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Original scientific paper

PERFORMANCE OF WEARABLE CIRCULARLY POLARIZED ANTENNA ON DIFFERENT HIGH FREQUENCY SUBSTRATES FOR DUAL-BAND WIRELESS APPLICATIONS

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Abstract. *This paper proposes the effect of different dielectric constants to construct a microstrip patch antenna deployed on Jean's textile covering military wireless applications. Initially, the structure is designed with double L-shaped slits inserted on both sides of the patch with an FR4 dielectric constant of 4.4. Antenna dimensions are 40 × 25 mm^2, which is miniature compared to the wave's length (λ) at the desired operating frequency. The proposed antenna performance in terms of simulated parameters such as gain in dBi, reflection loss (S_{11}), directivity, and patch antenna radiation efficiency are executed by the CST MW EM simulator. However, the conventional way of this design with FR4 may not be so reliable when it is designed on Jean's substrate. Besides all the above parameters extracted from the simulator should hold a low value to implement a high-performance deployed wearable antenna. The paper's outcome shows the importance of simulations and measurements undertaken for the proposed antenna assuming both the dielectric constants of FR4 and Jeans cloth material (with ε_r of 1.7). The main contribution of the antenna is to resonate at the frequencies of 3.17 GHz with circular polarization and 5.04 GHz with linear polarization. The antenna prototype is described, and its performance is validated using measurements. The proposed structure also provides a better enhancement in terms of 10-dB impedance bandwidth, with an average gain of 5 dBi.*

Key words: *Jean's Dielectric, FR4 Substrate, SAR, Textile Antenna, Dual-Band, Circular Polarization*

1. INTRODUCTION

Wearable antennas are becoming extremely popular due to their profound potential in multiple applications covering services such as military soldiers, firefighters, and paramedics. Establishing a communication link from the wearable antenna to the base station camp would undoubtedly help the military soldier get rid of heavy-weight telecommunication equipment to

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carry along with them [1]-[2]. Several current and upcoming modern wireless modules either require or can exhibit a solution by implanting one or more antennas on a piece of textile or cloth or directly integrated in to personal accessories which cover shoes, glasses, buttons, and helmets [3]. Specific operating and thermal conditions in which textile antennas designed impose with specific requirements explicitly listed would be included in the performance criteria of antenna experimentation. To be developed as wearable, an antenna must combine a suitable choice of materials, both for the conductive and non-conductive parts, with a standard adopted antenna configuration.

The most straightforward approach is to combine, knit, or conductive yarns into a portion of clothing [4]-[5]. For a designated wearable antenna, the wearer's placement, stance, and movements detrimentally impact the input impedance and radiation pattern. Wearable antennas are usually broadband to compensate for such casual variations [6]. Several techniques have been applied to design single and multiband wearable antennas over the past years, and few include slit [7] or U or L-shaped slot-loaded configurations [8], EBG structure [9], and monopole/planar antennas [10]. Although these wearable antennas exhibit single/dual-band characteristics, a limited bandwidth is exhibited at higher resonant modes.

Furuya et al. [11] proposed a wearable antenna with a wideband for Digital TV reception in the frequency range of 470-700 MHz. However, antenna radiation efficiency needs to be sufficiently improved with the required -10dB return loss and 3-dB axial ratio bandwidth. Earlier, several slits/slots were loaded along boundaries of the various patch configurations [12]-[13] fabricated on non-flexible substrates to generate orthogonal modes for circularly polarized (CP) radiation by adequately positioning the feed point. Owing to the interest in obtaining dual bands and the circular polarization feature, the proposed antenna is discussed to resonate frequencies covering wireless military applications.

This article designs a novel CP-based antenna with double L-shaped slits. Dual L-shaped slits are fixed on either side of the conductive surface of the textile. Slits on either side of the wearable patch antenna provide bandwidth variation. Furthermore, the design obtains circular polarization exciting two orthogonally polarized TM01 and TM10 modes by placing the exact location of the feed point.

