Progress In Electromagnetics Research M, Vol. 62, 167–174, 2017

Design and Analysis of Wideband Monopole Antennas for Flexible/Wearable Wireless Device Applications

B. N. Balarami Reddy, Sandeep Kumar P., T. Rama Rao*, Nishesh Tiwari, and M. Balachary

Abstract—Compact wideband flexible monopole antennas are designed and analyzed for its performance for Body Centric Wireless Communications (BCWC). Two antennas with identical radiators on different substrates are designed and fabricated on polyamide and teslin paper substrates, deploying a modified rectangle-shaped radiator. With the aid of modifications in the radiating plane and defecting the ground plane, the polyamide based antenna is designed to operate between 1.8 and 13.3 GHz, and teslin paper based antenna is designed to operate between 1.45 and 13.4 GHz to cover the wireless communication technology frequencies and ultra-wideband range for various wireless applications. The reflection coefficient characteristics of the fabricated antennas on free space and on various sites of the body are measured and match reasonably well with the simulated reflection coefficient characteristics. The specific absorption rate (SAR) analysis is also carried out by placing the antennas on tissue layered model.

1. INTRODUCTION

In recent past, the emphasis and demand on wearable technology has amplified several folds around the globe. This marvelous technology will continue to dominate in the years to come. The goal of wearable technology is to create expedient, portable access to information in real-time in all walks of life and in all types of information formats. Sensors communicate with off-body systems, by means of antennas which are the key source of electromagnetic (EM) radiations. They function in an environment at proximity to the body, and hence they are subject to technical and compatibility constraints. The heterogeneous body tissues, with high loss and permittivity, impact the performance of a transceiver operating close to it. Wearable antenna designs are affected by numerous parameters and necessitate the need for flexible and multi-functional antennas. The field of wearable antennas is a multidisciplinary one that combines electromagnetics, material science and bio-electronics. Wearable antennas are important for applications related to health care, sports monitoring and firefighter tracking, etc. [1] utilizing Wireless Body Area Networks (WBAN). Wearable wireless devices (WWD) primarily focus in frequency bands below 3 GHz and at ultra-wideband (UWB) [2].

Antenna geometries such as rectangle, triangle, circle, ellipse, polygon and fused polygon have been proposed for printed monopole antennas [3–5]. Planar monopole antenna is a substitute for conical and cylindrical structures, and was first reported by Meinke and Gundlach in 1968 [6]. Wang and Arslan [7] have designed a monopole antenna for wearable applications. Polyester with $\epsilon_r = 3.2$ is a substrate for antenna, and polydimethylsiloxane (PDMS) with $\epsilon_r = 2.3$–2.8 is used for artificial magnetic conductor (AMC). The bandwidth is from 2.8 to 13.8 GHz. The antenna gain is reported as 10 dBi at 6 GHz. In [8], Phan et al. have designed a patch antenna for WLAN applications. E4D paper with $\epsilon_r = 3.184$ is the substrate for antenna, and the bandwidth is 2.2–10 GHz. Antenna gain is reported as 0.92 dB

Received 21 September 2017, Accepted 10 November 2017, Scheduled 21 November 2017
* Corresponding author: Thipparaju Rama Rao (ramaraotr@gmail.com).
The authors are with the Department of ECE, SRM University, Chennai, India.

at 2.45 GHz and 0.93 dB at 5.5 GHz. In [9], the researchers have designed a spiral type dual-polarized antenna for implantable neural recording systems. Polyimide with $\epsilon_r = 3.5$ is taken as the antenna substrate. The antenna bandwidth is 2–11 GHz. In [10], researchers have designed a planar windmill type antenna equipped with AMC for off-body communication applications. Flexible Panasonic R-F770 with $\epsilon_r = 3.2$ is used as the antenna substrate and flexible Ethylene-vinyl acetate (EVA) foam with $\epsilon_r = 1.17$ as interlayer. Antenna peak gain with AMC is 8 dB, and front to back ratio is 15 dB. In [11], Hong et al. have designed a transparent and flexible monopole antenna for wearable glasses for Bluetooth and Wi-Fi applications. Polyimide with $\epsilon_r = 3.5$ is chosen as the substrate. Antenna gain is 4.1 dB at 2.45 GHz. In [12], Chen et al. have designed a textile patch antenna using snap on buttons for mobile communication, medical diagnosis and military applications. Cuming Microwave C-Foam PF-4 with $\epsilon_r = 1.06$ is the antenna substrate, and a gain of 8 dBic at 5 GHz is reported.

