electronics

MDPI

Article

Reconfigurable 3-D Slot Antenna Design for 4G and Sub-6G Smartphones with Metallic Casing

Peng Yang

School of Electronic Science and Engineering, University of Electronic Science and Technology of China, No. 2006 Xiyuan Street, Chengdu 611731, China; yangpeng@uestc.edu.cn

Received: 1 January 2020; Accepted: 24 January 2020; Published: 25 January 2020

check for updates

Abstract: The design of a reconfigurable three-dimensional (3-D) slot antenna for 4G and sub-6G smartphone application is presented in this paper. The antenna is located at the bottom of the smartphone and integrated with a metallic casing. Positive-Intrinsic-Negative (PIN) diodes are loaded at the dual-open slot and the folded U-shaped slot, respectively, which are used to realize four working states. The antenna has a compact volume of $42 \times 6 \times 6$ mm^3, which can cover the long term evolution (LTE) bands of 698–960 MHz and 1710–2690 MHz, and the sub-6G bands of 3300–3600 MHz & 4800–5000 MHz. The design processes are presented and the structure is optimized, fabricated and measured. The comparison to other state-of-the-art antennas shows that the proposed design has multiband characteristics with small size.

Keywords: reconfigurable antenna; smartphone; slot antenna; sub-6G

1. Introduction

Recently, the wireless communication network environment has become a mixture of different kinds of heterogeneous networks. The WRC-15 (Word Radio Communication Conference 2015) identified the frequency spectrum of 3400–3600 MHz for global mobile broadband services in November 2015 [1]. From November 2017, the frequency spectrums of 3300–3600 MHz and 4800–5000 MHz have been identified for fifth-generation (5G) application by the ministry of industry and information technology of the People's Republic of China [2]. In addition, the mobile antenna is required to be operated at 698–960 MHz and 1710–2690 MHz for fourth-generation (4G) mobile communications [3]. To provide these services for different frequencies and communication protocols, the antenna in smartphones should cover multiple bands. On the other hand, in order to meet the consumers' requirements, the mobile phones are being designed to provide a low profile and a large display with a narrow frame for entertainment. Therefore, designing a multiband/wideband mobile phone antenna with limited space is undoubtedly a technological challenge.

A mobile phone with a metal casing (metal frame and metal back cover) has also become popular since the metal casing not only increases mechanical strength but also enhances the esthetical appearance. For the traditional internal antennas [4], such as the monopole, planar inverted-F antenna (PIFA), etc., the performance of the antenna will be adversely affected by the metal casing [5,6]. In [6], the effects of the metal frame on the performance of the antenna are analyzed, and the influences of the metal frame are reduced by inserting multiple gaps and grounded patches. For the approach proposed in [6], however, the multiple gaps on the metal frame may reduce the mechanical strength of the mobile phone. In [7,8], the effects of the metal frame on the antenna are completely eliminated by using the entire or partial frame as the radiation branch of the antenna. These proposed antennas in [7,8], however, occupy a large clearance size of 70×10 mm^2. In another design, an inverted-F antenna IFA frame antenna was proposed to cover multiple bands [9]. The bandwidth of the upper band was not wide enough to cover the sub-6G application bands of 3300–3600 MHz and 4800–5000 MHz.

Slot antennas are widely adopted as an alternative for mobile antenna designs [10–16]. Two folded slot antennas were introduced in [10,11] to cover dual bands. These antennas cannot apply to the mobile phone with metal casing, and the bandwidth is not sufficient to cover the lower band. In another T-shaped open-ended slot design for laptops with a metallic frame, two separate feed strips were adopted to excite the T-shaped slot antenna [12]. Open-slot antennas are reported for tablet computers [13–15] which have wide operating bands to cover 698–960 MHz, 1710–2690 MHz, and 3400–3600 MHz. However, the larger antenna size and the lack of integration with metal casing make it unsuitable for modern mobile phones. In other designs, the varactor diode and PIN diode were used for reconfiguration, resulting in multiple antenna states [16–18]. This is a very promising design, but only covers part of the high-frequency bandwidth, which limits its application in future 5G mobile phones. In [19], a multi-band loop antenna with six resonant modes is proposed. The antenna can cover the bands from 660 MHz to 5850 MHz. In [20], a reconfigurable loop antenna with two parasitic grounded strips for modern smartphone devices is presented. However, the antenna can only cover 4G bands.

There is no doubt that it is a challenging for antenna engineers to integrate antennas into a metal casing environment and to achieve multi-band/wideband coverage. In this paper, a reconfigurable 3-D slot antenna fed by an L-shaped feed strip is proposed. The 3-D slot antenna can achieve miniaturization and multi-band operation by folding the slot structure and introducing PIN diodes, respectively. The proposed 3-D slot antenna shows four bands that cover 698–960 MHz, 1500–3000 MHz, 3300–3800 MHz, and 4400–5000 MHz for LTE and sub-6G operations.

