CHAPTER VI

ACHIEVEMENTS, LIMITATIONS AND FUTURE DIRECTIONS

The thesis focuses on development of an antenna, which is intended to be used in wearable technology and which can withstand bending without compromise on the performance. Thus, the impetus of the work was on having a WBAN antenna which is sufficiently flexible with strong adherence to its conducting layers with minimum effect in its resonating frequency when under bent condition, exhibits stability in terms of its impedance bandwidth, gain and directivity when in proximity of a human body and emanates reduced back radiation for good isolation from the human body along with compliant SAR values.

Low adhesion of flexible silicone substrate to copper metal has been improved by using foam as an adhesion facilitator. The modified silicone substrate with its advantages of flexibility and water resistance is used to develop a patch antenna for wearable technology. A simple mechanical interlocking technique is employed to bind the silicone substrate onto the surfaces of the foam and an inexpensive PU binder to adhere the copper sheet to the other surface of the foam. The physical and dielectric properties of the novel substrate developed is highlighted in Table 6.1. 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 [1]. Bending along two orthogonal configurations viz., XZ and YZ with bending radii of 40mm, 30mm and 20mm showed a marginal shift in the frequency, while the return loss values being still below -20 dB. The directivity and gain values are also consistent with bending with a gain of more than 7 dBi for all the bending configurations.

Table 6.1 Physical and dielectric properties obtained from the study

Substrate Material	*Tensile strength*	*Adhesion strength w.r.t copper tape*	*Water absorbance*	*Dielectric constant*	*Loss tangent*
Silicone-polyurethane foam (open cell)	*375 % elongation at break*	*275 % elongation at break (peel strength)*	*<0.02 % for 72-hour immersion time*	*8.2 -12.4 GHz*	
				2.08-2.20	*0.01-0.06*

The Table 6.2 depicts the parallelism to other wearable antenna in the framework mentioned in the review article [2].

Table 6.2 Comparison of reported literature on flexible and wearable antennas

Reference	*Substrate type*	*Substrate properties*	*Conductive layer*	*Flexible/water resistant*	*Realized Gain (dBi)*
[3]	EVA copolymer	$\epsilon_r \approx 2.8/3.2$; $\tan\delta \approx 0.002$ @ 1-10 GHz	Conductive silver paste	Yes/no	2.39
[4]	Polyester fabric	$\epsilon_r \approx 2.3$; $\tan\delta \approx 0.01$ @ 5 GHz	Conductive silver ink	Yes/yes	3.6
[5]	PDMS ceramic composite	$\epsilon_r \approx 6$; $\tan\delta \approx 0.05$ @ 5 GHz	Conductive fabric $\sigma \approx 10^3$-10^5 S/m	Yes/yes	1.3
[6]	Ferrite-PVA composite	$\epsilon_r \approx 3.5$-9; $\tan\delta \approx 0.015$-0.05 @ 2-6 GHz	Silver/copper layer deposited by RF sputtering	Yes/yes	3
[7]	PDMS	$\epsilon_r \approx 2.8$; $\tan\delta \approx 0.01$ @ 5 GHz	Zoflex + copper $\sigma \approx 10^3$-10^5 S/m	Yes/yes	6.18
Current work	Silicone rubber + foam multi-layered substrate	$\epsilon_r \approx 2.12$; $\tan\delta \approx 0.02$ @ 10 GHz	Copper sheet	Yes/yes	7.34

Shift in resonant frequency with bending has been counter-veiled with self-frequency compensation technique that does not require any external component or device to induce the real time variation. The technique has been realized through two effects – (1) change in effective dielectric constant achieved by injecting dielectric fluids into grooves incorporated in the antenna substrate and (2) change in the cross-sectional shape of the grooves due to bending. These two supplementary effects have been quantified and an optimized antenna structure has been designed to achieve frequency compensation along two orthogonal bending planes. A frequency compensation of ≈ 20 MHz (XZ-bending) and ≈ 60 MHz (YZ bending) has been achieved using this technique as compared to the 'ungrooved' version. The antennas exhibited measured gain value of more than 6.7 dBi along with a consistent -10 dB impedance bandwidth for all the bending configurations.

