A Soft Surface Based Low Profile Wearable Antenna for Biomedical Telemetry

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Abstract—**A soft surface based low profile wearable antenna operating on 5.8 GHz Industrial, Scientific and Medical (ISM) band (5.725-5.875 GHz) is presented for high speed biomedical telemetry. The flexible substrate of Ethylene-Vinyl Acetate (EVA) foam makes the structure water proof, ultra-violet resistant and mechanically stable. First, the basic antenna structure (reference) with inset feeding is designed. Initially, the forward to back power ratio obtained is 14.1 for basic design. The back radiation is further reduced by introducing soft surface around the patch. Use of two different materials as soft surface has been studied and analyzed. The maximum gain of 5.2 dBi and Front to Back Ratio (FTBR) of 25.63 is achieved for the chosen resonant frequency. The absorption of electromagnetic field by the body is reduced by 9.35 % and gain is improved by 23.68/24.40 % with reference to our basic design of antenna without soft surface. The value of Specific Absorption Rate (SAR) is 1.26 W/kg for 10 gm of human body tissue which is within the specified limits. The software simulated and experimented results are presented.**

Index Terms—**Antenna, back radiation, directivity, gain, soft surface, wearable**

I. Introduction

The wearable technology has motivated the researchers to design the flexible and textile antennas for various applications. The geometry of patch antenna is most suitable for its integration with wearable cloths. Some of the applications include monitoring of patient's health from the remote place, operations in battle field, independent communication network in fire-fiting, tracking and monitoring of children and aged people etc. Presently the use of Body Area Network (BAN) has opened new oportunities for biomedical telemetry. The spectrums for body area network such as 402-405 MHz Medical Implant Communication Services (MICS), 2.45 GHz, 5.2 GHz and 5.8 GHz Industrial, Scientific and Medical (ISM) have been considered for medical applications [1]. The communication between on-body and off-body devices requires a radiation pattern which is in broadside direction away from the body. Many configurations have been reported to provide such radiation pattern for biomedical telemetry including cavity supported slot antenna [2], [3] and artificially designed magnetic conductor based antenna [4]. Antenna performance degrades due to mismatch if the thickness of substrate is less than $\lambda_0/6$ (λ_0 is free space wavelength). Various methods of matching the impedance of antenna have been reported such as printed transition [5], air via perforated dielectric slab [6], ridged Surface Integrated Waveguide (SIW) [7] and shorting vias [8].

The radiation parameters of a wearable antenna are dependent on body loading and the radiation from antenna also affects the body tissues. It is required that the back radiation toward body should be controlled and must be within the limits prescribed by International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Federal Communications Commission (FCC) [9], [10]. Various methods/approaches have been reported for reducing the back radiation and improving the specific absorption rate. High impedance surface on flat and curved surfaces have the same reflection phase and help in reducing the back radiation [11]. The hard and soft material in [12] showed that polarization remains constant after reflection from these surfaces. A metalized reflector has been used to reduce back radiation towards body [13]. Reference [14] showed that soft surfaces can reduce mutual coupling from one antenna to other. The shorted microstrip has been used to form electromagnetic band gap (EBG) structure for reduction of size and the dense location of metallic structures provides high degree of decoupling between patches [15]. The use of soft surface showed a reduction of coupling between two planar inverted-F antennas operating on two different frequencies simultaneously in [16]. A large metallic reflector has been used to stop back radiation and improvement of Specific Absorption Rate (SAR) in multilayered structure [17]. Reference [18] demonstrated that by increasing the ground plane size of antenna by 5% of its original value, 35% reduction in SAR is achieved. Artificial Magnetic Conductor (AMC) has been used for reduction of SAR for Wireless Body Area Network (WBAN) applications [19]. A leather substrate based antenna for dual band operation for wearable applications was designed in which a conductive fiber sheet is used to provide isolation between body and antenna for reduction of SAR [20]. Reference [21] proposed a circularly polarized antenna with Polydimethylsiloxane (PDMS) substrate and graphene as radiator. This antenna operates at ISM band with low SAR. A Quarter Mode Substrate Integrated Waveguide (QMSIW) design was proposed for unidirectional radiation with low SAR in [22]. The effects

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of body on performance of antenna have been studied in [23] and [24]. It is demonstrated that how size of antenna is reduced and same antenna starts resonating on two bands from single band by using EBG structure [25]. A High Impedance Surface (HIS) of flexible material integrated with antenna was placed between antenna and body for reducing the SAR in [26]. Reference [27] proposed a flexible metamaterial structure for reduction of SAR. The use of periodic reflecting surfaces as Frequency Selective Surface (FSS) and HIS was shown for reduction of SAR in [28].