2. Wearable Antenna Design and Simulations

The propagation and loss properties at the desired frequency band(s) must be known for the candidate material before antenna design and fabrication. In addition, permittivity and loss tangent have to be characterized to choose textile dielectric material as a substrate with different constructions and thicknesses. Effective permittivity and loss tangent can be extracted using the formula based on the resonant frequency [14]-[15].

2.1. Proposed Antenna Structure

The structure of the proposed antenna with the dimensions of Ls × Ws is represented as shown in Figure1 with the placement of narrow dual L shapes slits. A modified ground plane for the improvement of characteristics is shown in Figure 1. By optimizing the dimensions of the wearable patch, it is observed that there is an improvement in impedance bandwidth and circular polarization feature.

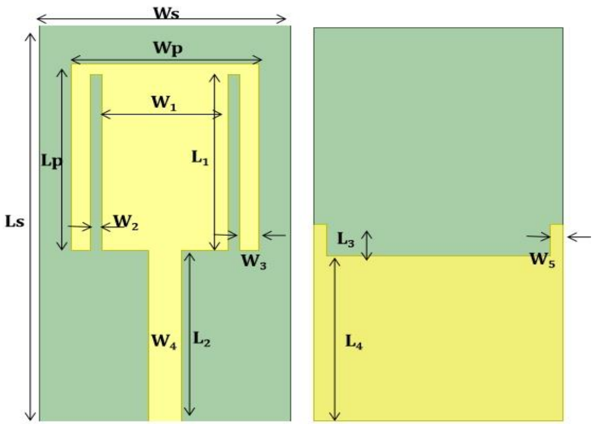


Fig. 1 (a) Top and (b) Bottom layers of the wearable antenna

2.2. Design Parameters

The parametric study of both dielectric materials (FR4 and Jeans) with microstrip line feed is analyzed in this section. A single L-shaped slit on the top layer of the conventional patch makes an additional resonant band possible and slightly enhances the bandwidth. Moreover, an additional L-shaped slit introduces a circular polarization feature with the formation of orthogonal modes at the initial resonant band of 3.17 GHz. The dimensions (in mm) for the parameters are listed as follows: L_S = 75, W_S = 40, W_P = 25, L_P = 40, W_1 = 15, W_2 = 1, W_3 = 3.95, W_4 = 2.8, W_5 = 2, L_1 = 39, L_2 = 26, L_3 = 10, L_4 = 20. The effect of both dielectric substrates FR4 (4.4) and Jean's cloth (1.7) are discussed to analyze various characteristics. The relevant critical parameter is the fabric's conductivity (σ), holding the units as Siemens per meter (s/m) as part of the antenna design. Equation (1) gives the relation between the surface resistivity (ρ_S) and the thickness (t) of the fabric:

$$\sigma = \frac{1}{\rho_S t} \tag{1}$$

2.3. Effect of different substrates with simulations

The proposed wearable antenna with dual L-shaped slits and monopole ground plane improves gain and impedance bandwidth at the resonance bands 3.17 GHz and 5.04 GHz, respectively. It is shown from Figure 2 that the degenerate modes are formed at 3.17 GHz leading to an axial ratio bandwidth of 8 MHz for the circular feature. Additionally, a high impedance bandwidth is obtained at both resonant bands compared to the FR4. The coverage area using CP would better the short-range communication for military applications. This is the reason for which the prototype is implanted in textile materials. For this study, the characteristics of the wearable design are compared with the FR4 type substrate. Fig. 3 shows the comparison of the VSWR values for both bands. The values of the VSWR are maintained less than 2 to evaluate the simulated results of impedance bandwidth and VSWR responses. CST Microwave studio simulator is used to analyze the case studies of both dielectric constants for different thickness values. For this study, the thickness values are 1 mm and 0.8 mm.

