

Design and Validation of a Compact Printed Antenna for 2.4 GHz WLAN Applications with USB Wi-Fi Dongle Integration

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This work presents a compact low profile printed antenna useful for operation in the 2.4 GHz Wireless local area network (WLAN) band. The antenna is fabricated on an FR4 substrate, which provides a low-cost platform suitable for practical communication systems. The dimensions for initial antenna were obtained using conventional microstrip antenna design equations and were later optimized through parametric simulations available in CST Microwave Studio. The importance of main geometrical parameters was investigated to obtain improved impedance matching at the resonance frequency. An antenna prototype was fabricated using a PCB etching process and measured using vector network analyzer. The antenna has a measured return loss of approximately -38 dB at 2.45 GHz, a bandwidth of about 350 MHz ($VSWR \leq 3$), and a measured gain of 2.2 dBi. The measured reflection coefficient (S_{11}) shows a good agreement with the simulated results, which confirms that the antenna resonates at 2.45 GHz with acceptable bandwidth and stable radiation characteristics. To check the antenna performance for practical applications, it was integrated with a commercially available USB Wi-Fi dongle connected to a laptop, the received signal (in dBm) strength was monitored using a laptop and a hotspot-enabled mobile phone is used as the wireless source. The measurement results prove that a reliable wireless connectivity link is established under both short-range and long-range conditions. These results indicate that the proposed antenna not only provides a simple structure but also suitable for practical solution useful for compact portable wireless communication systems.

Keywords: Microstrip antenna, WLAN antenna, 2.4 GHz antenna, Printed antenna, USB Wi-Fi dongle, FR4 substrate, Wireless communication

1 Introduction

Wireless communication technologies have expanded rapidly in recent years, creating a strong demand for compact and radiation efficient antennas capable of supporting modern wireless standards. Among the commonly used frequency bands, the 2.4 GHz Industrial, Scientific and Medical (ISM) band has become particularly important because it supports several widely used wireless technologies such as wireless local area networks (WLAN), Bluetooth communication, and Internet-of-Things (IoT) devices^{1, 2}. As many of these systems are implemented in portable electronic platforms, antennas used in such devices must be compact, inexpensive, and easy to integrate with printed circuit boards and electronic circuitry.

Microstrip patch antennas have emerged as one of the most widely used antenna structures for wireless communication applications due to their low profile,

lightweight configuration, and compatibility with standard PCB fabrication techniques³. Their planar structure allows a direct integration with microwave circuits and compact low-cost electronic modules. In addition, printed microstrip antennas offer considerable design flexibility, as their electrical characteristics can be tuned by modifying the geometry of the planar structure or the width of feeding configuration⁴. Despite these advantages, conventional planar antennas often exhibit few limitations such as narrow impedance bandwidth and low gain, which opens path for continuous research aimed at enhancing their performance⁵.

Several research studies have proposed many compact antenna configurations specifically designed for WLAN applications targeting short-range wireless communication systems operating at 2.4 GHz frequency band. Different design approaches, including variations in rectangular patches, structures with slot-loaded, and planar monopole configurations, have been explored to enhance impedance matching and radiation efficiency

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while maintaining compact antenna dimensions⁶⁻⁸. These physical structural modifications are typically introduced in the design to improve the bandwidth and radiation efficiency of conventional microstrip patch antennas.

Another important aspect in planar antenna design is the integration of the such an antenna with the electronic platform. In many communication devices, such as USB Wi-Fi adapters, sensors, and other embedded communication modules, the antenna operates in proximity to the printed circuit board (PCB) which is surrounded by many electronic components. The presence of nearby metallic based structures and ground planes can drastically influence the antenna parameters mainly resonant frequency, radiation pattern, and impedance bandwidth characteristics⁹. Therefore, evaluating the antenna performance considering these realistic operating conditions is required to ensure reliable operation under practical wireless systems.

