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DEVELOPMENT OF TEXTILE ANTENNAS FOR BODY WEARABLE APPLICATIONS AND INVESTIGATIONS ON THEIR PERFORMANCE UNDER BENT CONDITIONS

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Abstract—Utilization of wearable textile materials for the development of microstrip antenna segment has been rapid due to the recent miniaturization of wireless devices. A wearable antenna is meant to be a part of the clothing used for communication purposes, which includes tracking and navigation, mobile computing and public safety. This paper describes design and development of four rectangular patch antennas employing different varieties of cotton and polyester clothing for on-body wireless communications in the 2.45 GHz WLAN band. The impedance and radiation characteristics are determined experimentally when the antennas are kept in flat position. The performance deterioration of a wearable antenna is analyzed under bent conditions too to check compatibility with wearable applications. Results demonstrate the suitability of these patch antennas for on-body wireless communications.

1. INTRODUCTION

Portable electronic devices have become part and parcel of everyday human life. Modern mobile phones are quite often carried throughout the day and they allow not just telephone calls alone but also provide internet access, multimedia, personal digital assistant and GPS functionality. This form of 'always on' and constantly connected status is a step towards the pervasive computing paradigm [1]. In future, a person is likely to carry a range of devices and sensors, including medical sensors which constantly communicate with each other and the outside world. It is of paramount importance to provide

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this functionality as unobtrusively as possible. A key technology to achieve this goal is wearable electronics and antennas. Because of its almost global availability, the 2.45 GHz ISM unlicensed band is utilized for the development of wearable antennas. For the convenience of the user, wearable antennas need to be hidden and of low profile. This requires a possible integration of these antenna elements within everyday clothing. Microstrip patch is a representative candidate for any wearable application, as it can be made conformal for integration into clothing [2–10].

In line to their previous research work on circular disk antennas [11–13], the authors present the design, development and assessment of flexible rectangular shaped microstrip wearable antennas for Bluetooth applications in this paper. The advantages of rectangular wearable antenna compared to a circular antenna of same design are as follows: (i) Bandwidth of a rectangular wearable antenna is marginally higher due to its larger physical area. (ii) Higher order modes are separated far apart in the case of rectangular patch antenna whereas the circular patch needs a shorting pin at its centre to suppress higher order modes. (iii) Design of a rectangular patch is easy and its electromagnetic simulation takes less time. (iv) Analysis of slots on rectangular patch antenna is easier compared to that on circular patch antenna. Four antennas are considered in this work; antenna 1 makes use of wash cotton (textile material used for manufacturing of Bermuda) fabric as its dielectric material and curtain cotton fabric is used in antenna 2. Polyester and polyester combined cotton (65 : 35) fabric materials are the respective dielectric materials used in antennas 3 and 4. In all four cases, the conducting parts are made up of copper. The theoretical and experimental results on impedance characteristics of these individual wearable antennas are presented when they are kept in flat position. Antennas 1, 2 and 3 are considered for the study of radiation characteristics. However, in the case of on-body environment, it is difficult to keep the wearable antenna flat all the time and it becomes bent quite often due to body movements. The bending may modify the performance characteristics of the antenna as its resonant length gets altered. Hence an experimental study is carried out with at least one of the antennas (antenna 3) to investigate the effects of antenna bending on its performance characteristics like resonant frequency, return loss, impedance bandwidth, gain and radiation patterns. The rest of the paper has been organized as follows: Section 2 explains the steps involved in the antenna design procedure. Section 3 describes the electromagnetic modeling and fabrication of antennas. Both theoretical and experimental results on performance characteristics of flat antennas under investigation are presented in

Section 4. Effects of antenna bending on impedance and radiation characteristics of a wearable antenna are illustrated in Section 5 with supporting measured data. Concluding remarks of this research work are offered at the end of this paper in Section 6.

2. ANTENNA DESIGN PROCEDURE

The geometry of an antenna developed for body wearable applications as shown in Fig. 1, comprises of a thin, conducting rectangular copper patch on an insulating fabric substrate backed by a copper ground plane.The value of dielectric constant of fabric substrate materials is determined experimentally by employing a novel technique (based on resonance method) proposed by the authors in [14]. The design specifications of the four antennas developed are given below in Table 1.

The design of microstrip patch radiator involves the computation of its patch dimensions. The patch width (W) has a minor effect on the resonant frequency (f_r) and it is calculated using the following formula [15].

$$W = c/(2f_r)\sqrt{2/(\epsilon_r + 1)} \tag{1}$$

where c is the velocity of electromagnetic wave and ϵ_r is the relative permittivity of the fabric material. Actually, the microstrip patch lies between air and the dielectric material and thus the electromagnetic

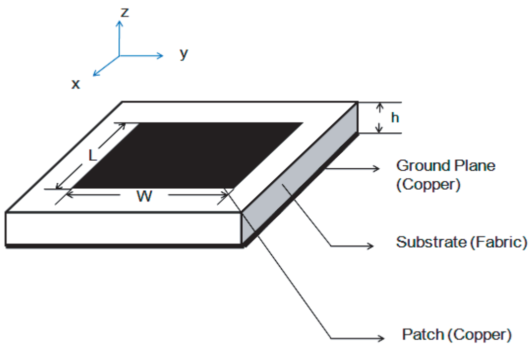


Figure 1. Geometry of a rectangular patch antenna.

