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TEXTILE ARTIFICIAL MAGNETIC CONDUCTOR WAVEGUIDE JACKET FOR ON-BODY TRANSMISSION ENHANCEMENT

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Abstract—Diamond dipole antennas with textile Artificial Magnetic Conductor (AMC) sheet-like waveguide were designed to investigate the possibility of improving transmission between antennas. Fleece fabric is used as the substrate of the textile AMC while SHIELDIT fabric is used as the conductive patches and ground plane. The AMC surface is designed to resonate at 2.45 GHz with the goal to enhance the transmission between antennas. A small textile AMC waveguide sheet as well as an AMC waveguide jacket were fabricated. The S-parameters performance of the two antennas with textile AMC sheet was investigated in a free space environment and near to human body setting. The effect of different antennas' orientations was also considered. Measurements were conducted thoroughly to validate the simulated findings. Compared to free space environment, S_{21} transmission between two dipoles is improved up to maximum -10 dB when having textile AMC waveguide sheet beneath them. For both off-body and on-body placements, significant transmission enhancement has been observed with the introduction of the AMC sheet-like waveguide. Directive radiation patterns with high gain have also been achieved with the proposed AMC waveguide jacket.

1. INTRODUCTION

Body centric communication refers to human-self and human-to-human networking. The need of such communication in today's society is evident based on its wide range of applications [1–3], especially in

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healthcare [4–6]. Even though security and privacy issues arise with the implementation of this type of communication [7], its importance can be observed by the rising number of related researches conducted over the years. As such, one of the purposes of this research is to suggest improvements to the existing body centric systems.

Antennas transmit and receive electromagnetic signals. The performance of an antenna in an electromagnetic communication system will determine the efficiency of the system. Thus, choosing the right antenna to be used is very important. For on-body communication, apart from choosing the suitable type of antenna, it is also crucial for the antenna to have a pattern and polarization that support the electromagnetic signal propagation close to the body. Since it is applied on-body, the orientation of the body that determines the antennas' spacing and mutual orientation have to be considered as well [8].

Wearable antennas are usually used in body centric communications [9–12], until recently. Although wearable antennas suffer performance distortion when applied to human body, this field is still widely explored by researchers. One of the most researched wearable antenna types is the wearable fabric based antenna [13–18], initially designed in the form of a helmet [19] as well as a vest [20, 21], and since then, it is always meant to be a part of clothing. In general, fabrics have low dielectric constant, hence this property helps in getting a wide bandwidth from the antenna. Fleece is found to obtain a very good bandwidth, provided it is applied with enough thickness [22]. But even with this finding, and although it was greatly researched on, there are several significant challenges faced when designing fabric wearable antennas. Since it is fabric based, it is easily bended, flexed, and wrinkled. In addition, on-body propagation channels are exposed to fading and shadowing effect. On-body channels are subject to variation due to local scattering, geometry of the body and body movements. On-body antennas also experience high propagation loss. Thus, under all these circumstances, it is hard for the antennas attached on human body to remain operational. Due to the drawbacks mentioned, a new approach was fabricated [23]. The new method complements wearable antennas with waveguide structure, which enables better wave propagation. Waveguide is a structure that guides electromagnetic waves from point to point. Waveguide sheet had been implemented in short range wireless communication [24, 25] as well as in design of jackets and blankets for body-centric wireless communication [26–28].

In this research, the body centric communication is applied in the form of a jacket. The jacket is equipped with conformal Artificial Magnetic Conductor (AMC) waveguide sheet and is to be applied to improve the transmission of vital signals to Electrocardiography (ECG) machine wirelessly. The waveguide jacket will act as a data collecting medium that offers efficient wireless telemonitoring of ECG system. Wireless sensors will couple to the jacket and data will be collected to a control unit through the jacket. Instruction will then be sent to the ECG action unit based on the collected vital data. This approach is taken as an initiative to improve the state of the current ECG system, which has multiple wires and can be messy (Figure 1).

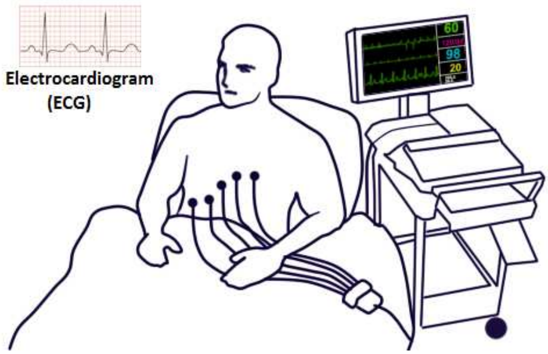


Figure 1. Patient with conventional wired Electrocardiogram (ECG) setup.

In the design, the transmission between on-body antennas is enhanced by implementing waveguide jacket as the communication medium (Figure 2(a)). On top of that, the structure of the waveguide used is a textile waveguide sheet equipped with AMC patches (Figure 2(b)). AMC structures are categorized as one of the many metamaterials type. Efforts to investigate the potential of metamaterials structure in the antenna field have been blooming ever since the discovery of metamaterials that benefited antenna performance [29–31].

AMC has been widely studied as a prospective antenna substrate [32] for its behaviour as perfect magnetic walls at resonance [33], enabling the design of low-profile antennas [34–36]. Such ability to mimic Perfect Magnetic Conductor (PMC) is deemed suitable to be applied to enhance the signal transmission between antennas. Previous results prove that AMC is capable of improving transmission between antennas as well as its performance [37, 38]. This special property of AMC made it chosen to be incorporated in the design of an efficient textile waveguide sheet for body centric

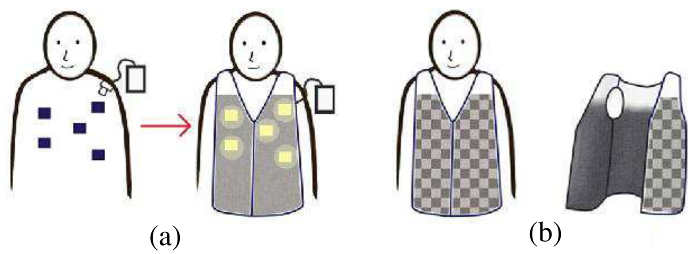


Figure 2. The concept of sheet-like waveguide jacket for transmission enhancement between antennas. (a) Waveguide jacket with ECG sensors to improve transmission and performance between wireless antenna sensors. (b) Proposed waveguide jacket with AMC structures.

communication. The textile material of the waveguide sheet adds practicality and conformity to the design, and is suitable for on-body communication.

