SIMULATION AND EXPERIMENTAL VERIFICATION OF A PATCH ANTENNA FOR 2.4 GHz BAND APPLICATIONS

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Abstract: *The paper presents the design and development process of a microstrip patch antenna prototype intended for operation in the 2.4 GHz band, with applications in wireless communications for unmanned aerial vehicles (UAVs). The initial design was carried out using* ***MATLAB*** *software, in order to optimize key parameters such as* ***S11****,* ***VSWR****,* ***gain****, and* ***radiation pattern****. A prototype was fabricated using* ***laser engraving*** *and* ***chemical etching*** *techniques based on the obtained results.*

Experimental verification was conducted using specialized measuring equipment, namely a ***spectrum analyzer*** *to assess the real performance of the antenna. The experimental results were compared with the simulations, showing a satisfactory correspondence between the two stages.*

The paper confirms the feasibility of using a ***patch antenna*** *suitable for drone integration, offering a* ***compact*** *and* ***easily integrable*** *solution for UAV communication systems. This process provides a practical foundation for the development of* ***efficient communication solutions*** *for UAVs.*

Keywords: *patch antenna, MATLAB simulation, antenna parameters*

1. INTRODUCTION

Patch antennas are a subcategory of microstrip antennas**.** The patch antenna concept was first introduced in 1972 by Howell, and due to its shape and dimensions, it was quickly integrated into systems where space and weight are particularly important. Their flat structure offers the advantage of being manufactured using printed circuit board (PCB) techniques, which are both cost-effective and efficient.

Patch antennas consist of a metal plate or conductive patch, usually made of copper or gold, placed on a dielectric substrate and a ground plane. The standard shape of such an antenna is shown in FIG. 1.

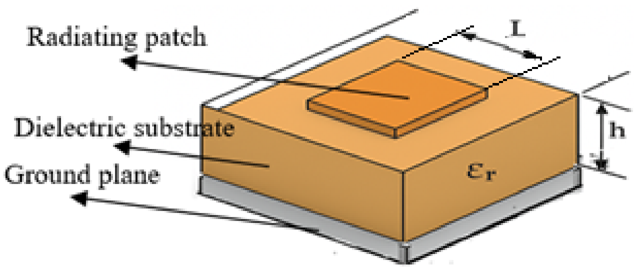


FIG.1 Patch antenna and standard parameters

The three regions of the antenna are:

1. Radiating patch – the part that transmits and receives the electromagnetic signal; it is the active component that radiates, and its shape and dimensions, L and W, determine the resonance frequency.
2. Ground plane – serves as a reference, reflecting the electromagnetic fields to ensure proper radiation and aiding in the impedance matching of the antenna.
3. Dielectric substrate – characterized by its relative permittivity ε_r; it influences the antenna dimensions, resonance frequency, and the losses determined by the loss tangent (tan δ).

In this study, the physical implementation of the antenna was carried out as a rectangular patch, using FR-4 as the dielectric substrate material, commonly used in PCB manufacturing. FR-4 is characterized by a relative permittivity $\varepsilon_r = 4.4$ and a loss tangent $\tan\delta = 0.025$. The radiating patch and the ground plane were made of copper due to its high electrical conductivity, which helps reduce losses and achieve efficient radiation.

This configuration is intended for integration into UAV-type applications, where miniaturization and efficiency requirements are essential. The following sections present the design and simulation stages of the antenna using MATLAB Antenna Toolbox, as well as the experimental verification of its characteristics through measurements performed with RF domain-specific testing equipment.

2. THEORETICAL FOUNDATIONS

The construction of the antenna involves correctly defining its dimensions and performing simulations to evaluate the antenna's behavior. It must be directive, meaning that all the radiated energy should be concentrated in a specific direction [1, 2].

2.1. Antenna design. After defining the format and simulation settings, the next step was the creation of the antenna and the determination of its physical dimensions. The effective wavelength for the 2.4 GHz frequency is 125 mm.