In this paper, two compact same sized antennas with identical radiators (by the inspiration of the shape of the radiator [7]) on polyamide and teslin paper substrates are designed and fabricated. Both antennas, with dimensions of 50×40 mm, are designed to operate between 1.8 and 13.3 GHz, and between 1.4 and 13.4 GHz, respectively. Wideband is achieved by increasing the electrical path in the course of etching out the edges at the corners of the rectangular radiator, introducing a slot in the ground, and tapering the ground plane. Next section deals with the design aspects of wide band wearable monopole antennas, followed by results and discussions. The last section concludes the research manuscript.

2. ANTENNA DESIGN

The wearable antennas are designed on a polyamide flexible substrate with a dielectric constant of 4.3 and loss tangent of 0.002, and a teslin paper with a dielectric constant of 2.23 and loss tangent of 0.014. The thicknesses of the polyamide and teslin paper are 0.8 mm and 0.712 mm, respectively. By etching out the edges at the corners of a rectangular radiator, introducing a slot in the ground and tapering the ground plane, wideband is obtained. Antenna schematics and their dimensions are shown in Fig. 1.

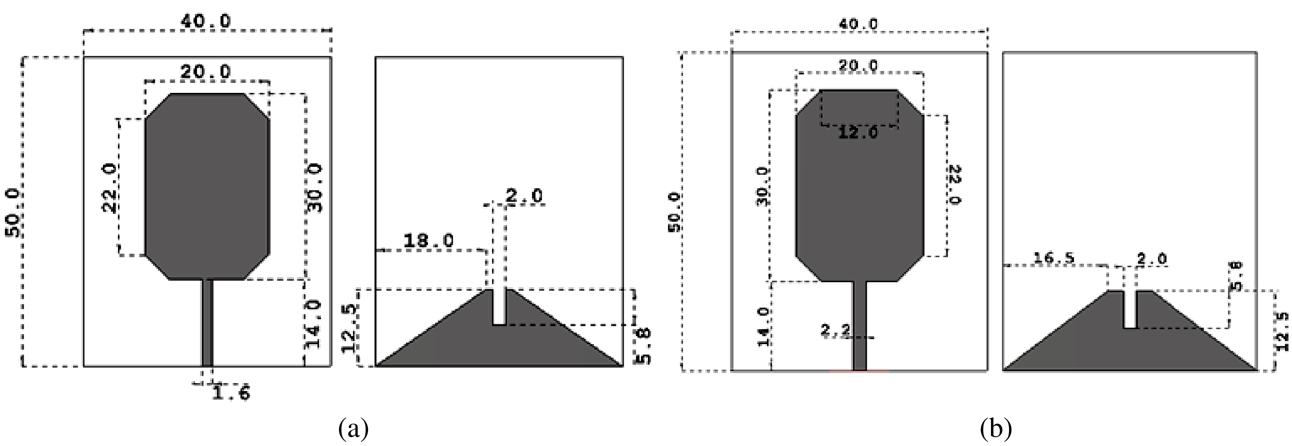
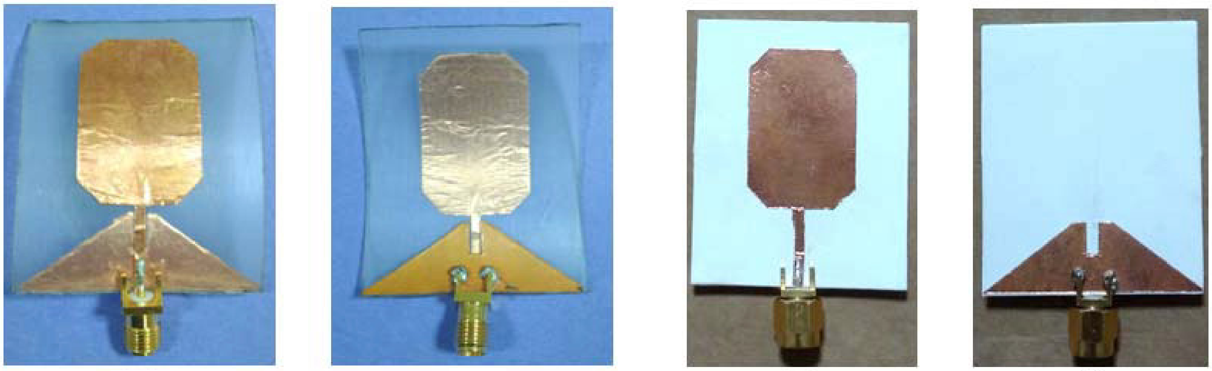


