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A New Differentially-Fed Frequency Reconfigurable Antenna for WLAN and Sub-6GHz 5G Applications

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ABSTRACT A new differentially fed frequency reconfigurable antenna adopting proximity-coupling feeding for WLAN and sub-6-GHz 5G applications is proposed in this paper. It consists of two substrates that are separated by a 2.5-mm-thick air gap. By configuring the four p-i-n diode switches arranged on the two substrates, the excitation of the radiating patch and the length of the feed-lines can be controlled, and then, two different operating frequency bands can be obtained. The experiments indicate that the designed antenna can be switched between two states operating at 2.45- and 3.50-GHz band, respectively. Good agreement between the simulated and measured results is achieved, and the radiation patterns and gains are similar for the two states. The proposed antenna is a good candidate for WLAN (2.45 GHz) and sub-6-GHz 5G (3.50 GHz) applications.

INDEX TERMS Differentially-fed, frequency reconfigurable antenna, PIN diode switch.

I. INTRODUCTION

Wireless technologies have been widely used in communication and are developing rapidly toward highly-integrated, multi-function and ultra-wide band. As an indispensable part of any wireless system, antenna must develop and innovate constantly as well. Reconfigurable antennas [1]–[8] are very popular in recent years. According to the function of reconfigurable antennas, there are mainly three classifications: radiation pattern, polarization and frequency reconfigurable antennas. In this paper, we study the frequency reconfigurable antennas, which can change its operating frequency in real-time without affecting other characteristics, including radiation pattern and polarization. On the basis of existing researches about frequency reconfigurable antennas, most of them use tunable components, such as PIN diodes [9], [10], micro-electromechanical systems (MEMS) switches [11], [12], varactor diodes [13], [14], liquid metal [15], [16] or field effect transistor (FET) [17]. Besides, some antennas also use special materials. For example. in [18], graphene is adopted as the parasitic layer making the patch antenna's resonant frequency can be controlled by external DC voltage. However, the PIN diode is the most popular because of its small size, low price and easy assembly.

Studies about differentially-fed antennas have entered into a mature stage. One of the key parameters of a differential antenna is its differential mode reflection coefficient. Actually, common mode excitation at two ports of a differential antenna normally will not excite an effective radiation mode on the differential antenna, and the majority of common mode power will be reflected. When the two ports of a differential antenna are excited by a differential signal, the excitation at port 2 is constrained to be equal in amplitude but out of phase with that at port 1.

Many differential antennas operating at a single frequency or multi-frequency have been reported [19]–[24], but none of them achieves the frequency reconfigurability. To the best of the authors' knowledge, there are only a few preliminary studies of the antennas with differential scheme and reconfigurable abilities. The antenna in [25] is a differential pattern reconfigurable patch antenna, but the bandwidth is narrow and the gain is low because of the feeding scheme and structural limitations. In [26], a differential frequency reconfigurable antenna is studied for the first time. Frequency

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reconfigurability is obtained by integrating three pairs of varactor diodes to the patch antenna.

References [27] and [28] are single-ended frequency reconfigurable antennas controlled the length of the slotted patch by configuring the states of RF switch, and the excited patches or the parts being connected are on the same substrate layer. However, the reconfigurable antenna with the combination of stacked structure [29], [30] or proximity-coupled technique and differentially-fed technology has yet to come out due to its challenged structure designing work. Therefore, different antenna's structure placed on multilayered substrate can be a more flexible structure to combine with the differentially-fed scheme. All in all, it's advanced and exploratory to design an antenna with those technologies. After runing a lot of simulations, we find that the differentially-fed frequency reconfigurable antenna should be designed according to the following two principles:

(1) The main goal is to realize the differential feeding and frequency reconfigurable, and require other characteristics, including the radiation pattern and polarization, to be similar or identical under different work states.

(2) It is challenging to make the antenna achieve frequency reconfigurability by changing the physical structure of the antenna. These changes should be as fewer as possible to reduce the structural complexity and avoid bringing in other unnecessary losses. Loading PIN diodes on the radiation structure or the feeding network would be a good choice to realize this goal.

The proximity-coupled feeding method needs the antenna to be stacked structure, which also provides the antenna with an advantage that the antenna's radiation patches can be arranged on different layers, as reported in [16], [17], [22], and [24]. All of them with three substrate layers have obvious disadvantages such as complicated configuration and dissimilar radiation pattern. In a word, designing proximity-coupled feeding antennas with fewer layers is preferred.

