Abstract—This paper presents a rectangular patch antenna fed by proximity coupling fabricated on textile substrate. The antenna was designed aiming at two objectives simultaneously: to facilitate the manufacture of the textile antenna and increase its operating frequency bandwidth. The antenna feeding circuit consists of a quarter wavelength impedance transformer cascaded to an open-ended transmission line, which is electromagnetically coupled to the antenna radiating element. Both impedance transformer and open-ended transmission line are realized by embedded microstrip lines and have the same width, facilitating the manufacture of the textile antenna. The antenna bandwidth can be increased by properly choosing the widths of the rectangular patch and feed lines. In the present study, the design and performance of textile rectangular patch antennas fed by proximity coupling and by coaxial probe are presented for comparison purposes. The antennas were designed for operation in the 2.45 GHz band and were fabricated using denim for the dielectric substrate and conductive fabric for the radiating element, ground plane, and feed lines. The experimental results are in good agreement with the simulated ones. The antenna fed by coaxial probe showed a fractional impedance bandwidth of 5.7% and the antennas fed by proximity coupling demonstrated bandwidths of 11.8% and 15.5%.

Index Terms—Microstrip antennas, Proximity coupling, Textile antennas.

I. INTRODUCTION

Patch antennas are an attractive solution for various wireless communication systems, due to their simplicity of structure, reduced weight and thickness, and low cost. Moreover, these antennas can be easily integrated into RF circuits using single or multilayer substrate [1], [2].

In recent years, patch antennas using textile substrates [3], [4] have attracted the attention of researchers due to the increasing interest in wearable electronics and the rapid progress of wireless communication applications. In this area, wireless networks employing BAN protocols (Body Area Networks) operating in the 2.45 GHz ISM band are suitable for use in radio frequency identification systems RFID and Smart Houses [5], [6]. When compared to antennas using conventional microwave substrates, patch antennas using textile substrates have the advantage of being easily integrated into clothing, for applications such as real-time tracking and rescue activities [7], [8]. Patch antennas fed
by coaxial probe or indented microstrip line are the simplest ones, but usually have narrowband performance [9]. Some simple design techniques can be applied to increase the operating frequency band of these antennas, such as the use of thicker substrates, parasitic elements added to the radiator, and reduced ground plane. However, these solutions have some drawbacks. The use of thicker substrates increases the excitation of surface waves, reducing the antenna efficiency [9]. Moreover, the reduction of the ground plane of textile antennas is not desirable, since it protects the user’s body tissues from electromagnetic radiation. Furthermore, the use of parasitic elements leads to more complex topologies, making difficult the manufacture of textile antennas.

The materials that are usually employed as dielectric substrates and conductive layers of textile antennas have moderate losses, which cause unintended bandwidth increase at the expense of reducing the radiation efficiency of the antenna and thus its gain [9]. For practical applications, it is of interest to study textile antennas topologies that are easy to manufacture and have the potential to achieve increased operating bandwidths. Rectangular patch antennas fed by proximity coupling are promising for meeting this goal [10]–[12].

The organization of this paper is as follows: Section II presents the antennas design and describes a modified topology of proximity coupled patch antenna. The manufacturing process of the designed antennas using denim substrate and conductive fabric is described in Section III. In Section IV, simulated and experimental results of the designed antennas are presented and discussed. Finally, Section V shows the conclusions of the present research work.

II. ANTENNAS DESIGN

Rectangular patch antennas on textile substrate were designed using two different feeding methods: coaxial probe and proximity coupling. The antennas were designed to operate at the center frequency of 2.45 GHz. The performance of the designed antennas was investigated, in order to compare their operation bandwidths. The materials used in the antennas design and fabrication are: denim, as dielectric substrate, and PCPTF (Pure Copper Polyester Taffeta Fabric) for the radiating element, feeding lines, and ground plane [13]. The electrical characteristics of the denim used in the antennas design were determined experimentally using the technique presented in [14], resulting in dielectric constant \( \varepsilon_r = 1.77 \) and loss tangent \( \tan\delta = 0.05 \). The thickness of the substrate was measured along a denim sample area of 10 mm × 10 mm using a caliper, resulting in an average value of 0.7 mm. The parameters of PCPTF were provided by the manufacturer: conductivity \( \sigma = 2.5 \times 10^5 \text{ S/m} \) and thickness \( t = 0.08 \text{ mm} \).