2. DESIGN CONSIDERATION

A diamond dipole antenna (Figure 3(a)) has been designed to be incorporated with a textile AMC waveguide jacket. The diamond dipole is used to investigate the transmission performance between antennas when placed over the AMC sheet-like waveguide. Diamond dipole antenna is used as opposed to the conventional planar dipole since it offers wider bandwidth. The dipole resonates at 2.45 GHz and its dimensions are as shown in Figure 3(a). The substrate of the dipole is made of Fleece fabric with permittivity $\varepsilon_r = 1.3$, tangent loss $\delta = 0.025$ and thickness $h = 1\,\text{mm}$.

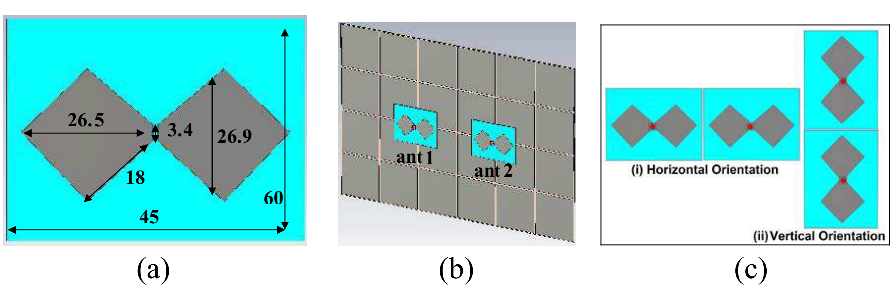


Figure 3. Diamond dipole antennas with textile AMC sheet. (a) Antenna's dimensions in [mm]. (b) Simulation layout. (c) Antenna's orientation.

In parallel, a textile AMC structure is also designed to have in-phase reflection at 2.45 GHz (Figure 3(b)). After optimization, the patch size is 51 mm with 2 mm gap between the patches. Similarly, the substrate of the AMC is made of Fleece fabric whilst the conducting patches and ground plane are made of SHIELDIT fabric. The Fleece AMC comprises of 6×4 conductive patches backed with a ground plane. Two different antenna's orientations were investigated in this work, namely horizontal and vertical orientations as depicted in Figure 3(c).

The Fleece fabric's material properties were characterized using dielectric probe method (Figure 4). This method is used since it offers good accuracy and quick measurement. Initially, calibration was conducted for the probe using the three standard calibration steps, i.e., air, short circuit and water) by verifying its permittivity accordingly. Following that, the tip of the probe is pressed onto the Fleece fabric to retrieve the permittivity and loss tangent values. Data from vector network analyzer is extracted and calculated by Agilent software that gives the permittivity and loss tangent values immediately. Graph in Figure 4 depicts the measured dielectric properties of Fleece fabric. The permittivity ranges from 1.3 to 1.5 while the loss tangent varies from 0 to 0.05.

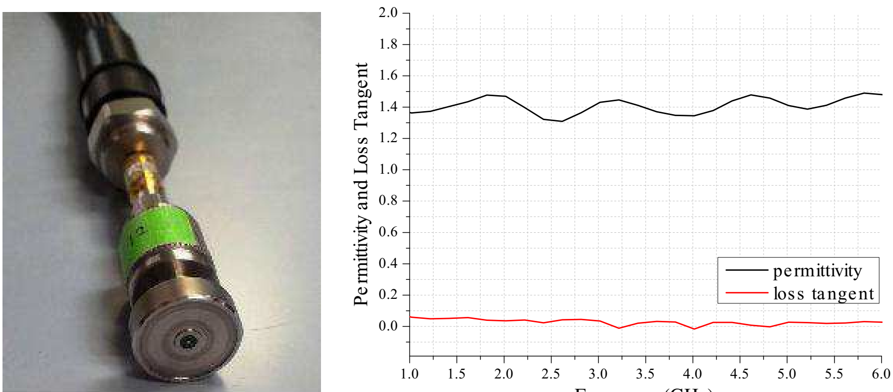
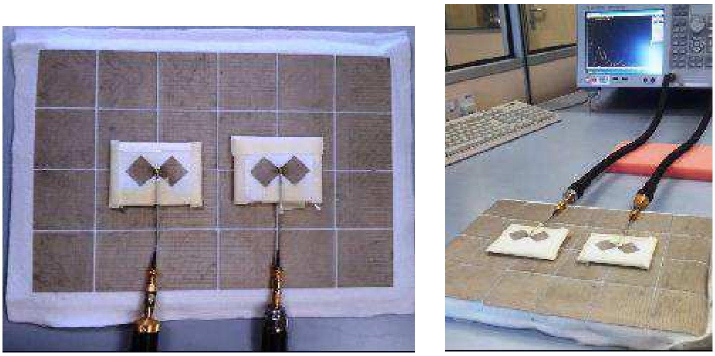


Figure 4. Fleece fabric characterization using coaxial probe method.

Figure 5(a) shows the fabricated textile AMC waveguide sheet with two diamond dipole antennas. A special cutter machine was used to fabricate the AMC patches for better accuracy. The two diamond dipoles are placed 5 mm above the textile AMC surface. A special material, Rohacell 31HF with dielectric constant of 1.05, is used as the spacer between the antennas and AMC surface. Such material has permittivity that is very close to air which is suitable to replace the air gap in the simulation.



