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A PARAMETRIC STUDY OF TEXTILE ARTIFICIAL MAGNETIC CONDUCTOR WITH WIRE DIPOLE AT 2.45GHZ AND 5.8GHZ

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ABSTRACT

Textile Artificial Magnetic Conductor (AMC) with wire dipole is presented. The AMCs are made of fleece and Shieldit fabrics and were designed to have in-phase reflections at 2.45GHz and 5.8GHz. Thorough parametric studies based on AMC unit cell have been performed to obtain the optimized design. Performance comparison between different types of environments, fabrics and arrays size were also conducted. The proposed AMC and wire dipole are designed, simulated, fabricated and tested. Results of return loss, radiation pattern and gain are presented. Results show that forward directive radiation pattern with improved gain are achieved with the introduction of the AMC at both 2.45GHz and 5.8GHz. The proposed textile AMC is suitable for body centric communication systems.

Keywords: artificial magnetic conductor, textile AMC, dipole antenna, wire dipole.

INTRODUCTION

Wearable antennas are exposed to performance degradation such as bandwidth reduction, frequency detuning and radiation distortions when positioned near to human flesh [1]. In addition, the radiation that goes into the human body is a crucial health issue [2]. To overcome such problems, textile AMC waveguide sheet is proposed, which is flexible and appropriate for wearable communications [3]. AMC surface helps by reducing the radiation exposure to the human body, apart from improving the gain [4]. AMC is a type of metamaterial that has been actively used in microwave and antenna engineering [5]. AMC can complement and improve antenna's performance when they are integrated together. By altering the reflection current to be in-phase with the incident current, the antenna's directivity and gain can be significantly improved by maintaining a low profile configuration. Recently, AMC application in body centric communication has been getting a lot of attention due to health and safety concern. For wireless on-body application, a directional radiation pattern is desired to minimize the users' exposure to electromagnetic radiation. In body centric applications, antenna with AMC ground plane enables the isolation of human body from the antenna's electromagnetic radiation. It also eliminates the antenna's impedance mismatch caused by the human tissues [6]. Textile AMC is more appealing for body communication, compared to conventional design that uses printed circuit technology that is not flexible and heavy to be applied for on-body application. Contrarily, textile AMC can be used more comfortably and effectively in body area network (BAN) and personal area network (PAN) communications. In this study, textile AMC with wire dipole are proposed. The development of textile AMC structure is explored by designing the AMCs to have in-phase reflections at 2.45GHz and 5.8GHz. The substrate of the AMC is made of fleece fabric whereas the conducting patches and ground plane are made of Shieldit fabric. The AMC performance is investigated with wire dipoles at 2.45GHz and 5.8GHz. The simulated and measured results are presented to validate the AMC's in-phase reflection characteristic that is suitable to be used in body centric communication.

Unit cell investigation

The design of the AMC structures is initially started with unit cell investigation. AMC structures comprise of an array of conducting patches. To design the AMC array, a unit cell characterization using CST transient solver is performed. The unit cell simulation represents infinite array by manipulating the boundary conditions in CST. Through unit cell simulation, computational time in designing an AMC arrays can be largely reduced. The simulation is setup using waveguide port with Transverse Electromagnetic (TEM) mode excitation. With boundary conditions assigned as perfect electric and perfect magnetic boundaries that are perpendicular to each other, an infinite array approach can be achieved. Plane wave is set to illuminate the surface of the AMC unit cell and the phase of the reflected wave is recorded to obtain the reflection phase graph.

$$Z_{in} = \frac{j\omega L}{1-\omega^2 LC} \tag{1}$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

$$C = \frac{W\varepsilon_0(1+\varepsilon_r)}{\pi}\cosh^{-1}\left(\frac{W+g}{g}\right) \tag{3}$$

$$L = \mu_0 h \tag{4}$$

In this study, a simple geometry of square AMC structure is proposed due to the limitation of textile materials as well as constraints in fabrication. Such design

