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RESEARCH ARTICLE

A Flexible and Bandwidth Reconfigurable Antenna for Cognitive Communication

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ABSTRACT This paper introduces a compact antenna with bandwidth reconfigurable and flexible characteristics for cognitive radio applications. The antenna consists of a monopole as a primary radiator and is excited by a coplanar waveguide to have a single-layer design. To adjust the operating bandwidth (BW) by fixing the lower frequency and varying the upper one, an additional stub is connected to the feeding line. This stub causes a disturbance in the current distribution, which significantly degrades the matching performance. By controlling its length, the rejected band can be changed and thus, the upper frequency is varied. To validate the proposed approach, two stubs are used, and they are connected to the feeding line through two PIN diodes. By switching the ON/OFF state of the diodes, three different states with different operating BW are attained. The fractional BWs for these states are 18.9, 33.2, and 64.3% respectively. Besides, it is also worth noting that the antenna achieves good performance when bent over a curved surface.

INDEX TERMS Bandwidth reconfigurable, flexible, monopole.

I. INTRODUCTION

In recent years, the cognitive radio (CR) technique has attracted considerable attention from researchers all around the world due to its advantage in spectrum utilization [1], [2]. The cognitive communication system has the ability to use the frequency spectrum in a flexible manner according to system demands. This challenge can be addressed by designing an antenna with multifunctional or reconfigurable characteristics. Reconfigurable antennas are preferred due to their various advantages of reducing system complexity and overall antenna cost as well [3], [4], [5], [6]. Semiconductor switches, varactors, and PIN diodes are widely used to control the antenna parameters, such as radiation pattern, resonant band, polarization, and operating bandwidth. On top of that, PIN diodes are the most popular component to be used in reconfigurable antennas.

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Proposing antennas capable of varying their bandwidth (BW) is appropriate in the context of cognitive radios or any other frequency-reconfigurable wireless system. Regarding the noise level, it is calculated by $N = kTB$, where k is the Boltzmann constant, B is the system BW, and T is the system noise temperature. This equation implies that the more BW the system has, the more noise it collects. Thus, the best performance is the case where the BWs of the system and the signal are matched. This is very important for ultra-wideband (UWB) systems, where the signal is spread over a large portion of the spectrum [7], [8].

Various types of reconfigurable antennas, whose operating bands can be varied, have been reported in the literature. The BW can be changed from narrowband to narrowband [9], [10], [11], [12], [13] or wideband to narrowband [14], [15], [16], [17], [18], [19]. However, they might not be suitable for UWB communication systems with a large portion of the spectrum. According to the different communication environments or the different required BWs, the UWB systems can change the operating BW to match the signal

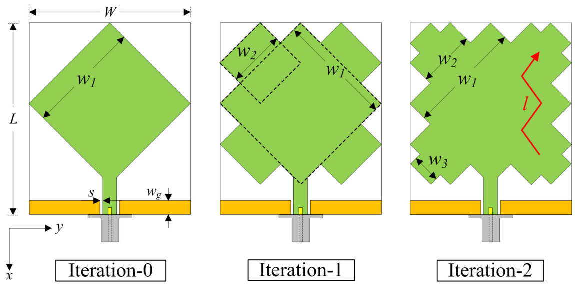


FIGURE 1. Evolution of the proposed fractal monopole antenna. The optimized dimensions are as follows: $L = 38$, $W = 32$, $w_1 = 22.6$, $w_2 = 11.3$, $w_3 = 5.65$, $w_f = 3.0$, $w_g = 7.0$, $s = 0.4$ (unit: mm).

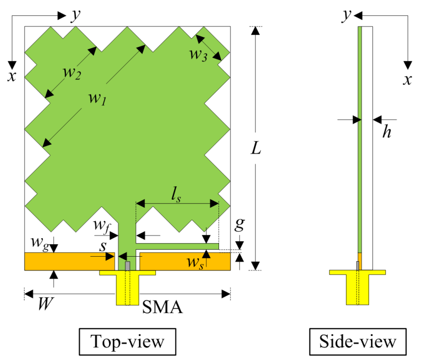


FIGURE 2. Geometry of the passive antenna. The optimized dimensions are as follows: $L = 38$, $W = 32$, $w_1 = 22.6$, $w_2 = 11.3$, $w_3 = 5.65$, $w_f = 3.0$, $w_g = 7.0$, $s = 0.4$, $w_s = 1.0$, $g = 0.2$ (unit: mm).

