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A Digital SIW-Slot Antenna Array

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ABSTRACT

The future satellite platform and 5G communication systems place high demands on antennas, in which the antenna should offer low-cost, lightweight, electronically steerable features. In this paper, the design of a digital slot antenna element based on substrate integrated waveguide (SIW) is proposed. The slot antenna element is realized by implementing PIN diodes across the gaps on both sides of the pad in the center of the slot antenna, to provide the switching freedom of the slot antenna element between radiating and non-radiating states. Besides, radial decoupling stubs are introduced into the bias line so as to reduce the leakage of the energy in the SIW structure. Applying a series of on/off states to the diodes produces various radiation patterns, thus wide range scanning is possible supposing that enough array elements are equipped. Finally, a digital SIW-slot array composed of 8 by 4 elements with tunable field programmable gate array (FPGA) circuits are fabricated and measured. The measured results validate the reconfigurable characteristics for the radiation pattern of the proposed digital SIW-slot antenna array without heavy engineering of phase shifter in conventional antenna arrays.

Introduction

Typically, traditional phased arrays can achieve ±50° cone scanning with the cost of the decrease of gain, except that, active reflection coefficient also deteriorates because of the element mutual coupling[1,2]. Moreover, phase shifters and T/R modules further increase volume and manufacturing costs[3–5], which makes traditional phased arrays difficult for applying to the mass market.

To overcome those drawbacks of traditional phased arrays, various types of electronically reconfigurable reflectarrays[6–9] have been reported. In these cases, reflecting elements forms the planar reflectarray aperture and a horn antenna is usually used for feeding. Reflecting elements in Ref.[6,7] contain liquid crystal, whose dielectric constant changes in different bias voltage, while diodes are equipped in[8,9]. All these methods could change the elements' reflection phase with variable bias voltage, thus realizing reconfigurable beam. Nevertheless, the distance between feed antenna and reflector arrays is considerable, and it is difficult to integrate them.

In recent years, dynamic metasurface antennas (DMAs) developed rapidly and applied in satellite communication[10,11], synthetic aperture radar[12–14], coding metasurfaces[15], metasurface imager[16] and so on. The traditional DMA is composed of a planar array with many tunable resonant elements evenly placed at equal intervals and fed by the TE10 mode wave propagating in a rectangular waveguide beneath the elements[10]. Compared with the reflectarrays, their feed structures are integrated with radiated antenna elements, which makes the whole structure more compact. Within this structure, each element influences the amplitude and phase of guided wave at each position, and with discrete-dipole approximation (DDA)[17–19], it is possible in search of good control patterns.

In these studies, complementary electric LC (cELC) resonators were generally adopted as the radiation elements. For instance, Ref.[20] presents a tunable cELC resonator integrated into a microstrip line, where PIN diodes are introduced to control the on and off characteristic of each cELC element. Though the metamaterial elements indeed reduce the size of array, for example, element spacing is only one fifth of a wavelength in Ref.[11]. However, the entire radiation efficiency is relatively low such as Ref.[13].

Differing from aforementioned, we use digital SIW-slot antenna with relatively high radiation efficiency as the radiation element and investigate the performance of switched beam in the case of array. As the carrier of the radiation elements, the SIW is generally used in the area of planar array antenna. If the radiation elements of the antenna are the slot type, the antenna can be considered as the SIW-slot antenna. Each radiation element can be turned on or off through integrating PIN diodes.

And the main lobe direction of the antenna is varied with different permutation of on/off status of each radiation element, and this process is also the realization of beam scanning. In short, the antenna in our work can be considered as a kind of digital SIW-slot antenna. This paper is organized as follows. Section II describes the design process of the tunable SIW-slot antenna array in detail. Section III presents the fabrication and measurement results of prototype with FPGA circuits and devices. Finally, conclusions are drawn in Section IV.

The Process Of Antenna Element Design Based On SIW

First of all, a SIW structure (shown in Fig 1a) is designed with reference to Ref.[21]. Then, a SIW-based four elements slot array is constructed in which the PIN diodes are introduced to guarantee each element can be switched between radiating and non-radiating states. Finally, a digital SIW-slot array composed of 8 by 4 elements is established, where radial decoupling stubs are utilized to prevent energy from leaking to the FPGA circuits and devices.