2. Antenna Configuration

Figure 1a shows the proposed 3-D slot antenna mounted on a mobile phone with a size of $135 \times 75 \times 6$ mm. The mobile phone has a metallic frame and back cover. A slot starts from one narrow side of the frame, (see 'A' in Figure 1b), along 'B' at the back cover, folded to the upper layer 'C', and short-ended at 'D'. Three black rectangles noted as 'd1', 'd2' and 'd3' are PIN diodes. The 3-D slot is fed by an L-shaped strip line, as shown in Figure 1c. The feed line is between the back cover and the system circuit board ground. A 0.8 mm-thick print circuit board type of (FR4) substrate with a relative permittivity of 4.4 and a loss tangent of 0.02 was used as the system circuit board which mounted on the back metal cover. There is no gap between the system circuit board and the metal casing. At the end of the feed line, a lumped port is used to simulate the source.

The topology of the PIN diodes (d1, d2 and d3) is shown in Figure 2. The back-to-back configuration shown in Figure 2a was used here to overcome the problem of equal voltages on both sides of the slot. The PIN diode is Infineon BAR64-02V. The diode is switchable between 'OFF' and 'ON' states depending on a DC bias. Combining the data sheet of the diode and the test results, the equivalent circuit of the diode is shown in Figure 2b. When the diode is 'ON', it has a forward resistance of 2.1 Ω [21]. When the diode is 'OFF', we obtained the values of the corresponding components experimentally at different frequency bands and show them in Table 1.

Table 1. Equivalent circuit parameters for the state 'OFF'.

Frequency (MHz)	R	C	L
800–1000	3933 Ω	148 fF	2.1 nH
1500–3000	3014 Ω	148 fF	5.5 nH
3000–4000	2079 Ω	154 fF	200 pH
4000–5000	2419 Ω	113 fF	181 pH

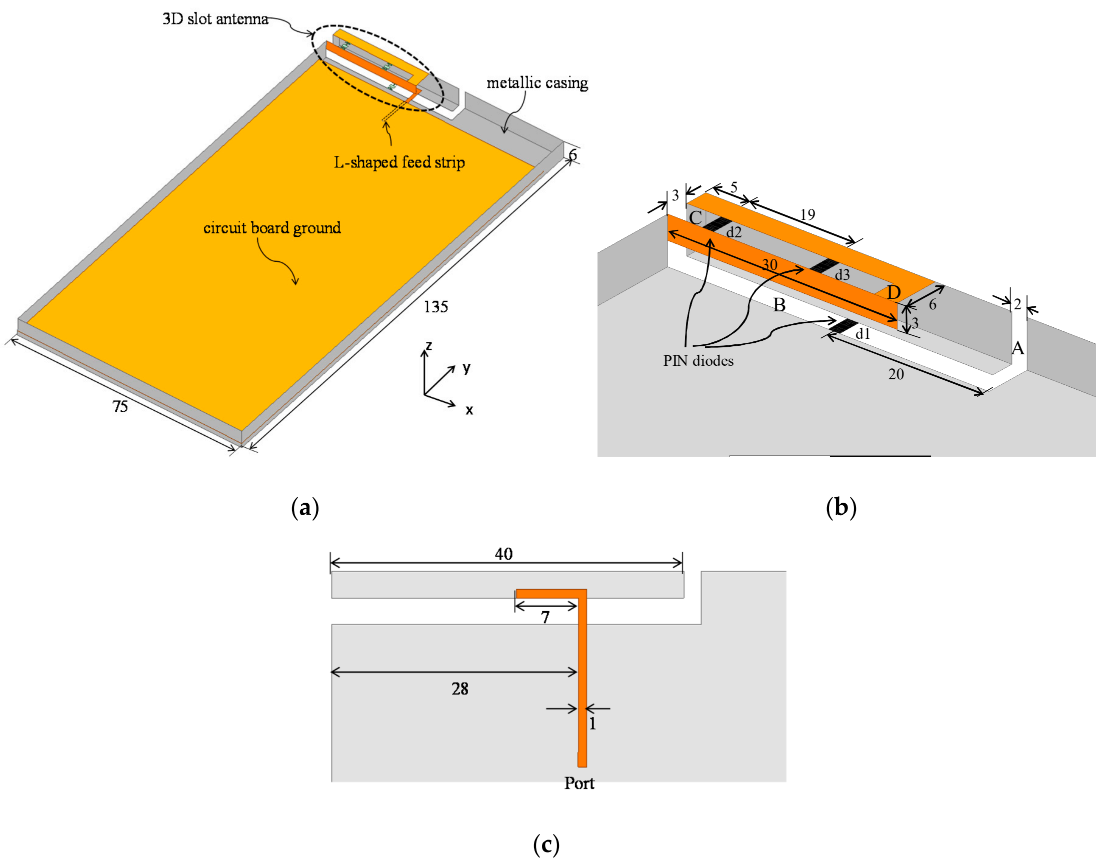


Figure 1. Geometry of the structure. (**a**) Side view of the proposed antenna; (**b**) 3-D view of the antenna; (**c**) the slot and the L-shape feed strip (all in millimeters).

