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Textile Antenna with Simultaneous Frequency and Polarization Reconfiguration for WBAN

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Abstract— **This paper proposes the design of a reconfigurable circularly polarized textile antenna. The circular polarization feature in the proposed antenna is generated by the edge-truncation of a rectangular patch and the incorporation of a slotted ground plane, whilst the frequency re-configurability feature is realized by slot size modification via the use of three embedded RF PIN diode switches. Consequently, the antenna operation can be switched between six frequencies (1.57 GHz, 1.67 GHz, 1.68 GHz, 2.43 GHz, 2.50 GHz and 2.55 GHz) depending on the seven switch configurations. The proposed antenna is validated experimentally to be operable within the WBAN, WLAN and GPS range in a compact and wearable format, with gains of up to 4.8 dBi.**

Index Terms — **Textile antenna, circularly polarized antenna, reconfigurable antenna.**

I. INTRODUCTION

A reconfigurable antenna is defined as an antenna with the capability to reconfigure one or more characteristic such as frequency, polarization and/or pattern in order to fulfill a specified requirement. Such antennas are capable of offering flexible operation across different frequency bands using a single hardware which is compact, flexible, and cost-effective without compromising performance. In recent years, frequency-reconfigurable antennas have received attention among the researcher and industry communities, especially for future wireless communication systems. Such operation of frequency reconfigurable antenna is potentially capable to reduce the size of front end system and also intended for performances improvement, especially to minimize interference with other wireless system and maximizing throughput [1].

Generally, the resonant frequency of an antenna is determined by the effective length of the radiator. There are several methods of switching that may be used to control the effective length such as; varying the patch [2]–[3]; a reconfigurable matching network [4]; changing the current flow [5]; mechanical configuring using a metasurface [6]; and varying the length of the slot [7].

A reconfigurable monopole patch antenna proposed in [2] is capable of switching between up to eight different frequency bands using four PIN diodes. These RF switches are used to connect the main patch to four different smaller patches to enable the total radiating area of the antenna. Meanwhile, the antenna in [4] proposed a reconfigurable matching network using only two PIN diodes. As a result, three different frequencies bands can be realized. However, such method consumes more space for the intended matching and allows limited frequency reconfiguration. The current flow modification technique is described in a reconfigurable cedar-shaped microstrip antenna presented in [5]. Frequency re-configurability is controlled via six RF switches placed on the slits, hence altering the current flow of the cedar-shaped radiator. While copper strips are used to represent switches in this work, greater complexity is expected when this antenna is implemented using PIN diodes. Another alternative to embedded switching circuits for the purpose of enabling frequency re-configurability is by using metasurfaces [6]. The proposed metasurface located on top of a patch is rotated around the center to enable frequency reconfiguration.

Overall, the method of achieving frequency reconfiguration can be categorized in two groups, namely patch modifications and ground plane modifications. In particular, the second category is more attractive since the DC biasing networks will have minimal effect on other characteristics of the antenna, such as cross polarization and radiation pattern. This is evident in [7] where the proposed antenna is capable of achieving frequency reconfiguration with minimal effect on cross polarization. Further investigations are conducted in the work presented here to introduce other antenna configurations. The contributions from this work can be summarized as follows. Firstly, the proposed antenna does not only can reconfigure frequency, but is also capable of switching polarization from CP to linear polarization. Secondly, a method to achieve frequency reconfiguration with specified lower frequency (1.575 GHz) and upper frequency (2.45 GHz) is proposed. Finally, an in-depth investigation is conducted of the location of the slots on the ground plane to ensure the antenna operates at 1.575 GHz with good axial ratio (AR) bandwidth. The presented reconfigurable antenna is fully fabricated using textiles to enable ease of integration with clothing and to ensure users' comfort [8]–[9]. This design was initially studied

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in [10] using ideal switch representation (copper strips), while its simulated axial ratio and radiation patterns were discussed in [11]. The design was then re-optimized and fabricated using three actual PIN diodes embedded on its ground plane. This design is capable of operating in dual-polarized mode: in circular polarization in the lower band (1.575 GHz) and in linear polarization in the upper frequency band (2.45 GHz) compared to [12] and [13] which are only linearly polarized. The simulated and measured performance of the antenna will be presented in the following sections.

