AMC Integrated Textile Monopole Antenna for Wearable Applications

A. Alemaryeen and S. Noghanian

Department of Electrical Engineering
University of North Dakota, Grand Forks, ND 58202-7165, USA
ala.alemaryeen@my.und.edu, sima.noghanian@engr.und.edu

Abstract **─** In this paper, performance of monopole textile antenna integrated with a flexible artificial magnetic conductor (AMC) surface is presented. The integrated antenna is designed for operating within the 2.45 GHz Industrial, Scientific and Medical (ISM) band. The addition of AMC is to reduce the backward radiation toward the human body and increase the antenna gain. Characteristics of the AMC antenna based on simulation and measurement results under different bending conditions have been studied and presented to validate the antenna for its usefulness in wearable applications. Besides, the causes that lead to the discrepancies between simulations and measurements are discussed.

Index Terms **─** Artificial Magnetic Conductor (AMC), Coplanar Waveguide (CPW), monopole antennas, wearable antennas.

I. INTRODUCTION

Recently, industrial and academic researchers have shown significant interest in the field of wearable antennas, especially for medical applications. In general, wearable antennas possess light-weight and low-profile characteristics, while they can be easily worn and conformed to the body. Such properties are considered as one of the key components in many applications such as health monitoring for military, firefighting, and space applications.

Extensive research has been carried out on the usage of flexible materials, spatially textile materials, as a part of planar antennas [1-3]. Moreover, the effect of different electro-textile materials on the performance of wearable antenna has been studied [4,5].

In wearable applications, antennas are worn in close proximity to the human body. Frequency-detuning problems might arise because of the high dielectric properties of the human body. Besides, reducing the radiation towards the body is desirable, [6]. It is well known that AMCs and Electromagnetic Bandgap (EBG) structures have the potential to reduce both effects, thereby improve the antenna's radiation characteristics.

In [7], reflector patch element was utilized in order to decrease the back radiated field. The performance of this technique is highly dependent on the reflector size, furthermore, antenna design is based on a stack of multiple layers which leads to a high profile antenna system. In [8], inkjet-printed EBG array on paper substrate was designed for gain enhancement of microstrip monopole antenna. Despite that the proposed design is efficient on human body phantom, substrate material puts limitations on the compactness of the proposed antenna for wearable antenna applications. In [9], enhancement in the backward radiation and gain of a coplanar-waveguide (CPW) fed monopole antenna is obtained using AMC reflector. However, another limitation imposed by wearable antenna applications in terms of antenna flexibility has been faced in the proposed antenna system.

In this paper, we provide results from a study of CPW fed monopole textile antenna integrated with 4×4 flexible AMC array to cover ISM 2.45 GHz. The proposed antenna is flexible and compact which makes it suitable for wearable antenna applications. Bending analysis is performed to validate wearable antenna as in [2,6]. The prototype provides stable reflection coefficient characteristics under different bending conditions.

II. DESIGN OF MONOPOLE ANTENNA

The proposed monopole antenna configuration is based on the proposed design in [9], and is optimized using commercial electromagnetic simulation software CST Microwave Studio [10]. The radiating element and the CPW feeding line are printed on the same side of a Pellon fabric substrate having a thickness of 3.6 mm, dielectric constant ε_r= 1.08 and loss tangent tanδ = 0.008. Figure 1 depicts dimension details and fabricated prototype of the monopole antenna. Pellon fabric is chosen as the antenna's substrate since it exhibits a low profile and flexible characteristics, which enable stacking multiple layers to control the thickness of the substrate.