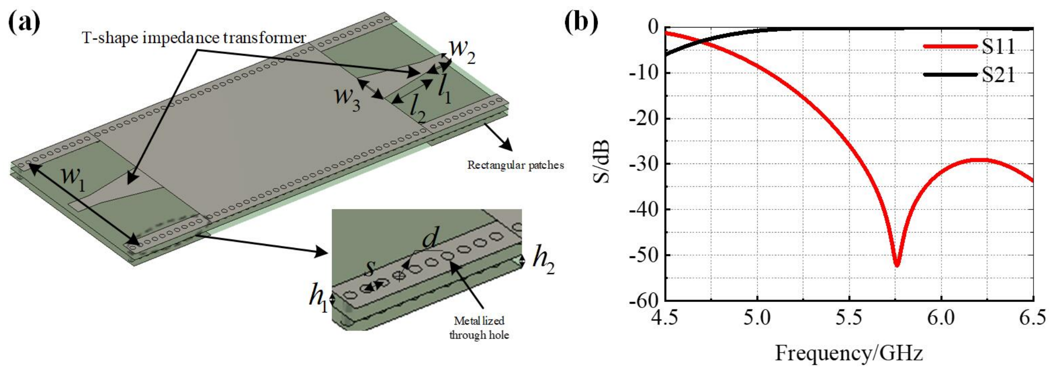

Figure 1. (a) The sketch of a SIW structure. Some key parameters (length in mm) are: h_1=0.762, h_2=0.762, w_1=17.6, w_2=1.7, w_3=4.4, l_1=2, l_2=7, s=1, d=0.3. (b) Scattering parameters of the SIW structure.

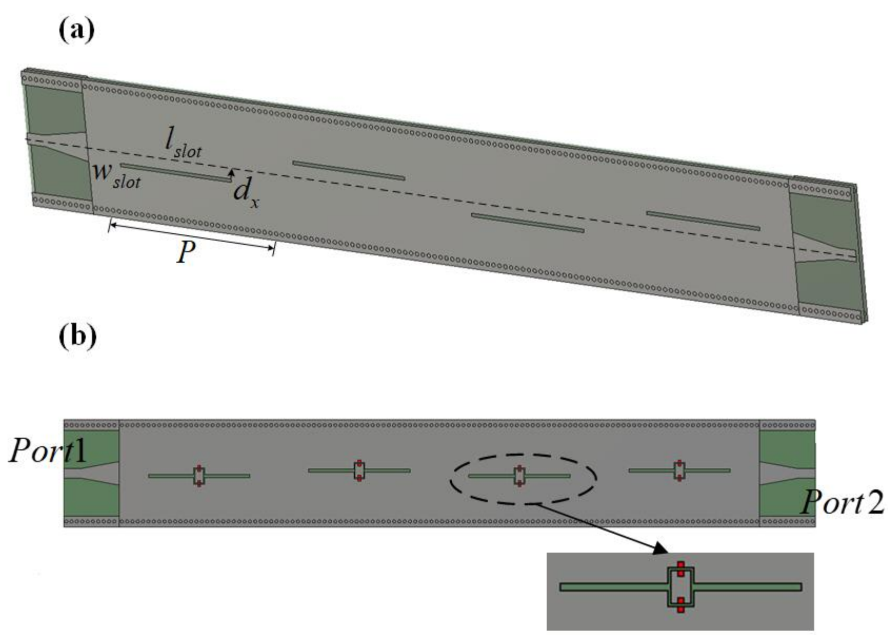

Figure 2. (a) The general view of a SIW-based slot antenna without on/off characteristics. Some optimized key parameters (length in mm) are: w_slot=0.5, l_slot=18.4, d_x=0.5, P=30. (b) SIW-based slot array with ideal on-off characteristics.

Design of a SIW structure

In this subsection, a SIW structure with microstrip-to-SIW transition is optimized (see in Fig 1a), where two Roger 4350B dielectric plates ($\varepsilon_r = 3.66, \tan\delta = 0.0037$) are adopted, serving as support for SIW and tunable circuits and devices respectively, and they are laminated together with a piece of prepreg. In addition, rectangular patches are printed on the back of the multilayer substrate, which is connected to the SIW structure via metallic through holes. Fig 1b is the simulated results of the SIW structure, which shows satisfactory matching performance and insertion loss in entire WiFi-5G band.

Four element slot array

Sequentially, a SIW-based slot array with four identical elements is constructed for the convenience of optimization and quick validation. The performance of SIW slot array[22] could be dependently adjusted through several dimensions shown in Fig 2a and the optimization procedure for the radiation efficiency is applied, mainly about the positions of the slot, to achieve the good performance in desired frequency band.