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is simple, low cost and easy to fabricate apart from giving satisfactory performance. Initially, Equations (1 - 4) are referred, in order to have a rough parameters' estimation of the AMC unit cell. Following that, unit cell simulation is conducted to investigate the reflection phase characteristics of a square textile AMC (Figure-1). The AMC consists of a conductive patch on a textile substrate that is backed with a ground plane. Figure-1 illustrates the visualization of the unit cell lattice with the related parameters, W, W1, g and h. The respective dimensions of the simulated AMC unit cells at 2.45GHz and 5.8GHz are tabulated in Table 1. The size of the AMC unit cell is 52x52mm and 22x22 mm at 2.45GHz and 5.8GHz respectively. AMC is able to reflect electromagnetic waves (EM) without phase reversal as opposed to PEC that reflects EM waves with 180° phase reversal. With AMC, the incident and reflected waves are in phase within certain range of frequency. The useful AMC bandwidth is from +90° to -90° with 0° crossing at the centre frequency. To investigate the characteristics of AMC structure, reflection phase graphs need to be plotted. Series of parametric studies have been conducted to explore the behaviours of the AMC cell before obtaining the optimized AMC configuration. According to (1), the capacitance of the AMC, C relates to patch width, W1, gap between the patches, g and substrate permittivity, ε_r. On the other hand, (2) shows that thickness, h associates with inductance, L. The resonant frequency of the AMC, f_r, is inversely proportional with C and L as given by (3).

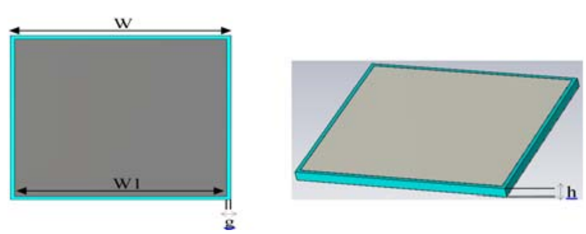


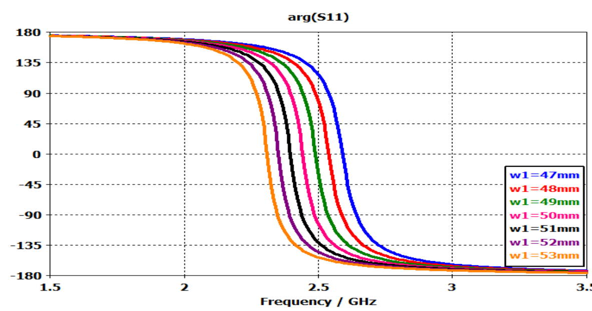
Figure-1. Unit cell model of a textile square patch AMC.

Table-1. The dimension of 2.45GHz and 5.8GHz AMC unit cells.

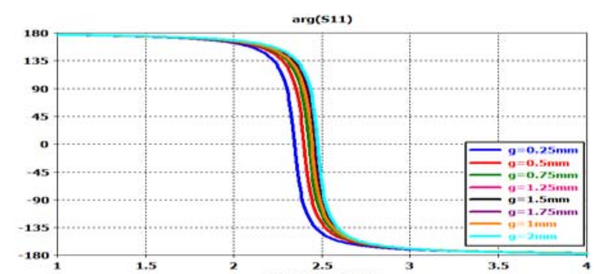
Parameters	Dimensions (mm)	
	2.45GHz	5.8GHz
W	52	22
W1	50	20
g	1	1

Initially, the patch width, W1's influence on the reflection phase has been explored. Figure-2(a) shows the reflection phase with varying W1. From the graph, it can be observed that frequency decreases as W1 increases. With reference to (1), C is proportional to W1. As the patch becomes larger, the total capacitance of the AMC cell becomes higher. As a result, the resonant frequency decreases when the patch size increases. Such result agrees with the relationship of C that is inversely proportional with f_r as given in (3). Another parameter that is being investigated is the gap between the patches, g. From the result in Figure-2(b), it can be seen that as the gap increases, the frequency increases. The increment of the gap, g associates with a decrement of the capacitance that leads to the rise of frequency.