BW. To solve this problem, Mansoul and Ghanem in [20] and [21] has proposed reconfigurable monopole antennas with multiple slots in the ground plane, in which the operating BW can be gradually adjusted. Alternatively, the design in [22] also acquired BW reconfigurability using monopole and cascaded bandpass structures. However, a complicated switching approach is the critical drawback of such designs. Besides, they are not suitable for devices, where compact size and flexible characteristics are required.

This paper presents a bandwidth-reconfigurable antenna with a flexible configuration. The monopole is used as a primary radiator for UWB operation. Meanwhile, the BW reconfigurability is achieved by using an additional stub connected to the feeding line through PIN diodes. The antenna can gradually change the operating BW from 18.9 to 64.3%. Note that for each state, the lower frequency is fixed while the upper one is altered. For validation of the proposed concept, two stubs are connected to the feeding line through two PIN diodes. By switching the ON/OFF states of these PIN diodes, three different states with different fractional BW are realized. In addition, the antenna also obtains good radiation performance when it is bent over a curved surface.

II. DESIGN METHODOLOGY

This work aims to design a BW reconfigurable antenna, whose lower band limit is fixed and the upper one is varied.

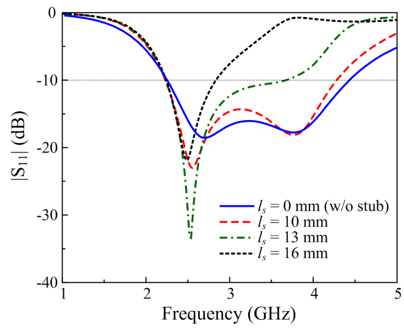


FIGURE 3. Simulated reflection coefficient $|S_{11}|$ against the variation of the stub, l_s.

Before presenting the reconfigurable design, the mechanism to tune the BW of the passive antenna with a compact size is discussed. In general, the design process of the proposed antenna can be summarized as follows:

Step 1: Design an antenna with UWB operation and compact size using fractal geometry

- For wideband operation, a monopole structure is utilized. There are various configurations developed from the fundamental geometries such as circular, square, and elliptical shapes. Here, we choose the square patch.
- For size miniaturization, various techniques have been reported including defected ground structures, meandered-line radiators, and fractal geometries. Here, we choose the fractal technique.

Step 2: Design a monopole antenna with UWB operation, compact size, and tunable BW

- For bandwidth reconfigurability, the current distribution on the antenna needs to be disturbed. In other words, the impedance matching in an arbitrary frequency band should be controlled. Here, a stub is used since it can effectively control the current flowing on the antenna.
- Design BW reconfigurable antenna with PIN diodes.

III. A COMPACT UWB ANTENNA

First of all, an evolution of a compact monopole antenna with fractal geometry is presented in Fig. 1. Note that fractal geometry can be used for UWB operation [23] or size reduction [24]. In this paper, it is utilized for size miniaturization purposes. The design is modelled on the top side of a ROGERS 5880 dielectric substrate, which has a thickness of 0.127 mm, a dielectric constant of $\varepsilon_r = 2.2$, and a loss tangent of 0.0009. A coplanar waveguide is utilized to feed the radiator. The antenna is designed to have the lowest operating frequency at 2.2 GHz. The resonant length (l) of the monopole at 2.2 GHz is calculated as following equations:

$$\varepsilon_e \approx \frac{\varepsilon_r + 1}{2} \qquad (1)$$

$$l \approx \frac{\lambda_e}{4} = \frac{c}{4\sqrt{\varepsilon_e}} \qquad (2)$$

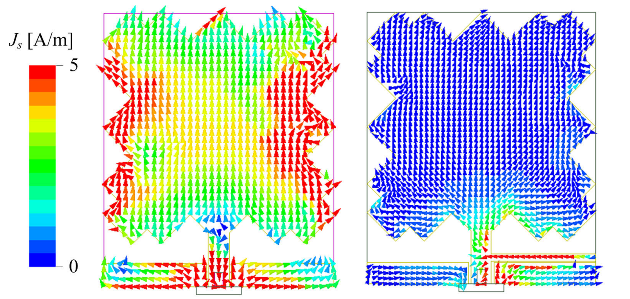


FIGURE 4. **Current distributions at 3.5 GHz for antennas without stub and with stub.**