Conventional rectangle shape geometry with L-shaped slits is chosen as implantable on electro textiles due to its simplicity. However, the thickness intensity of the yarns in the woven structures would be an ideal choice for the prototype design. Minor variation in the selection of length and width of the conductive fabric as a wearable antenna results in a slight variation in the antenna characteristics, as displayed in Figure 2. In general, wearable material holds a very low dielectric constant. Therefore, the thickness and substrate dielectric impact are vital in designing the wearable patch to extract the efficient parameters.

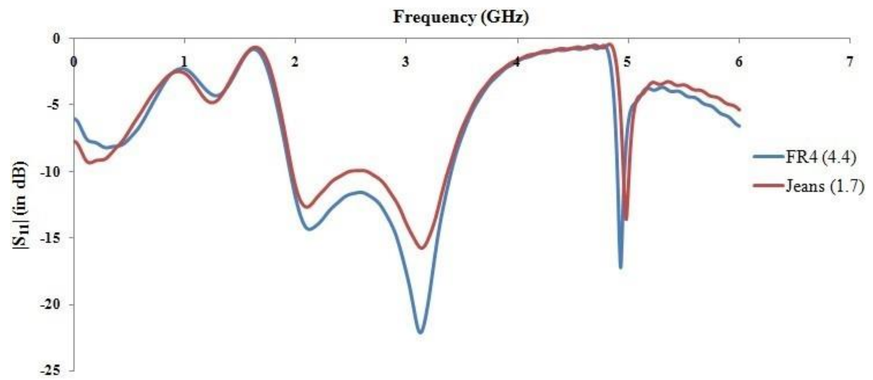


Fig. 2 S_{11} response of different dielectric constants(FR4 and Jean's)

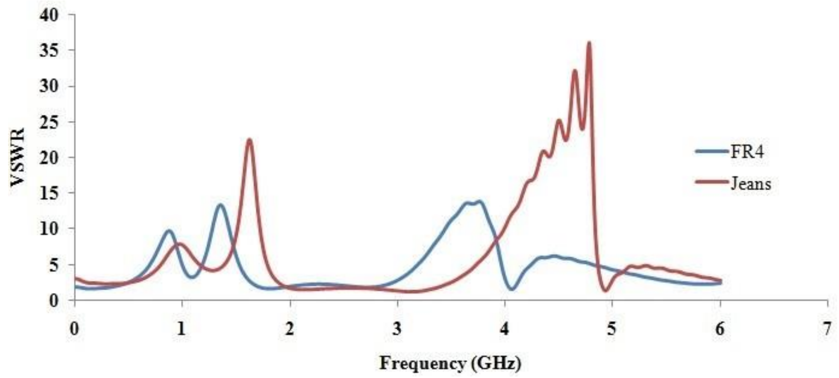


Fig. 3 VSWR response of different dielectric constants (FR4 and Jean's)

Table 1 highlights the summary of comparing the executed parameters for both the substrates performed for this work, along with the effect of different thickness values considered. In addition, it mentions the high impedance bandwidth of 1470 MHz (54%) and 60 MHz (1.2%) with a thickness of 1 mm obtained at 3.17 GHz and 5.04 GHz, respectively.

