Design and Experimental Evaluation of a Printed Monopole Antenna for GPR Applications

Abderrezak Khalfallaoui1,*, Abdelhalim Chaabane1, and Abdesselam Babouri2

1Laboratoire des Télécommunications-LT, Université 8 Mai 1945 Guelma, BP 401, Guelma 24000, Algeria
2Laboratoire de Génie Électrique de Guelma-LGEG, Université 8 Mai 1945 Guelma, BP 401, Guelma 24000, Algeria
Email: khalfallaoui.abderrezak@univ-guelma.dz (A.K.), abdelhalim.chaabane@univ-guelma.dz (A.C.), babouri.abdesselam@univ-guelma.dz (A.B.)

Abstract—In this paper, a printed monopole antenna is designed and experimentally evaluated for Ground Penetrating Radar (GPR) applications. The antenna resonates at two narrow frequency bands centered at 0.5 GHz and 2 GHz. Four stages are used to achieve the final model, which is based on a rectangular patch, a simple microstrip feed line, and a reduced ground plane. The proposed antenna consists of a simple patch with notches and a quarter-wavelength feed line. The introduced notches help to reduce the conductor losses and decrease the weight of the design. The antenna prototype is fabricated on a low-cost FR-4 epoxy substrate with dimensions of 17.55 cm×21.25 cm, using the LPKF S103 laser printer, and then measured with the R&S®ZNB Vector Network Analyzer. The experimental results demonstrate that the operating bands range between 0.48–0.52 GHz (8%) and 1.94–2.04 GHz (5.02%). The antenna exhibits good radiation patterns with a reasonable gain of 1.5/2.6 dBi and a high radiation efficiency of 97/78% at the two resonating frequencies 0.5/2 GHz, respectively. To validate the usefulness of the designed antenna for GPR applications, a penetrability test is conducted through a concrete separator wall. The electric field probe HZ551 is used to receive the electromagnetic waves behind the obstacle, and the power received by the probe is measured with the GSP-730 spectrum analyzer. The obtained results confirm that the proposed model performs well in the UHF band at 0.5 GHz and 2 GHz, with a high level of penetrability.

Index Terms—Printed monopole antenna, narrow frequency bands, dual band, Ground Penetrating Radar (GPR)

I. INTRODUCTION

The antenna is one of the most important devices in wireless communication systems. Numerous printed antennas have been proposed in the literature for various applications, including millimeter-wave and terahertz integrated circuits and systems [1–4], communication systems and microwave devices [5–8], and radio transceivers [9]. Ground penetrating radar (GPR), which focuses on detecting hidden objects, has attracted significant attention from researchers. To meet the diverse applications and requirements of GPR systems, various antenna systems have been proposed. However, these systems need to be adapted to the evolving technology of GPR. Antenna types such as Bow tie [10], Vivaldi [11], Quasi-Yagi [12], Tapered slot [13], and Dipole [14] have been suggested for GPR applications. Unfortunately, many of these antennas suffer from drawbacks such as large size, high cost, and complexity, limiting their practicality. Therefore, it is crucial to develop new antenna models that are simple, affordable, and offer improved performance.

Planar patch antennas, in comparison to traditional microwave antennas, have the advantages of being compact, lightweight, inexpensive, and easily integrated into different systems [15]. However, most of these antennas are Ultra-wideband (UWB) [16, 17], wideband [18], or processes only a single resonating band [19]. The investigation of multi-band antennas for GPR application is a significant research area that aims to provide greater flexibility in the detection process with different degrees of penetration.

Until now, only a limited number of studies have been conducted on multi-band microstrip antennas for GPR applications such as those presented in [20–22]. The penetration capability through different surfaces and obstacles primarily relies on the frequency of the signal emitted by the antenna, with lower frequencies generally enabling deeper penetration [23]. Consequently, the selection of the appropriate frequency is crucial and should align with the specific requirements of each application. For instance, low frequency waves have the ability to penetrate multiple surfaces with substantial thickness [24]. Thus, it is of a great importance to develop antennas that can operate effectively at low frequencies while also processing steady radiation characteristics, and compact size.

