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Design of Compact Wideband/Bi-Band Frequency Reconfigurable Antenna for IoT Applications

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Abstract
This paper discusses the design and performance of a frequency reconfigurable antenna for Internet of Things (IoT) applications. The antenna is designed to operate on multiple frequency bands and be reconfigurable to adjust to different communication standards and environmental conditions. The antenna design consists of monopole with one PIN diode and 50Ω feed line. By changing the states of the diode, the antenna can be reconfigured to operate in a dual-band mode and a wideband mode. The performance of the antenna was evaluated through simulation. The antenna demonstrated good impedance matching, acceptable gain, and stable radiation patterns across the different frequency bands. The antenna has compact dimensions of (26×19×1.6) mm^3. It covers the frequency range 2.95 GHz -8.2 GHz, while the coverage of the dual- band mode is (2.7-3.8) GHz and (4.57-7.4) GHz. The peak gain is 1.57 dBi for the wideband mode with omnidirectional radiation pattern. On the other hand, the peak gain of the dual-band mode is 0.87 dBi at 3 GHz and 0.47 dBi at 6 GHz with an omnidirectional radiation pattern too.

Keywords
Wideband Antenna, Dual-Band, Reflection Coefficient, IoT Applications.

I. INTRODUCTION

The reconfigurable antenna is an antenna that can be electronically adjusted to operate on different frequencies or radiation patterns. These antennas are designed to be adapted to variable signal environments, such as different frequencies, polarizations, or directions of radiation. Reconfigurable antennas typically use one or more tuning elements, such as varactors, PIN diodes, or MEMS (Micro-Electro-Mechanical Systems) switches to change their operating frequency or radiation pattern. By changing the configuration of these elements, the antenna can be re-tuned to operate at different resonant frequencies or to adjust its radiation pattern to focus its energy in a specific direction [1], [2]. In recent years, a number of different configurations of reconfigurable microstrip antennas have been presented [3], [4], [5], [6], [7]. Microstrip antennas are widely used because of their skinny, low-cost, lightweight, and low profile, which make them suitable for space-limited applications [8], [9].

Reconfigurable antennas have several advantages over traditional fixed antennas, including increased flexibility, adaptability, and functionality. They can be used in a wide range of applications, such as wireless communication systems, radar, and satellite systems, where their ability to overcome the harsh conditions of these channels can improve the performance and reliability of the entire system. However, the challenge of the design and implementation of reconfigurable antennas is serious since it requires careful optimization of the antenna structure, tuning elements, and control circuitry. In addition, reconfigurable antennas may have higher complexity and cost compared to fixed antennas [10], [11], [12].

Reconfigurable antennas can be used in Internet of Things (IoT) applications to adapt their operation to variable environments of the channels in order to improve wireless communication performance. In IoT systems, reconfigurable an-

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tennas can enable devices to operate at different frequency bands or communication protocols according to the variation of environmental conditions. The design of a frequency-reconfigurable multimode antenna requires careful consideration of several factors, including the frequency range, size, bandwidth, gain, radiation pattern, impedance matching, cost, and tuning methods. The antenna should be able to switch between different configurations quickly and efficiently while maintaining high performance in terms of gain, efficiency, and radiation pattern [13]. Generally, the frequency reconfigurable multimode antennas are a promising solution for wireless communications in IoT devices, which enable devices to operate at multiple frequency bands and modes as well as their ability to adapt the system to the fluctuated channel conditions. Some of the most important examples of IoT applications that use reconfigurable antennas are listed below [14], [15], [16], [17]:

1. Smart homes and buildings: Reconfigurable antennas can adapt to different wireless communication standards, such as Wi-Fi, ZigBee, or Bluetooth to ensure reliable wireless communication between IoT devices.
2. Industrial IoT: Reconfigurable antennas can enable wireless communication in harsh environments with high levels of interference or signal attenuation by adjusting the antenna's radiation pattern or frequency band.
3. Healthcare: Reconfigurable antennas can be used in wearable medical devices, such as biosensors, to improve wireless communication reliability and reduce interference from other sources.
4. Agriculture: Reconfigurable antennas can improve wireless communication in agricultural IoT systems, such as precision farming, by adjusting the antenna's radiation pattern to focus the energy in a specific direction.