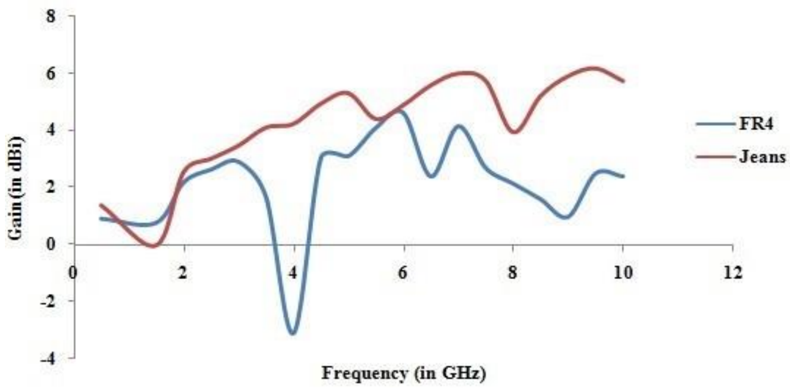


Fig. 4 Gain versus frequency response for both (FR4 and Jean's) substrates

It is proved that the reduction in the wearable dielectric constant increases the antenna performance with the novel structure design proposed. Moreover, it is observed that a moderate gain of 5dBi is displayed with a wearable antenna when compared with the low-value gain for FR4 substrate, maintaining the same thickness of the substrate. Feature of circular polarization is also obtained for the operating frequency of 3.17 GHz. Gain response curve drawn for Jean's substrate show the gain values for 0.9 GHz and 3.2 GHz, respectively as 2 dBi and 3.2 dBi.

Table 1 Performance comparison of both the substrates (Jean's and FR4) in terms of gain and impedance bandwidth

Dielectric (FR4)-4.4				
Substrate thickness	Frequencies (GHz)	Impedance Bandwidth (MHz), %	VSWR	Gain(dBi)
t=0.8mm	1.82	100, 5.49	1.86	2
	4.17	30, 1.79	1.79	1.8
t=1mm	1.81	270,14.6	1.6	1.6
	2.72	200,7.3	1.8	2.5
	4.06	60,1.4	1.5	3.68
Dielectric (Jean's Cloth)-1.7				
t=0.8mm	3.17	1420,52.3	1.31	3.5
	5.07	30, 0.6	1.56	4
t=1mm	3.17	1470,54	1.1	4.1
	5.04	60,1.2	1.3	5

SAR simulated response for an operating frequency of 0.91GHz is represented in Figure 5 and it shows that the SAR value denoted on the scale is moderately at 18.2 W/Kg. This SAR value is to be maintained at low since the textile antenna is worn on a conductive body. Material thickness, conductivity, operating frequency range and resonant behavior are carefully chosen to be distinct to better understand the resulting SAR. SAR is a measure of power absorbed per unit mass (kg), in the human body tissue.

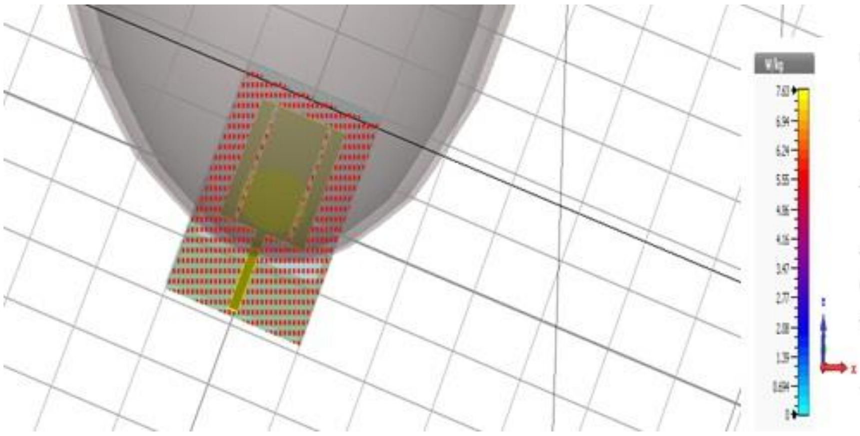
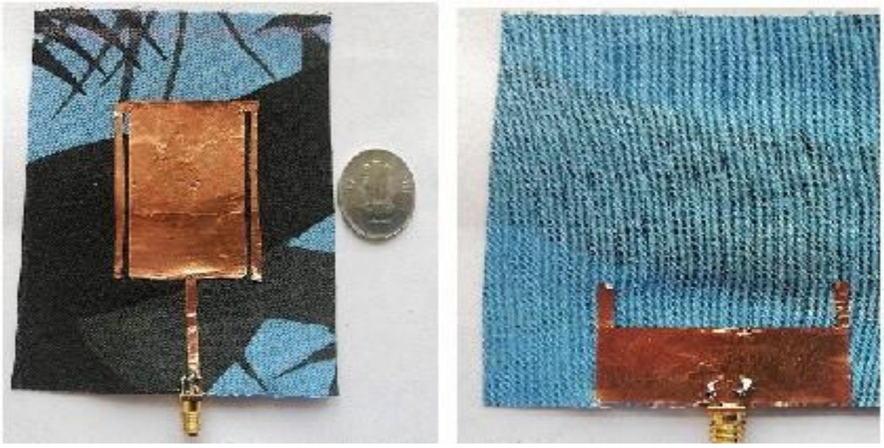


