Impact of Bending on the Performance of Circularly Polarized Wearable Antenna

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Abstract— Wearable electronic devices are becoming a part of human clothing for applications such as sensing, navigation and health monitoring. Textile antennas are a strong candidate for transceiver node in wearable applications due to their flexibility and low cost. In wearable systems, flat surfaces are not always available so the antenna should be able to retain its performance in bent conditions. This paper analyses the effects of bending on the performance of a circularly polarized textile antenna. The antenna under test is made on Denim substrate for Industrial, Scientific and Medical (ISM) band and Wireless Body Area Network (WBAN) applications at 2.45 GHz. Copper tape is used as the conductive material for the patch and the ground plane on 1 mm thick Denim substrate. Rectangular slot along diagonal axes at the center of the circular patch is used for achieving circular polarization at 2.45 GHz while bandwidth enhancement is done by using partial and slotted ground plane. The measured operating frequency range of antenna spans from 2.42 GHz to 2.58 GHz with gain of 2.25 dB at 2.45 GHz. Bending in both xz and yz plane is done by placing the antenna on cylinders with different radii (50 mm and 75 mm) and then analyzing the effects on return loss, bandwidth, axial ratio and radiation characteristics. Fabricated antenna shows good conformity between simulated and measured results. A set of comparative results of antenna in free space and bending conditions are compared to validate the operability of antenna with bending in different planes. In future, the performance of antenna can be analyzed on different body parts like arms and legs etc. to validate its operability for BAN applications in vicinity of human body.

1. INTRODUCTION

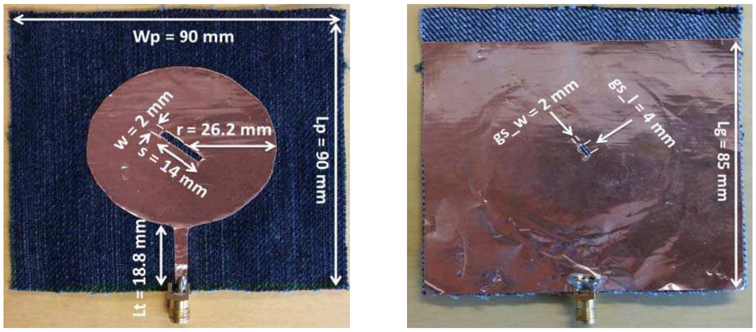
Wearable electronics is an emerging technology of the present time that attracts interest in many applications, ranging from health monitoring, multimedia, sports, and military. One of the most important parts of any such system is the antenna, which is required to ensure reliable communication. With the development of wearable electronics, a new type of antennas is introduced which can easily be embedded inside human clothing, called textile antennas. Textile antennas have the advantage of flexibility, lightweight and low cost, and can easily be integrated in daily used garments. Multiple techniques have been proposed for designing and improving the performance of textile antennas for use in WBAN applications [1]. However, flexibility of the textile antenna allows it to easily bend when mounted on human body; hence it becomes necessary to study the effects of bending on the performance of textile antennas [1].

In WBAN applications, single or multiple antennas are mounted as transceiver nodes on human body. The transceiver nodes may communicate with one another or some remote server for sending data depending on the application. Due to the constant motion of the body, it becomes difficult to always align the transceiver nodes for better power reception. Circular polarization (CP) operation eliminates the need to continuously align the two nodes for receiving maximum power [2, 3]. Previously reported wearable antennas are mostly non-flexible [3], thick substrate [4], linearly polarized [4, 5] or large in size [5] which makes them difficult to be used in wearable applications. Literature review shows that the bending analysis of linearly polarized textile antennas has been done to study the effect toward antenna's performance in terms of return loss, gain and radiation pattern [6–8] but it misses the details of effect on the efficiency and beam width of the antennas.