II. ANTENNA DESIGN CONFIGURATION AND ANALYSIS

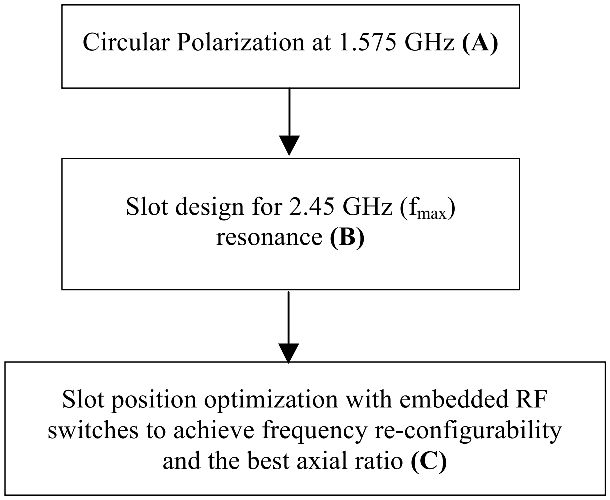
The methodology illustrated in Fig. 1 is used to design the proposed antenna. In this work, the frequency reconfigurable antenna is specifically designed to operate with f_{min} of 1.575 GHz and f_{max} of 2.45 GHz. Therefore, a simple and useful design strategy is proposed in this work, as follows. First, the conventional rectangular patch antenna is designed to operate at 1.575 GHz. Next, the antenna is modified with a truncation [denoted as r] to obtain circular polarization. The next step is the introduction of a slot on the ground plane of the antenna. The slot dimension, width and length are optimized to obtain f_{max} resonance at 2.45 GHz. Finally, the position of the slot is parametrically shifted along the $\pm y$ axis to investigate the changes on reflection coefficient and axial ratio. With this strategy, an optimized slot location to result in the best axial ratio bandwidth can be identified. In the next stages, the positioning of the switches and modification of the ground plane for DC biasing network are performed. A detailed design and antenna analysis will be performed in the following subsection.

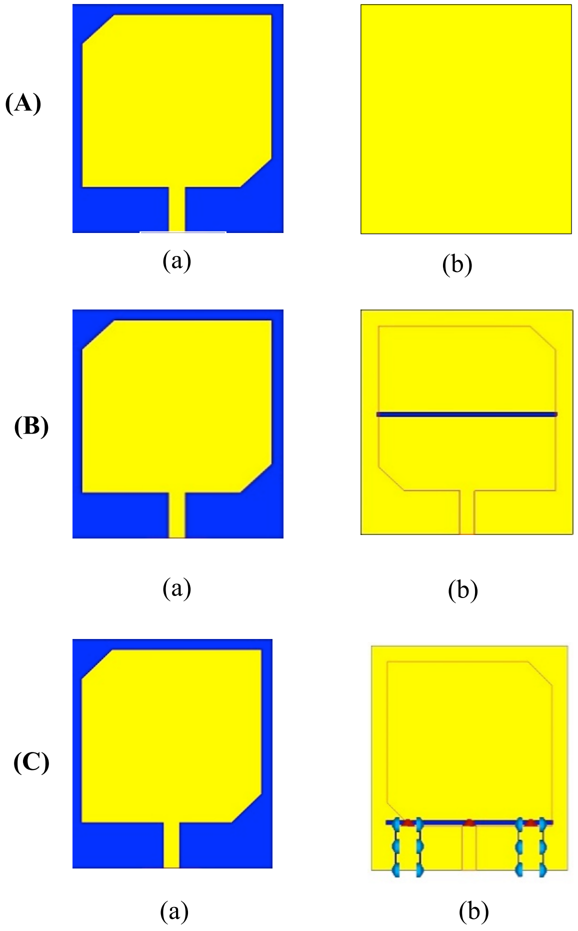
A. *Parameter Optimization of the Circularly Polarized Textile Antenna (CPTA)*

This section describes the technical procedure employed when designing the circularly polarized microstrip antenna based upon the truncation of two diagonal corners of a square patch [14]. In order to achieve circular polarization operation at 1.575 GHz, an analysis of the truncation lengths is performed by varying from 8 mm, 10 mm, 12 mm, 14 mm, 16 mm to 18 mm, as illustrated in Fig 2.

Comparison of the six different truncation lengths as shown in Fig. 3 indicates that the antenna only achieved operation at 1.575 GHz using lengths of 10 mm, 12 mm and 14 mm. The best reflection coefficient of -18.77 dB is achieved using a truncation length of 12 mm, with an impedance bandwidth from 1.54 GHz to 1.60 GHz. Meanwhile, the truncation lengths of 10 mm and 14 mm also achieved satisfactory reflection coefficients of -11.28 dB and -16 dB, respectively. Further analysis for these selected lengths will consider the axial ratio to ensure the circular polarization feature of the antenna.

Fig 4 shows the simulated axial ratios for six different truncation lengths, indicating that the truncated length of 14 mm results in CP behavior. Specifically, an axial ratio of 0.13 dB at 1.575 GHz with an AR bandwidth from 1.56 GHz to 1.62 GHz. Truncation lengths of 12 mm and 16 mm resulted in an axial ratio of 4.16 dB and 5.26 dB, which does not meet the minimum 3 dB requirement. Thus, the truncation length of 14 mm is chosen and used for further analysis.





