

A Wideband Circularly Polarized Jeans-Based Antenna at 2.45 GHz

Miroslav Joler, Anamaria Kolonić, Maja Boljkovac

Department of Computer Engineering, Faculty of Engineering, University of Rijeka, Rijeka, Croatia

Email: mjoler@riteh.hr

How to cite this paper: Joler, M., Kolonić, A. and Boljkovac, M. (2020) A Wideband Circularly Polarized Jeans-Based Antenna at 2.45 GHz. *Open Journal of Antennas and Propagation*, 8, 1-18.

<https://doi.org/10.4236/ojapr.2020.81001>

Received: March 17, 2020

Accepted: March 28, 2020

Published: March 31, 2020

Copyright © 2020 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Development of textile antennas is an important segment towards the goal of creating *smart clothing*. In this paper, we report on a jeans-based circularly polarized textile antenna designed for the E-band (around 2.45 GHz). We present three variations of the design and the respective results. The antenna comprises a multi-layer jeans-fabric as the substrate, a conductive fabric as the patch, which is concealed with another layer of jeans, and the ground plane is formed by either a copper foil or another conductive fabric. A multi-layer structure was chosen to provide a wider bandwidth and better efficiency, whereas the upper surface of the antenna was covered by one more layer of jeans to both make the antenna less conspicuous, when worn on the arm, and protect the patch and substrate from mechanical damages and moisture. All three variants are characterized by a good realized gain of about 3 dB, a wide beam width and a wide bandwidth of 21% or better, around 2.45 GHz, having the radiation efficiency around 36%, and front-to-back ratio of 5 dB or better, with the ground plane being just slightly larger than the patch.

Keywords

Textile Antenna, Circular Polarization, Jeans-Based Antenna, Probe Feed

1. Introduction

Technological developments have enabled us to envision a new type of solutions, commonly referred to as *wearable electronics*. Various areas of research and development can be recognized within that term, such as: wearable sensors, wearable haptic devices, electronic textiles (knitted and woven), energy harvesting, body area networks, or smart textiles [1] [2]. Among them, *textile antennas* have also taken an important place when it comes to developing *smart clothing* of the future. Realization of such R & D endeavors will be beneficial for various team

and emergency services such as law enforcement, military services, paramedic teams, healthcare services and patient monitoring, to mention some. Increased research interest in this sense can be dated back to the second half of the 2000s [3] [4]. Textile-based antennas are naturally designed as replicas of the conventional microstrip antennas, with some variations when it comes to materials utilized in use for the substrate, ground plane, and the patch. Benefits of textile antennas are low cost of manufacturing, availability of materials, some degree of flexibility of the antenna structure, and possibility to fabricate it by handcrafting without a need to possess or rent sophisticated machines or order outsourced services for circuit fabrication. But there are also inherent limitations, such as a lower precision of fabrication, possibly higher dielectric losses, difficulty to work with more complex antenna geometries, thermal and moisture sensitivity, and attachment of a connector to the textile ground plane. The above limitations seem to be the reason why most of the works proposed so far, mostly deal with just a few (simplest) types of antenna geometry and feeding, yet that fact does not lessen the importance of that research in the overall development of wearable technology. A variety of materials have been utilized to serve as the antenna substrate. In [5] [6] [7] polydimethylsiloxane (PDMS) was examined as a convenient material for flexible antenna. Cordura textile was examined in some other works (e.g. [8] [9] [10]). Some fabrics that are commonly used in garment industry have been the basis for the substrate in [11].

When it comes to jeans-based antenna specifically, we can make a short overview of prior art by grouping them by the material that was used for the patch and/or ground plane, the polarization type and the line feed. In particular, in [12] [13] [14] [15] [16], a copper tape or foil was used for the patch and/or the ground plane. Most of the antennas in references [12] [13] [16] [17] [18] [19] generate linear polarization and are all excited by a line feed, while [15] [20] are among the rare works where antennas create a circular polarization, yet they also used the line feed to excite the antenna. Moreover, a great majority of the cited works utilizes only one layer of jeans for the substrate.

In this work, we propose a *wideband* and *circularly polarized* textile antenna that is based on jeans fabric as the substrate in combination with electro-conductive fabrics as the radiating patch and the ground plane, while the antenna excitation is based on the *probe feed* for the design frequency at 2.45 GHz. The objectives here were to: 1) apply a fabrication process that is simple; 2) use materials that are easily available; 3) make the antenna small to be suitable for wearing on clothing apparel in the area of upper arm and be visually inconspicuous; 4) make it more effective for communication by the use of a circular polarization.

2. Antenna Design and Fabrication

2.1. On the Selection of Materials

Textile materials have a property to conform to body movements by bending or

twisting, thus changing its original geometry and electromagnetic properties, affecting the antenna resonance frequency, impedance matching, and radiation characteristics. Elasticity of a fabric also complicates the cutting and adhesion of multiple layers. Amongst conductive fabrics, there exist *coated fabrics* (with silver or copper) and *single- or double-sided* conductive fabrics (e.g. [21]). Amongst fabrics with dielectric properties, the most common are denim (*i.e.* jeans), cotton, and polyester.

2.2. On Adhering Techniques

It is an imperative to keep the antenna geometry and dimensions precise and stable, because errors in geometry are expensive at these frequencies with regard to antenna characteristics. One way of adhering the layers of the fabric constituting the substrate is to use adhesive foils. Adhering by double-sided adhesive foils is practical for creating a flat surface between the two layers, but the impractical side is the fact that the foil introduces additional losses in the substrate and the adhesion is based on hot ironing of the upper fabric, which causes oxidation of metallic surfaces, while hot steam also increases surface resistance and lowers an antenna efficiency. Additionally, one must try to avoid possible air bubbles that can be present between the two layers.

Sewing is another possibility because it is a simple and straightforward technique, but also carries risks because stitches must be straight and without pleats, which is challenging to accomplish with soft fabrics. Moreover, stitches pass through all the layers and make it possible to create accidental short-circuits between the layers.

Yet another approach is to use a liquid glue, but it is hard to apply evenly over the fabric surface. If a glue is in the form of a stick, its application is a bit easier than that of a liquid glue, but an additional caution is advised when a glue is applied to a conductive fabric because the glue can eventually penetrate between the conductive threads of the fabric and act as an isolator.