In this study, we analyzed the impact of bending on the performance of circularly polarized wearable antenna in free space. The antenna operates for ISM and WBAN applications at 2.45 GHz. The antenna uses thin substrate and has improved impedance and 3-dB Axial Ratio (AR) bandwidth, in free space measured results, than previously reported work [3, 6]. Simulated and measured results are compared in different antenna positions and bending. The test setup for bending includes two cylinders with the radii of 50 mm and 75 mm. These dimensions are typical for the human body parts, e.g., arm and leg. Antennas are bent around the cylinder along two principal planes, xz and yz planes, respectively, and results are measured for comparison purposes. Performance with respect to return loss, axial ratio and radiation characteristics have been presented, compared and discussed briefly. Design of the antenna is explained in Section 2, while Section 3 discusses the flat antenna performance in free space. Section 4 presents the effects of bending on the performance of the antenna in free space whereas section 5 concludes the paper.

2. ANTENNA DESIGN

Figure 1 shows the fabricated antenna with dimensions. The antenna is fabricated on Denim fabric (commonly used in jeans) with the dimensions of $90 \times 90 \times 1\,\text{mm}^3$, dielectric constant ($\varepsilon_r$) 1.68 and loss tangent($\delta$) 0.03. Copper tape with thickness 0.25 mm is used as conductive material (patch and ground). To achieve circular polarization a slot "s" is introduced on the patch. The position of slot "s" will excite two orthogonal modes of equal amplitude while their phase is controlled by its length. The resonant frequency of the antenna should be slightly higher than the desired resonant frequency because inserting the slot will shift the frequencies downward. Increasing the length of slot "s" till certain point (14 mm), increases the return loss and shifts the frequency to lower bands, but afterwards it splits the single frequency band into two bands and starts decreasing the return loss, which is not desirable. The designed antenna is fed by transmission line having the impedance of $50\,\Omega$ and width of 3.4 mm. The angle between the slot "s" and feed line is 45°.



(a) (b)

Figure 1: Fabricated antenna. (a) Patch. (b) Ground.

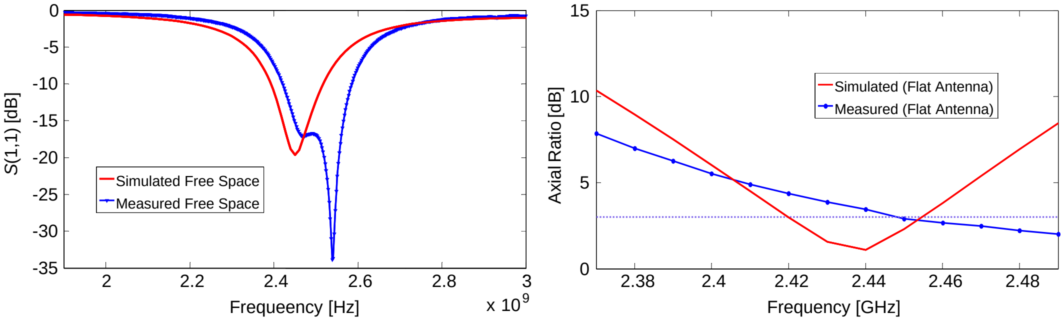
Micro-strip patch antennas are typically narrowband; to increase the bandwidth, partial and slotted ground plane techniques are used. The reason for the increase in bandwidth is due to the lowering of the Q factor of the antenna, which is inversely related to bandwidth [9]. Q factor of the antenna depends on the gap capacitance between the patch and the ground. Using partial ground will reduce the energy stored in capacitance between patch and ground, thus lowering the Q factor [9]. After partial grounding the bandwidth is increased to 80 MHz; starting from 2.40 GHz to 2.48 GHz. To cover the complete ISM band (2.40 GHz to 2.50 GHz), without changing the size of the radiating patch, slot "gs" was added to the ground plane which further lowers the Q factor of the antenna and increases the bandwidth. Due to the small size of the slot "gs", it will have very small effect on the resonant frequency. The increase in backward radiation due to slot "gs" is 1.4 dB, which shows that leakage radiation from slot is less. The final bandwidth of the antenna, after using slotted ground plane, increases to 120 MHz; starting from 2.39 GHz to 2.51 GHz.

