Low-density foam as an adhesion facilitator between silicone rubber and copper sheet for use in flexible microwave antennas

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Abstract
An effective solution is presented to address the issue of poor adhesion of metal to silicone for the realization of flexible antennas for wearable applications. The low surface energy of silicone creates difficulties in adhering metal layers to it. Low-density polyurethane (PU) foam is used as an adhesion facilitator for interlocking silicone and a good adhesion strength with the copper layers is obtained via a commercially available polyurethane (PU) binder. The developed multi-layered substrate illustrates a high elongation at break of around 375% and very low water absorbance. The microwave characterizations show that the substrate exhibits a low permittivity value of 2.12 and a loss tangent of 0.02 at 10 GHz. The application of the substrate for wearable purpose is demonstrated by fabricating a simple microstrip antenna and testing its performance in both flat and bending profiles. The antenna characteristics exhibit a gain greater than 7 dB. The gain and bandwidth are almost consistent for all the bending profiles.

1. Introduction
The ubiquity of wearable antennas over the last decade has created an ever-growing interest in flexible microstrip antenna designs. The physical and the microwave properties of the substrate of such wearable antennas play an important role in determining its performance as a body area network (BAN) device. A review of the current state of the art [1] classifies wearable antennas, depending upon the type of the material used and the fabrication technique involved, into the following basic categories, fabric-based [2], print-based [3], microfluidic [4], and polymer-based [5] antennas. Polymers, generally are low permittivity materials with low loss, exhibit high flexibility, generally non-reactive, stable and resistant to environmental changes and hence are suitable for antenna substrates. Polydimethylsiloxane (PDMS), liquid crystal polymer (LCP), silicone rubber etc are some of the commonly used polymers used as substrates for flexible antennas [1]. Amongst such polymers silicone rubber [6–8] have the advantage of being able to be molded and cured at the room temperature making the fabrication process easier and hence it has been considered as the substrate material in the current work.

Apart from the substrate, the conducting metallic layers vide the patch and ground plane are inevitable components of a microstrip antenna. Flexibility in antennas requires proper adherence of these metallic layers to the substrate (flexible) such that it can withstand repeated bending cycles throughout its lifetime. Polymers with low surface energy such as silicone rubber, polydimethylsiloxane (PDMS), etc do not adhere strongly [9] with metals, which poses a major hindrance in the use of such polymers as substrates.

Substantial effort has been made using sophisticated and expensive equipment to achieve strong adhesion between polymers and metals often leading to degradation and loss of special properties [10]. To the best of the author’s knowledge, most of these techniques used to improve the adhesion of metal sheets with silicone rubber have not been tested for use in flexible antennas. Few techniques reported to improve the usability of silicone rubber/PDMS for flexible antenna include using metallic mesh instead of the sheets for the patch and the ground plane, this might introduce potential imprecision due to the imperfection of the mesh itself [11], which may aggravate with multiple bending. Another technique reported, is by encapsulating the patch and ground
plane within layers of silicone [12], which leads to an overall thicker structure. Others have used non-metallic materials [13, 14] and patterned metal sheets [14], which affects the gain of the antennas.

Adhesion between two surfaces, generally, results from any one or more than one of the phenomena viz. van der Waals interactions, diffusion, chemical interactions, and mechanical interlocking. Van der Waals interactions are insufficient for adhering the metal to silicone rubber as the latter is known to have very low surface energies [10]. Silicone rubber is insoluble in all but perfluorinated solvents and materials, thus diffusive adhesion is also excluded [15, 16]. The chemical inertness of silicone rubber reduces the provision of adhesion mechanisms due to chemical interactions [10].