(a) (b)

Fig 1. The design methodology to achieve CP and frequency specified reconfigurable antenna. a) Front view and b) Back view.

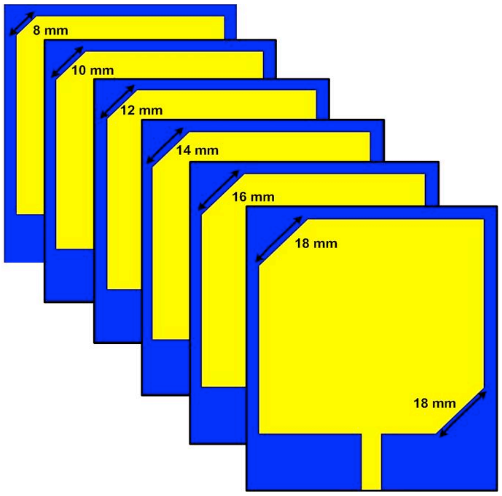


Fig 2. Structure of the proposed CPTA with different truncation lengths.

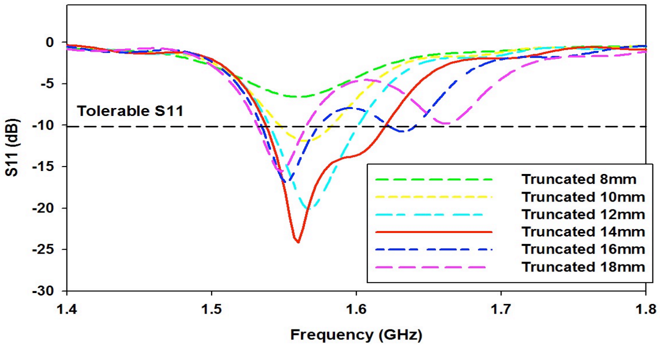


Fig 3. Simulated S_{11} of the proposed CPTA with different truncation lengths.

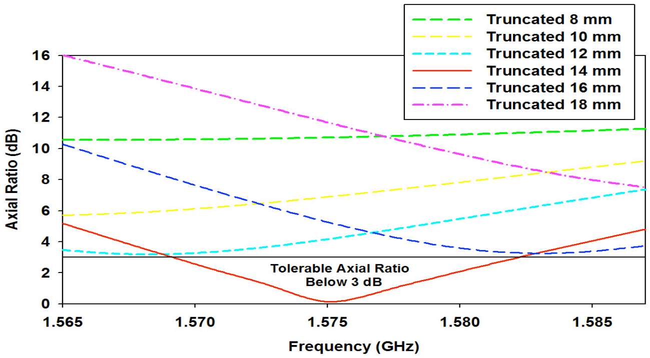


Fig 4. Simulated axial ratio of the CPTA with different truncation lengths.

B. *Optimizing the Slot Position on the Ground Plane of the Antenna.*

The key parameter impacting on in this design is the position of the slot on the ground plane. As discussed in [7], it is possible to configure the frequency by optimizing the slot size. However, the proposed antenna by author Majid is designed for linear polarization only. Unlike the antenna developed in this work, which needs to maintain a circular polarization pattern at 1.575 GHz. Thus, Fig 5 shows the analysis of different slot positions on the antenna ground plane.

Fig 6 indicates that the operating frequency shifts in line with changing slot position. The slot positions of 104 mm, 24 mm and 95 mm have lower operating frequencies of 1.68 GHz, 1.71 GHz and 1.86 GHz. Meanwhile, the slot positions of 86 mm, 77 mm and 68 mm produce a resonant frequency at 2.10 GHz, 2.41 GHz and 2.81 GHz respectively. The other slot positions do not achieve an operating frequency between 1 GHz to 3 GHz. The changing slot position changes the geometry of the antenna and affects the surface current behavior. By locating the slot towards the top or bottom edges of the antenna, the geometry of the antenna reflection to the patch remains similar and the antenna achieves a certain operating frequency. However, when the slot is placed at the middle of the ground plane, the geometry of the antenna is divided into two parts and the surface current behavior changes. For this geometry, none of the slot positions achieve the targeted operating frequency as the main consideration is to achieve a CP pattern while the frequency can be configured by adding switching.

The slot positions of 41 mm, 32 mm and 24 mm resulted in less than 3 dB of AR, with AR bandwidths centered at 1.575 GHz, as shown in Fig 7. Specifically, slot position 41 mm resulted in an AR bandwidth from 1.56 GHz to 1.58 GHz, slot position 32 mm from 1.56 GHz to 1.59 GHz and 24 mm from 1.57 GHz to 1.58 GHz.