Figure 1. Dimensions of the proposed antenna, (a) polyamide, (b) teslin paper (all values are in mm).

3. RESULTS AND DISCUSSIONS

The proposed antennas on flexible substrates are fabricated, and their reflection coefficient characteristics are measured by Anritsu MS2073C vector network analyzer (VNA). Fig. 2 shows the pictures of the fabricated antennas (i) Polyamide antenna and (ii) Teslin paper antenna. The simulated and measured reflection coefficient characteristics of the proposed antennas are depicted in Fig. 3 and Fig. 4. As seen in Fig. 3, the polyamide-based antenna bandwidth ($|S_{11}| \geq 10$ dB) ranges from 2 to 13.1 GHz in simulation, and the corresponding measured reflection coefficient bandwidth is from 1.85 to 13.3 GHz. The teslin paper based antenna bandwidth ($|S_{11}| \geq 10$ dB) ranges from 1.6 to 15.8 GHz in



(a) (b) (c) (d)

Figure 2. Front and rear views of fabricated antennas, (i) polyamide antenna, (a) front view, (b) rear view, (ii) Teslin paper antenna, (c) front view, (d) rear view.

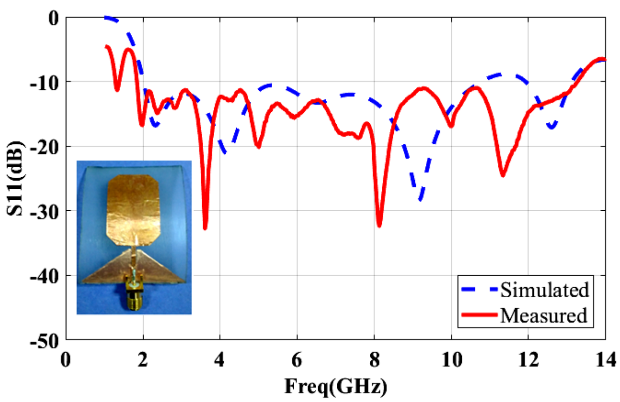


Figure 3. Simulated and measured reflection coefficient characteristics of polyamide antenna.

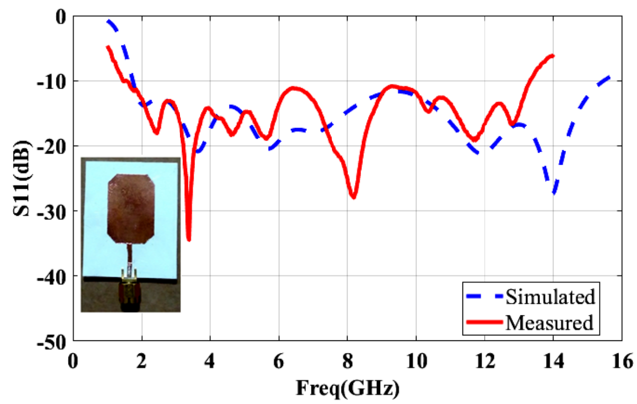
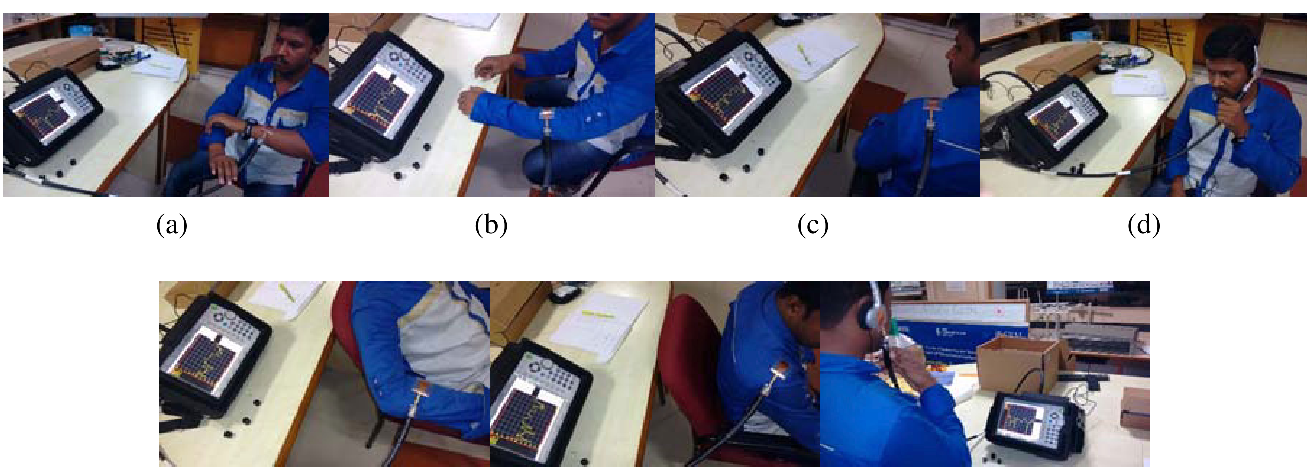