Figure 2 presents simulated and measured reflection coefficient (S_{11}) of the monopole antenna. Reflection coefficient measurements are carried out using Agilent E5071C Network Analyzer. Simulation result yields a -10 dB impedance bandwidth of 2.58 GHz (1.75 GHz - 4.33 GHz) with a good impedance matching at 2.45 GHz (S_{11} = -16.01 dB). On the other hand, measurement result (see Antenna 1) shows a wider impedance bandwidth of 3.58 GHz (1.28 GHz - 4.86 GHz) with a better matching

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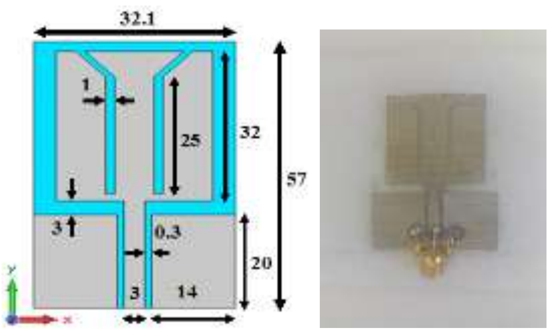
characteristic at 2.45 GHz (S_{11}=-20.97 dB). Discrepancies between simulations and measurements (see Antenna 1) were observed in the obtained results. This may be attributed due to errors during simulation, fabrication, and measurement phases of our investigation. It is worth mentioning that the textile monopole antenna was made by hand. Therfore, we first looked at the errors due to fabrication process. We thus decided to fabricate a new monopole antenna in order to avoid the effect of fabrication errors on the obtained results. We found out that errors due fabrication process didn't explain the discrepancies between simulations and measurements (see Antenna 2). However, the precision of the fabrication process has been increased in the second fabrication phase and the new fabricated antenna was used in the following investigations.



(a) (b)

Fig. 1. CPW-fed monopole antenna: (a) dimension details are given in mm, and (b) fabricated prototype.

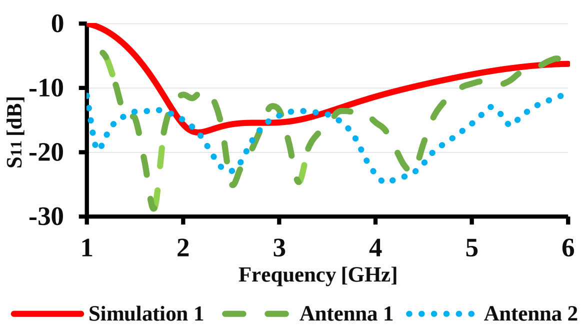


Fig. 2. Reflection coefficient of monopole antenna.

Another possible cause we found for discrepancies between simulations and measurements is the errors in material properties that used during the simulation phase of our investigation. In the first simulation, we have assumed the used conductive material in monopole antenna is copper material ($\sigma = 5.8\times10^7$ S/m) for simplicity. However, the conductivity of the electro-textile materials is different from that for a good conductor such as copper. To validate this conclusion, a parametric study on the conductivity of the electro-textile material was carried out based on simulations. As shown in Fig. 3, S_{11} results when the conductivity of electro-textile material is 500 S/m (see Simulation 2) are with a good agreement with the measurement results, as expected. Thus, we can conclude from the above discussion that the conductivity of the textile material is one of the error sources in our investigation.

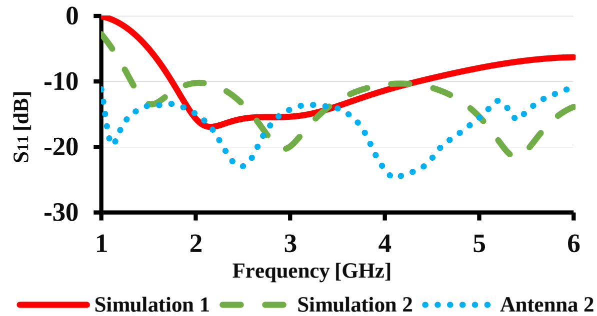


Fig. 3. S_{11} of monopole antenna using different conductive material.