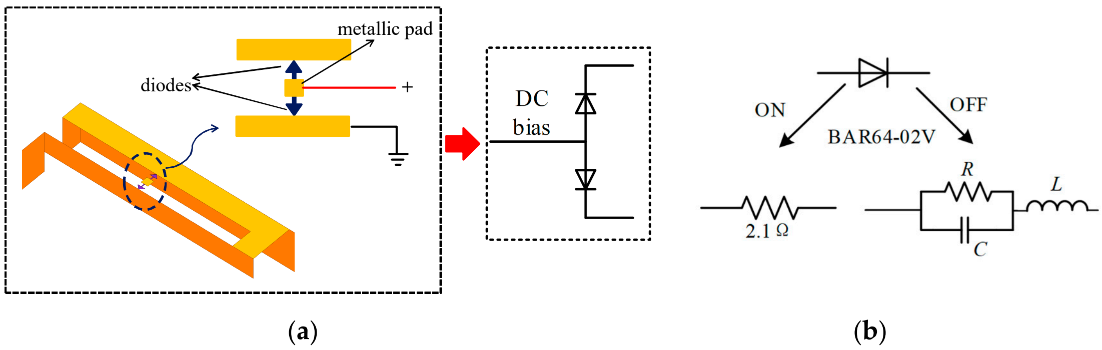


Figure 2. The description of the PIN diodes. (**a**) Topology of the back-to-back diodes; (**b**) Equivalent circuit model of BAR64-02VPIN diode in two states.

3. Design Process

3.1. The Principle of the Design

The idea of the design starts from a simple open-ended slot antenna, as shown in Figure 3a. A slot is etched on the edge of a metal. One end of the slot is opened and the other end is shorted. The slot can support a quarter of a standing wave. Details of the radiation mechanism of the slot can be found in [22]. For the lowest frequency (around 700 MHz) that we need, the length of the slot is about 107 mm, which is too long to be used for smart phones. To reduce the length, the slot is modified by three steps: firstly, the open-ended position is moved from the long frame side of the phone to the narrow frame side, as shown in Figure 3b; secondly, the slot length is extended by folding the structure to upper layer, see Figure 3c; and thirdly, an L-shaped feed line was used to feed the slot. By tuning the location and the length of the feed line carefully, four resonate modes can be excited.

It can be seen from Figure 4a that the slot is expected to resonate at a low frequency around 740 MHz owning to 0.25 λ slot mode (since the slot is covered by a FR4 substrate, the actual length is shorter than the length in free space). In addition, a second resonance produced at 2.1 GHz, which is mainly due to a fictitious short circuit near the capacitive feed strip [23,24]. Similarly, two resonances (3.2 GHz & 5 GHz) can also be excited. However, the slot still cannot cover the bands of 824–960 MHz and 1710–2690 MHz due to the narrow bandwidth characteristics.

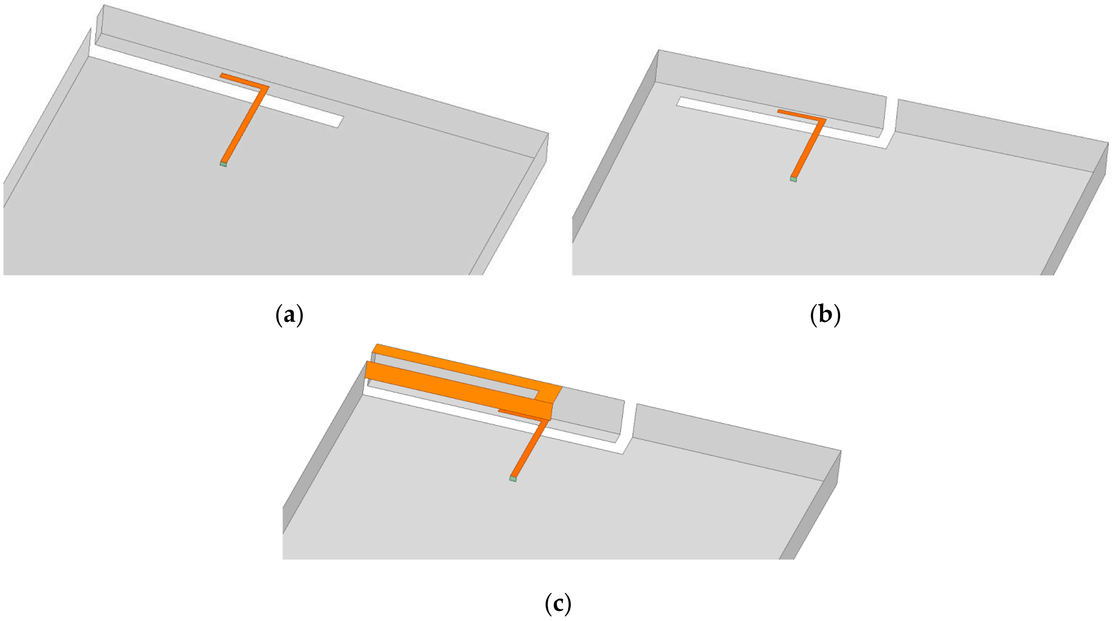


Figure 3. Evolution of the configuration. (**a**) Open-ended slot antenna with the open position at the long frame side; (**b**) open-ended slot antenna with the open position at the narrow frame side; (**c**) folded 3-D slot.

