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Design of New Circularly Polarized Wearable Dielectric Resonator Antenna for Off-Body Communication in WBAN Applications

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ABSTRACT A unique circularly polarized (CP) compact wearable dielectric resonator antenna (DRA) has been proposed for off-body communication in wireless body area network (WBAN) applications. The design is singly fed and a new H-shaped conformal metal strip has been used to excite the DRA. A circular polarization over a bandwidth of ~9.6% (7.47–8.25 GHz) in conjunction with an impedance matching bandwidth of ~20.7% (6.95–8.68 GHz) has been offered by the antenna. A prototype has been fabricated and measured. The antenna has been tested both in free space and on-body environment. A robust performance has been offered by the antenna against human body lossy effects. The measured results agree very well with the simulated results.

INDEX TERMS Wireless body area network, ultra-wideband, dielectric resonator antenna, circular polarization, off-body communication, specific absorption rate.

I. INTRODUCTION

From the last decade the wireless body area network (WBAN) has gained much more popularity due to increasing demand of wireless commutation in various applications such as multimedia, sports monitoring, health care, personal equipment, rescue operations and the military [1]–[9]. The Federal Communications Commission (FCC) has defined any wireless transmission scheme that occupies a bandwidth of more than 1.5 GHz has been categorized under ultra-wideband technology [10]. The ultra-wideband systems are much more reliable because of their significant features such as broad bandwidth, high date rate and robustness to interference [11]. Recently many UWB antenna for BAN have been reported in literature [7]–[9]. However, the polarization mismatch issue of wearable antennas has not been focused much. The issue already reported in handheld terminal communications [12], the polarization loss factor could be further amplified by human body movements for these antennas, causing problems in reliable communication. Moreover, in off-body communication the circular polarization is mandatory as the orientation of transmitting and receiving antennas changes with movement [13]. A promising solution regarding these issues is to design a circularly polarized wearable antenna rather than a linearly polarized antenna.

The microstrip strip antenna has inherently narrow bandwidth. In wearable applications the bending and crumpling due to movements of human body causes frequency shift which could be a serious problem in narrowband antenna such as microstrip [14]. Recently researchers are focusing more on DRAs because of their attractive features such as wider bandwidth, compact size, flexible design, high radiation efficiency, no metallic losses [15]–[33]. The circularly polarized DRAs can designed using dual feeding techniques [18]–[20]. But singly fed circularly polarized DRAs are much more desirable because of simple feeding mechanism and

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compact size [21]–[24]. Very few DRAs for WBAN applications has been reported in literature so far. For instance, an annular conical dielectric resonator antenna (DRA) that is inverted truncated and probe fed for in potential use in BAN applications in UWB has been reported in [25]. In [26] a bow-tie shaped wearable DRA fed by microstrip line has been investigated, a wide impedance matching bandwidth has been offered by the antenna. A probe fed RDRA with wide impedance matching bandwidth for on-body applications has been studied. The low-profile designed has been accomplished by using multi-dielectric layers and copper patches attached on ground plane as presented in [27]. An annular cylindrical shaped wearable DRA excited by microstrip line has been reported in [28]. In [29] a microstrip line fed flexible cylindrical DRA has been investigated for body centric communication in WiMAX and WLAN applications. A textile-based cylindrical DRA for WLAN application has been reported in [30], the antenna is fed by three different techniques for comparison. A high-temperature tolerant wearable DRA excited by probe for BAN applications has been studied in [31]. A dual-port diversity antenna designed by combination of DRA and a slot loop for BAN applications has been presented in [32]. A monopole DRA for medical applications in UWB has been reported in [33]. In all discussed articles the DRAs presented for BAN applications are linearly polarized, no circularly polarized DRA for BAN applications has been reported yet.

In this article a singly fed circularly polarized compact wearable DRA has been proposed for the first time. An H-shaped conformal metal strip has been used to excite the degenerate higher-order mode pair $TE^{x}_{\delta 13}$ and $TE^{y}_{1\delta 3}$ to generate CP wave. A broadband circular polarization along with an ultra-wide impedance matching bandwidth over same frequency range have been achieved. The return losses, axial ratio (AR), radiation patterns and gain of the proposed antenna has been simulated and measured. The antenna has been tested in both free space and on body-equivalent phantom block to study the human body loading effect. Antenna provides a great isolation from the body due to ground plane as low specific absorption rate (SAR) values have been computed. A good agreement between simulated and measured results have been observed. The proposed antenna is suitable for BAN applications in UWB upper (6 – 10 GHz).

The antenna design and structure has been provided in Section II, simulated result analysis has been explained in Section III, and the discussion on the measured results of the proposed antenna has been summarized in Section IV. In Section V, the conclusion has been drawn.