Patch width:

$$W = \frac{c}{2f\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{1}$$

As a result of electromagnetic field losses, part of the electromagnetic field propagates through the dielectric substrate, while another part "radiates" into the air. The effective permittivity will have a value given by equation (2), where the which is h = 1 mm.

$$\varepsilon_{ef} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}} = 4{,}182 \tag{2}$$

At the edges of the patch, the **fringing effect** of the electromagnetic field occurs, through which the field lines partially extend into the air, modifying the field distribution and leading to an effective increase in the electrical length of the antenna. For this reason, the physical length of the patch must be designed shorter than λ/2, with the correction introduced by the term ΔL in the calculation formulas.

$$\Delta L = 0.412h\frac{(\varepsilon_{ef} + 0.3) \times (\frac{W}{h} + 0.264)}{(\varepsilon_{ef} - 0.258) \times (\frac{W}{h} + 0.8)} \tag{3}$$

With the mentioned equation, the dimensions of the radiating patch are obtained.

$$L = L_{ef} - 2\Delta L = \frac{c}{2f \cdot \sqrt{\varepsilon_{ef}}} \quad (4)$$

1.2.Parameters of the designed antenna

To characterize the performance of the designed antenna, the main specific parameters were analyzed:

1. Return loss (S11) reflects the level of matching between the antenna and the feed line; values lower than –10 dB indicate satisfactory performance.
2. Bandwidth (BW) indicates the frequency range over which the antenna maintains proper impedance matching and operates efficiently.
3. VSWR expresses the degree of the impedance matching between the antenna and the transmission line; values below 2 indicate proper impedance matching.
4. Antenna gain indicates how effectively the antenna directs radiated power in a given direction, considering internal losses.
5. Directivity describes the antenna's capability to focus radiation on a specific direction, independent of material or matching losses.
6. The radiation pattern illustrates the spatial distribution of the electromagnetic field emitted by the antenna and allows the evaluation of its directionality.

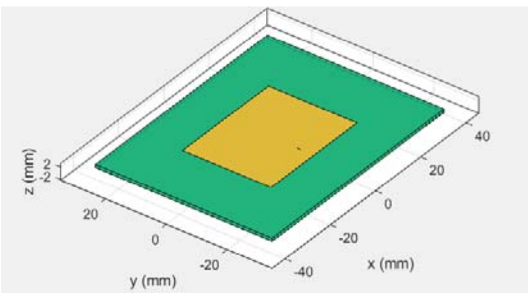
3. MATLAB SIMULATION

For the MATLAB [3] design of the patch antenna, the following conditions were imposed:

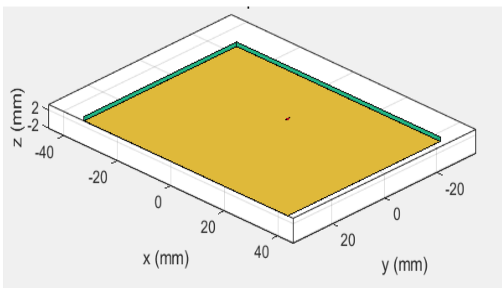
- operating frequency of 2.4 GHz, specific to UAV applications;
- use of the FR-4 dielectric substrate, a material commonly used for PCB manufacturing and prototyping;
- initial dimensions determined based on relations (1) – (4).

Based on the theoretical design, the resulting patch dimensions are: width W = 38 mm and length L = 29.12 mm. The feed point position, determined for matching to the standard 50 Ω impedance, was calculated at the coordinates 19 mm / 4.81 mm.

This section presents the obtained results, in the form of characteristic parameters and the corresponding graphical representations.

