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Frequency Reconfigurable Antenna Based on Substrate Integrated Waveguide for S-Band and C-Band Applications

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ABSTRACT A novel frequency reconfigurable antenna based on substrate integrated waveguide (SIW) for S-band and C-band applications is proposed. The antenna employs a SIW resonant cavity structure with a rectangular-ring slot and a long slit etched on the top surface. An extra via post is introduced to adjust the resonance frequency of the low-frequency mode independently without affecting the impedance matching of the high-frequency mode or decreasing the gain. Several PIN diodes are symmetrically placed along the rectangular-ring slot to attach the patch to the top surface. The working state of PIN diodes is controlled by a simplified bias structure. A prototype was fabricated and measurements show the proposed antenna has a bandwidth of 18 MHz in S-band low-frequency mode and 322 MHz in C-band high-frequency mode. Good agreements between the simulated and measured return losses, as well as radiation patterns, are observed.

INDEX TERMS Reconfigurable antenna, frequency-reconfigurable, substrate integrated waveguide, PIN diode.

I. INTRODUCTION

With the rapid development of wireless communication technology, multifunctional and miniaturized communication systems are widely used. Reconfigurable antennas, which can realize the functions of multiple antennas simultaneously, decrease the number of wireless devices and reduce the aperture area. Besides, compared with multiple frequency and wideband antennas, crosstalk from the neighboring bands is avoided in frequency reconfigurable antennas. It is also of great value to communication security. The reconfiguration is achieved by redistributing the antenna currents to alter the field distribution of the antenna's effective aperture [1]. The switches of reconfigurable antennas can be loaded on the radiator [2] or on the feed network [3]. For the former approach, the switches change the structures of the radiation elements and consequently the distribution of the surface current changes. For the latter strategy, the switches alter the effective radiator to achieve the reconfiguration of the functions. PIN diodes [2], [4], [5], varactors [6]–[8] or RF MEMS [9], are loaded at the appropriate position of the antenna, driven by bias circuit, to achieve the switching function. In [2], by using PIN diodes and U-shaped structure, the proposed antenna can operate at 3.24 GHz-4.03 GHz or 4.44 GHz-5.77 GHz when the ON-OFF of PIN diodes changes. The antenna proposed in [6] provides dual-band frequency reconfigurable characteristics by a reconfigurable microstrip feedline using varactor diodes. Most frequency reconfigurable antennas suffer from limited frequency range and complex bias circuits.

Substrate integrated waveguide(SIW), as a planar structure of waveguide, retains most of the advantages of the traditional waveguide, such as low loss, high Q factor and high power capacity. At the same time, it also has the advantages of low profile and easy integration to planar circuits. In recent years, it has been widely used in wireless communication systems, showing good performance in microwave and millimeter-wave applications. Recently reconfigurable antennas based on SIW structure has drawn increasing attention, including polarization [10], pattern [11] and frequency reconfigurable

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TABLE 1. Comparison of the performance of frequency reconfigurable antennas.

Ref.	Dimension(λ_0)	Bandwidth/Tuning range(GHz)	SFR	Gain(dBi)
[2]	0.78×0.78×0.1	3.24-4.03 4.44-5.77	1.78	6.86/8.14
[4]	0.50×0.45×0.01	3.04-5.89	1.93	3.1/4.04/4.41 4.43/4/39/4/44
[6]	0.52×0.26×0.007	1.3-2.6	2	2.48
[14]	0.33×0.24×0.02	six different states between 1.1-2.2	2	0/2.2/5
[15]	0.29×0.29×0.02	4.13-4.50	1.09	4
This work	0.42×0.42×0.01	2.406-2.424 5.683-6.005	2.50	6.74/2.37

[1] λ_0:wavelength of minimum frequency.
[2] Gain:Maximum gain in each mode.
[3] The bandwidth and the tuning range are provided for discrete and continuous tuning, respectively. The ratio between the maximal and minimal frequency in the switchable frequency range is denoted as SFR.