3. FLAT ANTENNA PERFORMANCE

Measurements are carried out using vector network analyzer (VNA) Agilent PNA E8358A and near field measurement device Satimo Starlab. Figure 2 shows the comparison of simulated and measured results in terms of return loss and axial ratio of the antenna.

Measured return loss is similar to simulated with a shift towards higher frequencies. The reason for shifting is inaccuracies in fabrication as the antenna is fabricated by manually cutting the jeans and copper tape. The measured impedance bandwidth of the antenna is 160 MHz (2.42 GHz–2.58 GHz). The same trend is followed in the axial ratio, as it shifts toward higher frequencies with circular polarization ($\text{AR} < 3\,\text{dB}$). The measured 3-dB AR bandwidth of the antenna is 60 MHz (2.45 GHz–2.51 GHz).

Figure 3 shows the comparison of simulated and measured results in terms of the axial ratio and gain at 2.45 GHz in xz plane. The measured 3-dB AR beam width at 2.45 GHz is approx. 218° in xz plane (from $-157°$ to $+61°$). Flat antenna measurements show that antenna can efficiently operate on the desired frequency band with circular polarization in the main beam. The measured Front



(a) (b)

Figure 2: Simulated and measured results. (a) Return loss. (b) Axial ratio.

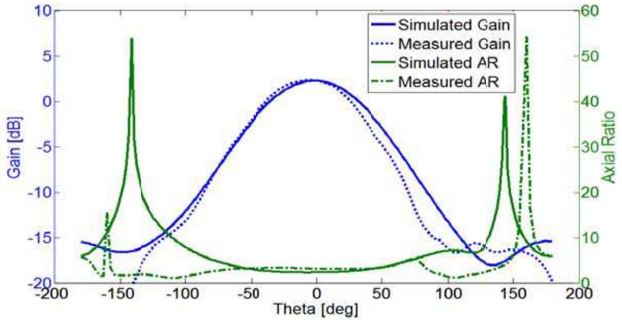
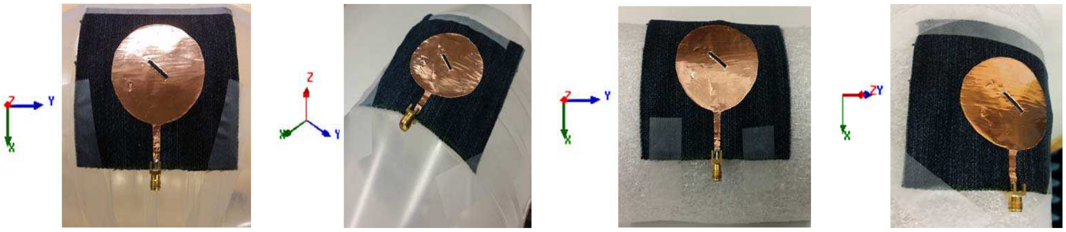


Figure 3: Simulated and measured results for gain and axial ratio at 2.45 GHz.



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

Figure 4: Bending. (a) xz 75 mm. (b) yz 75 mm. (c) xz 50 mm. (d) yz 50 mm.

to Back Ratio (FBR) is 20.09 dB which is good for wearable applications as maximum radiation is away from the antenna even with partial grounding. The antenna exhibits left hand circular polarization (LHCP).

4. ANTENNA BENDING

To demonstrate the effect of bending, two cylindrical shaped plastic bottles with radii 50 mm (small cylinder) and 75 mm (large cylinder) are used. The radius of the cylinder is inversely proportional to the bending angle. The selected radii are for typical human body parts like arms and legs etc.. The material of the cylinder does not affect the surface currents of the antenna. The antenna is bent on the cylinder in both xz and yz plane. Transparent paper tape is used to hold the antenna in proper positions during experiments. Performance of the antenna is evaluated by analyzing the effects of bending on return loss, axial ratio and radiation characteristics. Radiation characteristics include radiation patterns (xz and yz plane), peak gain, and radiation efficiency at 2.45 GHz. Figure 4 shows the bent antenna in different planes.