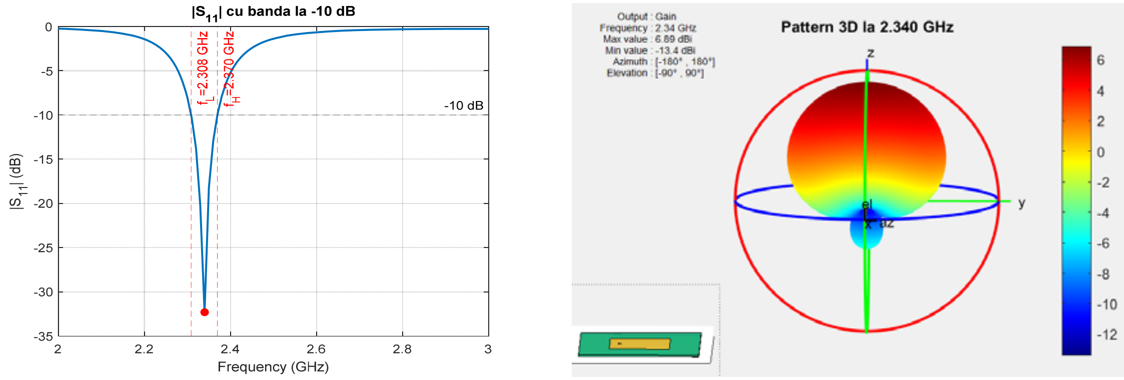


(a)



(b)

FIG.2 Patch antenna obtained in MATLAB. (a) radiating patch, (b) ground plane



(a) **(b)**

FIG.3 (a) Return loss. (b) Radiation pattern

S11 expresses how much of the incident power is reflected by the antenna. For a minimum below –30 dB obtained through simulation (FIG. 3), the matching is very good, meaning that practically all the power enters the antenna.

4. PRACTICAL IMPLEMENTATION OF THE ANTENNA

4.1. Physical implementation of the patch antenna. For this purpose, well-established methods for processing conductor-coated boards specific to PCB technology were used. The prototype fabrication process aimed to obtain a precise structure with appropriate electromagnetic performance. The following stages were carried out for prototype realization:

1. Definition of the antenna geometry.

According to the calculations and simulations obtained in MATLAB, the contour of the patch and the ground plane were transferred onto the FR-4 dielectric substrate, characterized by a relative permittivity εr = 4.4 and a thickness of h = 1 mm.

2. Laser engraving.

To define the copper areas, a CNC machine equipped with a laser module was used to remove the protective layer and expose the copper in the regions to be etched away. This method ensures high precision of the patch contour (FIG. 4).

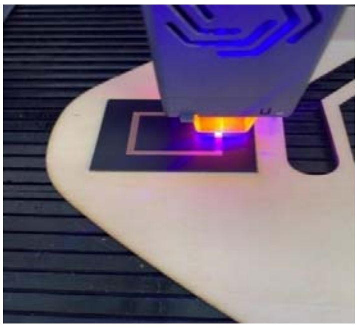


FIG.4 Patch antenna engraving [4]

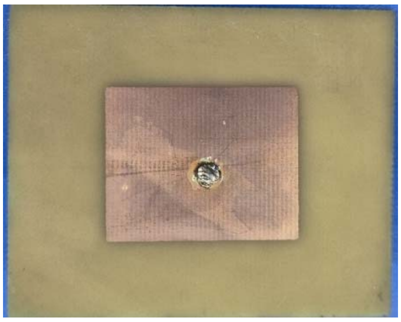


FIG.5 Patch antenna prototype

3. Chemical etching:

The board was immersed in a ferric chloride ($FeCl_3$) solution, a process through which the exposed copper was selectively removed, leaving the radiating patch and the ground plane intact. After etching, the protective layer was removed, obtaining the final geometry of the antenna.

4. Feed point implementation:

In the designated connection area, the substrate was drilled, and a coaxial connector was mounted, ensuring proper soldering with tin to provide high-quality electrical contact and good mechanical stability.

5. Final prototype:

The manufactured antenna is a rectangular patch design on an FR-4 substrate, with copper used for both the patch and the ground plane, prepared for characterization through experimental measurements. (FIG. 5).

4.2. Manufacturing alternatives. In addition to traditional methods for fabricating patch antennas on dielectric substrates (mechanical engraving, laser engraving, and chemical etching), modern rapid prototyping technologies have recently been adopted. 3D printing represents an alternative option with increasing applicability in the field of antennas. This technology allows the creation of complex geometries and three-dimensional structures that are difficult to achieve using conventional methods. Moreover, 3D printing enables the direct integration of antennas into the mechanical structures of UAV platforms, reducing overall weight and increasing the level of functional integration. Although the presented prototype used the conventional FR-4 substrate and chemical processing of the conductive layer, including 3D printing in the prototyping process represents a promising direction for future developments of this study.