Mechanical interlocking is another process inspired by the ‘Velcro’ mechanical interlocking approach, wherein an adhesion facilitator is used to improve the adhesion between two low surface energy substrates, for e. g Zinc Oxide (ZnO) nanoparticles were used as adhesion facilitators to adhere polytetrafluoroethylene (PTFE) substrates [10]. A simpler and inexpensive concept based on ‘Velcro’ mechanical interlocking is presented in the current study, wherein a foam layer is used as an adhesion facilitator to adhere the metal (copper) layers with silicone. Also, foam is quite flexible and has an effective permittivity close to that of the air, exhibiting low losses in the microwave regime and does not affect the properties of the composite adversely. The hypothesis of the mechanism is that the adherence of the silicone layer to the foam layer can be achieved by employing the capillary rise phenomenon due to the surface tension of the uncured silicone liquid. The silicone ‘capillaries’ are then cured to retain their position inside the foam thereby forming a grip and adhering the foam layer to it. The metal sheet can then be adhered to the foam layer with the help of commercially available polyurethane-based binders (PU-binder) thus forming a metal-foam-silicone multilayer substrate.

The proposed multilayered substrate is tested for use in the development of a flexible microstrip patch antenna in this work. Before molding the material as the substrate for microstrip patch antenna (MPA), its physical and thermal properties, relevant to the application as flexible antenna substrate such as tensile strength, peel strength, and water absorbance have been studied. Complex permittivity of the silicone-foam substrate is measured in the range 8.2–12.4 GHz. A simple rectangular patch antenna is then designed on the silicone-foam substrate using a transmission line model (TLM) technique at 10 GHz, and antenna performance is tested with different bending radii.

2. Fabrication of the copper laminated silicone rubber-foam substrate

2.1. Adhesion of silicone rubber and foam

The adhesion of silicone to foam is carried out in a two-step process. In the first step, uncured silicone rubber (purchased from MoldSil, India) is mixed with 5 wt% hardener (purchased from MoldSil, India) and mixed thoroughly in a glass container. The mixture is then poured gently into a 3D printer (Boxzy, USA) printed Polylactic Acid (PLA) mold of dimension 50 mm × 50 mm × 0.75 mm. The mixture is very slowly poured so as to avoid the formation of any air bubbles until it fills up to the height of the mold. Once the uncured silicone rubber settles, in the second step, a low-density polyurethane foam sheet (density—8.54 kg m⁻³) of dimension 50 mm × 50 mm × 3 mm (length × breadth × height) is gently placed over the uncured silicone rubber. Open-cell type foam is chosen, so that the foam’s cells act as air pockets allowing the uncured liquid silicone rubber to rise up along these pockets. The air pockets in the foam sheet act as the capillaries and the silicone rubber is the liquid in question. As the foam sheet is placed over the uncured silicone rubber, the silicone liquid rises up along the foam air pockets due to surface tension. This rise (height) is governed by the following relation (1)

\[ h = \frac{2T \cos \theta}{\rho g r} \]  

wherein, \( T \) is the surface tension of the silicone rubber, \( \theta \) is the contact angle between silicone rubber and foam sheet, \( \rho \) is the density of the silicone rubber, \( g \) is acceleration due to gravity and \( r \) is the radius of the air pockets of the foam sheet.

In the current case, the surface tension, \( T \), of silicone is a function of its state, that changes with time and temperature. \( T \) decrease as the silicone hardens and further penetration is stalled. Thus, a trade-off needs to be attained in order for the silicone to get rooted inside sufficiently to achieve the required interlocking between the foam sheet and the silicone layer and at the same time avoid deeper penetration to sustain the structure of the substrate. Moldsil silicone rubber hardens completely in a time span of 24 h at room temperature. Considering this fact, several rounds of trials were carried out and it was found that, if the initial curing process (i.e. the first hour after mixing the liquid silicone with hardener) is carried out at a higher temperature of about 60 °C, it fastens the process of curing and hardens the silicone to stall further penetration into the foam layer and also
giving sufficient bonding with the silicone surface. The remaining curing process can be carried out at room temperature conditions. The schematic of the process explained above is shown in figure 1.