The design of reconfigurable antennas for IoT applications requires careful consideration of the communication standards, frequency bands, and environmental conditions in which the antenna operates. The use of multimode reconfigurable antennas for IoT applications has been the subject of extensive research in recent years. These antennas can operate on multiple frequency bands and communication protocols, making them suitable for various IoT applications.

In [14], the authors propose a frequency-reconfigurable antenna with a combination of an open loop filter and a hairpin bandpass filter. The reconfigurability is achieved by PIN diodes for various switching conditions, the designed antenna resonates at 2.47 GHz, 7.18 GHz, 12.14 GHz, 3.42 GHz, 14.55 GHz, and 8.4 GHz. A reconfigurable pattern multifunctional compact antenna was proposed in [18]. The feeding network changes and the ground plane is used as a reflector to make the pattern changeable. To make it compatible with brand-new Internet of Things devices, the antenna is reformed to be like a credit card. The proposed reconfigurable antenna is achieved with four PIN diodes, and the configuration efficiencies are achieved with a low-cost, lossy FR-4 substrate. In [19], a reconfigurable printed antenna for portable IoT applications was proposed. A design for an air gap-separated smart-printed monopole antenna and a hexagonal matching load (HML) is suggested. A coplanar waveguide supplies the patch, and two PIN diodes connect the HML to the ground plane to control the surface current motion and enable antenna reconfiguration. A microwave frequency band-operating low-profile frequency reconfigurable monopole antenna was suggested in [20]. The proposed structure is printed on an FR-4 substrate, and four PIN diodes are embedded between transmitting patches for exchanging the different working modes. The proposed design covers single, dual, and triple bands. At the appropriate resonant frequency (or frequencies), the designed antenna has a gain of 1.2 to 3.6 dBi and an efficiency of 84% and with an overall size of $40 \times 32 \times 1.6\ mm^3$. The antenna is usable in both IoT-enabled systems in smart cities and modern handheld fifth-generation (5G) devices due to its relatively small size and its support for multiple wireless standards.

In general, these studies demonstrate the potential of multimode reconfigurable antennas for IoT applications. The reconfigurability of these antennas enables them to operate at multiple frequency bands and communication protocols, as well as to improve their flexibility and versatility. The compact size and wideband operation of these antennas also make them suitable for various IoT devices. However, further research is needed to optimize the design and performance of these antennas and to evaluate their performance in real-world IoT applications.

In this article, a compact frequency reconfigurable antenna for IoT applications is suggested. A single PIN diode is used to modify the current of the radiating patch to ensure a wideband mode at the ON state. The OFF state of the PIN diode results in two monopoles with different lengths that make the antenna operate in dual-band mode. The diode is positioned on a slit engraved on the antenna patch to change the electrical length of the radiating element by altering the distribution of the surface current according to its state. The whole size of the antenna is $(26{\times}19{\times}1.6)\ mm^3$ with two modes of operation. The operational range for the ON-state is (2.95-8.2) GHz, whereas the OFF-state provides bi-band operation of 3 GHz and 6 GHz for WiMAX and WLAN applications.

The proposed frequency reconfigurable antenna design steps are discussed in Section II. Section III illustrates the PIN diodes configurations, their states, and their operating modes. In order to find the optimal parameter values for the proposed design, a parametric study has been carried out in Section IV. The proposed antenna simulated results are discussed in Section V in addition to a comparison with some relevant works. Section VI summarized this work with a brief conclusion.

II. ANTENNA DESIGN

The structure of the proposed antenna is shown in Fig. 1. A monopole patch antenna is used to obtain a wide bandwidth, which is characterized by its partial ground plane. The structure of the monopole patch antenna typically consists of the following main components: radiating element, ground plane, dielectric substrate, and feed line. The radiating element is a metal patch that is located on the top layer of a dielectric substrate. In the top layer of the substrate, the rectangular metal patch of the proposed antenna is fed by a microstrip line. The ground plane of a monopole patch antenna is a conductive layer that is located on the bottom layer of the dielectric substrate. The ground plane serves as a reflecting surface for electromagnetic energy radiated by the patch. The dielectric substrate is a non-conductive material that separates the radiating element and the ground plane. The feed line is a transmission line that connects the monopole patch antenna to the transmitter or receiver. The initial structure is based on the basic shape of the rectangular monopole antenna shown in Fig. 2(a) using the low-cost FR4 substrate, which has a dielectric constant of 4.3, a loss tangent of 0.025, and a height of 1.6mm. The microstrip feed line characteristic impedance is set to be 50 Ω. The overall dimensions of the proposed antenna are 26mm × 19mm, and the initial parameters are given in Table I. The reflection coefficient of the initial design is shown in Fig. 2(b), whose -10dB bandwidth covers the range (2.98-8.37) GHz. The conventional design equations for the initial monopole antenna at a center frequency of f_o=3.5 GHz are as follows [21]:

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

$$L = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}} - 0.824h[\frac{(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{W}{h}+0.8)}] \tag{2}$$

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_{reff}}[\frac{W_f}{h}+1.393+0.667ln(\frac{W_f}{h}+1.444)]} \tag{3}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+12\frac{h}{W_f}]^{\frac{-1}{2}} \tag{4}$$

where W is the patch width, f_o is the antenna resonant frequency, L is the radiator length, ε_r is the substrate dielectric constant, ε_{reff} is the substrate effective dielectric constant, h is the substrate height, and Wf is the feedline width.

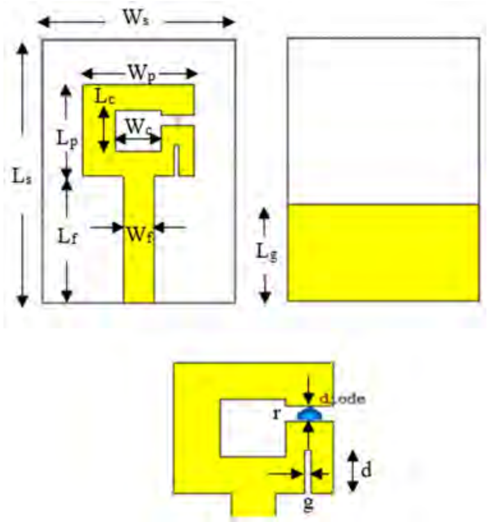
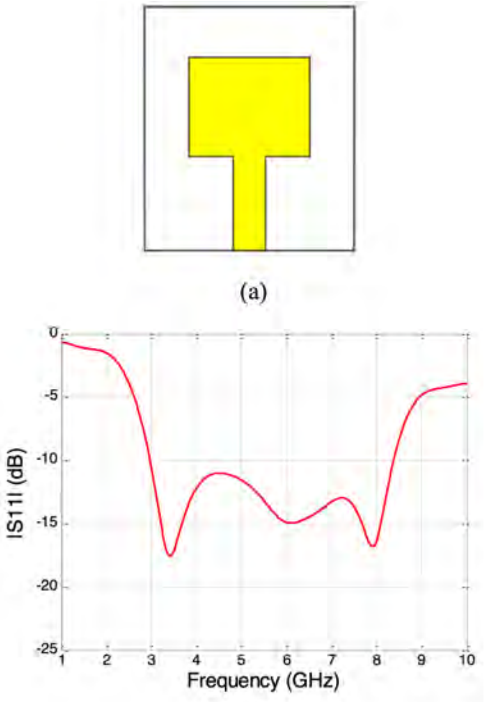


Fig. 1. The proposed antenna structure.

TABLE I.
The initial dimensions of the proposed antenna

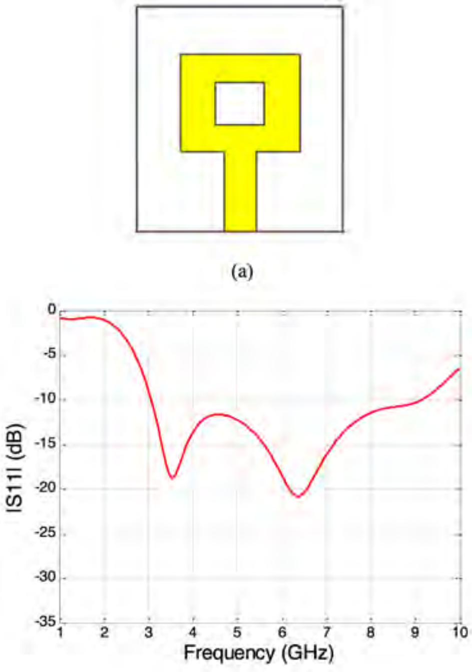
Parameter	Dimension (mm)	Parameter	Dimension (mm)
W_s	19	L_p	9
L_s	26	L_f	12
L_g	9.5	W_f	3
W_p	11		