In this paper, a soft surface based wearable antenna with very simple design is proposed. This work is mainly aimed at reducing the back radiation towards body while ensuring the antenna structure to be low profile. It is shown that SAR value of a basic antenna (reference) can be reduced by introducing the soft surface. The study on the effects of two soft surface materials on antenna parameters is carried out. The antenna is also tested for body loading conditions. The shorting vias along with inset feed provide proper tuning of the resonant frequency. Therefore the frequency of antenna can be changed just by changing the location of the vias without changing any other dimension. The soft surfaces are used for reducing the back radiation to make this antenna suitable for body-centric communication. An improvement of 81.77 % in front to back ratio is achieved in this design.

II. STRUCTURAL DESIGN

The structure of proposed design is depicted in Fig. 1. The following equations are used for claculating the geometrical dimensions of antenna [29]. The parametric analysis by iterative method is used in simulation to optimize the design parameters for desired results.

$$W = \frac{c}{2f_o\sqrt{(\varepsilon_r+1)/2}} \tag{1}$$

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{1+12(h/W)}\right) \tag{2}$$

$$L = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 0.824h\left[\frac{(\varepsilon_{eff}+0.3)(W/h+0.264)}{(\varepsilon_{eff}-0.258)(W/h+0.8)}\right] \tag{3}$$

where W is width of antenna, L is length of antenna, ε_r is relative permittivity of substrate, ε_{eff} is effective permittivity, h is thickness of the substrate, f_o is resonant frequency and c is velocity of light.

The ground plane size is 60 mm × 56 mm ×0.05 mm. The substrate material is ethylene-vinyl acetate (EVA) foam with relative permittivity ε_r =1.2, loss tangent δ =0.02 and physical dimensions of 60 mm × 56 mm × 1.65 mm. The radiating element consists of copper tape of size 24.64 mm × 21.67 mm × 0.05 mm. The size of slot is: width W_2 =8 mm and length L_2 =11.67 mm. The width and length of inset feed are: W_3=3.5 mm and L_3=28.15 mm. The gap between feed line and patch in left and right sides is 2.25 mm.

The equivalent electrical circuit of the antenna is shown in Fig. 1 (c) with calculated component values. The calculated values satisfy the resonant frequency. The parameters of equivalent circuits are calculated as:

$$Z_{11} = R + jX_L, \quad R = Z_o\left(\frac{1+S_{11}}{1-S_{11}}\right), \quad X_L = \omega L \tag{4}$$

where Z_{11} is impedance at input terminal, R is resistive value of impedance, S_{11} is reflection parameter at input terminal, ω is resonant frequency, L is inductance, X_L is inductive reactance. X_L will be equal to X_c at resonance.

Soft surfaces are added to basic antenna structure for reduction of back radiation as shown in Fig. 1 (d). The width of outer ring of soft surface W_4=4 mm and that of inner ring W_5=3 mm. The shorting vias are used on both rings and patch as shown in geometry. The gap between both the rings of soft surface (g_1) and that between inner ring of soft surface and patch (g_2) is 1 mm. The lateral and bottom views are shown in Fig. 1 (e) and Fig. 1 (f) respectively. The detailed dimensions of structure are given in Table I. The fabricated antenna is illustrated in Fig. 2.

