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A Hybrid Mutual Coupling Reduction Technique in a Dual-Band MIMO Textile Antenna for WBAN and 5G Applications

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ABSTRACT This paper presents a hybrid mutual coupling reduction technique applied onto a dual-band textile MIMO antenna for wireless body area network and 5G applications. The MIMO antenna consists of two hexagonal patch antennas, each integrated with a split-ring (SR) and a bar slot to operate in dual-band mode at 2.45 GHz and 3.5 GHz. Each patch is dimensioned at 47.2 x 31 mm^2. This hybrid technique results in a simple structure, while enabling significant reduction of mutual coupling (MC) between the closely spaced patches (up to 0.1λ). This technique combines a line patch and a patch rotation technique, explained as follows. First, a line patch is introduced at an optimized distance to enable operation with a broad impedance bandwidth at both target frequencies. One of the patches is then rotated by 90° at an optimized distance, resulting in a significant MC suppression while maintaining the dual and broad impedance bandwidth. The proposed MIMO antenna is further evaluated under several bending configurations to assess its robustness. A satisfactory agreement between simulated and measured results is observed in both planar and bending conditions. Results show that the MIMO antenna achieves an impedance bandwidth of 4.3 % and 6.79 % in the 2.45 GHz and 3.5 GHz band, respectively. Moreover, very low MC ($S_{21} < -30$ dB) is achieved, with a low (< 0.002) envelop correlation coefficient, and about 10 dB of diversity gain at both desired frequencies using this technique. Even when bent at an angle of 50° at the x- and y-axes, the antenna bent maintained a realized gain of 1.878 dBi and 4.027 dBi in the lower and upper band, respectively. A robust performance is offered by the antenna against the lossy effects of the human body with good agreements between simulated and measured results.

INDEX TERMS Array antennas, wearable antenna, MIMO antenna, mutual coupling reduction, antenna and propagation, bioelectromagnetics, wearable.

I. INTRODUCTION

Antennas are increasingly being developed in a more compact format and on flexible materials. This is especially attractive in wearable applications, as these antennas are used in many applications such as health monitoring, tracking and etc. [1]. These applications also demands that these antennas can operate across a wide range of frequencies, within the framework of the Internet of Things (IoT). Besides that, the combined IoT connectivity to high speed fifth

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generation (5G) systems will be advantageous in demanding systems such as healthcare using a single set of antenna. Moreover, flexible antennas can be worn while the users move freely, without affecting their morphologies requires these antennas to be wide in bandwidth. Moreover, real-time information transmission with minimal losses needed in these systems when applied for managing critical illnesses and procedures also adds to the challenge in flexible antenna design.

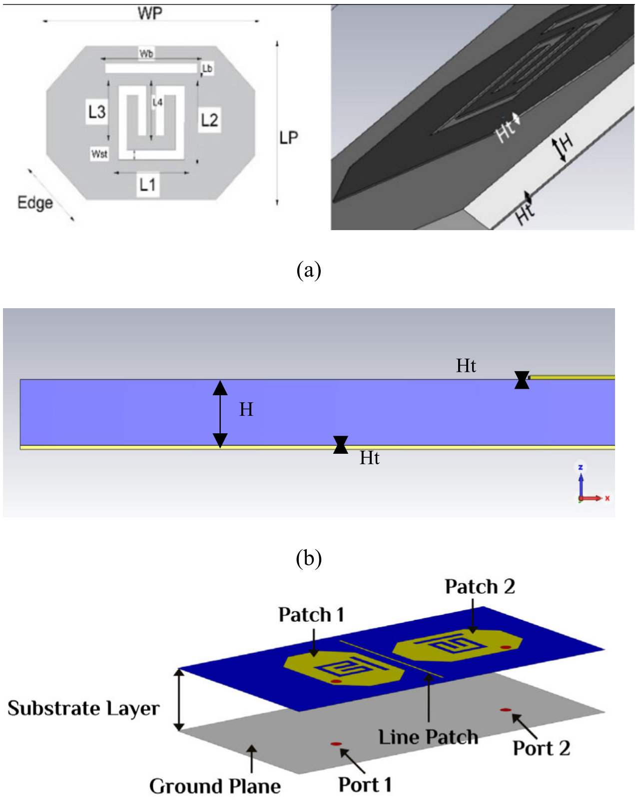
On the other hand, the multiple elements of MIMO wearable antennas need to be spaced as close as possible to achieve compactness, while maintaining good overall performance. However, the closely spaced elements will then result in higher radiation interaction, leading to higher mutual coupling. Several mutual coupling reduction techniques have been proposed in literature. They include the modification of the antenna structure by adding electromagnetic bandgap (EBG) [2]–[4], introducing slot [5], neutralization lines [7], [8], metamaterial structure [9]–[11], parasitic elements [12]–[15], hybrid techniques combining defected ground plane structures (DGS) and stubs [16]–[18], split ring resonators (SRR) [19], [20], diagonal placement of array elements [21], [22] and truncated of the patch structure [23]. A comprehensive study on mutual coupling suppression techniques have been reported in [24], [25].

Considerable published work has reported on the effects of mutual coupling in dual band antenna arrays. However, the alleviating the effects of coupling (S_{21}) for dual-band MIMO textile antennas, specifically operating at 2.45 and 3.5 GHz is hardly discussed. This research proposes a unique hybrid technique to suppress the mutual coupling of the $\mathbf{2 \times 1}$ MIMO antenna. This is aimed at achieving an S_{21} of less than -30 dB with the closest possible placement of elements (an edge-to-edge spacing of 0.1λ). This antenna is benchmarked against the performance of the same antenna with and without applying the proposed hybrid technique. Finally, the robustness of the proposed MIMO antenna against bending deformation is evaluated thoroughly.

This paper is organized as follows. Section II outlines the characterization of the antenna element, after which a study on the mutual coupling effects antenna is presented. The three main parameters are analyzed and presented in three parts: distance analysis, mutual coupling reduction and gain, and envelope correlation coefficient. The measurement results of the prototype are presented in Section IV prior to the conclusions in Section V.