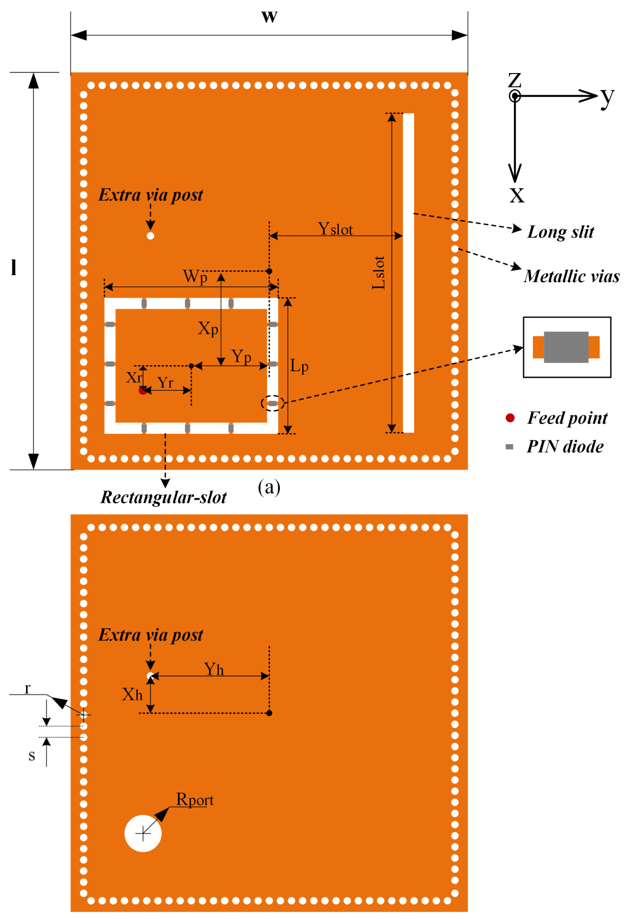

FIGURE 1. Configuration of the proposed antenna. (a) top view; (b) bottom view.

[12]–[15] antennas. A two-layer reconfigurable substrate integrated waveguide cavity-backed slot antenna is presented in [14]. By choosing different on and off combinations of PIN diodes, six different states in the range of 1.1 GHz-2.2 GHz are achieved, but the fabrication of a two-layer structure is more complicated than single layer one. A frequency reconfigurable SIW-interdigital capacitor (IDC) antenna is presented in [15]. Its resonant frequency varies from 4.13 GHz to 4.50 GHz by changing the bias voltages of the varactors on the slot of the IDC from 0 V to 36 V. However, it merely provides a 9% frequency tuning range.

In this article, a novel frequency reconfigurable antenna for S-band and C-band applications is proposed. It combines the form of microstrip and SIW slot antenna and can be applied to specific local area wireless communication. The antenna consists of a SIW cavity with a rectangular-ring slot and a long slit etched on the top surface. Several PIN diodes are symmetrically placed along the rectangular-ring slot and a coaxial cable is used to feed the antenna. An extra via post is introduced to slightly change the resonance frequency of the SIW cavity. Table.1 compares the figures of merit (including the dimensions, bandwidth, switchable frequency ratio(SFR), gain) of frequency reconfigurable antennas in the references. It can be seen that the proposed antenna is relatively small in size and a high SFR is achieved. The proposed single-layer structure is easy to fabricate and the bias structure of PIN diodes is simplified. Simulated and measured results show a dual-band frequency reconfiguration between S-band and C-band is achieved.

TABLE 2. Antenna dimensions(unit: mm).

Parameters	(mm)	Parameters	(mm)	Parameters	(mm)
w	53.5	Y_p	10.5	X_h	5
l	53.5	X_r	3.7	Y_h	18
W_p	23.4	Y_r	6.5	r	0.5
L_p	18.3	L_{slot}	45	s	1.5
X_p	12.5	Y_{slot}	18	R_{port}	2.5

II. DESIGN AND IMPLEMENTATION

A. PROPOSED ANTENNA STRUCTURE

The configuration of the proposed antenna is illustrated in Fig. 1. The proposed antenna is designed on a Rogers RT/duroid 5880 substrate with a thickness of 1.575 mm, a dielectric constant of 2.2 and a loss tangent of 0.0009. The top and bottom surfaces of the antenna are covered with a metal layer. A rectangular-ring slot and a long slit are etched on the top surface. The width of the slots is 1.5 mm. The rectangular slot divides a rectangular patch from the upper surface. Twelve PIN diodes (SMP1345 SC-79 from Skyworks) are symmetrically placed along the rectangular-ring slot to attach the patch to the upper surface. A 50Ω coaxial cable is used to feed the antenna, placed at the appropriate position below the rectangular patch. The dimensions of the antenna are exhibited in Table. 2.