2.3. Calculation of the Antenna Geometry

We designed a probe-fed rectangular patch microstrip antenna for the resonant frequency $f_r = 2.45$ GHz (**Figure 1**). This type of the patch shape was chosen as being simple enough for cutting of the textile, yet providing good enough radiation properties of the antenna. The jeans that was chosen as the substrate material was 0.78 mm thick. Relative permittivity of jeans is known to be about $\epsilon_r = 1.6$ [22]. The overall substrate thickness h affects the antenna impedance bandwidth, input impedance, and the resonant frequency [23] and is an important design parameter. For thin substrates (*i.e.* $h \ll \lambda_0$, where λ_0 is the free-space wavelength) with a low permittivity, an increase in the substrate height makes the antenna bandwidth wider and improves the efficiency, yet this benefit has a limit at the point when surface waves, which are introduced by it, start degrading the antenna radiation pattern and polarization characteristics

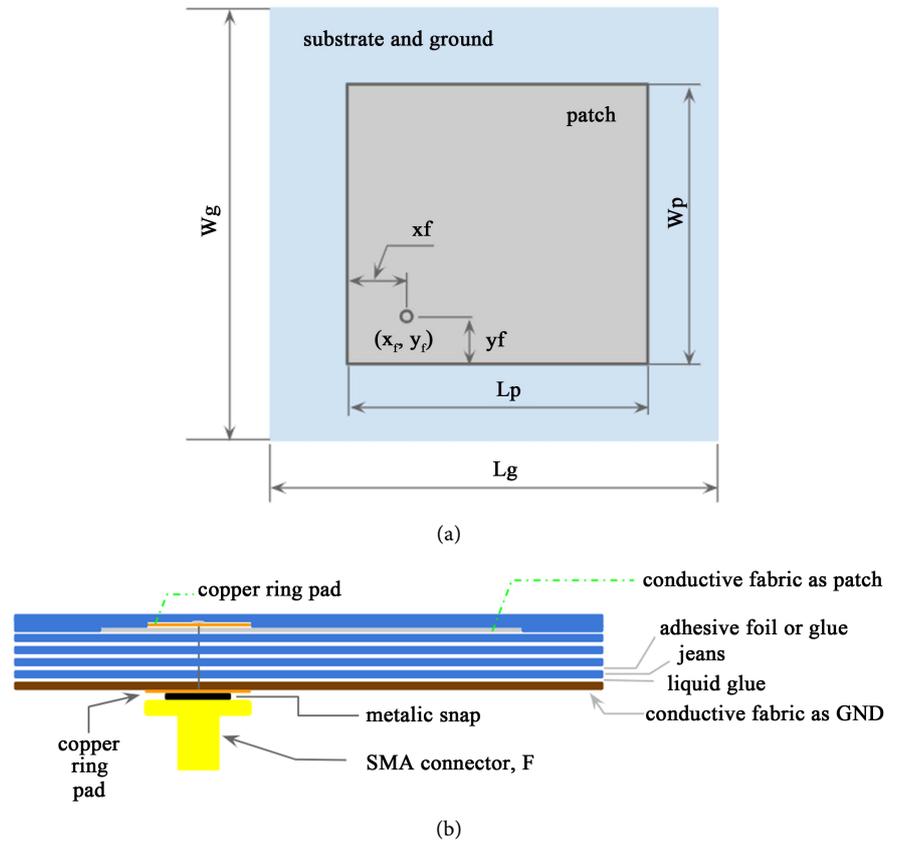


Figure 1. The antenna geometry: top view and the cross-section. (a) Top view; (b) Cross-section.

[24]. With the above-mentioned jeans, we designed three antenna models having two different substrate thicknesses and two ground plane (and substrate) sizes for the reason to compare the difference in the antenna characteristics due to different substrate heights and ground plane sizes. One substrate thickness was obtained by stacking up 6 layers of jeans, which gave the total substrate thickness of $h = 4.68$ mm, while another one comprised 5 layers, making the substrate height equal to $h = 3.9$.

The patch width W_p and length L_p for $h = 4.68$ mm and $h = 3.9$ mm were initially determined using the *transmission line method* given by [23]

$$W_p = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \tag{1}$$

where c is the velocity of light and f_r is the resonant frequency, and

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \cdot \left(1 + \frac{12h}{W_p} \right)^{-1/2} \tag{2}$$

$$\Delta L = h \cdot 0.412 \frac{\epsilon_{eff} + 0.3}{\epsilon_{eff} - 0.258} \cdot \frac{\frac{W_p}{h} + 0.264}{\frac{W_p}{h} + 0.8} \tag{3}$$

$$L_p = \frac{1}{2f_r \sqrt{\epsilon_{eff}} \sqrt{\mu_0 \epsilon_0}} - 2\Delta L \quad (4)$$

where ϵ_{eff} and ΔL are the effective permittivity of the structure and the length extension due to fringing effects, respectively. To achieve a circular polarization using only a single-location probe feed, the feed coordinate (p_x, p_y) was initially set following the theory in [23] [25] and then optimized, together with the antenna dimensions, using simulations in CST Microwave Studio 2014 [26] to achieve the best performance by balancing between the S_{11} parameter at the resonant frequency, the radiation- and total-efficiency as well as the directivity value. Within this procedure, two sizes of the ground plane were also prepared for the antenna with $h = 3.9$ mm to make the antenna dimension as small as possible without much compromising the performance. The three antenna models that will be analyzed in Section 3 in more detail are:

- 1) Antenna with ground plane size 50×57 mm and substrate thickness $h = 4.68$ mm;
- 2) Antenna with ground plane size 50×57 mm and substrate thickness $h = 3.9$ mm;
- 3) Antenna with ground plane size 70×80 mm and substrate thickness $h = 3.9$ mm.