(a) (b)

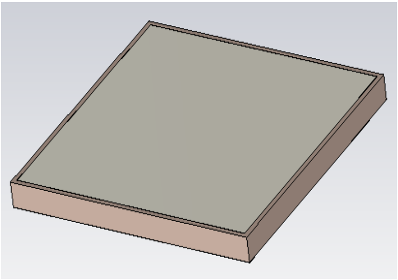
Figure 5. Fabricated textile AMC sheet with diamond dipole antennas.

In this study, investigation for both off-body and on-body environments is considered. A small AMC waveguide sheet as well as an AMC waveguide jacket were fabricated to rigorously investigate the antennas' transmission performance. Vector network analyzer was used to measure the S-parameters readings to verify the simulation (Figure 5(b)). For both sheet-like waveguides, several placements were thoroughly investigated in two different orientations.

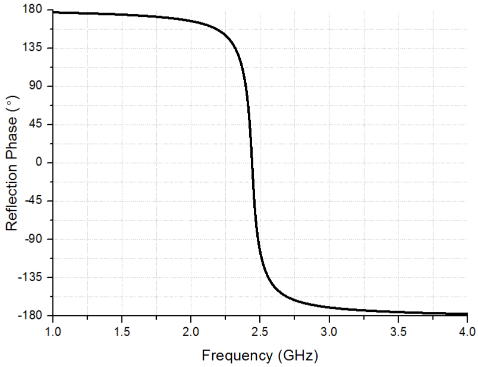
3. RESULTS AND DISCUSSION

3.1. Textile Artificial Magnetic Conductor

In this work, the transmission performance between diamond dipoles when placed above a textile AMC surface was investigated in free space environment as well as in a close proximity to human body setting. Series of simulations using CST Microwave Studio were performed to explore the possibility of transmission improvement between two antennas with the presence of textile AMC waveguide sheet. Initially, unit cell simulation was conducted to investigate reflection phase characteristic of a square AMC (Figure 6(a)). After performing rigorous parametric studies, the optimized reflection phase diagram was obtained. Figure 6(b) depicts the reflection phase diagram of a Fleece square patch with 50 mm width resonating at 2.45 GHz.



(a)



(b)

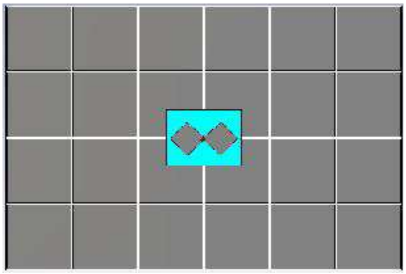
Figure 6. Textile square patch AMC. (a) Unit cell, (b) reflection phase.

3.2. Antenna above AMC Sheet

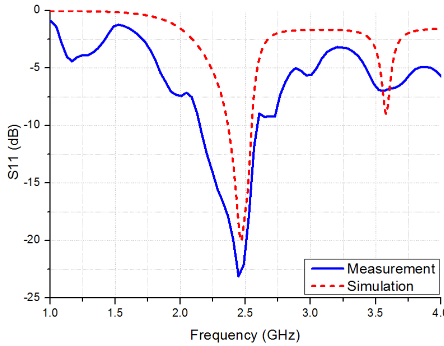
Wearable antennas suffer performance degradation in terms of radiation characteristics and input impedance when placed on human body. In addition, the radiation that goes towards human body is a major health concern. To overcome such issues, textile AMC waveguide sheet is proposed, which is flexible and suitable for wearable communications.

Following the unit cell simulation, AMC arrays were designed and the diamond dipole performance when placed above the structure was investigated (Figure 7(a)). Figure 7(b) shows the simulated and measured S_{11} of the diamond dipole above textile AMC structure. Measured result shows reasonable agreement with the simulation with resonance at 2.45 GHz.

Simulation and measurement were also conducted to explore the radiation patterns of diamond dipole above Fleece AMC sheet. The simulated and measured radiation patterns in E and H planes are shown in Figure 8. Similarly, measured results agree well with the simulated results, giving directive patterns with small back lobes. Such results show that by having an AMC surface, the radiation towards human body is minimized, with significant gain improvement. The simulated gain of the antenna above AMC sheet is observed as 5.43 dB and 2.1 dB without the AMC surface. The measured gain gives similar trend with 6.53 dB for antenna with AMC and 3.09 dB for antenna only.

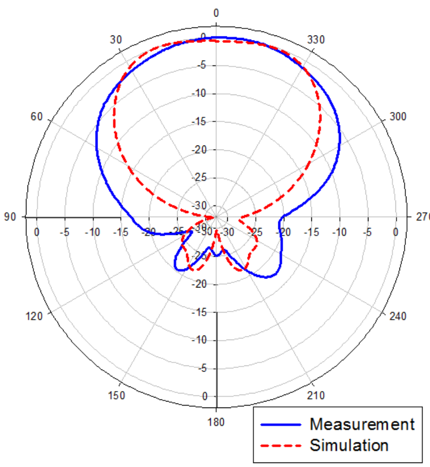


(a)

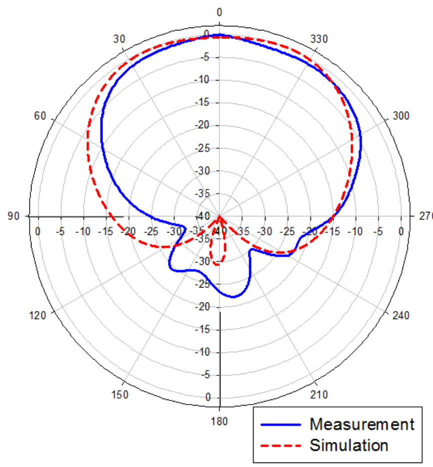


(b)

Figure 7. Diamond dipole above AMC sheet. (a) Simulation layout, (b) return loss (S_{11}).