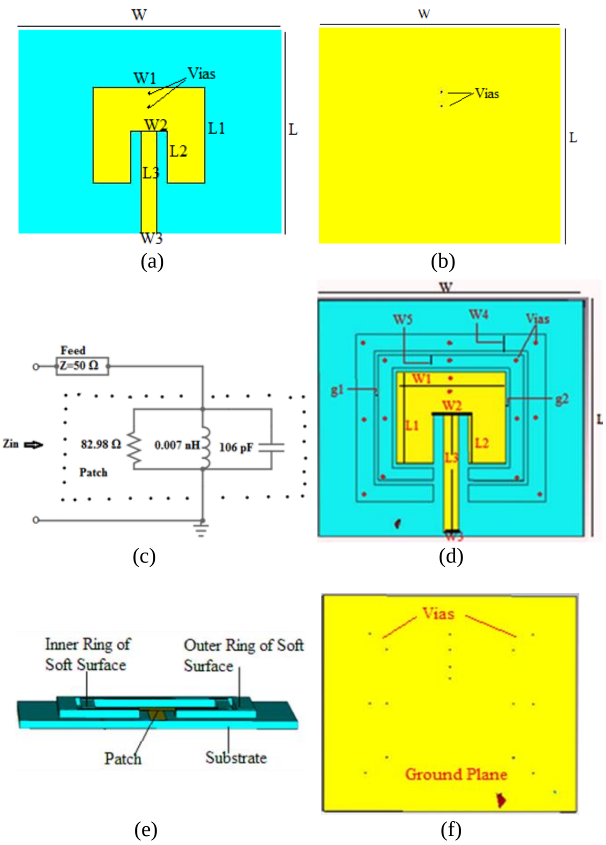
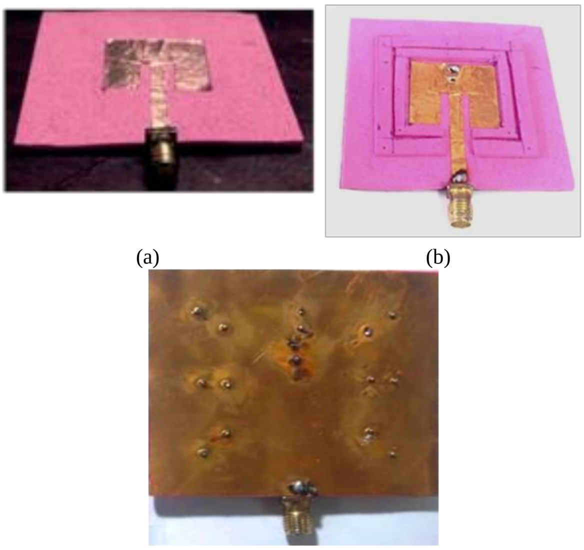


Fig. 1. Antenna structure: (a) top view of basic antenna, (b) bottom view of basic antenna, (c) equivalent electrical circuit of antenna, (d) top view of soft surface based antenna, (e) side view of soft surface based antenna, and (f) bottom view of soft surface based antenna.

TABLE I: ANTENNA DIMENSIONS

Structure	Length (mm)	Width (mm)	Thickness (mm)
Ground Plane	L=56	W=60	0.05
Substrate	L=56	W=60	1.65
Patch	L_1=21.33	W_1=24.64	0.05
Patch slot	L_2=11.67	W_2=8	0.05
Feed	L_3=28.15	W_3=3.5	0.05
Outer Ring of Soft surface	140.62	W_4=4	1.65
Inner Ring of Soft Surface	78.28	W5=3	1.65



(a) (b)

(c)

Fig. 2. Fabricated antenna: (a) top view without soft surface, (b) top view with soft surface, and (c) bottom view with soft surface.

III. Structural Analysis

The antenna structure is simulated and optimized using CST MW studio. The conductive layer of thickness 0.05 mm with EVA foam substrate of thickness 1.65 mm make the structure low profile and flexible. First the basic antenna was designed with inset feed and simulated at 5.8 GHz (ISM band) frequency. It was observed that even after best optimization of feed, antenna was not resonating exactly at 5.8 GHz but having slight deviation within the band (5.725 GHz to 5.875 GHz). Then two shorting vias (Diameter=0.3 mm) were introduced on the patch as shown in Fig. 1 (a). By optimization of location and spacing between the vias, the fine tuning of input impedance was done and antenna was tuned exactly to 5.8 GHz. A human body equivalent model of length L =98 mm, width W =94 mm and height H =70 mm with thicknesses of layers as 60 mm, 7 mm and 3 mm for muscle, fat and skin respectively has been considered for SAR calculation. The soft surfaces in the form of two rectangular rings surrounding the patch are realized. The substrate material EVA foam with same thickness as substrate (1.65mm) and copper with same thickness as patch (0.05mm) have been used to make the soft surfaces in this design. The shorting vias on both the rings of soft surface are formed and their locations have been optimized.