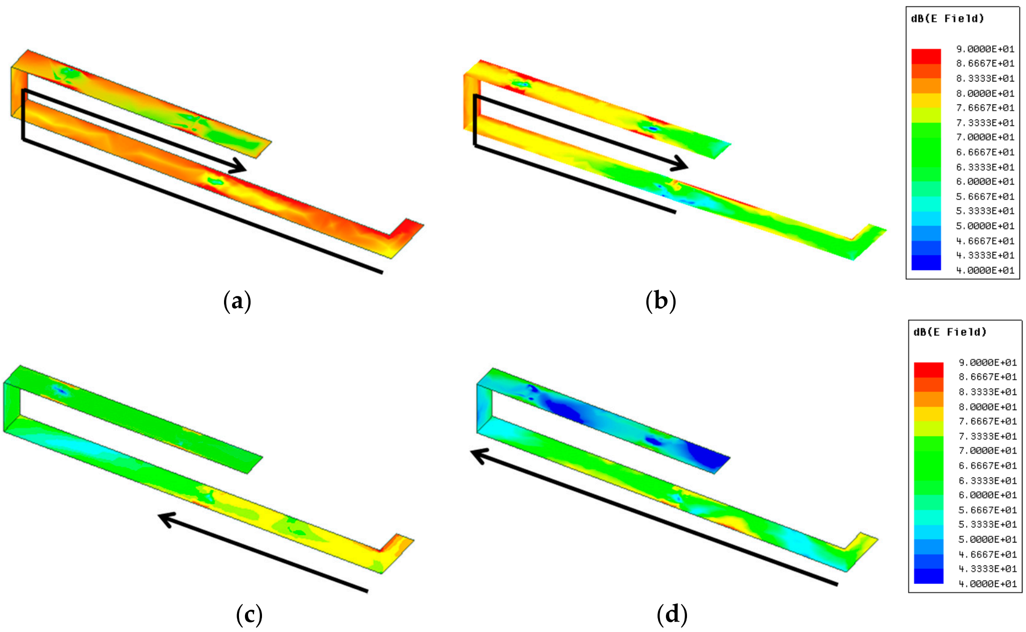


Figure 4. Electric field distribution of state 1 at different resonate modes: (**a**) 0.74 GHz (0.25λ); (**b**) 2.1 GHz (0.5λ); (**c**) 3.2 GHz (0.25λ); (**d**) 5 GHz (0.75λ).

To solve the problem, three PIN diodes are integrated into the slot at proper positions to provide more resonances. On the upper layer, the diodes d2 and d3 are used to change the total length of the slot, which will generate two additional resonances around 820 MHz and 920 MHz. The diodes d1 on the bottom layer are used to generate the LTE band from 1710–2690 MHz. These diodes make the antenna reconfigurable to enable multi-band operation. The states of these diodes are summarized in Table 2. The simulated reflection coefficients of the antenna for different states are shown in Figure 5.

Table 2. States of three back-to-back diodes.

	d1	d2	d3	Frequency
State 1	OFF	OFF	OFF	700~770 MHz 2000~3600 MHz 4800~5200 MHz
State 2	OFF	OFF	ON	770~870 MHz
State 3	OFF	ON	OFF	850~960 MHz
State 4	ON	OFF	OFF	1300~3000 MHz

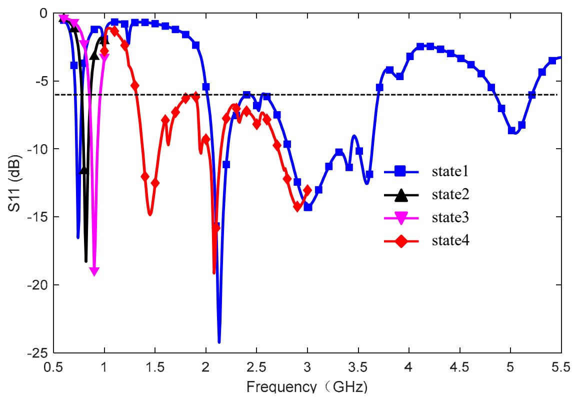
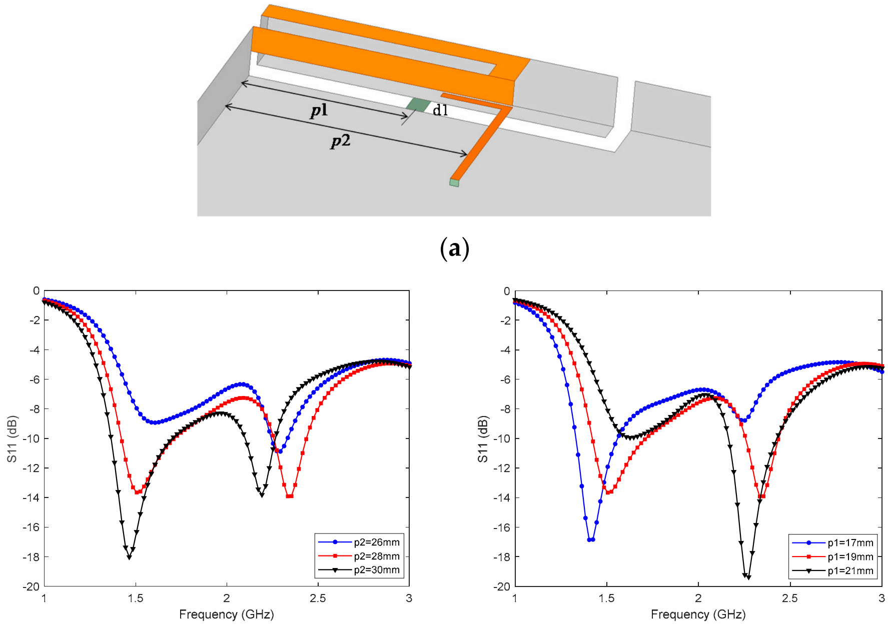


Figure 5. Simulated reflect coefficients of the proposed antenna for different diode states.

