured and simulated results of reflection and transmission coefficients are in good agreement. A matching impedance corresponding to magnitude of $|S11| < -10$ dB around 27 GHz is obtained. The discrepancy between the simulated and measured results is probably due to the integration of the biasing circuit which is not taken into account in the simulation.

C. RADIATION PATTERNS

Two array configurations, corresponding to $\Delta\phi = 0^\circ$ and $\Delta\phi = 180^\circ$, are selected as an example to see the efficiency of the fabricated antenna.

Fig. 10 represents the simulated and measured far-field radiation patterns of the H plane, which correspond to $\Delta\phi = 0^\circ$ and $\Delta\phi = 180^\circ$. These patterns show that the beam can scan 0° and $\pm 33^\circ$, respectively at 27.25 GHz.

Measurements have a good agreement with the simulations. A small shift in operating frequency of 0.5GHz is noticed between the passive and active antennas, this may be due to the integration of the active components, but even this new operating frequency is fine for the application.

V. CONCLUSION

A fixed-frequency beam-scanning reconfigurable LWA based on SIW structure was presented at an operating frequency of around 27 GHz. The ability to beam-scan is achieved by

exciting the slot configurations electrically, fed with plated-through holes (PTH). The SIW is designed with two slots fed by plated-through holes technology, and via feeding are connected to the ground plane and top wall through binary switches. By switching the pin diode states “low loss or isolation” using respectively +10mA or 0V to ensure the bias conditions; the array configuration and the corresponding beam direction can be changed electronically. Finally, different passive antenna prototypes are simulated and measured to validate this principle, based only on physical short circuits instead of using pin diodes for controlling the array configurations. Verified experimentally, the beam can be steered from -33° to $+33^\circ$ in discrete steps of 8° . The directivity can be improved by increasing the number of radiating elements.

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