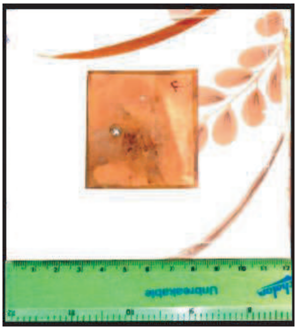


Figure 2. Photograph of fabricated antenna.

Table 1. Design specifications of various antennas developed.

Design parameter	Antenna # 1	Antenna # 2	Antenna # 3	Antenna # 4
Resonant frequency (GHz)	2.45	2.45	2.45	2.45
Substrate dielectric constant	1.51	1.47	1.44	1.48
Substrate thickness (mm)	3.0	3.0	2.85	3.0
Loss tangent of the substrate	0.02	0.02	0.01	0.02
Materials used for ground plane and patch	copper	copper	copper	copper
Insulating fabric material employed	wash cotton	curtain cotton	polyester	polycot

wave sees an effective permittivity (ϵ_{reff}) given by [15],

$$\epsilon_{reff} = \left[\frac{\epsilon_r + 1}{2}\right] + \left[\frac{\epsilon_r - 1}{2}\right]\left[1 + \frac{12h}{w}\right]^{-1/2} \tag{2}$$

where h is the height of the substrate.

The patch length determines the resonant frequency and is a critical parameter in design because of the inherent narrow bandwidth of the patch. The design value for L is given by [15],

$$L = \left[c/(2f_r\sqrt{\epsilon_{reff}})\right] - 2\Delta L \tag{3}$$

where ϵ_{reff} is the effective permittivity. The additional line length ΔL on either ends of the patch length, due to the effect of fringing fields, is given by [15],

$$\Delta L/h = 0.412\left[(\epsilon_{reff} + 0.3)/(\epsilon_{reff} - 0.258)\right]\left[\left(\frac{w}{h} + 0.264\right)\Big/\left(\frac{w}{h} + 0.8\right)\right] \tag{4}$$

The effective patch length L_e is written as

$$L_e = L + 2\Delta L \tag{5}$$

The computed values of the patch dimensions for all the four antennas considered are listed in Table 2.

3. MODELING AND FABRICATION OF ANTENNAS

The modeling of antennas is performed using Method of Moments (MoM) based IE3D simulator [16] from Zeland Software Inc., USA.

Table 2. Designed values of dimensions of various antennas developed.

Name of the antenna	Length (L) in mm	Width (W) in mm
Wash cotton (#1)	46.9	54.65
Curtain cotton (#2)	47.4	55.06
Polyester antenna (#3)	47.9	55.43
Polycot antenna (#4)	47.5	55.20

An infinite ground plane is assumed in the simulation so as to avoid back lobes in the radiation patterns whereas the dimensions of the ground plane in the fabricated antennas are taken as 120 mm × 120 mm. The top signal layer and the bottom ground plane of the antennas are made up of copper sheets having thicknesses of 0.1 mm and 0.5 mm respectively. The patch and ground plane of the antenna are cut using CNC machine so that the accuracy is about 20 microns. As far as the dielectric material is concerned, antenna 1 employs wash cotton fabric whereas antenna 2 makes use of curtain cotton fabric. Polyester and polyester combined cotton (65 : 35) fabrics are the respective dielectric materials employed in antennas 3 and 4. The size of the fabric material in each case of the antenna is equal to that of ground plane. The fabric pieces are stacked and stitched properly to get required thickness. While assembling the antenna elements, the copper sheets are just fixed on the fabric material with tape and due care is taken such that there is no air gap between the fabric material and the conducting parts of the antenna. A snapshot of one of the fabricated antennas is shown in Fig. 2. While modeling the coaxial probe feed to patch, the inner and outer diameters of the probe are taken as 1.3 mm and 4.1 mm respectively. The feed position is optimized to get good matching characteristics (50 ohm impedance) at the center frequency.