II. ANTENNA DESIGN AND STRUCTURE

A wearable DRA fed by a unique H-shaped monopole has been depicted in Figure 1 (a). The CST® Microwave Studio has been used for theoretical design phase [34]. The proposed antenna has to fulfill two goals, that is, compact size and wideband circular polarization. The size of the dielectric block has been optimized using dielectric waveguide model (DWM) [35], to make it compatible for BAN applications. To achieve circular polarization the degenerate mode pair has to be excited [22]. The second goal has been achieved using H-shaped conformal feeding strip because this excitation is capable of radiating two far-field components which are equal in amplitude and in phase quadrature that are needed to generate the circular polarization [36]. The iterative design procedure has been used to finalize the feeding strip shape and position. The new H-shaped feeding strip comprises of three individual strips. The lengths and widths of feeding strips have been optimized for by running several simulations using different parameter sweeps. The final geometry of the proposed antenna has been described in Table 1.

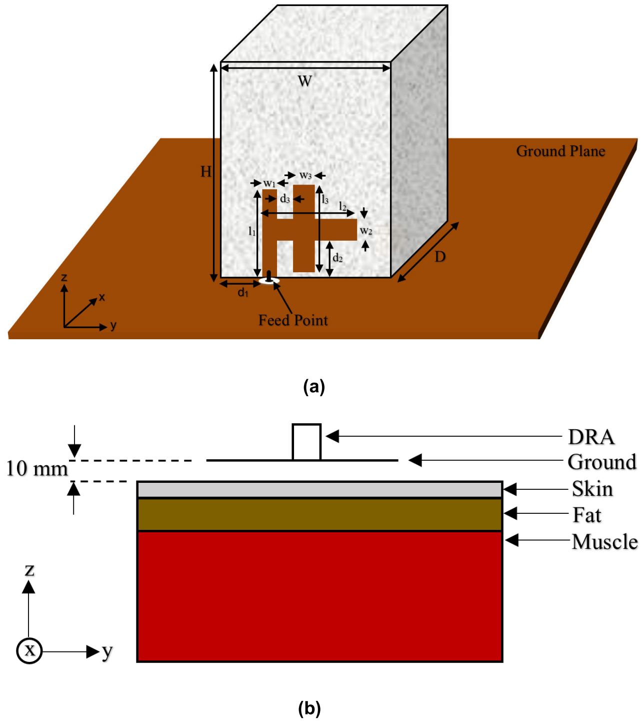

FIGURE 1. Circularly polarized wearable DRA. (a) The CP wearable DRA fed by H-shaped conformal metal strip. (b) The CP wearable DRA mounted on three-layer human tissue model.

TABLE 1. Parameters of the proposed wearable DRA.

Parameters	Unit (mm)	Parameters	Unit (mm)
H	15	l_1	6
W	12	w_1	1
D	8	l_2	6.5
d_1	3	w_2	1.5
d_2	2.5	l_3	6
d_3	1	w_3	1.5

In order to understand the complex electromagnetic characteristics of human body and its impact on antenna performance, a three-layer tissue model for on-body environment has been designed in CST [9]. The antenna has been placed

TABLE 2. Dielectric properties of three-layer tissue model.

Tissue	Thickness (mm)	ε_r	σ (S/m)	tan δ
Skin	1 mm	33	5.9	0.39
Fat	2 mm	4.7	0.45	0.21
Muscle	10 mm	45	7.93	0.388

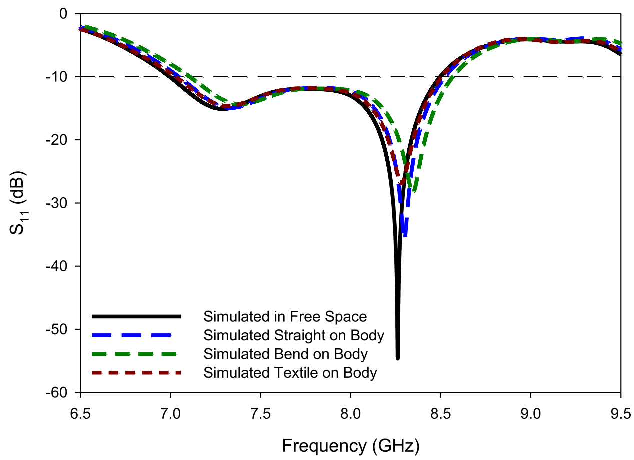

FIGURE 2. **Simulated return losses of the CP wearable DRA in free space and on-body with different ground situations.**

at a distance of 10 mm from the tissue model as shown in Figure 1 (b). The gap between the antenna and human body emulates the actual situation to accommodate the feeding network [37]. The dimensions of tissue model has been set as 90 × 90 × 13 mm^3, where the thickness of skin, fat, and muscle is 1 mm, 2 mm, and 10 mm, respectively. The human body characteristic are approximately based on Table 2 [9].

III. SIMULATED RESULTS ANALYSIS

The proposed wearable CP DRA has been simulated both in free space and on-body environment. The performance has been computed with both straight and bend ground plane topologies, to be placed on chest and arm respectively. Similarly, the wearable DRA has also been excited on different ground materials and sizes to estimate the real life situation. Moreover, the proposed antenna has also been simulated at various distances from body to ensure the close proximity operation.

A. RETURN LOSSES OF THE WEARABLE DRA

The simulated return losses of the wearable DRA in free space and on-body condition have been depicted in Figure 2.