A. Antenna using coaxial probe feed

Microstrip patch antennas used in microwave frequencies employ radiators composed by laminar elements, i.e., with thickness much smaller than the antenna operating wavelength in free space – \( \lambda_0 \). In its simplest form, the patch antenna consists of two parallel conductive layers separated by a thin
dielectric layer, known as substrate, one of the conductive layers being the radiating element and the other one being the ground plane.

The radiating element can be designed using virtually an unlimited number of geometric shapes, resulting in antennas with different radiation characteristics. In a typical procedure for manufacturing textile antennas, the radiating element is cut from a sheet of conductive material and then fixed on a textile substrate by gluing or sewing [15]. In this case, rectangular patch radiators are often used, since its geometry simplicity facilitates the textile antenna manufacture. Fig. 1 shows the topology of a rectangular patch antenna fed by coaxial probe, where \( W \) and \( L \) are the width and the length of the radiating element, respectively, \( h \) is the substrate thickness, and \( d \) is the distance between the radiator and substrate edges. The coaxial probe is connected at a distance \( y_0 \) from the edge of the radiating element that provides good input impedance matching.

![Fig. 1. Microstrip antenna fed by coaxial probe.](image)

A thick substrate comprising two stacked layers of denim was used in the antenna design, resulting in an average substrate thickness \( h = 1.4 \) mm. The use of a thicker substrate aimed to reduce the conductive losses of the antenna [16]. The rectangular patch textile antenna using coaxial feed was designed following the procedure described in [9], using (1)–(4) and considering \( \varepsilon_r = 1.77 \) and \( h = 1.4 \) mm.

\[
W = \frac{c}{2f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}
\]

\[
\varepsilon_{ref} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{h}{W} \right)^{\frac{1}{2}} \tag{2}
\]

\[
L = \frac{c}{2f_{\varepsilon_{ref}}} \frac{2\Delta L}{2\Delta L} \tag{3}
\]

where,

\[
\Delta L = 0.412 h \frac{\left( \varepsilon_{ref} + 0.3 \right) \left( \frac{W}{L} + 0.264 \right)}{\left( \varepsilon_{ref} + 0.258 \right) \left( \frac{W}{K} + 0.8 \right)} \tag{4}
\]

The dimensions of the patch radiator and connection position of the coaxial probe antenna feed were optimized using the electromagnetic simulation program HFSS™, resulting \( W = 38 \) mm, \( L = 43.3 \) mm, \( h = 1.4 \) mm, \( y_0 = 8.2 \) mm, and \( d = 25 \) mm. According to the simulation, the designed antenna is expected to operate at the center frequency of 2.45 GHz with 5.3% fractional bandwidth for 10 dB return loss.
B. Antenna fed by proximity coupling

Two rectangular patch antennas fed by proximity coupling were designed. The design procedure was focused on obtaining antennas with increased bandwidths when compared to rectangular patch antennas using coaxial probe feed. Fig. 2 shows the topology of the designed antennas, which employ two attacked denim layers as dielectric substrate. The radiating element is placed on the upper face of the stacked substrate, and the ground plane on its lower face. A metallic strip is inserted between the two substrates and, together with ground plane, composes an embedded microstrip line that conducts the input signal up to the antenna radiator [17]. This line is terminated by an open-circuit and electromagnetically couples the microwave signal to the radiator.

Fig. 2. Patch antenna fed by proximity coupling.

A small length of the upper dielectric layer of the stacked substrate is removed, creating a bonding pad for soldering the input connector. The bonding pad is designed as a 50 Ω microstrip line with width \(W_1\) and length \(L_1\). The signal feed line covered by the upper dielectric layer of the substrate has width \(W_2\) and consists of two parts: the coupling line located below the radiating element – an embedded microstrip line with length \(S\), and the open-ended line with length \(L_2\) placed below the antenna radiator.

The design of this kind of antenna has a higher degree of complexity than that of the coaxial probe fed antenna. The length \(S\) of the coupling line affects the level of signal coupled to the radiating element. The radiator impedance seen by the feed line circuit at the radiating element edge depends on the ratio of \(S\) to \(W\), where \(W\) is the patch width.

The design procedure consisted of determining a set of initial values for the antenna parameters, which were next optimized using 3D EM simulation. The initial values for the radiator dimensions, \(W\) and \(L\), were calculated using (1)–(4). The start value used for the length of the feed line below the radiating element was \(S = L/2\), a suitable condition for maximum signal coupling [12].