4. RESULTS ON PERFORMANCE CHARACTERISTICS OF WEARABLE ANTENNAS WITHOUT BENDING

4.1. Return Loss Characteristics

4.1.1. Simulated and Measured Results

Simulations and measurements are carried out over the frequency range of 2.0 GHz to 3.0 GHz with a frequency step size of 20 MHz for all the four antennas developed. Fig. 3 shows the simulated and measured S_{11} plots of wash cotton Bluetooth antenna (#1). As depicted by the simulation results, this wearable antenna resonates at a frequency of 2.44 GHz and exhibits a −10 dB return loss bandwidth of 108.97 MHz. Fig. 4 corresponds to the simulated and measured return loss characteristics of wearable WLAN antenna employing curtain cotton fabric. Fig. 4 reveals that the simulated values of resonant frequency and impedance bandwidth of curtain cotton antenna are 2.44 GHz and 106.91 MHz respectively. Fig. 5 is the simulated and measured return loss plots obtained with polyester antenna. The theoretical values of resonant frequency and impedance bandwidth of this antenna are 2.44 GHz and 87.31 MHz respectively. The simulated and measured return loss plots are given in Fig. 6 for the case of polycot antenna. The simulated results show that this antenna resonates at 2.43 GHz and yields an impedance bandwidth of 106.05 MHz. The measurements are done using a vector network analyzer (Model #5071 B) from Agilent Technologies. Initially, the network analyzer is calibrated using the 2 port Ecal module [17], bearing model #85092C for an operating frequency ranging from 300 KHz to 9 GHz, which provides excellent accuracy. The fabricated wash cotton antenna (#1) structure measures a resonant frequency of 2.41 GHz and an impedance bandwidth of 148 MHz with a return loss of −15.698 dB at the resonant frequency as shown in Fig. 3. Curtain cotton antenna (#2) resonates at 2.40 GHz (return loss −16.051 dB) and yields an impedance bandwidth of 128 MHz as depicted in Fig. 4. The developed polyester antenna (#3) measures a resonant frequency of 2.43 GHz (return loss −18.002 dB) and an impedance bandwidth of 113 MHz. The measured resonant frequency and impedance bandwidth

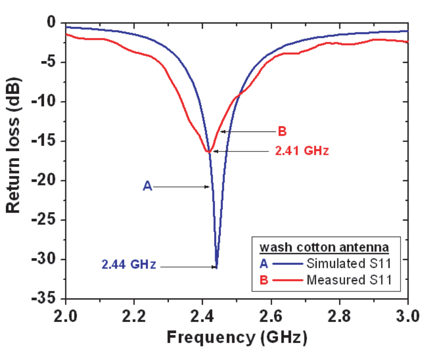


Figure 3. Return loss characteristics of antenna 1 (wash cotton).

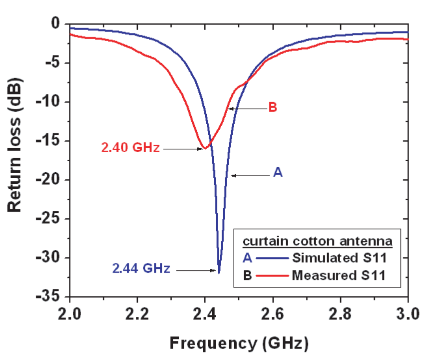


Figure 4. Return loss characteristics of antenna 2 (curtain cotton).

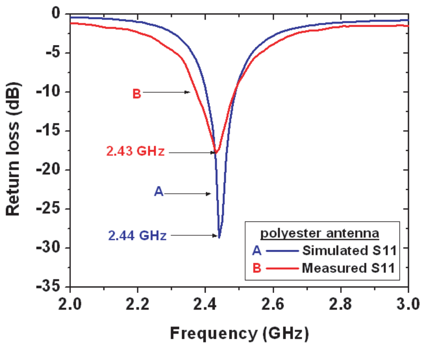


Figure 5. Return loss characteristics of antenna 3 (polyester).

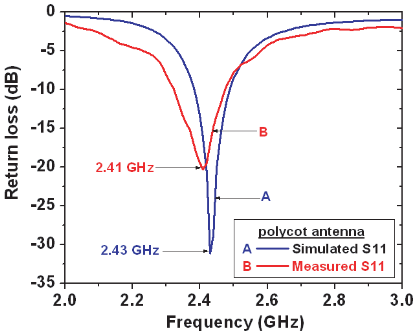


Figure 6. Return loss characteristics of antenna 4 (polycot).

of polycot antenna (#4) are 2.41 GHz and 152 MHz respectively. The return loss is better than −20.284 dB at resonance in this case.

4.1.2. Discussions

The measured results are tabulated in Table 3 along with the corresponding theoretical predictions for all the four antennas studied. Among these antennas, the polyester antenna (#3) shows an excellent agreement between simulated and measured values of resonant frequency, the deviation being 0.41% only. The polycot antenna (#4) exhibits better performance among the remaining three antennas. The measured resonant frequency differs by 0.82% from the corresponding theoretical value in this case. The deviation between simulated and measured values of resonant frequency for the other two antennas namely, wash cotton (#1) and curtain cotton (#2) antennas, is 1.23% and 1.64% respectively. It is observed that for all the four antennas tested, the deviation of measured resonant frequency from its corresponding theoretical value is less than 2%, which is well acceptable for practical applications. As far as the impedance bandwidth is concerned, the measured antennas show superior performance compared to their modelled counterparts. The measured value of impedance bandwidth is greater than the simulated value for all the four cases, which may be due to small changes in the probe inductance offered by the coaxial probe. It is quite interesting to note the bandwidth yielded by all these antennas is greater than the ISM (Industrial, Scientific and Medical) bandwidth of 85 MHz and therefore these antennas can be designed and employed for Bluetooth applications straightaway.