The proposed antenna has been excited with both straight and bend ground plane. Similarly the wearable DRA has been tested on conductive textile ground plane, with thickness of 0.17mm and 1.18 × 10^5 S/m [38]. As shown a good impedance matching i.e. $|S_{11}| \leq -10$ dB has been observed at 6.99 – 8.50 GHz i.e. in free space. At on-body condition the S_{11} bandwidth of 7.03 – 8.52, 7.1 – 8.56, and 7.02 – 8.51 GHz has been offered by the antenna in case of straight, bend, and textile ground plane. The small variations in free space and on-body results have been observed due to dielectric properties of three layer model.

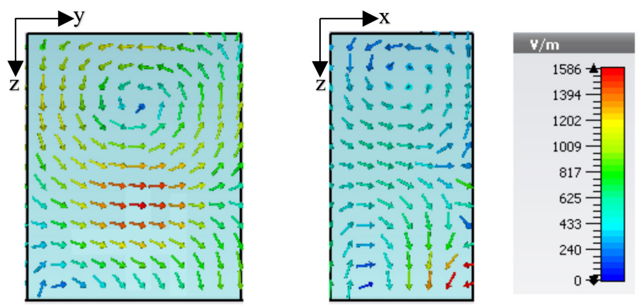

FIGURE 3. **E-field distribution of the CP wearable DRA (a) $TE^x_{\delta 13}$ at 7.29 GHz and (b) $TE^y_{1\delta 3}$ at 8.26 GHz.**

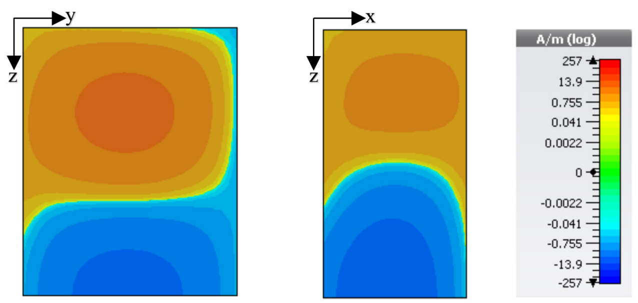

FIGURE 4. **H-field distribution of the CP wearable DRA (a) $TE^x_{\delta 13}$ at 7.29 GHz and (b) $TE^y_{1\delta 3}$ at 8.26 GHz.**

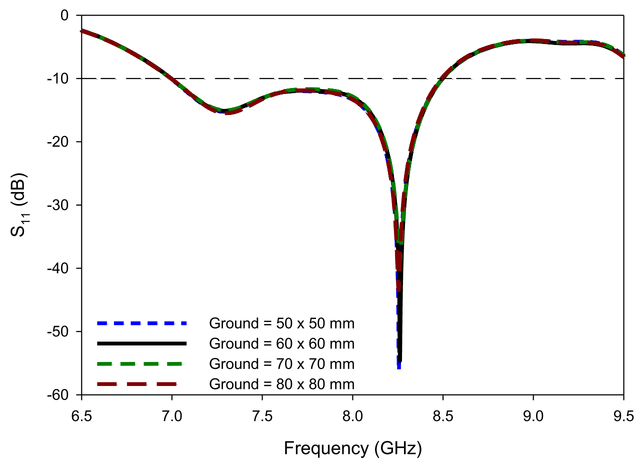

FIGURE 5. **Simulated return losses of the CP wearable DRA in free space and on-body with different ground sizes.**

The E-field and H-field distribution of the wearable DRA has been presented in Figure 3 and Figure 4 respectively. As shown the orthogonal degenerate mode pair of first higher-order $TE^x_{\delta 13}$ at 7.29 GHz and $TE^y_{1\delta 3}$ at 8.26 GHz has been excited to generate circularly polarized wave. Moreover, the return losses of the antenna with different ground sizes has been depicted in Figure 5. As shown the return losses of the antenna are not sensitive to ground sizes.

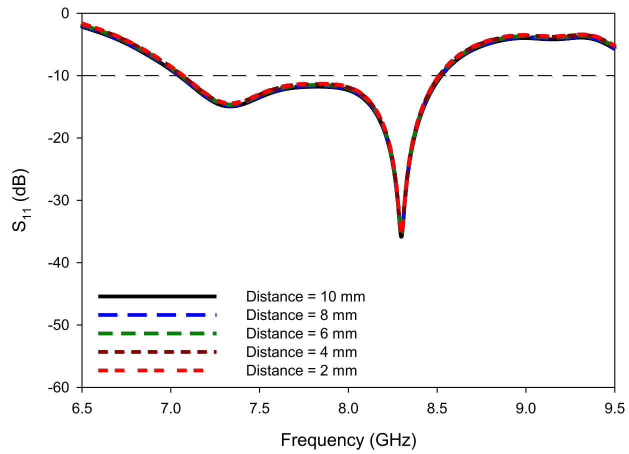

FIGURE 6. Simulated return losses of the CP wearable DRA placed at various distances from body.