II. ANTENNA CHARACTERIZATION

The proposed antenna is designed to operate in dual band mode, centered at 2.45 for the wireless body are network (WBAN) lower band, and at 3.5 GHz for 5G as the upper band. Felt textile is used as the substrate and is sandwiched between top radiator and a full ground plane. It has a relative permittivity (ε_r) of 1.44, a loss tangent ($\tan\delta$) of 0.044, and a thickness (H) of 3 mm. The conductive elements are formed using ShieldIt Super electro-textile from LessEMF Inc., which is 0.17 mm thick and features an estimated conductivity (σ) of 1.18×10^5 Sm^{-1}. As an initial step, a rectangular-shaped patch radiator is designed to operate in the lower band, centered at 2.45 GHz, as shown in Figure 1.



(a)

(b)

(c)

FIGURE 1. (a) Antenna dimensions with the gap added between L2 and L3 [27], (b) side view, and (c) perspective view with port 1 and port 2 location.

Then, its design is modified with a slotted ring based on [26] to produce another resonant frequency at 3.5 GHz. The SR shaped slot in the middle of the rectangular-shaped patch antenna enables the bandwidth broadening of the upper 3.5 GHz band. The feeding points are placed on the bottom left edge for first element, labelled as Port 1, and bottom right edge for second element, labelled as Port 2, as illustrated in Figure 1. A detailed design procedure is presented in [27] which can be summarized in four steps, as follows:

- First, the dimensions of the patch without SR-shaped slot are calculated based on the upper band resonance.
- Second, the probe feed structure is optimized to obtain a suitable matching in the upper band.
- Third, the SR shaped and the bar slot are added to broaden the bandwidth, and to provide operation in the respective bands.
- Fourth, the dimensions of the SR-shaped slot are tuned to provide operation in the respective lower band
- The overall dimension is of 132.8×70 mm^2, whereas the top radiator is dimensioned at 47.2 x 31 mm^2,

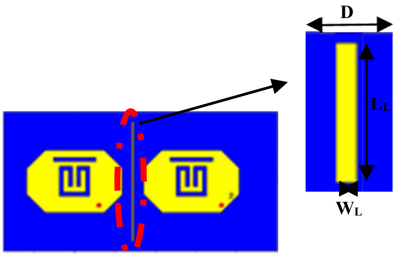
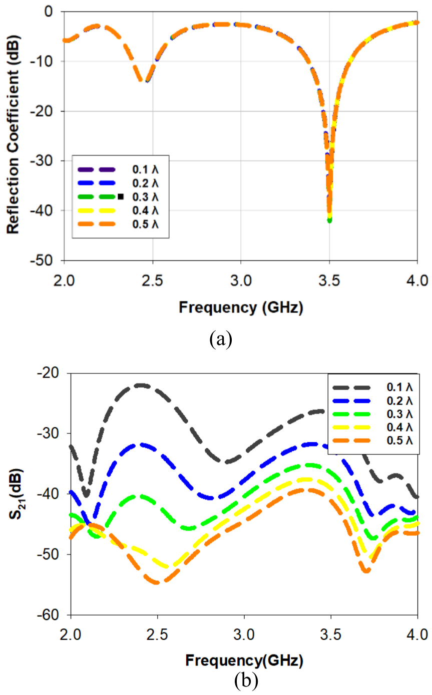


FIGURE 2. MIMO antenna with a line patch.



(a)

(b)

FIGURE 3. Simulated performance of the antenna with different patch distances in λ (a) S_{11} and (b) S_{21}.

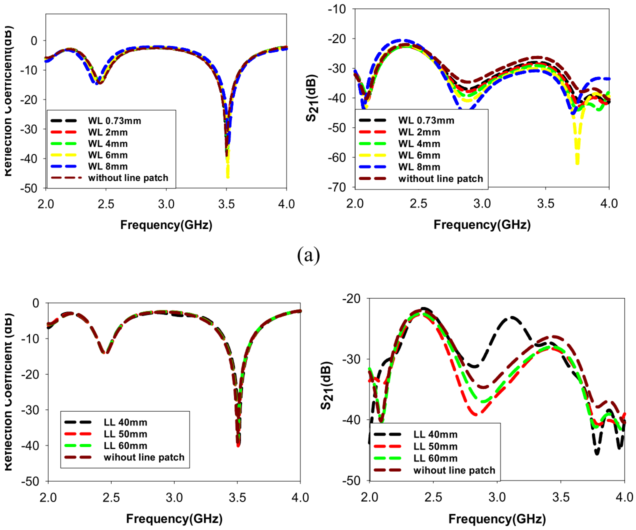
as shown in Figure 1. All simulations and optimizations are performed using CST Microwave Studio software.

III. MUTUAL COUPLING

In this section, the distance between and orientation of the patch elements are studied to optimize the proposed antenna in terms of reflection coefficient and mutual coupling. Details of this study are discussed in the next subsections.

A. DISTANCE ANALYSIS

The distance between the patch elements affects the antenna performance in terms of reflection coefficient (S_{11}) and mutual coupling (S_{21}). The distance between antennas is varied from 0.5λ to 0.1λ, as illustrated in Figure 2. The results shown in Figure 3 indicated that the S_{11} and bandwidth of the antenna is preserved in both bands with the variation of antenna gap. However, as shown in Figure 3(b), the S_{21} values increased with decreasing distance, indicating higher coupling between the patches. The coupling increases from −56 dB to −22 dB at 2.45 GHz and −45 dB to −27 dB at 3.5 GHz.

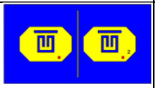
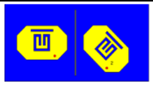
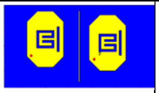
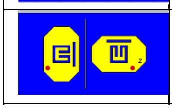


(a)

(b)

FIGURE 4. Simulated results of the antenna with difference line patch dimension (a) Width of line patch (WL) and (b) Length of line patch (LL).

TABLE 1. Summary of S_{11} and S_{21} for different antenna rotations.