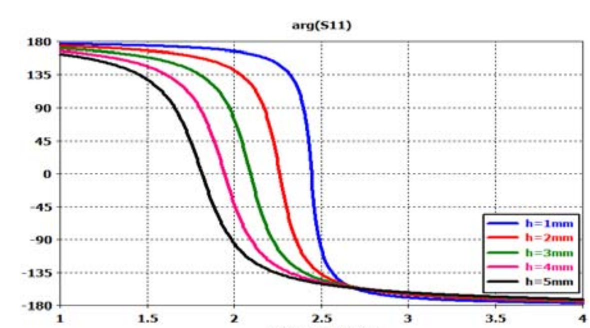
Finally, the height of the substrate, h is varied to investigate the performance of the reflection phase as depicted in Figure-2(c). From the graph, the frequency is seen to decrease as the height increases. The height, h relates to (2) that is proportional to the inductance, L. Referring to (3), L is found to be inversely proportional to the resonant frequency, hence validating the simulation findings. On the other hand, the bandwidth is observed to increase as the height increases. Based on (4), the bandwidth is proportional to the inductance, L. Therefore, an increase of height, h leads to increment in L as well as the bandwidth. Following the parametric studies, three different AMC unit cells with different fabrics have been investigated at 2.45GHz. Fleece, denim and wool AMCs have widths, W1 of 50mm, 45mm and 47mm respectively.



(a)



(b)



(c)

Figure-2. Simulated reflection phase of textile AMC with varying (a) W1 (b) g (c) h.

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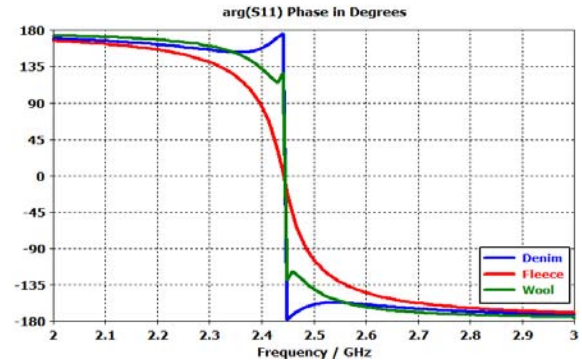

Figure-3. Simulated reflection phase of textile AMC with different substrates.

The reflection phase curves of 2.45GHz AMCs made from these three fabrics are plotted in Figure-3. The plotted graph shows the optimized AMC curves for each fabric. From the results, it can be seen that AMCs made of denim and wool yield a very narrow reflection phase curve. The low thickness of the wool AMC, with h=0.5mm is believed to contribute to such narrow slope. As for the denim AMC, the high tangent loss of 0.085 is predicted to cause the narrow curve. On the other hand, AMC made of fleece fabric offers wider reflection phase curve with 4.1% bandwidth ranging from 2.39GHz to 2.49GHz. AMC structure is known of its narrow bandwidth characteristic, therefore the bandwidth offers by the fleece AMC is reasonably satisfactory. Fleece fabric yields better reflection phase curve due to its higher thickness, h of 1mm and relatively low tangent loss of 0.025. After performing the rigorous parametric studies and comparing different fabrics, the optimized reflection phase diagram is obtained for fleece AMC. Figure-4 illustrates the optimized reflection phase diagrams of a fleece square patch with 50mm width resonating at 2.45GHz and 20mm width at 5.8GHz.

