Robustness Analysis of the Polymer-Conductive-Mesh Composite for the Realization of Transparent and Flexible Wearable Antennas

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***Abstract*—In this paper the morphology of the polydimethylsiloxane (PDMS)-flexible-conductive-mesh composite has been studied to evaluate its suitability in the realization of robust, flexible, transparent, wearable antennas that can withstand multiple bending operations. We have utilized conductive mesh made out of VeilShield from Less EMF which has about 70% light transmittance and is highly flexible. On the other hand, PDMS is a highly flexible and optically transparent polymer. Uncured PDMS is in liquid form and upon curing it transforms to a robust flexible substrate and forms a strong bonding with the conductive mesh, VeilShield. We have examined the composite through Scanning Electron Microscope (SEM) images during and after multiple bending operations. Later, we have designed a simple patch antenna operating at 2.45 GHz band using our selected materials. For performance evaluation the antenna is tested in both free space and under bent conditions and the results are presented in this paper.**

***Index Terms*—Flexible, mesh, polydimethylsiloxane, transparent, wearable.**

I. INTRODUCTION

Wearable antennas is one of the most demanding research topics in the area of microwave and antenna technologies. The applications of wearable antennas can be found in tele-healthcare systems, security services, defence and sports. But, in order to be wearable, an antenna should pose some peculiarities which are not necessary for the conventional antennas. Flexibility, small size and low backward radiation are the inevitable properties of the wearable antennas. So, the design process of wearable antenna is different from conventional antenna designs [1], [2] and the traditional rigid materials used in antenna fabrication are not compatible in wearable applications.

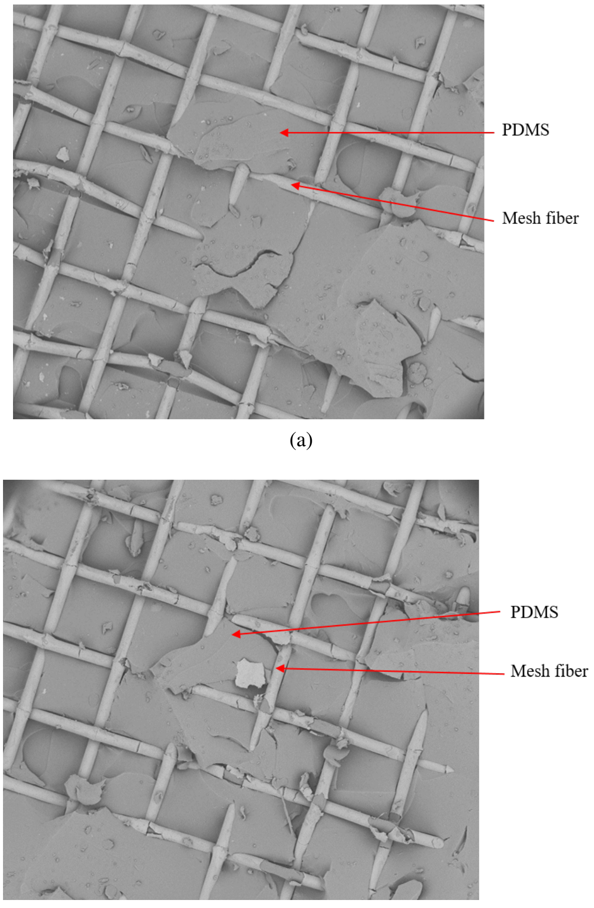
In addition to the required properties of flexibility and small size the other desired property of a wearable antenna is optical transparency [3], [4], [5] which is important for not only to exalt the aesthetic appearance but also to make it compatible in a broader range of applications. The common areas of the applications of transparent wearable devices are mental healthcare monitoring systems, securirty providers and defence. Realizing flexible transparent antenna is very challenging owing to the unavalability of the perfect materials for antenna fabrication. The commonly used transparent conductors and substrates are not suitable for the realization of flexible transparent antennas due to their instability when subjected to multiple bending operations. The traditional transparent conductors include indium-tin-oxide (ITO) [6], [7], fluorine-doped tin oxide [8], aluminum-zinc-oxide [9], silver-coated polyester film (AgHT) [10], and metallic meshes [11], [12], [13], [14]; the traditional transparent substrates are polyethylene terephthalate (PET), acrylic and glass. These materials perform poorly in multiple bending operations and thus are not appropriate candidates for the realization of robust, flexible, transparent antennas.