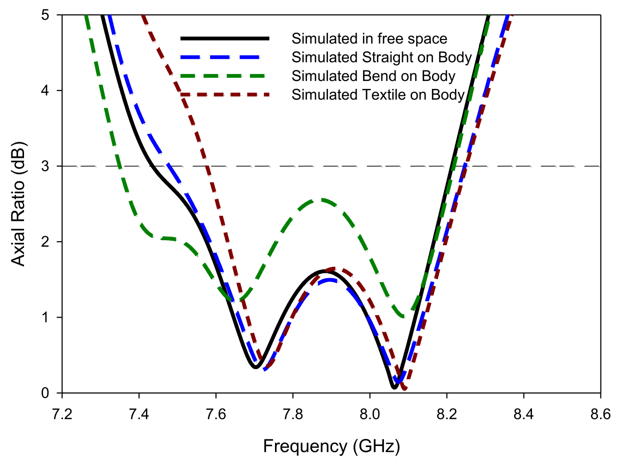

FIGURE 7. Simulated axial ratio of the CP wearable DRA in free space and on-body with different ground situations.

Furthermore, the return losses of the proposed wearable DRA have been computed at various distances from body to ensure the close proximity operation. As shown in Figure 6 a robust performance has been provided by the antenna against body lossy effects even at a distance of 2 mm from three layer model.

B. AXIAL RATIO OF THE WEARABLE DRA

In Figure 7, the simulated axial ratio of the proposed antenna in free space and on-body scenario has been illustrated. The 3-dB axial ratio extends from 7.42 – 8.21 GHz in free space. In presence of human body model the axial ratio offered by the antenna is 7.47 – 8.24, 7.34 – 8.22, 7.57 – 8.25 GHz in case of straight, bend, and textile ground plane. Moreover, the optimum AR frequency is found to be at 8.1 GHz. Some changes between free space and on-body results have been observed because of lossy effects of human body model. Similarly, small frequency shift in case of straight and bend

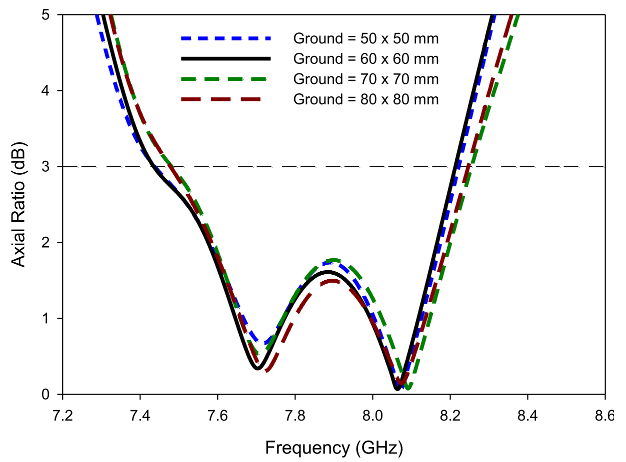

FIGURE 8. Simulated axial ratio of the CP wearable DRA in free space and on-body with different ground sizes.

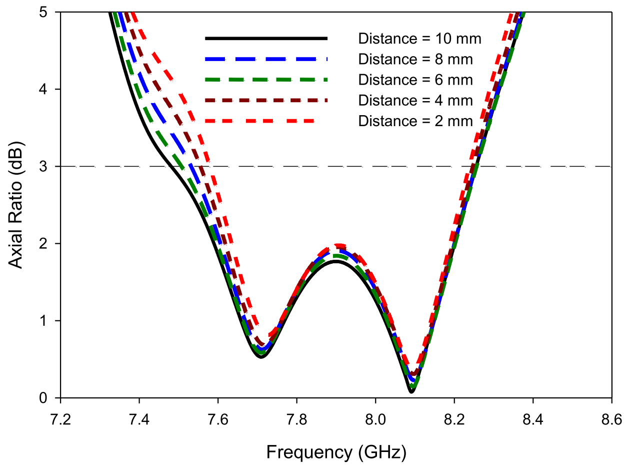

FIGURE 9. Simulated axial ratio of the CP wearable DRA placed at various distances from body.

ground plane has been observed but still the proposed antenna successfully achieve the desired AR bandwidth.

The simulated axial ratio of the proposed antenna with different ground sizes has been depicted in Figure 8. The size of ground is not a real issue in antenna implementation and thus larger ground plane sizes are allowed. The results confirm that the proposed antenna can be used with textile ground plane for BAN applications.

Moreover, the effect of close proximity of body on axial ratio performance of the proposed wearable DRA has been depicted by simulated results in Figure 9. As observed the effect of the lossy body is very modest even at a very close distance of 2 mm from antenna. The ground plane is shielding the antenna from the body loading effects [38].