(a)



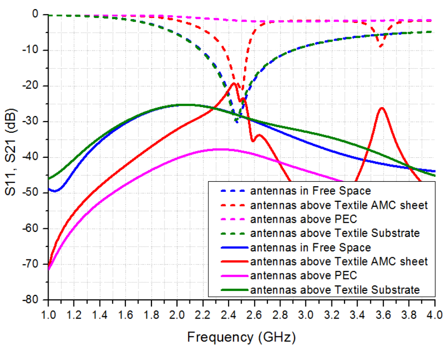
(b)

Figure 8. Radiation patterns of diamond dipole above AMC sheet. (a) E plane, (b) H plane.

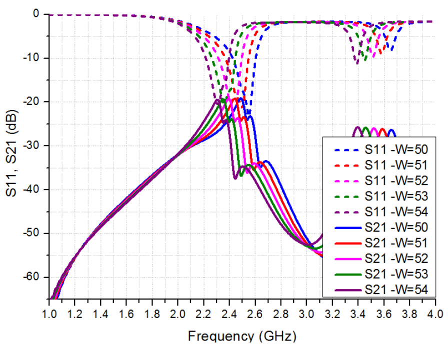
3.3. Transmission between Antennas

On-body antennas experience high transmission loss between themselves with the presence of human body. Good transmission between antennas is crucial for an efficient wireless networking system within human body. A non-reliable body centric system can get under way with undesired high transmission loss. Thus, this study will thoroughly explore the transmission characteristics between two antennas (Figure 5). Initially, investigation was conducted to study the performance of two diamond dipoles in four different environments. The settings include diamond dipoles in the free space, above metal plate, above textile substrate and above AMC waveguide sheet. The antennas were positioned 5 mm above all respective surfaces.

Figure 9(a) depicts the S_{11} and S_{21} of the four different diamond dipoles' conditions. S_{11} results for the four environments at 2.45 GHz are −29.1 dB for free space, −1.5 dB for Perfect Electric Conductor (PEC) surface, −29.6 dB for textile substrate and −18.7 dB for AMC surface. It can be observed that dipoles placed above PEC plate suffer a poor return loss, while a good return loss is obtained with the AMC sheet. In addition, Figure 9(a) also illustrates the S_{21} transmission



(a)



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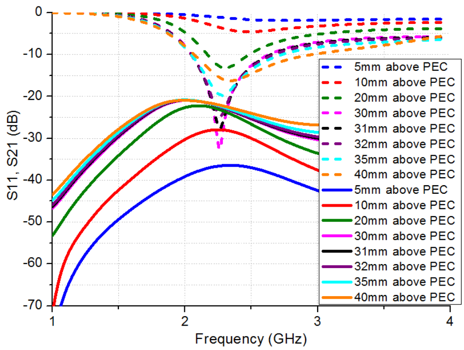


(c)

Figure 9. Simulated S_{11} and S_{21} of textile diamond dipoles with (a) different conditions, (b) above PEC plate with varying distance, (c) above AMC sheet with different patch width.

results between two diamond dipoles that read −27.9 dB for free space, −38 dB for PEC surface, −27.9 dB for fleece substrate and −19.3 dB for AMC sheet. It can be noticed that the S_{21} of AMC setting peaks up to −19.3 dB, an increment of 8.3 dB from the free space transmission. The results show that by having the AMC waveguide sheet beneath the two diamond dipoles, high S_{21} transmission can be obtained with significant transmission improvement at the resonant frequency.

Further study was conducted to investigate the placements of dipoles above PEC sheet. Figure 9(b) shows the S-parameters of dipoles above PEC sheet with varying distance. From the results, it can be seen that the antennas are not functioning well when placed at 5 mm and 10 mm above the metal sheet. The antennas start to have good performance at 30 mm, 31 mm and 32 mm. This shows that the antennas start to perform well only when they are placed for a minimum of $\lambda/4$ above the metal plate. From both graphs (Figures 9(a) and 9(b)), it is obvious that the S_{11} and S_{21} of the diamond dipoles when positioned above metal plate suffer a very high mismatch and transmission loss. This occurs since the antennas were not placed for more than the required $\lambda/4$ above the PEC surface. In contrary, such distance constraint is not required for the AMC surface. Hence, giving a low profile configuration advantage to the AMC sheet compared to metal plate setting. AMC sheet acts as a high impedance surface that gives low profile configuration benefit, apart from improving the transmission between antennas. Electromagnetic waves are concentrated into the AMC surface hence resulting to low transmission loss between two excited antennas. This allows high transmission capability that has been achieved by the textile AMC sheet.

Next, simulation of the two diamond dipole antennas above AMC arrays was performed to achieve the most optimized configuration. Figure 9(c) shows the graph of the S_{11} and S_{21} of diamond dipoles above AMC sheet with varying patch's width. It can be observed from the graph that by adjusting the patch size, the resonant frequency can be tuned accordingly. Figure 9(c) shows that when the patch width is 51 mm, the S_{11} and S_{21} achieve resonance at 2.45 GHz. The resonant frequency is observed to decrease as the patch's size increases in accordance with the conventional antenna's rule of thumb.

3.4. Different Antenna's Orientations

Further study was carried to investigate the positioning of the diamond dipoles above the AMC waveguide surface. Two types of orientation, i.e., the horizontal and vertical arrangements were examined (Figure 3(c)). For the horizontal orientation, four types of

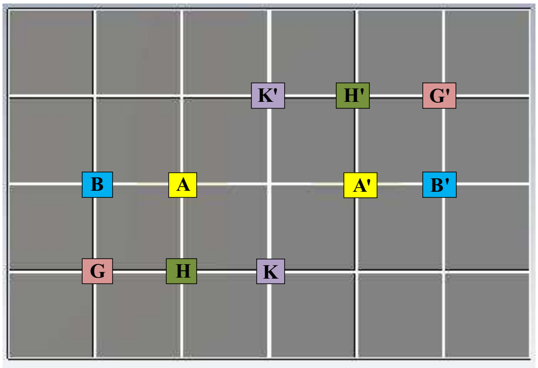


Figure 10. Antenna's positioning above AMC waveguide sheet.

placement were investigated while three types of position were tested for vertical orientation, as depicted in Figure 10. Positions A and B represent parallel horizontal arrangement with different distances with A having shorter distance. Position K denotes the parallel positioning for vertical orientation. The diagonal arrangements with different distances are indicated by H and G with Position G being further than H.