Chapter III analysed the effect of human body on the performance of the developed WBAN flexible antenna. The performance study is carried out through realistic hand/wrist EM phantoms developed using 50% graphite-silicone composites. The microwave dielectric characterizations of developed composite divulge their agreement with properties of a human hand in the band 9.7-10.3 GHz. The simulation studies have been conducted using a six-layered wrist phantom. The antenna is tested with varying hand radii (40mm, 30mm and 20mm) as well as along two orthogonal bending planes. A review of the properties of the state-of-the-art WBAN antennas tested on human phantom/body is listed in Table 6.3.

Table 6.3 State of the art of antennas tested on human body/phantoms

Ref.	***Type of phantom***	***Dimension of phantom***	***Bending orientation***	***Maximum detuning w.r.t free space in %***	***Peak gain (dBi)***	***-10dB % Bandwidth***
[8]	*Numerical arm/actual arm (for S_{11} only)*	*Fixed thickness*	*Single bending plane*	*2.5*	*-*	*3.27*
[9]	*Wrist numerical phantom*	*Fixed thickness*	*Flat*	*8.3*	*2.1*	*6.2*
[10]	*Numerical muscle/actual body (for S_{11} only)*	*Fixed thickness*	*Single bending plane*	*1*	*6.88*	*4.88*
[11]	*Numerical body – chest/arm*	*Fixed thickness/two postures*	*Single bending plane*	*6.6*	*4.7*	*12.2*
[12]	*Numerical wrist/actual arm (for S_{11} only)*	*Fixed thickness*	*Single bending plane*	*8*	*1.67*	*20*
[13]	*Numerical phantom/Muscle gel phantom*	*Fixed thickness*	*Flat*	*1.4*	*0.5*	*3*
Current Work	*Wrist numerical phantom/solid hand phantom*	*Varying hand radii – 40mm 30mm and 20 mm*	*Two orthogonal planes*	*<1.5*	*>6.6*	*Max - 11.7 Min - 5.7*

The antenna exhibited a detuning of ~1.5 % for maximum bending, in our case it is 20mm, with respect to antenna over free space. The -10 dB impedance bandwidth varied in the range from 5.7% to 11.7%, which is within the working bandwidth for maximum detuning. The gain and directivity values are ≥ 6.6 dBi and 8.9 dBi respectively for all the bending configurations on the phantom.

A lossy shield based on Expanded Graphite (EG) is developed and demonstrated for reduction in back radiation of antenna and penetration of E-fields inside a human wrist phantom in Chapter V. WBAN antenna with two topologies backed by the EG shield is tested in direct contact with the phantoms of varying radii (40mm, 30mm and 20mm) along two orthogonal bending planes for its resonating and radiation characteristics. Both simulated and experimental results revealed marginal variation in the -10 dB bandwidth for the EG shield backed antenna as compared to without the EG shield. The SAR of all the configuration is below the ICNIRP compliance standard of 4 W/kg (10 g limb average) and a maximum reduction of 5.3 % along with decrease in SAR exposure depth is achieved using the EG shield. Experimental verification of reduction in back radiations is realized through the Front-to-Back Ratio (FBR) values and an average increase in FBR by a maximum of 76% was demonstrated by the EG backed antenna. The developed shield is easy to fabricate and can be conveniently attached to any antenna system to reduce the coupling to a human body. Additionally, the low mass density of the EG shield (1.82 gm/cc) has a trivial effect on the weight of the EG backed antenna as shown in Table 6.4. Moreover, inclusion of the EG shield and the spacing layer to the WBAN antenna system increases its thickness by just 1.25 mm and thus maintaining the compactness. The measured characteristics of the EG shield backed antenna for Topology I i.e., XZ bending and Topology II i.e., YZ bending are summarized in Table 6.4. The range of the values shown in the parameters is the variation due to bending over different wrist sizes.