IV. Results and Discussion

A. Antenna without Soft Surface

Firstly, the basic antenna structure (reference) with EVA foam substrate is developed and simulated. The return loss (RL) is –32 dB in off-body condition and it is –30 dB in on-body condition (at 5.8 GHz) when antenna is placed on body equivalent model. The comparison of S_{11} in Fig. 3 shows that the resonant frequency of antenna is stable in body loading condition also. The bandwidth of 125.3 MHz is achieved at center frequency of 5.8 GHz. The far field directivity is 8.93 dBi in broadside direction. The side lobe level (SLL) is −12.1 dB and half power beam width (HPBW) is 45.6 degree. The front to back ratio (FTBR) is 14.1.

For biomedical telemetry, the antenna is to be worn on body by the patient. The data received from on-body sensors for various parameters of patient is transmitted to an off-body device. Therefore it is necessary to evaluate the SAR value to maintain it within the limits specified by the ICNIRP and FCC [9], [10]. The calculation of Specific absorption rate (SAR) value has been done by keeping the antenna very close to human body equivalent model. The simulated value of SAR is 1.39 W/kg for 10 gm of tissue when antenna is kept 2 mm away from the body.

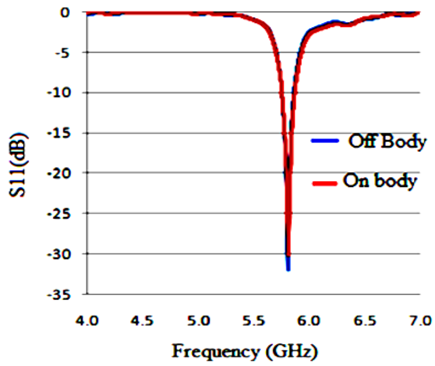


Fig. 3. S_{11} in on-body and off-body conditions (without soft surface).

B. Antenna with Soft Surface Design

The specific absorption rate value is 1.39 W/kg for 10 gm of tissue in normal structure and is well within the limits. However, an attempt is made to have further improvement in SAR. For this purpose, the soft surfaces are introduced on the substrate of antenna [14], [16]. First, only one ring of the soft surface was designed and it was observed that reduction in back radiation is very less. Then second ring was introduced and a good reduction in back radiation was obtained. When third ring was introduced, there was no significant change in the results. Thus we have used only two rings in this design. Here, two different types of materials have been studied as soft surfaces.

1) Copper Soft Surface

Firstly, two rectangular rings of width 4 mm and 3 mm are put around the patch. The gap between both the rings and between inner ring and patch is optimized as 01 mm. Here, the strips of copper work as soft surfaces and their thickness are same as patch (0.05 mm) above the substrate level. These rings along with various vias perturb the surface waves on top surface of antenna and contribute to reduction of back radiation toward the body. The radiation parameters are: return loss RL = –21.14, band width BW =192 MHz, half power beam width HPBW =51.5 degree, side lobe level SLL = –9.6 dB, Maximum gain= 5.20 dBi, far field directivity = 9.4 dBi and front to back ratio is 20.30. The antenna was tested for SAR value by putting the soft surface based structure on body model of the same size and with the same spacing. The SAR value in this case is reduced to 1.29 W/kg for 10 gm of tissue.

2) EVA Foam Soft Surface

Secondly, the soft surfaces are now designed with EVA foam having the same thickness as substrate (1.65 mm). The widths, spacing and lengths of strips are kept constant like copper strips. The ring of soft surface around the patch provides anisotropic surface impedance to reduce the radiation from the edges of the antenna which helps in reduction of back radiation. The material of Ethylene-Vinyl Acetate (EVA) foam is flexible and robust to the environmental conditions. Its mechanical properties will not be affected due to bending as this material is crack resistant. It is very low cost and easy to fabricate. The simulated and measured values of S_{11} and gain at resonant frequency are shown in Fig. 4. The return loss of –14.5 dB and gain of 5.17 dB is obtained. The comparison of radiation patterns in Fig. 5 shows the reduction of back radiation with soft surface. The cubic body model and simulated SAR calculations are displayed in Fig. 6 and dimensions of body model with electrical parameters are presented in Table II.