2.4. Selected Fabrics and Final Parameters Values

The following fabrics were selected to constitute specific layers of the antenna. For the ground plane, a conductive MedTex180 [27] fabric was chosen. It comprises a nylon coated with silver, that provides surface resistivity lesser than $1 \Omega/\text{sq}$. It is 0.35 mm thick and endures temperatures from -30°C to 90°C and is stretchable in both directions. For the substrate, as introduced earlier, jeans was chosen for its availability, firmness, and softness. At 2.45 GHz, its relative permittivity is about 1.6 and its thickness is 0.78 mm. For the patch, a Ripstop conductive fabric was chosen [28]. It comprises three layers: nylon, nickel, and silver, with surface resistivity being lesser than $0.02 \Omega/\text{sq}$. Its thickness is 0.1 mm and it withstands temperatures from -30°C to 90°C . For the adhesion of the jeans-based substrate layers, a Gütermann liquid glue was used, while for the adhesion of the ground plane and the patch with the substrate, a Clover glue, packaged in stick, was used (Figure 2).

The final design values, which also included one layer of jeans laid on top of the patch, with the idea of better thermo-mechanical protection of the patch and better visual appearance of the antenna surface, are listed in Table 1.

2.5. Antenna Fabrication

While cutting the jeans, we experimented with two types of cuts: a *straight* cut with the scalpel and a *zig-zag* cut with a pair of tailor scissors. The interest was to see if and how much the zig-zag cut affects the results. Experience during the cutting process showed that zig-zag cutting was more damaging for the textile. It



Figure 2. Application of a liquid glue to the jeans layers.

Table 1. Antenna design parameters.

Parameter (in mm)	Antenna Models		
	Model 1	Model 2	Model 3
	Fabric Cutting Types		
	Straight	zig-zag	zig-zag
ground plane thickness, t_g	0.35	0.35	0.35
substrate length, L_g	50	50	70
substrate width, W_g	57	57	80
substrate height, h	4.68	3.9	3.9
patch length, L_p	39	39	39
patch width, W_p	46	46	46
patch thickness, t_p	0.1	0.1	0.1
feed x-coordinate, p_x	7.7	7.7	7.7
feed y-coordinate, p_y	5.5	5.5	5.5
patch cover thickness, t_c	0.78	0.78	0.78

also inherently modifies the antenna dimensions in a way that only the outer cut-line equals the design size of the layer while the inner cut-line is shorter. The difficulty while cutting the MedTex180 fabric (*i.e.* the ground plane textile) was due to its elasticity and stretching during the cutting pressure, thus extending its length and jeopardizing cutting it to the exact size. The zig-zag cutting was also difficult for that matter. The Ripstop fabric (*i.e.* the patch textile) was somewhat easier to cut because it is thinner and less elastic than MedTex180 fabric. The hole for the feed location was prepared using a needle of 1.2 mm in diameter to punch through the layers and then slightly widening the hole for the inner conductor of the connector that had a diameter of 1.25 mm. Such a CAD-optimized feed location enabled us to achieve a *right-hand circular polarization* (RHCP) of the antenna by a single-feed and without having to trim the corners, as some other techniques suggest. **Figure 3** shows a simulated directivity pattern for the *left* and *right* polarization. It clearly indicates the overall polarization is RHCP.

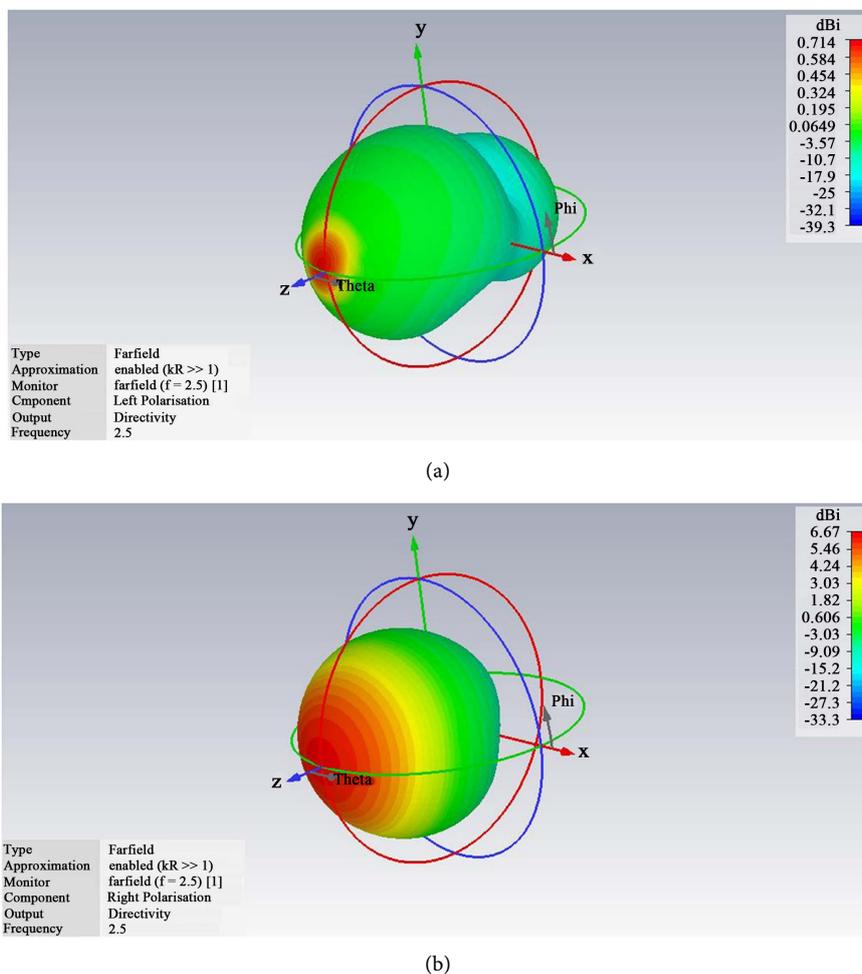


Figure 3. The simulated directivity pattern indicated the overall polarization is RHCP. (a) Left polarization; (b) Right polarization.

Figure 4 shows the back side (left) and the front side (right) of the antenna prior to adding an SMA connector and the cover layer. At first, the connector was adhered to the ground plane by a conductive silver that served as a cold solder, but that did not produce solid enough a contact between the connector and the ground plane, which is why we initially substituted the ground plane textile with the copper foil. One completed antenna is shown in **Figure 5**. Later, we managed to replace the conductive textile as the ground plane and make a firm connection between the ground plane textile and an SMA connector (see Section 4). Measurements were done for both of these cases and will be presented in the following sections.