In contrary to the conventional transparent conductors and substrates polymer-mesh composite [15] is an effective solution for the realization of highly flexible and optically transparent antennas. In this paper the stability of the polymer-mesh composite against multiple bending operations has been studied, alongside its morphology through Scanning Electron Microscope (SEM) imaging. For concept demonstration, a rectangular microstrip antenna is fabricated and tested. The antenna is backed by a full ground plane, which minimizes backward radiation towards the wearer's body. The antenna is bent on a human hand-shaped-phantom and the performance is measured to confirm its stability in bending scenario.

II. ANALYSIS OF THE MATERIALS

The transparent conductor selected in this study is the conductive mesh sheet, VeilShield from Less EMF Inc. VeilShield is very thin (57 μm) and light weight (40 g/m^2). The fibers of the VeilShield are coated with Zinc-blackened Nickel over Copper. It has about 70% light transmittance capability and has high electrical conductivity (sheet resistance is 0.1 Ω/sq).

Our proposed polymer is PDMS which is highly flexible, optically transparent and water resistant substrate. In our measurement from 0.5 to 10.6 GHz by using Agilent's 85070E Dielectric Kit the dielectric constant of the PDMS was 2.75 and loss tangent varied from 0.008 to 0.07. The uncured PDMS is in liquid form and when it is cured it turns into a flexible substrate. After curing PDMS forms a strong bond with the proposed transparent conductor VeilShield as shown in the

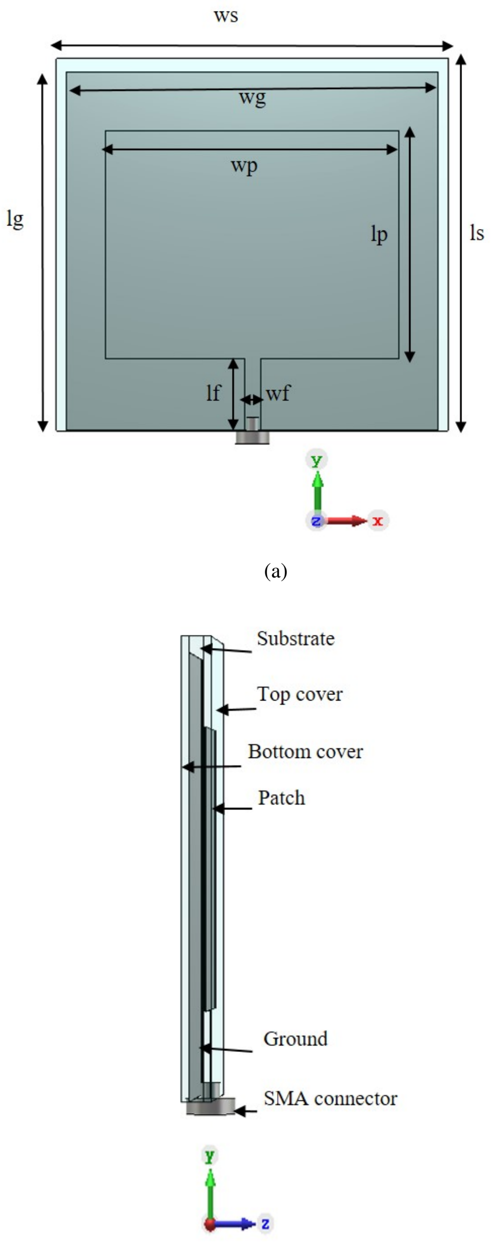


(a)

(b)

Fig. 1. SEM images of the composite-(a) without subjected to bending, (b) after 10 cycles of bending.