4.3. Experimental verification. After fabricating the patch antenna for the 2.4 GHz band, experimental tests were carried out to evaluate its performance. The verification process included several stages and the use of dedicated equipment: a signal generator, a spectrum analyzer, and a vector network analyzer.

In the first stage, emission testing was performed by connecting the patch antenna to a signal generator (Rigol DSG3065B-IQ) and a log-periodic antenna to a real-time spectrum analyzer (SSA 3075X-R). The settings were configured for a central frequency of 2.4 GHz, with a power of 10 dBm, and 2m between the antennas (FIG. 6).

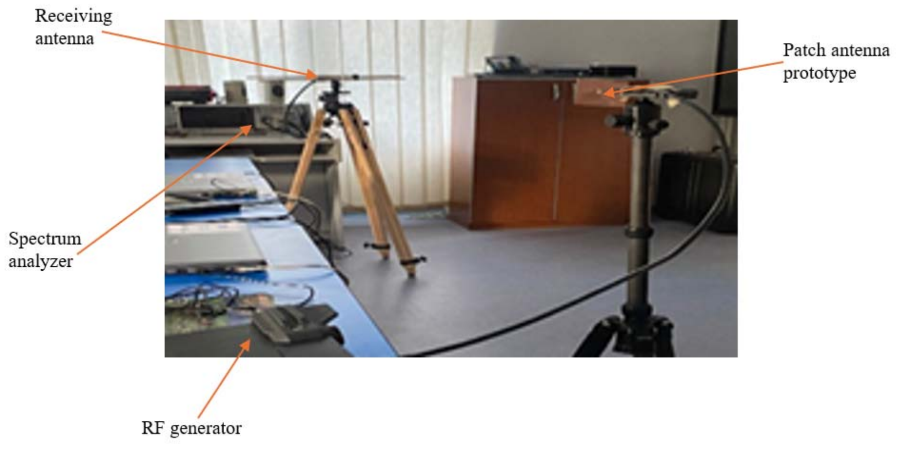


FIG.6 Experimental verification of the patch antenna prototype

For reception testing of the designed patch antenna, the two antennas shown in FIG. 6 were reversed: the patch prototype operated as a receiver, while the log-periodic antenna acted as a transmitter. The results demonstrated proper signal reception at the 2.4 GHz frequency, confirming the dual functionality of the antenna (FIG. 7. (a)).

(a) **(b)**

FIG.7 Resonant frequency obtained on the spectrum analyzer [4]. (a) Signal reception with the patch antenna at 2.4 GHz. (b) Reflection coefficient

The matching performance was analyzed using a vector network analyzer (VNA SNA5012). The monitored parameter was the reflection coefficient S11, measured within the 2.2–2.6 GHz range. The experimental values indicated a minimum of approximately –3 dB and a VSWR ≈ 3, suggesting partial matching to the 50 Ω impedance and moderate efficiency. (FIG. 7. (b)).

ANALYSIS OF RESULTS AND CONCLUSIONS

The comparison between the simulated and experimental data revealed moderate differences, which can be explained by:

- Additional losses in cables and connectors, which led to significant attenuation with a loss of about 23dB.
- Reflections from the testing environment. The measured reflection coefficient of –3.033dB is closer to the desired value.
- Variations in the actual parameters of the FR-4 dielectric substrate compared to nominal values.

Nevertheless, the real antenna's behavior was close to the simulated one, confirming the validity of the design.

Conclusion. The fabricated patch antenna prototype operates in the 2.4 GHz band but exhibits imperfect matching.

The next stage will include:

- adjusting the patch dimensions to recalibrate the resonance frequency,
- optimizing the feed point position,
- using dielectric materials with lower loss tangents.

Although testing in an anechoic chamber or controlled environments could provide more precise characterization and eliminate external influences, considering the intended applications and operating conditions of the antenna, experiments conducted in environments like real operational conditions are preferable for the designed patch antenna.

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