The dual-band frequency switch of the proposed antenna is achieved by the reconfiguration of the radiation element. The size of the SIW cavity is determined by the target resonance frequency of low-frequency mode and the size of the rectangular patch is decided by the target frequency of high-frequency mode. Therefore, the dimensions of the antenna should be fixed at first. W_p and L_p are designed to ensure that the resonance frequency of the patch is 5.8 GHz and the calculation method is the same as that of the microstrip antenna. The size of the cavity is set using SIW technology. In order to limit the leakage of electromagnetic waves from the space between the adjacent holes, two conditions must be satisfied according to [12].

$$s/d < 2. \tag{1}$$

$$d/w < 0.2. \tag{2}$$

$$w_{eff} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w}. \tag{3}$$

$$l_{eff} = l - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{l}. \tag{4}$$

$$f_{101} = \frac{c}{2\sqrt{\varepsilon_r \mu_r}}\sqrt{\left(\frac{1}{w_{eff}}\right)^2 + \left(\frac{1}{l_{eff}}\right)^2}. \tag{5}$$

s, w, l and r are noted in Fig. 1 and d is twice of r. The equivalent method of a metal waveguide is often used to analyze the transmission characteristics of SIW. According to [13], the dimension of the SIW cavity is determined by (3)-(5). In (5), $f_{101} = 2.4$ GHz is the target frequency. c is the speed of light in a vacuum. ε_r and μ_r are the relative permittivity and permeability of the substrate, respectively. The length of the long slit is about λ/2, where λ is wavelength in medium.

Second, an extra via post is introduced to slightly adjust the resonance frequency of the SIW cavity. Next, twelve PIN diodes are placed along the rectangular-ring slot and a simplified bias circuit is used. Finally, the position of the coaxial cable is optimized to achieve a satisfactory reflection coefficient in two modes. Fig. 2 depicts the input impedance of the proposed antenna in high-frequency mode is tuned by optimizing X_r or Y_r. Fig. 3 shows X_p and Y_p influences the input impedance of the proposed antenna in low-frequency mode.

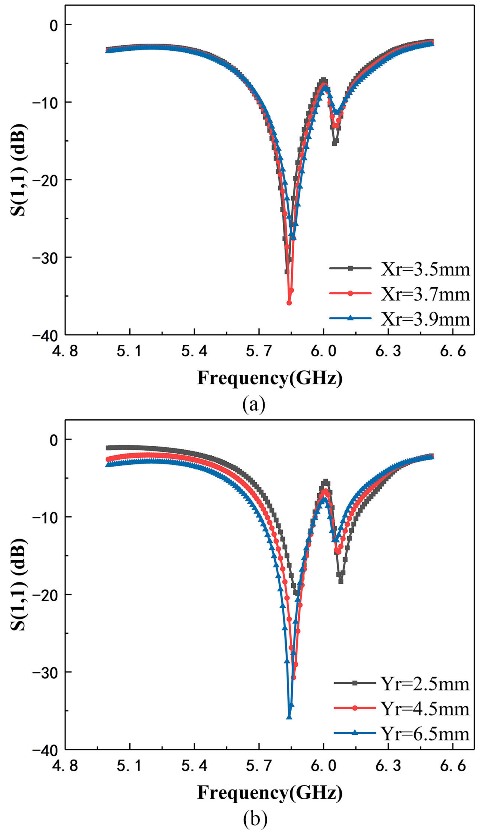

FIGURE 2. Simulated reflection coefficients in high-frequency mode for (a)3.5mm < X_r < 3.9mm (b)2.5mm < Y_r < 6.5mm.