Table 3. Impedance characteristics of various wearable antennas investigated.

Name of the antenna	Resonant frequency (GHz)		Impedance bandwidth (MHz)	
	Simulated	Measured	Simulated	Measured
Wash cotton (#1)	2.44	2.41	108.97	148.0
Curtain cotton (#2)	2.44	2.40	106.91	128.0
Polyester antenna (#3)	2.44	2.43	87.31	113.0
Polycot antenna (#4)	2.43	2.41	106.05	152.0

4.2. Far-field Radiation Pattern Characteristics

4.2.1. Radiation Patterns (Simulated and Measured Results)

To study the radiation characteristics, first three antennas (1–3) are considered. The total far-field radiation patterns of these modeled antennas, in both principal planes of $\phi = 0^\circ$ (x-z plane) and $\phi = 90^\circ$ (y-z plane), are obtained at their corresponding simulated resonant frequencies. The fabricated antennas are subjected to far-field radiation pattern measurements at their corresponding measured resonant frequencies in a rectangular shielded anechoic chamber of dimensions 10.6 m in length, 6.9 m in width and 6 m in height. The chamber has performance in a spherical quiet zone with a diameter of 1.5 m. The centre of the quiet zone is positioned at the centre of the chamber. The transmitting antenna is positioned 3 m above the ground on a fixed positioner at the transmit end wall side. The receiving antenna is positioned in the quiet zone at the same height as the transmitting antenna, on a traversing mechanism with azimuth and roll positioner near the receive end wall. The chamber has the maximum transmission length between the apertures of the antennas as 6.75 m. This indoor far-field measurement system has Agilent make network analyzer (Model # PNA E8362B) along with automated positioner controller with integrated PCU. The instrumentation system is housed in a control room adjacent to the chamber. The chamber is equipped with CCTV facility to visualize the activity inside during antenna pattern measurement. Two snapshots of the pattern measurement set up recorded by the CCTV arrangement housed in the indoor far-field measurement facility are shown in Fig. 7. The simulated and measured far-field patterns of antenna 1 in azimuth plane are shown in Fig. 8(a).

The far-field patterns in the elevation plane of this antenna are shown in Fig. 8(b). Figs. 9(a) and 9(b) correspond to the far-field patterns in azimuth and elevation planes of antenna 2 respectively. Similarly, Figs. 10(a) and 10(b) show the radiation pattern plots pertaining to antenna 3.

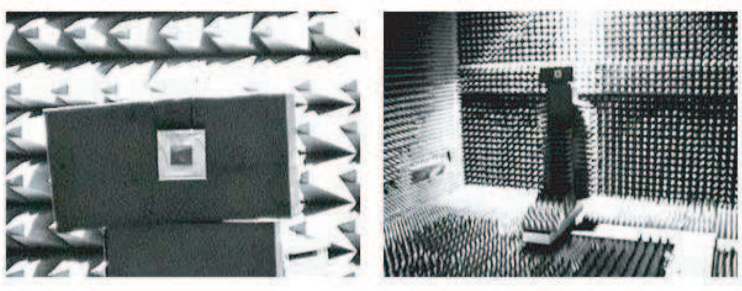


Figure 7. Snapshots of radiation pattern measurement setup inside an anechoic chamber (test antenna is seen mounted at the receiving end of the measurement set up).