In order to beat the over mentioned challenges, a novel dual-band monopole patch antenna suitable for GPR applications has been designed, fabricated, and experimentally evaluated. The antenna operates in the UHF band at frequencies of 0.5 GHz and 2 GHz. The design process utilized CST Microwave Studio™ software and the physical prototype was fabricated using LPKF S103 laser printer. The experimental evaluation of the antenna’s performance was conducted using the R&S®ZNB Vector Network Analyzer, the HZ551 electric field probe, and the GSP-730 spectrum analyzer.

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*Corresponding author
This work presents additional contributions, including 1) experimental evaluation of a novel, low-cost dual-band monopole patch antenna designed specifically for GPR applications 2) the proposed antenna exhibits dual resonating frequencies and reduced size compared to existing antennas operating at similar frequencies, 3) a new experimental penetration test is conducted through a concrete wall using the electric field probe HZ551 and the spectrum analyzer GSP-730, 4) the usefulness of the fabricated antenna prototype for GPR applications is demonstrated through experimental validation, showcasing a high level of penetrability.

This paper is structured as follows: Section II provides a detailed description of the design process employed to develop the final antenna design. Section III presents the measured results and compares them with the simulated ones. In Section IV, an experimental evaluation of the antenna’s the penetration capability is performed to affirm its suitability for GPR applications. Finally, the paper concludes with a summary and concluding remarks.

II. ANTENNA GEOMETRY

The configuration and dimensions of the proposed model are depicted in Fig. 1. Four stages were implemented to obtain the final design of the antenna, as illustrated in Fig. 2. In the first stage (antenna 1), which is inspired from [25], a standard printed monopole antenna formed by a rectangular radiating element with a simple microstrip feed line and a reduced ground plane (less than 10% of the total ground plane) was considered. In the second stage (antenna 2), the conventional rectangular patch was transformed into a new shape by cutting rectangular slots and inserting splits into the patch. In the third stage (antenna 3), a quarter-wavelength feed line was introduced. In the last stage (antenna 4), two additional rectangular strips were added along the feed line on the lower edge of the patch. The proposed model was optimized to enhance its performance at specific frequencies. The optimized dimensions are given in Table I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimensions (cm)</th>
<th>Parameters</th>
<th>Dimensions (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>9</td>
<td>L</td>
<td>13</td>
</tr>
<tr>
<td>W1</td>
<td>0.2</td>
<td>L2</td>
<td>6.2</td>
</tr>
<tr>
<td>W2</td>
<td>0.8</td>
<td>L3</td>
<td>0.8</td>
</tr>
<tr>
<td>W4</td>
<td>3.5</td>
<td>L4</td>
<td>1.6</td>
</tr>
<tr>
<td>W5</td>
<td>1.5</td>
<td>L5</td>
<td>2.35</td>
</tr>
<tr>
<td>W6</td>
<td>1</td>
<td>L6</td>
<td>1.5</td>
</tr>
<tr>
<td>W7</td>
<td>2.2</td>
<td>L7</td>
<td>1.5</td>
</tr>
<tr>
<td>W8</td>
<td>0.9</td>
<td>L8</td>
<td>1.5</td>
</tr>
<tr>
<td>L0</td>
<td>0.9</td>
<td>L9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The proposed antenna was fabricated using a double-sided FR-4 epoxy substrate with a relative permittivity of 4.4 and a loss tangent of 0.025. The substrate has a thickness of 1.5 mm. The overall dimensions of the substrate are 13 cm × 9 cm × 0.15 cm, which is smaller compared to other commercially available GPR antennas operating at the same frequency bands.

III. RESULTS AND DISCUSSION

The reflection coefficients of the antennas presented in Fig. 2 are compared in Fig. 3. The initial antenna (Antenna 1), which has a reduced ground plane, resonates at two fundamental frequencies of 0.55 and 2.13 GHz. It is evident that the modifications introduced in the second stage (antenna 2) allow for tuning the higher operating frequency to 2.04 GHz and improving the resonance level in this range to −34 dB. As mentioned in [26], the inclusion of cuts and notches in a printed antenna can help reduce its weight and minimize conductor losses. Besides, the use of a half quarter-wavelength feed line in antenna 3 effects both operating bands. Finally, the introduction of a notch in antenna 4 ensures that the lower band is centered at 0.5 and the upper band at 2 GHz with good impedance matching. The designed model was adapted by exploiting different techniques including a quarter-wavelength, notches, and strips.