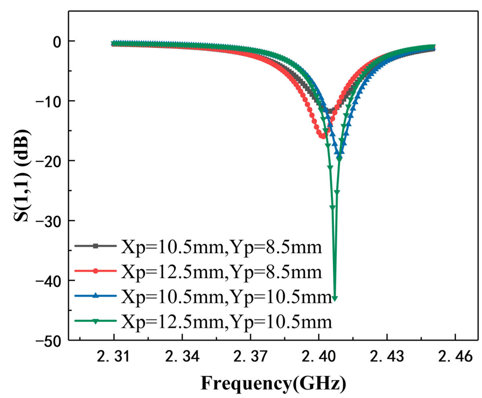

FIGURE 3. Simulated reflection coefficients in low-frequency mode for 10.5 mm < X_p < 12.5mm and 8.5mm < Y_p < 10.5mm.

B. EXTRA VIA POST TO ADJUST THE RESONANCE FREQUENCY

An extra via post is introduced to slightly adjust the resonance frequency by changing the distribution of the surface current. The current distribution of the top surface at 2.407 GHz with and without the proposed via post is exhibited in Fig. 4. Actually, the via post conducts a portion of the current into the ground plane, which reduces the equivalent electric length and increases the resonance frequency.

Generally, we increase the resonance frequency of an antenna by adjusting the electrical length. For the proposed antenna, we can use a smaller SIW cavity or decrease the length of the long slit(L_{slot}). However, if the cavity dimension of the proposed antenna is reduced, it is more difficult to achieve favorable matching in the two modes. Also, the location of the rectangular patch is closer to the lower-left corner of the top surface, which increases the difficulty of welding PIN diodes.

Besides, if we decrease the length of the long slit(L_{slot}), the resonance frequency of the antenna will increase, but the gain will decrease. In Fig. 5, the resonance frequency of the antenna with 37 mm L_{slot} is the same as the proposed antenna with the extra via post, but the gain of the former is less than the latter. In conclusion, an extra via post is introduced to independently adjust the resonance frequency

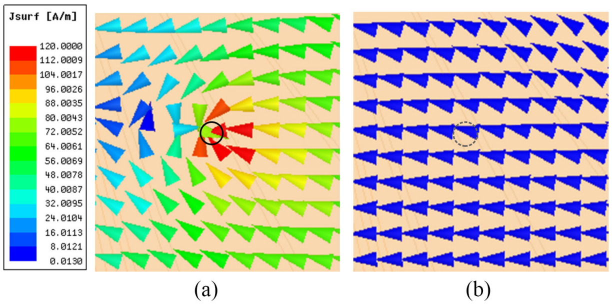

FIGURE 4. Current distribution of the top surface (a)with the via post (b)without the extra via post.

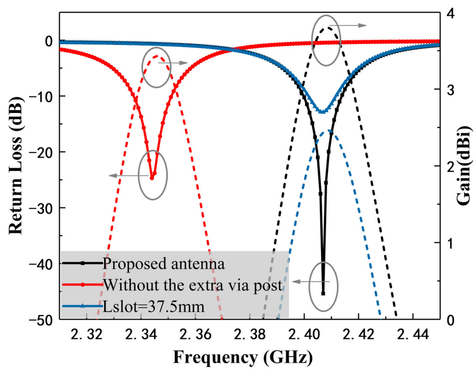

FIGURE 5. Simulated reflection coefficients and gain of the antennas (PIN diodes are turned on).

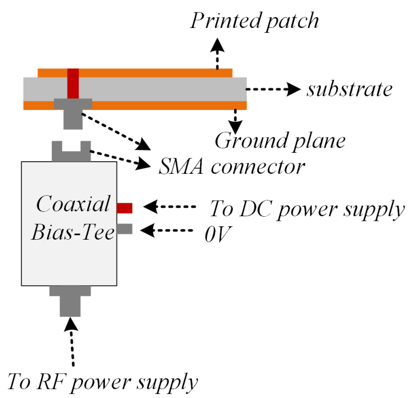

FIGURE 6. The side view of coaxial bias-tee, rectangular patch and lower portion.

of the low-frequency mode without affecting the impedance matching of the high-frequency mode or decreasing the gain.