Radiation patterns measurements have been performed using the anechoic chamber in Antenna Measurements Laboratory at University of North Dakota. Figure 4 shows the normalized E-plane radiation pattern of the monopole antenna at 2.45 GHz based on simulation and measurement results. The simulated cross-pole component isn't shown in the figure since it is less than -60 dBi. The simulated antenna gain is 2.45 dBi while the measured value is 3.39 dBi.

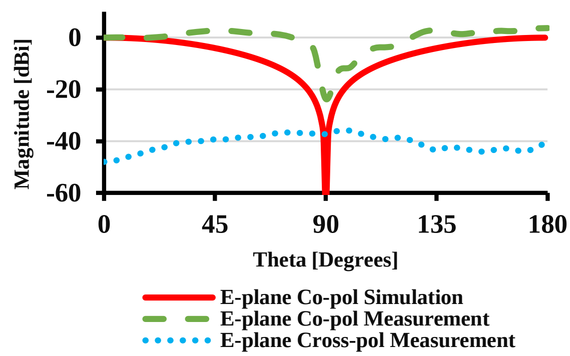
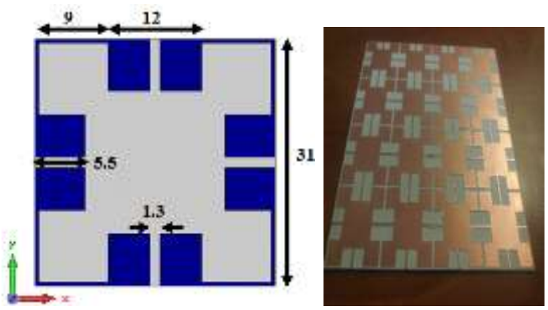


Fig. 4. E-plane radiation pattern of CPW-fed monopole antenna at 2.45 GHz.

III. DESIGN OF AMC GROUND SURFACE

The proposed antenna is placed on a symmetric 4×4 AMC array measuring 124×124 mm^2. To determine the array size, it was increased by one row and one column at a time until satisfactory performance in terms of high gain within the frequency range of interest was achieved, while maintaining a relatively small size. The geometry of the AMC unit cell is based on the proposed design in

[10] and optimized using CST MWS software. AMC cell measures 31×31 mm^2, and it is printed on 1.52 mm thick RO3003 flexible material with $\varepsilon_r = 3$ and $\tan\delta = 0.0013$. Figure 5 shows dimension details of the proposed AMC unit cell and the prototype of the fabricated AMC array.



(a) (b)

Fig. 5. Geometry of AMC structure: (a) dimension details are given in mm, and (b) fabricated prototype.

AMC reflector is designed by means of reflection phase characterization. The AMC reflection phase characterization procedure follows the same methodology applied in [11]. In the proposed cell, the exact point of zero phase is located at 2.45 GHz, having a narrow bandwidth of 138 MHz (2.34 GHz to 2.48 GHz) within ±90 phase values, as shown in Fig. 6.

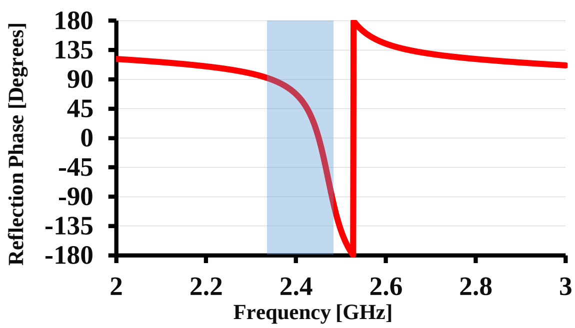


Fig. 6. Reflection phase diagram of an AMC unit cell.