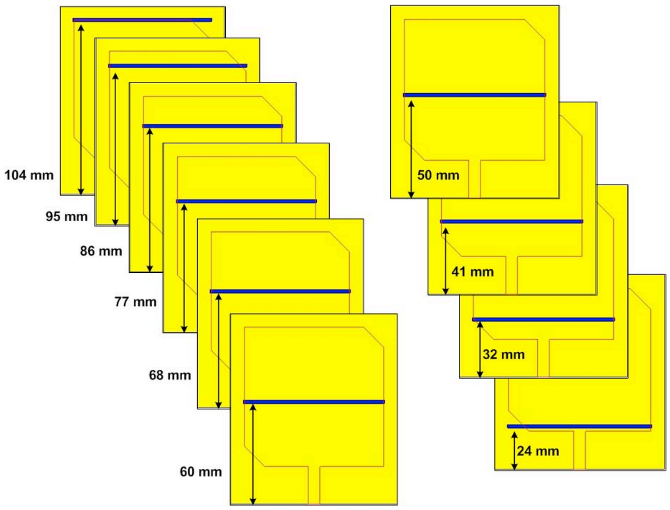


Fig 5. Analysis of slot positions on the ground plane.

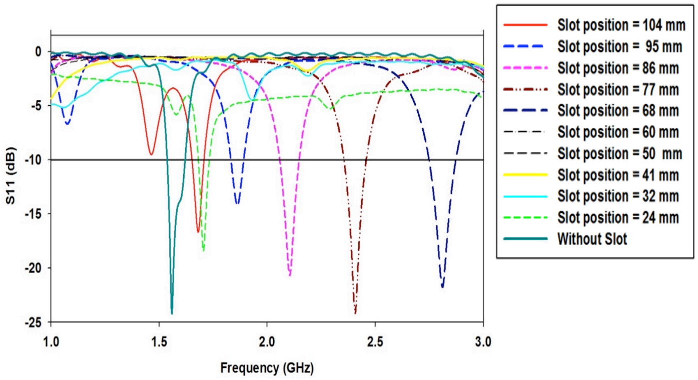


Fig 6. Simulated reflection coefficient with different slot positions.

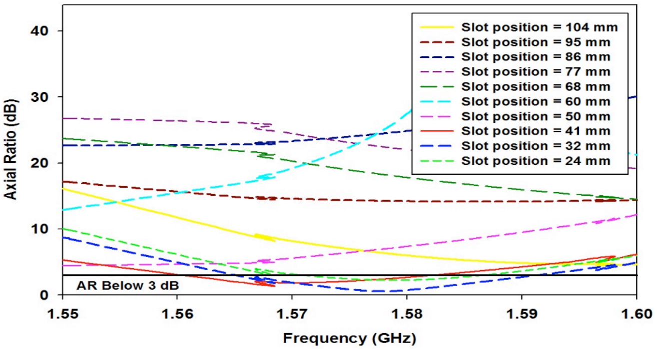


Fig 7. Simulated axial ratio of slot positioning.

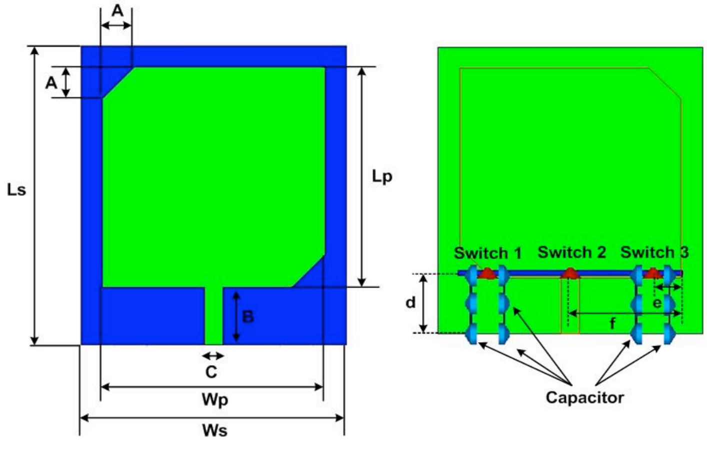
C. *Optimization of the Frequency-Reconfigurable Textile Antenna using PIN Diodes*

This section provides a brief description of the proposed antenna structure and its principal of operation with respect to the switched PIN diode configuration. The main challenge in designing this antenna is to enable frequency reconfiguration whilst maintaining circular polarization at 1.575 GHz. Therefore, the reconfigurable antenna must be designed with care to ensure the circular polarization property of the antenna is not altered with each switching condition.