Once the silicone rubber gets cured in about 24 h, it gets well rooted into the foam sheet (figure 2). This phenomenon is quite evident if the foam sheet is removed by force the top layer of the silicone appears to contain microspikes which were formed due to the capillary rise of silicone rubber inside the foam sheet cells. A photograph of the silicone layer as it appears to be after the foam sheet is detached is shown in figure 3(a). A magnified image of a region of the layer is taken using the foldscope [17] and is shown in figure 3(b). The sample is kept on a glass slide which is attached to the foldscope and the image is taken using a mobile phone. In order to brighten the image, the slide is lighted from its rear using a led flashlight. Therefore, the silicone spikes appear dark in the image as shown below.

The height of the spike as seen from the image is estimated using a standard grid line image taken by the same foldscope. The height of this spike is found to be 0.3 mm.

2.2. Adhesion of silicone foam substrate to a metal layer
The second step of the fabrication process is copper lamination (figure 4). A thin copper sheet of dimension 50 mm × 50 mm × 0.03 mm is prepared by scrubbing and cleaning its surface with ethanol and then dried in a hot air oven at 60 °C for 60 min. The foam surface of the silicone-foam substrate, fabricated in the above process, is cleaned by blowing dry air. A polyurethane-based binder (PU-binder) is chosen for binding the copper sheet and the silicone-foam substrate. The binder is uniformly applied on the foam side of the silicone-foam substrate.
until it completely percolates the foam layer and then on the copper sheet. The surfaces are then left to dry at room temperature for about 5 min so that the solvent of the binder evaporates. The smeared copper sheet is then placed on the substrate and pressed uniformly in a standard table vice for about 12 h to get a sufficiently strong adhesion. The obtained copper laminated silicone-foam substrate is shown below in Figure 5.

Since for an antenna, metallic layers are required on both top and bottom of the substrate the above mentioned two processes, are repeated in the same manner to obtain another set of the silicone-foam copper multi-layered substrate with the same dimension 50 mm × 50 mm × 0.75 mm (length × breadth × thickness). The obtained pair of substrates are then bonded together by applying a very thin layer of silicone (mixed with hardener) over the silicone side of the substrates and then placed over one another. The structure is left to dry at room temperature for 24 h.

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**Figure 3.** (a) Photograph illustrating the spikes on silicone surface exposed after removing the foam sheet by force from the silicone-foam substrate (left); (b) a magnified image of one of such spikes using a foldscope (right).

**Figure 4.** Schematic of the workflow for the adhering copper sheet to the silicone-foam substrate using PU-binder. (Colour code of the layers: Grey—silicone rubber; Green—foam; Red—PU binder; Brown—copper sheet).
3. Testing and Characterization of the fabricated silicone-foam substrate

The physical properties such as tensile strength, adhesive (peel) strength, thermal stability, water absorbance of the developed substrate are tested to determine its usability as an antenna substrate. Apart from these, the dielectric property (in the microwave X-band frequency range) of the substrate is also determined.

3.1. Tensile and adhesive strength test

A silicone-foam–binder substrate (without copper lamination) and a pure silicone substrate (without the foam and copper lamination) is subjected to a tensile strength test, for determining its flexibility and stretchability using universal Testing Machine (UTM); Make—Zwick; Model—Roel 10kN; Testing Standard—ASTM D 882 at room temperature with a 500 N load cell and a crosshead speed of 20 mm min⁻¹. The Schematic of the measurement is shown in figure 6.

From figure 7 it is seen that the elongation at break for the multi-layered silicone-foam substrate is higher at around 375% compared to pure silicone at around 325%. The increased elongation at break for the multi-layered substrate could be due to the interlocking of silicone in the pockets of foam (figure 3).

The adhesion strength (peel strength) of copper to the foam-silicone substrate via the PU binder is also tested using UTM. The schematic set up for measuring the peel strength is as shown in the figure 8. Two similar sets of the multilayer substrates are adhered together through a copper sheet layer having a surface contact area of 4 cm². The substrates are then subjected to a standard force and the corresponding elongation is measured until the copper sheet is peeled off from any of the two substrates.