Initially, simulations were carried to investigate the S-parameters performance of two diamond dipoles above AMC waveguide sheet with different placements and orientations. The simulation results of S_{11} and S_{21} for different antenna's positions are as shown in Figure 11. Figure 11(a) shows the S-parameters results for horizontal arrangement and the vertical orientation results are as shown in Figure 11(b). Simulated results reveal that the S_{21} peaks for position A and position B are -19.6 dB and -38.4 dB at 2.45 GHz respectively. While the S_{21} peaks for positions horizontal H and G are -27.7 dB and -39.7 dB.

On the other hand, position K of vertical orientation gives -19.5 dB transmission peaks, whereas the S_{21} of diagonal H and G are -30.8 dB and -29.8 dB respectively. From these results, it can generally be observed that the S_{21} transmission decreases as the distance increases. In addition, the S_{21} results are also influenced by the arrangement, where the diagonal arrangement leads to higher transmission loss in comparison to parallel arrangement. The S_{11} results remain to resonate at 2.45 GHz for all the seven positions.

In order to verify the simulation results, measurements were then conducted. Figure 12 shows the measured results of diamond dipoles with and without AMC sheet. The dipoles in this case are in position

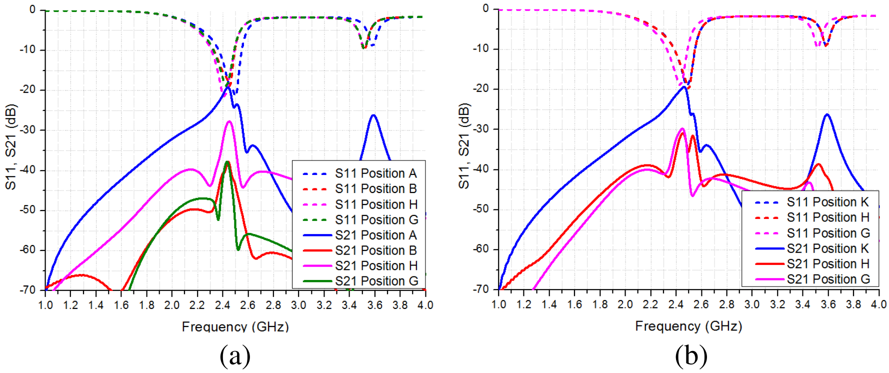


Figure 11. Simulated S_{11} and S_{21} of textile diamond dipoles for different orientations. (a) Horizontal, (b) vertical.

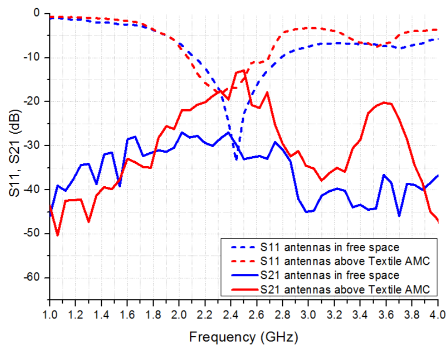
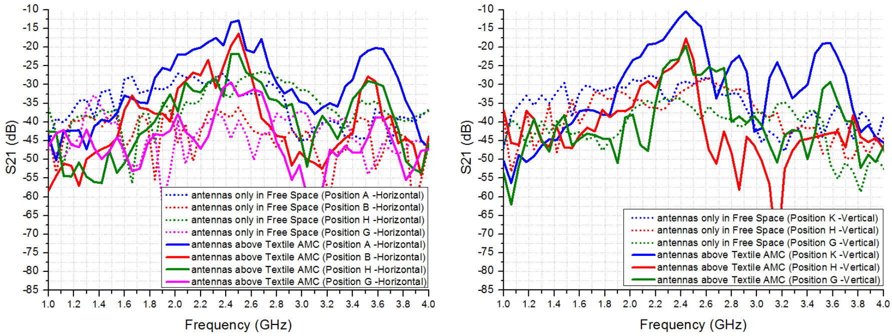


Figure 12. Measured S_{11} and S_{21} of textile diamond dipoles with and without AMC waveguide at position horizontal A.

horizontal A. The highest S_{21} peak for diamond dipoles above AMC sheet is −13.4 dB compared to −29.7 dB for free space transmission at resonance 2.45 GHz. Significant improvement of 16.3 dB is obtained when having the AMC sheet-like waveguide. As suggested in the simulation, measured results validate the transmission enhancement between antennas with the presence of textile AMC sheet.

Accordingly, measurements were also carried for two orientations with different placements. Figure 13 depicts the measured results for different antenna's positioning of horizontal and vertical orientations. S_{21} peaks are observed at 2.45 GHz for all cases. Compared to free space transmission, significant S_{21} improvements are realized for all positions at both orientations. For horizontal orientation, S_{21}



(a) (b)

Figure 13. Measured S_{21} of textile diamond dipoles above AMC in off-body environment for different orientations. (a) Horizontal, (b) vertical.

transmission improves by a massive 19.2 dB at 2.45 GHz resonance for position B, with −19.6 dB peak. As for the horizontal diagonal arrangements, the transmissions are enhanced by 11.5 dB and 15 dB, with peaks of −21.9 dB and −29.4 dB at positions H and G respectively. Similarly, high S_{21} peaks are also observed for vertical arrangements with −10.4 dB, −17.6 dB and −19.6 dB for positions K, H and G accordingly. As opposed to free space settings, transmission enhancement of 18.8 dB, 13.5 dB and 15.4 dB is achieved for vertical positions K, H and G.

