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Planar textile antennas with artificial magnetic conductor for body-centric communications

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Abstract Two textile antennas namely diamond dipole and coplanar waveguide (CPW) monopole are designed to test the proposed textile artificial magnetic conductor (AMC). Performance comparison including return loss, radiation pattern, and gain between the two antennas above AMC is observed. Results show gain improvement with reduced backlobes when having AMC. Bending and wetness measurements are also conducted. Bending is found not to cause performance disruption, while wetness influences performance distortion. However, once the antennas and AMC dried out, the original performance is retrieved.

1 Introduction

Body-centric wireless communication is getting more exposure these days due to the need of a short-range wireless communication within human body [1]. Wearable antennas have been mostly implemented in body-centric communication [2, 3] due to their flexibility to be equipped on textiles that can be worn as part of clothing. Moreover, wearable antennas are also cheap, light, and can work in a wide range of frequencies [4]. Recently, wearable fabric-based antennas are gaining popularity, since fabrics have low dielectric constant that contributes in getting a wide bandwidth from the antenna [5, 6]. Unfortunately, wearable antennas for on-body environment are exposed to performance degradation caused by the human body [7]. In addition, the electromagnetic radiation from the wearable antenna that goes into human body is a crucial health issue. Due to the drawbacks mentioned, wearable artificial magnetic conductor (AMC) was introduced using flexible [8] and textile [9, 10] materials. Antenna with AMC ground plane enables the isolation of human body from the antenna's electromagnetic radiation, apart from enhancing the gain. It also eliminates the antenna's impedance mismatch caused by the human tissues [11]. In spite of the benefits that it may offer, there are issues need to be solved in the design of textile antenna and AMC. It should practically be catered to the human body condition. Since wearable antennas and AMC are to be worn by human who moves all the time, the most important factors that need to be taken into consideration are the capability of the antennas and AMC to withstand bending [12]. Another factor that needs to be considered in designing textile antenna and AMC is its ability to remain operational after being exposed to water [13]. This study proposes planar textile antennas and textile AMC for body-centric communication. The proposed antennas and AMC sheet are entirely made off textile materials that offer flexibility and comfort and can be incorporated into clothing; that are suitable for wearable applications. The proposed textile AMC can act as an electromagnetic shield apart from improving the impedance matching, gain, and radiation pattern. In this study, the performance of the proposed antennas and AMC will be evaluated through rigorous

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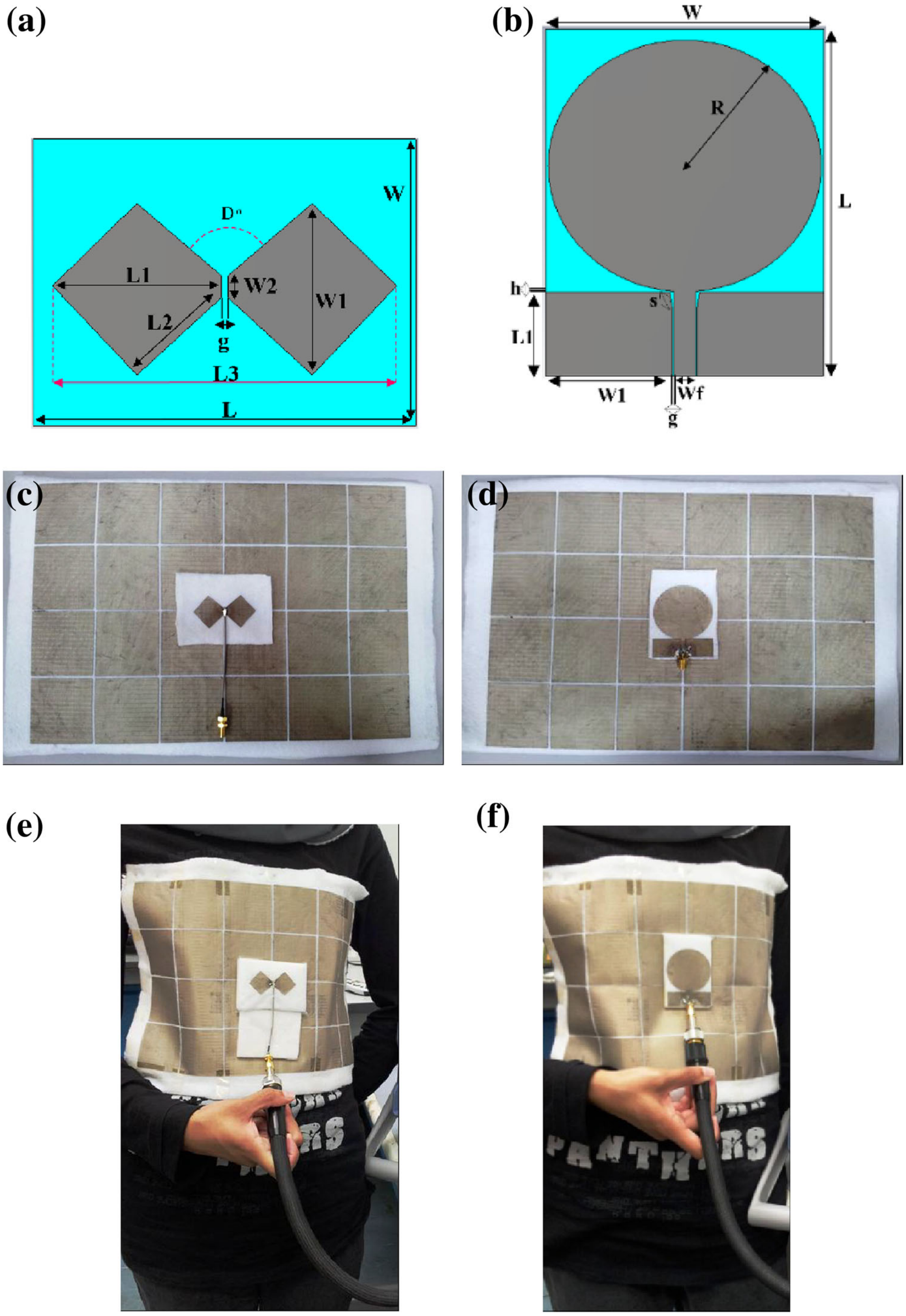