The multi-layered substrate with copper sheet attachment vide PU binder shows an elongation of up to around 275% (marked as silicone-foam-metal in figure 9) which is about three times of the original substrate length before the copper sheet peeled off completely. It is noteworthy to mention here that the silicone does not stick to metal vide PU binder directly (because of low surface energies). On adhering copper sheet directly to
silicone via another common binder based on cyanoacrylate exhibits an elongation of 75% (marked as silicone-metal in figure 9) as shown in figure 9. Foam could not be used as an adhesion facilitator in this case, as cyanoacrylate dissolves the foam as soon as it comes in contact with it.

The results of the adhesive strength characterizations, indicate that the developed silicone-foam substrate’s adherence to the metallic layer is sufficiently high [10], so that the layer do not tend to come off due to bending
and thus, the foam layer in the silicone-foam substrate acts as an adhesion enhancer for silicone to copper adhesion.

3.2. Thermo Gravimetric Analysis (TGA)

The thermo-gravimetric analysis (TGA) of the fabricated silicone-foam-binder (without copper lamination) substrate was carried out using a thermogravimetric analyzer, model STA-6000. 14 mg piece of the sample was heated at a rate of 10 °C min⁻¹ in the temperature range of 15 °C–600 °C under a constant nitrogen atmosphere to determine the decomposition temperatures.

As evident from the figure 10, the structure exhibits a mass loss of 1% up to 180 °C, beyond which the rate of degradation increases. The major weight losses take place at around 200 °C and 400 °C because of the decomposition of foam [18] and PU-binder [19], silicone rubber [20] respectively.

3.3. Water absorbance test

The developed multilayer silicone-foam-binder substrate is submerged in distilled water at room temperature condition for around 72 h and their respective weights are recorded before submerging and after submerging to determine the percentage of water absorbance of the substrates under study. The water absorbance test reveals that there is no change in the weight up to an accuracy of 0.001 gm, for silicone-foam-binder substrate, after submerging it in water for a period of 72 h. The result is quite evident, because of the fact that silicone is known to have a water repellent property and is commonly used in industries as sealants and moisture protective sheets. The PU binder layer is also water repelling in nature, however, the foam does absorb water. The PU binder and the silicone that penetrates inside the air pockets of the foam layer alienates the possibility of water seepage into the multi-layered substrate.

3.4. Complex dielectric properties (8.2–12.4 GHz)

The microwave characterizations of the multi-layered substrate i.e. silicone attached to foam on both its top and bottom surfaces along with the PU binder applied over the foam surface are measured using Agilent WR-90 X11644A rectangular waveguide line compatible to Agilent E8362C VNA employing Nicolson Ross method X-band with sample size 22.86 mm × 10.16 mm. The components of the multi-layered substrate vide the silicone, foam-binder (the PU-binder penetrates the foam as it is spread on it and thus has been considered as a distinct layer) and binder are also individually characterized for their dielectric properties using the same method mentioned above.

Figure 11 shows the permittivity and loss tangent of the individual layer materials that make up the multi-layered silicone-foam substrate. The measurements are taken over the frequency range 8.2–12.4 GHz (X-band) as the substrate is intended to be used in an antenna working in the X-band regime.

The measured values of the individual layer materials are used for obtaining the calculated permittivity values of the multi-layered substrate and the multi-layered substrate is characterized to obtain the measured values as well. The calculated dielectric permittivity for the three-layer substrate is obtained using the equation (2) as shown below,
Wherein, $\varepsilon_i$ & $h_i$ are the dielectric permittivity and height of the individual component layers of the multi-layered substrate respectively. The individual permittivity values are obtained from the measured permittivity curves. The height of the individual layers is measured and accordingly put in equation (2), to obtain the calculated values. Here the thickness of the individual layer is kept the same as the actual dimensions.

The measured and calculated permittivity plots are shown in figure 12 and are in good agreement with each other. Figure 12 shows the measured permittivity and loss tangent plots of the silicone-foam multi-layered substrate.

The permittivity and the loss tangent values of the silicone-foam substrate in the frequency range 8.2–12.4 GHz vary in the range 2.08 to 2.20 & 0.01 to 0.06 respectively. The dielectric characteristics also show that the substrate has low permittivity and low loss in the X-band frequency range indicating that the gain of the antenna would not be adversely affected [21].