Then, lumped resistors are used to simply imitate the on-off performance of the PIN diodes which are connected across the pads. These resistors are modeled as $R = 10^9\Omega$ and 0Ω to coarsely simulate on and off state of PIN diodes respectively. The simulated performance of the four elements slot array shown in Fig 2b are plotted in Fig 3, where the diodes are in their reverse and forward bias states. It is noted that the slots in Fig 4 are different from those in Fig 3 because the pad of diodes (the red parts shown in Fig 2b) is necessary in experiments, and these pads are nearly no effect on performance of the slot elements. It is seen that when all diodes are in off state, S21 reaches the lowest value at 5.8GHz, meaning that most of the energy radiates through the slots. On the other hand, S21 magnitude is almost 0dB which indicates that the slot array is in the cut-off state when all diodes are in on state. That is to say, when a bias voltage is applied to the PIN diodes in the fabricated device (see the following), the resonance of the shorted slot shifts to higher frequency, thus in-band radiation blocking property is realized, which indicates the realization of digital slot element.

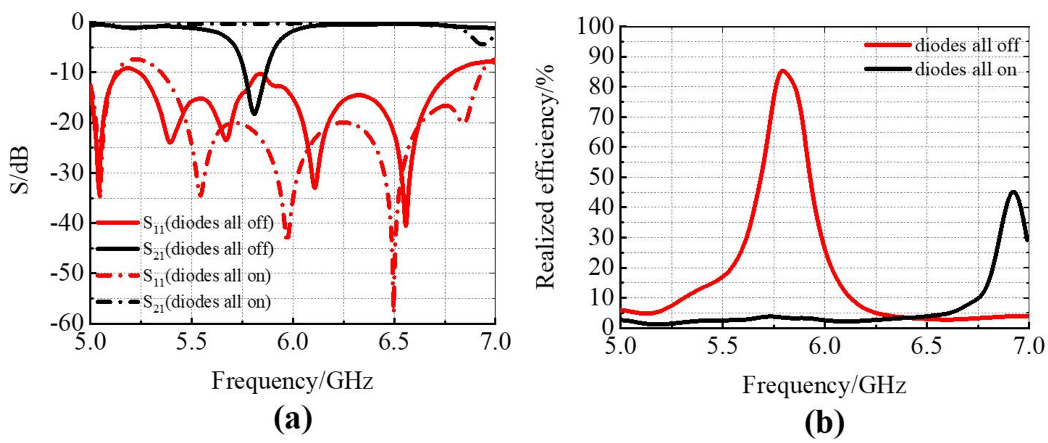

Figure 3. Simulated performance of the designed SIW-based slot antenna (four slot elements) with diodes (All on means diodes are in the on state, all off indicates the opposite) (a) Scattering parameters. (b) Realized radiation efficiency.

Tunable SIW-slot antenna array

On the basis of the above design, DC bias lines are introduced to apply voltage to the diodes, and they consist of radial decoupling stubs and metallic vias, as shown in Fig 4a & Fig 4b. Due to biasing diodes, the SIW antenna are designed as a multilayer structure in order to print the decoupling stubs on the bottom layer. The decoupling stubs are used to alleviate the leakage of electromagnetic energy. Metallic vias are introduced for the purpose of the electrical connection between the pads placed on the top layer and the decoupling stubs placed on the bottom layer.

As shown in Fig 4b, we set Port-3 at the upper site of bias line so as to test the performance of the decoupling. In Fig 4c, the magnitude of S31 represents the severity of energy leakage from SIW structure to the bias circuitry. It is evident that strong energy couples to the bias line without the stub, while the radial decoupling stub effectively reduces the leakage compared with the former. Therefore, our designed decoupling stub plays a role of ‘bias TEE’ between the RF source and the bias circuitry, and allow to integrate the tunable controlling circuits with each slot element and to realize element-specific electrical control for them.