4.1. Effects on Return Loss and Bandwidth

Figure 5 compares the measured return loss of the antenna in flat and bent states. In general, bending an antenna changes the effective length which ultimately changes the resonant frequency. Increasing the bending, decreases the effective length, thus the resonant frequency is shifted to

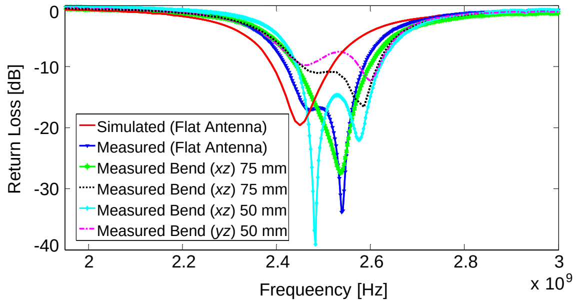


Figure 5: Variation of return loss with bending.

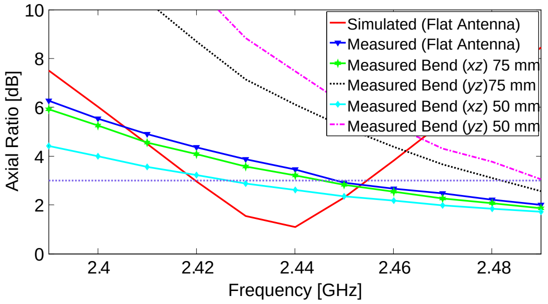


Figure 6: Variation of axial ratio with bending.

Table 1: Change in radiation characteristics of antenna with bending.

Antenna Position	*Return Loss at 2.45 GHz [dB]*	*Bandwidth [MHz]*
Simulated (Flat)	−19.620	120 (2.39 GHz–2.51 GHz)
Measured (Flat)	−15.378	160 (2.42 GHz–2.58 GHz)
Bending 50 mm xz	−11.850	180 (2.44–2.62 GHz)
Bending 50 mm yz	−9.537	50 (2.57–2.62 GHz)
Bending 75 mm xz	−11.010	150 (2.44 GHz–2.59 GHz)
Bending 75 mm yz	−9.628	160 (2.45 GHz–2.61 GHz)

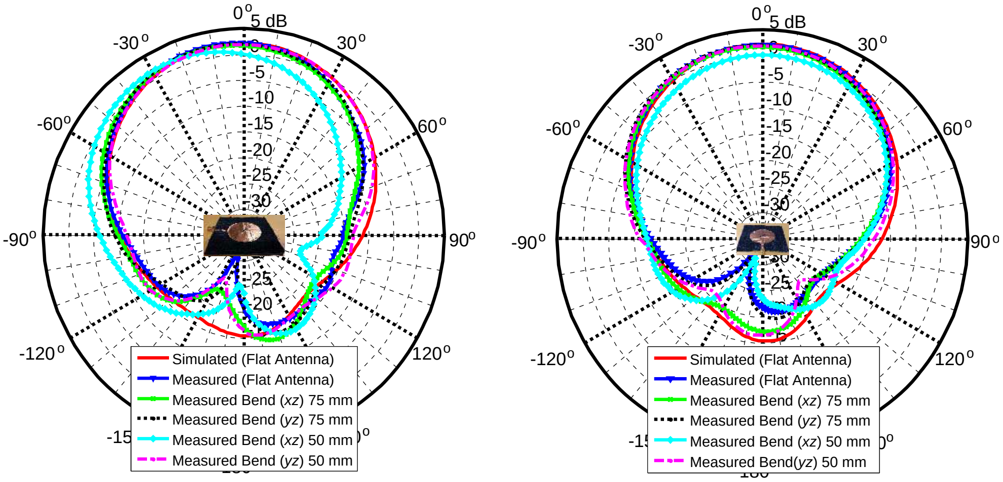
higher bands. From the measured data, this is very clear in case of bending on the small cylinder. Return loss on the large cylinder is almost similar to the measured return loss of the flat antenna because of the small bending angle. The impedance band breaks into two when the antenna is bent in xz plane on the large cylinder. Effect of bending in yz plane is the worst as it shifts the resonant frequency to higher bands as well as degrades the return loss. One reason for this can be that the effective dimensions of transmission line and slot "s" are slightly modified, which detunes the input matching of the antenna. Compared with the measured results (flat antenna), yz plane bending does not have significant effect on the return loss. In all studied cases of the antenna bending, except small cylinder in yz plane, the measured impedance bandwidth is larger (25% to 50%) than the simulated impedance bandwidth of 120 MHz. Table 1 summarizes the change in return loss and bandwidth of antenna with bending.