The S_{21} trend between simulated and measured results for both orientations indicates good agreement. As such, measured results verify that the transmission between the two antennas improves when placing them above AMC surface for all positions, as opposed to free space transmission. Despite the decrease in transmission when the antennas are placed further apart from each other, the transmission is still higher compared to free space settings. Also, antennas' orientation does not affect the S_{21} performance. This gives more freedom and flexibility that is desired for wearable communication.

3.5. On-body Transmission

The investigation of diamond dipoles above textile AMC was then extended to on-body environment. Figure 14 shows the measurement setup for the on-body investigation. Vector network analyzer with two low loss flexible cables were used to investigate the S-parameters performance of two antennas above AMC surface, on top of human

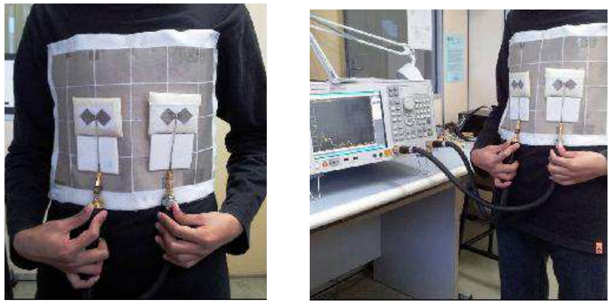


Figure 14. Textile AMC sheet on-body measurement.

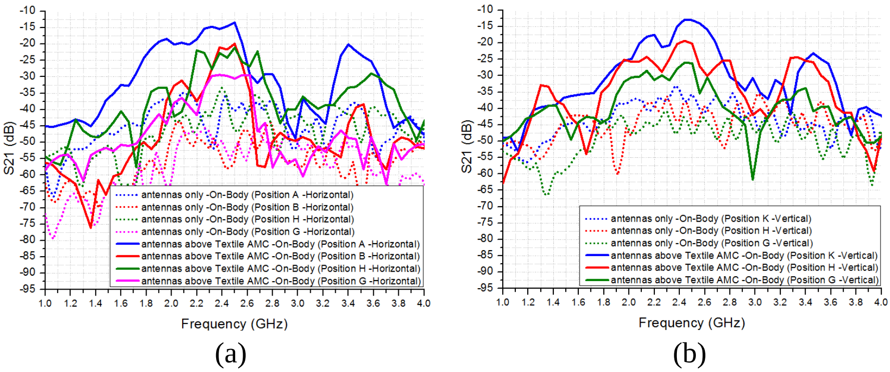


Figure 15. Measured S_{21} of textile diamond dipoles above AMC in on-body environment for different orientations. (a) Horizontal, (b) vertical.

body. The AMC sheet was closely attached to the human body to minimize the air gap.

On the other hand, Figure 15 illustrates the measured S_{21} of the two diamond dipoles above AMC sheet in the on-body settings. Figure 15(a) depicts the horizontal arrangement whilst Figure 15(b) represents vertical orientation. From the graphs (Figure 15), the S_{21} of the two diamond dipoles suffer a very high transmission loss when placed on human body. With the presence of human body, the transmission between the dipoles fall to -38.8 dB compared to -29.7 dB in the free space settings, for position horizontal A. The antennas experience transmission degradation for all positions in both horizontal and vertical orientations when placed on human body. The worst S_{21} transmission at 2.45 GHz can be observed at position horizontal B with a very low -57.7 dB while the highest is -38 dB at position vertical K.

However, when the textile sheet-like AMC waveguide is placed beneath the antennas, the S_{21} transmission improves significantly. From the results in Figure 15, all S_{21} results show transmission improvement between the antennas at 2.45 GHz when having AMC sheet. The transmission enhancements for horizontal arrangement are 24.2 dB, 36 dB, 17.9 dB and 25.6 dB for positions A, B, H and G respectively. On the other hand, the maximum transmission is obtained for position vertical K with maximum −12.9 dB, while positions H and G with −19.4 dB and −26 dB peaks. The S_{21} transmission improves by 25.1 dB, 19.1 dB and 18 dB for vertical positions K, H and G.

Table 1 summarizes the measured S_{21} values of the two diamond dipole antennas for off-body and on-body environments. As mentioned earlier, all the S_{21} results show transmission improvement with high S_{21} peaks observed at 2.45 GHz for all the tested positions in both off-body and on-body environments, with the presence of AMC sheet.

Table 1. Measured S_{21} for off-body and on-body investigation at 2.45 GHz.

Orientation	**Position**	**Antennas Only**				**With Textile AMC**			
		A	**B**	**H**	**G**	**A**	**B**	**H**	**G**
Horizontal	**Off-Body**	−29.7	−38.8	−33.4	−44.4	−13.4	−19.6	−21.9	−29.4
	On-Body	−38.8	−57.7	−42.1	−55.3	−14.6	−21.7	−24.2	−29.7
Vertical		**K**	**H**	**G**		**K**	**H**	**G**	
	Off-Body	−29.2	−31.1	−35		−10.4	−17.6	−19.6	
	On-Body	−38	−38.5	−44		−12.9	−19.4	−26	

From the results, it can be concluded that antennas transmitted on human body suffer worse performance degradation compared to free space transmission. Similar as previous off-body case, the S_{21} transmission decreases as the distance increases. Moreover, compared to diagonal placement, parallel arrangement gives better transmission performance. Nevertheless, significant enhancement with high S_{21} peak is still attained for all positions with the AMC sheet, as opposed to without one. The electromagnetic waves are being confined and strongly coupled to the AMC waveguide itself. As a result, small transmission loss in on-body channel has been acquired. The AMC surface creates independent transmission path that can minimize distortions caused by human flesh.

3.6. Textile Waveguide Jacket

For practical realization, finally the fabricated waveguide jacket was tested to investigate the transmission of two diamond dipoles above the jacket. The prototype of the jacket is realized in the form of vest for simplicity and minimum cost (Figure 16). The prototype is made of 20×7 arrays of square conductive patches. Similarly, the jacket was also closely attached to the wearer's body to minimize the air gap.