In this paper, a new differentially-fed frequency reconfigurable antenna for WLAN and Sub-6GHz 5G applications operating at two frequency bands is proposed. It only has two layers separated by a 2.5mm-thick air gap. Two PIN diode switches are placed on the top layer's main radiating patch and the other two PIN diode switches are on the feed lines on the up side of the bottom layer. The employment of the PIN switches makes the antenna can operate in dual frequency bands (i.e. 2.45 and 3.5GHz), which are illustrated by analyzing the current distributions of the radiating patch and feed lines on two states. There is a good agreement between the measured and simulated results. The radiation patterns are directional and stable for two states. In addition, the simple structure makes the proposed antenna easy to fabricate.

II. ANTENNA DESIGN

A. ANTENNA CONFIGURATION

The new differentially-fed frequency reconfigurable antenna is a combination of differential scheme and proximity-coupled technique or stacked structure, in which the radiating patch and feed lines are located on two parallel FR4 substrate layers, respectively, as shown in Fig. 1. FR4 substrate has a dielectric constant of 4.4, loss tangent of 0.02, and thickness of 1.6mm. The radiating patch is placed on the down side of the top substrate layer, which is a circular patch with a crooked slot implemented with two PIN diode switches, as shown in Fig. 1(a). The feed line is on the bottom substrate layer. Two sections of feed line integrated with two PIN diode switches are at the up side of the bottom substrate, as shown in Fig. 1(b). The ground plane is at the down side of this substrate. The two feed lines are fed by two coaxial cables through the driving points on the bottom substrate layer, as shown in Fig. 1(c). The two parallel substrate layers are separated by an air gap. The thickness of the air gap is H = 2.5mm with dielectric constant ε_r equal to 1, as shown in Fig. 1(d).

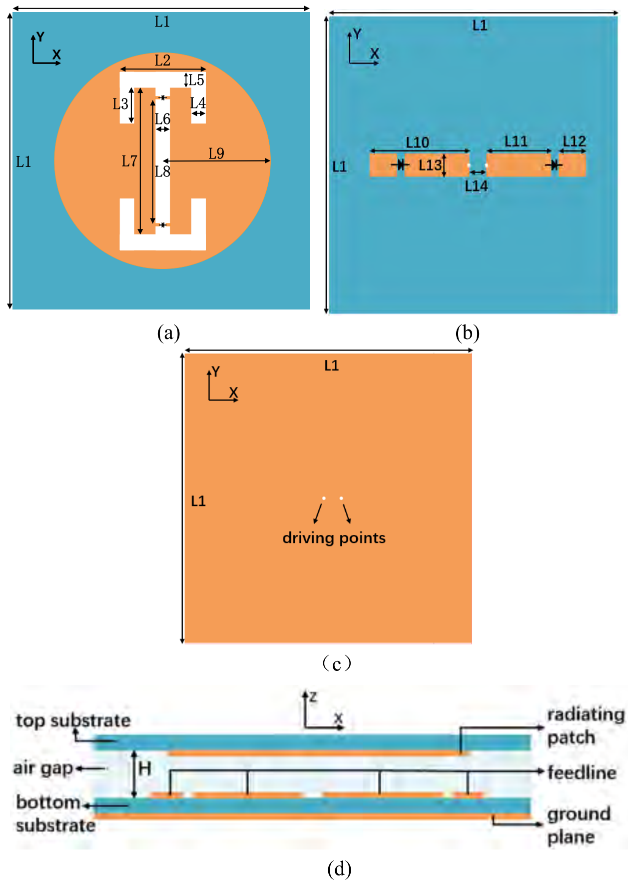


FIGURE 1. The structure of the proposed antenna. (a) Geometry of the radiating patch. (b) Geometry of the feed lines. (c) Ground plane. (d) Side view.

The parameters related to the proposed antenna are optimized and given in Table 1. The switches' status of the frequency reconfigurable antenna's two states is listed in Table 2.

For the prototype of the antenna, four identical DC bias circuits are applied to control each of the four PIN diodes. Fig. 2 gives one DC bias circuit (the DC bias circuit of

TABLE 1. Optimized parameters of the proposed antenna.