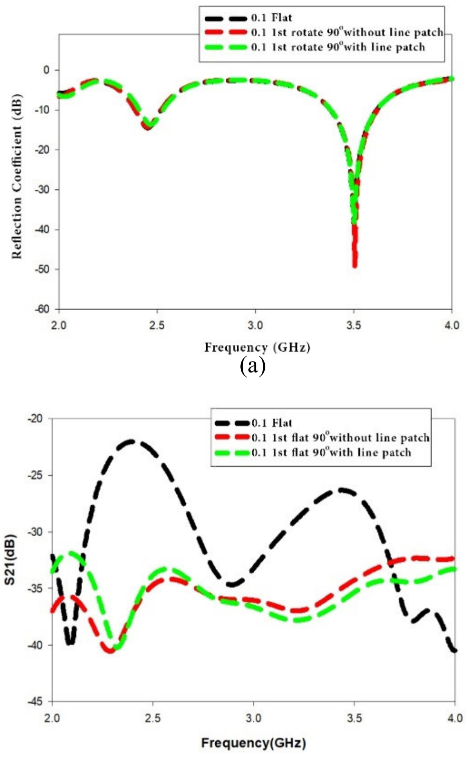
Rotation	Rotation Degree (°)	Freq (GHz)	S_{11} (dB)	S_{21} (dB)
	0	2.45 3.5	-14.27 -30.22	-22.63 -28.20
	Ant2 45	2.45 3.5	- 15.9 -26.9	-32.1 -33.2
	Ant1 & Ant2 90	2.45 3.5	-10 -24.1	-27.78 -29.04
	Ant1 90	2.45 3.5	-13.9 -31.95	-35.31 -35.62

*Ant1 (antenna 1), Ant 2 (antenna 2)

B. MUTUAL COUPLING REDUCTION TECHNIQUE

A hybrid technique involving a line patch and rotation of antenna elements is then applied in this subsection. In the first step, a line patch of *WL* x *LL* is introduced at the optimized guided distance (*D*) of 0.1λ, as shown in the Figure 3. Next, the width (*WL*) and the length (*LL*) of the line patch are studied. They are varied as follows: $WL = 0.73, 2, 4, 6, 8$, and 10 mm, and $LL = 40, 50$, and 60 mm. Aimed at obtaining an optimized length and width of the line patch, the results are shown in Figure 4.

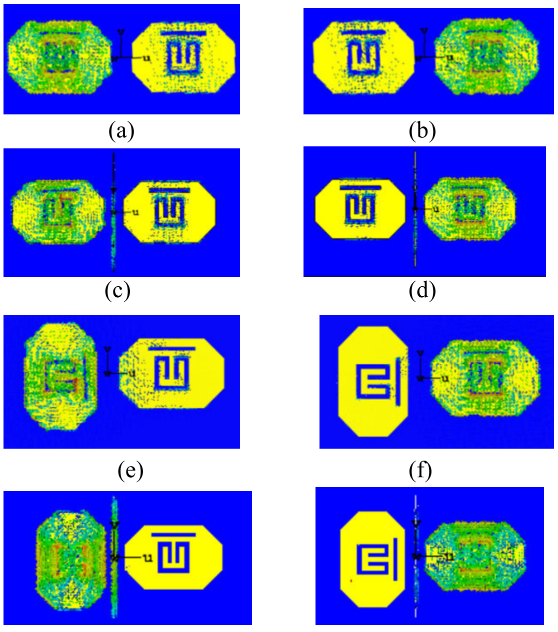
While the size of the line patch did not affect the S_{11}, the S_{21} of the antenna varied with the variation of *WL* and *LL*, particularly at higher frequencies. From the analysis, the final optimized WL and LL value is 0.73 mm and 60 mm,



(a)

(b)

FIGURE 5. Simulation results of the proposed MIMO with and without the hybrid technique. (a) S_{11} and (b) S_{21}.



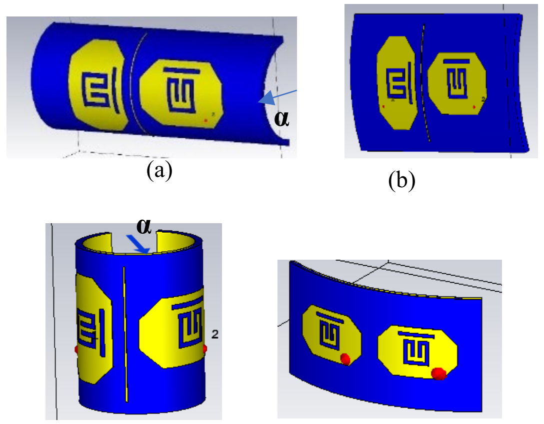
(a) (b)

(c) (d)

(e) (f)

(g) (h)

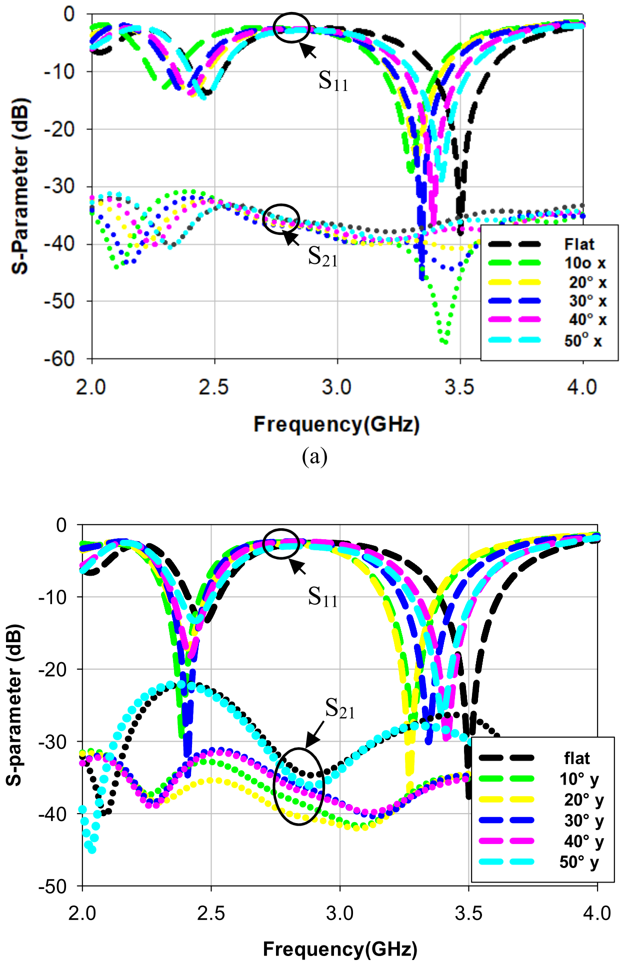
FIGURE 6. Surface current distribution for different configurations at 2.45 GHz from: (a), (c), (e) and (g) port 1 and (b), (d), (f) and (h) port 2.