The microstrip antenna is transformed into a planar monopole antenna by the partial coverage of the ground plane to convert it from $\lambda_g/2$ resonator to $\lambda_g/4$ resonator [21]. In Fig. 3(a), the parameter values are modified by engraving 4×4.5 mm2 rectangular slot on the radiating patch. The reflection coefficient also has wideband coverage with -10 dB bandwidth covering the range (3-9) GHz as shown in Fig. 3(b). After that, a slit of 1 mm width is inserted to make two unequal monopole antennas as shown in Fig. 4(a). As can be seen in Fig. 4(b), this step leads to a dual-band centered at 3 GHz and 6.4 GHz with -32.35 dB and -22.75 dB, respectively. Finally, another slit is engraved on the shorter monopole as illustrated in Fig. 5(a) to increase the length of the current path of the antenna that leads to shifting the resonant frequency down to 3 GHz and 6 GHz as shown in Fig. 5(b). The PIN diode used to switch the operation of the antenna is SMP1340-079LF. The purpose of inserting the PIN diode is to accomplish the frequency reconfigurability as will be explained in the next section. The ON-state of the PIN diode results in a complete square ring with wideband operation, while the OFF-state results in a dual-band operation due to the presence of the two unequal monopoles.



(b)

Fig. 2. (a) The basic shape and (b) the reflection coefficient response.



(b)

Fig. 3. (a) The radiator element with rectangular slot and (b) the reflection coefficient response.

III. PIN DIODE CONFIGURATION AND OPERATION

PIN diodes can be used to design frequency reconfigurable antennas by controlling the effective length of the radiating element. By incorporating multiple PIN diodes into the antenna design, different parts of the antenna can be switched ON or OFF to switch the antenna frequency response to different operating frequencies.

The PIN diode can be modeled in a reconfigurable antenna design as a variable reactance element. The model can be represented as a shunt or series element, depending on the design requirements. In a shunt configuration, the PIN diode is placed in parallel with the radiating element. In the proposed design, one PIN diode was used to ensure the reconfigurability from wide band to bi-band [22].

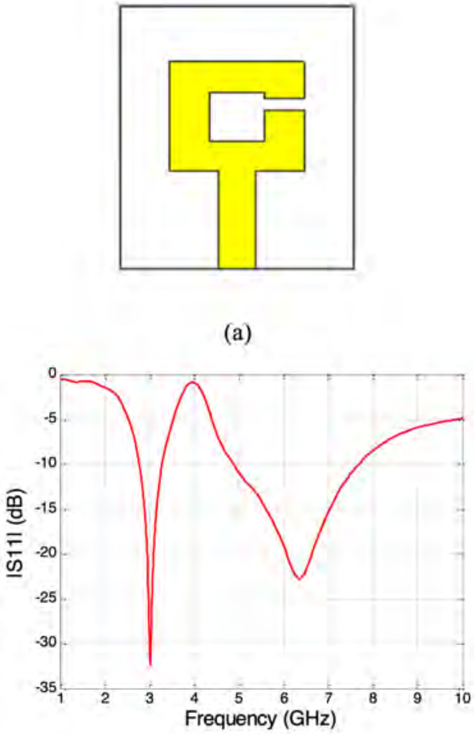
In this work, one PIN diode (SMP1340-079LF) is used to switch the frequency response of the antenna from wideband to bi-band. The PIN diode exhibits open and short circuit behavior that results in a reorganization of the antenna operating frequency and a change in its effective resonant length. In order to ensure that the appropriate current density flows through the radiator, the ON and OFF states of diodes are used. As a result, the ON-state of the diode results in a complete square annular patch that operates as a wideband antenna.On the other hand, the OFF-state cuts the antenna patch into two unequal monopole antennas to operate as a dual-band antenna.Fig. 6 depicts the equivalent circuits of a PIN diode at its ON and OFF states [7].It is merely an RL series circuit with an inductor labeled ”L” and a low-value resistor labeled ”R1” for the ON-state. However, it is comparable to an RLC circuit in the OFF-state with an inductor named ”L” in series with parallel combination of a high-value resistor named ”R2” and a capacitor named ”C”. It has been modeled in CST with R1 = 0.85 Ω, R2 = 0.85 Ω, L = 0.7 nH, and C = 0.21 pF, according to datasheet of the SMP1340-079LF PIN diode.