Figure 17 illustrates the positioning of the antennas above the AMC waveguide jacket. Since the jacket has larger size of arrays, previous positioning (Figure 10) was further extended to explore additional positions. Likewise, horizontal and vertical orientations were investigated. Horizontal orientation is represented by positions A, B, W, X and Y for the parallel arrangement, whereas positions H, G, Z and V correspond to diagonal arrangement. As for the vertical

Figure 16. Textile AMC jacket on-body measurement.

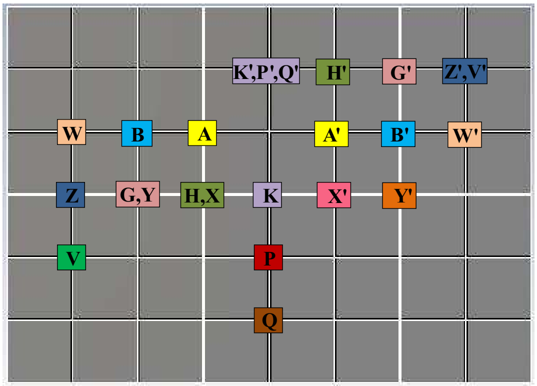
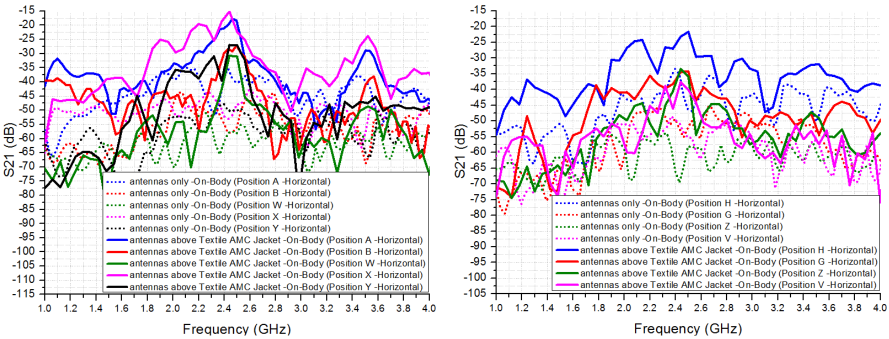


Figure 17. Antenna's positioning above AMC waveguide sheet.

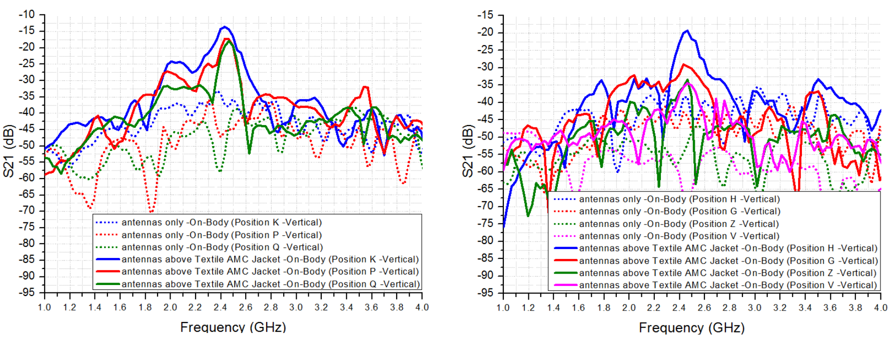
orientation, parallel placements consist of positions K, P and Q, while diagonal placements consist of positions H, G, Z and V. Positions horizontal A and B have the same distances with positions X and Y respectively, but are placed at different positions on the array.

Graphs in Figure 18 depict the measured S_{21} of antennas with waveguide jackets in horizontal orientation with Figures 18(a) and 18(b) denote the parallel and diagonal arrangements respectively. On the other hand, Figure 19 represents the vertical orientation also with parallel and diagonal placements. From the results, all the S_{21} rise



(a) (b)

Figure 18. Measured S_{21} of textile diamond dipoles above textile AMC jacket in on-body environment with horizontal orientation. (a) Parallel, (b) diagonal.



(a) (b)

Figure 19. Measured S_{21} of textile diamond dipoles above textile AMC jacket in on-body environment with vertical orientation. (a) Parallel, (b) diagonal.

at 2.45 GHz when placed above the waveguide jacket for all positions in both orientations.

For horizontal orientation, the S_{21} peaks are -17.8 dB, -29.2 dB and -30.7 dB for positions A, B and W above the textile jacket. Positions horizontal X and Y give similar values as positions A and B with -15.1 dB and -26.9 dB, since they have similar distances despite of different positioning. As for the horizontal diagonal arrangement, positions H, G, Z and V improves the S_{21} transmission by 18.9 dB, 20.9 dB, 31.2 dB and 16 dB at 2.45 GHz respectively, with the presence of the waveguide jacket. Positions K, P and Q represent parallel arrangement in vertical orientation with S_{21} peaks at -14.3 dB, -17.3 dB and -17.9 dB above the AMC jacket at resonance. Such observation is as expected since the transmission performance drops as the distance increases. Finally, the vertical diagonal placements give S_{21} performance of -19.3 dB, -29.6 dB, -33.4 dB and -34.4 dB for positions H, G, Z and V.

Table 2 shows the measured S_{21} results for antennas with and without AMC waveguide jacket in horizontal and vertical on-body arrangements. As tabulated in Table 2, the S_{21} transmissions are enhanced with the presence of AMC waveguide jacket for all the tested positions. Significant increase of the S_{21} transmission is achieved with the introduction of the waveguide jacket.

Table 2. Measured S_{21} for waveguide jacket for on-body investigation at 2.45 GHz.