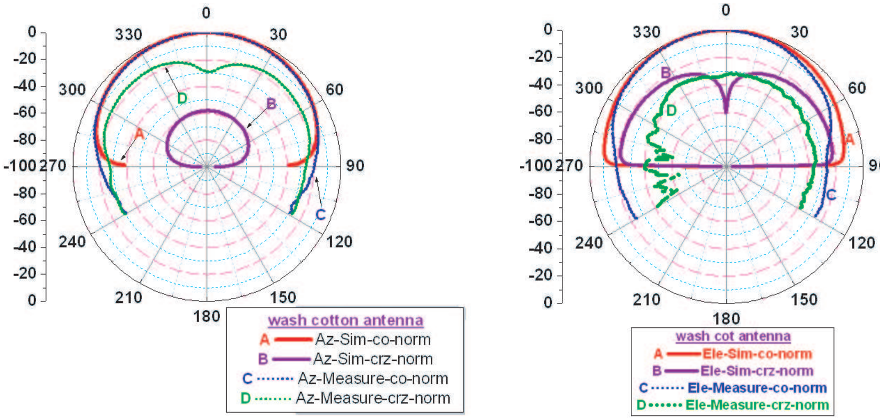
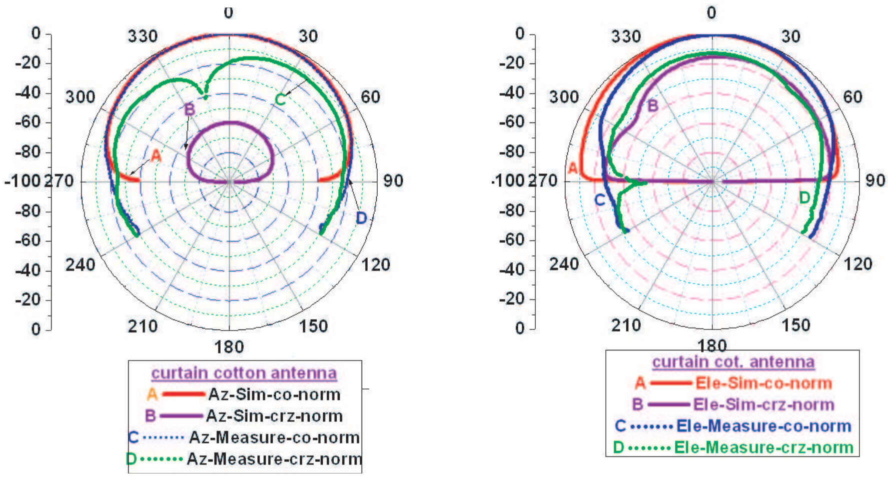
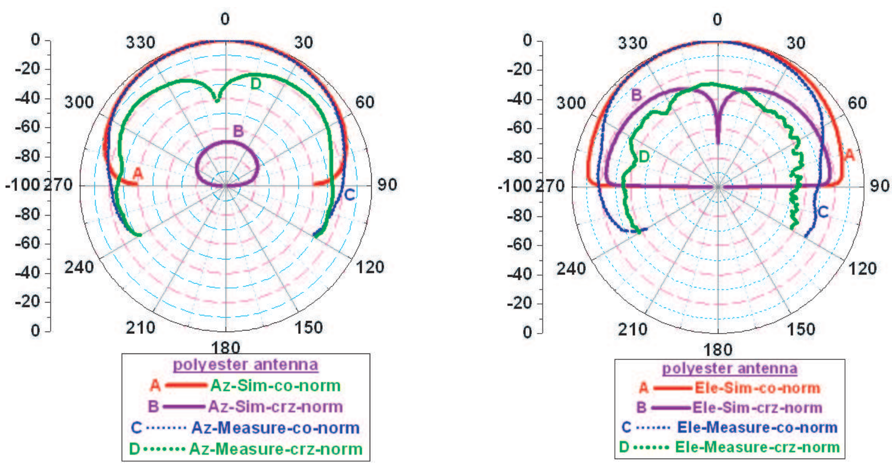


Figure 8. (a) Far-field radiation pattern of antenna 1 (wash cotton) in azimuth plane. (b) Far-field radiation pattern of antenna 1 (wash cotton) in elevation plane.



(a) (b)

Figure 9. (a) Far-field radiation pattern of antenna 2 (curtain cotton) in azimuth plane. (b) Far-field radiation pattern of antenna 2 (curtain cotton) in elevation plane.



(a) (b)

Figure 10. (a) Far-field radiation pattern of antenna 3 (polyester) in azimuth plane. (b) Far-field radiation pattern of antenna 3 (polyester) in elevation plane.

4.2.2. Gain, Directivity and Efficiency

Simulations are done for a range of frequencies from 2.0 GHz to 3.0 GHz in order to find the antenna parameters like gain, directivity and radiating efficiency. The gain of the antenna in the same frequency range is measured using gain-comparison method [15]. Variations of simulated gain, measured gain and simulated directivity as functions of frequency for the investigated antennas 1, 2 and 3 are plotted in Figs. 11(a)–(c). The simulated radiating efficiency plots of these antennas under study are shown in Fig. 12. The values of directivity of these antennas are computed from the corresponding measured radiation patterns using the standard formulae [18] and are tabulated in Table 4. The radiating efficiency of these antennas at the corresponding resonant frequencies is determined experimentally employing Wheeler cap method [19, 20]. These measured data are also tabulated in Table 4.