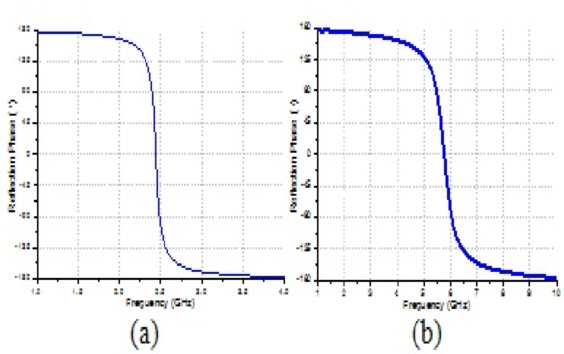

Figure-4. Optimized reflection phase diagram of a textile square patch AMCs (a) 2.45GHz (b) 5.8GHz.

Wire dipole above AMC

Continuing from the unit cell simulation, AMC arrays are subsequently designed and antenna performance when placed above the structure is investigated. The fleece AMC comprises of 6x4 conductive patches backed with a ground plane. Figure-5 shows the simulation layout of a 2.45GHz wire dipole above textile AMC arrays. The wire dipole is placed 5mm above the AMC surface. Series of simulation of the integration between antenna and AMC arrays have been conducted using CST Microwave Studio. After optimization, the patch size is 51mm with 2mm gap between the patches.

The wire dipole performance in four different environments has been investigated i.e. wire dipole in the free space, above PEC plate, above textile substrate and above AMC sheet. Figure-6 depicts the S_{11} performance of the wire dipole in those four settings. The wire dipole is placed 5mm on top of the mentioned surfaces. As can be seen from the results, the wire dipole is resonating well at 2.45GHz at three conditions, which are free space, above textile substrate and above AMC surface. The return loss depth for the wire dipole in the free space is -18.6dB, -16.2dB when placed above textile substrate and -17.5dB for above AMC setting. Contrarily, for the case of wire dipole above PEC plate, poor return loss is observed with return loss depth of -1.4dB at 2.45GHz.

From the results, it is obvious that the S_{11} of the wire dipole suffers a very high mismatch, when positioned above metal plate. This occurs since the antenna is not placed for more than the required λ/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 the metal plate setting. AMC sheet acts as a high impedance surface that gives low profile configuration benefit. Further investigations have been carried out to explore the performance of the wire dipole above the AMC sheet. Figure-7(a) illustrates the return loss of the wire dipole placed above AMC surface made of different fabrics i.e. fleece, denim and wool. From the graph, the antenna above all the textile AMCs yield resonance at 2.45GHz. Despite offering the deepest return loss of -30.3dB, wool AMC gives the lowest 10dB bandwidth of 4.52% from 2.38GHz to 2.49GHz. On the other hand, denim AMC gives 8.13% bandwidth ranging from 2.36GHz to 2.56GHz. The widest bandwidth is obtained by fleece AMC with operating range from 2.31GHz to 2.56GHz that gives 10.27% bandwidth.

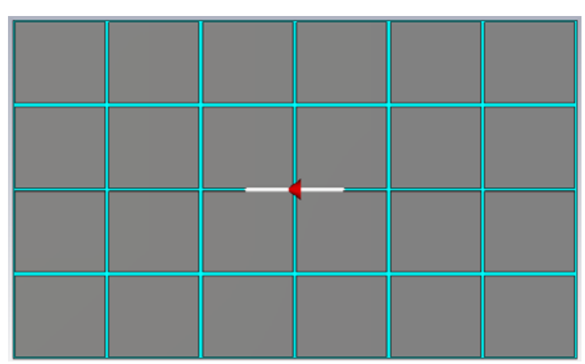

Figure-5. 2.45GHz wire dipole on AMC sheet.