Low-cost dielectric substrates are commonly used such as FR4 in commercial wireless devices mainly due to their wide availability and compatibility with standard PCB manufacturing processes¹⁰. Although FR4 board exhibits higher dielectric losses and low loss tangent compared to specialized microwave substrates, but it still remains an attractive option for practical antenna implementations where simple fabrication and low-cost considerations are important factors. Several compact antennas designs fabricated on such FR4 substrates have demonstrated significant performance for WLAN and IoT based applications¹¹.

In addition to conventional rectangular microstrip antennas, researchers have also explored various modified geometries to achieve antenna miniaturization. Techniques such as slot loading, meandered structures, and folded configurations have been reported as effective approaches for reducing antenna size while maintaining acceptable impedance bandwidth and radiation characteristics¹². Furthermore, different feeding methods including microstrip line feed, coaxial probe feed, proximity coupling, and aperture coupling have been investigated to improve impedance matching and radiation efficiency¹³.

The electrical properties of the dielectric substrate also play a significant role in determining antenna performance. Parameters such as dielectric constant and loss tangent influence the resonant frequency, radiation efficiency, and impedance bandwidth of microstrip antennas¹⁴. While specialized microwave substrates such as Rogers or PTFE provide improved performance, their

higher cost often limits their use in mass-produced wireless devices. Consequently, many practical WLAN antenna designs continue to employ FR4 substrates due to their favorable mechanical properties and cost effectiveness¹⁵.

Recent literature studies have also highlighted the importance of considering the integration between the antennas and nearby electronic components in compact wireless devices¹⁶. When antennas are integrated with PCB and other electronic components, coupling effects and ground plane variations may alter the antenna's electromagnetic behaviour and performance, resulting in shifts in resonant frequency or change in radiation characteristics¹⁷. Therefore, evaluating antenna radiation performance in configurations that closely resemble practical hardware environments is essential.

Motivated by these observations, this work presents the design, fabrication, and experimental evaluation of a compact printed antenna operating in the 2.4 GHz WLAN band. The antenna is first designed and analyzed using electromagnetic simulations and then fabricated on FR4 board and measured. To further examine its practical applicability, the antenna is integrated with a commercially available USB Wi-Fi dongle, and its wireless performance is evaluated using a hotspot-enabled mobile phone and a Wi-Fi analyzer application¹⁸.

The main contributions of this work can be summarized as follows:

- (i) A compact printed antenna design operating at 2.45 GHz suitable for WLAN applications is proposed.
- (ii) A detailed parametric analysis is carried out to understand the impact of geometrical parameters on antenna performance.
- (iii) The antenna is experimentally validated through fabrication and measurement, showing good agreement with simulations.
- (iv) A practical performance evaluation is conducted by integrating the antenna with a USB Wi-Fi dongle.

2 Antenna Design and Configuration

2.1 Antenna Geometry

The proposed antenna is designed as a compact printed microstrip structure designed to operate in the 2.4 GHz WLAN band, which is widely used in wireless networks and short-range communication systems. The antenna is fabricated on a single-layer FR4 substrate having a relative dielectric constant of 4.5, a substrate

thickness (h) of 1.5 mm, and a copper cladding thickness (t) of 35 μm . The selection of FR4 allows the antenna to be realized using low-cost and widely available PCB fabrication techniques.

The antenna consists of a top radiating metallic structure printed on single substrate, while a continuous ground plane is placed on the bottom side of the same layer. The geometry consists a modified radiating arms that enables the antenna to resonate near 2.45 GHz while maintaining a compact size. The antenna is fed through a 50- Ω microstrip feed line, which is commonly used in wireless communication circuits.

Several geometrical parameters define the antenna layout, including the overall length and width of the substrate, the feed line width, and the lengths and widths of the radiating arms that form the main radiating structure. These parameters were calculated initially and optimized later in order to obtain the desired resonant frequency. The complete geometry of the proposed antenna, including the antenna layout, fabricated top view, bottom view, and cross-sectional structure, are all shown in Fig. 1.

The overall dimensions of this antenna is approximately 60 mm \times 30 mm, making the structure most suitable for compact wireless platforms such as USB Wi-Fi adapters and other embedded communication modules. The resulting antenna structure with a broad ground plane, which can be used to make wireless device PCB.