Fig. 5 Simulated SAR response of the antenna operating at 0.91GHz

3. Experimental Results and Discussion

The proposed novel textile antenna prototype with optimized dimensions is constructed and investigated experimentally. Fig. 6(a) and (b) respectively shows the conventional and modified printed textile antennas fabricated. It is seen that the radiator patch with dual L-slits significantly improves the matching conditions of impedance for high resonance bands and maintains stable gain across the remaining bands. The experimental setup of the proposed dual-band antenna is shown in Fig. 7 to measure radiation pattern and axial ratio. Simulated and measured return losses of the antenna design are shown in Fig. 8. The impedance bandwidth values for the proposed antenna prototype are 1470 MHz and 60 MHz, respectively, for both the generated bands.

The anomalies between measured and simulated results are due to the in-house manufacturing and soldering losses. The return loss of the proposed antenna module is measured using the Keysight E5071C ENA series network analyzer. Fig. 9 presents the measured axial ratio of the designed antenna. The lower resonant band's 3-dB axial ratio (AR) bandwidth is about 11 MHz (3.17 to 3.172 GHz). The 3 dB AR bandwidth is within the 10 dB impedance bandwidth (overlapped), which is desirable. Though the measured response is not in close agreement with the simulated response due to tolerance issues and SAR, measured impedance bandwidths are about 60 MHz and 112 MHz, covering both the dual resonant bands at 900 MHz and 3.2 GHz.



(a) (b)

Fig. 6 Fabricated textile antenna prototypes (a) front-view and (b) rear view of proposed dual band antenna