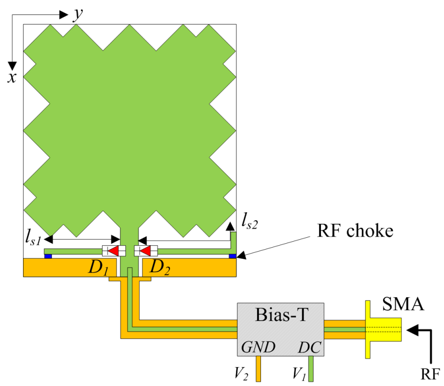


FIGURE 5. **Geometry of the proposed BW reconfigurable antenna. The optimized dimensions are as follows: $L = 38$, $W = 32$, $w_1 = 22.6$, $w_2 = 11.3$, $w_3 = 5.65$, $w_f = 3.0$, $w_g = 7.0$, $s = 0.4$, $l_{s1} = 12.3$, $l_{s2} = 17.3$, $w_s = 1.0$, $g = 0.2$ (unit: mm).**

TABLE 1. **Diode states for different operating states.**

Voltage	D1	D2	Operating states	Bandwidth
V1 = V2	OFF	OFF	State-1	58.1 % (2.2–4.0 GHz)
V1 >V2	ON	OFF	State-2	33.9 % (2.2–3.1 GHz)
V1 <V2	OFF	ON	State-3	16.7 % (2.2–2.6 GHz)

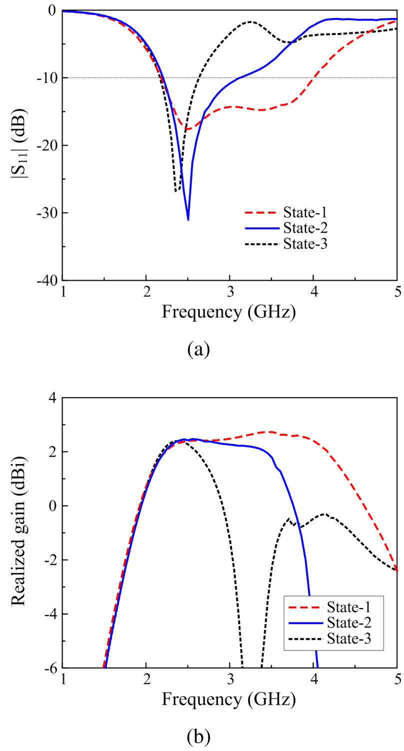


FIGURE 6. **Simulated (a) $|S_{11}|$ and (b) realized gain for different operating states.**

in which, ε_e is the effective dielectric constant of the used substrate, λ_e is the effective wavelength at 2.2 GHz and c is the light velocity. Based on these Equations, the calculated resonant length is about 27 mm. For the conventional square-shaped monopole similar to Iteration-0, its resonant length (w_1) will be around the calculated value. For the fractal design as Iteration-2, the dimensions are chosen so that w1 is two times bigger than w_2 and four times bigger than w_3, $w_1 = 2w_2 = 4w_3$. For this antenna type, the resonant length cannot be defined exactly as the conventional one. Based on the simulation, the resonant length of the fractal monopole (red line) is approximately equal to $2(w_2+w_3) = 33.9$ mm, which is 1.2 times bigger than the calculated value of 27 mm. It is worth noting that compared to the square-shaped monopole as Iteration-0, the fractal monopole has a smaller area of about 31% while having a similar lowest operating frequency.