(a) (b)

(c) (d)

FIGURE 7. The proposed MIMO with different bending angles: (a) bent at x-axis at 10°, (b) x-axis at 50°, (c) y-axis at 10° and (d) y-axis at 50°.

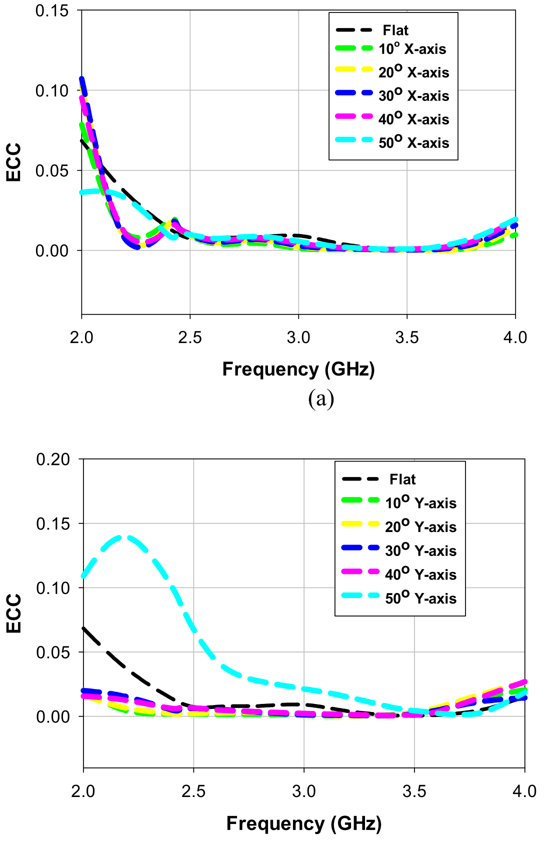


(a)

(b)

FIGURE 8. Performance of the proposed MIMO antenna when bent at different angles: (a) at x-axis and (b) at y-axis.

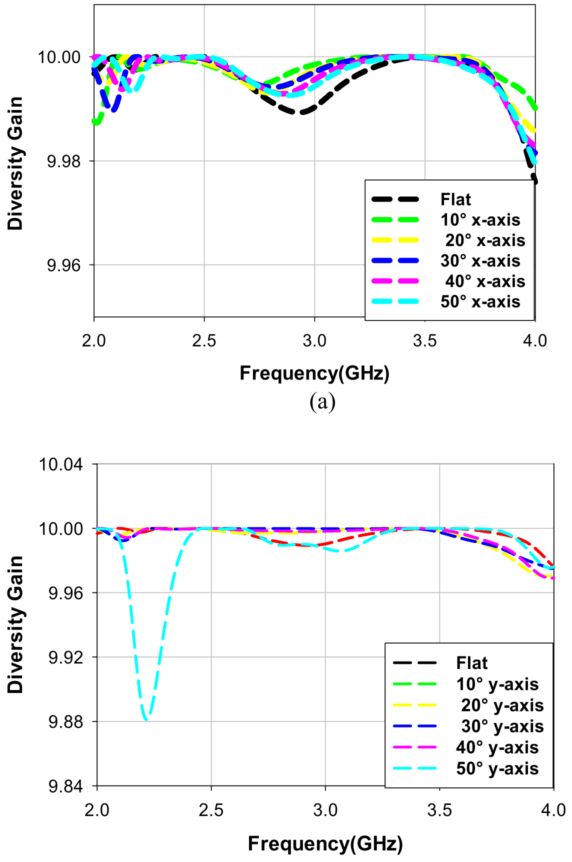
respectively. The next step in the proposed hybrid technique is by rotating the antenna elements to arrive at the final MIMO antenna design. The different rotations are illustrated in Table 1 and the optimized MIMO antenna is produced by rotating the other element by 90°. This hybrid technique is studied further with and without the line patch, and their S_{11} and S_{21} are illustrated in Figure 5. The addition of the line



(a)

(b)

FIGURE 9. **Envelope correlation coefficient of the MIMO antenna for different bending. (a) at *x*-axis and (b) at *y*-axis.**



(a)

(b)

FIGURE 10. **Diversity gain plot for the proposed MIMO, (a) x-axis and (b) y-axis.**

patch improved S_{21} significantly, up to 60 % and 33 % at 2.45 GHz and 3.5 GHz, respectively.

On the other hand, Figure 6 illustrates the surface current distribution when one of the ports is excited. As seen in this figure, a single technique of either only adding the line patch in between the antenna elements or rotating the patch element reduced the current interaction with the other patch element. However, in both cases, part of the current still overflows to the adjacent patch. Combination of both techniques significantly reduced the coupling between the antenna elements.