3. Antenna Characteristics

In this section, we show the measured characteristics of the three chosen antenna models by means of their S_{11} parameters, the bandwidth, and the radiation pattern, including the beamwidth, the radiation efficiency, the gain, and the front-to-back ratio. The three models described in **Table 1** and shown in **Figure 4**

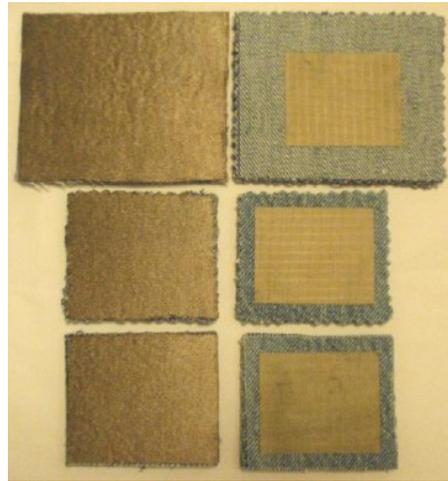


Figure 4. The back side (on the left) and the front side (on the right) of the three jeans-based antenna models that were compared.



Figure 5. One completed (zig-zag cut) antenna with a cover layer.

were selected for having the following distinctive features: **model 1** has a thicker substrate, having one more layer of jeans fabric that was cut straight. In contrast, **model 2** is one jeans-layer thinner (while retaining the same substrate width and length) and cut using zig-zag scissors. These two models are interesting for a comparison with respect to both the difference in the substrate thickness and the cutting type. The last one, **model 3**, has the substrate height of model 2, but has a larger area of the substrate and the ground plane and it will be interesting to see how much that larger ground plane size will improve the front-to-back ratio in the radiation pattern. The measurements were done using *MegiQ* vector network analyzer VNA-0460e, and the radiation measurement system RMS-0640 [29], for most of the results.

3.1. Measurement of the Antenna Model 1

The antenna model 1 has a thicker substrate ($h = 4.68$ mm) than the one in

model 2, while the substrate length and width are 50 mm and 57 mm, respectively (recall **Table 1** for a complete list of design values). From the measured S_{11} curve (**Figure 6**), we can read off that the -10 dB bandwidth is between 2.18 GHz and 2.73 GHz, which makes 550 MHz of the absolute bandwidth and 22.4% of the fractional bandwidth! The normalized radiation pattern shown in **Figure 7** was measured at 2.45 GHz. It exhibits an expected maximum radiation that is perpendicular to the antenna ground plane, with -3 dB beamwidth of over 80° and front-to-back (F/B) ratio of 5 dB or better. The realized gain is $G_r = 2.8$ dB and the radiation efficiency of $e_{rad} = 36.5\%$.

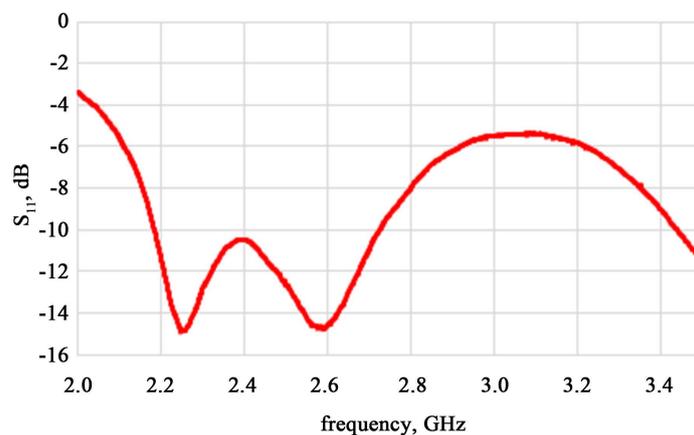


Figure 6. S_{11} parameter of the antenna model 1.

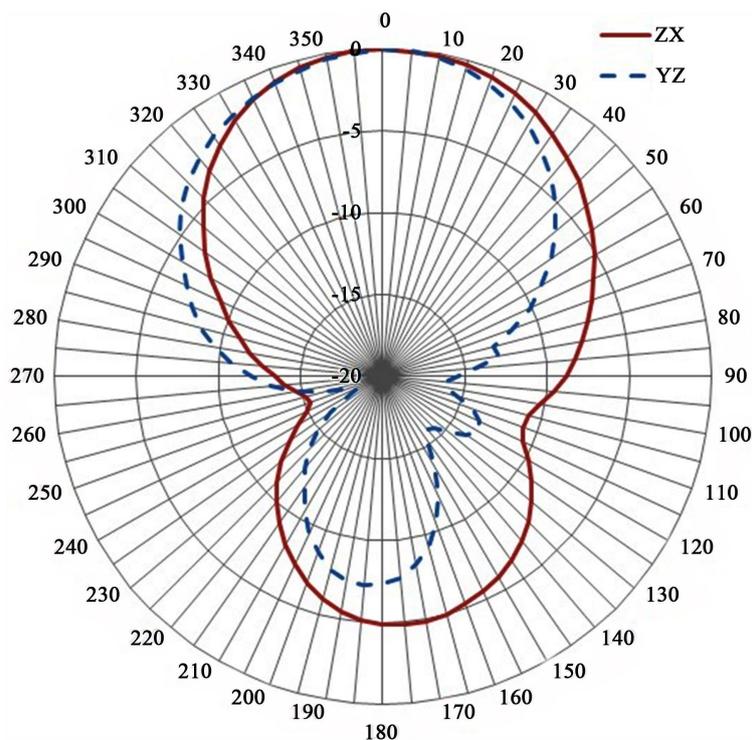


Figure 7. The normalized radiation pattern of the antenna model 1 measured at 2.45 GHz. Two major cut-planes of the electric field are shown: ZX- and YZ-cut plane.