In order to facilitate the manufacture of the textile antenna, it was imposed that the width of the input line should be \(W_2 \geq 5\) mm along the entire length of the embedded microstrip line, making the cutting process of the conductive fabric easier and more accurate.

However, electromagnetic simulations showed that the radiator impedance seen by the input line at the radiator edge was lower than 50 Ω for \(W_2 \geq 5\) mm. In order to achieve impedance matching to 50 Ω, the embedded line length \(L_2\) is designed to act as a quarter wavelength impedance transformer.
The length $L_2$ was computed using (5)–(7), where $e'_r$ is the effective dielectric constant of the embedded line [17].

Impedance matching to 50 $\Omega$ is achieved by using a quarter-wave transformer inserted between the antenna input and the radiator, composed by the embedded microstrip line section of length $L_2$.

$$L_2 = \frac{\lambda_{sf}}{4}$$  \hspace{1cm} (5)

where,

$$\lambda_{sf} = \frac{c}{f \sqrt{e'_r}}$$  \hspace{1cm} (6)

$$e'_r = e_r \left(1 - e \left(\frac{-1.55h_2}{h_1}\right)\right)$$  \hspace{1cm} (7)

Two antennas fed by proximity coupling were designed, one with $W_2 = 5$ mm and other with $W_2 = 6$ mm, which resulted in embedded microstrip lines with characteristic impedances of 28.3 $\Omega$ and 24.6 $\Omega$, respectively. The width $W$ of the radiator was optimized using 3D EM simulation, so that the antenna impedance at the plane of the radiator edge could be matched to 28.3 $\Omega$ by the designed embedded microstrip lines a quarter-wavelength long. It was found that values close to 46 mm for $W$ lead to good antenna input impedance matching for both values considered for $W_2$, resulting in two antennas with distinct bandwidths. The final dimensions of the designed antennas using $W_2 = 5$ mm and 6 mm are: $W = 46.2$ mm, $L = 42.3$ mm, $h_1 = 0.7$ mm, $h_2 = 1.48$ mm, $d = 10$ mm, $S = 18.2$ mm, $L_2 = 24.3$ mm, $W_f = 2.3$ mm, and $L_f = 5$ mm. Simulation results indicated operating center frequency of 2.45 GHz for both antennas and 10 dB impedance bandwidth of 11.8% for the antenna with $W_2 = 5$ mm, and 15.9% for the antenna with $W_2 = 6$ mm.

III. MANUFACTURING PROCESS

Initially, the denim fabric used as the antenna dielectric substrate and the PCPTF structures used as radiator, feed line, and ground plane were cut with a blade cutter. Subsequently, the conductive fabric structures were sewn on the denim substrate using dielectric line. A SMA launcher was connected to the antenna input, using soldering iron and tin-lead solder. Photographs of the fabricated antennas are shown in Figs. 3 and 4.

(a) Front view
(b) Back view

Fig. 3. Photograph of the antenna fed by coaxial probe.
IV. RESULTS AND DISCUSSION

The input return loss of the antenna prototypes were measured from 1 to 4 GHz using HP8722D Vector Network Analyzer. Fig. 5 shows the simulated and measured results for the coaxial probe fed antenna, which are in good agreement. This antenna has a center frequency of 2.45 GHz, and measured bandwidth of 5.7%.

Fig. 5. Return loss versus frequency – coaxial probe fed antenna.

Fig. 6 shows simulated and measured return loss of the proximity coupling fed antenna using feed line width $W_2 = 5$ mm. Good impedance matching is observed at the center frequency of 2.45 GHz. The measured bandwidth of the proximity coupling fed antenna was 11.8%, demonstrating a significant increase when compared to the antenna fed by coaxial probe.

Fig. 6. Return loss versus frequency – proximity coupling fed antenna with $W_2 = 5$mm.

The input return loss of the proximity coupling fed antenna with feeding line width $W_2 = 6$ mm, designed for additional increase in the operation bandwidth, is presented in Fig. 7. Again, it is noted
that the measured and simulated results are in good agreement. This antenna center frequency is 2.45 GHz, with good impedance matching to 50 Ω. The measured bandwidth of this antenna was increased to 15.5%.