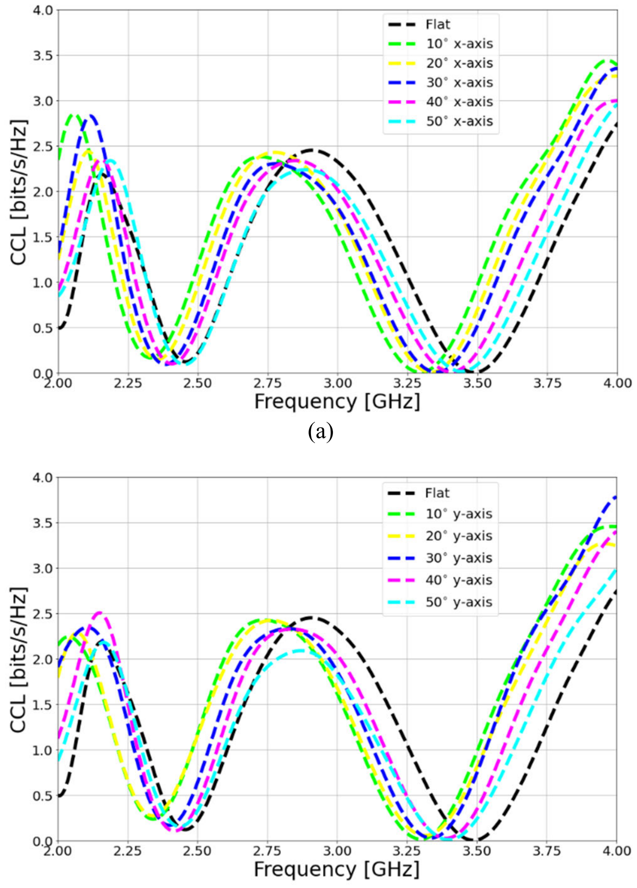
C. BENDING

A comprehensive analysis on the effects of the bending on the proposed MIMO antenna is presented in this section. Simulations of the bending evaluation curvatures are performed at different angles (α) of 10°, 20°, 30°, 40°, and 50°, which translates to 24.38, 30.48, 40.6, 69.8, and 121.9 mm radii, respectively, based on [28]. These bending values are selected to emulate the curvature of proposed MIMO antenna when wrapped around the arm in a regular body. Bending is investigated at two conditions, when bent at *x*- and *y*-axes for five different bending angles, as illustrated in Figure 7. The extreme condition is identified when the antenna is bent at *y*-axis with smallest angle/shortest radius, $\alpha = 10° @ 24.28$ mm. Measurements are then performed to observe the performance of the proposed MIMO antenna in these conditions.

The results obtained from the bent antennas are compared with simulations in flat condition, as illustrated in Figure 8. Decreasing the bending degree from 50° to 10° lowers the resonance in both bands, with a more significant change in the upper band. In contrast, different mutual coupling behavior can be observed when bent at the *x*- and *y*-axes. When bent at the *x*-axis at 2.45 GHz, lower S_{21} is seen with increasing bending degrees. This behavior is contrary at 3.5 GHz. On the other hand, when varying the bending degree at *y*-axis, the S_{21} fluctuates in the lower band, but is almost consistent in the upper band. As expected, bending at an angle of 50° resulted in high mutual coupling at both frequency bands. Hence, it can be concluded that bending of the antenna at different degrees affected particularly the performance at the higher frequencies.

D. GAIN, RADIATION EFFICIENCY AND CORRELATION ANALYSIS

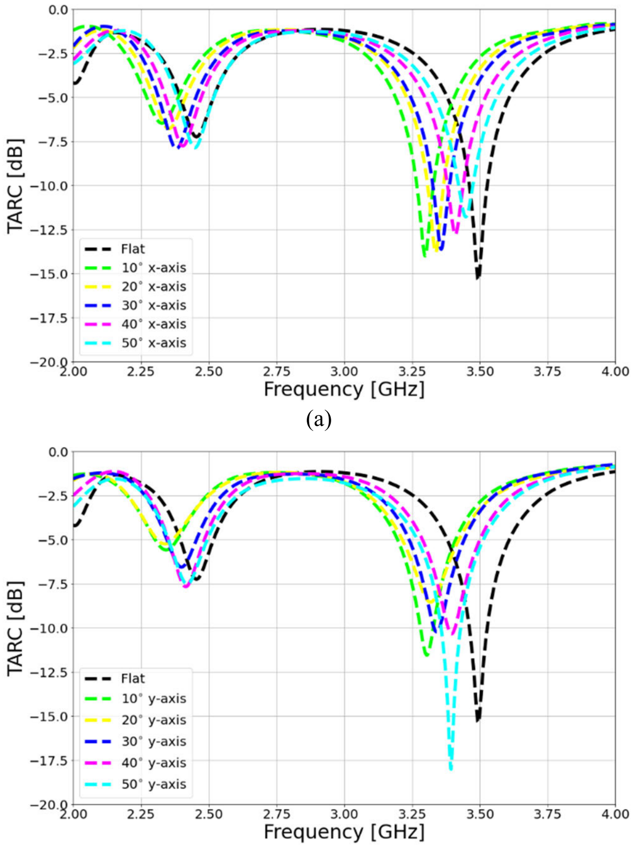
The proposed MIMO antenna is evaluated in terms of envelope correlation coefficient (ECC), diversity gain (DG), channel loss capacity (CCL) and total active reflection coefficient (TARC). The correlation between antenna elements is



(a)

(b)

FIGURE 11. **Channel capacity loss (CCL) of the MIMO antenna for different bending. (a) x-axis and (b) y-axis.**



(a)

(b)

FIGURE 12. **Total active reflection coefficient (TARC) of the MIMO antenna for different bending. (a) x-axis and (b) y-axis.**

described by the ECC (ρ_e) and the diversity gain. They are used to evaluate the correlation levels of the channels [29], and is calculated using equation (1), as follows:

$$\rho_e = \frac{\left|\iint \vec{E}_i(\theta,\phi)\,\vec{E}_j(\theta,\phi)d\Omega\right|^2}{\left|\vec{E}_i(\theta,\phi)\right|^2\left|\vec{E}_j(\theta,\phi)\right|^2 d\Omega} \tag{1}$$

A low ECC value indicates minimal correlation between antenna elements. Similarly, diversity gain (DG) is dependent on the spatial correlation coefficient between the patch elements. A low ECC (< 0.5) leads to high diversity gain, and both are related by equation (2), as follows:

$$DG = 10\sqrt{1-\rho_e^2} \tag{2}$$

The simulated and measured ECC within the frequency of interest is presented in Figure 9. ECC at all resonant frequencies are below 0.05 in both flat and bent conditions, and satisfies the minimum (< 0.5) diversity criteria [21]. A low ECC leads to high diversity gain, which is demonstrated by the plot in Figure 10. For an ECC value of less than 0.1, the diversity gain is almost 10 dB.