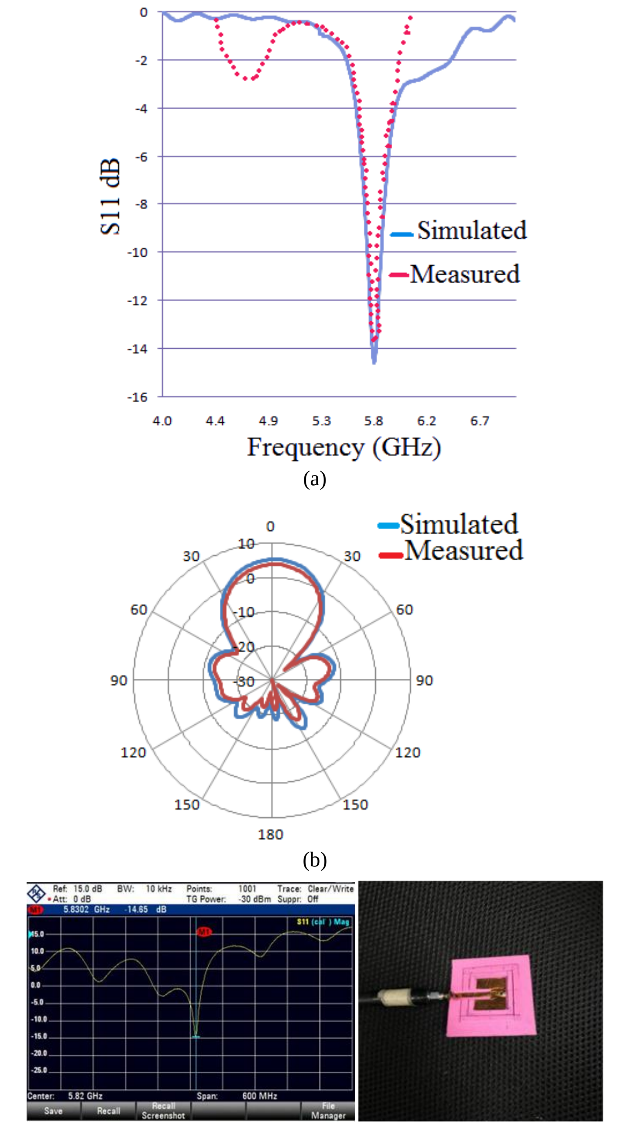


Fig. 4. S_{11} and gain (with EVA soft surface): (a) simulated and measured return loss, (b) simulated and measured gain, (c) measurement of S_{11}, and (d) antenna under test.

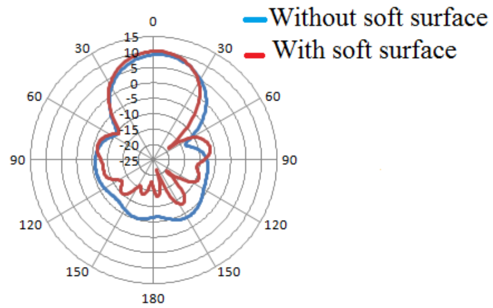


Fig. 5. Radiation pattern with and without soft surface.

TABLE II: DIMENSIONS/ELECTRICAL PARAMETERS OF EQUIVALENT HUMAN BODY MODEL

Dimensions/Electrical Parameters	Skin	Fat	Muscle
Length (L) (mm)	98	98	98
Width (W) (mm)	94	94	94
Height (H) (mm)	3	7	60
Relative permittivity	35	4.9	48.5
Conductivity (S/m)	3.7	0.2	4.9
Mass Density (kg/m³)	1090	930	1050