C. FREQUENCY RECONFIGURATION MECHANISM

The rectangular patch is attached to the top surface of the proposed antenna through twelve PIN diodes. Coaxial bias-tee (ZFBT-4R2G-FT+ from Mini-Circuits) provides the bias voltage to the PIN diodes, so there is no need for a complicated bias circuit. The bias-tee has the characteristic of high isolation, low insertion loss below 6 GHz. The device

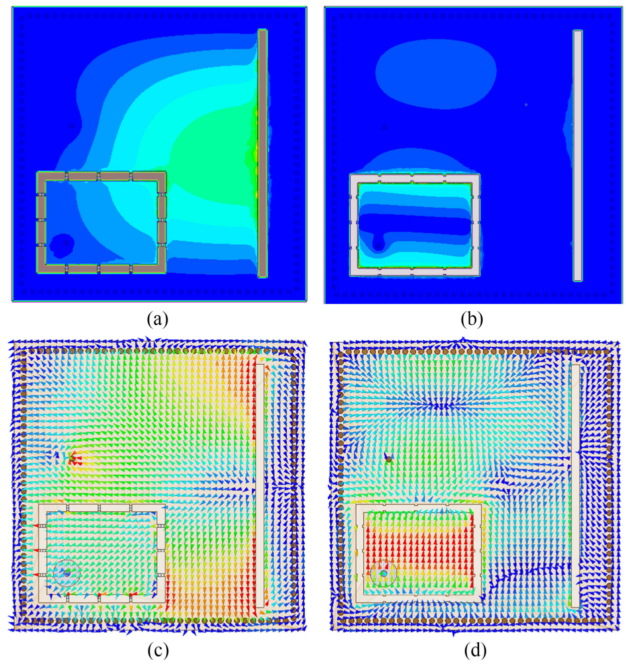

FIGURE 7. Magnitude of electric field distribution (a) in low-frequency mode (b) in high-frequency mode and vector of surface current (c) in low-frequency mode (d) in high-frequency mode.

is equipped with an isolation circuit inside, so DC and AC signal can be isolated [14].

Fig. 6 describes that the 50 Ω SMA connector of the bias-tee is connected to the 50 Ω coaxial cable, which can input AC and DC signal at the same time. Its AC and DC signals use a common ground. Two ports on its side are attached to DC power supply and ground, respectively. Thus, through the coaxial core, a positive polarity dc voltage is applied to the rectangular patch which is linked to the anode of PIN diodes. Meanwhile, the rest of the top surface connected to the cathode of PIN diodes is grounded through the vias near the boundary. A voltage drop of PIN diodes is created.

When the diodes are turned on, current can pass through the diodes, communicating between the rectangular patch and the metal surface. The antenna works around 2.4 GHz, radiating through the long slit. This working mode of the proposed antenna is defined as low-frequency mode. As shown in Fig. 7(a), the field distribution in low-frequency mode is similar to the TE101 mode of the SIW cavity. As illustrated in Fig. 7(c), the long slit cuts the surface current so the direction of the electric field is outward along the long slit. However, some components of the electric field are also distributed on the rectangular slit, which may cause energy loss at the target frequency. The working mode of the proposed antenna without PIN diodes is defined as high-frequency mode. In this mode, the rectangular patch is disconnected from the rest of the top surface. The antenna works around 5.8 GHz, radiating through the patch. Fig. 7(b) shows that the electric field distribution is TM10 mode. Besides, the vector of the electric field is parallel to the rectangular patch.

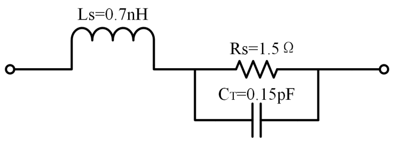

FIGURE 8. Equivalent circuit of the PIN diode.