2.2 Antenna Design Methodology

The design of the proposed printed antenna follows the classical transmission line model of rectangular patch antennas³. In this model, the patch behaves as a

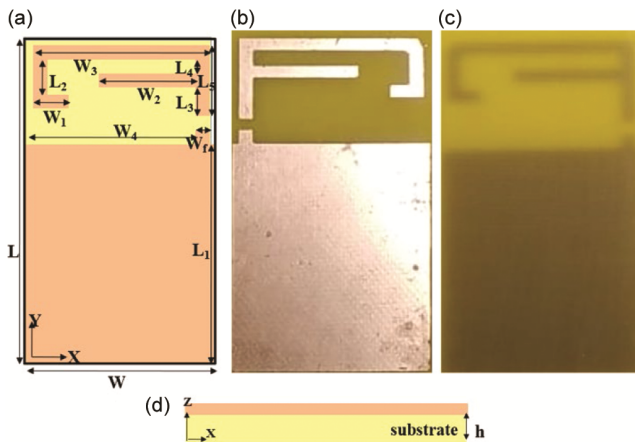


Fig. 1 — Geometry of the proposed antenna (a) antenna layout with dimension (b) top fabricated view (c) bottom fabricated view; and (d) cross sectional side view

resonant cavity in which the radiating edges act as slots separated by a distance that is approximately half of the guided wavelength. As a result, the resonant frequency of the antenna depends primarily on the effective length of the patch and the dielectric properties of the substrate material.

The width of the patch W can be estimated using;

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad \dots (1)$$

where c represents the velocity of light, f_r denotes the resonant frequency, and ϵ_r is the dielectric constant of the substrate.

Because the electromagnetic fields in a microstrip antenna extend partly into the surrounding air region, the antenna experiences an effective dielectric constant ϵ_{eff} that differs slightly from the actual dielectric constant of the substrate. The effective dielectric constant can be calculated as;

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W}\right)^{-1/2} \quad \dots (2)$$

where h represents the substrate thickness.

Using this effective dielectric constant, the effective length of the patch can be determined from;

$$L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_{eff}}} \quad \dots (3)$$

However, the presence of fringing fields at the radiating edges slightly increases the electrical length of the patch. Therefore, the physical length of the antenna becomes slightly smaller than the effective length. The extension in length caused by fringing fields can be expressed as;

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3)(W/h + 0.264)}{(\epsilon_{eff} - 0.258)(W/h + 0.8)} \quad \dots (4)$$

The actual patch length L can therefore be obtained from;

$$L = L_{eff} - 2\Delta L \quad \dots (5)$$

The resonance frequency of the proposed antenna can be explained by considering the effective electrical length of the radiating arms. In general, resonance usually occurs when the current path length approaches a fraction of the guided wavelength (λ_g) inside the dielectric substrate, which is given by $\lambda_g = \lambda_0 / \sqrt{\epsilon_{eff}}$. For the frequency of 2.45 GHz, the free-space wavelength (λ_0) is approximately 122 mm. For FR4 substrate with $\epsilon_r = 4.5$ and $h = 1.5$ mm, the guided

wavelength (λ_g) is approximately 67 mm. From the optimized antenna dimensions in Table 1, the effective outer arm length can be estimated as $W_1 + L_2 + W_3 + L_4 \approx 38.5$ mm, which is close to half of the guided wavelength ($\lambda_g/2$). The small difference is mainly due to fringing fields effect and the folded current path of the radiating arms. This slightly increases the electrical length of the antenna, which is supported by the surface current distribution.

2.3 Optimized Antenna Dimensions

The calculated dimensions obtained earlier were subsequently optimized using 3D full-wave electromagnetic simulations software to achieve improved impedance matching and radiation characteristics near the resonance 2.45 GHz band. The final antenna configuration consists of multiple parameters that define the radiating arms (outer and inner) and the feed region.

The final optimized dimensions of the antenna are summarized in Table 1. The width of the feed line was selected to achieve proper impedance matching with a 50- Ω input port, thereby ensuring efficient power transmission to the radiating structure. The arrangement of the inner and outer radiating arms jointly contributes to the effective current distribution on the antenna surface, which mainly responsible for the radiation behaviour of the antenna.