In consideration of high isolation between excited port and radial decoupling stubs, and the fact that tunable circuits and devices are placed on the back of antenna which has ignorable effect for entire array, we expand the above 4 elements model

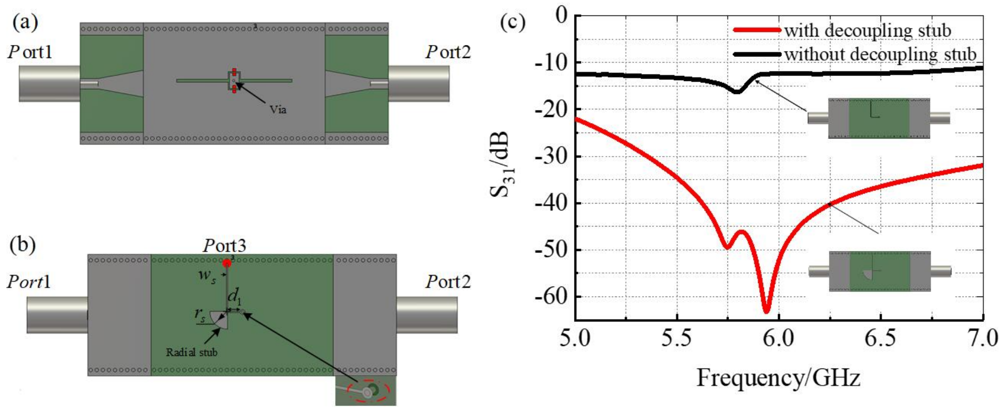

Figure 4. 2D sketch of slot element with the radial stub. (a) Front view. (b) Bottom view. Some optimized key parameters (length in mm) are: w_s=0.2, d_1=4, r_s=4.7. (c) Scattering parameters with ports 1 at end of the coaxial line and port 3 connected to the end of DC bias line with and without radial decoupling stub.

to a panel antenna structure which includes 8 by 4 elements and is shown in Fig 5. The SIW power dividers are applied and optimized for the integration with the slot array, the back of antenna exists many decoupling stubs, and each of them can individually control the on/off state of the corresponding slot antenna element by changing the bias voltage that is applied to the diodes.

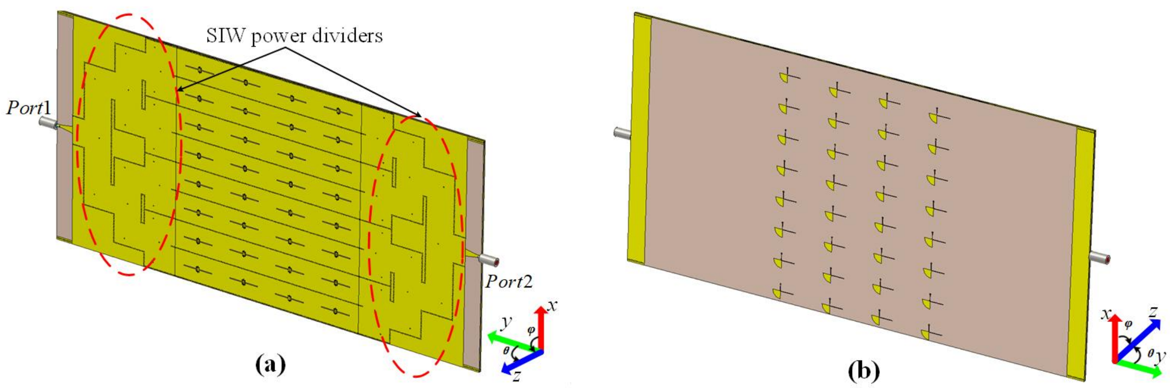

Figure 5. 3D schematic of SIW-slot antenna array. (a) Front view. (b) Bottom view.

The performance of proposed full structure array antenna is shown in Fig 6, it is clear that our antenna could operate around 5.8 GHz when diodes are in off state, while applying forward bias voltage to all diodes can stop energy radiating from the slots within operating band, it is similar with aforementioned four elements slot array. At the same time, the efficiency decreases on account of the power division network and dielectric loss. However, it is passable compared with the cases in Refs.[12–14].

Furthermore, the array can be tuned to generate various complex patterns once diverse bias voltages are applied to the diodes. Hence, we define 1/0 as high/low level, which correspond to the on/off state of diodes. For convenience's sake, 0/1 sequences change along the direction of propagation of the electromagnetic wave in the SIW structure and keep the same along the direction orthogonal to the above one, which is expressed more clearly in Fig 7a.

Here, three typical binary sequences are selected to simulate on CST Microwave Studio and the normalized radiation patterns at the center frequency of 5.8 GHz are plotted in Fig 7b, from which we can intuitively see the switched beams under different sequences, which acts like a phased array, though the lacking of the T/R modules.