S_{11} results of monopole antenna integrated on AMC reflector, which is defined as AMC antenna, using both copper material (see Simulation 1) and material of 500 S/m conductivity (see Simulation 2) are shown in Fig. 7 along with the measurement results. In general, a significant reduction in the impedance bandwidth by about 2.31 GHz (based on measurements) is obtained due to the use of AMC ground plane. However, the obtained bandwidth of AMC antenna is obviously sufficient for ISM-2.45 GHz operation with a good matching characteristics. Moreover, changing the conductivity of the monopole antenna has an effect of increasing the bandwidth of AMC antenna by about 2.5%, based on simulations. However, changing the material didn't explain the discrepancy in the obtained results. Many challenges were faced during the measurement phase due to the stiffness of the vector network analyzer cables and the softness of the designed textile antenna. We could not firmly fix the antenna and we noticed a large variation in the resonances and S_{11} level when we changed the position of the antenna and cables during the setup of the test. Also, a large variation in S_{11} with the pressure on the antenna connector while moving the cable was confirmed. Hence, problems in terms of misalignment of the monopole antenna on the AMC structure and air gap between monopole antenna and AMC structure were faced.

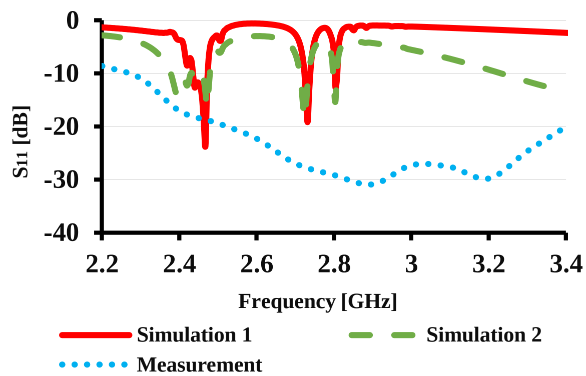
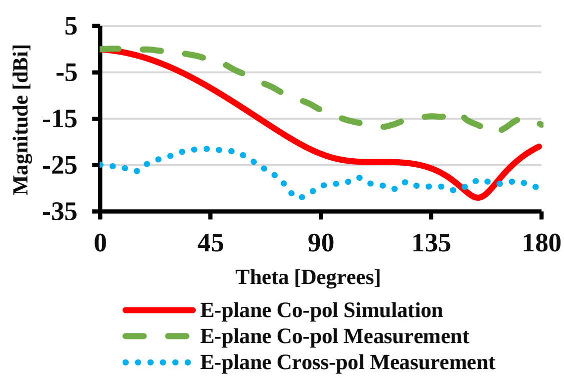


Fig. 7. Reflection coefficient of AMC antenna.

Normalized radiation patterns in E- and H-plane of AMC antenna based on simulation and measurement results at 2.45 GHz are shown in Fig. 8. Cross-pole components of both planes aren't shown here since they are less than -40 dB. The measured AMC antenna gain is 6 dBi while the simulation-based value is 8.41 dBi. This reduction might be due to error sources discussed previously.



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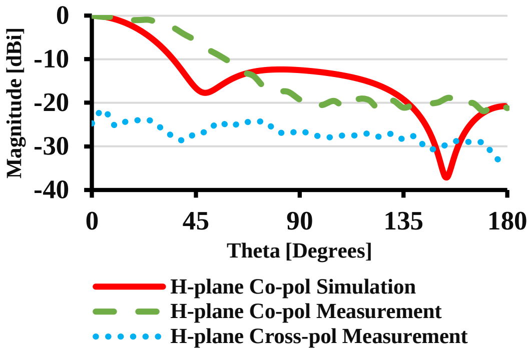
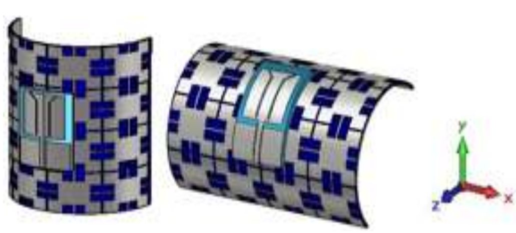


(b)

Fig. 8. Radiation patterns of AMC antenna at 2.45 GHz: (a) E-plane and (b) H-plane.