Figure 4. Simulated and measured reflection coefficient characteristics of teslin paper antenna.



(a) (b) (c) (d)

(e) (f) (g)

Figure 5. Measurement setup for Antenna placed in different locations, (i) on left-side, (a) wrist, (b) hand, (c) shoulder, (d) head phone, (ii) on the right-side of the body, (e) hand, (f) shoulder, (g) head phone.

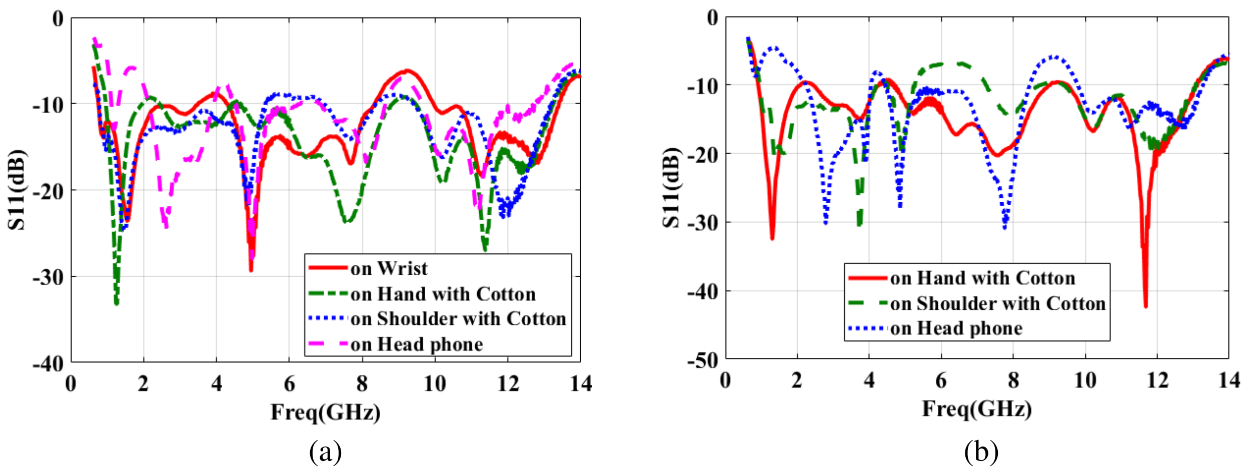


Figure 6. Measured reflection coefficient characteristics of polyamide antenna placed on different locations on the body, (a) left-side, (b) right-side.