IV. BW RECONFIGURABLE ANTENNA

A. BW RECONFIGURABLE MECHANISM

To adjust the operating BW, a stub is connected to the feeding line. The configurations in terms of the top-view and side-view of the proposed antenna are shown in Fig. 2. Fig. 3 shows the simulated $|S_{11}|$ against the variation of the stub. It can be seen that for the design without stub, the impedance BW is from 2.2 to 4.5 GHz, which is equivalent to about 68.6%. With the presence of the stub, the impedance BW is changed. When tuning the stub's length (l_s), the impedance BW is also significantly affected. Longer stub results in smaller impedance BW. It is noted that changing l_s only affects the upper frequency, while the lower one remains unchanged. The BW is gradually reduced from 64.6% (2.2–4.3 GHz) with $l_s = 10$ mm to 20.4% (2.2–2.7 GHz) with $l_s = 16$ mm.

For a better demonstration of the stub's effect, current distributions at 3.5 GHz for the antennas without and with stub are shown in Fig. 4. To note that for the antenna with the stub, the stub's length is chosen as 16 mm, which is about quarter wavelength at 3.5 GHz. As observed for the case without stub, the current flows symmetrically from the feeding line to the radiating patch. This is completely different from the design with the stub, the current is blocked by the stub. Therefore, the matching at this frequency is significantly degraded.

B. BW RECONFIGURABLE ANTENNA WITH DIODES

Based on the aforementioned mechanism, the BW reconfigurable antenna is realized as shown in Fig. 5. For this design,

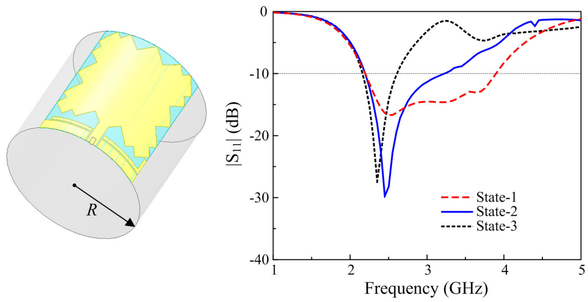
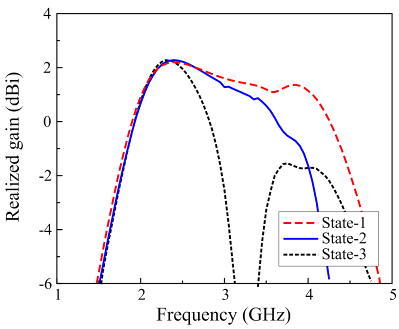
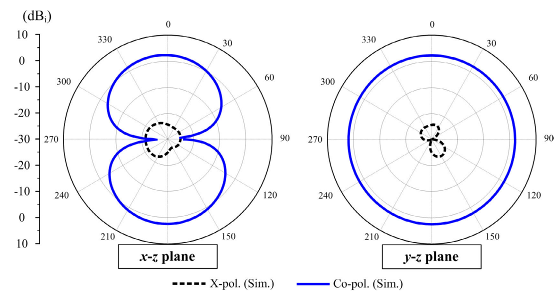


FIGURE 7. Simulated model and $|S_{11}|$ results of the flexible antenna.



(a)



(b)

FIGURE 8. Simulated (a) realized gain and (b) radiation pattern of the flexible antenna.

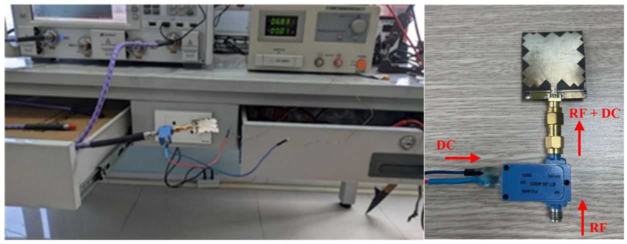


FIGURE 9. Fabricated antenna and setup with Bias-T for measurement.