Parameter	Size(mm)	Parameter	Size(mm)
L1	100	L9	37.8
L2	31.5	L10	32.5
L3	11.55	L11	22.05
L4	5.25	L12	9.45
L5	5.25	L13	7.9
L6	6.3	L14	6.4
L7	48.3	H	2.5
L8	42	——	——

TABLE 2. Switch status of the two states.

Operating states	Switch 1	Switch 2	Switch 3	Switch 4
State 1	off	off	on	on
State 2	on	on	off	off

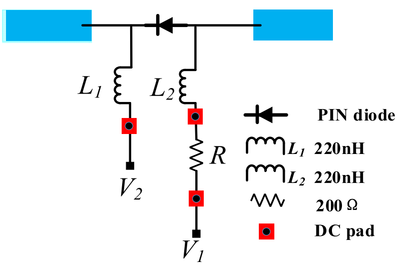


FIGURE 2. DC bias circuit.

the other three diodes are the same as it), the diode is BAR64-02V, and two inductors are used to prevent the AC on the antenna from leaking into the bias circuit. The proposed antenna can well realize the characteristic of frequency reconfiguration when the "on" or "off" state of all diodes are properly controlled by the DC voltage.

B. CURRENT PATH ANALYSIS

The proposed differentially-fed frequency reconfigurable stacked patch antenna is simulated by the commercial software Ansys HFSS. The simulated surface current distributions of the proposed antenna are depicted in Fig.3, which can explain the working principle intuitively.

On state 1, both switch 1 and 2 are "off". It can be seen that the current distributions on the radiating patch mainly concentrate on the four ends of the crooked slot symmetrically, as shown in Fig. 3 (a). The current path length (4L3+2L4) approximates to $0.46\lambda_{(2.45GHz)}$, which is responsible for 2.45 GHz resonance. Meanwhile, both switch 3 and 4 are "on" to realize impedance matching.

On state 2, both switch 1 and 2 are "on". The current distributions on the radiating patch consists of two parts, as shown in Fig. 3 (b). The first part concentrates on the four ends of

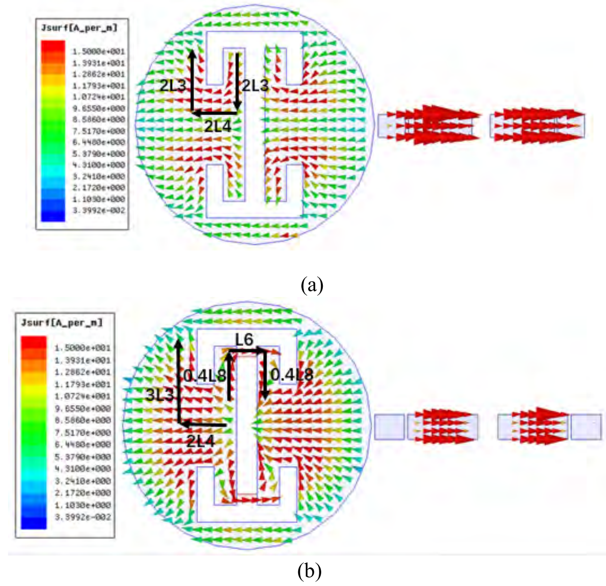


FIGURE 3. Current distributions of the radiating patch and feed lines. (a) State 1. (b) State 2.

the crooked slot, the current path length (3L3+2L4) approximates to $0.53\lambda_{(3.50GHz)}$, which is responsible for 3.5 GHz resonance. The second part concentrates on the patch near switch 1 and 2, the current path length (0.8L8+L6) also approximates to $0.46\lambda_{(3.50GHz)}$. Both switch 3 and 4 are "off" to realize impedance matching.

C. PARAMETRIC STUDY

The changes of any parameters may have effects on the performance of the antenna more or less. Here we discuss four key parameters that have significant impacts on antenna's performance.

The first one is the length of the crooked slot's ends, i.e. L3. Fig. 4 clearly shows that L3 is a significant parameter of the antenna, which determines the resonant frequencies both on state 1 and 2. These results also verify the analysis of the current path length on two states. To achieve the resonance frequencies 2.45GHz at state 1 and 3.50GHz at state 2, the optimized size of L3 is 11.55mm.

The second one is the extended part of the feed line, i.e. L12. As shown in Fig. 5, on state 1, switch 3 and 4 being "on" connect L11 with the extended part L12. For good impedance matching with the radiating patch, the optimized value for L12 is 9.45mm. On state 2, since switch 3 and 4 are "off", the L11 part matches well with the radiating patch and L12 almost has no effect on the antenna.