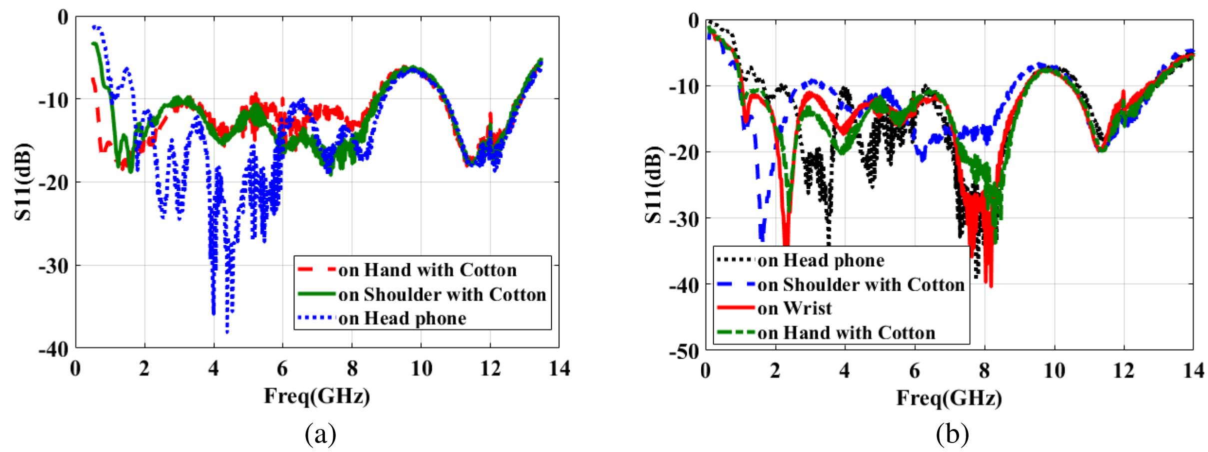


Figure 7. Measured reflection coefficient characteristics of teslin paper antenna placed on different locations in (a) left-side, (b) right-side of the body.

simulation, and the corresponding measured reflection coefficient bandwidth is from 1.45 to 13.4 GHz. The tolerable discrepancies in the measured results correspond to the minute fabrication errors, the limitations of the SMA connector used, and the miniaturized size of the ground plane compared to the measurement cable which completely modifies the currents distribution [13].

For the proposed flexible antennas to be used in wearable applications, the antennas should be tested on body for reflection coefficient characteristics, and the SAR values must be within the acceptable limit. Further, the reflection coefficient characteristics of the proposed flexible antennas are measured for both the antennas, by placing the antenna in different locations on the body as shown in Fig. 5 and plotted in Fig. 6 and Fig. 7. It is seen that antenna bandwidth remains almost constant with a small shift in the lower cutoff frequency due to the influence of the body. The proposed antennas exhibit an extremely low susceptibility to performance dilapidation due to bending in terms of impedance mismatch, shift in resonant frequency and bandwidth. It is also noted that the variations in the reflection coefficient characteristics are due to the placement of the antennas over the curvature of the various parts of the body, change in the effective dielectric constant and effect of the smaller ground plane used in both of the proposed antennas.

Figure 8 shows the measured radiation pattern of the proposed antennas. It is evident that the proposed monopole antennas radiate omnidirectionally over the H-plane. The gain plots for the