Orientation		Antennas Only					With Textile AMC Jacket				
Horizontal	Parallel	A	B	W	X	Y	A	B	W	X	Y
		-38.8	-57.7	-57.4	-51.7	-50.0	-17.8	-29.2	-30.7	-15.1	-26.9
	Diagonal	H	G	Z	V		H	G	Z	V	
		-42.1	-55.3	-64.7	-53.6		-23.2	-34.4	-33.5	-37.6	
Vertical	Parallel	K	P	Q			K	P	Q		
		-38	-44.9	-43.1			-14.3	-17.3	-17.9		
	Diagonal	H	G	Z	V		H	G	Z	V	
		-38.5	-44	-51.9	-68.4		-19.3	-29.6	-33.4	-34.4	

Both parallel and diagonal orientations with various positioning show consistent transmission improvements. Such results validate the possibility of the textile-based AMC waveguide jacket to act as a new approach that improves wireless on-body transmission. Small transmission loss is obtained since electromagnetic waves are concentrated into the AMC waveguide surface, and data travels through the waveguide itself. Furthermore, results show that the S_{21}

transmission enhancement is independent of the antennas' orientation. Despite having higher transmission loss when the antennas are placed with an increased distance, the S_{21} still improves compared to when the antennas are transmitting without the AMC surface. Therefore, such AMC waveguide jacket is deemed fit as a subsidiary waveguide for an efficient wearable wireless body-centric communications.

3.7. Current Distribution and Radiation Pattern

Current flows between antennas above an AMC surface is observed by retrieving the simulated current distribution for a visible view. Figure 20 shows the current distribution of two diamond dipoles positioned above textile AMC waveguide surface. Strong current distribution is observed between two diamond dipoles along neighbouring patches. The diagram depicts electromagnetic waves concentrating into the AMC surface. High strength of current is seen flowing between the diamond dipoles through the middle patches. Therefore, it is evidenced that improved transmission between antennas is obtained when placing them on top of AMC sheet.

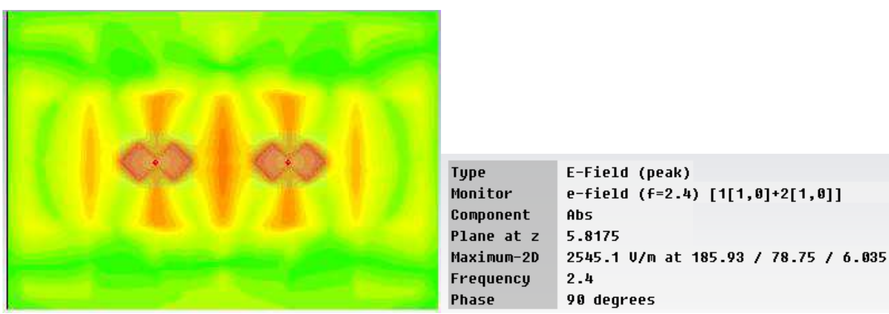


Figure 20. Current distribution of two diamond dipoles above textile AMC.

Finally, the radiation patterns of the two diamond dipoles were explored. Radiation patterns of antenna 1 and antenna 2 in both E and H planes are as shown in Figure 21. From the E plane graph, directional radiation patterns with small back lobe can be observed (Figure 21(a)). It can be noticed that the back lobe of antenna 1 is shifted to the left while antenna 2's back lobe is shifted to the opposite right. This is due to the coupling effect between the two antennas since they were positioned and excited in parallel to each other.

Figure 21(b) illustrates H plane radiation patterns. For both antennas 1 and 2, similar directional patterns are obtained. When

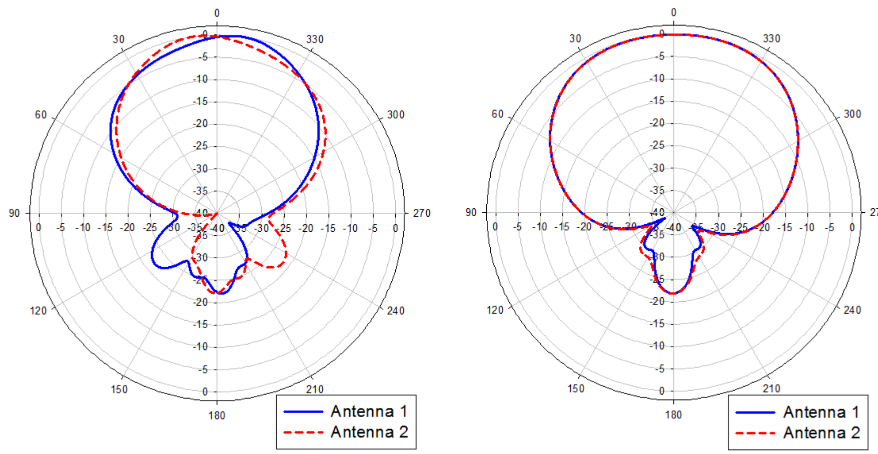


Figure 21. Radiation patterns of two diamond dipoles above AMC sheet. (a) E plane, (b) H plane.

having an AMC ground plane that acts as high impedance surface, forward radiation with small back lobe is expected. Owing to the characteristic of AMC array, high gain of 6.66 dB and 6.64 dB for antenna 1 and 2 respectively is achieved.

4. CONCLUSIONS

In this study, a textile AMC waveguide jacket with diamond dipole antennas have been designed and investigated. The substrate of the proposed textile AMC is made of Fleece fabric while the conductive patches and ground plane are made of SHIELDIT fabric. The AMC sheet acts as a subsidiary waveguide that offers a new independent transmission path that can minimize the transmission loss. External antennas can be easily excited to the AMC waveguide jacket. The performance of S_{21} transmission between two diamond dipoles was thoroughly explored for off-body as well as on-body environments. Two different antenna orientations were investigated in this work. Simulated and measured results show significant transmission improvement up to maximum -10 dB when placing the AMC sheet beneath the antennas. Electromagnetic waves are strongly concentrated into the AMC surface that allow transmission through the waveguide sheet. Therefore, small transmission loss is achieved, contributing to transmission enhancement between the antennas.

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