![Fig. 1. Structure of the proposed model.](image1)

![Fig. 2. Design stages of the designed model.](image2)

![Fig. 3. Reflection coefficient curve in each design stage.](image3)
Fig. 4. Surface current distributions at (a) 0.5 GHz, (b) 2 GHz.

As mentioned above, the antenna prototype is fabricated by using the LPKF S103 laser printer. Fig. 5(a) and Fig. 5(b) respectively illustrate the front and back views of this prototype. It occupies an area of 13 cm × 9 cm × 0.15 cm.

The reflection coefficient response of the fabricated antenna prototype was obtained using the R&S®ZNB Vector Network Analyzer. Fig. 6 illustrates the reflection coefficients ($S_{11}$ (dB)) plotted against frequency, showing a good agreement between the measured and simulated results. It can be observed that the antenna exhibits good impedance matching at the two resonating frequencies, with $|S_{11}|$ values of 16 dB at 0.5 GHz and 30 dB at 2 GHz. The simulated and measured results confirm that the fabricated antenna prototype operates in two frequency bands, the lower band ranging from 0.48 to 0.52 GHz (8%) and the upper band ranging from 1.94 to 2.04 GHz (5.02%).

Fig. 7 showcases the simulated and measured far-field radiation patterns in the $xoz$ plane (E-plane) and $xoy$ plane (H-plane) at the two resonating frequencies 0.5/2 GHz. The measured patterns closely align with the simulated ones, indicating that the fabricated antenna prototype exhibits omnidirectional patterns in the $xoz$ plane and bidirectional patterns in the $xoy$ plane, which are typical for this type of antenna. As indicated in Fig. 8, the gain at the two frequencies is simulated to be 1.5 dBi and 2.6 dBi, respectively, furthermore, the radiation efficiency is calculated to be 97% at 0.5 GHz and 78% at 2 GHz.

Fig. 5. Front and back view of the fabricated antenna.

Fig. 6. Comparison of the measured and simulated reflection coefficients.
IV. GROUND PENETRATION TEST

In this section, an experiment was conducted to validate the level of penetrability of the proposed model. As revealed in Fig. 9(a), the fabricated antenna prototype was positioned near a concrete separator wall with a width of 40 cm. Throughout the measurement process, a distance of approximately 5 cm was maintained between the antenna and the obstacle. The antenna was connected to a radio frequency generator ED-3200A, which operates at fixed frequencies including 0.5 and 2 GHz. An electric field probe HZ551 was placed behind the obstacle to serve as a receiver. A photograph of the measurement setup is shown in Fig. 9(b). The power received by the probe and the resonating peaks behind the concrete wall were measured using the spectrum analyzer GSP-730.

The measured results, obtained using the spectrum analyzer, are shown in Fig. 10. The results demonstrate that the signals emitted by the antenna at 0.5 GHz and 2 GHz, and received by the probe behind the concrete wall, exhibit acceptable power levels of approximately \(-63\) dBm and \(-62\) dBm, respectively. In addition, it is noteworthy that the signal remains detectable by the probe even when the probe's location behind the wall is altered. A summary of the obtained results is provided in Table II.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Free space (40 cm)</th>
<th>Wall (40 cm)</th>
<th>Wall+Free space (80 cm)</th>
<th>Wall+Free space (120 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>(-55)</td>
<td>(-63)</td>
<td>(-66)</td>
<td>(-72)</td>
</tr>
<tr>
<td>2</td>
<td>(-54)</td>
<td>(-62)</td>
<td>(-67)</td>
<td>(-74)</td>
</tr>
</tbody>
</table>

This test confirms that the electromagnetic waves transmitted by the proposed antenna are able to penetrate the studied obstacle effectively, indicating a strong penetration capability of the antenna. Consequently, the measured results provide evidence that our proposed antenna is highly suitable for GPR applications. To further demonstrate the convenience of the fabricated antenna, its parameters are compared with those of some existing GPR models in Table III. As it can be seen, the proposed antenna offers double resonating frequencies
and a smaller size compared to the other existing antennas.