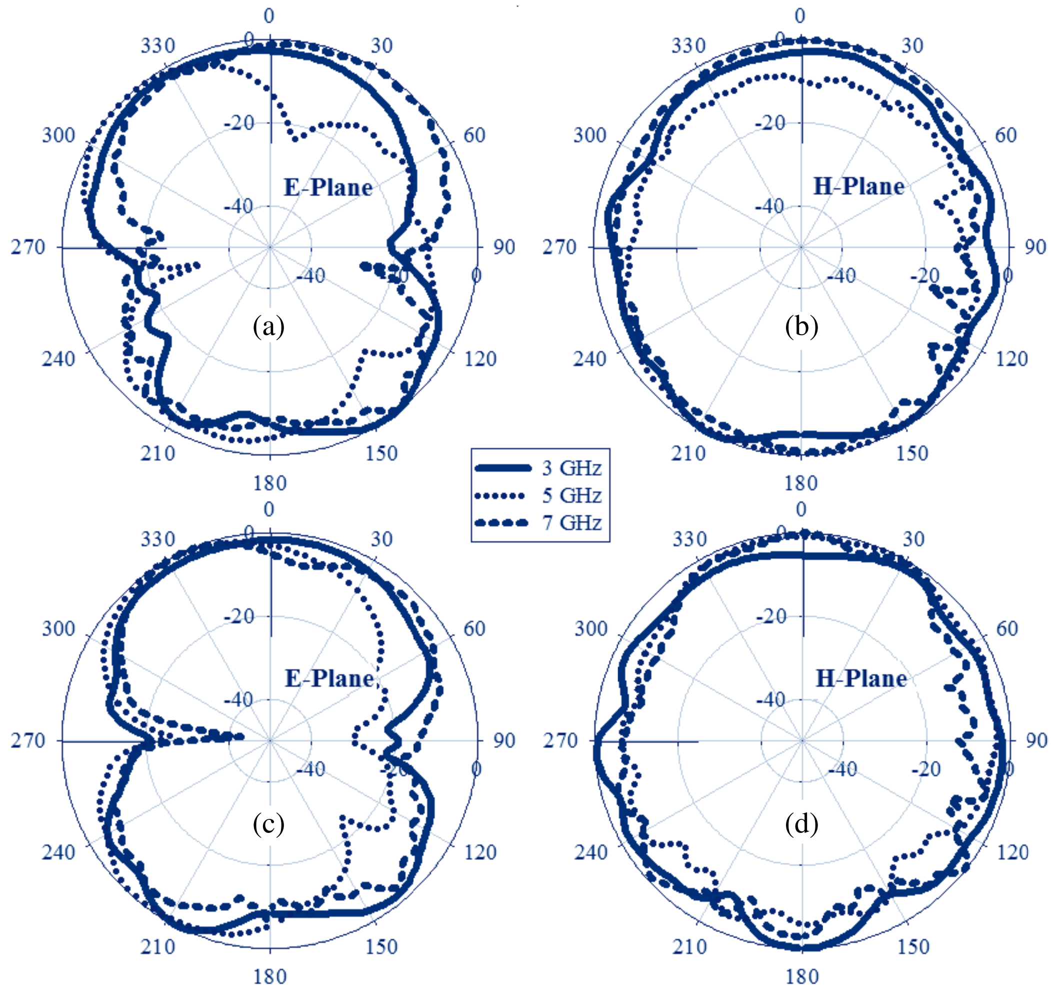


Figure 8. Measured radiation patterns of polyamide antenna, (a) E-plane (yz plane), (b) H-plane (xz-plane) and teslin paper antenna, (c) E-plane (yz plane), (d) H-plane (xz-plane).

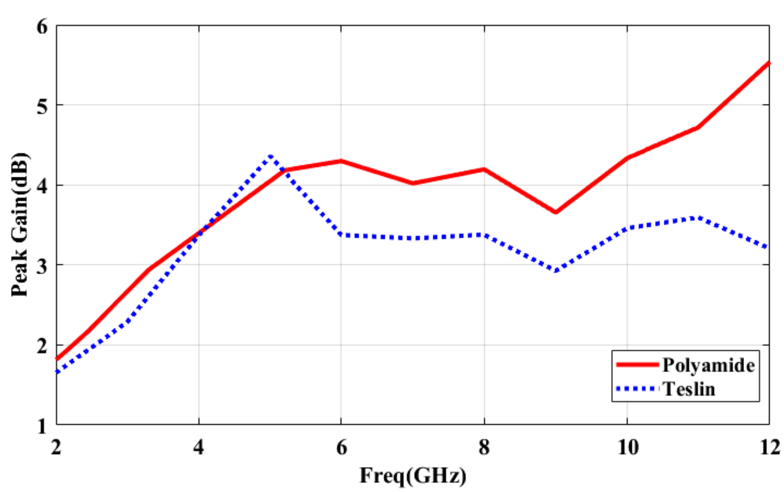


Figure 9. Gain versus frequency of the proposed antennas.

antennas are depicted in Fig. 9. The simulated peak gain of the polyamide based antenna is 5.53 dBi, and that of the teslin paper antenna is 4.35 dBi over the operating bandwidth. The reduction in gain of the teslin paper antenna is accounted by the variation in dielectric constant and loss tangent values used for the fabrication. The average efficiencies of the polyamide and teslin paper antennas are 96% and 83%, respectively. The lower efficiency of the teslin paper antenna is due to the lossy nature of the substrate used (loss tangent of 0.014).

Apart from reflection coefficient characteristics, the SAR values must be within the acceptable limit for the proposed flexible antennas to be used for BCWC. In [14, 15], different techniques such as infrared thermography and in [16], simple mathematical computations have been carried out to estimate the SAR of a wearable antenna. In general, monopole antennas have high SAR values due to the partial ground plane. Thus in order to reduce the SAR values, a ground plane of size 80 × 80 mm is placed

Table 1. Tissue model chosen for SAR calculations.