Fig. 1 Simulated and fabricated planar textile antennas and AMC **a** diamond dipole, **b** CPW monopole, **c** diamond dipole above AMC, **d** CPW monopole above AMC, **c** diamond dipole with AMC on body, **d** CPW monopole with AMC on body

wearable and body-centric experiments that include bending and wetness measurements.

2 Planar textile antennas and AMC design

Two planar textile antennas namely diamond dipole and coplanar waveguide (CPW) monopole are designed to be tested on the proposed textile AMC. Diamond dipole represents narrowband antenna, while CPW monopole represent wideband antenna that is utilized to test the performance of the AMC sheet with both narrowband and wideband antennas. As shown in Fig. 1a, the dimensions of the diamond dipole in mm are $L = 60$, $W = 45$, $L1 = 26.5$, $L2 = 18$, $W1 = 26.9$, $W2 = 3.4$, $g = 1$. On the other hand, the CPW monopole has dimensions of $W = 50$, $L = 62$, $Wf = 4$, $g = 0.2$, $L1 = 15$, $W1 = 22.8$, $h = 0.025$, $R = 23$, $s = 3$ in mm (Fig. 1b). The antennas

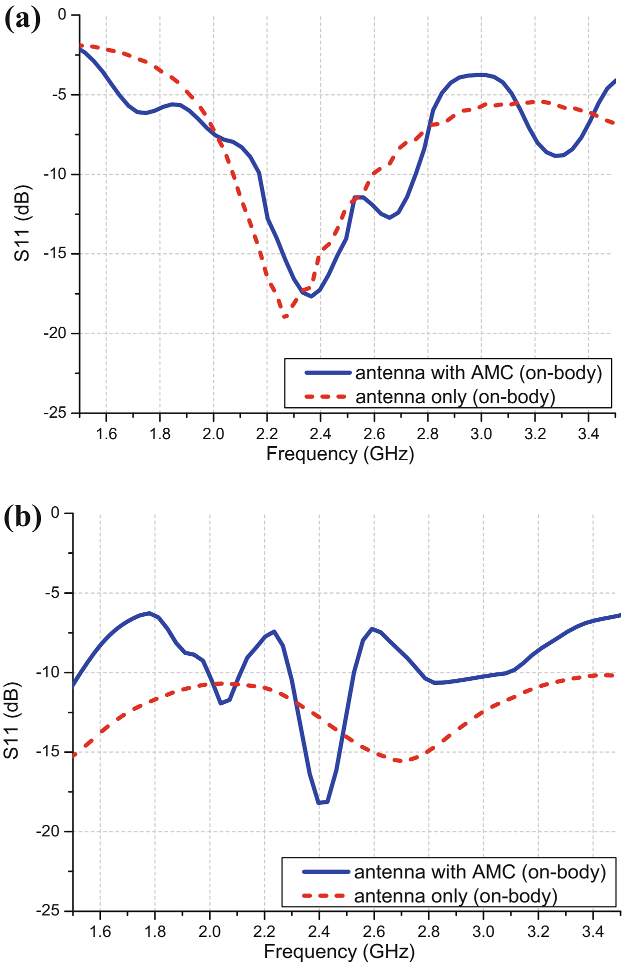


Fig. 2 S_{11} of planar textile antennas with and without AMC in on-body environment **a** Diamond dipole, **b** CPW monopole

and AMC are made entirely from textile using fleece and Shieldit fabrics. The fleece used in this work has permittivity $\varepsilon_r = 1.3$, tangent loss $\delta = 0.025$, and thickness $h = 1$ mm. The diamond dipole resonates at 2.45 GHz with measured return loss depth of -34 dB. On the other hand, the CPW monopole is an ultra-wideband antenna with measured bandwidth of 11.2 GHz operating from 1.78 to 13 GHz.