Table 6.4 Performance parameters of the developed WBAN antenna with EG shield

Antenna profile	Dimension and Weight (antenna + shield)	RF parameter values (range) on human wrist (bending radii range – 40mm to 20mm)					
		Resonant frequency	Impedance bandwidth (-10 dB) %	Directivity (dBi)	Gain (dBi)	SAR (simulated) 10g average (W/kg)	Front-to-Back Ratio (dB)
Topology I	40x40x3.25 mm^3 4.23 g	9.89-9.86 GHz (S_{11} : -27 to -19 dB)	11.0-9.4	7.6-6.7	7.6-6.7	2.73-1.96	26-22
Topology II	40x40x3.25 mm^3 4.34 g	10.12-10.30 GHz (S_{11} : -26 to -30 dB)	11.1-10.9	7.1-6.8	7.1-6.8	2.6-2.72	31-12

A photographical abstract of the developed antennas in the current study is illustrated in Figure 6.1.

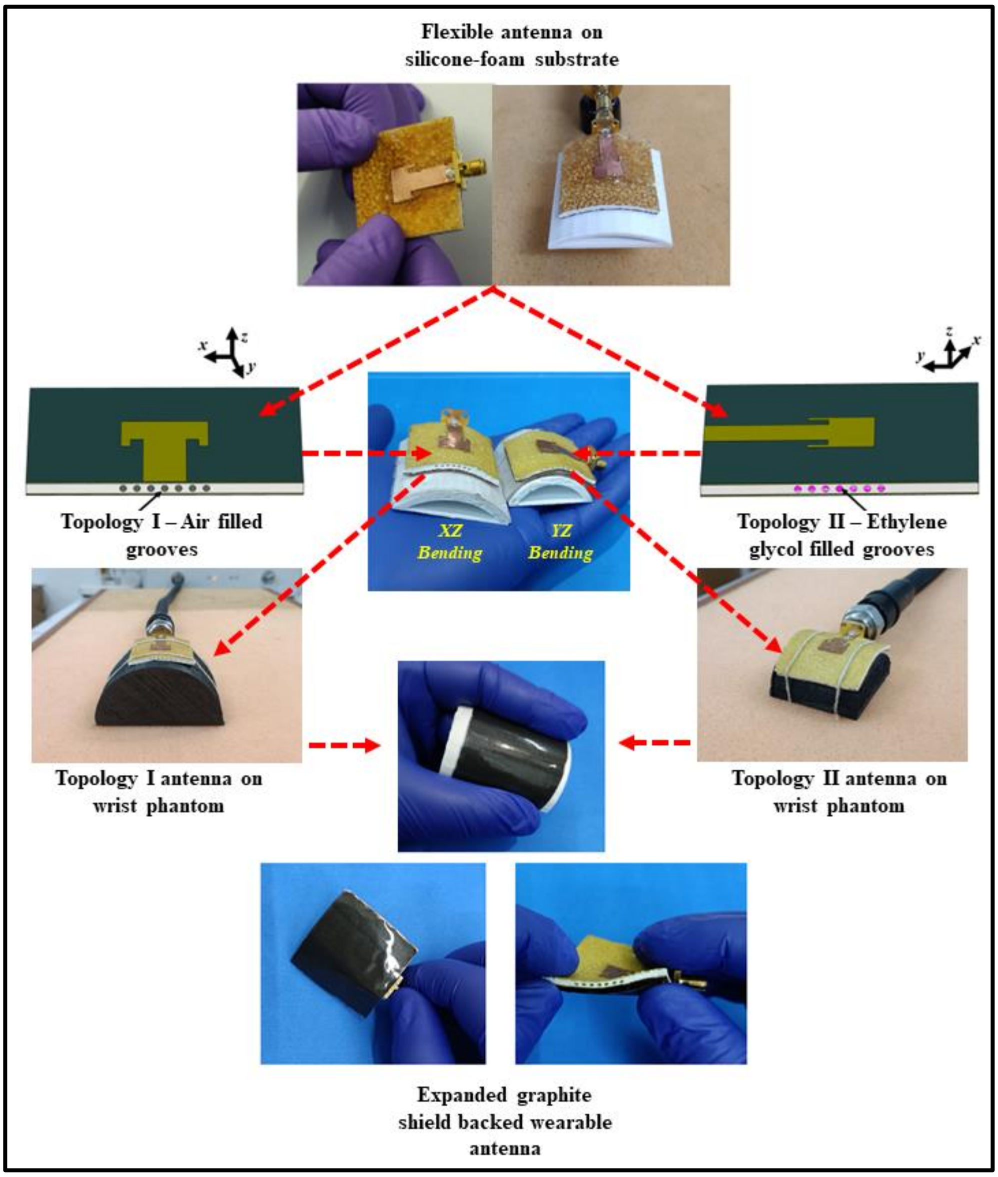

Figure 6.1 Photographical abstract of the antennas developed in the study

Highlights of the present work

- Silicone-foam substrate is synthesized that is flexible, water resistant, exhibits low permittivity and loss in X-band regime. A technique based on mechanical interlocking is developed for strong adherence of copper with the substrate making it suitable for the design of wearable antennas exhibiting gain ~ 7.0 dBi.
- A technique of self-compensating nature is demonstrated to mitigate the detuning effects of bending which is sustainable without the requirement of any external aid. A minimum frequency compensation of ~35-50% is exhibited by the self-compensating antennas.
- The self-compensating antennas divulged stable performance over wrist phantom of three different sizes and for two orthogonal bending planes signifying the suitability of the antenna to be worn over the human wrist/hand.
- Expanded graphite based shield demonstrated reduction in back radiations of the wearable antenna along with SAR compliance. The shield post integration to the antenna structure has hardly any detrimental effect on the antenna performance and hence exterminating the requirement of modification of the radiating elements.

The EG shield backed wearable antenna acts as a stand-alone prototype which is a suitable candidate for WBAN applications in the X-band regime especially wherein design considerations such as compactness, conformability, comfortability, and crucial performance parameters such as impedance bandwidth, radiation gain and low SAR are a feature of interest in addition to being sufficiently versatile to be worn by individuals with different form factor.

Limitations