IV. PARAMETRIC STUDY

Antenna dimensions play a critical role in determining its operating characteristics, including its radiation pattern, bandwidth, and impedance matching. These dimensions are the length and width of the radiator, the length of partial ground, the feed line dimensions, as well as the length and width of the slits.

The insertion of a slit in the antenna radiator has a significant impact on the antenna's operating characteristics.

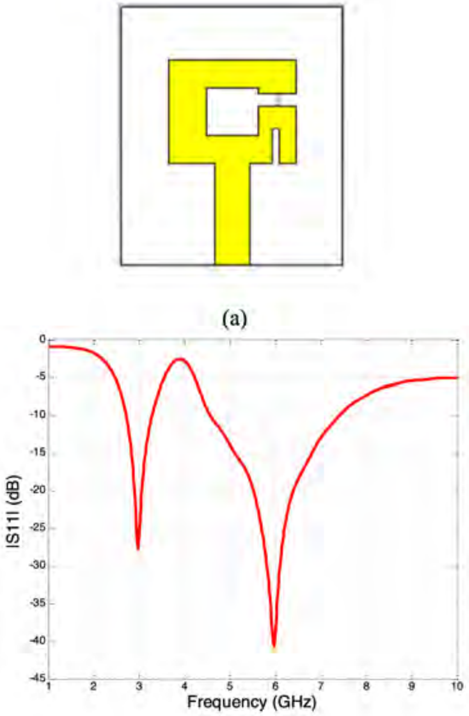
Fig. 7 displays the effect of slit width g and slit length d on the ON-state antenna reflection coefficient response. The



(a)

(b)

Fig. 4. (a) A small slit for integrating diode and (b) the reflection coefficient response.



(a)

(b)

Fig. 5. (a) The second slit on the lower corner and (b) The reflection coefficient response.

effect of slit width *g* and slit length *d* on the OFF-state antenna reflection coefficient response is shown in Fig. 8. The dual-band response and the wideband response are both affected by the variation the parameter d.At the wideband mode, the bandwidth decreases as the value of *d* increases.For the dual-band mode, it controls the matching of the second resonant frequency because the slit is located at the shorter monopole that is responsible for the generation of that resonant frequency. At *d* equal to 3mm, a wide bandwidth for the wideband mode and good matching characteristics for the dual-band mode are guaranteed. At both wideband and dual-band, the parameter *g* does not cause a noticeable influence on both modes, but *g*=0.5 mm provides better matching than the other values especially at the second resonant frequency.

Overall, antenna dimensions are critical parameters that need to be optimized to achieve the desired operating characteristics. A careful parametric study of antenna dimensions can help in designing antennas that are efficient, compact, and well-suited for IoT applications. The proposed antenna final structure is optimized as shown in Table II, as determined by the parametric study. The CST Microwave Studio software is used to obtain all of the simulation results [23].

V. RESULTS

The antenna reflection coefficient at the diode ON-state is illustrated in Fig. 9. The -10 dB bandwidth of the antenna covers the range from 2.95 GHz to 8.2 GHz. When the diode is at OFF-state, the effective length of the radiator is changed due to altering of surface current distribution so that the corresponding response shows a dual-band that resonate at 3 GHz and 6GHz with reflection coefficient values of -27.78 dB and -40.7 dB, respectively, as shown in Fig. 10. In addition, the fractional bandwidths are 19% at 3 GHz and 47% at 6 GHz band.

Fig. 11 shows the proposed antenna simulated surface current distributions at the OFF-state. At 3GHz, the majority of the currant is concentrated at the longer monopole, while the majority of the current is concentrated at the shorter monopole and the lower slit at 6 GHz. In addition, Fig. 12 shows the proposed antenna surface current distributions at the ON-state at the three resonant frequencies of the antenna. As expected, the first resonant frequency results in a current covering the entire patch. Meanwhile, the second and third resonant frequencies result in current concentrations at two and three different regions, respectively, along the edge of the patch.

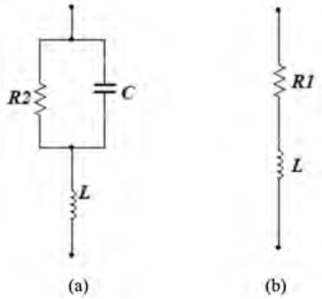


Fig. 6. The equivalent circuit of the PIN diode (a) OFF-state (b) ON- state.