C. GAIN OF THE WEARABLE DRA

In Figure 10, the simulated gain of the wearable DRA has been depicted in free space and on-body environment. The gain of the proposed antenna has been computed with both

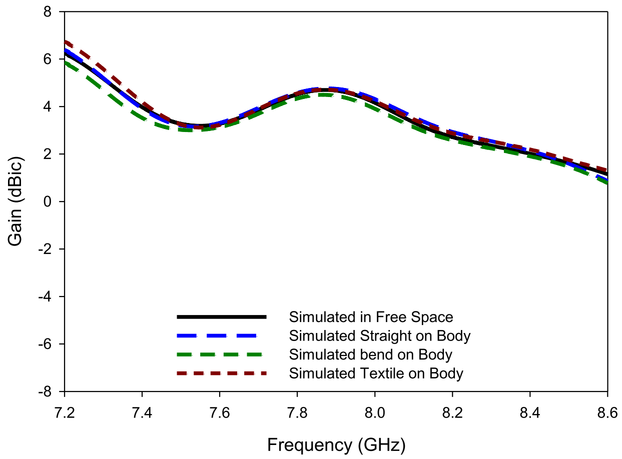

FIGURE 10. Simulated gain of the CP wearable DRA in free space and on-body with different ground situations.

straight and bend ground plane. Moreover, the gain has also been computed by replacing the copper with textile ground plane to monitor the performance under particle environment. The antenna provides a stable gain of ~5 dBic with different ground topologies. Moreover, the gain of the proposed wearable DRA is comparable to that recently reported in [39].

D. SAR OF THE WEARABLE DRA

To observe the antenna proximity influence on human body, the SAR values have been computed according to the IEEE C95.3 standard averaged over 1g and 10g of tissue. The SAR values at optimum AR frequency i.e. 8.1 GHz are found to be 0.237 W/Kg, and 0.112 W/Kg for 1g, and 10g respectively as shown in Figure 11. The calculated values are much lower than allowed limit for 1g and 10 g SAR, that is, 1.2 W/Kg, and 2 W/Kg respectively [40]. Together with the fact that antenna performance is robust to the human body lossy effects, these low SAR values represents the capability of the proposed DRA for a close proximity operation to the human body.

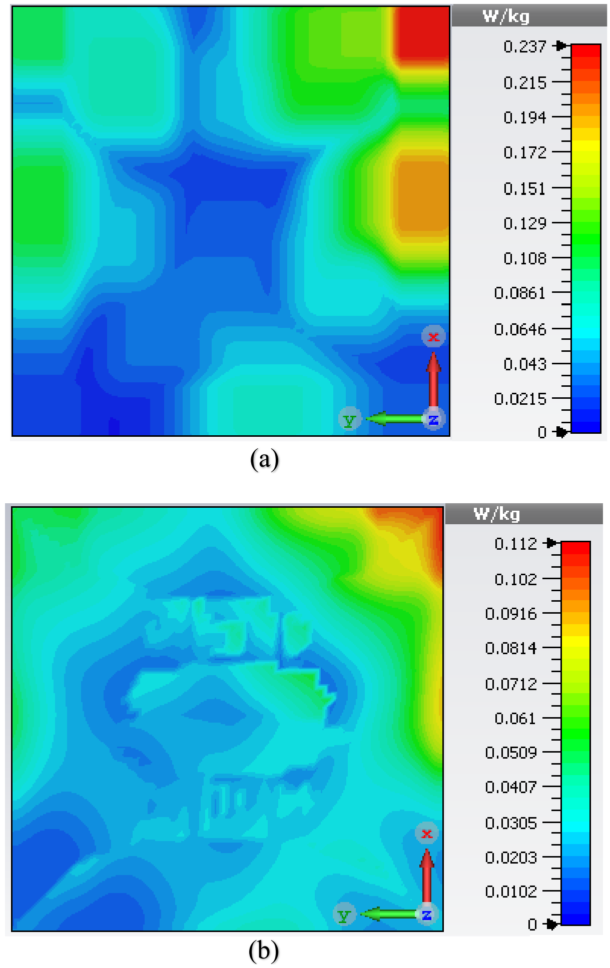

FIGURE 11. Computed SAR values 8.1 GHz (a) 1g averaged SAR (b) 10 g averaged SAR.

IV. MEASURED RESULTS AND DISCUSSION

The prototype of the proposed design has been built using the ECCOSTOCK HiK with permittivity $\varepsilon_r = 10$ and loss tangent (δ) of 0.002 as shown in Figure 12.

The H-shaped strip has been cut from adhesive-backed copper tape to stick easily on DRA surface. The flexible ground plane of 60×60 mm^2 has been constructed using copper tape. Note that flexible ground plane depicts the textile nature of our antenna and in practice can be replaced with conductive textile material. A double-sided adhesive conducting copper tape has been used to remove the possible air between the DRA and the ground plane as reported in [41].

The antenna has been excited by soldering an SMA connector to the edge of conformal strip at the feed point. In real-life application antenna can be fed by mini-SMA connector or directly from on-body circuitry located under the antenna to further reduce the distance from human body [5]. A vector network analyzer (VNA) has been used for measurements. A 50-Ω coaxial cable has been used to connect SMA to the VNA for measurements. The S_{11} has been measured on both on human chest and arm as shown in Figure 12 (c) and Figure 12 (d) respectively. The return losses on the proposed antenna have also been measured on phantom under both straight and bend ground topologies to check the performance comparison on real human body and phantom as depicted in Figure 12 (e) and Figure 12 (f) respectively. A biological tissue equivalent model according to [42] has been used.