Tissue	**Frequency = 1–15 GHz**		
	Dielectric constant (ϵ_r)	**Loss tangent (tanδ)**	**Thickness (mm)**
Skin	40–26.2	0.347–0.636	2
Fat	5.42–4.25	0.158–0.264	10
Muscle	54.3–36.1	0.28–0.596	20

Table 2. SAR values of the proposed antennas.

Proposed Antenna Type	**Frequency (GHz)**	**SAR(W/Kg) for 1 g tissue model**	
		Without the ground plane placement	**With ground plane placement at 10 mm from the proposed monopole antennas**
Polyamide based antenna	3	3.43	0.1
	7	2.08	0.52
	10	1.41	0.41
Teslin Paper based antenna	3	3.75	0.09
	7	2.50	0.37
	10	2.69	0.75

Table 3. Comparison with existing literature.

Reference Antenna	**Measured Impedance BW (GHz)**	**Peak gain (dBi)**	**Size (mm)**
[1]	3.1–10.6	7.7	97 × 88
[3]	1.6–11.2	4.65	50 × 50
[8]	2.2–10	0.93	45 × 28
[10]	5.7–11	8	46 × 46
[19]	2.4, 3.51, 4.69	2.1	80 × 80
[20]	4–10.6	4	38 × 22
[21]	3.1–10.6	3.99	60 × 60
Proposed Polyamide based antenna	1.85–13.3	5.53	50 × 40
Proposed Teslin based antenna	1.45–13.4	4.4	50 × 40

at a distance of 10 mm from the proposed antenna. The three-layer human body model details for SAR calculation are shown in Table 1 as in [16]. The SAR values for the proposed antennas at 3, 7 and 10 GHz are reported in Table 2. The SAR values over the frequencies are very much within the FCC limits of 1.6 W/Kg value for a 1 g tissue model [17]. Further, if the proposed monopole antennas are to be placed in a near proximity to humans (without the usage of ground plane), then electronic band gap structures can be used for the SAR reduction as in [18]. The comparisons of the proposed antennas with existing antennas in terms of bandwidth, peak gain and size are shown in Table 3. The features of the proposed antennas are low cost, low surface profile, and they finds main application in the flexible electronics and over conformal surfaces. With respect to teslin paper based antenna, it is environmentally friendly and is a good candidature for low-cost "green" electronics.

4. CONCLUSION

This research work presents the design and analysis of two compact monopole antennas for wearable wireless applications. The designed antennas are of low profile, simple configuration and cost effective. From the results it is evident that the proposed antennas provide high bandwidth at -10 dB of ($|S_{11}|$) from 1.85 to 13.3 GHz for polyamide based antenna and for teslin paper antenna from 1.45 to 13.4 GHz. Measured reflection coefficients ($|S_{11}|$) of the designed antennas agree reasonably well with the simulation results. The on-body reflection coefficient characteristics of the fabricated antennas are measured, and it is noted that the bandwidth of the antennas remains almost the same as that in free space. From the SAR analysis for the proposed antennas, acceptable SAR values are reported for 1 g tissue standards. These antennas can support wearable wireless applications with acceptable SAR values and are attractive for flexible/wearable wireless devices using ultra-wideband frequencies.

ACKNOWLEDGMENT

The authors are thankful to the DRDO, Government of India for their assistance in execution of this research work.