3.2. Measurement of the Antenna Model 2

The S_{11} -parameter of the antenna model 2 is shown in **Figure 8**. Its -10 dB impedance bandwidth spans from 2.22 GHz to 2.93 GHz, which makes 710 MHz of the absolute bandwidth and 21.36% of the fractional bandwidth. The normalized radiation pattern is shown in **Figure 9**. It has the beamwidth wider than 75° in either cut-plane and the F/B ratio better than 6 dB. The realized gain is $G_r = 3$ dB and the radiation efficiency of $e_{rad} = 36.7\%$. Due to minor difference in the designs of model 1 and model 2, and various imperfections that occur during the assembly of the models, it turned out that model 2 exhibited a slightly larger bandwidth in spite of its nominally thinner substrate and also showed a little bit better gain, radiation efficiency, and F/B ratio.

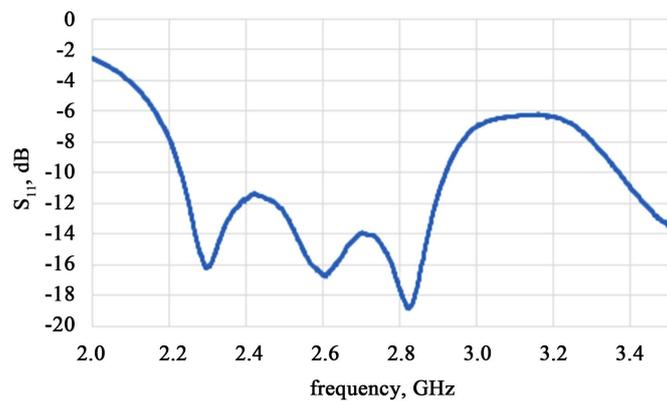


Figure 8. S_{11} parameter for antenna model 2.

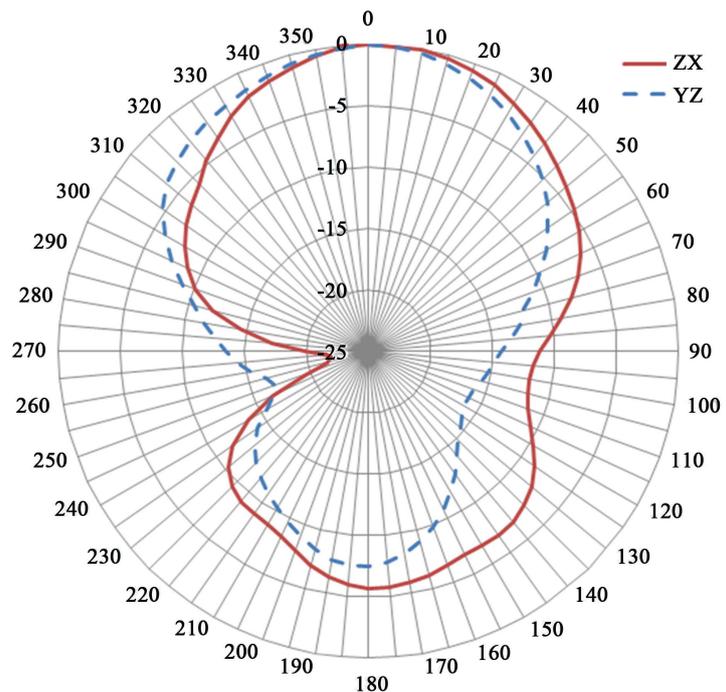


Figure 9. The normalized radiation pattern of the antenna model 2 measured at 2.45 GHz and presented by means of the ZX- and YZ-cut plane.

3.3. Measurement of the Antenna Model 3

The model 3 differs from the model 2 merely for having a larger ground plane (and substrate) and we will compare its results with respect to the results of model 2. The S_{11} -parameter of the antenna model 3 is shown in **Figure 10**. Its -10 dB impedance bandwidth spans from 2.237 GHz to 2.9 GHz, which makes 663 MHz of the absolute bandwidth and 21.41% of the fractional bandwidth. The respective normalized radiation pattern is shown in **Figure 11**. It has the beamwidth of over 70° in the YZ-plane and 90° in the ZX-plane, and F/B ratio of 8 dB, which is better than model 2. The realized gain is $G_r = 3.3$ dB and the radiation efficiency equal to $e_{rad} = 42.3\%$, which are both slightly better than the respective results for the model 2. The summary of the measured results is presented (**Table 2**).

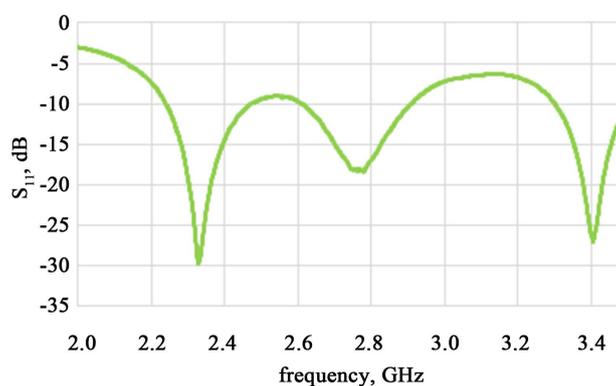


Figure 10. S_{11} parameter for the antenna model 3.

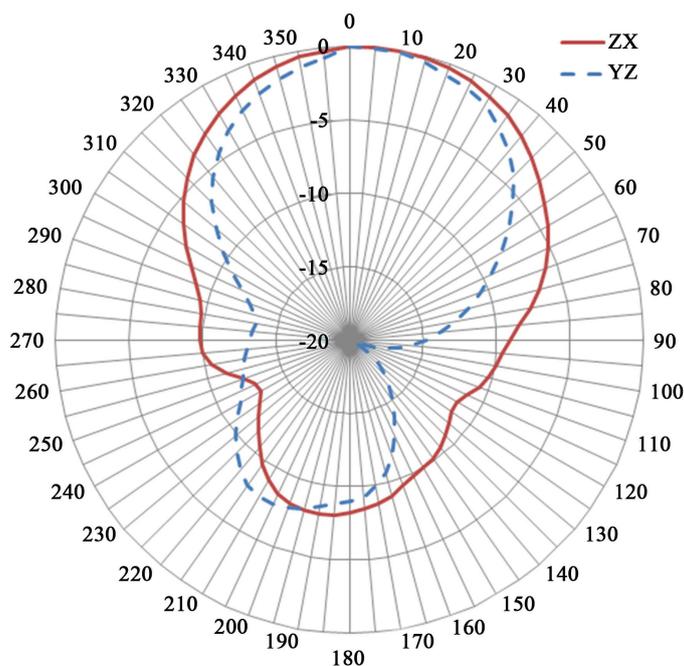


Figure 11. Radiation pattern of antenna model 3 measured at 2.45 GHz and presented by two major cut-planes.