The prototype has been simulated and measured both in free space and under human body environment. The measurements has been done both on human body (chest and arm) and on phantom. The comparison between simulate and measured return losses of the wearable DRA in free space has been demonstrated in Figure 13. Similarly, in Figure 14 the simulated and measured reflection coefficient of the proposed antenna on chest and on phantom with straight ground plane has been shown. The computed and measured S_{11} of the antenna on arm and on phantom with bend ground plane has been depicted for comparisons in Figure 15. An ultra-wide impedance matching band width of ~20.7% (1.73 GHz) has been measured.

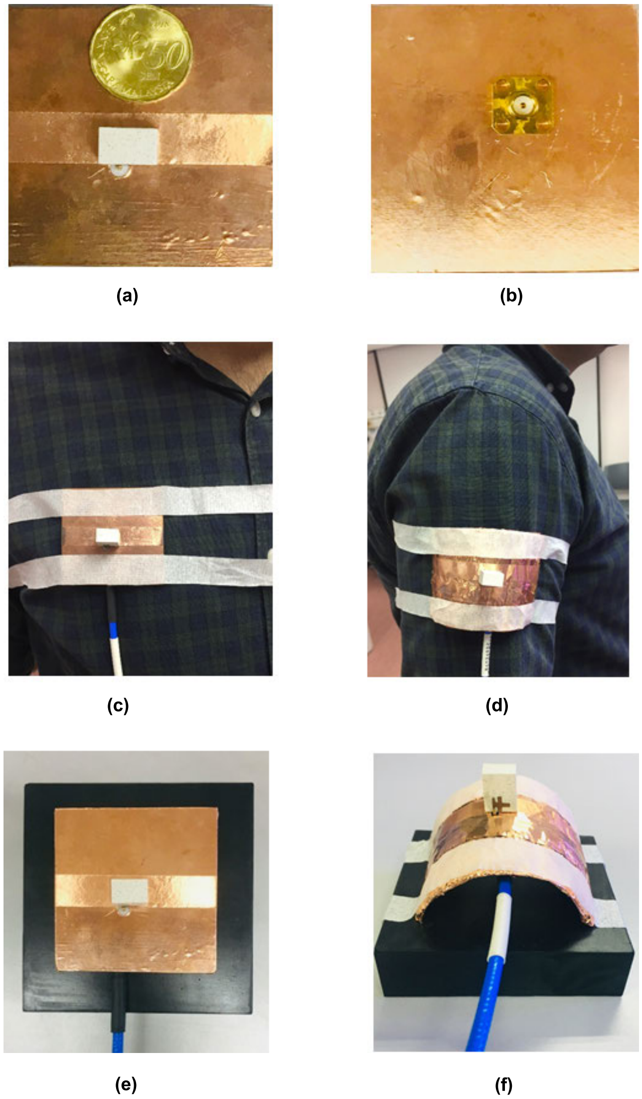

FIGURE 12. Photographs of the fabricated wearable DRA (a) Top view. (b) Back view. (c) Antenna on human chest. (d) Antenna on human arm. (e) Antenna on phantom in straight. (f) Antenna on phantom under bend.

The two degenerate modes $TE^x_{\delta 13}$ and $TE^y_{1\delta 3}$ necessary for CP wave generation have been measured at 7.32 GHz, and 8.34 GHz respectively. The degenerate resonance mode frequencies of the DRA have also been predicted using mathematical equations on DWM as explained in [35] for comparison. The resonant frequency f_{mn} of $TE^x_{\delta mn}$ mode has been predicted using following transcendental equation:

$$k_x \tan\left(\frac{k_x D}{2}\right) = \sqrt{(\varepsilon_r - 1)\, k_{mn}^2 - k_x^2} \quad (1)$$

where

$$k_{mn} = \frac{2\pi f_{mn}}{c}, \quad k_y = m\frac{\pi}{W},$$
$$k_z = n\frac{\pi}{2H}, \text{ and } k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_{mn}^2$$

and c is the speed of light. Similarly resonant frequency for $TE^y_{m\delta n}$ mode has been predicted.

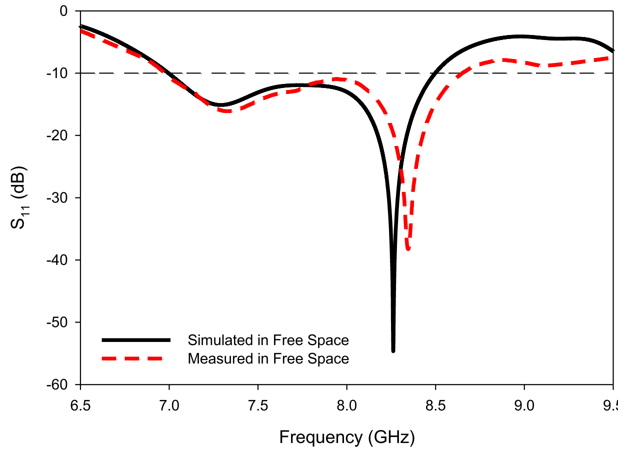

FIGURE 13. Simulated and measured return losses of the CP wearable DRA in free space.