The frequency re-configurability feature is enabled by varying the total length of the ground plane slot. Initially dimensioned with a width and length of 2 and 84 mm, respectively, the three BAR50–02V PIN diodes located along this slot are switched between ON and OFF states to enable different effective slot lengths. The other optimized antenna dimensions are the feed length, $B = 22$ mm, feed width, $C = 7$ mm, the ground plane slot position at $d = 23$ mm, and the positions of *Switch 2* and *Switch 3* at $e = 11$ mm and $f = 42$ mm. A total of seven switch configurations are enabled, as summarized in Table 1.

Another four 0.5 mm vertical slots connect the horizontal slots and the edge of the ground plane for DC biasing circuitry purposes. Twelve RF capacitors, each with a value of 100 pF are mounted along these four vertical slots to preserve RF current flow on the ground plane whilst blocking direct current (DC). Conversely, DC is used to switch the PIN diodes to the ON state.

The geometry of the optimized frequency-reconfigurable textile antenna is shown in Fig 8. Metallic elements (ground and patch) are fabricated using ShieldIt Super which is 0.17 mm thick with an estimated conductivity of 1.18 x 10^5 S/m [15]. Felt is used as its substrate, with 1.7 mm thickness and measured permittivity (ε_r) of 1.22 at 1.575 GHz and 1.18 at 2.45 GHz. The dimensions of the patch are Lp x Wp = 83 mm, and it is placed on a substrate of size Ls x Ws (113 x 99 mm^2) for operation at 1.575 GHz. The two opposite corners are truncated with A of 14 mm to obtain circular polarization [14].

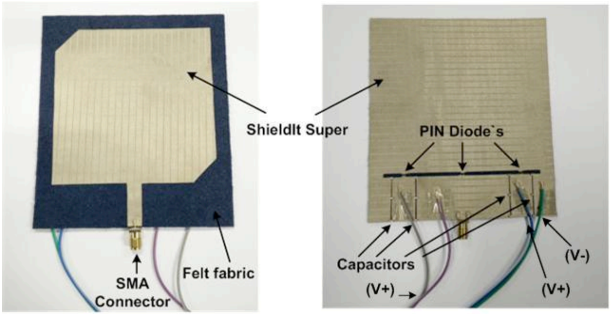


(a) Front view (b) Back view

Fig 8. Geometry of the proposed antenna. (a) front view and (b) back view.

TABLE I SWITCHING CONFIGURATION OF THE PROPOSED ANTENNA

Configuration	Switch 1	Switch 2	Switch 3
T1	ON	OFF	OFF
T2	OFF	ON	OFF
T3	OFF	OFF	ON
T4	ON	ON	OFF
T5	ON	OFF	ON
T6	OFF	ON	ON
T7	ON	ON	ON

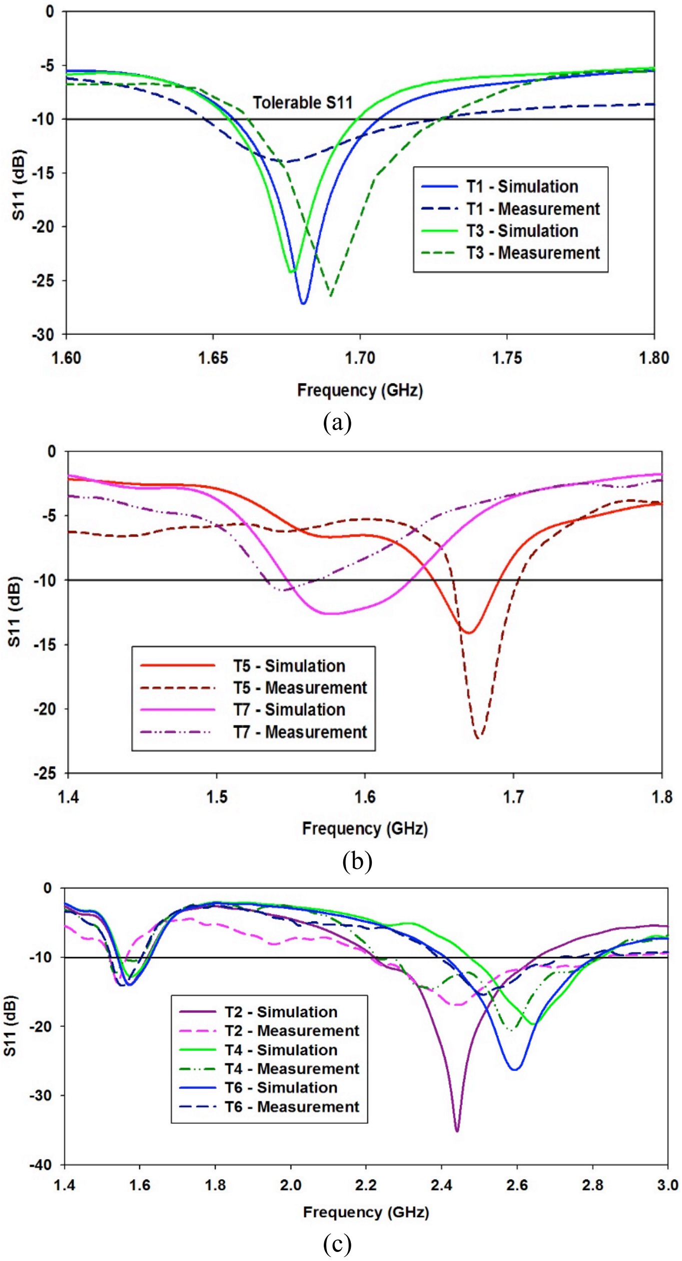


(a) (b)

Fig 9. Photograph of the fabricated antenna. (a) front view. (b) back view.