Fig. 10. Power received by the probe at (a) 0.5 GHz, (b) 2 GHz.

Table III: Comparison of the Proposed Antenna with Some Other Existing GPR Antennas

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Sizes (cm$^3$)</th>
<th>BW (GHz)</th>
<th>Average Gain/Efficiency</th>
<th>Ant. type</th>
<th>Test of penetrability/Surfaces</th>
<th>Design complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>[27]</td>
<td>43.37</td>
<td>3–14.64</td>
<td>7 dBi/83%</td>
<td>UWB</td>
<td>Yes/Sand</td>
<td>Complex</td>
</tr>
<tr>
<td>[28]</td>
<td>1980</td>
<td>0.6–4.6</td>
<td>4.5 dB/Not studied</td>
<td>Wideband</td>
<td>Yes/Sandy soil</td>
<td>Complex</td>
</tr>
<tr>
<td>[29]</td>
<td>103.5</td>
<td>0.5–5.5</td>
<td>3.13 dB/Not studied</td>
<td>Wideband</td>
<td>Yes/wooden Table</td>
<td>Easy</td>
</tr>
<tr>
<td>[30]</td>
<td>7497</td>
<td>0.4–2.53</td>
<td>6.7 dB/Not studied</td>
<td>Wideband</td>
<td>No</td>
<td>Complex</td>
</tr>
<tr>
<td>This work</td>
<td>17.55</td>
<td>0.48–0.52</td>
<td>1.5/2.5 dB/97/78%</td>
<td>Multiband</td>
<td>Yes/Concrete Wall</td>
<td>Easy</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A novel printed monopole antenna that resonates at two narrow bands has been designed, fabricated, and experimentally measured for GPR applications. The antenna prototype was fabricated on an FR-4 epoxy substrate with a size of 17.55 cm$^3$. Excellent agreement is shown between the measured results and the simulated ones. The measured impedance bandwidths extend from 0.48 GHz to 0.52 GHz and from 1.94 GHz to 2.04 GHz. Moreover, the radiation patterns at the center of these two resonating ranges are good. A penetration test of the fabricated antenna through a concrete wall is conducted to verify its ability to function as a GPR antenna. The HZ551 electric field probe is used to receive the electromagnetic waves behind the wall. Satisfactory results are obtained by the probe and measured using the GSP-730 spectrum analyzer, confirming that the proposed antenna is well-suited for GPR applications.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Abderrezak Khalfallaoui: simulating and measuring the antenna, collecting and presenting the results, writing and editing the paper; Abdelhalim Chaabane: supervising and validating the results, methodology, and reviewing/editing; Abdessalam Babouri: providing advice on measurement methods and reviewing/editing. All authors had approved the final version.

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Abderrazak Khalfaillahou received the Ph.D. degree in electronics from the University of Littoral Côte d’Opale, France, in 2010 at the Laboratory of Materials and Components for Electronics (LEMCEL). In 2011, he joined the Laboratory of Telecommunications at the University 8 Mai 1945 of Guelma, Algeria, where he is currently an Assistant Professor. His research interests include the design and processing of radio-frequency integrated circuits, tunable ferroelectric devices, and their applications in microwaves. Since 2020, he has been focused his research on antennas, multiband antennas, and ground-penetrating radar antennas.

Abdelhalim Chaabane received his Ph.D. degree in electronics in 2017 and completed his habilitation in 2020. He currently holds the position of associate professor and serves as the director of the Telecommunications Laboratory at the University 8 Mai 1945 Guelma, Algeria. His current research areas of interest encompass fractal antennas, MIMO antenna systems, reconfigurable antennas, millimeter-wave high-gain and wide-band antennas, UWB applications and radar, as well as biomedical engineering.

Abdesselam Babouri is full professor and the head of the Department of Electrical and Automatic Engineering in the Department of Electrical Engineering at the University of Guelma, Algeria. He received his Ph.D. degree in Electronics from the University of Nancy, France in 2007. He is a member and Team Leader of Electromagnetic compatibility and biomedical systems at the LGES Laboratory.

With over 70 papers published in international journals and conference proceedings, his research focuses on sensor networks and biomedical application, VLC, clinical evaluation of pacemaker systems and arrhythmia problems.