4. Realization of a wearable antenna on the silicone-foam substrate

A simple microstrip patch antenna is designed on the developed substrate to resonate at 10 GHz, considering the dielectric constant at 10 GHz to be 2.12, loss tangent to be 0.02 (as obtained from figure 12) and the substrate thickness to be 2 mm. The standard transmission line model [22] is employed to determine the patch size. The obtained patch dimensions are then used to model a simple microstrip patch antenna using CST Microwave...
Studio simulation software. The schematic of the modeled patch, as well as the cross-section of the modeled substrate, are shown below in figure 13.

The S11 & radiation pattern results of the simulation show that the designed antenna resonates at 10 GHz and also radiates at 10 GHz with a gain of 7.03 dB. The simulated S11 & radiation pattern plots are shown in figures 16 and 18 respectively.

This simulated antenna structure is then fabricated for experimental verification. The copper laminated (top + bottom) silicone-foam substrate is obtained by following the procedure described in the previous section. One side of the copper lamination is cleaned thoroughly by using ethanol and washed with water several times to remove traces of the chemical before drying it in a hot air oven at 60 °C for 30 min. The patch design artwork is printed on a plain photo paper sheet and transferred onto the cleaned side of the copper lamination by hot press technique. The other copper laminated side is masked by tape. The structure is dipped into a solution of ferric chloride and the solution is stirred slowly until the desired patch design is completely etched. The photographs of the fabricated antenna are shown in figure 15.

The antenna is characterized for its S11 to determine its resonating ability and for its radiation characteristics. All the parameters are measured using Agilent E8362C PNA series VNA in the range 8.2–12.4 GHz frequency range and Antenna Measurement System from Diamond Engineering, USA. Both the simulated and measured plots are shown below.

The radiation measurements are carried out along two orthogonal broadside planes XZ & YZ as shown in the figure 17.

Slight deviation as observed from the simulated and measured curves may be due to fabrication tolerances and modeling limitations in the CST microwave studio owing to the cell restrictions in the version of the software used in the laboratory. A summary of the obtained results is tabulated in table 1.

As seen from table 1, the antenna exhibits a measured gain of 7.34 dB, which is high considering similar single element rectangular patch antenna on standard substrates.
As the antenna is fabricated on the flexible substrate for wearable applications, subsequent study of the effect of bending on the antenna characteristics is performed (figure 20 and 21). Bending is carried by placing the antenna on three semi cylinders (3D printed PLA material) of radii 40 mm, 30 mm and 20 mm. These radii values have been chosen keeping in view the range of radii of a healthy human arm [23]. Two bending configurations—(a) XZ bending & (b) YZ bending, as shown in the figure 19, are employed for performance testing.

The effect on the $S_{11}$ parameters, both measured and simulated are shown in the figure 22 and figure 23 respectively. A good agreement of measured and simulated results can be clearly seen from the plots. The trend of the shift of resonant frequency is opposite in both the cases, i.e. for XZ bending it is towards the lower frequency side while for YZ bending towards the higher frequency side.

The lower frequency shift indicates an increase of electrical patch length, and the shift to higher frequency indicating a decrease in the electrical patch length. A similar trend is reported in [24] also. The $-10$ dB % bandwidth remains consistent with different bending configuration, with a maximum diminution of 2% for the 20 mm XZ bending case. A decrease in the return loss occurs with bending, however, in all the cases it is seen that the resonant frequency notch is below $-20$ dB. Also, the original resonant frequency of 10.05 GHz (i.e. for the flat case) lies within the $-20$ dB bandwidth region for the XZ bending and within the $-10$ dB bandwidth region for the YZ bending.

The effect of bending on the radiation characteristics are plotted in figures 24–27. The simulated and the measured results are plotted separately for better clarity. Both YZ and XZ plane measurements are carried out for XZ and YZ bending.