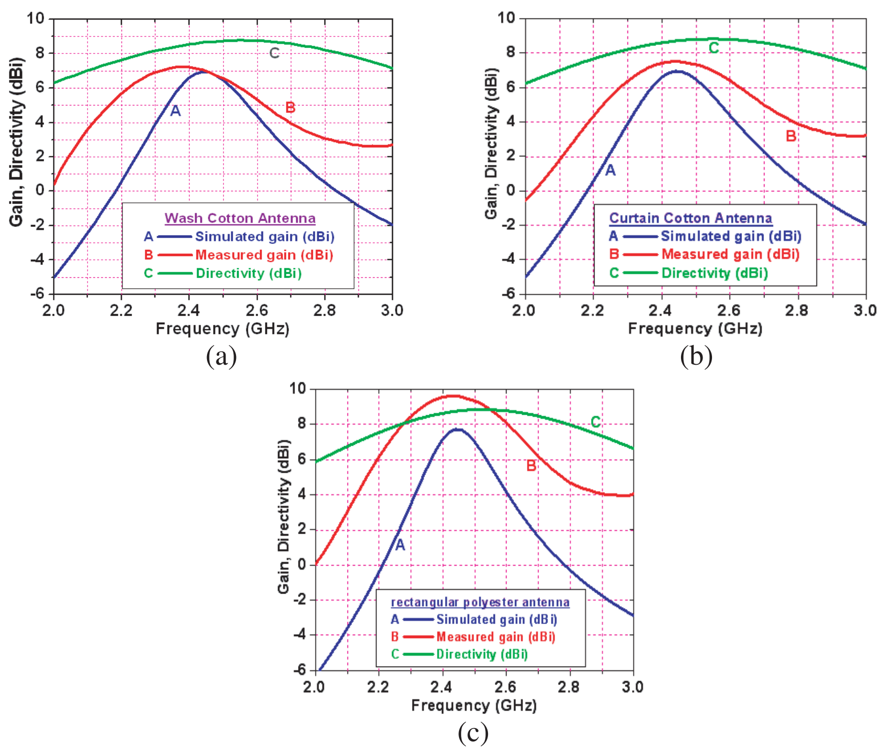


Figure 11. Gain and Directivity plots for (a) antenna 1 (b) antenna 2 (c) antenna 3.

Table 4. Radiation characteristics of various wearable antennas studied.

Parameter / Name of the antenna		Antenna #1	Antenna # 2	Antenna # 3
Gain (dBi)	simulated	6.946	7.037	7.730
	measured	7.225	7.520	9.623
Directivity (dBi)	simulated	8.645	8.725	8.750
	measured	9.713	9.685	9.775
Efficiency (%)	simulated	67.43	67.86	79.20
	measured	63.00	61.00	70.00
3 dB beam-width in azimuth plane (deg)	simulated	74.90	73.95	73.46
	measured	71.00	70.00	66.00
3 dB beam-width in elevation plane (deg)	simulated	72.83	72.65	72.47
	measured	58.00	59.00	62.00
Azimuth cross polar discrimination (dB)	simulated	57.96	59.66	69.54
	measured	29.22	19.67	30.73
Elevation cross polar discrimination (dB)	simulated	45.45	15.52	43.95
	measured	34.16	12.80	28.95

4.2.3. Discussions

Referring to the radiation patterns of all the antennas studied, the simulated and measured co-polar components show an excellent match. The simulation process yields cross polar components of very small magnitude which are not practically achievable. However, the discrimination between co-polar and cross polar components obtained for all the fabricated wearable antennas is reasonably good for practical applications. The simulated and measured values of 3 dB beamwidth in the principal planes of the three antennas, as obtained from the corresponding radiation pattern plots, are tabulated in Table 4. It is seen that a there exists a reasonable match between estimated and measured values of 3 dB beamwidth.

At the resonant frequency, the respective predicted values of gain and directivity of antenna 1 are 6.946 dBi, and 8.645 dBi. The measured values of gain and directivity of this antenna at its resonant frequency are 7.225 dBi and 9.713 dBi respectively. Antenna 2 measures a practical gain of 7.52 dBi against its simulated gain of

7.037 dBi at resonance. Its simulated and measured directivity values are 8.725 dBi and 9.685 dBi. Likewise, the simulated and measured gains of antenna 3 are 7.73 dBi and 9.623 dBi respectively. All these three antennas yield simulated radiating efficiency in the order of 65–80% as plotted in Fig. 12. The corresponding values of measured radiating efficiency vary from 60–70%. Among the antennas tested for radiation characteristics, the polyester antenna's performance is excellent in terms of gain, directivity and efficiency. This is because the polyester fabric has got a relatively low value of loss tangent. All the performance characteristics of the antennas investigated are listed in Table 4. The characteristics exhibited by the developed antennas are very useful for practical considerations.

5. EFFECTS OF ANTENNA BENDING ON ITS PERFORMANCE CHARACTERISTICS

5.1. Impedance Characteristics

5.1.1. Measured Results

In wearable systems, it is very difficult to keep the antenna flat all the time especially when the antenna is made of textile materials. Moreover, the wearable antenna is bent frequently due to human body movements. Therefore, it becomes necessary to investigate the antenna's performance characteristics under bent conditions too. An experimental study is carried out by bending the polyester antenna (antenna 3) around curved surfaces of cylindrical PVC pipes with different radii. Four cylindrical pipes with radii 50.8 mm, 63.5 mm,

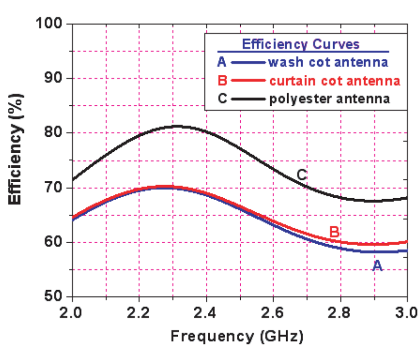


Figure 12. Efficiency vs frequency plots for antennas 1, 2 and 3.