IV. PERFORMANCE OF AMC ANTENNA UNDER BENDING CONDITIONS

In wearable antenna system, it is difficult to keep the antenna flat all the time, especially when the antenna is made out of flexible material. Moreover, the wearable antenna will be subject to several shape distortion forms due to the human body movements. Therefore, investigation of the antenna's performance on the dynamic body environment such as under bending conditions due to the antenna conformability with the surface of the body is one of the important factors to be studied. Bending radii (*R*) chosen in our investigation are: 40 mm, 100 mm and 140 mm to approximate a human adult's arm, leg and thigh. Moreover, investigations of antenna performance were executed for two bending directions: E- and H-plane, illustrated in Figs. 9 (a) and (b), respectively.



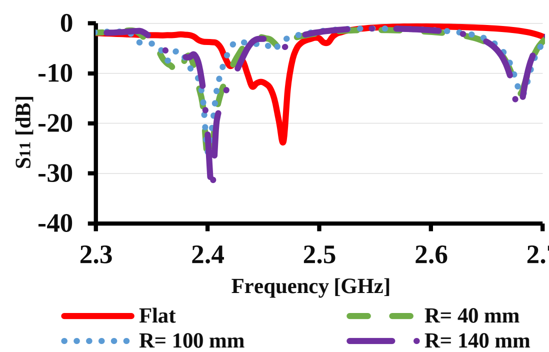
(a) (b)

Fig. 9. AMC antenna bent around cylinders for different directions: (a) E-plane and (b) H-plane.

A. Reflection coefficient

Reflection coefficient results of AMC antenna based on simulations and measurements in flat form and under different bending conditions in E- and H-plane are depicted in Figs. 10 and 11, respectively. It is worth mentioning that it is impossible to reach a specific bending in the measurements as accurately as in the simulations. Hence, errors in bending radii are unavoidable. In addition, S_{11} measurement results for *R* = 40 mm are not shown here due to the difficulty to get to that bending degree accurately. However, simulation results are shown to test the flexibility of the design based on simulations.

Despite best efforts, discrepancies between simulations and measurements still exist. However, bending AMC antenna resulted in shifting the resonance frequency toward lower values for both bending directions, which is independent from the bending radius, based on simulations and measurements. In addition, based on measurement results, bending AMC antenna in H-plane direction has changed its matching properties dramatically in terms of impedance bandwidth and S_{11} level compared to bending conditions in E-plane direction.



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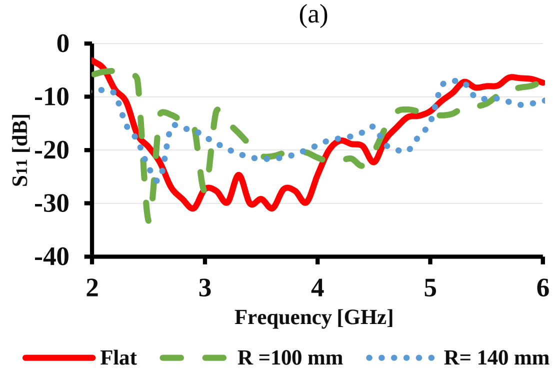
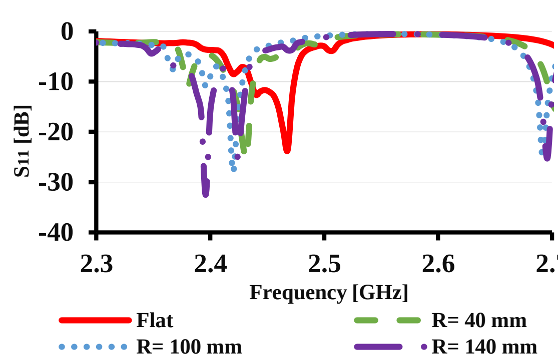


(b)

Fig. 10. S_{11} for different bending radius at the E-plane direction: (a) simulations and (b) measurements.