In parallel, the AMC is designed to have in-phase reflection at 2.45 GHz. Single-band square patch AMC was proposed due to its simplicity for easy and accurate fabrication. The AMC comprises of 6×4 conductive patches, fleece substrate, and ground plane. The antennas are placed 5 mm above the AMC surface using Rohacell 31HF as the spacer. The optimized patch size is 51 mm with 2-mm gap between the patches.

Figure 1c, d shows the fabricated prototypes of textile AMC with diamond dipole and CPW monopole. The on-body measurement setup for the planar textile antennas above the AMC sheet is illustrated in Fig. 1e, f. The S-parameter performance is measured using Vector network analyzer. To minimize the air gap, the AMC is closely attached to the wearer's body.

3 Results and discussions

3.1 Planar antennas above AMC

Continuing from the design of the proposed antennas and AMC, study has been conducted to integrate the planar

Fig. 3 Gain and radiation pattern measurements **a** Anechoic chamber, **b** Antenna and AMC measurement

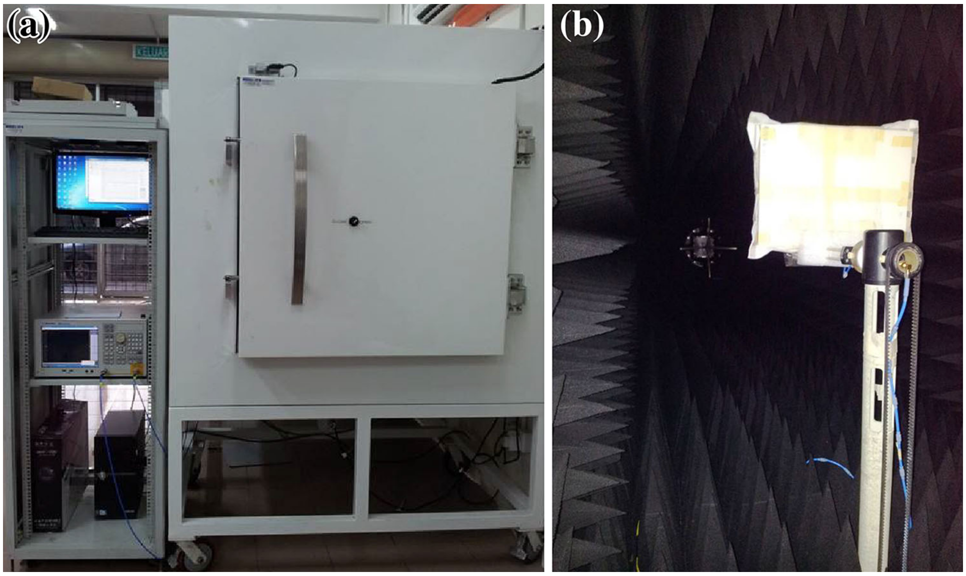
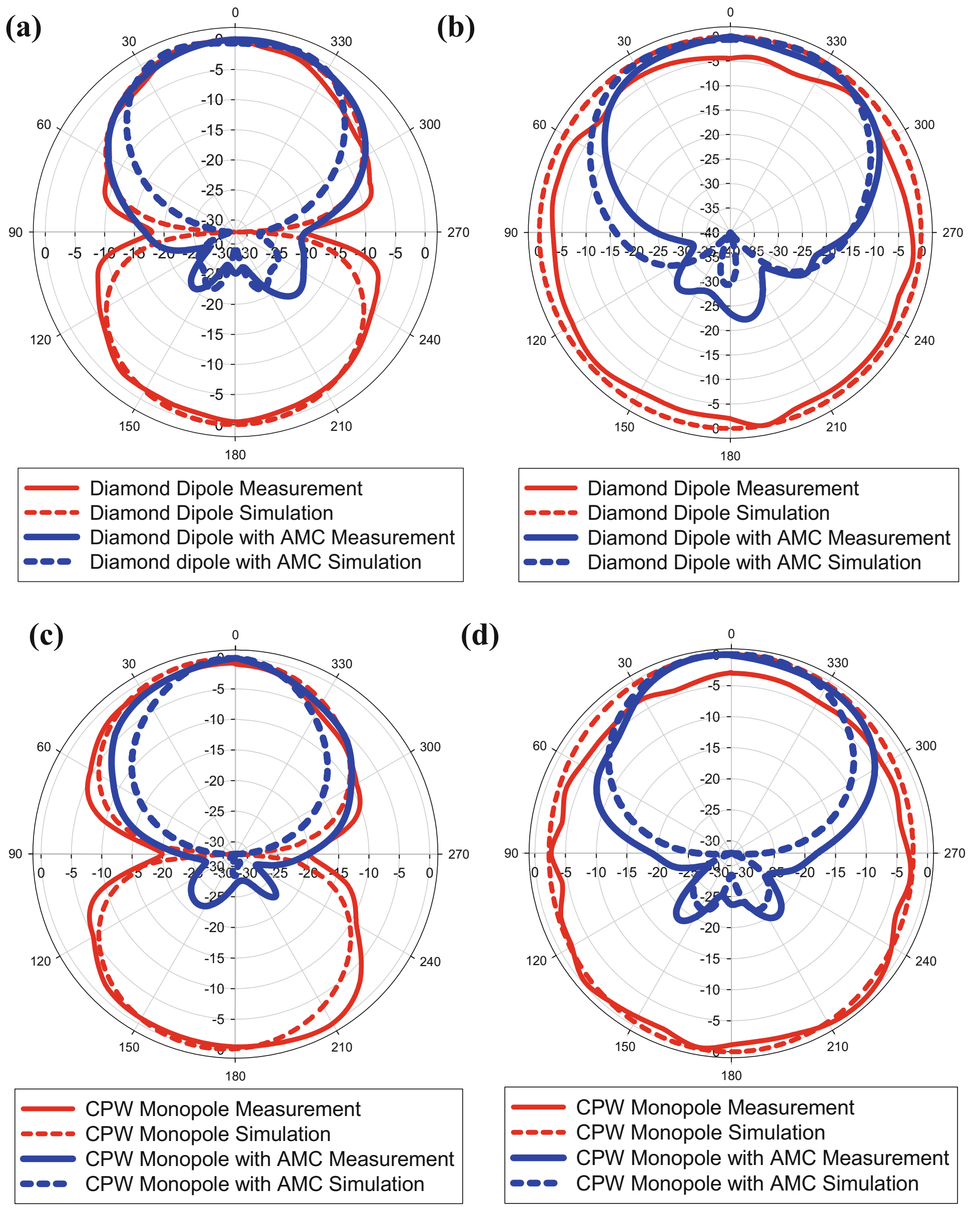