The XZ plane radiation patterns do not undergo a change in shape, except for a broadening of the pattern in the broadside direction and increase in the back-lobe levels. In the case of YZ plane radiation patterns, the main lobe suffers a deviation, which might be due to the change in the current distribution along the YZ plane and also due to the effect of the microstrip feed line which is lying along the YZ plane.

Gain measurements were also carried out using standard gain horn antennas and have been tabulated in the summary table 2.

The gain and directivity of the bent antennas are less as compared to the flat structure, although it may be noted that bent antennas still exhibit a gain of above 7 dB.

Review article [9] specifies the use of textile materials [25, 26] and polymer-based substrates [27–29] for the development of flexible and wearable antennas. The table 3 depicts the properties reported in the articles.

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Table 1. Antenna characteristics in flat profile (unbent).

|                      | Resonant Frequency (GHz) | $S_{11}$ (dB) | $−10$ dB % Bandwidth | Directivity (dBi) | Gain (dB) |
|----------------------|--------------------------|---------------|----------------------|-------------------|-----------|
| Measured             | 10.05                    | $-31.9$       | 8.0                  | 12.91             | 7.34      |
| Simulated            | 10                       | $-28.9$       | 7.3                  | 9.45              | 7.03      |

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Figure 15. (a) Patch view of the fabricated antenna (left) & (b) ground plane view of the fabricated antenna (right).
Textile material-based substrates have the advantage of low dielectric permittivity and losses while polymer-based substrates are attractive because of their robustness, low wettability, and high flexibility. The silicone-foam substrate developed in the current work have both the advantage of being robust and flexible and also having a
low value of effective dielectric constant due to the presence of foam. The antenna developed on the silicone-foam substrate also exhibits a high gain compared to other reported works [9], the low permittivity of the substrate (as seen from table 3) contributes to higher radiation and unlike other wearable antennas, the patch and ground plane uses only high conducting copper layers.

Figure 19. Bending profiles carried out in the current study (a) YZ bending (left) (b) XZ bending (right).

Figure 20. Illustration of XZ bent antenna (bent on a 3D printed PLA 40 mm semi-cylinder) connected to one port of a VNA for S11 measurements.

Figure 21. Illustration of antenna bent on a 40 mm 3D printed PLA semi-cylinder and mounted on a 360° turntable for radiation pattern and gain measurements.
Figure 22. Variation of $S_{11}$ (measured) with different bending profiles (left) & a magnified image of the adjacent graph for better clarity.

Figure 23. Variation of $S_{11}$ (simulated) with different bending profiles (left) & a magnified image of the adjacent graph for better clarity.

Figure 24. (a) figure denoting the bending configuration of the antenna and the red circle denoting the radiation pattern plane. (b) Variation of the measured radiation pattern of the XZ plane (bottom left) & (c) Variation of the simulated radiation pattern of the XZ plane (bottom right) with varying bending radii in the XZ plane.
Figure 25. (a) figure denoting the bending configuration of the antenna and the red circle denoting the radiation pattern plane. (b) Variation of the measured radiation pattern of the YZ plane (bottom left) & (c) Variation of the simulated radiation pattern of the YZ plane (bottom right) with varying bending radii in the XZ plane.

Figure 26. (a) figure denoting the bending configuration of the antenna and the red circle denoting the radiation pattern plane. (b) Variation of the measured radiation pattern of the XZ plane (bottom left) & (c) Variation of the simulated radiation pattern of the XZ plane (bottom right) with varying bending radii in the YZ plane.
Table 2. Quantitative summary of the antenna characteristics in flat profile (unbent) and bent profiles.