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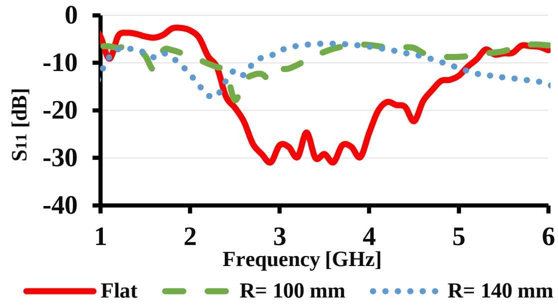

(b)

Fig. 11. S_{11} for different bending radius at the H-plane direction: (a) simulations and (b) measurements.

B. Radiation patterns

Radiation patterns at the resonance frequency of E- and H-plane bent AMC antenna are shown in Figs. 12 and 13, respectively. In general, it can be observed that as the AMC antenna is bent more and more (bending radius gradually decreased), antenna gain and directivity have been decreased due to both E- and H-plane bending conditions. The least value of AMC antenna gain of 3.4 dBi is obtained due to R = 100 mm bending in H-plane direction. Moreover, the power level of the cross-pol components has been increased under bending conditions in H-plane direction, while less deformation has been achieved due to bending in E-plane direction.

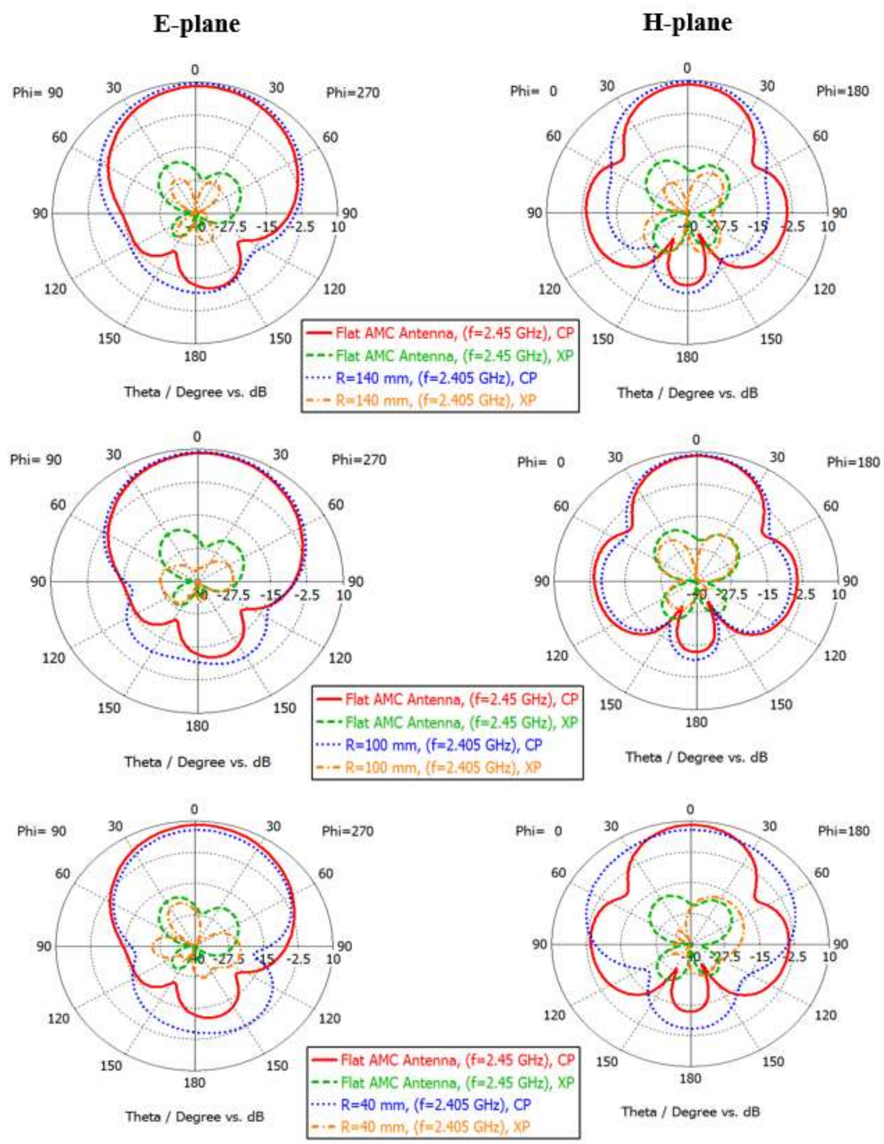

Fig. 12. Simulated radiation patterns of AMC antenna bent in E-plane at f_r: (left) E-plane and (right) H-plane; Co Polarization (CP) and Cross Polarization (XP).