Fig. 4 Measured radiation patterns of planar textile antennas above AMC at 2.45 GHz **a** E plane–diamond dipole, **b** H plane–diamond dipole, **c** E plane–CPW monopole, **d** H plane–CPW monopole



textile antennas with the AMC structure. The diamond dipole and CPW monopole are to be employed to test the performance of the proposed AMC sheet. Investigations for both free space and on-body environments are conducted.

Figure 2 shows the measured return loss of diamond dipole and CPW monopole above AMC in on-body environment. The graphs compare the return loss performance of the antennas with and without the AMC surface when placed above human body. For the diamond dipole case (Fig. 2a), it can be observed that the antenna experiences a shift in resonant frequency to 2.27 GHz when placed on human body. As for the AMC surface case, a shift in resonant frequency to 2.37 GHz is also observed. Nevertheless, in both cases of with and without the AMC surface, the antenna is still performing at 2.45 GHz with return loss of −13 and −15 dB, respectively.

Figure 2b shows the reflection coefficient of the textile CPW monopole when placed on the human body with and without the presence of AMC sheet. From the graph, it can be observed that the return loss depth of the CPW monopole at 2.45 GHz has worsened to −14 dB when placed on human body compared to −18 dB when radiating in free space. On the other hand, when the monopole is placed above AMC sheet in on-body environment, the reflection coefficient is seen to establish resonance at 2.45 GHz. By having AMC sheet, the return loss depth at 2.45 GHz is −16 dB with bandwidth of 9.52 % ranging from 2.3 GHz to 2.53 GHz.

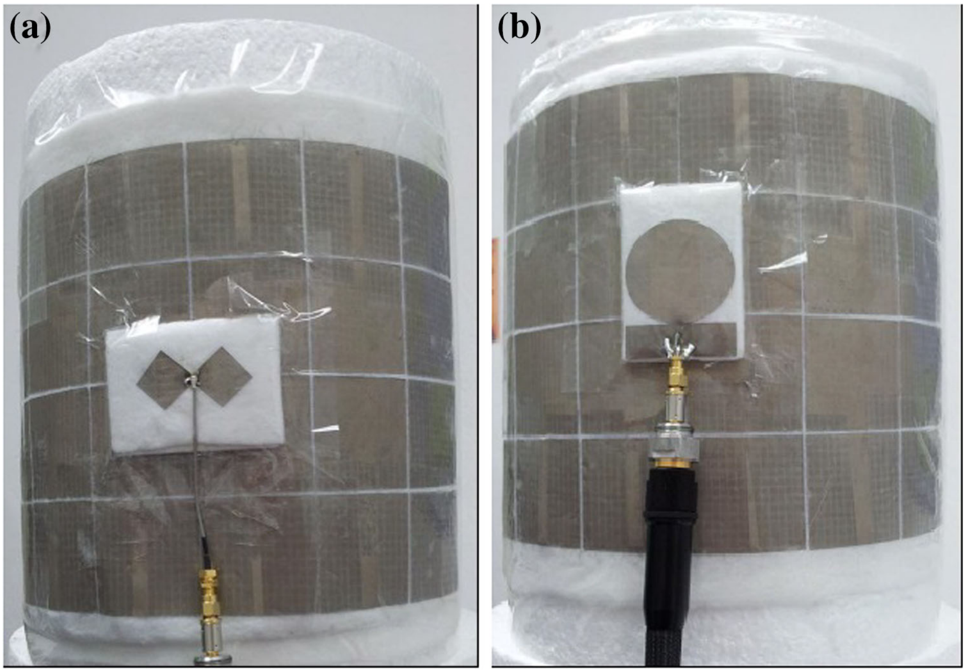


Fig. 5 Planar textile antennas with AMC sheet under bending condition **a** Diamond dipole, **b** CPW monopole