REFERENCES

1. Samal, P. B., P. J. Soh, and G. A. E. Vandenbosch, "UWB all-textile antenna with full ground plane for off-body WBAN communications," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 1, Jan. 2014.
2. Abbasi, Q. H., M. U. Rehman, K. Qaraqe, and A. Alomainy, "Advances in body-centric wireless communication: Applications and state-of-the-art," *The Institution of Engineering and Technology (IET)*, London, U.K., Jul. 2016.
3. Dastranj, A., "Optimization of a printed UWB antenna: Application of the invasive weed optimization algorithm in antenna design," *IEEE Antennas and Propagation Magazine*, Vol. 59, No. 1, 48–57, Feb. 2017.
4. Palaniswamy, S. K., Y. P. Selvam, M. G. N. Alsath, M. Kanagasabai, S. Kingsly, and S. Subbaraj, "3-D eight-port ultrawideband antenna array for diversity applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 569–572, 2017, doi:10.1109/LAWP.2016.2590144.
5. Palaniswamy, S., M. Kanagasabai, S. Arun Kumar, M. Alsath, S. Velan, and J. Pakkathillam, "Super wideband printed monopole antenna for ultra wideband applications," *International Journal of Microwave and Wireless Technologies*, Vol. 9, No. 1, 133–141, 2017, doi:10.1017/S1759078715000951.
6. Meinke, H. and F. W. Gundlach, *Taschenbuch der Hochfrequenztechnik*, 531–535, Springer-Verlag, Berlin, New York, 1968.
7. Wang, F. and T. Arslan, "A wearable ultra-wideband monopole antenna with flexible artificial magnetic conductor," *2016 Loughborough Antennas & Propagation Conference (LAPC)*, Nov. 14–15, 2016.

8. Phan, H. P., T. P. Vuong, P. Benech, P. Xavier, P. Borel, and A. Delattre, "Printed flexible wideband microstrip antenna for wireless applications," *International Conference on Advanced Technologies for Communications (ATC)*, 12–14, Oct. 2016.
9. Bahrami, H., S. A. Mirbozorgi, R. Ameli, L. A. Rusch, and B. Gosselin, "Flexible, polarization-diverse UWB antennas for implantable neural recording systems," *IEEE Trans. on Biom. Ckts and Sys.*, Vol. 10, No. 1, 38–48, 2016.
10. Liu, X. Y., Y. H. Di, H. Liu, Z. T. Wu, and M. M. Tentzeris, "A planar Windmill-like broadband antenna equipped with artificial magnetic conductor for off-body communications," *IEEE Antennas and Wireless Propag. Letters*, Vol. 15, 64–67, 2016.
11. Hong, S., S. H. Kang, and C. W. Jung, "Transparent and flexible antenna for wearable glasses applications," *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 7, 2797–2804, 2016.
12. Chen, S. J., T. Kaufmann, D. C. Ranasinghe, and C. Fumeaux, "A modular textile antenna design using snap-on buttons for wearable applications," *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 3, 894–903, 2016.
13. Chen, Z. N., T. S. P. See, and X. Qing, "Small printed ultrawideband antenna with reduced ground plane effect," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 2, 383–388, Feb. 2007.
14. Varshini, K. and T. R. Rao, "Investigations on SAR and thermal effects of a body wearable microstrip antenna," *Wireless Personal Communications*, Springer, 2017, doi.10.1007/s11277-017-4059-9.
15. Karthik, V. and T. Rama Rao, "Estimation of specific absorption rate using infrared thermography for the biocompatibility of wearable wireless devices," *Progress In Electromagnetics Research M*, Vol. 56, 101–109, 2017.
16. Gabriel, C., "Compilation of the dielectric properties of body tissues at RF and microwave frequencies," Report N.AL/OE-TR-1996-0037, Occupational and environmental health directorate, Radiofrequency Radiation Division, Brooks Air Force Base, Texas (USA), Jun. 1996.
17. Means, D. L. and K. W. Chan, "Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields, supplement C edition 01-01 to OET bulletin 65 edition 97-01," Office of Engineering and Technology, FCC, Washington, D.C. 20554, Jun. 2001.
18. Velan, S., E. F. Sundarsingh, M. Kanagasabai, A. K. Sarma, C. Raviteja, S. Ramprabhu, and J. K. Pakkathillam, "Dual-band EBG integrated monopole antenna deploying fractal geometry for wearable applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 249–252, 2015.
19. Mandal, B. and S. K. Parui, "Wearable tri-band SIW based antenna on leather substrate," *Electronics Letters*, Vol. 51, No. 20, 1563–1564, Oct. 1, 2015.
20. Zahran, S. R., M. A. Abdalla, and A. Gaafar, "How bending affects a flexible UWB antenna," 1–6, www.mwrf.com, 2017.
21. Jose, A. and S. J. Kappan, "High gain coplanar feed ultra wide band wearable antenna using artificial magnetic conductors," *5th International Conf. on Advances in Computing and Comm.*, Sep. 2–4, 2015.