4.2. Effects on Axial Ratio (AR)

Figure 6 compares the measured axial ratio of the antenna in flat and bent states. The measured AR follows the same trend as measured return loss in different bending scenarios. AR < 3 dB is maintained at 2.45 GHz when the antenna is bent in xz plane, while in yz plane, AR degrades at 2.45 GHz. Circular polarization changes to linear (or is highly elliptical) in yz plane bending. Improvement in AR is observed for xz plane bending. Circular polarization can easily change with bending because both length and width are in resonance with 90° phase shift and bending affects the effective resonating area of patch. It is always preferred to place the textile antenna on flat body parts like back and chest etc.. One solution to this problem can be designing an elliptically polarized antenna and bending it along the longer dimension to achieve circular polarization. The antenna then should be placed in specific bending for use in the wearable applications.

4.3. Effects on Radiation Characteristics

Figure 7 shows the 2D radiation patterns of antenna in xz and yz plane. Position of the antenna is shown in Figure 7 to have a better understanding of the radiation pattern around it. In xz plane bending, the beam width increases in both planes (xz and yz) on the larger cylinder, but as the bending is increased more by placing the antenna on smaller cylinder, the beam width tends to increase more in the plane of bending. The same change is observed in yz plane bending. This leads to the conclusion that antenna bending broadens the radiation pattern in the bending plane. The gain and efficiency of the antenna mainly reduces with bending. Table 2 summarizes the change in radiation characteristics of the antenna with bending. The measured results follow the theoretical relationship between gain, efficiency and directivity (calculated using beam widths) of the antenna.



(a) (b)

Figure 7: Radiation patterns. (a) *xz* plane. (b) *yz* plane.

Table 2: Change in radiation characteristics of antenna with bending.

Antenna Position	*3 dB Beam width (xz-plane or Phi 0°)*	*3 dB Beam width (yz-plane or Phi 90°)*	*Peak Gain at 2.45 GHz [dB]*	*Efficiency at 2.45 GHz [%]*
Simulated (Flat)	77° (+37° to −40°)	72° (+37° to −35°)	2.2612	27.505
Measured (Flat)	73° (+30° to −43°)	74° (+35° to −39°)	2.2524	25.076
Bending 50 mm *xz*	78° (+13° to −65°)	74° (+37° to −37°)	1.6579	22.387
Bending 50 mm *yz*	74° (+32° to −42°)	80° (+37° to −43°)	1.9904	26.699
Bending 75 mm *xz*	78° (+30° to −48°)	75° (+32° to −43°)	1.8872	24.582
Bending 75 mm *yz*	77° (+31° to −46°)	77° (+33° to −44°)	2.1133	26.345

5. CONCLUSION

The paper focuses on the effects of bending on the performance of the circularly polarized wearable antenna. A prototype antenna, with Denim fabric as substrate and copper tape as conductive material, is used for analysis. Two different planes, *xz* and *yz*, were selected to study the effects of bending on return loss, axial ratio and radiation characteristics of the antenna. Results show that the effect on performance is increased when the antenna is bent along the direction which determines its resonance length. In the presented work, the *yz* direction specifies the resonance length. Impedance matching is improved when the antenna is bent in *xz* plane. Beam width increases in the plane of bending which results in decreased antenna gain. Even after bending, the antenna is able to operate efficiently on the resonance frequency of 2.45 GHz. In future, the performance analysis of the antenna on different body parts like arms and legs etc. will be done to validate its operability for WBAN applications in the vicinity of human body.

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