On the other hand, CCL is the estimated maximum message transmission which can take place without any loss in the communication channel. The acceptable rate should be less than 0.4 bits/s/Hz. Calculated using equations (3) to (5), the CCL result is presented in Figure 11.

It shows that the proposed MIMO exhibits acceptable CCL for all bending conditions with varying operating frequency.

$$CCL = -\log_2 \det(\alpha) \tag{3}$$

where

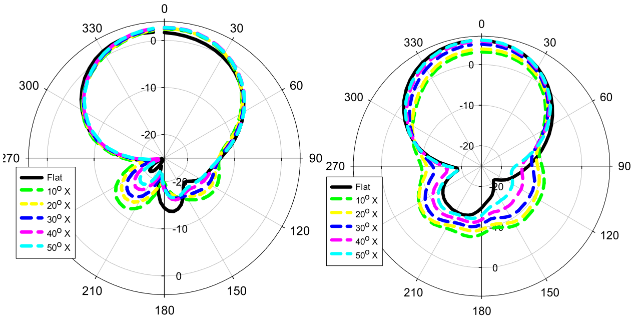
$$\alpha = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \tag{4}$$

and

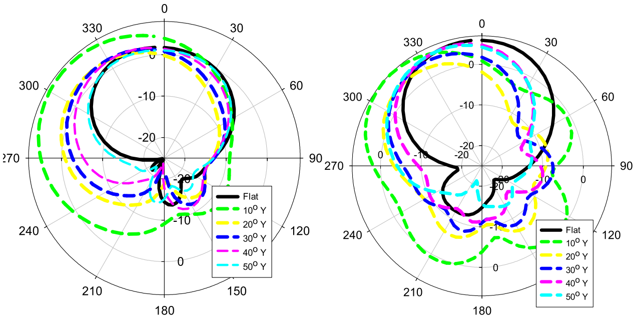
$$\alpha_{ii} = 1 - \left(\sum_{j=1}^{2} \left|S_{ij}\right|^2\right),$$

$$\alpha_{ij} = -\left|S_{ii}^{*}S_{ij} + S_{ji}^{*}S_{jj}\right|. \tag{5}$$

Another evaluated parameter for this antenna is TARC, defined as the ratio of reflected and incident power for a MIMO antenna system. For a two-port MIMO antenna, TARC is calculated using equation (6) and must be below −0 dB. For the proposed MIMO antenna at both operating



(a) 2.45 GHz x-axis bend (b) 3.5 GHz x-axis bend



(c) 2.45 GHz y-axis bend (d) 3.5 GHz y-axis bend

FIGURE 13. **Radiation pattern of the proposed MIMO for different bending conditions.**

frequencies, the TARC are below -5 dB as seen in Figure 12.

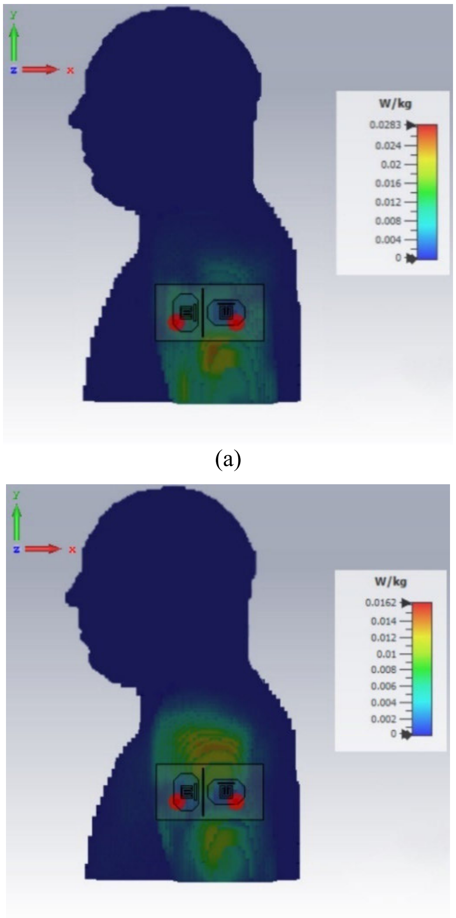
$$TARC = \frac{\sqrt{\left|S_{11} + S_{12}e^{j\theta}\right|^2 + \left|S_{21} + S_{22}e^{j\theta}\right|^2}}{\sqrt{2}} \tag{6}$$

E. RADIATION PATTERN

Radiation pattern of the proposed MIMO antenna is shown in Figure 13. It is observed that the main lobe of the radiation pattern is maintained while there are increasing in back lobe when the bending degree is decrease from 50° to 10° in both the lower and upper operating bands of the antenna. On the other hand, significant variation in the radiation patterns of the antenna is seen when bent at the y-axis. As the bending degree is reduced, the main lobe direction tilted to the left, with slightly higher back lobes pattern.

F. SPECIFIC ABSORPTION RATE (SAR) ANALYSIS

The SAR values for the proposed antenna are calculated using CST MWS by mounting the proposed antennas in proximity of a truncated Hugo human body model (on the upper arm). The proposed antenna is placed 1 mm away from these models, as seen in Figure 14. The SAR distributions averaged over 10 g of tissue are then calculated at 2.4 GHz and 3.5 GHz for this antenna with an input power 1 W when placed on the left upper arm. SAR levels for this antenna in planar condition presented in Figure 10 indicate that the maximum 10 g SARs are observed to be 0.0283 W/kg and 0.0162 W/kg at 2.45 GHz and 3.5 GHz, respectively. These simulated SAR results are verified against the measured SAR of the antennas in [30], which used the same textile materials and full ground plane as the proposed MIMO antenna. The maximum 10 g measured SARs in [30] are 0.1 W/kg and 0.5 W/kg at 2.45 GHz and 5.2 GHz, respectively. A satisfactory agreement between the simulated and measured SAR is observed. Due to the use of the full ground plane, the SAR values for antenna in this antenna did not exceed 0.1 W/kg in both bands.