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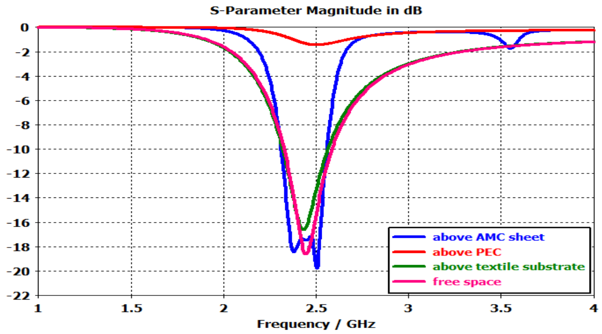

Figure-6. Simulated S_{11} of wire dipole in four different environments.

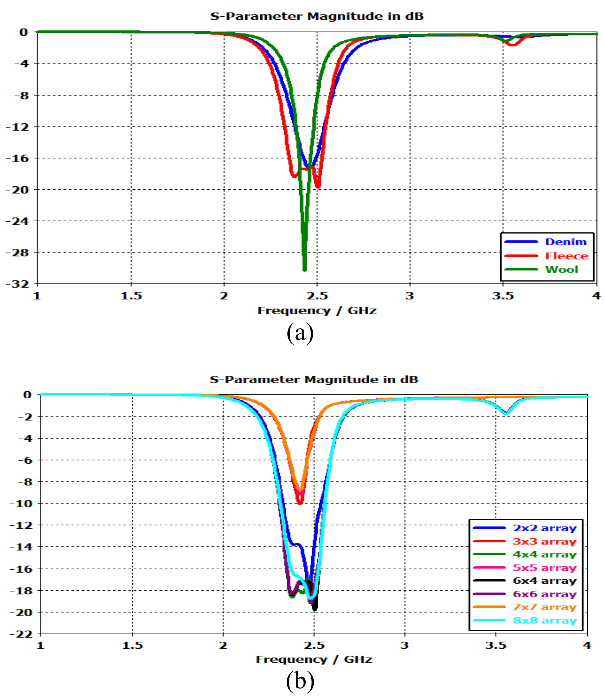

Figure-7. Simulated S11 of wire dipole above textile AMC with (a) different substrates (b) varying arrays size.

Figure-7(b) shows the S_{11} of the wire dipole above AMC sheet with varying arrays size. From the results, it can be observed that even combination of arrays i.e. 2x2, 4x4, 6x4, 6x6 and 8x8 yield good return loss performance. However, AMC arrays with odd numbers size exhibit poor return loss performance. This finding suggests that the antenna is performing well when placed at the intersection of the patches, instead of above and in the middle of the patch. On the other hand, the S_{11} performance of the wire dipole above 2x2 AMC arrays is improved when having a larger array size of 4x4 combinations. Nonetheless, AMC arrays of large sizes i.e. 6x4, 6x6 and 8x8 offer similar return loss performance as 4x4 AMC arrays. Simulated radiation patterns of the wire dipole in four different conditions are laid in Figure-8. From the polar plots, it can be seen that radiation pattern of wire dipole in free space is similar to the wire dipole above textile substrate, giving a typical dipole's radiation patterns. On the other hand, wire dipole above PEC and AMC sheets yield a directive radiation patterns in both E and H planes. Both AMC and PEC surface act as reflectors hence the forward direction of the radiation with small backlobes. The wire dipole has a free space gain of 1.78dB with 97.01% total efficiency. When placing the wire dipole above textile substrate, no significant changes in gain and efficiency are observed with achieved gain of 1.95dB and 96.81% efficiency. The gain is improved to 5.64dB with the presence of AMC sheet. The efficiency of wire dipole above AMC surface is 65.79%. PEC plate increases the gain up to 3.36dB but yield a poor efficiency of 26.8%

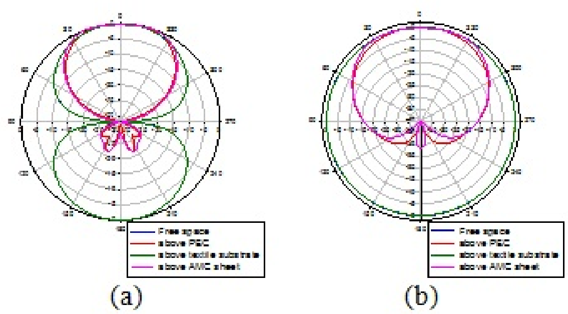

Figure-8. Condition when wheel zigzag gets over block.