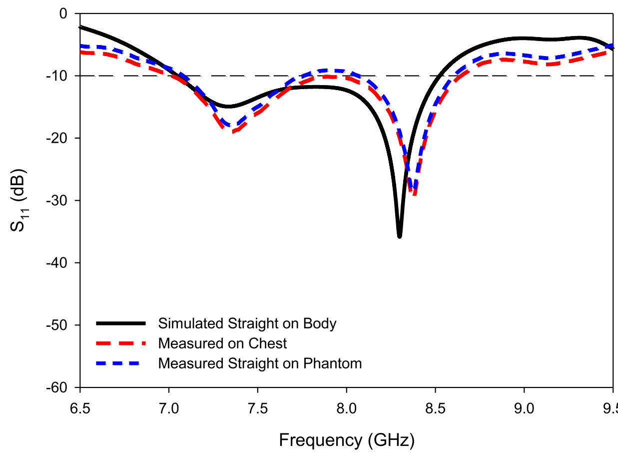

FIGURE 14. Simulated and measured return losses of the CP wearable DRA under human body environment with straight ground plane.

TABLE 3. Comparison between predicted, calculated and measured mode frequencies.

Resonance modes of the wearable DRA	Predicted by DWM f_{DWM}(GHz)	Calculated by Simulation f_{CST}(GHz)	Measured by Fabrication f_{MEA}(GHz)
$TE^x_{\delta 13}$	7.22	7.29	7.32
$TE^y_{1\delta 3}$	8.15	8.26	8.34

A good agreement between the predicted, theoretical and experimental results have been observed as summarized in Table 3. A small variation between the simulated and measured results have been observed because of cable losses, connector losses, and other measurement limitations. Despite of these small changes the proposed antenna shows a significant potential to be integrated in wearable systems for different BAN applications. Moreover, as depicted by the measured results the behavior of human body and phantom used for measurements is quite similar.

Far field measurements have been made using an anechoic chamber. For on-body measurements the wearable CP DRA has been mounted on phantom. In Figure 16 the simulated

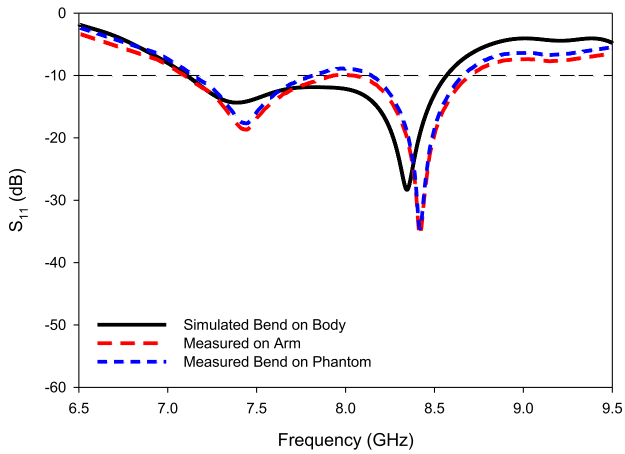

FIGURE 15. Simulated and measured return losses of the CP wearable DRA under human body environment with bend ground plane.

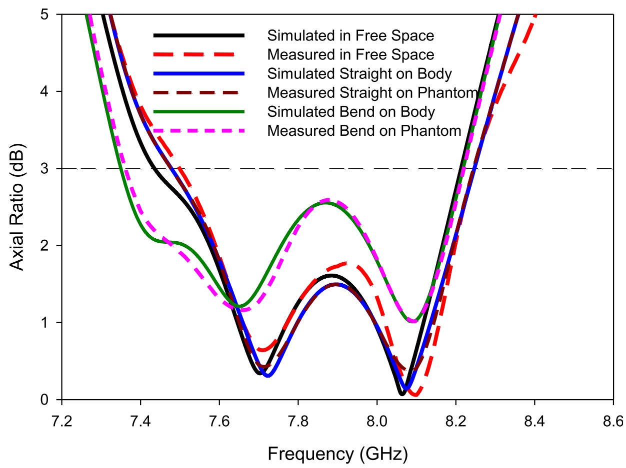

FIGURE 16. Simulated and measured axial ratio of the CP wearable DRA.

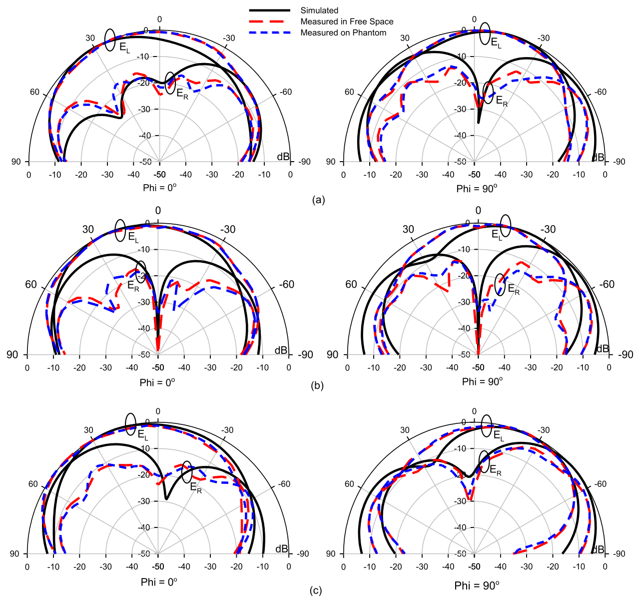

FIGURE 17. Simulate and measured radiation patterns of the CP wearable DRA at (a) 7.5 GHz (b) 8.1 GHz and (c) 8.2 GHz.