(a)

(b)

FIGURE 14. **SAR evaluation on Hugo body model at 10g on left upper arm. (a) 2.45 GHz and (b) 3.5 GHz.**

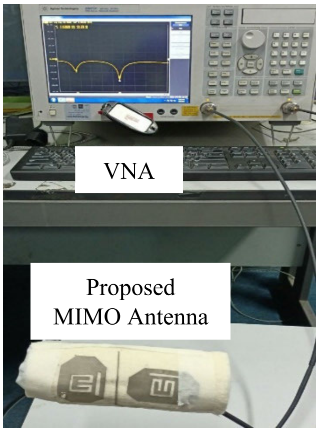
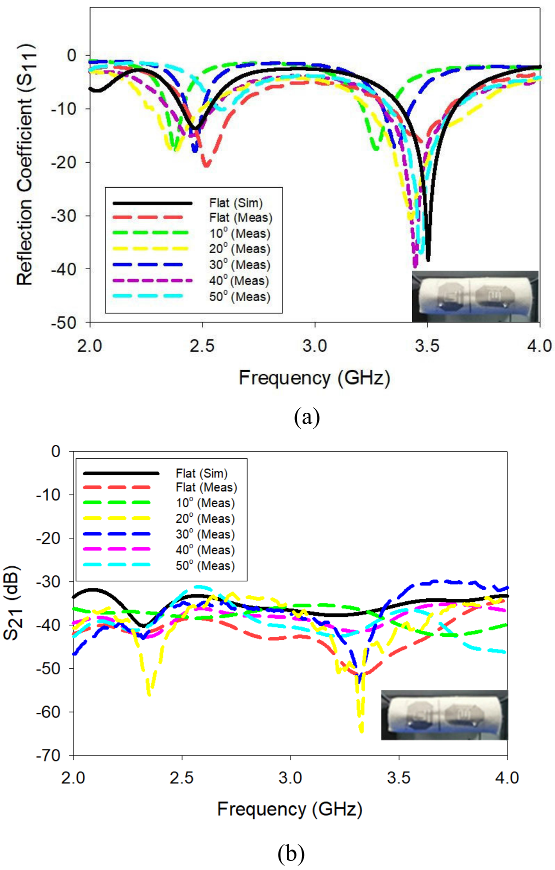


FIGURE 15. **Measurement setup for bending at x-axis.**



(a)

(b)

FIGURE 16. Comparison of simulated and measured S-parameters of the proposed MIMO antenna: (a) S_{11}, (b) S_{21}.

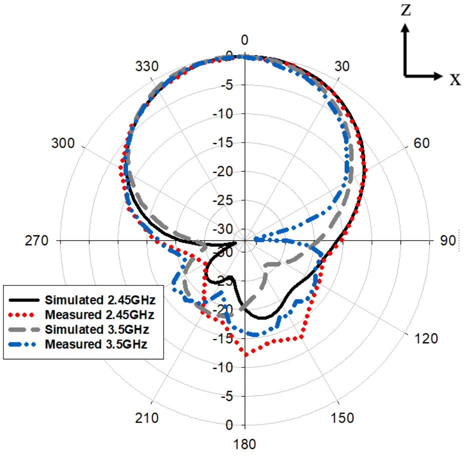
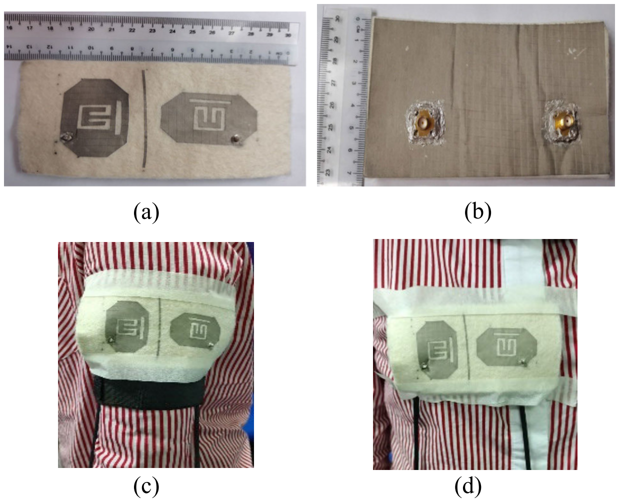


FIGURE 17. Simulated and measured radiation patterns of the proposed MIMO antenna in the XZ-plane.


(a) (b)

(c) (d)

FIGURE 18. Photograph of the fabricated antenna. (a) Front view, (b) back view, (c) antenna on upper arm and (d) antenna on chest.

TABLE 2. Performance comparison of the proposed MIMO antenna for flat condition in free space at 2.45 GHz and 3.5 GHz.

Parameter	Simulation		Measurement	
	2.45 GHz	3.5 GHz	2.45 GHz	3.5 GHz
S_{11} (dB)	-14.47	-37.9	-20.94	-16.39
S_{21} (dB)	-22.24	-26.64	-38.74	-48.8
Fmin (GHz)	2.39	3.38	2.43	3.33
Fmax (GHz)	2.50	3.62	2.65	3.59
% Bandwidth	3.53	7.1	8.66	7.51
Realized Gain (dBi)	1.4	5.8	1.5	5.9
Radiation Efficiency	30%	48%	30.5%	49.5%
Directivity (dBi)	7.56	9.08	7.64	9.15

IV. EXPERIMENTAL EVALUATION RESULTS

The proposed MIMO antenna is then fabricated and experimentally assessed in the planar condition and when bent at both axes, as shown in Figure 15 (with 20° of bending radius). The measurements are performed using Keysight Technologies E5071C E-series Vector Network Analyzer (VNA). A 50-Ω coaxial cable has been used to connect SMA to the VNA for measurements. Their S_{11} and S_{21} results are presented in Figure 16, with the solid lines representing the simulated performance, whereas measurement are represented by the dashed lines. The simulated S_{11} for the proposed antenna in planar form are observed to be consistent with measurements in free space, as illustrated in Figure 16(a), except for a slight upwards shift in the lower band. Satisfactory agreements are also seen between measured S_{11} for all bending configurations at *y*-axis, including their bandwidths. However, when bent at the most extreme condition ($\alpha = 10°$ at *y*-axis), the proposed MIMO antenna showed a downwards shift in the lower band. In planar condition, its measured S_{21} is about −35 dB in both bands, with improvements of 6 dB and 10 dB at 2.45 GHz and 3.5 GHz, respectively. On the other hand, t is observed that the measured S_{21} is less than −30 dB when the antenna is bent at the *y*-axis for all bending conditions in the lower and upper bands. This indicates that the MC is reduced significantly even in the extreme bending condition. This validates the design's robustness against any *y*-axis bending and maintained its dual band characteristic.