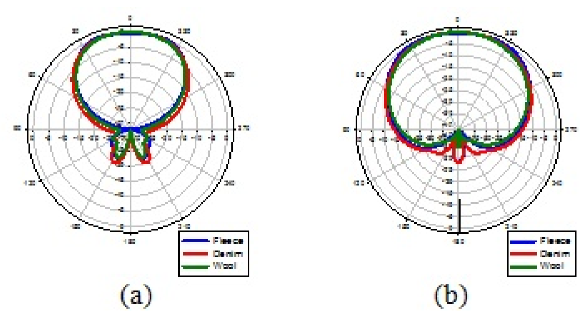

Figure-9. Condition when wheel zigzag gets over block.

Figure-9 plots the computed radiation patterns of 2.45GHz wire dipole above textile AMC made of different fabrics. From the graphs, it can be clearly seen that all three substrates exhibit similar radiation pattern trends with forward directive patterns for both E and H planes at 2.45GHz. The fleece AMC increases the wire dipole gain to 5.64dB. Gain improvements have also been achieved with denim and wool AMCs with gain of 4.26dB and 5.78dB respectively. From the presented results, fleece fabric is found to be the most suitable fabric to be used in this study since it offers better performance in terms of reflection phase, return loss and gain compared to denim and wool AMCs. Wire dipole above 5.8GHz AMC sheet has also been simulated for comparison purpose.

Figure-10 depicts the simulation layout of a wire dipole above 5.8GHz textile AMC sheet, made of fleece fabric. The arrays are made of 12x8 of conducting patches.

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The optimized patch width when combine with wire dipole is 21.5mm. Figure-11 shows the simulated return loss of the wire dipole above 5.8GHz fleece AMC arrays. The antenna is observed to resonate at 5.8GHz with return loss depth of -19.6dB. The antenna operates from 5.22GHz to 5.96GHz with bandwidth of 13.24%. The simulated radiation patterns of wire dipole above 5.8GHz textile AMC are presented in Figure-12. The polar plots compare radiation pattern of wire dipole with and without 5.8GHz AMC sheet in E and H planes. Results show that at both planes, forward directive patterns have been obtained at 5.8GHz when having AMC sheet beneath the wire dipole. The gain of the 5.8GHz wire dipole is 2.07dB with total efficiency of 99.9%. With the introduction of the textile AMC arrays, the gain at 5.8GHz has been improved to 6.53dB with efficiency of 74.65%.

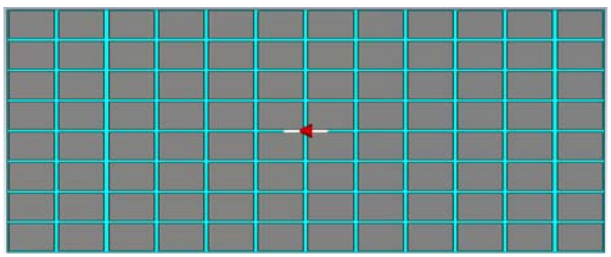

Figure-10. 5.8GHz wire dipole on AMC sheet.

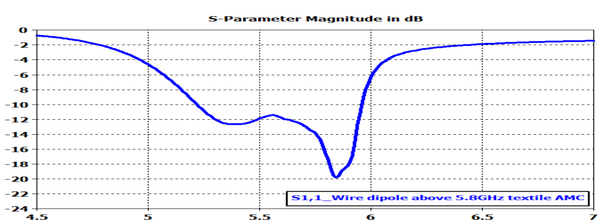

Figure-11. Simulated S_{11} of 5.8GHz wire dipole above AMC sheet.