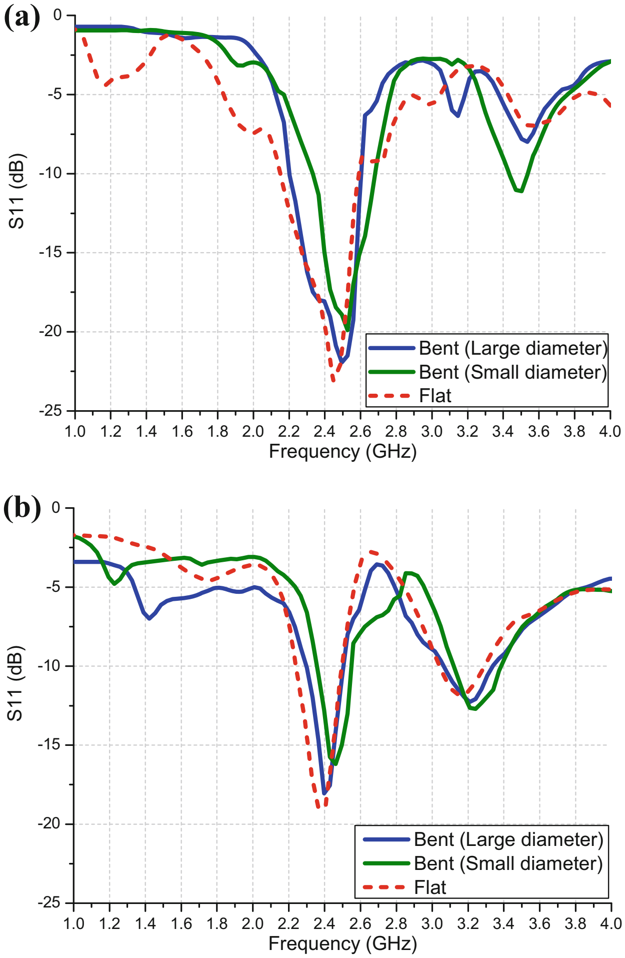


Fig. 6 Measured S_{11} of planar textile antennas above AMC under bending measurements **a** Diamond dipole, **b** CPW monopole

Simulation and measurement are also conducted to explore the radiation patterns of the planar textile antennas above the fleece AMC sheet. Radiation patterns measurement is conducted in an anechoic chamber as shown in Fig. 3a. The antenna and AMC are held together using polystyrene, tapes, and holder during the radiation patterns measurement (Fig. 3b).

Figure 4 plots the radiation patterns of the diamond dipole and CPW monopole with and without AMC sheet, respectively, in E and H planes. Simulated and measured radiation patterns with and without AMC are compared in the polar plots. The cross-components of the radiation patterns are not included since both of the antennas under test are linearly polarized that yield low cross-polar components.

Reasonable agreement between the simulated and measured radiation patterns validates the simulation results. The slight discrepancies between simulated and measured pattern are predicted due to dissimilarity between simulated structure and measurement setup. In the measurement, polystyrene, tapes, and holder are used which are not modelled in the simulation.

From the polar plots, it can be seen that for the cases without AMC, the radiation patterns yield the expected dipole and monopole patterns, i.e., E plane patterns are similar to the shape of number eight and H plane plots give circle shapes. On the other hand, directive radiation patterns with minimum backlobes have been achieved in both E and H planes for both antennas when placed above AMC surface. The AMC surface acts as reflector, hence the