TABLE II.
The optimized parameters of the proposed antenna.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
W_s	19	W_f	3
L_s	26	L_c	4
L_g	9.5	W_c	4.5
W_p	11	d	3
L_p	9	g	0.5
L_f	12.5	r	1

Figures 13 and 14 depict the antenna simulated normalized power patterns at OFF-state and ON-state of the PIN diode, respectively. It is clear that the power pattern of the antenna is omnidirectional for both states of the PIN diode, which is preferable for IoT portable devices since this pattern is location independent.

Fig. 15 (a) and (b) depicts the simulated gain responses for the dual-band mode and the wideband mode,respectively. For dual-band mode, the peak value of the simulated gain is 0.86 dBi at 3 GHz and 0.47 dBi at 6 GHz, while the peak gain is 1.57 dBi for the wideband mode. As long as the gain values are larger than 0dB, the antenna radiation characteristics are acceptable for short range applications [21].

It is important to note that, despite the antenna small size, the gain value is perfect and extremely beneficial for IoT applications. The characteristics of the proposed antenna structure are compared to those of some previous frequency reconfigurable antennas in Table III. The table makes it abundantly clear that the proposed antenna has excellent radiation performance, a wide bandwidth in spite of its compact size compared to the other antennas.

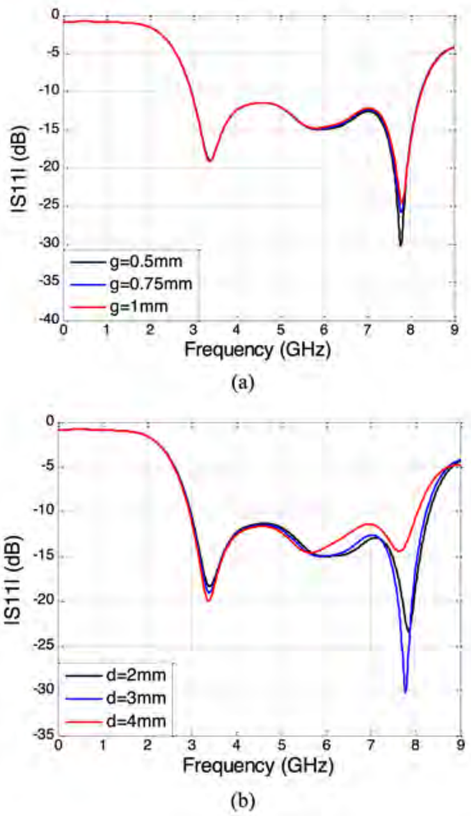


Fig. 7. (a) The effect of slit width at ON-state (b) The effect of slit length at ON-state.

VI. CONCLUSION

A compact frequency-reconfigurable antenna with dual-band and wideband operational modes is designed in this paper. The structure of the antenna patch is modified in accordance with the PIN diode ON and OFF states. The presented antenna covers dual frequency bands of 3GHz and 6 GHz when the switch is turned OFF. Meanwhile, the antenna operates at wideband mode when the PIN diode at its ON-state. The wideband mode has a peak value of the realized gain of 1.57 dBi with an omnidirectional power pattern, while the peak gain of the dual-band mode is 0.85 dBi with omnidirectional power pattern too. These results make the antenna very compatible with the IoT portable WIMAX and WLAN devices. The proposed antenna has numerous advantages including its small size, low cost, and simple configuration, which make it suitable for integrated with any IoT gadgets.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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TABLE III.
The optimized parameters of the proposed antenna.