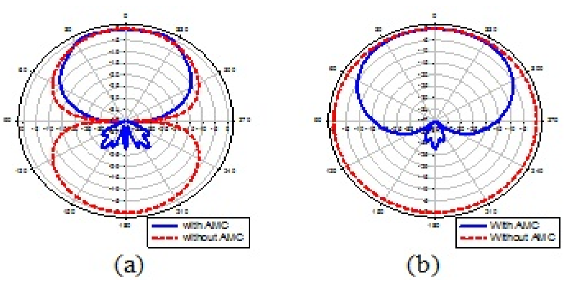

Figure-12. Simulated radiation pattern of wire dipole above AMC sheet at 5.8GHz (a) E plane (b) H plane

Figure-13 shows the fabricated 2.45GHz and 5.8GHz textile AMCs with the respective wire dipoles. The 2.45GHz and 5.8GHz AMC arrays measure at 318x212mm and 282x188mm each. As mentioned previously, fleece fabric and Shieldit conducting fabric are used in the textile AMC fabrication. A special cutter machine is used to fabricate the AMC patches for better accuracy. Copper wire is used to build the wire dipoles prototype. S_{11} measurements have been conducted using the available vector network analyzer.

Figure-14(a) shows the measured return loss of 2.45GHz wire dipole above textile AMC made of different fabrics. Similar as preceded cases, three types of AMC made of fleece, denim and wool fabrics are measured. The same conducting fabric i.e. Shieldit is used in these three AMC sheets. From the measured results, fleece AMC gives the deepest return loss of -21.34dB and widest bandwidth of 13.2% from 2.3GHz to 2.63GHz. Wool AMC exhibits shorter bandwidth from 2.33GHz to 2.56GHz with 9.3%. The return loss depth of wire dipole above wool AMC is -16.88dB. As for the denim AMC, a low return loss depth of -13.2dB is obtained with bandwidth of 10.42% from 2.37GHz to 2.63GHz. The narrow bandwidth yield by wool and denim AMCs is evident from the previously discussed reflection phase characteristics. In addition, the low return loss observed from denim AMC is mainly due to the high tangent loss of the denim fabric itself. Therefore, fleece has been chosen as the preferred fabric that is to be used as the substrates of the textile antennas and AMC sheets in this research.

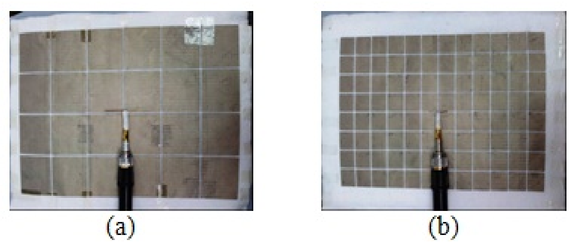

Figure-13. Fabricated wire dipoles above AMC sheet (a) 2.45GHz (b) 5.8GHz.

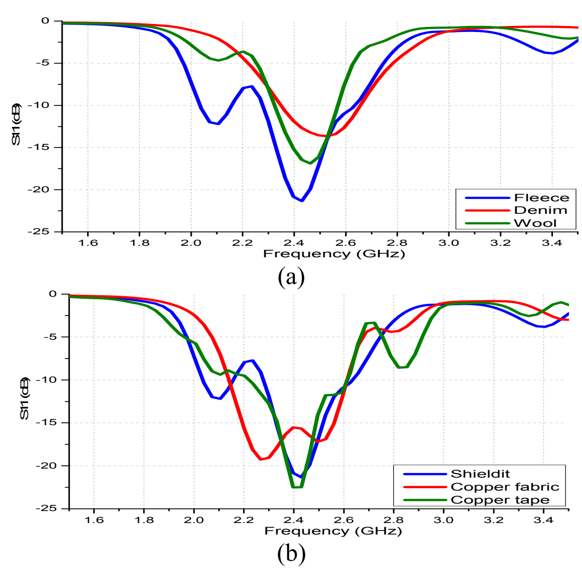

Figure-14. Measured S_{11} of wire dipole above 2.45GHz textile AMC with (a) different substrates (b) different conducting materials.