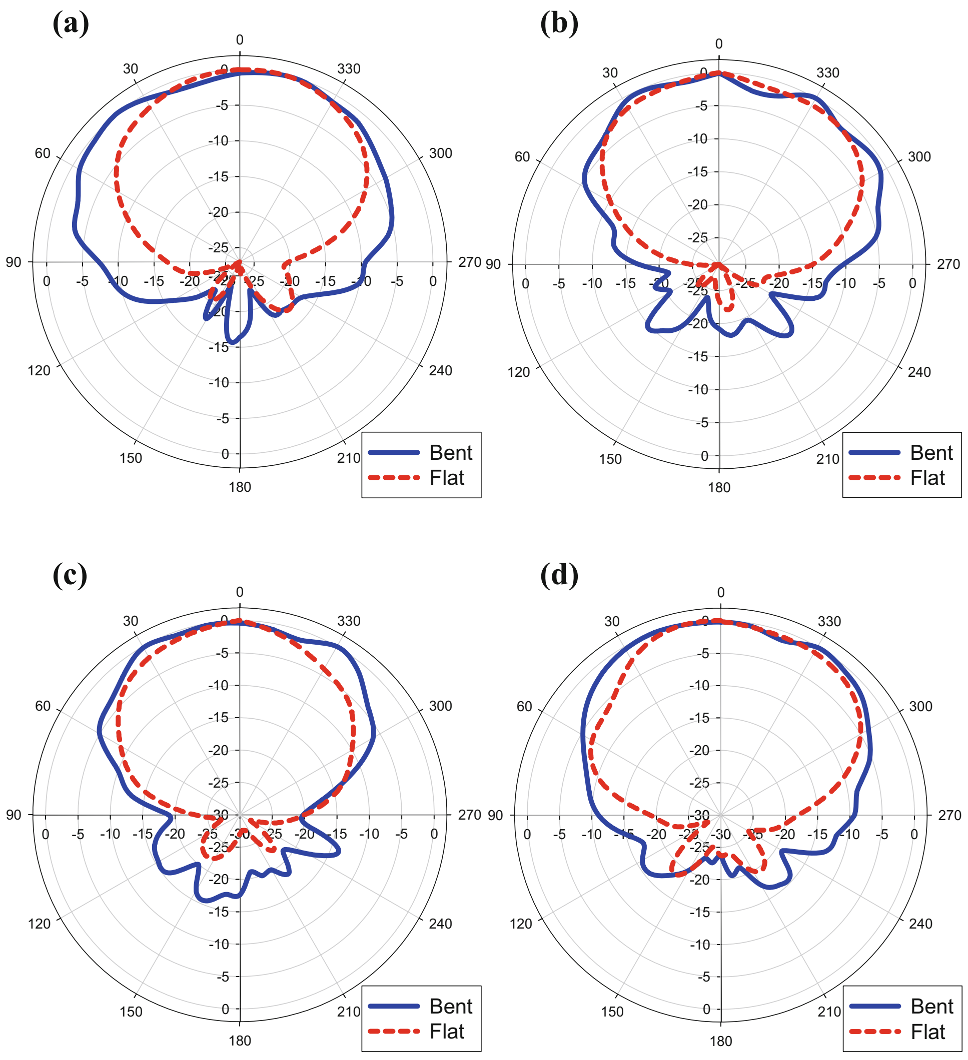


Fig. 7 Measured radiation patterns of planar textile antennas above AMC under bending condition at 2.45 GHz **a** E plane–diamond dipole **b** H plane–diamond dipole **c** E plane–CPW monopole **d** H plane–CPW monopole

forward direction of the radiation with small backlobes. Such forward directive radiation pattern is appropriate for wearable application since it minimizes the radiation that penetrates into the human body. This in turn enhances the gain of the antennas when placed above the AMC sheet. The simulated gain of the diamond dipole with and without AMC structures is 2 and 5 dB, respectively, which suggests significant gain improvement with the introduction of AMC sheet. Validating the simulation claim, measured gain is observed as 3 and 7 dB for the antenna with and without AMC arrays giving the same trend of gain improvement for AMC case. The simulated gain of the CPW monopole alone is 3 and 7 dB when placed above AMC sheet. The measured gain is 2 dB for the antenna alone and 7 dB with the presence of AMC. From both simulation and measurement results, the gain is observed to increase with the introduction of the textile AMC. Significant gain improvement is expected due to the AMC in-phase reflection properties.

3.2 Wearable and body-centric measurements

The proposed AMC and antennas are also tested with wearable and body-centric measurements. Bending and wetness experiments are performed to investigate the antennas and AMC performance for body communication realization.

3.2.1 Bending measurement

Bending experiment is carried out for the planar textile antennas with AMC. Two polystyrene cylinders of diameter size 250 and 310 mm are used to represent the size of small and large human's torso. Such cylinders that represent the size of the torso are used since the AMC sheet is relatively large and is meant to be worn around the torso area.

Textile diamond dipole and CPW monopole with AMC sheet are tested under bending condition. Figure 5 shows