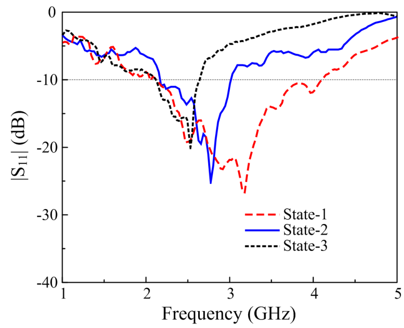


FIGURE 10. Measured $|S_{11}|$ results of the proposed antenna.

two stubs are connected to the feeding line through two PIN diodes type MADP-042305-130600 (MACOM Technical Solutions). In the simulation, the ON state of the diode is equivalent to a forward bias resistance of RPIN = 1.32 Ω and the OFF state is equivalent to a reverse bias capacitance of CPIN = 0.15 pF [25]. The arrangement of two diodes is inverse as shown in Fig. 5. In addition, the stubs are linked to the ground through two surface mount inductors, which act as the RF chokes to prevent RF currents from flowing from the stub to the ground while allowing DC current to go through. Finally, the antenna is excited by a 50-Ω coaxial cable through a Bias Tee component.

With the above biasing circuit, the DC wires are not necessary for the proposed design. This contributes to reducing the design complexity and the unwanted effect of the DC cables on the antenna performance. In addition, the ON/OFF states of two PIN diodes can be controlled independently. Here, only two DC potentials V_1 and V_2 are applied to the Bias Tee. The voltages of the feeding line and the inner conductor of SMA are similar to the DC pin of the Bias Tee, V_1. Meanwhile, the stub and the ground have a similar voltage as the GND pin of the Bias Tee, V_2. When $V_1 > V_2$, the diode D1 is ON while the D2 is OFF. In this case, the short stub is directly connected to the feeding line, while the longer stub is isolated. Conversely, the longer stub is linked to the feeding line when $V_1 < V_2$. These diodes are both in the OFF state if no voltage is applied. The operating states and the corresponding diode states of the proposed antenna are summarized and presented in Table 1.

Fig. 6 illustrates simulation $|S_{11}|$ and realized gain results of three states. As can be seen from the graph, the antenna introduces a wideband state (State-1) with an operating BW of 58.1%, ranging from 2.2 to 4.0 GHz. In this case, both diodes are OFF, and disconnect the stubs with the feeding line. The BW for State-2 is reduced to around 33.9%, from 2.2 GHz to 3.1 GHz, when the D1 is ON state. The impedance BW of State-3 is the smallest at 16.7% (2.2–2.6 GHz). It is noted that for these different states, only the upper frequency is varied while the lower one is almost stable around 2.2 GHz. The results confirm the effectiveness of the proposed approach, where the stubs are utilized to control the operating BW. In terms of realized gain in the broadside direction, outside the −10 dB $|S_{11}|$ frequency range, the gain is significantly reduced. The reason is that the current is blocked in the stub rather than flowing into the radiating element.

V. FLEXIBLE CHARACTERISTIC

Due to being modelled on the thin dielectric substrate, the proposed antenna is expected to operate normally while being attached to curved surfaces. This feature would allow the antenna to be applied in various devices and systems under different surface conditions. To investigate the conformability of the proposed design, the simulation is set so that the antenna model is wrapped outside a cylinder with a radius R. It is found that with different values of $R = 20$, 30, and 40 mm, the simulated results are almost identical. Therefore, only the reflection coefficient characteristic with $R = 20$ mm is shown here for brevity.

The simulated model and $|S_{11}|$ feature the flexible mode with $R = 20$ mm are illustrated in Fig. 7. It can be seen obviously that the antenna has stable operation, which is almost similar to the normal case (as depicted in Fig. 6). For the flexible mode, the antenna is still able to switch BW from wideband to a narrowband effectively. In addition, the lowest resonant frequencies of these operating states are similar. The gain and radiation pattern at 2.4 GHz are presented in Fig. 8. As observed, the gain behaviour is similar to the unbent case (Fig. 6b). Besides, the antenna also has good omnidirectional radiation pattern. This demonstrates the flexible characteristic of the proposed BW reconfigurable antenna.