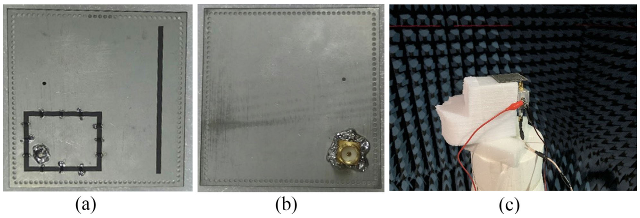

FIGURE 9. The fabricated prototype of the proposed antenna. (a) top view (b) bottom view and (c) radiation pattern measurements in an anechoic chamber.

D. ANTENNA DESIGN WITH PIN DIODES

According to the datasheet of SMP1345 [19], typical values of diodes are F = 100 MHz, I = 10 mA, R = 1.5 ohm, and dc forward bias is 0.89 V. The value of parasitic inductance Ls = 0.7 nH and junction capacitance $\mathbf{C_T}$ = 0.15 pF are also provided in the datasheet. The equivalent circuits of SMP1345 are also provided in [20]–[22]. Therefore, the equivalent circuit model of PIN circuit when turned on is depicted in Fig. 8. When PIN diodes are turned off, an ideal diodes-off model is used. Besides, according to the datasheet, the insertion loss of the PIN diode is −0.15dB at 2.4GHz when the value of forward current is 10 mA.

As Fig. 1 shows, the protruded metal parts on both sides are designed to leave the appropriate space for the diodes to be welded to the upper metal surface.

A tradeoff on the number of PIN diodes is discussed in [23]. Fewer diodes cannot effectively communicate the rectangular patch and other parts of the top surface. Thus a complete TE101 resonance mode cannot be formed. Besides, there is more energy leakage at the gap. More diodes will add complexity, cost and fabrication difficulty. Also, the loss of welding spots will increase. The number of diodes is chosen to be twelve eventually. Besides, PIN diodes are symmetrically evenly placed along the rectangular-ring slot to minimize the energy leakage at the gap.

III. EXPERIMENTAL RESULTS

The prototype of the proposed antenna is shown in Fig. 9. Both measured and simulated reflection coefficients in two modes are shown in Fig. 10. The measured result is in good agreement with the simulated result in high-frequency mode. The measured resonance frequency is 5.86 GHz and the measured 10-dB bandwidth is 322 MHz (5.683 GHz-6.005 GHz) as shown in Fig. 10. It can meet the bandwidth requirements for WLAN (5.725 GHz-5.825 GHz) application. When the two ports on the side of bias-tee are connected to 0.99 V positive voltage and ground respectively, the PIN diodes are turned on. In this mode, the measured result agrees well with the simulated result in the operating band. There is a slight out-of-band frequency deviation. The measured resonance frequency is 2.416 GHz and the antenna has a bandwidth of 18 MHz (2.406 GHz-2.424 GHz) as illustrated in Fig. 10(b). In this working mode, the prototype is a narrow-band antenna. It can also be seen from Fig. 10 that the out-of-band suppression is good in both two modes.