Figure 13. Photograph of the various antenna structures bent with different radii.

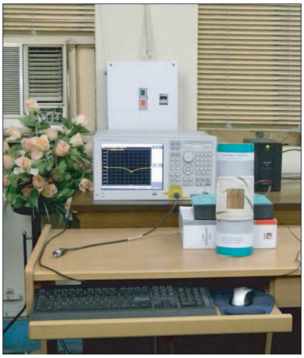


Figure 14. Snapshot of S_{11} measurement set up.

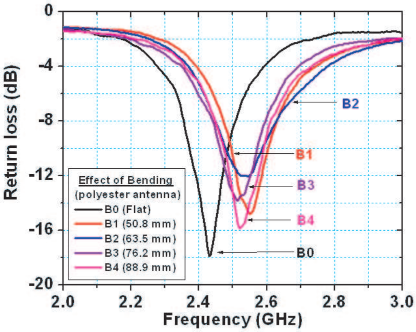


Figure 15. Measured S_{11} plots of the antennas bent with different radii.

76.2 mm and 88.9 mm are used in this experimental study as these dimensions are typical for different parts of human body like arm, leg and shoulder. Fig. 13 shows a photograph of the wearable antenna structures which are wrapped around the cylindrical pipes for this experimental study purpose. Fig. 14 shows a snapshot of the experimental set up used for return loss measurements. The measured S_{11} plots of the antennas bent with different radii are shown in Fig. 15. The deviations of resonant frequency, input matching and impedance bandwidth due to this antenna bending are observed and summarized in Table 5. Figs. 16(a)–(c) shows these experimental observations in graphical representation.

5.1.2. Discussions

It is observed that due to bending, the resonant length of the antenna gets changed and hence there are deviations in the resonant frequency too. The more the antenna is bent, in general, the more the resonant length gets reduced and so the resonant frequency gets shifted up. Considering the other parameters like input-impedance bandwidth and input-reflection co-efficient (S_{11}) at the resonant frequency, it is evident from the experimental observations that there are no severe changes as the antenna is bent with different radii.

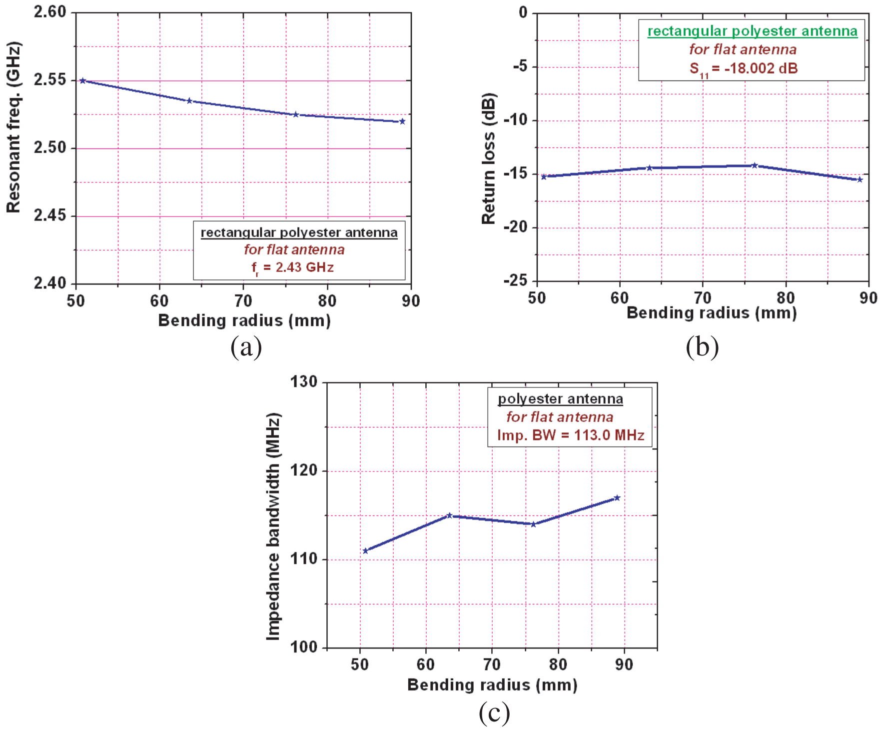


Figure 16. Effect of antenna bending on (a) resonant frequency (b) return loss (c) impedance bandwidth.