Body worn antennas undergo bending as well as stretching. However, the current work is limited to bending study owing to the intrinsic nature of copper which is not suitable for stretching applications.

In actual practice, a wearable antenna would require to endure multiple bending cycles, which has not been considered in the present work. Moreover, the recovery time of the antenna post bending is also another important aspect that can be evaluated.

The current work is limited to a linearly polarized simple patch antenna. Polarization independent broadband antennas would be desirable for certain wearable applications and thereby requiring complex patch designs which have not been considered in the present work.

Moreover, the compensation technique developed, requires two antenna topologies for the two orthogonal bending planes. A single integrated structure would be preferable in some scenarios.

Future directions

The wearable antenna developed in the current work, has been tested in the X-band regime and as an impending course of work, this study can be extended to 5G and other futuristic bands.

The adhesion between silicone-foam and copper has been improved in the study using a cost-effective technique. Copper metal has high conductivity although alike other metals it is prone to bending and stretching fatigue. Research on non-metallic conductors with the same order of conductivity as metals can be accentuated along with emphasis on other factors such as good adhesion strength to polymers and high stretchability and flexibility.

The detuning effect of bending has been addressed with two antenna topologies with self-compensating mechanism for two corresponding orthogonal bending planes. It would be a challenging study, if the two topologies be integrated into a single structure and studied as a wearable antenna.

Homogenous phantom was developed and antennas were studied over it. Realization of heterogenous multi-layer phantoms closely imitating the human arm/hand can be considered, in future, and can be used for testing the wearable antennas.

Novel dielectric lossy conducting shields based on expanded graphite were employed for reduction in back lobes. It would be an interesting future study, to amalgamate thin layers of distinct lossy materials which can further increase absorption thereby augmenting the isolation of the wearable antenna from the human body.

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