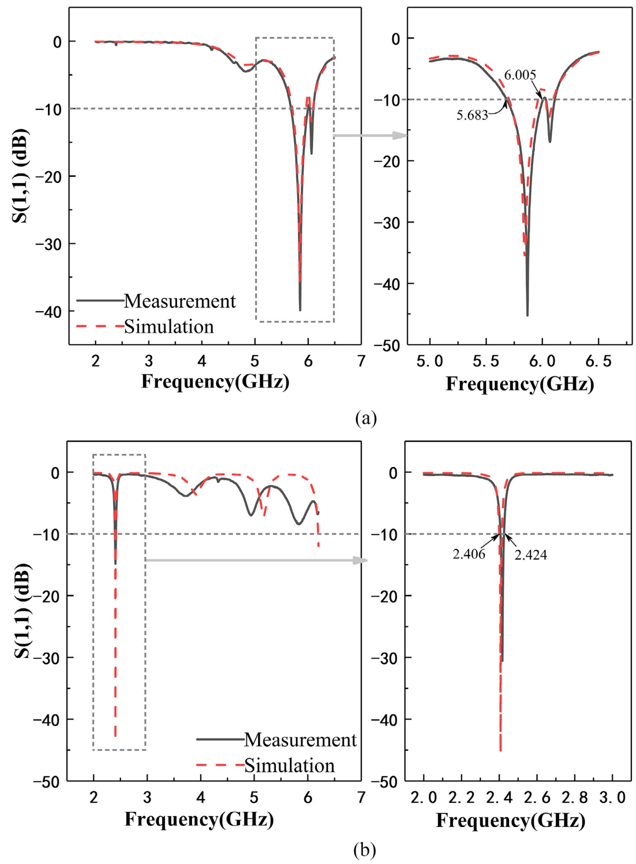

FIGURE 10. Measured and simulated reflection coefficients of the proposed antenna (a) in high-frequency mode; (b)in low-frequency mode.

Gain and radiation patterns of the proposed antenna were measured using the SATIMO system in an anechoic chamber as shown in Fig. 9(c). E plane(y-z plane) and H plane(x-z plane) far-field radiation patterns of the proposed antenna with PIN diodes turned on at 2.417 GHz are depicted in Fig. 11(a) and the results of proposed antenna with ideal diodes off at 5.84 GHz are shown in Fig. 11(b). Fig. 11(a) is measured with a bias voltage of 1.1 V. The measured and simulated results for both two modes agree well. In low-frequency band, the measured gain is approximately 1.26-2.37 dBi as shown in Fig. 11(c). As Fig. 11(d) shows, the measured gain is approximately 6.26-6.74 dBi in high-frequency band. As shown in Fig. 12, the radiation efficiency is 70-90% in high-frequency mode and 30-40% in low-frequency mode because of the insertion loss on PIN diodes.