III. RESULTS AND DISCUSSION

In Fig 10, The prototype of the proposed antenna shown in Fig 9 is compared to simulations in terms of reflection coefficient (S_{11}) for different switch configurations. Results indicate satisfactory matching with at least –10 dB of S_{11} at each frequency band. The slight deviation between the simulated and measured reflection coefficients tabulated in Table II is due to small fabrication inaccuracies of the PIN diodes. Also, the additional thickness of the self-adhesive upon the rear of the ShieldIt Super textile may affect its final performance.



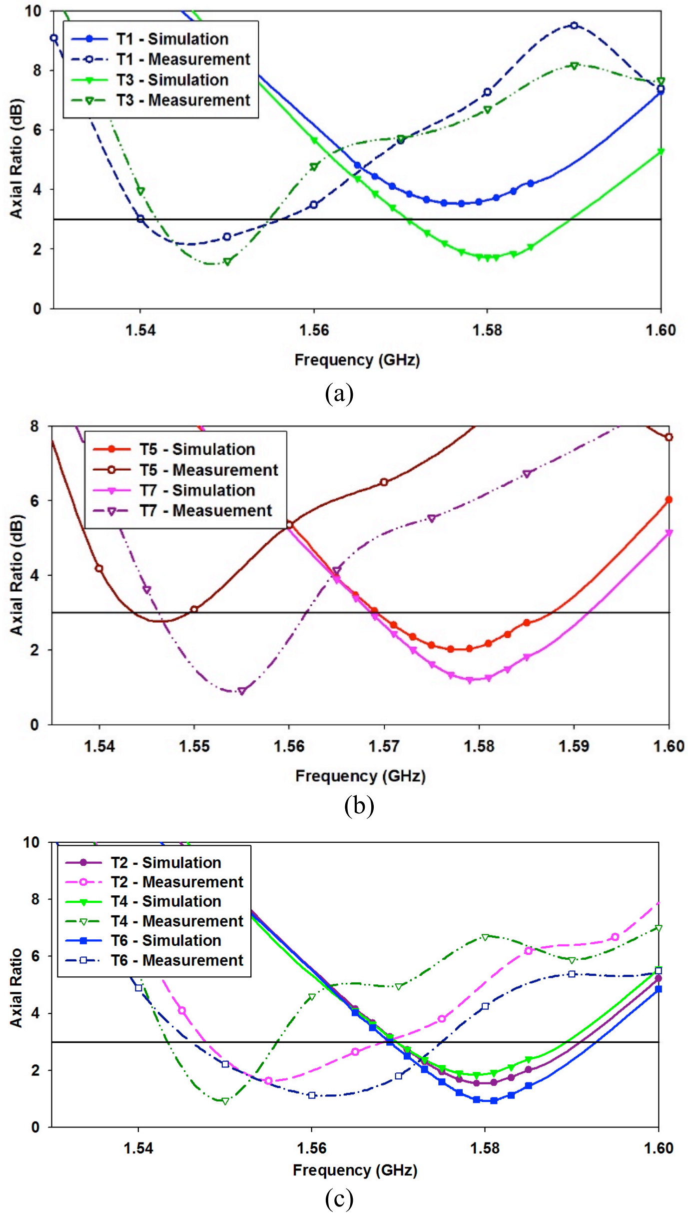
(a)

(b)

(c)

Fig 10. Simulated and measured reflection coefficients for different configurations: a) T1 and T3, b) T5 and T7 and c) T2, T4 and T6.

The simulated axial ratio presented in Fig 11 shows a good agreement of circular polarization for configurations *T2* until *T7* at 1.575 GHz. The measured AR is shifted to the lower frequency due to the deviation of measured S_{11}. The measured *AR* shown in Fig. 11 shows 3 dB bandwidths of 17 MHz (1.539 – 1.556 GHz) for configuration *T1*, 21 MHz (1.547 – 1.568 GHz) for *T2*, 13 MHz (1.541 -1.554 GHz) for *T3*, 12 MHz (1.543 – 1.555 GHz) for *T4*, 6 MHz (1.543 – 1.549 GHz) for *T5*, 30 MHz (1.545 -1.575 GHz) for *T6*, and 15 MHz (1.546 – 1.561 GHz) for *T7*.