Table 2. A comparison of the measured results.

Output Parameter	Antenna Model		
	Model 1	Model 2	Model 3
absolute bandwidth (MHz)	550	710	663
fractional bandwidth (%)	22.4	21.36	21.41
realized gain (dB)	2.8	3	3.3
radiation efficiency (%)	36.5	36.7	42.3
minimum beamwidth (°)	80	75	70
front-to-back ratio (dB)	5	6	8

Comparing the summarized results, one can notice that model 3 has slightly better results than the other two models, yet the question is whether it is actually worth to have the ground plane 20 mm larger (in comparison to the other two models) for achieving those slightly better results. In our opinion, it is not worth it, because it is probably more significant for most users to have a smaller antenna with comparable values of most of the parameters, while the back radiation suppression can be mitigated using some other and more efficient approach.

Furthermore, one can make an observation that the zig-zag cutting did not make the antenna behavior less competitive to the antenna model prepared with the straight cutting of the substrate layers, but we will also show a few more comparative analyses that can be of a practical value for the design and assembly of textile antennas.

3.4. Additional Comparisons of a Practical Value

We also want to comment on a few more interesting findings that can help a practical antenna design. In this section, we have already shown that there has generally not been any relevant difference between the straight- and zig-zag-cut textile, but it was shown on two slightly different models (*i.e.* model 1 vs. model 2). Here, we will make a direct comparison on the same model—model 2, but having two variants: with zig-zag cutting and with straight cutting. The result is shown in **Figure 12**, as obtained by the measurement of the S_{11} parameter using a KeySight Technologies FieldFox N9914A VNA. These curves are little less smooth than the curves before because the resolution in this case was set to 5 MHz unlike the earlier measurements where it was set to 1 MHz. The result for the straight cut is labeled as “Measured S_H” and the zig-zag cut as “Measured Z_H”.

The dotted curve is the result of the simulation, just for the reference, but the simulation was done for a lossless case, which is why its curve is so narrow and with a deeper notch than the other two curves. From the above two curves, it is apparent that the difference between the results for the straight- and the zig-zag-cut is negligible, which is perhaps a bit surprising for the reason that the

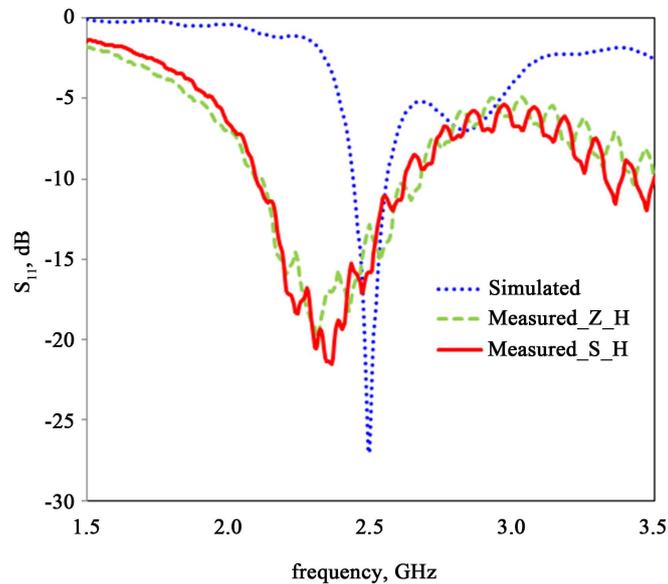


Figure 12. A comparison of S_{11} parameter for the antenna model 2 prepared with the straight- vs. the zig-zag cut substrate.

zig-zag cut creates uneven substrate edges, which can affect the fields at the substrate edges.

Another brief test was performed to see how much the resonance location will shift if the antenna surface is pressed. We did it by squeezing the antenna structure between the thumb on the upper surface and the rest of the fingers on the lower surface. **Figure 13** shows the results. It is evident that the pressure on the antenna surface (“Measured_H” curve) shifted the resonance lower. We can justify that by annihilating the air bubbles, which may have been present between the substrate layers as the consequence of an imperfect adhesion process. Namely, possible presence of air bubbles between the substrate layers contributes to a lower value of the effective permittivity ϵ_{eff} , which then causes the resonance frequency shift to a slightly higher value (see the solid line, labeled *Measured*). When the antenna body is pressed, the air bubbles are ejected from the space between the layers and ϵ_{eff} value gets closer to ϵ_r value, positioning the *Measured_H* curve (the dashed line) closer to the simulated curve (the dotted line). In fact, the activated pressure even improved the S_{11} characteristics to some degree, by making a better matching (lowering the values of the S_{11} curve), while having a similar bandwidth as the non-pressed case. It is a desirable behavior for the fact that the surface of a mounted wearable antenna can readily be pressed by an external force.

In the earlier sections, we presented only the measurement results of the antenna radiation patterns (which is what ultimately matters). However, to show that the radiation of the fabricated antennas is very close to the characteristics of the simulated antennas, in **Figure 14** we present the results for the case of the antenna model 2, while the results are very similar for the other two models. We can see that the simulated and measured patterns follow each other very closely

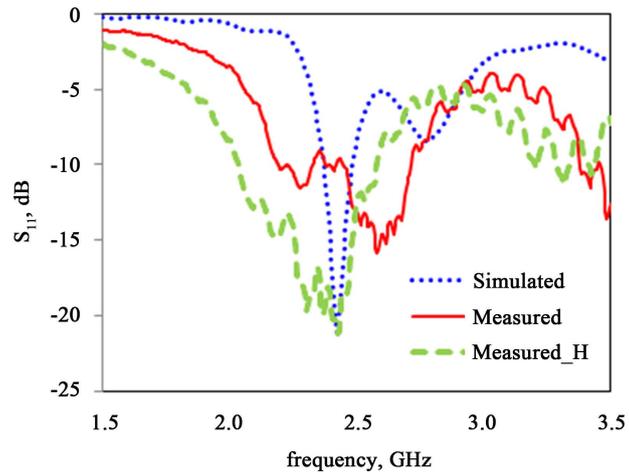


Figure 13. A shift in the resonance frequency of antenna model 2 measured without- and with- the pressure applied on the antenna surface.