The third one is the distance between switch 1 and 2, i.e. L8. As shown in Fig. 6, on state 1, because of switch 1 and 2 being "off", L8 almost has no effect on the antenna. From Fig. 6(b), we can know L8 is a main parameter to determine the resonance frequency. To achieve the resonance at 3.50GHz, the optimized size of L8 is 42mm.

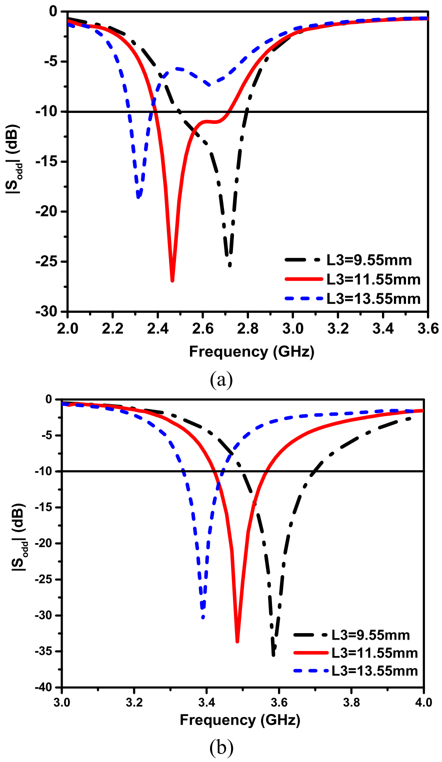


FIGURE 4. The $|S_{dd}|$ against parameter L3 (a) on state 1. (b) On state 2.

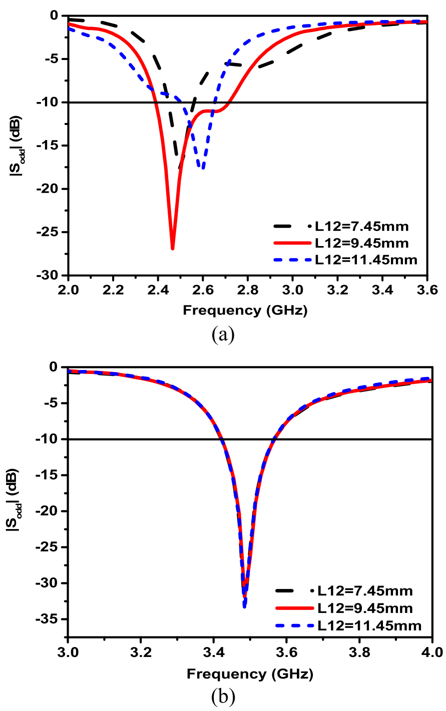


FIGURE 5. The $|S_{dd}|$ against parameter L12 (a) on state 1. (b) On state 2.

The last one is the height of the air gap, i.e. H. It can be seen from Fig. 7 (a) and (b) that H has a significant impact on the $|S_{dd}|$ of two states. To make the antenna achieve the best performance under both states, the optimal size of H is 2.5mm.

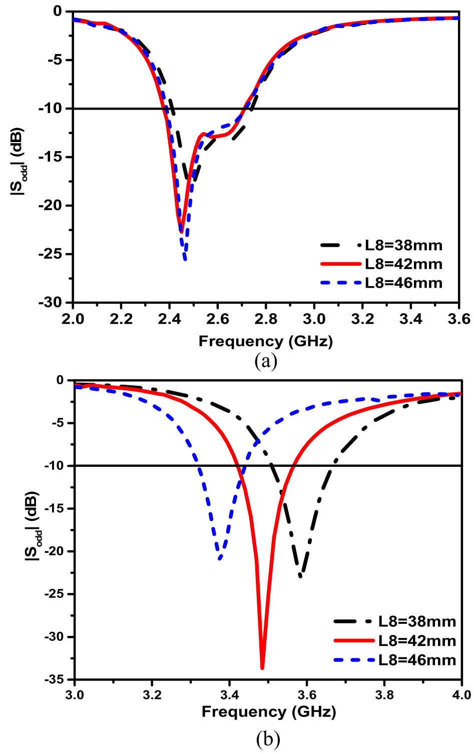


FIGURE 6. The $|S_{dd}|$ against parameter L8 (a) on state 1. (b) On state 2.