2.4 Simulation Setup

The complete antenna design and its optimization were carried out using CST Microwave Studio. During the simulation process, the antenna was excited using a discrete port connected to the feed line, while open boundary conditions were also applied in order to emulate free-space radiation. Several antenna parameters were analyzed during the simulation stage, such as reflection coefficient (S11), voltage standing wave ratio (VSWR), radiation pattern, and gain (dBi) over the frequency range. The antenna geometry was gradually optimized based on the simulation results until the desired performance is obtained. The optimized antenna design exhibited good impedance matching around

Parameter	Value (mm)	Parameter	Value (mm)
L	60	L ₅	14.5
W	30	W ₁	5
L ₁	40	W ₂	16
L ₂	6.5	W ₃	24
L ₃	7.5	W ₄	27
L ₄	3	W _f	2

2.45 GHz, which confirms that the proposed antenna is suitable for wireless communication applications.

3 Parametric Analysis and Antenna Evolution

3.1 Parametric Analysis

In order to better understand the variation of geometrical parameters on the proposed antenna characteristics, a parametric study of the parameters listed in Table 1 was carried out using simulation software. In particular, the dimensions associated with the outer radiating arm and the inner radiating arm were varied systematically because these parameters strongly affect the resonant frequency and impedance matching behaviour of the antenna.

The outer arm length determines the effective electrical path of the radiating structure and therefore plays an important role in controlling the operating frequency of the antenna. The simulated reflection coefficient responses obtained for different outer arm lengths are shown in Fig. 2. From the S11 curves, it can be observed that decreasing the outer arm dimension shifts the resonance toward higher frequencies. When the outer arm length was reduced from approximately 38.5 mm to 24.5 mm, the resonant frequency moved from 2.45 GHz to nearly 2.6 GHz, corresponding to a frequency variation of about 6.1%. In addition, the return loss changed from approximately -22 dB to -16 dB, and a reduction in impedance bandwidth was also observed. These results indicate that the outer arm length directly influences the effective current path and hence the resonant frequency of the antenna.

The dimension of the inner arm also plays a significant role in determining the antenna response. The

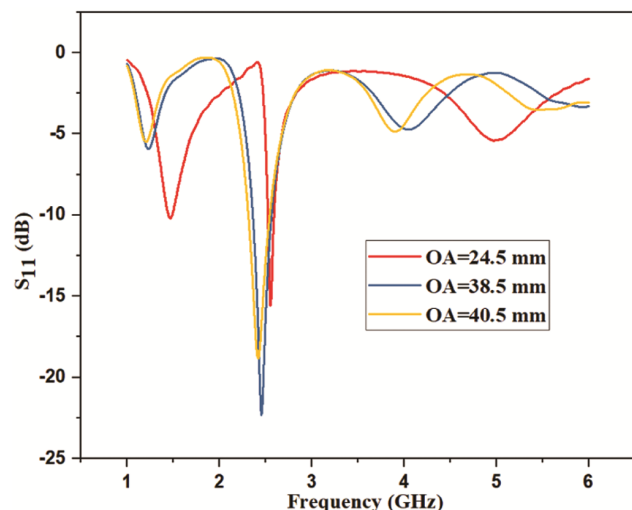


Fig. 2 — Simulated S₁₁ with different values of Outer Arm (OA=W₁+L₂+W₃+L₄) variation

simulated S_{11} characteristics corresponding to different inner arm dimensions are presented in Fig. 3. When the inner arm dimension was reduced from 16 mm to 14 mm, the resonant frequency shifted toward a higher value of approximately 2.75 GHz, which represents a frequency variation of about 12.2 %.

Conversely, increasing the inner arm dimension from 16 mm to 18 mm caused the resonance to move toward a lower frequency near 2.25 GHz. It was also observed that increasing the inner arm dimension improves the impedance matching performance, with the return loss reaching approximately -32 dB. These observations confirm that the inner arm parameter provides an effective means of controlling both the resonant frequency and impedance characteristics of the antenna.