Ref.	Size (mm3)	Coverage Bands	Operational Frequencies (GHz)	ReconfigurableTech.	Peak Gain (dBi)
[10]	30×30	Wide, Dual and Tri band	1.8–4.5 2.17-2.35 2.64–2.85 2.62–2.93	PIN-diode (2)	3.7
[14]	38 × 40	Multiband	2.13 to 3.0 6.8 to 8.36 12.039 to 13.14	PIN-diode (3)	5.6
[18]	30 × 23	Single and dual band	2.45 and 3.7	PIN-diode (2)	3
[24]	100×100	Single band	2.2–3.8	PIN-diode (2)	6.5
[25]	25×27	Single and Dual Band	2–6	PIN-diode (2)	2.8
[26]	50×33	Wide and Dual Band	2–3.75	PIN-diode (2)	3.2
[27]	88×88	Wideband and multiband	2-6	PIN-diode (4)	3
[28]	90 × 90	Wideband and dual band	3.1-10.6,3-4.5,4.4-6	PIN-diode (4)	3.9
[29]	35 × 25	Wideband and dual band	2.76-8.21, 2.45 and 5.8	PIN-diode (1)	2.49
[30]	60.8 × 48	Wideband and dual band	2.5 -10.5, 3.31 and 5.1	Ideal switch (5)	NR
[31]	35.8 × 35	Wideband and dual band	3-6, 3.7 and 5.8	metal switch (2)	4
This work	26 × 19	Wideband and dual band	2.95-8.2 3 and 6	PIN-diode (1)	1.57

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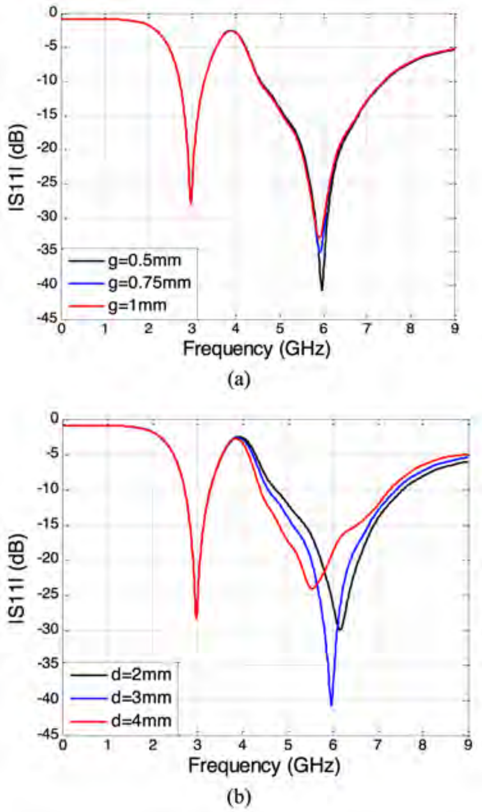

Fig. 8. (a) The effect of slit width at OFF-state (b) The effect of slit length at OFF-state.

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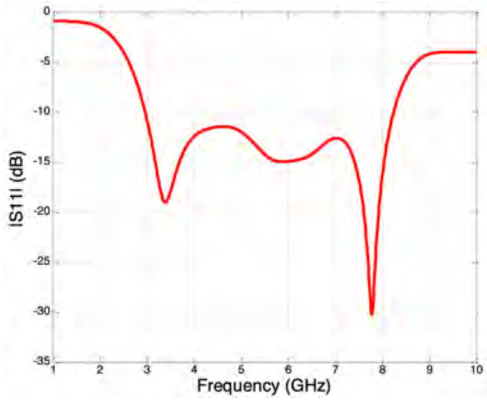

Fig. 9. The simulated reflection coefficient of the antenna at ON-state.

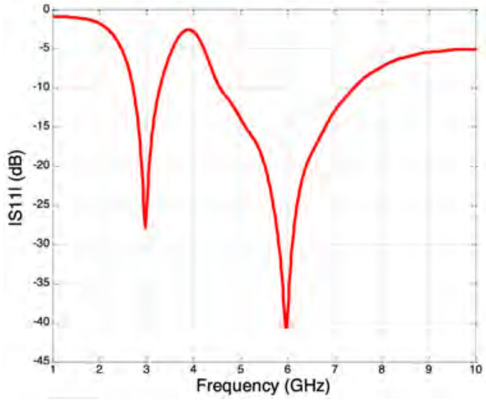

Fig. 10. The simulated reflection coefficient of the antenna at OFF- state.