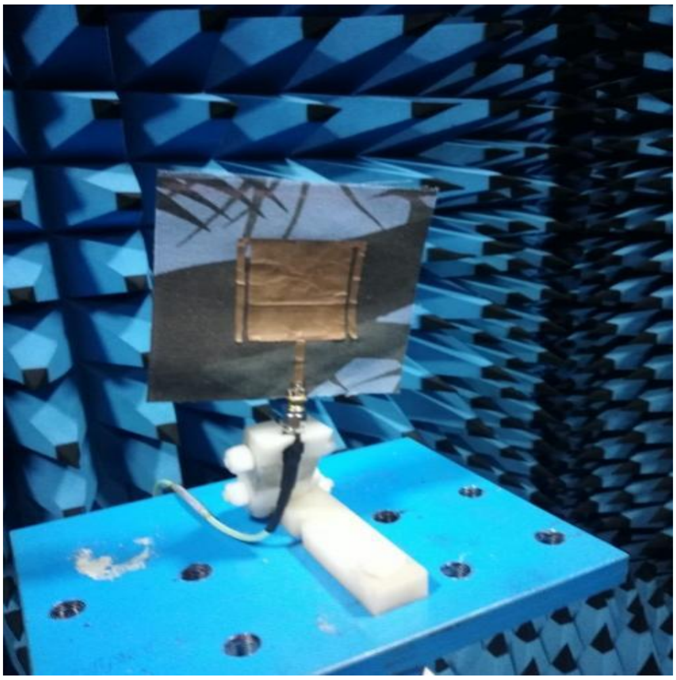


Fig. 7 Experimental setup of proposed dual band antenna

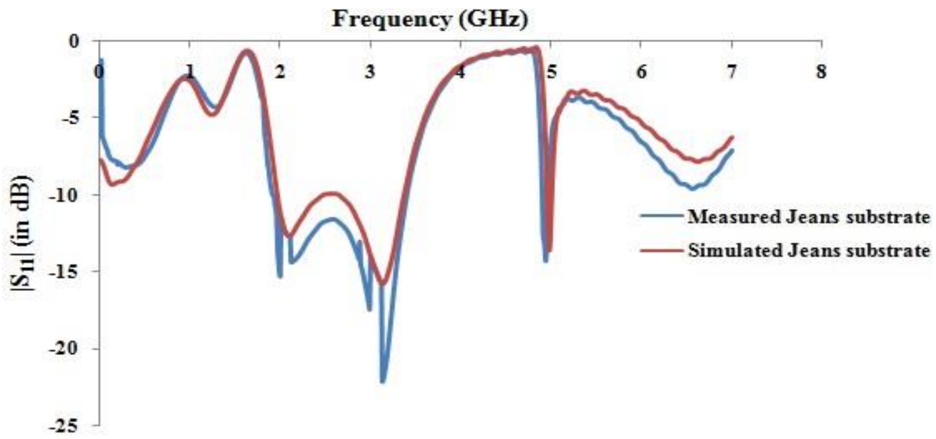


Fig. 8 Measured and Simulated return loss response of the proposed textile antenna

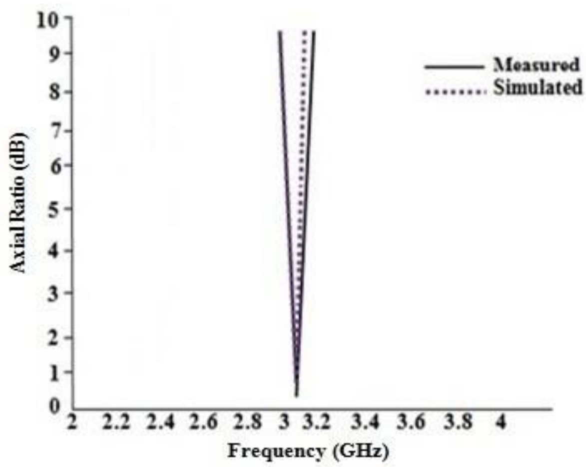


Fig. 9 Measured axial ratio against frequency of the proposed textile antenna

It is also found that the radiation pattern plots are drawn for both dual bands and observed that co-polarization patterns dominate, indicating the dual-band antenna is ideal for military applications. The measured radiation patterns are represented for Jeans substrate operating at frequency of 3.17 GHz in Fig. 10 and operating frequency of 5.04 GHz as shown in the Fig. 11. It is found that unstable pattern at 5.04 GHz for jeans substrate. This is due to the back radiation of the monopole structure on the ground plane.

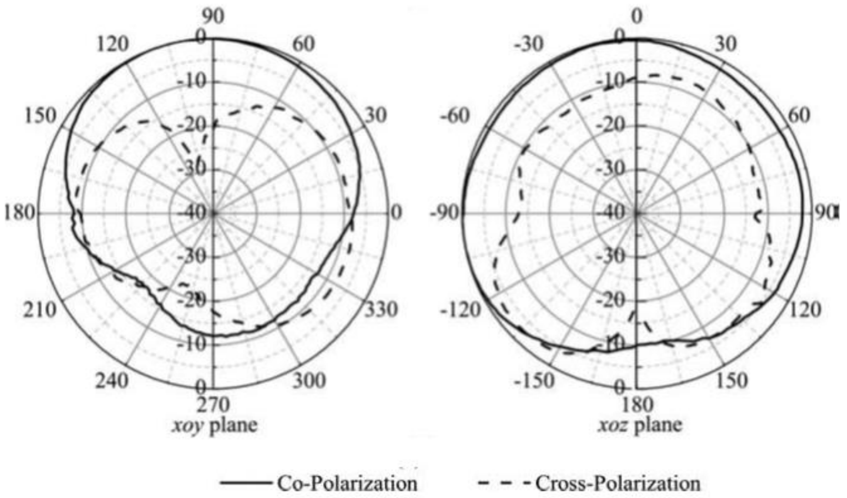


Fig. 10 Far field radiation patterns in *xoy* plane and *xoz* plane at 3.17GHz for Jean's cloth