3.2. Key Parameters of the Antenna

The structure of the design is very simple and only few parameters need to be determined. The lower resonate frequencies depend on the total length of the 3-D slot and the locations of diodes d2 and d3, while the impedance between 1710–2690 MHz is mainly affected by the locations of diodes d1 and the feed line.

To optimize the antenna performance of 1710–2690 MHz, the locations of the back-to-back diodes d1 and the feed line, and their effects are studied. In the simulations, the switching effect of the diodes is equivalent to the circuit shown in Figure 2b. Since the resonate frequency mainly depends on the location of diodes d1, we can first estimate the value of $p1$. Choosing the center frequency at 2200 MHz, the slot length from point 'A' in Figure 1b to d1 is about quarter wavelength of 2200 MHz. The length of the slot should be shorter than this because it is printed on a FR4 board with a permittivity of 4.4. Hence, the estimated value of $p1$ is around 20 mm. The S11 of the antenna working at state 4 for different $p1$ and $p2$ are studied and the results are shown in Figure 6b,c. In Figure 6b, the parameter $p1$ is fixed at 19 mm while in Figure 6c the parameter $p2$ is fixed at 28 mm. It can be seen that when $p1$ = 19 mm and $p2$ = 28 mm, the antenna can match well in this frequency band.



(**a**)

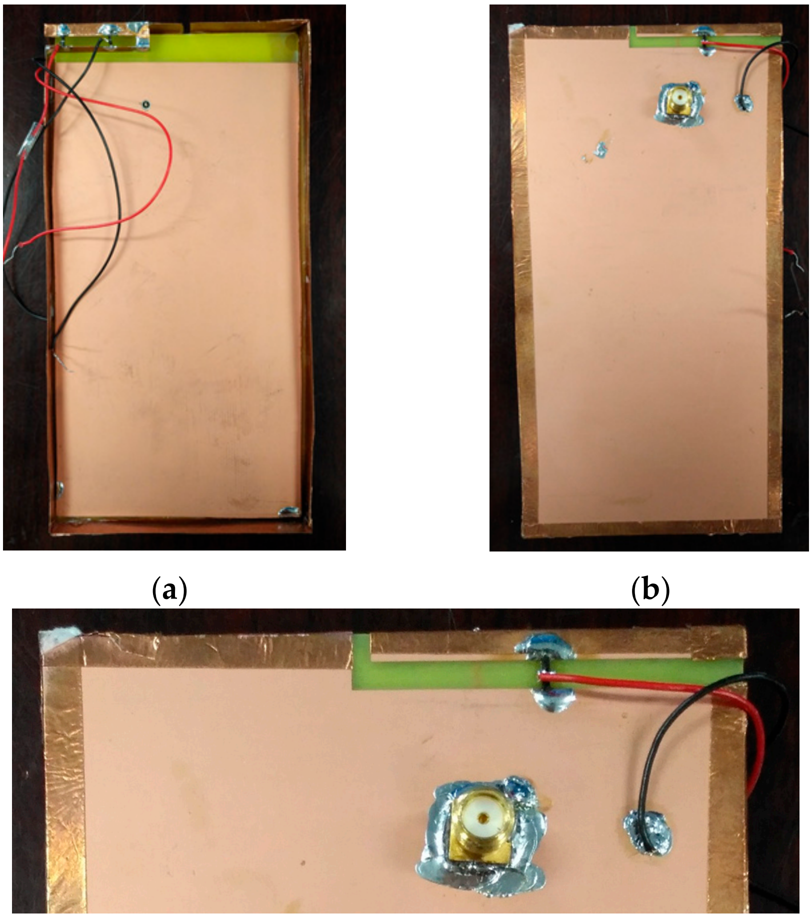
(**b**) (**c**)

Figure 6. Parameters studies of diode d1 and feed line. (**a**) Locations of diode d1 and the feed line. (**b**) and (**c**) S11 performance for different *p*1 and *p*2.

4. Measurement Results

The proposed reconfigurable 3-D slot antenna was fabricated and tested. Figure 7a,b show the front and back of the prototype, respectively. The detail of the control circuit of the diodes is shown in Figure 7c. When the positive pole of the voltage (red line) is connected to the center of the back-to-back diodes, as shown in Figure 2a, and the negative pole (black line) is connected to ground, the back-to-back diodes are 'ON'. When the red line is removed, the diodes are 'OFF'.