Fig. 7. Return loss versus frequency – proximity coupling fed antenna with $W_2 = 6$ mm.

Fig. 8 shows the measured return loss versus frequency curves of the three designed antennas. This figure shows an increased operating bandwidth for the proximity coupling fed antennas when compared to the coaxial probe fed antenna. It is also noted that the width $W_2$ of the feeding line of the proximity coupling fed antenna is a design parameter that can be used to increase the antenna bandwidth.

Fig. 8. Measured return loss versus frequency curves: antenna A: coaxial probe fed antenna; antennas B and C: proximity coupling fed antennas with $W_2 = 5$ mm and 6 mm, respectively.

The antennas’ radiation patterns were measured using a low cost anechoic chamber, as shown in Fig. 9 (a). The coordinate system employed in the measurements of the radiation patterns is presented in Fig. 9 (b).

(a) Anechoic chamber

(b) Coordinate system

Fig. 9. Measurement of the antennas’ radiation patterns.
Fig. 10 shows simulated and measured radiation patterns of the antenna fed by coaxial probe and Figs. 11 and 12 present simulated and measured radiation patterns for the antennas fed by proximity coupling.

![Fig. 10. Radiation patterns of the rectangular patch antenna fed by coaxial probe.](image)

![Fig. 11. Radiation patterns of the rectangular patch antenna fed by coupling proximity - W2 = 5 mm.](image)

![Fig. 12. Radiation patterns of the rectangular patch antenna fed by coupling proximity - W2 = 6 mm.](image)

Table I presents the simulated and measured half-power beamwidth of the designed antennas, and Table II shows their simulated and measured maximum gains. The proximity coupling fed
antennas presented gains slightly smaller than the coaxial probe fed one, shown a tradeoff between gain and bandwidth.

### Table I. Half-power beamwidth

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Plane</th>
<th>Half-power Beamwidth (degrees)</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaxial probe fed antenna</td>
<td>x-y</td>
<td>80</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>z-x</td>
<td>102</td>
<td></td>
<td>91</td>
</tr>
<tr>
<td>Proximity coupling fed antenna</td>
<td>x-y</td>
<td>120</td>
<td></td>
<td>93</td>
</tr>
<tr>
<td>W₂ = 5 mm</td>
<td>z-x</td>
<td>105</td>
<td></td>
<td>91</td>
</tr>
<tr>
<td>Proximity coupling fed antenna</td>
<td>x-y</td>
<td>120</td>
<td></td>
<td>91</td>
</tr>
<tr>
<td>W₂ = 6 mm</td>
<td>z-x</td>
<td>105</td>
<td></td>
<td>103</td>
</tr>
</tbody>
</table>

### Table II. Maximum antenna gain

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Maximum Gain (dB)</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaxial probe fed antenna</td>
<td>1.65</td>
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<td>1.42</td>
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<td>Proximity coupling fed antenna</td>
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<td>W₂ = 5 mm</td>
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<tr>
<td>Proximity coupling fed antenna</td>
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<td>0.33</td>
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<tr>
<td>W₂ = 6 mm</td>
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</tbody>
</table>

V. CONCLUSION

A study was carried out on rectangular patch antennas using textile substrates in order to obtain an antenna topology resulting in both increased operation bandwidth and non-critical dimensions that facilitate textile antennas fabrication. The investigation was focused on rectangular patch antennas fed by proximity coupling. A feeding structure was proposed, which employs a quarter-wavelength transformer cascaded to an open-ended transmission line electromagnetically coupled to the radiator. It was noticed that distinct bandwidths can be achieved by adjusting the feeding line dimensions and radiator width.

A design procedure for the modified proximity coupling fed antenna is presented. Two textile rectangular patch antennas employing distinct input line widths were designed on denim substrate for operation at 2.45 GHz ISM band. A textile patch antenna fed by coaxial probe was also designed at the same band for comparison purposes.

The measured performance of the fabricated antennas was in good agreement with simulation results, demonstrating the effectiveness of the design procedure used. The measured antenna bandwidths were 5.7% for the coaxial probe fed antenna and 11.8% and 15.5% for proximity coupling fed antennas using 5 mm and 6 mm input line widths, respectively. The measured performance of the designed antennas demonstrated the potential of the modified proximity coupling fed antenna for increased bandwidth operation when compared to coaxial probe fed antennas.
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REFERENCES