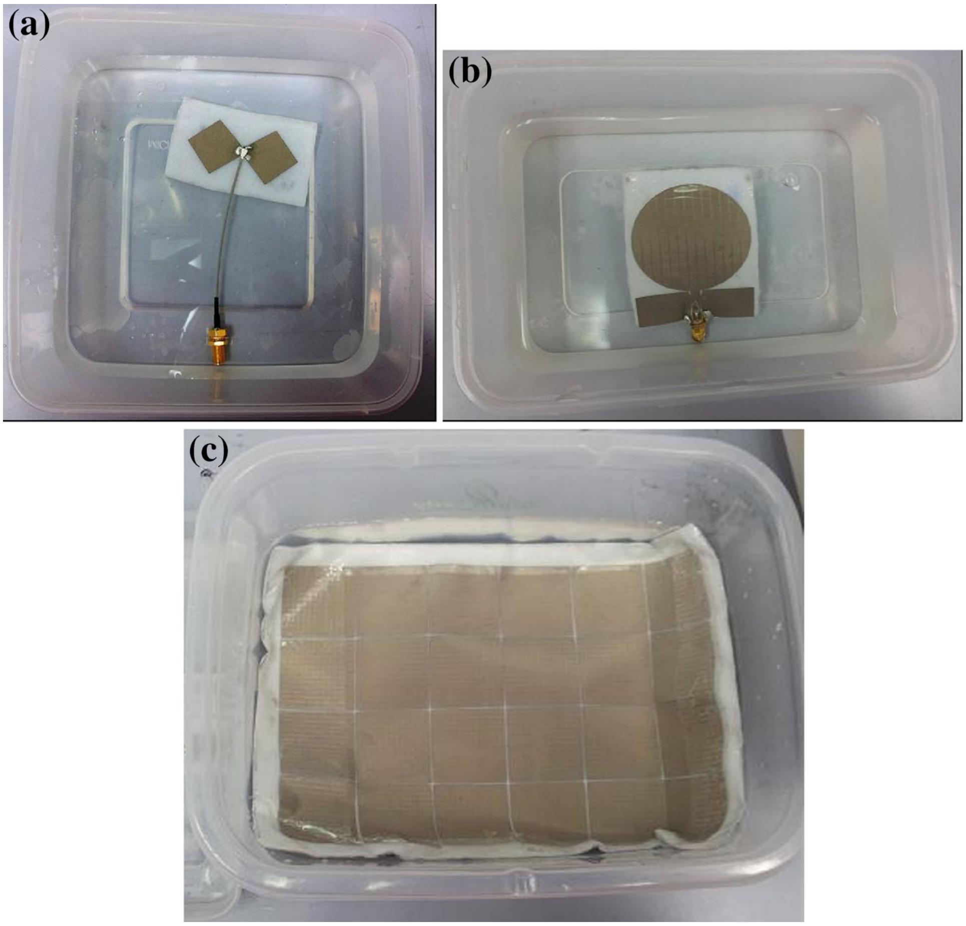


Fig. 8 Planar textile antennas and AMC soaked into water for wetness measurement **a** Diamond dipole **b** CPW monopole **c** AMC sheet

the bent textile diamond dipole and CPW monopole with AMC sheet on polystyrene cylinders, respectively. In this case, the textile diamond dipole is mounted in horizontal orientation above the AMC structure. On the other hand, the CPW monopole is positioned in vertical orientation above AMC sheet. A thin cellophane tape is used to maintain the position of the antennas and AMC on the cylinders.

The results of the measured return loss for the bent diamond dipole and CPW monopole with AMC sheet are compared in the following Fig. 6. The graph compares the reflection coefficient of a flat versus bent configurations, i.e., small and large bend diameters. Good agreement between the bent and flat cases has been achieved.

For CPW monopole case, the resonant frequencies for the bent configuration are 2.4 GHz and 2.46 GHz for large and small bend diameter, respectively. The large and small bend diameter configurations yield return loss depth of −18 and −16 dB, a reduction in depth compared to −19 dB for the flat case. For both antennas, the return loss shape is retained for all cases despite slight shift observed for both antennas and all bending cases. More apparent deviation of reflection coefficient results is seen for small cylinder bending which is due to higher degree of bending compared to larger cylinder. The measured radiation patterns are presented in Fig. 7 for bent and flat cases of textile diamond dipole and CPW monopole above AMC sheet, respectively. Only the small bending cylinder is used for the radiation pattern investigation. From the results, it can be observed that good radiation performance has been retained for the bent configuration in E and H planes for both antennas. Bending is found to give small effect to the radiation pattern. However, slightly larger backlobes are observed for the bent case.

Due to the curvature of the cylinder, the antennas and AMC yield less directional characteristic, hence the slightly higher backward patterns. The measured gain for diamond dipole and AMC in bent condition is 6 dB with small drop of 1 dB from 7 dB for the flat configuration.

Similarly, the measured gain for the bent CPW monopole with AMC sheet is 6 dB with a drop of 1 dB from 7 dB gain for the original flat configuration. The slight increase in backward patterns of the bent configuration results in the gain drop, as predicted. However, directional radiation pattern with small backlobes are still obtained with bent configuration.

3.2.2 Wetness measurement

The wetness measurement is then performed to test the performance of the antennas with AMC in wet condition. The textile antennas and AMC sheet are tested by observing four conditions, i.e., before washing, complete wet, damp, and dry.