Figure 8 shows the simulated and measured reflection coefficient of the three working states of the prototype. In this figure, good agreement between the simulated results and the measured data was obtained for overall bands. The measured −6 dBi impedance bandwidth can cover 690–1000 MHz, 1500–3800 MHz and 4400–5000 MHz, which can satisfy the desired bands for WWAN/LTE and 5G operations, respectively. The measured total efficiency and gain for different states of the proposed antenna are shown in Figure 9. For the lower band of 800–1000 MHz, the measured efficiency is not high enough. There are three reasons: The main reason is the small size of the antenna. The volume of the antenna is only $42 \times 6 \times 6$ mm^3 and its electric size is only 0.11λ around 800 MHz, so the radiation efficiency is relatively low. Secondly, the low efficiency is due to the resistor in the diode. The diode is not an ideal conductor but has a 2.1 Ohm resistor even in the 'ON' state. Hence, the back-to-back diodes have a 4.2 Ohm resistor, which will cause a big loss. Thirdly, the folded slot is printed on a FR4 board with a loss tangent of 0.02, which will further reduce the efficiency. For the higher bands of 1500–3000 MHz, 3100–3800 MHz and 4400–5000 MHz, the measured total efficiencies are between 40–80%. Similarly, the gain of the antenna varies from −5 dB to 5 dBi throughout the desired bands. The measured far field gain patterns at 800, 2100, 3500, and 4900 MHz are shown in Figure 10a-d. These patterns are not symmetrical due to the asymmetrical antenna structure.



(**a**) (**b**)

(**c**)

Figure 7. Prototype of the antenna. (**a**) Front; (**b**) back; (**c**) details of the control circuit of the diode.

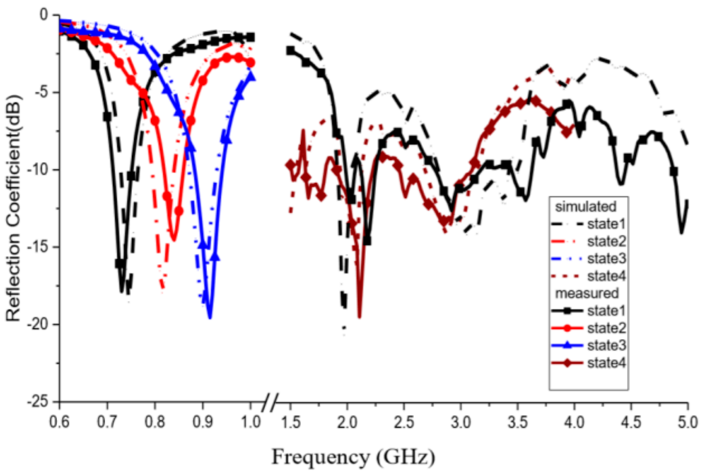
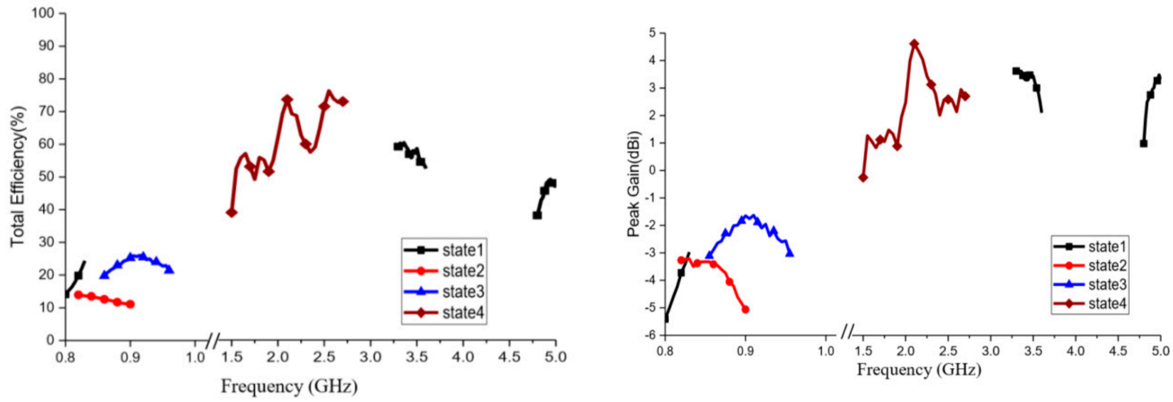
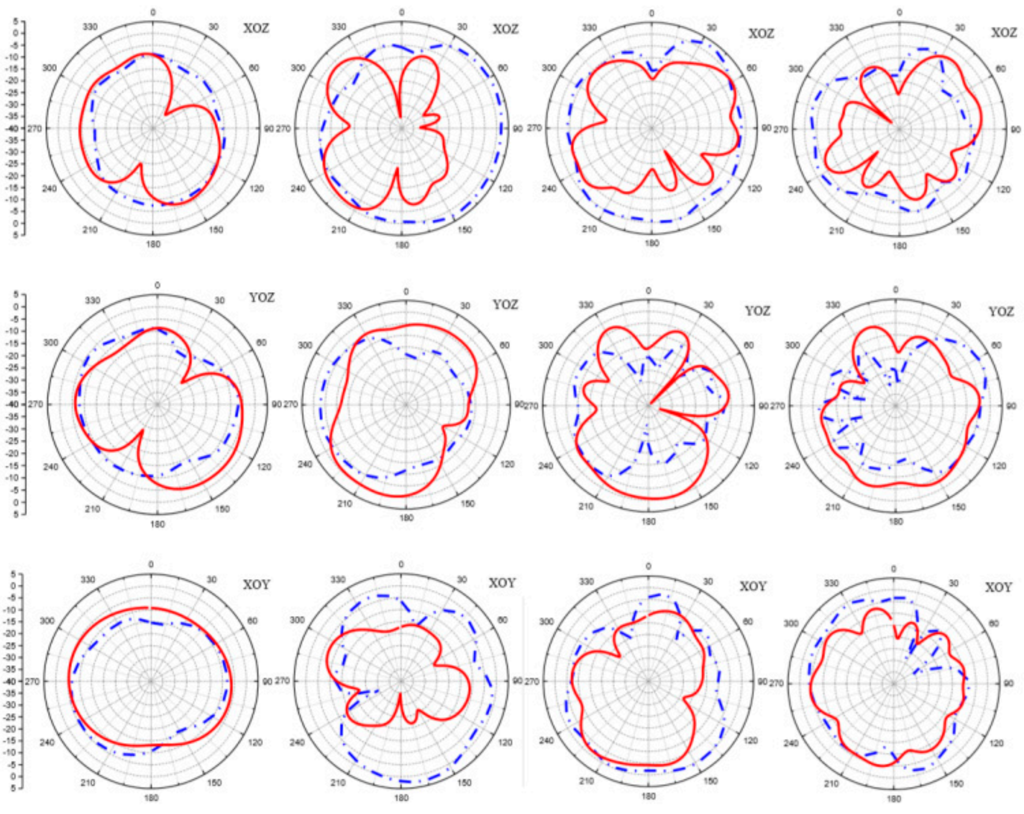