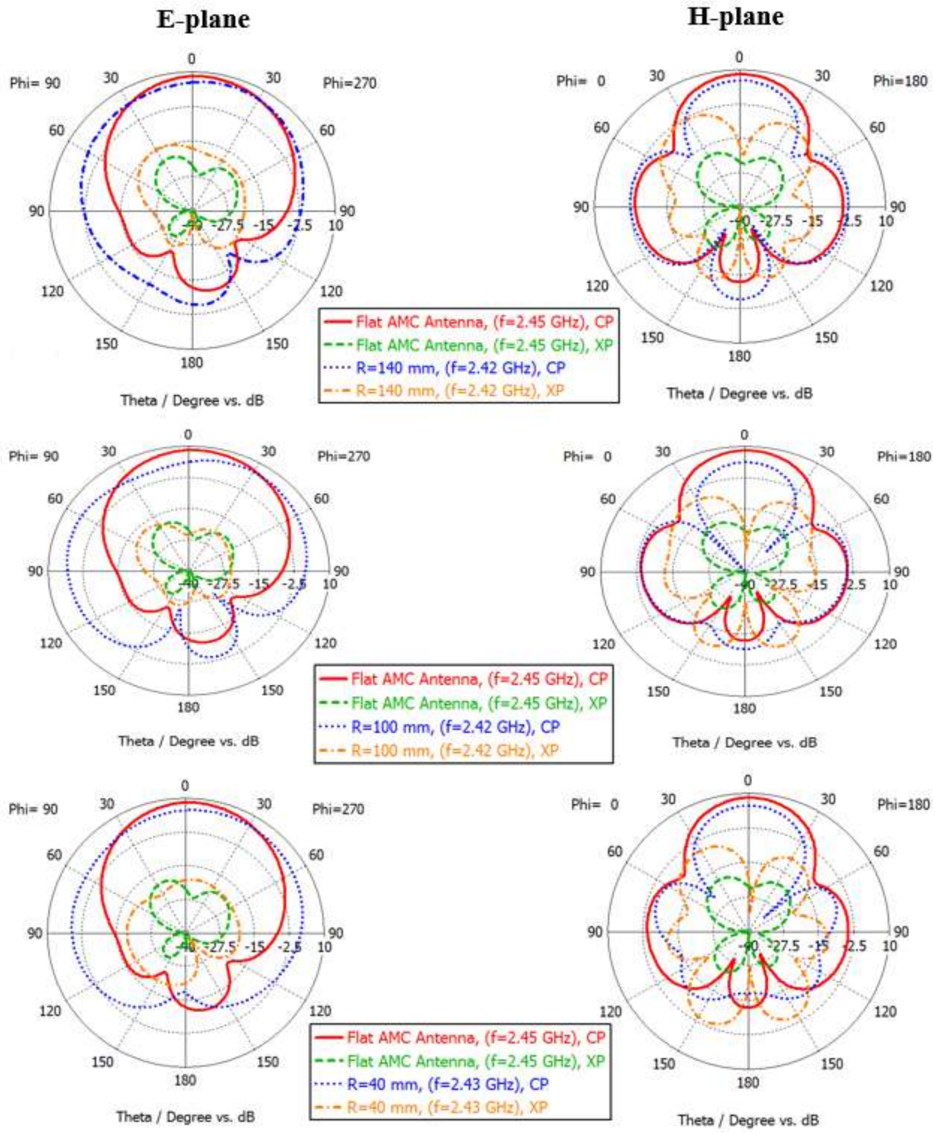

Fig. 13. Simulated radiation patterns of AMC antenna bent in H-plane at f_r: (left) E-plane and (right) H-plane; Co Polarization (CP) and Cross Polarization (XP).

In order to explain AMC antenna gain degradation due to bending conditions, effect of AMC antenna bending on the point of zero phase reflection was investigated based on simulations and summarized in Table 1. It can be concluded that bending AMC antenna has an effect of shifting the point of zero phase reflection, which is no more at the resonance frequency of the AMC antenna.

Table 1: Zero reflection point of AMC structure bent in E- and H-plane directions

Bending Radius	E-plane	H-plane
R = 40 mm	2.4868 GHz	2.4775 GHz
R = 100 mm	2.4776 GHz	2.4679 GHz
R = 140 mm	2.4902 GHz	2.4763 GHz

V. CONCLUSION

Textile monopole antenna integrated with flexible AMC surface operating in ISM 2.45 GHz band is investigated for wearable applications under different bending conditions. A detailed description about the design has been presented. Results demonstrated improvement in the antenna gain of the integrated antenna, which implies enhancement in the radiation characteristics, and reduction in the backward radiation toward the human body. Furthermore, measurement results showed that AMC antenna bending in H-plane direction has changed its matching properties dramatically in terms of impedance bandwidth and S_{11} level compared to bending conditions in E-plane direction.

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Ala Alemaryeen received the B.Sc. degree in Electrical Engineering from Mutah University, Karak, Jordan, in 2012, and the M.Sc. in Electrical Engineering in the field of Applied Electromagnetics with focus on Artificial Magnetic Conductors and Wearable Antennas, from University of North Dakota (UND), North Dakota, USA, in 2015. She is working towards the Ph.D. degree in Electrical Engineering at UND. Her research interests are in wearable antennas and metamaterial.