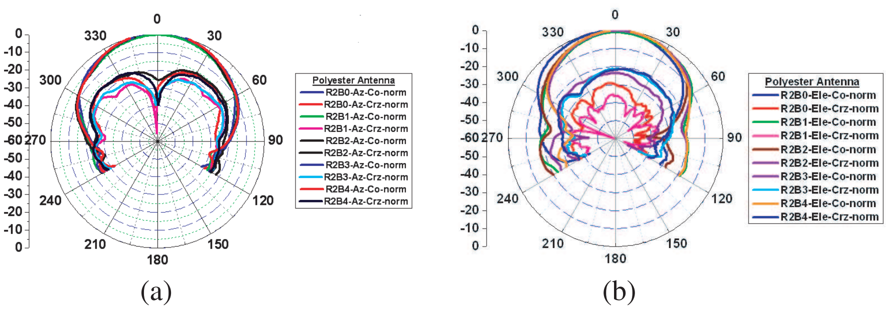


Figure 17. (a) Radiation pattern deformation in azimuth plane due to antenna bending. (b) Radiation pattern deformation in elevation plane due to antenna bending.

Table 5. Bending effects on performance characteristics of rectangular polyester antenna.

Parameter	Antenna's bending radius				
	∞ (Flat)	50.8 mm	63.5 mm	76.2 mm	88.9 mm
Resonant freq. (GHz)	2.430	2.550	2.535	2.525	2.520
Imp. Bandwidth (MHz)	113.0	111.0	115.0	114.0	117.0
3 dB beam-width in Azimuth plane (deg)	66.00	58.00	57.00	60.00	61.00
3 dB beam-width in Elevation plane (deg)	62.00	57.00	55.00	53.00	51.00
Azimuth cross polar discrimination (dB)	30.73	33.694	25.966	35.443	38.173
Elevation cross polar discrimination (dB)	28.95	34.813	23.643	21.187	21.663
Gain at resonance (dBi)	9.623	8.19	9.32	9.156	9.50

5.2. Radiation Characteristics

5.2.1. Measured Results

Radiation pattern deformation and gain variations are measured when the polyester antenna (#3) is bent around the cylindrical pipes of different radii viz. 50.8 mm, 63.5 mm, 76.2 mm and 88.9 mm. The radiation patterns are plotted in a single plot for all these 4 cases in addition to the flat case. In each case the pattern is measured at either measured resonant frequency or a frequency close to it. Figs. 17(a) and 17(b) show the radiation pattern deformations for all four cases of bent antennas with reference to the flat antenna in the azimuth and elevation planes respectively. Fig. 18 describes how the gain of the antenna varies with respect to bending. Table 5 summarizes the outcome of this experiment.

5.2.2. Discussions

It is observed that in the elevation plane the radiation pattern becomes wider and wider as the antenna is bent more and more (bending radius gradually decreased). This leads to a gradual increase in 3 dB beam width and hence a drop in gain within the operating band of frequencies

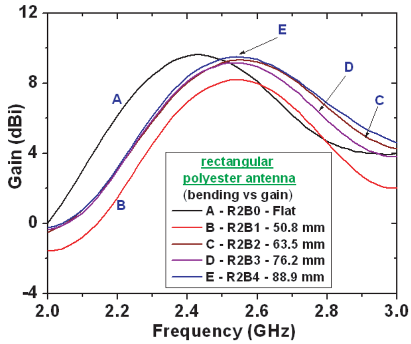


Figure 18. Effect of antenna bending on gain.

is expected. In the azimuth plane, though the antenna does not follow the same kind of trend as in the other principal plane, there are no severe variations in the value of 3 dB beamwidth as the antenna is bent with different radii. Considering the gain of the antenna, it is interesting to note that even the most bent antenna has got a moderate and acceptable gain within the operating frequency band and thus it may be concluded that these wearable antennas perform reasonably well even when they are subjected to bending due to human body movements.

6. CONCLUSION

The following conclusions may be drawn from this experimental work. Firstly, microstrip antenna is a suitable candidate for wearable applications, as it can be built using fabric substrate materials. In this paper four rectangular patch antennas have been designed, developed and tested in order to get their impedance and radiation characteristics. The antennas presented are very versatile and it is easy to make them operate at various frequency bands. In addition, the well known techniques [21] of improving bandwidth and obtaining different polarizations, adopted for microstrip patch antennas are readily suitable for wearable antennas too. It may be concluded that these textile microstrip patch antennas may eventually replace patch antennas on standard PCB substrates for various applications. These wearable antennas must be drapable as the fabrics can take diverse shapes because of human body movements. Therefore, the authors have investigated the effects of antenna bending on performance characteristics of wearable antennas in this present paper. However, the interaction between the wearable antenna and the human body can never be avoided and therefore, it requires further investigations. The authors' research activity is also underway to use electro-textiles instead of copper conductive parts in order to further facilitate antenna's integration into clothing.

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