Figure 8. Measured reflection coefficient of different states.



(**a**) (**b**)

Figure 9. Measured efficiency (**a**) and gain (**b**).



(**a**) (**b**) (**c**) (**d**)

Figure 10. Measured 2-D radiation patterns of the proposed antenna at three principal planes (red solid line E_θ, blue dashed line $E\varphi$, unit: dB): (**a**) 800 MHz; (**b**)2100 MHz; (**c**) 3500 MHz; (**d**) 4900 MHz.

5. State-of-Art Comparison

In order to evaluate the performance of the proposed reconfigurable 3-D slot antenna, its performance is compared with recently published designs. The results are summarized in Table 3. As can be seen, the proposed antenna exhibits a smaller clearance zone on the premise of integrating with the metal casing (metal frame and metal back cover). Also, it has more bands than most of the designs in the literatures.

Table 3. Comparison of proposed antenna performance with recent antenna designs.

Ref.	MF [1]	MBC [2]	Clearance Zone (mm^2)	BWlow [3] (MHz)/η/Gain	BWhigh [4] (MHz)/η/Gain
This work	Yes	Yes	42 × 6	698~1000/10~28%/−5~−1 dBi	1500~3000/40~75%/0~5 dBi 3100~3800/50~60%/2~4 dBi 4400~5000/40~50%/0~3 dBi
[7]	Yes	No	70 × 10 & 70 × 5	824~960/60~79%/1~2 dBi	1710~2690/54~79%/1~4 dBi
[8]	Yes	No	70 × 10	801~1002/>42%/0~3 dBi	1695~3000/>51%/2~5 dBi
[16]	Yes	Yes	68 × 11	698~960/45~90%/N.A.	1710~2690/50~95%/N.A.
[18]	No	No	75 × 10	820~960/40~90%/N.A.	1710~2690/40~80%/N.A. 3400~3600/40~70%/3~6 dBi
[19]	Yes	Yes	70 × 10	660~1100/25~65%/N.A.	1710~3020/60~90%/N.A. 3370~3900/50~90%/N.A. 5150–5850(70~90%)/N.A.
[20]	Yes	No	67 × 10	824~960/20~60%/−2~2 dBi	1710~2690/50~80%/2~4 dBi

[1.] MF = Metal Frame. [2.] MBC = Metal Back Cover. [3.] BWlow = Bandwidth at lower-band. [4.] BWhigh = Bandwidth at higher-band.η = efficiency. N.A. = Not Applicable.

6. Conclusions

In this paper, a novel and compact reconfigurable 3-D slot antenna with a metal casing which can be applied to 5G smartphones is proposed and studied. Three back-to-back PIN diodes are used to achieve four working states with the reflection coefficient less than −6 dB throughout the 698–1000 MHz and 1500–3000 MHz bands and the sub-6G bands (3100–3800 MHz & 4400–5000 MHz). The proposed antenna has a very small ground clearance. It is a promising candidate for LTE/5G smartphone application.

Author Contributions: Conceptualization, P.Y.; project administration, writing and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China under Grant 61871101, and in part by the National Key Research and Development Program of China under Grant 2016YFC0303501.

Conflicts of Interest: The author declares no conflict of interest.