VI. MEASUREMENT

As shown in Fig. 9, an antenna prototype is fabricated and measured to verify the design concept. The antenna is connected to the Vector Network Analyzer (VNA) through a Bias Tee type BT-26-400D. The RF pin of the Bias-T is connected to the VNA. The DC pins are connected to the DC voltage generator. Meanwhile, the other pin is connected to the antenna prototype. In general, a good agreement between the simulations and measurements is attained.

A. REFLECTION COEFFICIENT

The measured reflection coefficient results for three different operating states are presented in Fig. 10. The measured data indicate that the proposed reconfigurable antenna achieves good measured matching performance for all states with $|S_{11}|$ of less than -10 dB. These results are well-matched to the simulated results shown in Fig. 5(a). For State-1, the measured -10 dB impedance BW is from 2.12 to 4.11 GHz, equivalent to 64.3%. Regarding State-2, the BW is reduced to 33.2%, ranging from 2.16 to 3.02 GHz. Finally, the impedance BW of State-3 is the smallest, which is about 18.9% (2.11–2.55 GHz).

B. FAR-FIELD RESULTS

Fig. 11 shows the measured realized gain values in two principle planes of $x-z$ and $y-z$. The measured maximum gains are 2.25, 2.50, and 2.58 dBi for State-3, -2, and -1 respectively. It is noted that outside the -10 dB impedance BW shown in Fig. 10, the gain values are significantly reduced. In comparison with the simulated results presented in Fig. 5(b), the measured gain behavior is well-matched.

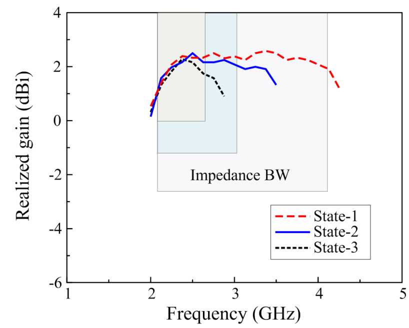


FIGURE 11. Simulated realized gain results of the proposed antenna.

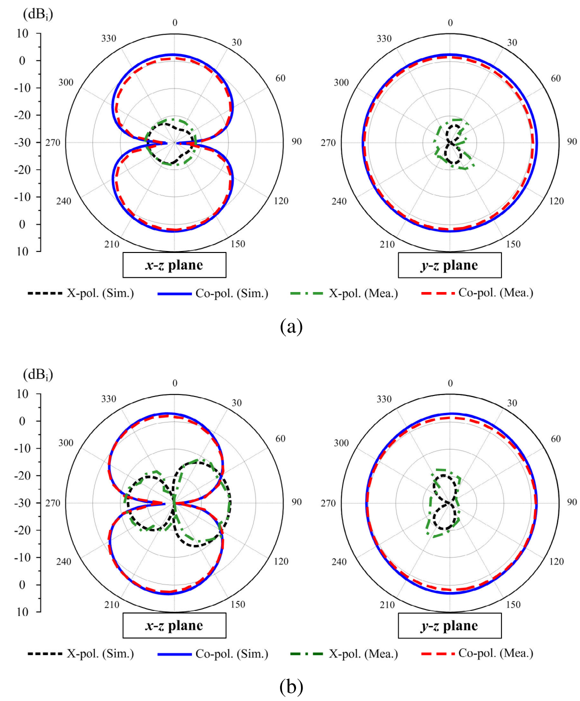


FIGURE 12. Simulated and measured gain results of the proposed antenna. (a) 2.4 GHz of State-3, and (b) 3.5 GHz of State-1.

The simulated and measured gain radiation patterns at different frequencies are plotted in Fig. 12. To save space, the radiation patterns at 3.5 GHz for State-1 and 2.4 GHz for State-3 are chosen to present. The radiation patterns for State-2 are not necessary since its operating frequency range is between State-1 and -3. The data in Fig. 12 indicate that the proposed antenna has an omnidirectional radiation pattern. This kind of pattern is useful for applications where wide coverage is required. Besides, it is also worth noting that the radiation patterns are quite similar entire the operating BW.

C. STRUCTURE CONFORMABILITY

The measured $|S_{11}|$ results in flexible mode with a 20 mm radius of the bent surface are depicted in Fig. 13. For the conformal test, the antenna is wrapped over the cylindrical foam with a radius of 20 mm. Note that this is the minimum value

TABLE 2. Performance comparison among reconfigurable monopole antennas.