(a)

(b)

(c)

Fig 11. Simulated and measured axial ratios for different configurations: a) T1 and T3, b) T5 and T7 and c) T2, T4 and T6.

The current distribution of the antenna is simulated and shown in Fig 12. At 0° phase, the majority of current is going downwards while at 90° phase, the current turns clockwise towards the left. The current flows move in a clockwise direction at 180° and 270° phase, indicating a left handed CP. Fig 13 depicts the simulated and measured radiation patterns for configurations *T2* and *T7*. Overall, the proposed antenna features a directional pattern in the lower band of 1.57 GHz for both configurations. Meanwhile, these configurations produce a bidirectional and omnidirectional pattern at the higher frequency of 2.45 GHz. Simulations indicated relatively higher gains at 1.575 GHz which decline with increase in frequency. The measured gain of the proposed antenna varies from 0.2 dBi to 4.8 dBi and efficiency varies from 17.9% to 47.9%. Table II indicated the summarized simulated and measured of resonant frequency, bandwidth, gain and efficiency of the proposed antenna.

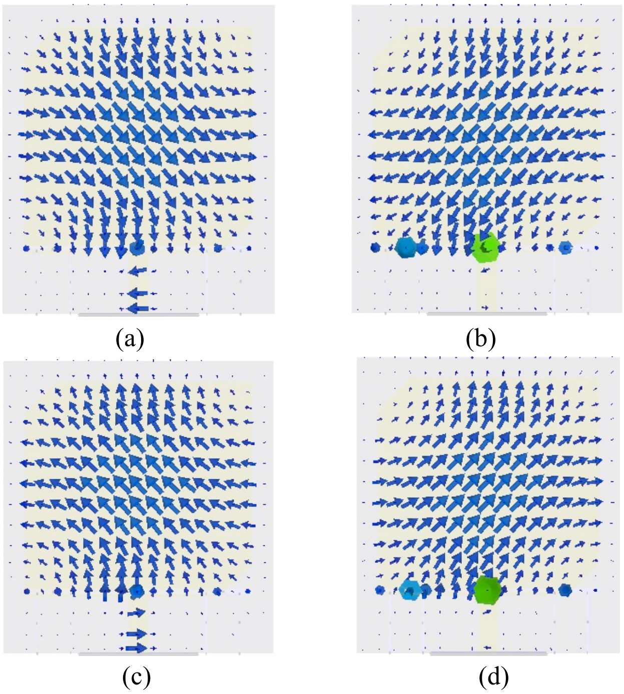
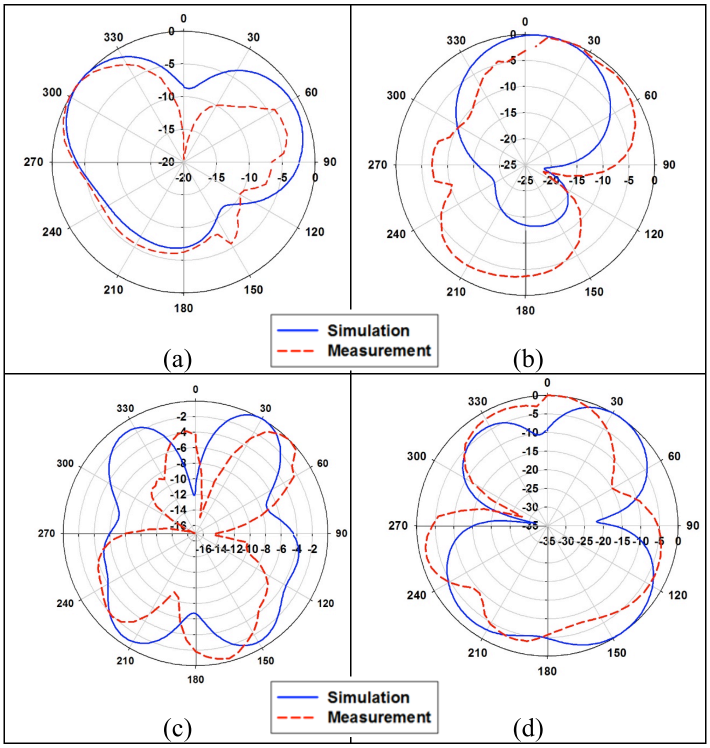


Fig 12. Surface current distribution of the proposed antenna with configuration *T7*: a) 0° phase, b) 90° phase, c) 180° phase, d) 270° phase.