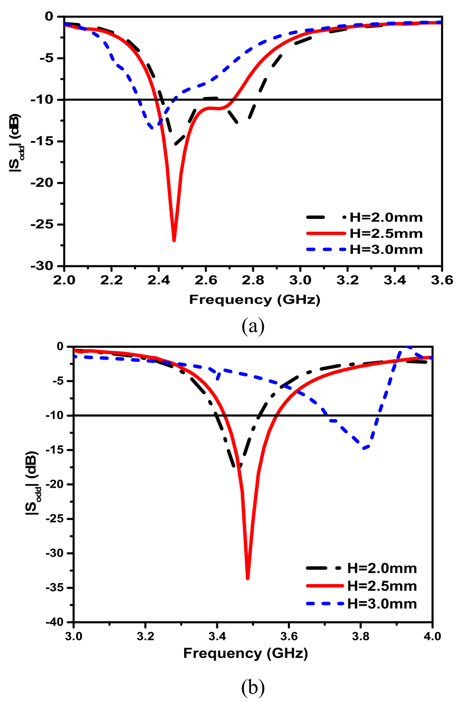
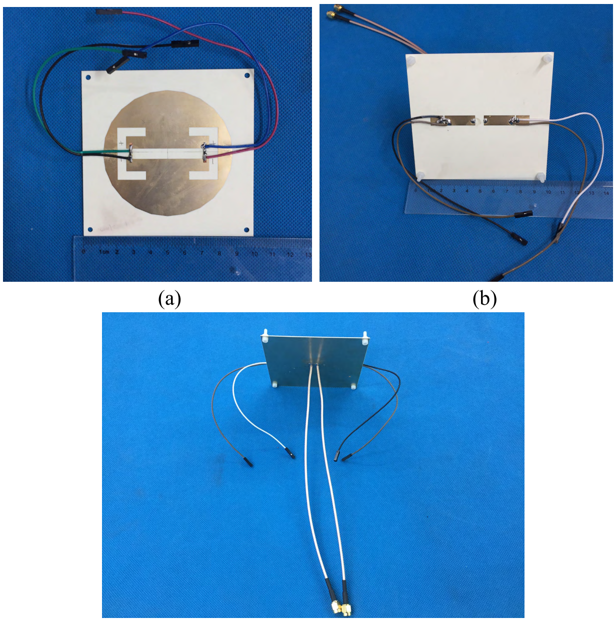


FIGURE 7. The $|S_{dd}|$ against parameter H (a) on state 1. (b) On state 2.

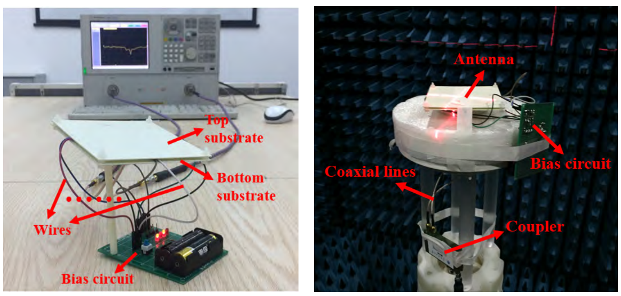
III. RESULTS AND DISCUSSION

The proposed antenna is fabricated and measured. Fig. 8 shows the photograph of the fabricated antenna. Fig. 9 shows the measuremental photograph of near field and far field.



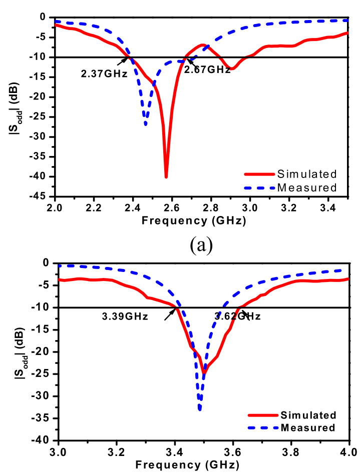
(a) (b) (c)

FIGURE 8. **Photograph of the fabricated antenna. (a) Top layer. (b) Up side of the bottom layer. (c) Down side of the bottom layer.**



(a) (b)