References	Frequency range (GHz)	Size (mm)	Profile (mm)	Modes of operation	Reconfigurability	Tunable BW (%)	Flexibility
[12]	4.6–5.4	56 × 56	0.05	Single-band	Frequency	No	No
[13]	1.5–13.1	130 × 77	0.6	Multi-band	Frequency	No	No
[14]	3.4–5.3	75 × 35	1.57	Wideband & Single-band	Frequency	No	No
[17]	3.8–8.9	32 × 24	1	Wideband & Single-band	Frequency	No	No
[18]	2.1–5.4	30 × 25	0.06	Wideband & Dual-band	Frequency	No	Yes
[19]	2.7–8.2	35 × 25	0.25	Wideband & Tri-band	Frequency	No	Yes
[21]	1.4–3.4	56 × 54	1.6	Wideband & Dual-band	Frequency & Bandwidth	43.2–74.8	No
[22]	1.5–2.5	99 × 40	1.5	Wideband	Bandwidth	16.0–55.0	No
Proposed	2.1–4.1	38 × 32	0.01	Wideband	Bandwidth	18.9–64.3	Yes

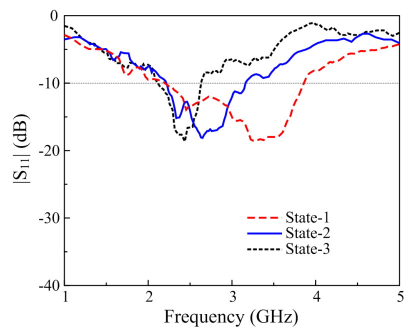


FIGURE 13. Measured $|S_{11}|$ results of the proposed antenna in the flexible mode.

of the bending radius. In the flexible mode, the reconfigurable feature is still maintained as the normal mode. The operating BW can be controlled by switching the ON/OFF states of the diodes. Additionally, the results also demonstrate the flexible characteristic of the proposed reconfigurable antenna.

D. COMPARISON

Table 2 shows a comparison between the proposed antenna and the other published works in the literature. Note that the frequency range indicates the lowest and highest operating frequencies, not the -10 dB impedance BW. For the size comparison with respect to the lowest operating frequency, the proposed design is smaller than most of the other works. Despite having a smaller size, the design in [18] has a significantly higher profile than the proposed work. In terms of reconfigurability, most of the reported designs have the potential to switch their operating frequencies. In [12], the antenna has a single-band operation, and the operating frequency can be tuned with the help of a varactor. In [13], a multi-band antenna can change its operating bands based on PIN diodes. Alternatively, antennas in [14], [17], [18], and [19] are able to alter the operation from wideband mode to single-, dual-, or tri-band mode by controlling the ON/OFF states of the PIN diodes. There are a few designs with BW reconfigurability. The designs in [21] and [22] can adjust their operating BW but cannot work in the bending condition. Besides, large sizes are also another critical drawback of these antennas. In contrast, the proposed antenna has a smaller size and also works in flexible mode. This demonstrates the advantages of the proposed antenna compared to the other related works.

VII. CONCLUSION

This paper presents and investigates the method to design a BW reconfigurable antenna with a fixed lower operating frequency. To achieve this, a stub is connected to the feeding line of the coplanar-waveguide-fed monopole antenna. By tuning the length of the stub, the matching in the high-frequency range can be controlled. Thus, the antenna operating BW can be varied while keeping the lower frequency unchanged. For better demonstration, two stubs are linked to the feeding line through two PIN diodes. By controlling the ON/OFF state of these diodes, the fractional BW of the reconfigurable antenna varies from 18.9 to 64.3%. The antenna also shows good performance when operating on curved surfaces. The proposed antenna can be used in wireless sensor networks, bio-medical imaging, and radar, which exploit the high-rate and short-range communication of UWB antenna. It is noted that the switching technique using diodes has a discrete change of the BW. In future work, the reconfigurability with the help of a varactor will be studied to achieve continuous change in operating BW.

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