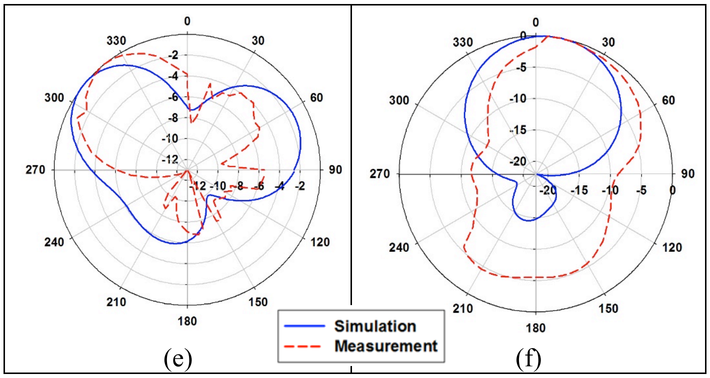


Fig 13. Simulated and measured radiation pattern. (a) *T2* at 1.57 GHz, *xy*-plane cut, (b) *T2* at 1.57 GHz, *yz*-plane cut, (c) *T2* at 2.45 GHz, *xy*-plane cut, (d) *T2* at 2.45 GHz, *yz*-plane cut, (e) *T7* at 1.57 GHz, *xy*-plane cut, and (f) *T2* at 1.57 GHz, *yz*-plane cut.

TABLE II
SIMULATED AND MEASURED RESONANT FREQUENCY, BANDWIDTH, GAIN AND EFFICIENCY

Configuration	Simulated				Measured		
	Resonant Frequency (GHz)	Bandwidth (%)	Gain (dBi)	Efficiency (%)	Resonant Frequency (GHz)	Bandwidth (%)	Gain (dBi)
T1	1.68	2.9	0.47	28.0	1.67	3.2	0.20
T2	1.57	4.8	3.19	34.5	1.54	3.9	0.86
	2.43	17.7	0.72	29.2	2.43	23.7	0.41
T3	1.67	3.0	0.82	27.7	1.68	3.5	0.32
T4	1.57	5.1	3.22	34.3	1.55	5.8	1.22
	2.64	13.6	0.94	30.2	2.54	19.0	0.92
T5	1.67	2.9	1.39	23.6	1.67	2.9	1.36
T6	1.57	5.1	3.27	34.1	1.55	5.1	1.96
	2.59	15.4	0.48	17.9	2.50	12.8	0.48
T7	1.57	5.7	4.8	47.9	1.54	3.1	4.8

Table III summarizes the performances of the available reconfigurable frequency/polarization antenna. The first two antenna comparisons [6-7] are designed for frequency configuration only. While, the following two antennas [16-17] only can performed polarization configuration. The antennas design from [18-19] are capable to performed frequency and polarization reconfigurable. Where, the polarization covers the Vertical Linear Polarization (VLP), Horizontal Linear Polarization (HLP), Right-Hand Circular Polarization (RHCP) and Left-Hand Circular Polarization (LHCP). However, it can be noticed that most previous antenna fabricated using rigid board material. This may have resulted to the uncomfortable to user while applying in to the human body. In contrast, the approach proposed antenna in this work using fabric material and compromise the use for on/off wireless body application. Most importantly, the previous reported wearable antennas usually do not have the configuration future like frequency or polarization in single antenna.

TABLE III

COMPARISON OF THE PROPOSED RECONFIGURATION SIMULTANEOUS FREQUENCY AND POLARIZATION RECONFIGURATION TEXTILE ANTENNA WITH PREVIOUS RESEARCHES

Research By	Frequency Configuration	Polarization Configuration	Material Used	Flexible
[7]	1.98 GHz - 3.41 GHz	None	Taconic RF35	No
[6]	4.77GHz – 5.51 GHz	None	Roger R04350B	No
[16]	None	RHCP, LHCP	RT/duroid 5880	No
[17]	None	LP, RHCP, LHCP	Taconic RF35	No
[18]	1.17 GHz – 1.58 GHz	VLP, HLP, RHCP, LHCP	Arlon AD450	No
[19]	1.5 GHz – 2.4 GHz	LVP, HLP, RHCP, LHCP	Roger 5880 RT	No
Proposed Antenna	1.57 GHz – 2.64 GHz	LP, LHCP	Felt fabric	Yes

IV. CONCLUSIONS

In this letter, a frequency reconfigurable textile antenna has been presented. This design has successfully achieved frequency re-configurability through modification of the slot at the ground plane. The slot size is controlled by three embedded RF PIN Diode switches on the intersection of the underneath slot. The proposed antenna is capable of varying the operating frequency from 1.54 GHz to 2.82 GHz with a ratio of 1.83:1. In addition, the antenna achieves circular polarization at certain frequencies. The proposed design has the potential to improve wireless communication systems that require multiple frequencies with the ability to perform CP suitable for GPS and WiFi applications.

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