3.2 Antenna Evolution

The final antenna configuration was obtained through a gradual modification of the antenna geometry in order to improve the reflection coefficient characteristics and overall radiation performance. The different evolution stages of the antenna, together with the corresponding simulated S_{11} responses, are presented in Fig. 4.

In the first stage (Antenna 1), the structure consisted of a relatively simple configuration that included only a single inner arm. The simulated reflection coefficient response showed a resonance with a return loss of approximately -15 dB, indicating that the antenna was capable of radiating in the desired frequency region. However, the impedance matching obtained at this stage was not sufficiently optimized for WLAN operation.

In the second stage (Antenna 2), an additional outer arm was introduced in order to modify the current

distribution on the radiating structure. This structural modification resulted in a noticeable change in the antenna response. In particular, the antenna at this stage exhibited a dual-band behaviour, with resonances appearing mostly around 1.5 GHz and 2.5 GHz, as observed in the S_{11} response shown in Fig. 4. The presence of these dual resonances suggests that the modified geometry supports dual band due to the altered current paths on the surface of antenna.

Finally, in the third and last stage (Antenna 3), the dimensions of both the arms (inner and outer) were further optimized to achieve a stable resonance near the 2.45 GHz. The final optimized reflection coefficient and improved impedance matching proves that the antenna has suitable performance for WLAN applications.

4 Fabrication and Measurement Results

After completing the simulation and optimization stages, the antenna was fabricated on a single layer FR4 substrate using a conventional PCB fabrication process based on chemical etching technique, which is commonly used for the fabrication of FR4 based printed antennas in laboratory environments. First, the antenna layout in terms of Gerber file is obtained from the simulation model, which later converted into a mask pattern and printed on photographic paper. This printed pattern is then transferred onto the copper-clad FR4 substrate through masking technique. The exposed copper regions were subsequently removed by immersing the substrate in a ferric chloride ($FeCl_3$) solution, which chemically etched away the unwanted copper. After the etching process was completed, the

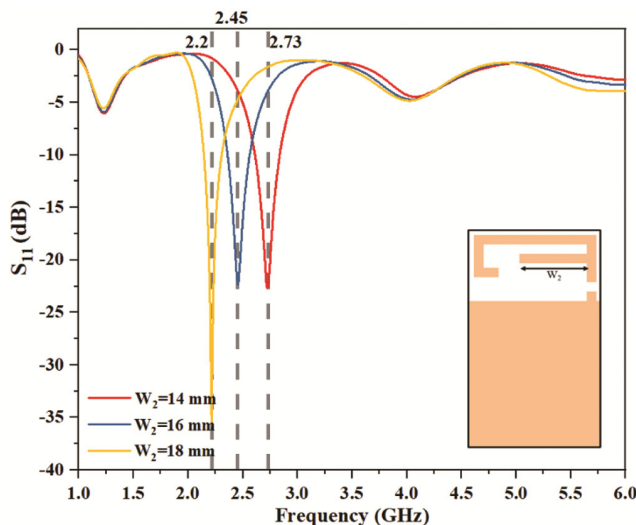


Fig. 3 — Simulated S_{11} with different values of Inner Arm (W_2) variation

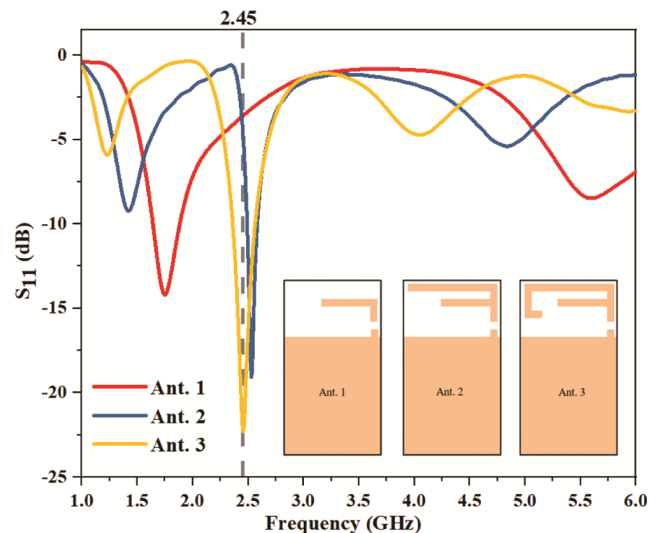


Fig. 4 — S-parameters during evolution steps of the proposed antenna

masking layer was cleaned using acetone solution, which leave only the required copper pattern that forms the radiating structure of the antenna. The fabricated antenna prototype along with the SMA cable and connector is shown in Fig. 5.