Theoretically speaking, the sequence of '0101' or '0110' is corresponding larger spacing between two radiated elements compared with '0000' one, meaning that more lobes would emerge, which is consistent with the simulation results. A beam envelope plotted in green dot could be extracted from these patterns which represents the dynamic range for beam scanning that

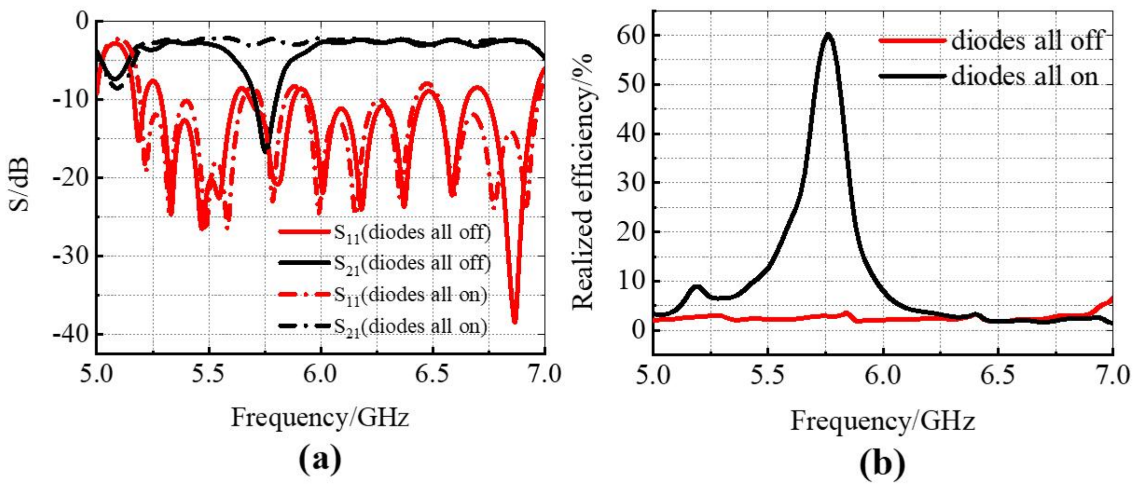

Figure 6. Simulated performance of the designed SIW-slot antenna array (8 by 4 slot elements) (a) Scattering parameters. (b) Realized radiation efficiency.

can be controlled under current sequences set. It is deduced that the binary sequences vary in two dimensions would introduce more degree of freedom, thus readily realizing arbitrary beam synthesis in a wide region of solid angle combined with DDA method as long as there are enough tunable elements according to Ref.[17].

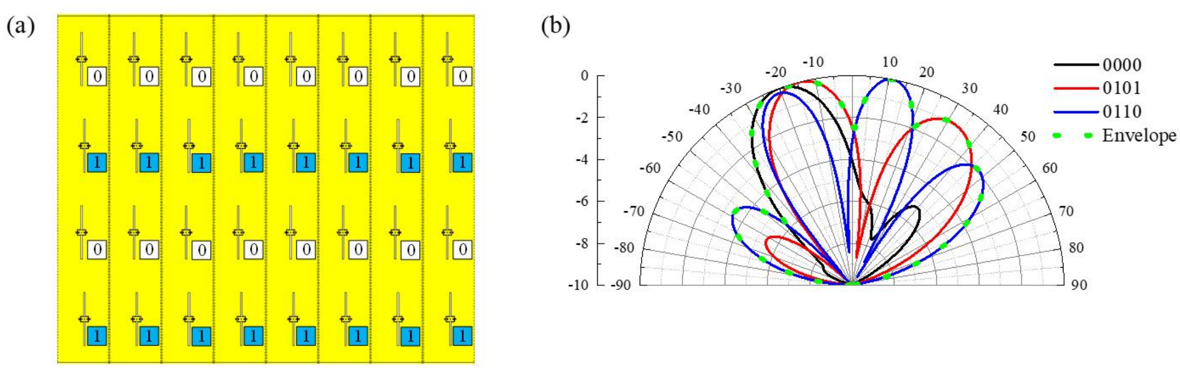

Figure 7. (a) Binary coding for bias voltage distributions ('0101' state as example). (b) Simulated far field normalized radiation patterns of the tunable designed SIW-slot antenna array in several on/off states of diodes ($\varphi = 90°$).

Fabrication And Measurement Results

As shown in Fig 8a & Fig 8b, the digital SIW-slot antenna array prototype with FPGA circuits was fabricated and assembled. The FPGA board is designed and customized for the antenna array, seeing the bottom of Fig 8b. Ultimately, they were connected electronically by welding the corresponding pads together with tin solder and fixed together by metal screws.