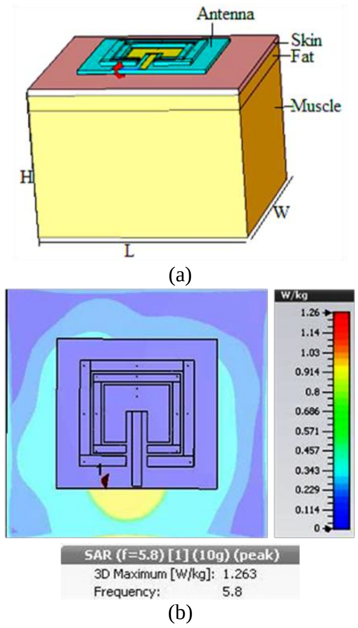


Fig. 6. SAR calculation: (a) cubic body equivalent model and (b) simulated SAR.

It is observed that the specific absorption rate is reduced to 1.26 W/kg for 10 gm of human body tissue. The far field directivity is increased to 10.4 dBi in broadside direction. The SLL is further reduced to –16.5 dB and HPBW is 42.4 degree. Now the front–back ratio is further improved to 25.63. The back radiation is calculated as:

$$\text{Back Radiation (\%)} = \frac{\int_0^{2\pi}\int_{\pi/2}^{\pi} |E|^2 \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi}\int_0^{\pi} |E|^2 \sin\theta \, d\theta \, d\phi} \times 100 \quad (5)$$

The back radiation is reduced when soft surface (EVA foam) is introduced on the antenna. Thus due to presence of two rings of soft surface, the far field directivity is increased by 16.46%. The comparison of radiation parameters obtained with both type of soft surfaces is presented in Table III. It is observed that antenna parameters: directivity, front to back ratio, side lobe level and SAR are having significant improvement in their levels and are better with soft surface of EVA foam than the copper. However, the bandwidth is more if copper is used as soft surface.

TABLE III: COMPARISON OF ANTENNA PARAMETERS WITH/WITHOUT SOFT SURFACES

Antenna Parameters	Without soft surface	Material of soft surface	
		Copper	EVA foam
Return loss (dB)	–30	–21.14	–14.5
Gain(dB)	4.18	5.20	5.17
SLL (dB)	–12.1	–9.6	–16.5
Directivity (dB)	8.93	9.4	10.4
Front to back Ratio	14.1	20.30	25.63
SAR W/kg (10 g tissue)	1.39	1.29	1.26
Bandwidth (MHz)	125.3	192	125.3

The structure transparent 3-D radiation pattern in broadside direction is given in Fig. 7. The radiation shows that back radiation towards body is very less and maximum directivity of 10.4 dB is obtained in perpendicular direction from the body (θ=0°).

The Table IV compares proposed work with some of the reported work in the area of mobile and wireless body area network (WBAN) applications. The comparison is done in terms of antenna performance parameters like size, type of structure, frequency of operation, amount of reduction in back radiation/coupling, technique, gain, and bandwidth. In comparison to proposed work, other reported works have complex structure with use of additional components like back reflector, array of AMC/EBG/FSS surfaces etc. resulting in larger size. In this work the antenna is optimized for 5.8 GHz ISM band with reduced back radiation while keeping the design simple, small in size and low profile (planar structure). As per the size and simplicity in design, the reduction in back radiation, gain and improvement in front to back ratio is better in this work.

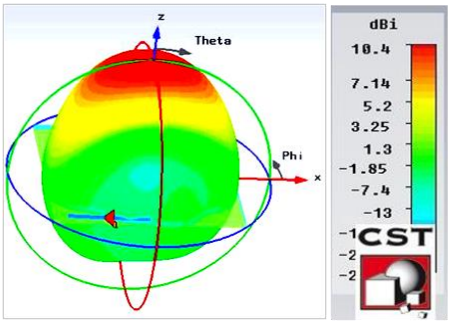


Fig. 7. 3-D Broadside radiation pattern.