The S-parameter measurements were carried out using a Vector Network Analyzer (VNA) (model: R&S[®] ZVH8). Prior to measurement, a standard open-short-load (OSL) calibration was performed to ensure measurement accuracy. The electrical performance of the antenna was initially investigated through simulations. The simulated reflection coefficient (S11) indicates that the antenna resonates near 2.45 GHz, with a return loss value of -22 dB. To verify the simulation results, the antenna is fabricated and was characterized experimentally. During measurement, a slight shift in the resonant frequency was observed when compared with the simulated S11 response.

Such variations usually occur due to fabrication tolerances, minor variations in substrate parameters, and connector losses that are common during practical implementation. Despite this minor frequency shift, the measured return loss reached approximately near to -38 dB at 2.45 GHz, indicating very good impedance matching. The comparison between simulated results and measured reflection coefficient responses is shown in Fig. 6. The voltage standing wave ratio (VSWR) was also measured to further evaluate the performance of the antenna and it is found to be approximately 1.5, which is close to the ideal value of unity (1). This result proves that only a very small portion of the input power is reflected back to the source and the majority of the power is radiated by the antenna. In addition, the antenna provides a usable bandwidth of approximately 350 MHz within the $VSWR \leq 3$ range, which satisfies



Fig. 5 — Final fabricated prototype of the proposed antenna along with SMA cable and connector

the bandwidth requirements applicable for WLAN applications. The radiation characteristics of the antenna were investigated through far-field region. The radiation patterns in the principal planes are shown in Fig. 7 is obtained inside anechoic chamber, where the antenna exhibits stable radiation behavior and matches with simulation at the operating frequency.

The gain of the antenna was also measured inside anechoic chamber, and the measured gain was found to be approximately 2.2 dBi at 2.45 GHz.

To gain further insight into the radiation mechanism of the antenna, the surface current distribution was analyzed at different phase angles at simulation stage itself. The simulated current distributions at phase $\omega t = 0^\circ$ and $\omega t = 180^\circ$ are plotted in Fig. 8. From these plots, it can be observed that strong current concentrations marked in red-orange color occur along the radiating arms of the antenna. These current paths confirm that the radiating elements contribute significantly to the antenna resonance and radiation at the desired operating frequency.

Overall, the fabricated prototype demonstrates good agreement between simulated and measured results, which confirms that the proposed antenna design is suitable for WLAN applications operating in the 2.4 GHz band.

5 Integration with USB Wi-Fi Dongle and Performance Evaluation

To examine the antenna for potential applications, it was integrated and tested with a Teconica USB Wi-Fi dongle¹⁸ and its performance was evaluated under real operating conditions. In compact wireless

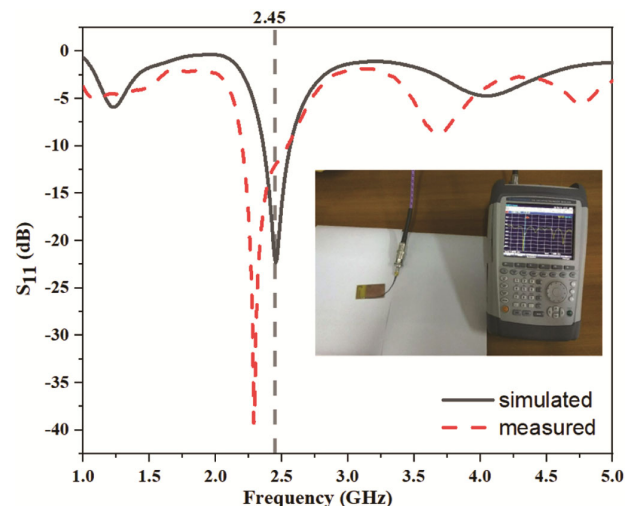


Fig. 6 — Comparison of simulated and measured S11 (dB) of proposed antenna

devices, antennas often operate in close proximity to electronic circuits and PCBs, which may influence their radiation efficiency of the antenna. Therefore, the antenna response was compared by incorporating