The far-field pattern measurements are conducted in an anechoic chamber. The measured antenna is fixed at a turntable to receive the far-field power, and a wideband ridged horn antenna operating over 1-16GHz is used for transmitting antenna. A personal computer is connected to the serial port on the FPGA circuit board, thus each element of array is individually controlled. Fig 8c shows the measured normalized radiation patterns of the fabricated antenna array in several states at the center frequency of 5.6 GHz. Though some discrepancies of center frequency occur due to diodes with complex equivalent circuit model, besides, the fabrication and assembly process also introduce some unknowns, experimental results still reach a good agreement with simulated results.

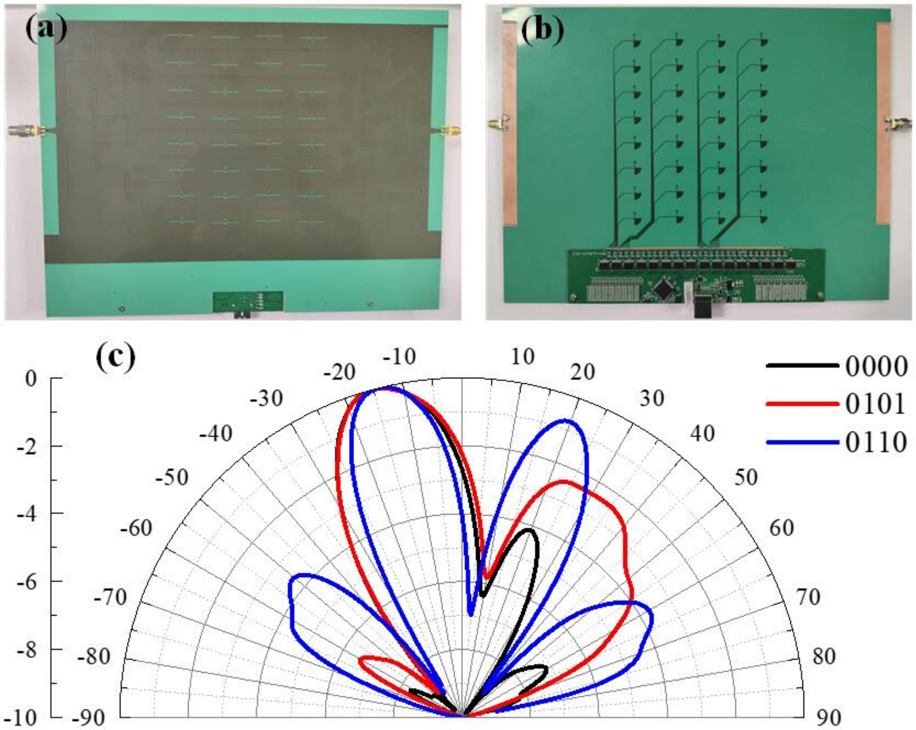

Figure 8. Overall view of the assembled tunable SIW-slot antenna array and the corresponding measured results. (a) Front view of the antenna.(b) Bottom view of the antenna. (c) Measured far field normalized radiation patterns of the tunable designed SIW-slot antenna array in several on-off states of diodes ($\varphi = 90°$).

Conclusion

Traditional phased arrays suffer from some disadvantage of heavy and expensive, in other words, some hardware such as phase shifters and T/R modules, thus usually applied to military rather than commercial use. This paper presents the design, fabrication and measurement of a digital SIW-slot antenna array with PIN diodes and tunable FPGA circuits, which can achieve considerable performance compared with phased arrays and mechanically scanned systems. Measured results verified that the arbitrary radiation patterns synthesis of the tunable SIW-slot array is potential. The performance can be improved through implementing larger array. Although only patterns in several on/off sequences of diodes are measured for proposed antenna, accurate and efficient methods for diverse, highly directive and complex radiation patterns can also be efficiently synthesized by applying the DDA method as mentioned above in larger array.

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Author contributions statement

C. H. and W. W. initiated the project; C. H. and X. Z. designed the device; H. L. and S. L. did the measurement and simulation; all authors analyzed the data; C. H., B. H., and H. L. wrote the manuscript.

Data availability

The datasets generated and/or analysed during the current study are not publicly available due to the patent filing but are available from the corresponding author on reasonable request.

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