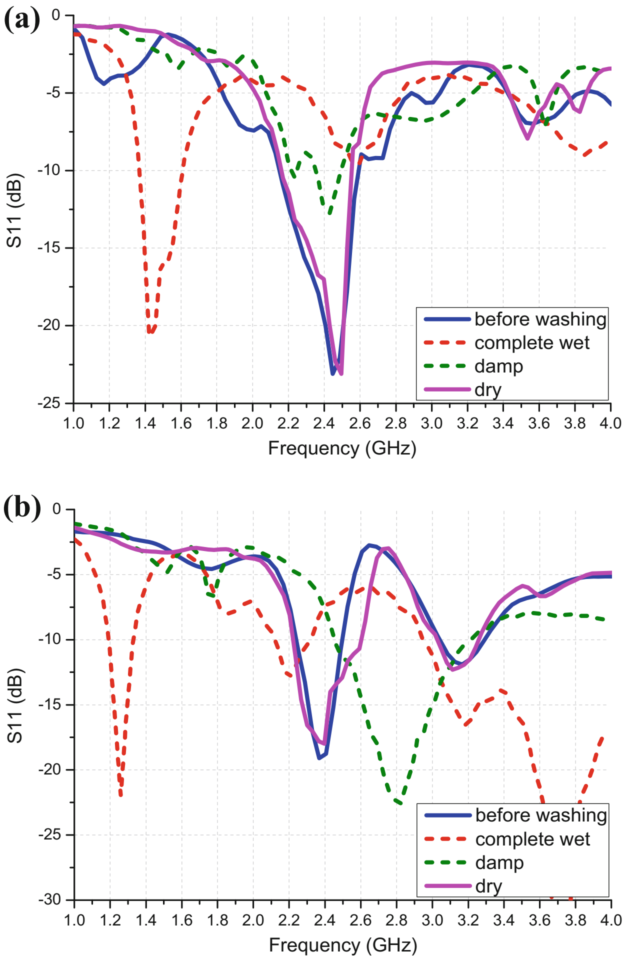


Fig. 9 Measured S_{11} of planar textile antennas above AMC under wetness measurements **a** Diamond dipole **b** CPW monopole

Diamond dipole and CPW monopole will be tested in this case together with AMC sheet. Initially, the antennas and AMC sheet are soaked into water overnight, for more than 12 h. Figure 8 shows the textile antennas and AMC sheet being immersed into water for the wetness measurement. Figure 9 plots the measured return loss of the diamond dipole and CPW monopole with AMC for the before washing, complete wet, damp and dry conditions. For both antennas, the complete wet result yields resonance to be shifted to a lower frequency due to the influence of water's high permittivity. For the case of diamond dipole, the damp result shows that the reflection coefficient magnitude is slowly returning to the original results.

On the other hand, as for the damp CPW monopole and AMC, resonance is found at 2.8 GHz. The resonance is found higher than expected for damp configuration that has moisture left in the antenna and AMC. This is probably due to the original properties of AMC's parameters that have changed due to the moisture, yielding resonance at higher frequency. However, once the antenna and AMC are completely dried, the reflection coefficient curve has returned quite close to the original result for both antennas. Small deviation between the dry and before washing results is expected, since due to shrinking, the properties of the monopole and AMC have changed. The substrate's shrinking has also caused the reduction in the gap between AMC patches, hence the original's return loss result cannot be exactly retrieved.

Table 1 tabulates the performance comparison in terms of reflection coefficient magnitude and gain between the two antennas when placed above AMC. Results show that the proposed AMC is able to tune the resonant frequencies of both antennas according to the AMC designated frequency. Directive radiation patterns with minimum back lobes are also achieved with significant gain improvement. With the AMC, on-body antennas performance is improved by mitigating the detuning problem caused by the human body as well as reducing the radiation that goes into the human flesh. In addition, results show that bending does not affect the antennas and AMC's return loss, gain, and

Table 1 Comparison of planar textile antennas with and without AMC under body-centric measurements at 2.45 GHz

	Diamond dipole		CPW monopole	
	Without AMC	With AMC	Without AMC	With AMC
S_{11} (dB)				
Free space	−34	−23	−18	−15
On body	−13	−15	−14	−16
Bent	−30	−18	−17	−16
After drying (wetness test)	−29	−22	−18	−13
Gain (dB)				
Free space	3	7	2	7
Bent	3	6	2	6

radiation pattern performance significantly. However, wetness measurement shows that severe reflection coefficient magnitude distortion is observed when the antennas and AMC are in completely wet state. Nevertheless, when the antennas and AMC are fully dried, the original performance is recovered.

4 Conclusions

In this study, textile AMC that is proposed for on-body wireless systems has been successfully designed and developed. Two types of planar antennas are designed, tested, and employed to evaluate the viability of the proposed AMC sheet. Diamond dipole and CPW monopole have been designed using entirely textile materials. This study proposed fully textile antennas and AMC sheet for wearable body-centric communication. The implementation of entirely textile materials for both antennas and AMC designs is appropriate and will offer higher flexibility and better comfort level for wearable applications. In addition, with the introduction of AMC ground plane, directive radiation patterns with high gain are obtained. Reduced backlobe patterns which minimize the radiation that penetrates into the human body are observed. Bending is found not to cause any significant performance disruption. On the other hand, since the proposed antennas and AMC are not made of waterproof material, the performance is distorted under wet condition. However, once the antennas and AMC sheet ware dried out, the original performance is achieved. For future work, the antennas and AMC are recommended to be laminated with plastic coating or to be made of waterproof fabrics to avoid the wetness drawback. From the body-centric measurement results, the proposed textile antennas and AMC are seen fit to be applied in the body-centric wireless communication especially for wearable applications for healthcare, sports, search and rescue, personal entertainment among others.

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