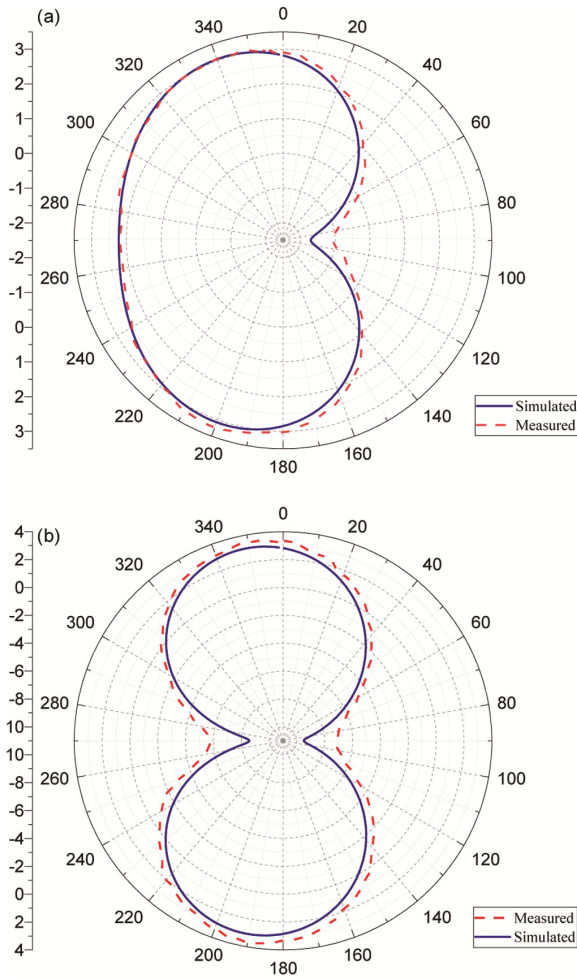


Fig. 7 — Radiation Pattern at 2.45 GHz (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$

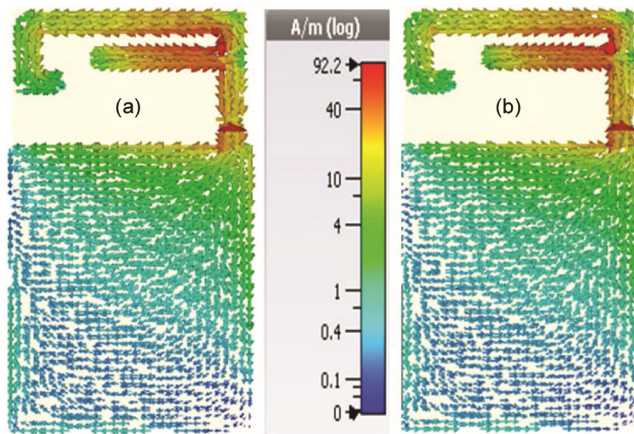


Fig. 8 — Current distribution of the proposed antenna at 2.45 GHz (a) $\omega t = 0^\circ$ (b) $\omega t = 180^\circ$

the complete ground and PCB layout of the dongle together during simulation stage itself, as illustrated in Fig. 9.

The PCB design tool available in CST Microwave Studio is used in generating the corresponding PCB layout, and later importing the resulting Gerber files into the simulation environment. The combined antenna-PCB configuration was then analyzed to evaluate its electromagnetic characteristics. The simulated S-parameter response obtained for the antenna with the integrated PCB is presented in Fig. 10.