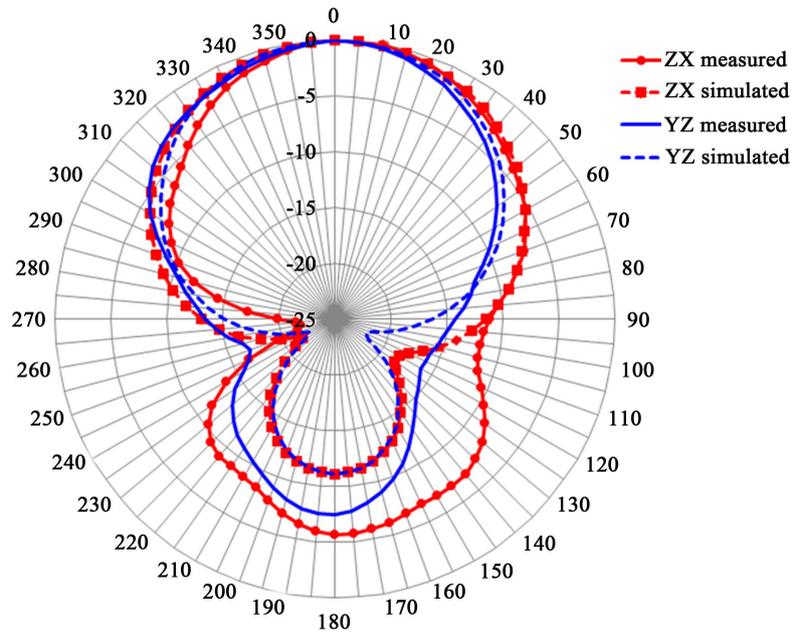


Figure 14. The normalized radiation patterns for the antenna model 2: measured vs. simulated results for the two major cut-planes.

in the main lobe direction, except for the fact that the simulation was prepared for a lossless substrate and there is some difference in the back lobe suppression between the simulated and the measured results.

We also wetted the antenna model 3 to test how strong an effect it makes on the S_{11} parameter curve. The impedance bandwidth remained comparably wide as earlier, but the resonance frequency shifted down to the center frequency at 2 GHz. That behavior was qualitatively expected because water has a much higher relative permittivity than jeans, yet the particular resonance frequency shift will depend on the quantity of water the substrate was wetted with. A more detailed study of that impact can be found in [30].

4. Antenna with a Conductive Textile Ground

While the above models were measured with the copper foil serving as the ground plane, we followed up by replacing it with a conductive textile layer. The SMA connector was attached to it via a metallic snap and a copper ring pad being placed between the connector plane and the ground plane (**Figure 1(b)**), to enable good electrical contact by standard soldering and protect the conductive textile from high temperature of the solder (**Figure 15**). In addition, there were just three layers of jeans serving as the substrate, which were adhered by hot-ironing adhesive foils, except for the ground plane and the patch that were glued in order to avoid their damaging by a high temperature of the iron. The S_{11} curve maintained a wideband characteristics by covering a band from 2.1 GHz to 2.88 GHz, thus having a 780 MHz of the absolute bandwidth, which is 31% of the fractional bandwidth. The radiation pattern was measured at 2.3 GHz and 2.5 GHz and the patterns exhibit the behavior similar to the previous one.

5. Conclusions

We presented a wideband, probe-fed, circularly polarized rectangular patch textile antenna that was designed for the E-band (2.45 GHz). A successful performance around the nominal resonance frequency was demonstrated, exhibiting a wide frequency band (of about 21%) and a good realized gain (of about 3 dB).

Inherent limitations in the design, simulation, and fabrication of textile antennas lie in the fact that working with fabrics cannot be as precise as working with hard substrates due to fabrics softness, stretchability, and susceptibility to fraying during the cutting process, as well as the property of humidity and water absorption. Because of these properties, it is also harder to create a textile antenna with a more complex patch layout as it is normally the case when hard substrates are used. With already mentioned possibility that air bubbles be present after adhering two layers, it is practically impossible to include these various and randomly present microscopic effects in the simulation model. Thankfully, the work presented here and in various other papers has shown that these imperfections do not drastically alter the predicted antenna characteristics.



Figure 15. A conductive textile sheet serving as the ground plane, with a connector attached to it.

And one less spoken-about challenge that can be identified in this context is related to feeding the power to the antenna. It stems from the fact that an SMA connector is relatively too bulky and inflexible for a structure like a textile antenna that is normally intended for seamless integration with a garment. For the future research, the motivation is to come up with an antenna feeding system that will have a lower profile than a typical combination of a coaxial cable and an SMA connector that is nowadays used as a standard.