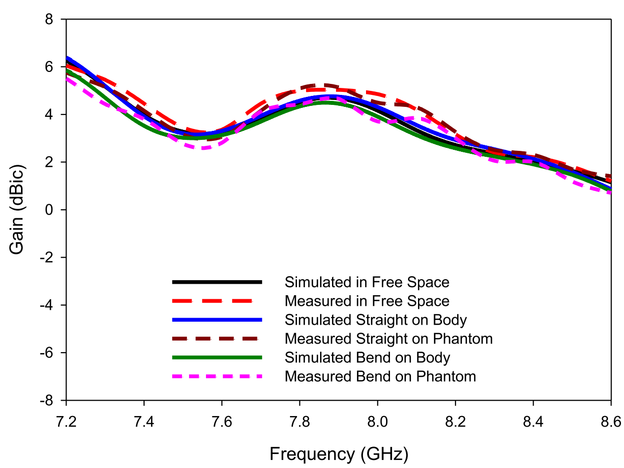

FIGURE 18. Simulated and measured gain of the CP wearable DRA.

and measured axial ration offered by the antenna in boresight direction ($\Theta = 0°$, $\Phi = 0°$) in free space and on phantom has been illustrated. The axial ratio of the proposed wearable DRA with straight and bend ground topologies have been measured. As presented a 3-dB AR bandwidth of ~9.6% (0.78 GHz) has been provided by the antenna. The small marginal shift has been observed due to difference of simulation and experimental environment. Moreover, the optimum AR frequency that is ~0.06 dB in case of straight and ~1.02 dB in case of bend ground plane, has been measured at 8.1 GHz. As observed the impact of human body is very modest. Because most of the back radiations have been shielded by the conductive ground plane. An overlap of ~100% has been observed between 3-dB AR and $|S_{11}| \leq -10$ dB bandwidths. The circular polarization achieved by the proposed design make it a suitable candidate for off-body channel applications.

The simulated and measured radiation patterns of the proposed DRA has been depicted in Figure 17. A left hand polarization has been achieved by the DRA because left-hand field component is greater than its right-hand field component by a difference of more than 30 dB at optimum AR frequency i.e. 8.1 GHz in the boresight direction as shown in Figure 17 (b). Small variations have been observed between the results due to measurement environment and lossy effects of phantom. As presented stable patterns have been offered by the antenna along the whole circular polarization bandwidth.

The simulated and measured gain of the CP wearable DRA in free space and under human body environment with straight and bend ground plane has been depicted in Figure 18. A stable performance has been observed in close proximity to human body with both straight and bending positions of the ground plane. The antenna provide a useful gain of ~5 dBic along the whole CP bandwidth. A good agreement between the simulated and measured results have been observed.

As evident from the results that a satisfactory performance in terms of S_{11}, axial ratio, radiation patterns, and gain have

TABLE 4. Comparison between proposed wearable CP DRA and other wearable DRAs in literature.

Literature	ε_r	S_{11} Bandwidth (GHz)	Axial Ratio Bandwidth (GHz)	Polarization
Ref. [25]	9.8	3 – 5	Nil	Linear
Ref. [26]	9.8	4.5 – 7.5	Nil	Linear
Ref. [27]	2.2/9.2/16	4.4 – 9.7	Nil	Linear
Ref. [28]	12.2	2.4 – 2.49	Nil	Linear
Ref. [29]	5.2	4.53 – 5.55	Nil	Linear
Ref. [30]	10.2	5.4 – 6.2	Nil	Linear
Ref. [31]	30	2.34 – 2.48	Nil	Linear
Ref. [32]	NA	2.35 – 2.45	Nil	Linear
Ref. [33]	7	3 – 13	Nil	Linear
Proposed wearable DRA	**10**	**6.95 – 8.68 (~20.7%)**	**7.47 – 8.25 (~9.6%)**	**Circular**

been observed both in free space and in close proximity to human body. Low SAR values have been computed which indicate that proposed antenna is a potential solution for wearable wireless applications. Moreover comparison of the proposed CP wearable DRA with other wearable DRAs reported in literature has been summarized in Table 4. In all discussed articles the DRAs presented for BAN applications are linearly polarized. The proposed circularly polarized DRA is a new and significant contribution for off-body communication in body area network applications.

V. CONCLUSION

A compact CP wearable DRA for off-body communications has been proposed, simulated, fabricated, and measured for the very first time. The antenna has been excited using H-shaped monopole. A circular polarization over bandwidth of ∼9.6% has been measured along with an impedance matching bandwidth of ∼20.7% over same frequency range. Stable radiation patterns along with a useful gain of ∼5 dBic has been offered by the antenna. As far as the authors can see, this is the only work featuring a wearable circularly polarized dielectric resonator antenna for BAN applications. A good agreement between the simulated and measured results have been observed.

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