FIGURE 9. **Photograph of the measurement. (a) Near field. (b) Far field.**



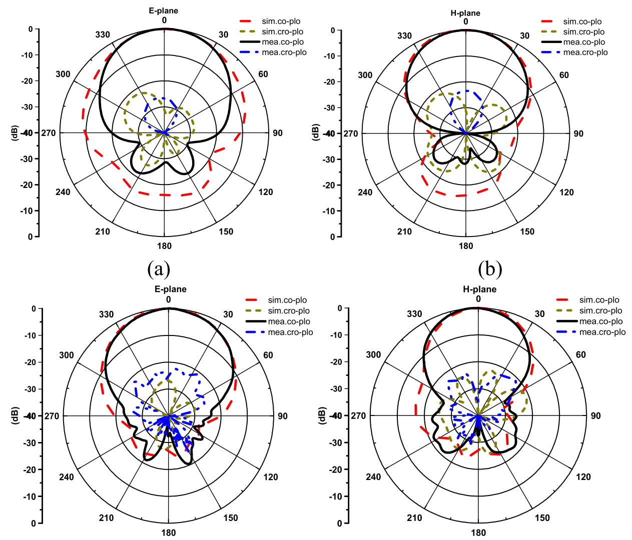
(a)

(b)

FIGURE 10. **Simulated and measured $|S_{dd}|$. (a) State 1. (b) State 2.**

Fig. 10 shows the simulated and measured differential mode reflection coefficient. The simulated results of the antenna are similar to the measured ones, which illustrate that the frequency reconfigurable antenna achieves an impedance bandwidth from 2.37 to 2.67 GHz (11.9%) and from 3.39 to 3.62 GHz(6.6%) for ($|S_{dd}|$) < -10 dB.

The simulated and measured results of the radiation pattern in the E-plane and H-plane under the two states are depicted in Fig. 11. Both states are directional and agree well with each other.

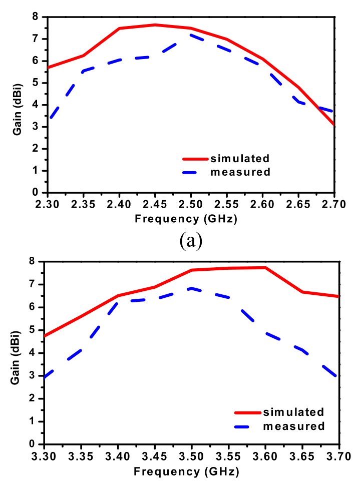


(a) (b)

(c) (d)

FIGURE 11. **Simulated and measured radiation patterns. (a) E-plane at 2.45GHz. (b) H-plane at 2.45GHz. (c) E-plane at 3.50GHz. (d) H-plane at 3.50GHz.**

Measured gains of the antenna are compared with simulated ones in Fig. 12. On state 1, the measured peak gain of the antenna is about 6.51dBi while the simulated one is 7.64dBi; on state 2, the measured peak gain of the antenna is about 6.82dBi while the simulated one is 7.71dBi. Measured efficiencies of the antenna are compared with simulated ones in Fig. 13, and the measured average efficien-



(a)

(b)

FIGURE 12. **Simulated and measured Gains. (a) State 1. (b) State 2.**

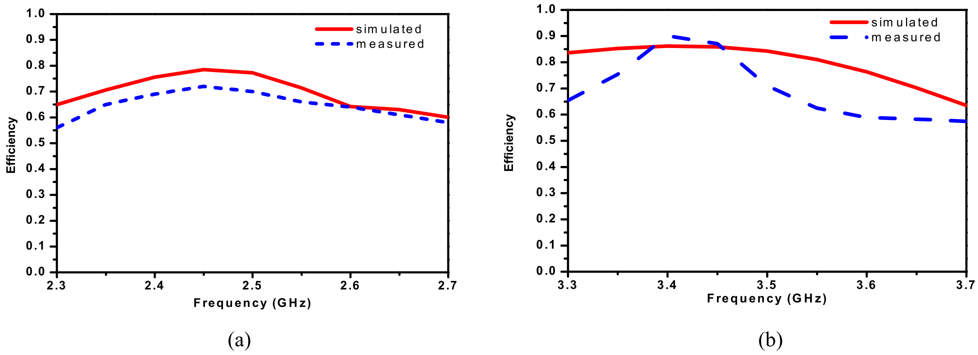


FIGURE 13. Simulated and measured Efficiency. (a) State 1. (b) State 2.

TABLE 3. Comparison with other frequency reconfigurable antennas/differential antennas.