| Profile      | Bending radii (mm) | Resonant frequency (GHz) | $S_{11}$ dB | $-10$ dB % BW | Directivity (dBi) | Gain (dB) | Resonant frequency (GHz) | $S_{11}$ dB | $-10$ dB % BW | Directivity (dBi) | Gain (dB) |
|--------------|--------------------|--------------------------|-------------|---------------|------------------|-----------|--------------------------|-------------|---------------|------------------|-----------|
| Flat         | —                  | 10.05                    | -31.9       | 8             | 12.9             | 7.9       | 10                       | -28.9       | 7.3           | 9.4              | 7.0       |
| XZ bending   | 40                 | 9.99                     | -31.4       | 7.1           | 12.7             | 7.7       | 9.93                     | -35.53      | 7.1           | 8.9              | 6.8       |
|             | 30                 | 10.00                    | -34.17      | 7.1           | 13.1             | 7.8       | 9.86                     | -39.68      | 7             | 8.7              | 6.6       |
|             | 20                 | 10.00                    | -28.65      | 7             | 12.4             | 7.6       | 9.78                     | -23.11      | 6.4           | 8.3              | 6.3       |
| YZ bending   | 40                 | 10.17                    | -25.74      | 6.2           | 13.0             | 7.5       | 10.03                    | -25.17      | 8             | 7.1              | 5.1       |
|             | 30                 | 10.17                    | -23.81      | 6.2           | 12.2             | 7.4       | 10.03                    | -25.17      | 8             | 8.5              | 6.6       |
|             | 20                 | 10.22                    | -22.49      | 5.8           | 12.6             | 7.6       | 10.09                    | -25.81      | 7.6           | 7.7              | 6.0       |
| Reference | Substrate type                      | Substrate properties          | Conductive layer                                        | Realized Gain |
|-----------|------------------------------------|------------------------------|---------------------------------------------------------|---------------|
| [25]      | EVA copolymer                      | $r_e \approx 2.8/3.2; \tan\delta \approx 0.002 @ 1-10 \text{ GHz}$ | Conductive silver paste                                 | 2.39 dB       |
| [26]      | Polyester fabric                   | $r_e \approx 2.3; \tan\delta \approx 0.01 @ 5 \text{ GHz}$           | Conductive silver ink                                  | 3.6 dBi       |
| [27]      | PDMS ceramic composite             | $r_e \approx 6; \tan\delta \approx 0.05 @ 5 \text{ GHz}$           | Conductive fabric $\sigma \approx 10^3-10^5 \text{ S m}^{-1}$ | 1.3 dBi       |
| [28]      | Ferrite-PVA composite              | $r_e \approx 3.5-9; \tan\delta \approx 0.015-0.05 @ 2-6 \text{ GHz}$ | Silver/copper layer deposited by RF sputtering         | 3 dB          |
| [29]      | PDMS                               | $r_e \approx 2.8; \tan\delta \approx 0.01 @ 5 \text{ GHz}$           | ZoFlex+copper $\sigma \approx 10^3-10^5 \text{ S m}^{-1}$ | 6.18 dBi      |
| Current work | Silicone rubber + foam multi-layered substrate | $r_e \approx 2.12; \tan\delta \approx 0.02 @ 10 \text{ GHz}$ | Copper sheet                                           | 7.34 dB       |
5. Conclusion

Low adhesion of silicone to metal has been improved by using foam as an adhesion facilitator to bind with metal. The modified silicone substrate with its advantages of flexibility and water resistance is used to develop a simple patch antenna for wearable technology. The substrate development technique uses simple mechanical interlocking to bind the silicone substrate onto one of the surfaces of the foam and an inexpensive PU binder to adhere the copper sheet to the other surface of the foam. The silicone-foam substrate has a high elongation at break of around 375% and also demonstrates a good adhesion strength between copper layers with the substrate. The low value of permittivity (∼2.12) and loss tangent (∼0.02 at 10 GHz) of the developed substrate along with the use of conducting copper sheets helps in achieving a high gain in antenna designed on it [30]. Bending along two different configuration—along XZ and YZ with bending radii of 40 mm, 30 mm and 20 mm show a marginal shift in the frequency, while the return loss values being still below −20 dB. The directivity and gain values are consistent with bending with a gain of more than 7 dB for all the bending configurations. In the current work, we are able to develop a flexible substrate that is resistant to moisture and adheres strongly with metal making it suitable for the design of wearable antennas. The antenna demonstrates higher gain as compared to similar wearable antennas and is tested successfully for bending performance.

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