Acknowledgements

This work has been supported in part by the University of Rijeka under the project number 1435.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Sazonov, E. and Neuman, M. R. (2014) *Wearable Sensors: Fundamentals, Implementation and Applications*. Academic Press, London.
- [2] Schneegass, S. and Amft, O. (2017) *Smart Textiles: Fundamentals, Design, and Interaction*. Springer, Berlin. <https://doi.org/10.1007/978-3-319-50124-6>
- [3] Salonen, P., Rahmat-Samii, Y., Hurme, H. and Kivikoski, M. (2004) Effect of Conductive Material on Wearable Antenna Performance: A Case Study of WLAN Antennas. 2004 *IEEE Antennas and Propagation Society Symposium*, Monterey, CA, 20-25 June 2004. <https://doi.org/10.1109/APS.2004.1329672>
- [4] Locher, I., Klemm, M., Kirstein, T. and Troster, G. (2006) Design and Characterization of Purely Textile Patch Antennas. *IEEE Transactions on Advanced Packaging*, **29**, 777-788. <https://doi.org/10.1109/TADVP.2006.884780>
- [5] Trajkovikj, J., Zurcher, J. and Skrivervik, A. (2012) Soft and Flexible Antennas on Permittivity Adjustable PDMS Substrates. 2012 *Loughborough Antennas & Propagation Conference (LAPC)*, Loughborough, 12-13 November 2012, 1-4. <https://doi.org/10.1109/LAPC.2012.6402953>
- [6] Rahman, H., Rahim, S., Abedian, M. and Najib, N. (2016) Design of a Flexible Antenna Using Printed Silver Loaded Epoxy on PDMS/Plastic Substrate for Wearable Applications. 2016 *10th European Conference on Antennas and Propagation*, Davos, Switzerland, 10-15 April 2016, 1-4. <https://doi.org/10.1109/EuCAP.2016.7481327>
- [7] Simorangkir, R.B.V.B., Yang, Y., Matekovits, L. and Esselle, K. (2017) Dual-Band Dual-Mode Textile Antenna on PDMS Substrate for Body-Centric Communications. *IEEE Antennas and Wireless Propagation Letters*, **16**, 677-680. <https://doi.org/10.1109/LAWP.2016.2598729>
- [8] Lilja, J., Salonen, P. and Maagt, P. (2009) Environmental Characterization of Industrial Fabric for Software Antenna. 2009 *IEEE Antennas and Propagation Society International Symposium*, Charleston, SC, 1-5 June 2009.
- [9] Usha, P. and Nagamani, K. (2018) Design, Simulation and Implementation of UWB Wearable Antenna. *3rd IEEE International Conference on Recent Trends in Elec-*

tronics, Information & Communication Technology (RTEICT), Bangalore, India.

<https://doi.org/10.1109/RTEICT42901.2018.9012446>

- [10] Rashid, M., Rahman, A., Paul, L. and Sarkar, A. (2019) Performance Evaluation of a Wearable 2.45 GHz Planar Printed Meandering Monopole Textile Antenna on Flexible Substrates. *1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT-2019)*, Dhaka, Bangladesh, 3-5 May 2019, 1-6.
- [11] Joler, M. and Boljkovac, M. (2018) A Sleeve-Badge Circularly Polarized Textile Antenna. *IEEE Transactions on Antennas and Propagation*, **66**, 1576-1579. <https://doi.org/10.1109/TAP.2018.2794420>
- [12] Purohit, S. and Raval, F. (2014) Wearable-Textile Patch Antenna Using Jeans as Substrate at 2.45 GHz. *International Journal of Engineering Research & Technology*, **3**, 2456-2460.
- [13] Gil, I. and Fernandez-Garcia, R. (2016) Wearable GPS Patch Antenna on Jeans Fabric. *Proceedings of 2016 Progress in Electromagnetic Research Symposium (PIERS)*, Shanghai, China, 8-11 August 2016. <https://doi.org/10.1109/PIERS.2016.7734859>
- [14] Khan, S., Singh, V.K. and Naresh, B. (2015) Textile Antenna Using Jeans Substrate for Wireless Communication Application. *International Journal of Engineering Technology Science and Research*, **2**.
- [15] Sharma, N. and Goen, A. (2015) Circularly Polarized Square Patch Antenna with Trimmed Corners Using Textile Material. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, **4**, 422-426.
- [16] Ibanez-Labiano, I. and Alomainy, A. (2020) Dielectric Characterization of Non-Conductive Fabrics for Temperature Sensing through Resonating Antenna Structures. *Materials*, **13**, E1271. <https://doi.org/10.3390/ma13061271>
- [17] Gil, I. and Fernandez-Garcia, R. (2017) SAR Impact Evaluation on Jeans Wearable Antennas. *2017 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 19-24 March 2017. <https://doi.org/10.23919/EuCAP.2017.7928181>
- [18] Murali, S.D., Muni, G.N.M., Varma, Y.D. and Chaitanya, S.V.S.K. (2014) Development of Wearable Antennas with Different Cotton Textiles. *International Journal of Engineering Research and Applications*, **4**, 8-14.
- [19] Wang, K. and Li, J. (2018) Jeans Textile Antenna for Smart Wearable Antenna. *12th International Symposium on Antennas, Propagation and EM Theory (ISAPE)*, Hangzhou, China, 3-6 December 2018. <https://doi.org/10.1109/ISAPE.2018.8634337>
- [20] Li, J., Jiang, Y. and Zhao, X. (2019) Circularly Polarized Wearable Antenna Based on Ninja Flex-Embedded Conductive Fabric. *International Journal of Antennas and Propagation*, **2019**, Article ID: 3059480. <https://doi.org/10.1155/2019/3059480>
- [21] LessEMF. <http://www.lessemf.com>
- [22] Sankaralingam, S. and Gupta, B. (2010) Determination of Dielectric Constant of Fabric Materials and Their Use as Substrates for Design and Development of Antennas for Wearable Applications. *IEEE Transactions on Instrumentation and Measurement*, **59**, 3122-3130. <https://doi.org/10.1109/TIM.2010.2063090>
- [23] Balanis, C.A. (2005) *Antenna Theory: Analysis and Design*. 3rd Edition, Wiley-Interscience, New York.
- [24] Pozar, D.M. (1992) Microstrip Antennas. *Proceedings of IEEE*, **80**, 79-81. <https://doi.org/10.1109/5.119568>
- [25] Nascimento, D.C., Schildberg, R. and da Lacava, J.C.S. (2010) Design of Probe-Fed

Circularly Polarized Rectangular-Patch Thick Microstrip Antenna Revisited. *Proceedings of 2010 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, Ontario, Canada, 11-17 July 2010.

<https://doi.org/10.1109/APS.2010.5562077>

- [26] Dassault Systemes. Computer Simulation Technology. Microwave Studio.
<http://www.cst.com>
- [27] SparkFun (2016) Conductive MedTex180 Fabric.
<https://www.sparkfun.com/products/10055>
- [28] SparkFun (2016) Conductive Ripstop Fabric.
<https://www.sparkfun.com/products/10056>
- [29] MegiQ (2018) <https://www.megiq.com/>
- [30] Bonefačić, D., Bartolić, J., Ivšić, B. and Katalenić, M. (2019) Wideband Textile Planar Monopole Antenna. 2019 *European Microwave Conference in Central Europe (EuMCE)*, Prague, Czech Republic, 13-15 May 2019.