On the other hand, Figure-14(b) presents the measured S_{11} of a fleece AMC with different conducting materials. Copper tape, copper fabric and Shieldit fabric have been applied as the conducting elements for the AMC sheets. From the results, it can be observed that all the AMC arrays with different conducting materials, show good return loss performance at 2.45GHz. Copper tape is observed to give the deepest return loss at 2.45GHz. However, a very close S_{11} has also been achieved with Shieldit fabric. Copper fabric on the other hand yields a wider operating bandwidth. Despite giving good S_{11} performance, copper tape is not suitable to be implemented in wearable communication due to its rigid characteristic. Copper fabric and Shieldit fabrics are more suitable since they offer flexibility. In this research, Shieldit fabric is chosen over copper fabric because of its hot-melt adhesive back that offers easier fabrication. The finalized 2.45GHz and 5.8GHz AMC sheets made of fleece as the substrate and Shieldit fabric as the conducting elements have been fabricated. The comparison between measured and simulated results is depicted in Figure-15. Both measured results of the wire dipoles above 2.45GHz AMC as well as above 5.8GHz give reasonable agreement with the simulation. Despite the slight shift in the resonant frequency for the 5.8GHz AMC case, the return loss at 5.8GHz is still observed to be lower than -10dB. These measured findings verify that by adjusting the AMC's patch size, the resonant frequency of an antenna can be tuned accordingly.

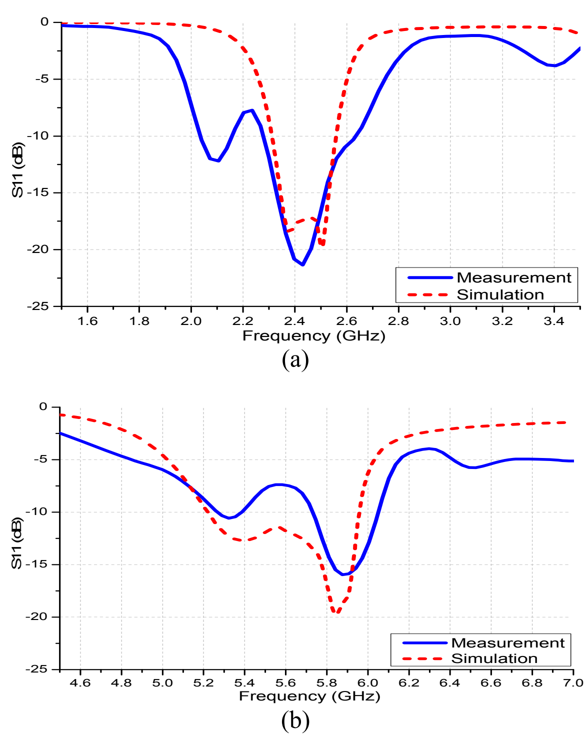

Figure-15. S_{11} of wire dipole above AMC sheets at two different frequencies (a) 2.45GHz (b) 5.8GHz.

CONCLUSIONS

Textile AMC sheet with wire dipole antenna have been designed and investigated. Fleece and Shieldit fabrics were used as the substrate and patches of the textile AMC surface. Parametric studies have been performed rigorously to investigate the reflection phase performance in order to achieve optimum AMC configuration. Comparison of different types of fabrics, environments and arrays size is also conducted. Two different operating frequencies were considered in the study i.e. 2.45GHz and 5.8GHz. Results show directive pattern with low backlobes with significant gain improvement when the dipole is combined with the textile AMC sheet at both frequencies under test. The in-phase reflection characteristic contributes to the forward radiation pattern and gain enhancement.

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