TABLE IV: COMPARISON WITH PREVIOUS WORK

Ref.	Size of Antenna (mm³)	Frequency (GHz)	Type of structure	Technique	Reduction in coupling/ back radiation	Gain (dBi)	Bandwidth (%)	Application
[13]	70×67×3.2	3.75-4.58	Double layers of substrate	Metalized reflector at the back of antenna	15% in back radiation	7.78	18.1	C band application
[14]	165×135×1.47	1.92	2 Antennas	Strips of soft surface between the antennas	5 dB in coupling	--	4	Wirelss communication
[15]	69.4×18×1.524	8.8	2 Antennas	EBG structure between the antennas	10 dB in coupling	--	--	Wirelss communication
[16]	133×21.5×11.5	1.6/2.5	Double layers of substrate	Strips of soft surface between the antennas	6 dB in coupling	4	--	Wirelss communication
[17]	80×61×4.51	3.1-10.6	Stack layered patch with three metalized and two substrate layers	Metalized reflector at the back of antenna	--	4-5	UWB	Wireless body area network
[19]	88×86×0.1	3.5/5.8	Double layer with slotted CPW ground	4×4 AMC Array reflector	15 dB in back radiation	5.1-7	14	Wireless body area networks
[20]	42×30×3.6	2.45/5.2/5.8	Double layer Layer	Conductive fiber isolator between body and antenna	--	3.31	10.2/23.1	Wireless body area network
[21]	27×23×2.57	5.8	Double layer	3×3 AMC Array reflector	--	5-6	6.8	Wireless body area network
[22]	76×48×21	3.5/ 4.9/ 5.4/ 5.8	Single layer in cabinet	QMSIW	--	4.4-5.7	3.2	Wireless body area network
[23]	30×12×5	2.4/5.8	Single layer	Liquid crystal EGAIn radiator	--	4.7	3.3	Wireless body area network
[24]	40×15×0.8	2.4/5.8	Single layer with reflector	Two ground planes	--	3.8-4.2	4/2.5	Wireless body area network
[25]	40.7×27.3×1.27	2.6/3.29	Double layer with superstrate	4×6 unit cell EBG reflector	--	4.9	3.8	5G mobile communication
[26]	45x45x2.4	2.45	Double layer	3×3 unit cell HIS array reflector	10.8 dB in back radiation	7.47	--	Wireless body area networks
[27]	30x25x0.05	2.45/5.8	Double layer	3×3 MS array reflector	70 % in SAR	5.2/7.7	4.4/7.1	Wireless body area networks
[28]	92x50x7.5	2.1	Double layer	FSS/HIS reflector	65/85 % in SAR	--	--	Mobile communication
This work	60×56×1.65	5.8	Single layer patch without any back reflector and array	Rectangular soft surface rings	11.53 dB in back radiation resulting in 81.77 % improvement in FBR	5.20	3.3	Wireless body area networks

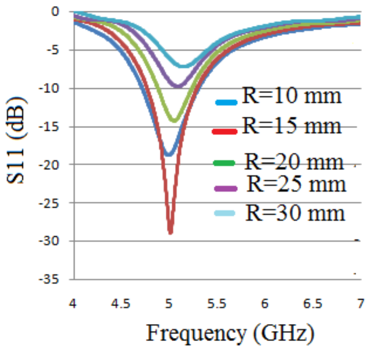


Fig. 8. S_{11} at different curvatures.

C. Bending Effects

The antenna structure is tested to be conformal so that it can be placed on curved places of body like wrist, arm, ankle etc. The antenna was placed on cylindrical structure mimicking the air gap and skin layer of body. The simulation was done on cylinders with different radii. The results of different S11 on different radii are shown in fig. 8. It is observed that there is a drift in the resonant frequency to higher side due to bending and return loss becomes poor as the radius (R) of cylinder increases.

V. Conclusion

This work proposes low cost and low profile antenna working in ISM band. The concept of reduction in back radiation by using the soft surface is well demonstrated. The use of EVA foam as soft surface provides better reduction in back radiation than copper. But the bandwidth is more when copper is used as soft surface. Therefore, it is always a trade-off between the parameters as per the required application. The experimented results are in acceptable limit with simulated results. The antenna parameters like bandwidth, gain and front to back ratio on resonant frequency are suitable for body centric communication. This antenna can be worn on back, chest or torso by stitching with clothes. The physical properties of substrate material, low value of SAR and broadside radiation pattern away from the body makes it good candidate for data communication in health care domain.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Devendra Kumar is pursuing doctoral research under the supervision of Dhirendra Mathur. Both the authors are in agreement with the final version.

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