SEM images of Fig. 1. VeilShield itself is not very robust in nature but when it integrates with PDMS a very robust composite material has been formed. For investigating the SEM analysis to observe the structural nature of the composite a small rectangular sample of the composite was fabricated with VeilShield and PDMS, and a small portion of PDMS was carefully cut out from the top of the composite to take the SEM images. SEM images were taken before the sample was subjected to bending, and after various cycles of bending applied to the sample. Fig. 1 illustrates that PDMS penetrates though the fibres of the mesh and thus the mesh is integrated with the PDMS strongly. It can be seen in Fig. 1(b), that even after bending and flattening the sample for 10 times, the bonding still remains in perfect condition. This strong attachment of the two classes of materials is the reason of the physical robustness of the composite and it can be a suitable candidate for the realization of flexible, optically transparent, wearable antennas having a robust performance in multiple bending operations. This investigation also illustrates an effective solution to join flexible conductors and substrates in a reliable and robust manner, which is a major realization challenge of flexible antennas.



(a)

(b)

Fig. 2. Antenna geometry-(a) front view, (b) side view.

III. REALIZATION OF ANTENNA FROM THE SELECTED MATERIALS

A simple patch antenna was realized with the selected materials and tested experimentally. The geometry of the antenna is shown in Fig. 2. The antenna is a rectangular patch antenna. The top and bottom PDMS layers are used as the protective layers. Full ground plane is selected for the the antenna to reduce the back radiation. Table I shows the dimensions of the antenna.

We fabricated the antenna prototype by following the same procedure as we mentioned in [15]. The fabricated prototype of

TABLE I
DIMENSIONS OF THE ANTENNA

Parameter	Description	Value (mm)
l_p	Length of the patch	34
w_p	Width of the patch	50
l_g	Length of the ground plane	52
w_g	Width of the ground plane	58
w_f	Width of the feed line	5
l_f	Length of the feed line	10.5
w_s	Width of the encapsulation	60
l_s	Length of the encapsulation	55
h_1	Thickness of the bottom cover	0.76
h_2	Thickness of the substrate layer	1.6
h_3	Thickness of the top cover	0.76

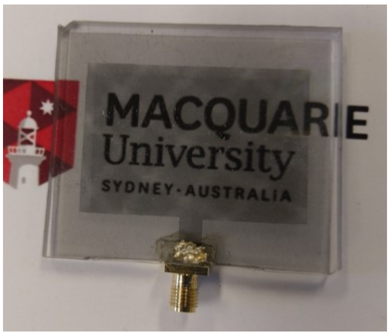


Fig. 3. Fabricated prototype of the antenna.

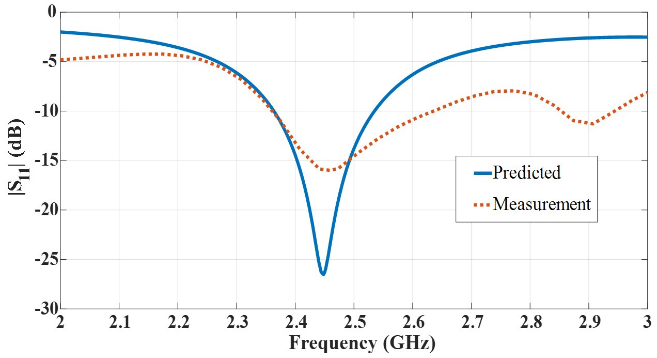


Fig. 4. Predicted and measured $|S_{11}|$ of the proposed antenna.

the antenna is shown in Fig. 3, which shows that our fabricated antenna is optically transparent.

The predicted and measured $|S_{11}|$ of our proposed antenna are shown in Fig. 4. The predicted result is the simulation result by utilizing CST Microwave Studio 2017. The results demonstrate that the antenna resonates at our desired band of 2.45 GHz. The small difference is due to the manufacturing error which occurs due to manual fabrication process of the antenna.