TABLE 3. **Performance comparison of the proposed MIMO with relevant state-of-the-art work in literature.**

Ref	Freq (GHz)	Flexible	Antenna size	Technique	S_{21} (dB)	Complexity	Gap (λ_0)
[5]	1.8, 2.4, 3.4, 4.18, 5.2, 5.5, 6.1	Not	1.28 × 1 λ_0	Slot	-37	Complex	NA
[8]	2.4	not	0.58 × 0.746 λ_0	Neutralization line	-20	average	NA
[9]	2.4, 5.2, 5.8	yes	1.03 × 0.465 λ_0	Metamaterial	−18	complex	0.1
[13]	16	not	2.37 × 1.19 λ_0	Parasitic	-24	average	0.32
[14]	2.6, 3.6	not	NA	Parasitic	-20	simple	-
[17]	2.4-8	yes	0.41 × 0.713 λ_0	DGS and stub	-22		-
[18]	2.5, 5.5	not	0.454 × 0.874 λ_0	DGS and metal strip	-20		~0.36
[19]	5.2	semiflexible	NA	DGS and SRR	-30	simple	0.75
[21]	3.5-4.9	not	NA	Hybrid	-28	Simple DRA	0.5
Proposed work	2.45, 3.5	yes	1.301 × 0.686 λ_0	Hybrid	-30	average	0.1

* NA – not available

Table 2 summarizes the performance of the proposed MIMO antenna in terms of S_{11}, S_{21}, impedance bandwidth, realized gain, radiation efficiency, and directivity when operating in flat condition in free space at 2.45 GHz and 3.5 GHz. As evident from these results, satisfactory performance for all parameters are observed in free space. A small difference exists between simulated and measured results due to the potential fabrication inaccuracies, the inhomogeneous thickness of the textile layers and inhomogeneous dielectric properties. The simulated and measured 2-D radiation patterns for the proposed antenna at 2.45 GHz and 3.5 GHz presented in Figure 17 indicate directional patterns with small back lobes. A good agreement between the simulated and measured radiation patterns have been observed.

Besides simulations, the prototype is measured in proximity of the human body on the chest and upper arm, as shown in Figure 18(c) and Figure 18(d), respectively. Comparison between simulated and measured S_{11} and S_{21} on the chest and upper arm are summarized in Figure 19. The impact of the human body on the antenna is minimal due to the shielding against coupling provided by the full ground plane. Measured impedance bandwidths of 6.95 % and 7.11 % are achieved in the lower and upper bands, respectively, when measured on the chest.

Meanwhile, when placed on the upper arm, the measured bandwidth is 7.78 % and 9.15 % in the lower and upper bands, respectively. Measured S_{21} are consistently less than −30 dB when the antenna is mounted on the chest and upper arm in both lower and upper bands. A good agreement between the on-body simulated and measured S_{11} and S_{21} is seen, with small marginal shift observed due to nonidealities in the experimental environment. The low MC exhibited by the proposed antenna makes it suitable for off-body MIMO in WBAN and 5G applications.

In summary, Table 3 compares the performance of the proposed MIMO antenna with previous 1 × 2 MIMO antennas in terms frequency, flexibility, antenna size, technique, S_{21}, and gap between elements. One of the most similar work in [8] presented a multiband wearable MIMO antenna with a comparable $0.1\lambda_0$ inter-element gap with the proposed design. However, the metamaterial technique applied to the structure result in a more complex structure. It is also worth noting that the proposed work is the first work proposed on wearable MIMO antenna operating at 2.45 GHz and 3.5 GHz designed using a hybrid method to result in a relatively simple and compact structure. Besides the extensive validation on antenna deformation, the proposed hybrid technique also resulted in less than 30 dB of S_{21} and a very small inter-element gap ($0.1\lambda_0$). Such method can potentially be applied to design MIMO antennas in space-constrained mobile devices.

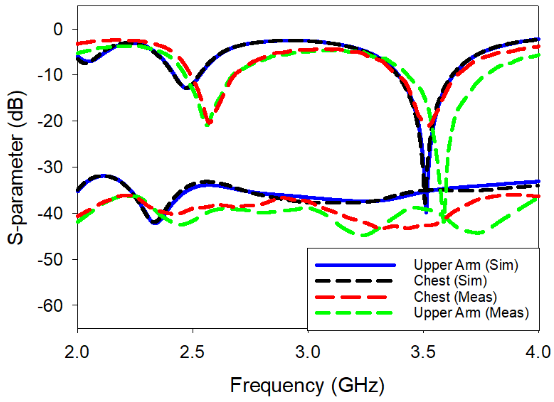


FIGURE 19. **Comparison of simulated and measured S-parameters of on-body of the proposed MIMO antenna.**

V. CONCLUSION

This study proposes a hybrid method of mutual coupling reduction applied in designing a textile MIMO antenna for on body applications. This antenna is designed by combining two octagonal structures each integrated with a SR and bar slot. Mutual coupling of the MIMO antenna is significantly reduced by rotating the patch element and adding a line patch between the antenna elements. Most importantly, the resulting optimized structure is simple and can be implemented as a textile antenna. Due to this, the agreement between simulations and measurements is satisfactory. Moreover, evaluation of this antenna under different degrees of bending and bending axes indicated robust performance, with minimal changes in terms of reflection coefficient, mutual coupling, and radiation characteristics. Further assessments of this antenna in terms of MIMO parameters such as ECC, DG, CCL and TARC also validated that this antenna can be potentially applied in the next generation of 5G wearable devices.

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