Design	Ref	Size	Feeding type	Center frequency (GHz)	Bandwidth (MHz)	Gain	Antenna Structure	Reconfigurable state/ Switches
1	This work	$0.8\lambda_0\times0.8\lambda_0\times0.02\lambda_0$	Differential	2.45GHz (1) 3.5GHz (2)	300 (1) 230 (2)	5.5-6.5 (1) 5-6.8 (2)	2-layer patch	2/4
2	[9]	$0.73\lambda_0\times0.73\lambda_0\times0.15\lambda_0$	single-ended	1.05GHz (1) 1.2GHz (2) 1.5GHz (3) 2.1GHz (4) 1.6GHz (5)	200 (1) 200 (2) 500 (3) 300 (4) 1600 (5)	2.0-4.5 (1) 3.5-5.5 (2) 4.8-7.0 (3) 3.8-5.5 (4) 3.0-10 (5)	Dipole with a rectangular cavity	5/12
3	[10]	$0.32\lambda_0\times0.24\lambda_0\times0.012\lambda_0$	single-ended	3.40 and 5.27 (1) 2.42 and 5.79 (2)	100 and 200 (1) 100 and 200 (2)	3.5-5.5 (1) 3.5-5.0 (2)	1-layer patch	2/3
4	[12]	$0.32\lambda_0\times0.32\lambda_0\times0.01\lambda_0$	single-ended	2.4 (1) 5.2 (2)	100 (1) 650 (2)	1.8 (1) 2.1 (2)	Annular Slot Antenna	2/3
5	[21]	$0.68\lambda_0\times0.52\lambda_0\times0.006\lambda_0$	single-ended	2.6 (1) 3.5 (2)	119.8 (1) 129.5 (2)	6.1 (1) 6.2 (2)	3-layer antenna	2/1
6	[19]	$0.29\lambda_0\times0.26\lambda_0\times0.005\lambda_0$	Differential	7.64	10004	1.34-4.75	1-layer patch	-
7	[22]	$0.28\lambda_0\times0.18\lambda_0\times0.008\lambda_0$	Differential	6.85	7500	1-5	1-layer patch	-

cies on state 1 and 2 are 64.5% and 69.5%, respectively. The loss is mainly from PIN diode switch, coaxial line and SMA connector.

In Table 3, the proposed frequency reconfigurable antenna is compared with some other recently reported frequency reconfigurable antennas and differential antennas. A reconfigurable dipole antenna is presented in [9]. The length of the dipole is determined by controlling the switches on the dipole, and it achieves five reconfigurable states. But the gains of the antenna under different states are very different. A frequency reconfigurable slot antenna operating in two modes is presented in [10]. The antenna uses 3 PIN diode switches to alter its operating frequency by changing both the location and the length of the slots and arms. But the antenna's operating bands for the two states range from 100 to 200MHz, which are not enough for many applications. A frequency reconfigurable annular slot antenna is proposed in [12]. They use three switches to get two reconfigurable states. Though this idea is novel, it is hard to realize. A frequency reconfigurable stacked patch microstrip antenna with three substrate layers is presented in [21]. References [9], [10], [12], and [21] are all frequency reconfigurable antennas, but they are single-ended antennas, which are not suitable for differential RF systems. References [19] and [22] are differential patch antennas, both of which can achieve a wideband over 7.5 GHz (105%). The proposed antenna in this paper achieves frequency reconfigurability based on differential technology. By configuring the four PIN diode switches arranged on the two substrates, the excitation of the radiating patch and the length of feed-lines can be controlled, and then two different operating frequency bands can be obtained.

IV. CONCLUSION

In this paper, a new differentially-fed frequency reconfigurable antenna for WLAN and Sub-6GHz 5G applications is presented. This new antenna is designed with a combination of proximity-coupled technique, stacked structure and differential scheme. It can operate at 2.45GHz or 3.50GHz by controlling the states of four PIN diode switches directly driven by bias networks. The proposed antenna is a symmetrical structure having only two substrate layers and four PIN diodes, which is easy to design and fabricate. This model also generates insight into the current distributions of the radiating patch and feed lines on two states to illustrate frequency reconfigurable principle. The measured differential mode reflection coefficients generally agree with the simulated ones. In addition, the measured radiation patterns of the proposed antenna are in good orientation and stable. All of these characteristics demonstrate that the proposed antenna is a good candidate for WLAN (2.45GHz) and Sub-6GHz 5G (3.50GHz) applications.

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