For bending test the antenna was bent on a human-hand-shaped phantom of radius 28 mm (see the inset of Fig. 5). The measured $|S_{11}|$ of the antenna under bending is shown in Fig. 5. The result of the bent antenna illustrates that resonance frequency shifts to lower position in bending condition due to the increase in electrical length of the patch. However, the antenna still operates in the desired band of 2.45 GHz. The result of the bent antenna ascertains that the antenna is physically stable under bent state, this robustness is the reason of the strong attachment of our selected conductive and dielectric materials as explained earlier.

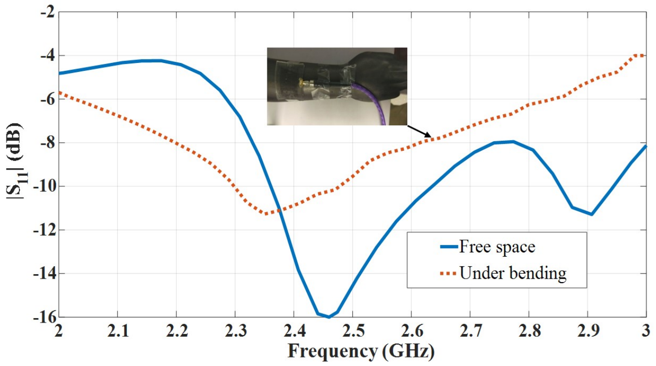


Fig. 5. Measured $|S_{11}|$ of the proposed antenna in free space and in bent condition.

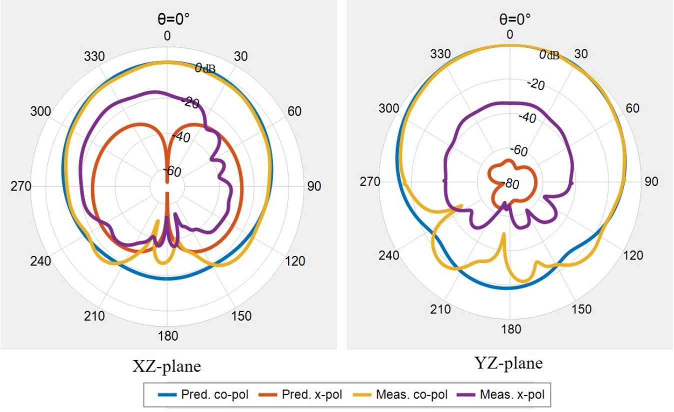


Fig. 6. Predicted and measured radiation patterns of the proposed flexible antenna at 2.45 GHz.

The predicted and measured normalized radiation patterns of our proposed antenna are shown in Fig. 6. Excellent similarities between the predicted and measured results can be seen in the displayed results. The antenna radiates at broadside direction with a gain of 1.8 dBi and 35% efficiency. The poor gain and efficiency are due to the high loss tangent of PDMS. The performance of the antenna can be improved by increasing the substrate thickness and improving the matching in feeding position.

IV. CONCLUSION

In this paper the physical properties of the polymer-flexible-conductive-mesh composite have been investigated to demonstrate its suitability for the realization of highly flexible and optically transparent wearable antennas that have excellent robustness in multiple bending operations. The lack of suitable transparent materials for antenna fabrication and the inherent challenge of the integration of flexible conductive and substrate materials impose realization difficulties on the flexible transparent antennas. Our proposed flexible transparent materials can be effective alternative for the realization of robust, flexible, optically transparent antennas and sensors. The scanning electron microscope (SEM) images of our proposed composite materials show the robust integration of the two classes of materials that remains stable even after multiple times of bending operations. This analysis demonstrates the superiority of our proposed materials over the existing materials used in the realization of transparent antennas. The fabricated prototype of the antenna from our selected materials shows stable performance when bent on human-hand-shaped phantom. So, it can be concluded that our proposed PDMS-conductive-mesh composite can be a potential candidate for the development of robust, flexible transparent, wearable antennas and sensors.

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