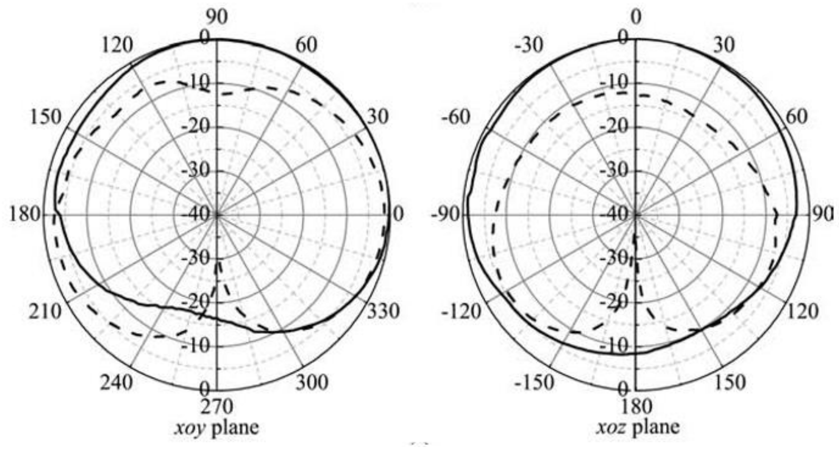


Fig. 11 Far field radiation patterns in xoy plane and xoz plane at 5.04GHz for Jeans cloth

The parameters covering dimensions, operating frequencies, return loss bandwidth, and axial ratio bandwidth and gain are compared with the existing design as tabulated in Table 2 below. The wearable antenna proposed in this work is evaluated at a small size and operates at dual-band with circular polarization at one band.

Table 2 Calculated bandwidth and gain parameters of proposed wearable antenna comparing with existing structures

Ref.	Dimensions (mm^2)	Frequency (GHz)	10-dB RLBW (MHz) (%)	3-dB ARBW (LP/CP)	Gain (dBi)
[8]	110×130	1.927	-6 dB	LP	0
		2.45	-	LP	0
[9]	120×120	2.45	4 %	LP	3
		5.5	16%	LP	2
[11]	240×125	6.2	48%	LP	-
[14]	80×80	10	20%	LP	8.5
[Proposed]	40×25	3.17	60%	11 MHz (CP)	4.1
		5.04	1.2%	LP	5
[Measured]	40×25	0.91	2%	LP	2
		3.2	10%	LP	3.2

RLBW: Return loss bandwidth, ARBW:Axial ratio bandwidth,
LP: Linearly polarized, CP: Circularly polarized

4. CONCLUSIONS

A novel double L-shaped slit textile antenna is analyzed and developed for military wireless applications. The comparative study is performed for both FR4 and Jeans dielectric and tabulated the parameters extracted. This paper majorly focuses on obtaining good CP radiation at the first band and LP at the second resonant band as obtained from multiple iterations of the antenna. Moderate gain of 4.1 dBi and 5 dBi is achieved for 3.17 GHz and 5.04 GHz frequencies, respectively. Displayed results show high impedance bandwidth with Jean's wearable dielectric compared to the conventional FR4 substrate. It is observed that the proposed wearable antenna gives 0.2 dB AR, indicating good quality CP (close to 0 dB) for the resonant band. Though this extended slit-based model executes tri-band CP, the radiation patterns are degraded. Top and bottom layered structures with line feeding techniques conclude that the proposed prototype antenna could benefit the operating frequencies of military wireless applications. Experimental evaluation and significance of the latest wearable dielectrics with different substrate thicknesses are also carried as part of future work.

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