Sima Noghanian received the B.Sc. degree in Electrical Engineering from the Sharif University of Technology, Tehran, Iran, in 1992, and the M.Sc. and Ph.D. degrees both in Electrical Engineering, from the University of Manitoba, Winnipeg, Canada, in 1996 and 2001, respectively. In 2001, she was a Researcher at YottaYotta Corporation, Edmonton, Canada. She received a Postdoctoral Fellowship from Natural Sciences and Engineering Research Council of Canada in 2002, which she took at the University of Waterloo.

She was an Assistant Professor in the Department of Electrical Engineering, Sharif University of Technology, Iran, during 2002-2003. From 2003 to 2008, she was an Assistant Professor in the Department of Electrical and Computer Engineering, University of Manitoba, Canada. She is currently an Associate Professor of the Department of Electrical Engineering, University of North Dakota, USA. Her research interests include antenna design and modeling, wireless channel modeling, ultra-wideband antennas, and microwave imaging. Noghanian is a Senior Member of IEEE and served as the IEEE Winnipeg Waves Chapter (joint Chapter of Antenna & Propagation, Microwave Theory & Techniques, and Vehicular Technology societies) Chair during 2004-2005. She is a Member of Eta Kappa Nu, a Member of International Union of Radio Science URSI Commission B, and a Member of the Applied Computational Electromagnetics Society. She is currently an Area Editor for AEU - International Journal of Electronics and Communications.