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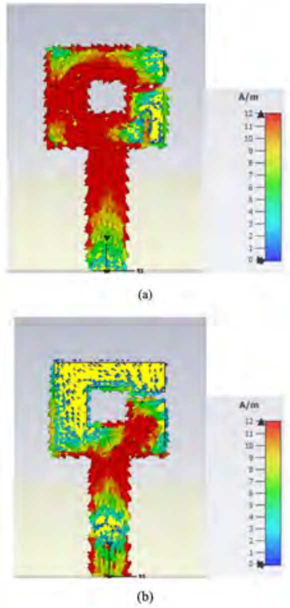
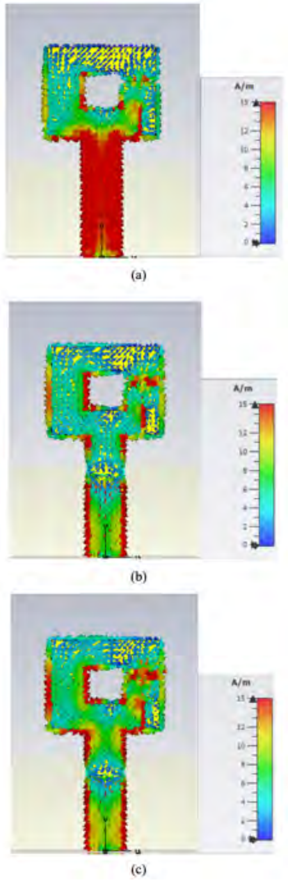


(a)
(b)

Fig. 11. The OFF-state surface current distribution at a- 3 GHz, b- 6 GHz.



(a)
(b)
(c)

Fig. 12. The ON-state surface current distribution at a- 3.4 GHz, b- 6 GHz, c- 7.8 GHz.

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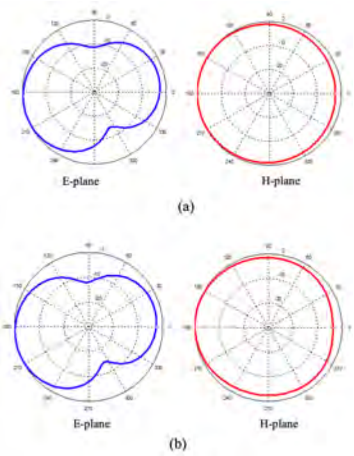

Fig. 13. The radiation patterns of the proposed antenna for the OFF- state at (a) 3 GHz, (b) 6 GHz.

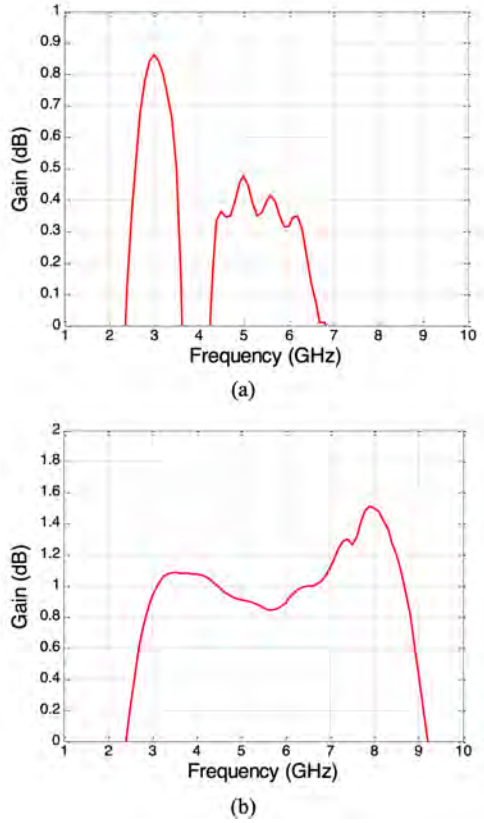

Fig. 15. The gain of the proposed reconfigurable antenna (a) ON-state (b) OFF-state.

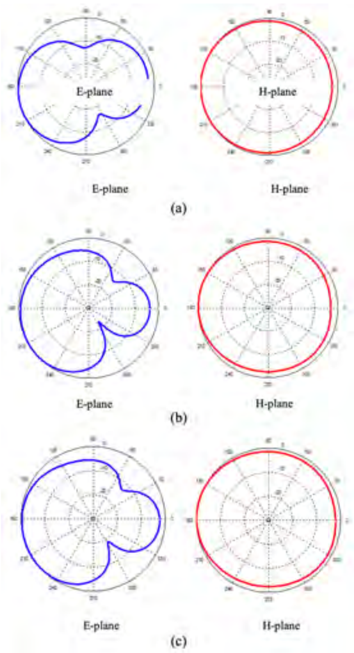

Fig. 14. The radiation patterns of the proposed antenna for the ON- state at (a) 3.4 GHz, (b) 6 GHz, (c) 7.8 GHz.