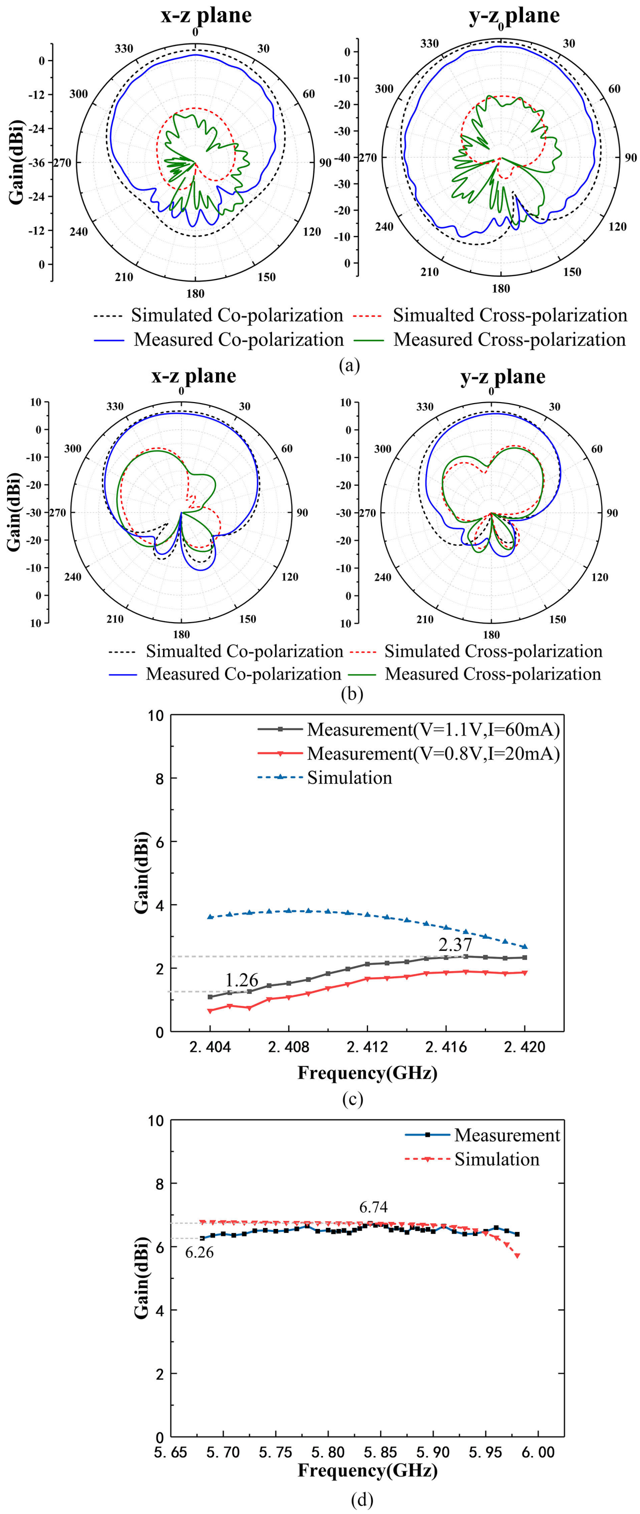

FIGURE 11. Simulated and measured radiation patterns of the proposed antenna (a) at 2.417 GHz in low-frequency mode (b) at 5.84 GHz in high-frequency mode and simulated and measured gain (c) in low-frequency mode and(d) in high-frequency mode.

In Fig. 11(c), the measured gain is lower than the simulated one. Besides, with the rise in the voltage across PIN diodes, the forward current and the gain of the proposed antenna are

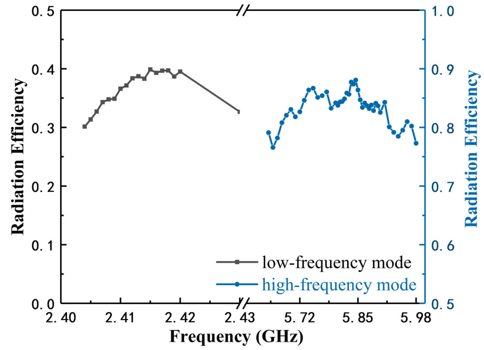

FIGURE 12. Measured radiation efficiency of the proposed antenna in two modes.

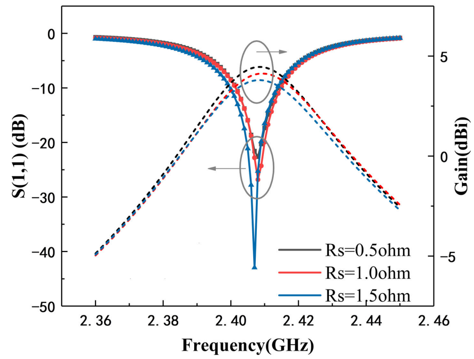

FIGURE 13. Simulated gain and reflection coefficients of the proposed antenna with different diode equivalent on-resistance in low-frequency mode.

enhanced. We have discussed the reason in Fig. 13. The on-resistance of PIN diodes hardly impacts on the resonance frequency. However, when the voltage increases, the equivalent resistance inside PIN diodes is reduced. Thus the ohmic loss of the diodes decreases and the gain is enhanced.

IV. CONCLUSION

A novel frequency reconfigurable substrate integrated waveguide antenna is proposed, which combines SIW slot antenna and microstrip antenna. The proposed antenna has a bandwidth of 18 MHz (2.406 GHz-2.424 GHz) in S-band (low frequency mode) and the measured gain varies from 1.26 dBi to 2.37 dBi. The bandwidth in high-frequency mode is 322 MHz (5.683 GHz-6.005 GHz) in C-band and the measured gain is approximately 6.26-6.74 dBi in this band. The measured results agree well with the simulated results for both two modes. By changing the radiation element, it can achieve a dual-band frequency reconfiguration. In the antenna design process, the size of the SIW cavity and the rectangular patch can be tuned according to the target frequency of two working modes to meet different needs. The proposed antenna has the advantages of low profile, easy integration, no complicated bias circuit and good out-of-band suppression. In addition, a new way to adjust the resonance frequency slightly without changing the cavity dimension is proposed, which may provide an independent tuning method for the design of the multi-modes integrated antenna in the future.

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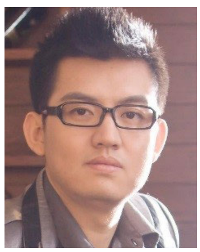

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