References

1. World Radio Communication Conference Allocates Spectrum for Future Innovation. Available online: http://www.itu.int/net/pressoffice/press_releases/2015/56.aspx (accessed on 23 November 2019).
2. The Ministry of Industry and Information Technology Has Been Informed of the Use of 3300–3600MHz and 4800–5000MHz Frequency Bands in the Fifth Generation Mobile Communication System. Available online: http://www.miit.gov.cn/ (accessed on 23 November 2019).
3. LTE Frequency Bands and Spectrum Allocations. Available online: http://www.radio-electronics.com (accessed on 23 November 2019).
4. Wong, K.L. *Planar Antennas for Wireless Communications*; Wiley: New York, NY, USA, 2003.
5. Hossa, R.; Byndas, A.; Bialkowski, M.E. Improvement of compact terminal antenna performance by incorporating open-end slots in ground plane. *IEEE Microw. Wirel. Compon. Lett.* **2004**, *14*, 283–285. [CrossRef]
6. Guo, Q.; Mittra, R.; Lei, F.; Li, Z.; Ju, J.; Byun, J. Interaction between internal antenna and external antenna of mobile phone and hand effect. *IEEE Trans. Antennas Propag.* **2013**, *61*, 862–870. [CrossRef]
7. Ban, Y.-L.; Qiang, Y.-F.; Chen, Z.; Kang, K.; Guo, J.-H. A dual-loop antenna design for hepta-band WWAN/LTE metal rimmed smartphone applications. *IEEE Trans. Antennas Propag.* **2015**, *63*, 48–58. [CrossRef]
8. Zhang, L.-W.; Ban, Y.-L.; Sim, C.-Y.-D.; Guo, J.; Yu, Z.-F. Parallel dual-loop antenna for WWAN/LTE metal-rimmed smartphone. *IEEE Trans. Antennas Propag.* **2018**, *66*, 1217–1226. [CrossRef]

9. Wong, K.-L.; Wu, Y.-C. Small-size dual-wideband IFA frame antenna closely integrated with metal casing of the LTE smartphone and having decreased user's hand effects. *Microw. Opt. Technol. Lett.* **2016**, *58*, 2853–2858. [CrossRef]
10. Song, Y.; Modro, J.; Wu, Z.; O'Riordan, P. Miniature multiband and wideband 3-D slot loop antenna for mobile terminals. *IEEE Antennas Wirel. Propag. Lett.* **2006**, *5*, 148–151. [CrossRef]
11. Chang, C.-H.; Wong, K.-L. Internal multiband surface-mount monopole slot chip antenna for mobile phone application. *Microw. Opt. Technol. Lett.* **2008**, *50*, 1273–1279. [CrossRef]
12. Wong, K.-L.; Tsai, C.-Y. Low-Profile dual-wideband inverted-T open slot antenna for the LTE/WWAN tablet computer with a metallic frame. *IEEE Trans. Antennas Propag.* **2015**, *63*, 2879–2886. [CrossRef]
13. Wong, K.-L.; Tsai, C.-Y. Dual-wideband U-shape open-slot antenna for the lte metal-framed tablet computer. *Microw. Opt. Technol. Lett.* **2015**, *57*, 2677–2683. [CrossRef]
14. Wong, K.-L.; Huang, C.-Y. Triple-wideband open-slot antenna for the LTE metal-framed tablet device. *IEEE Trans. Antennas Propag.* **2015**, *63*, 5966–5971. [CrossRef]
15. Wong, K.-L.; Li, Y.-J. Low-profile open-slot antenna with three branch slots for triple-wideband LTE operation in the metal-framed smartphone. *Microw. Opt. Technol. Lett.* **2015**, *57*, 2231–2238. [CrossRef]
16. Stanley, M.; Huang, Y.; Wang, H.; Zhou, H.; Tian, Z.; Xu, Q. A Novel reconfigurable metal rim integrated open slot antenna for octa-band smartphone applications. *IEEE Trans. Antennas Propag.* **2017**, *65*, 3352–3363. [CrossRef]
17. Ban, Y.-L.; Qiang, Y.-F.; Wu, G.; Wang, H.; Wong, K.-L. Reconfigurable narrow-frame antenna for LTE/WWAN metal-rimmed smartphone applications. *IET Microwaves Antennas Propag.* **2016**, *10*, 1092–1100. [CrossRef]
18. Chen, Q.; Lin, H.; Wang, J.; Ge, L.; Li, Y.; Pei, T.; Sim, C.-Y.-D. Single ring slot-based antennas for metal-rimmed 4G/5G smartphones. *IEEE Trans. Antennas Propag.* **2019**, *67*, 1476–1487. [CrossRef]
19. Xu, H.; Wang, H.; Gao, S.; Zhou, H.; Huang, Y.; Xu, Q.; Cheng, Y.J. A compact and low-profile loop antenna with six resonant modes for LTE Smartphone. *IEEE Trans. Antennas Propag.* **2016**, *64*, 3743–3751. [CrossRef]
20. Zhang, H.-B.; Ban, Y.-L.; Qiang, Y.-F.; Guo, J.; Yu, Z.-F. Reconfigurable loop antenna with two parasitic grounded strips for WWAN/LTE unbroken-metal-rimmed smartphones. *IEEE Access* **2017**, *5*, 4853–4858. [CrossRef]
21. Yang, Z.-X.; Yang, H.-C.; Hong, J.-S.; Li, Y. Bandwidth enhancement of a polarization-reconfigurable patch antenna with stair-slots on the ground. *IEEE Antennas Wirel. Propag. Lett.* **2014**, *13*, 579–582. [CrossRef]
22. Zhang, Z.J. *Antenna Design for Mobile Devices*; John Wiley & Sons Singapore Pte. Ltd.: Singapore, 2017.
23. Behdad, N.; Sarabandi, K. A wide-band slot antenna design employing a fictitious short circuit concept. *IEEE Trans. Antennas Propag.* **2005**, *53*, 475–482. [CrossRef]
24. Behdad; Sarabandi. A multiresonant single-element wideband slot antenna. *IEEE Antennas Wirel. Propag. Lett.* **2004**, *3*, 5–8. [CrossRef]