The results indicate that the presence of the PCB slightly modifies the electromagnetic behaviour of the antenna. In particular, the impedance bandwidth is reduced when the antenna is integrated with the PCB due to changes in the effective ground plane dimensions and coupling between the antenna and surrounding metallic structures. The simulated impedance bandwidth of the antenna with PCB integration was approximately 100 MHz, whereas the

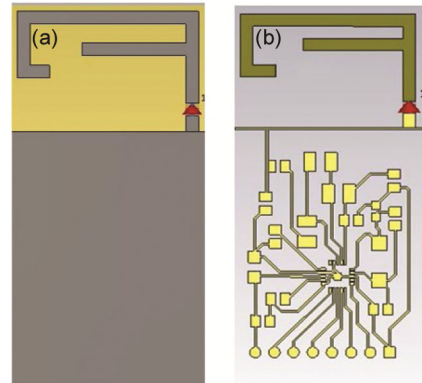


Fig. 9 — Proposed antenna integrated with (a) ground plane and (b) PCB layout

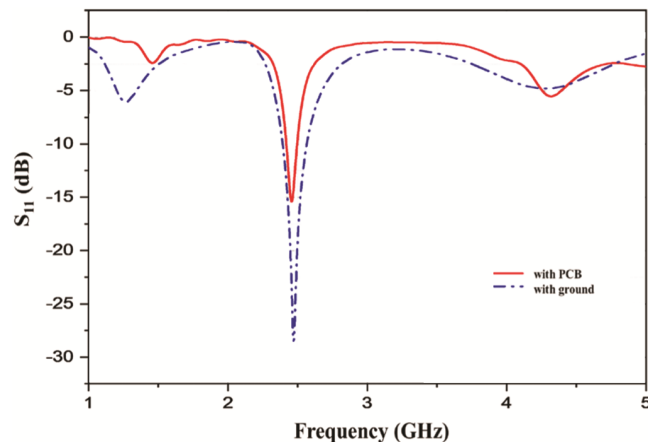


Fig. 10 — Magnitude of S_{11} with PCB and ground plane

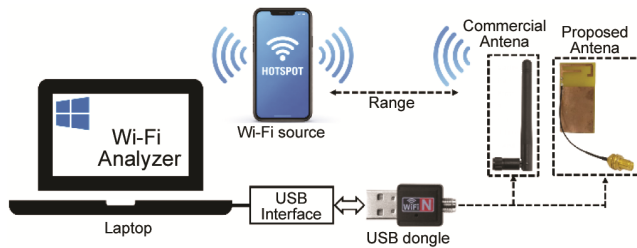


Fig. 11 — Complete experimental setup with USB Wi-Fi Dangle

optimized antenna exhibited a bandwidth of about 182 MHz. The gain characteristics also show a minor variation after PCB integration, with simulated gain values ranging from approximately 2.27 dB to 2.35 dB, depending on the ground plane configuration. Despite these minor changes, the antenna continues to provide adequate radiation performance for WLAN communication.

To further evaluate the antenna performance under practical conditions, experimental measurements were carried out using a commercially available Teconica USB Wi-Fi dangle, since fabrication of the complete dangle PCB was not feasible within the available laboratory facilities. The proposed antenna was connected to the dangle and its performance was compared with the original antenna integrated within the device. The received signal strength was monitored using a Wi-Fi analyzer application¹⁸, which reports the received power level in dBm. Two test scenarios were considered in order to investigate the antenna performance under both moderate-distance and short-range communication conditions as shown in Fig. 11.

In Case 1, a mobile phone operating in hotspot mode was used as the Wi-Fi source and positioned approximately 25 m away from the receiving system. When the dangle operated with its existing antenna, the received signal strength was measured to be approximately -47 dBm, as shown in Fig. 12 (a). Under the same conditions, when the proposed antenna was connected to the dangle, the received signal strength was measured to be about -51 dBm, as illustrated in Fig. 12 (b). Although a small reduction in received signal level was observed, the antenna maintained stable connectivity with the wireless network, demonstrating that the proposed design is capable of supporting WLAN communication over practical distances.

In Case 2, the same mobile phone hotspot was placed very close to the receiving device at a distance of approximately 5 cm. Under these conditions, the

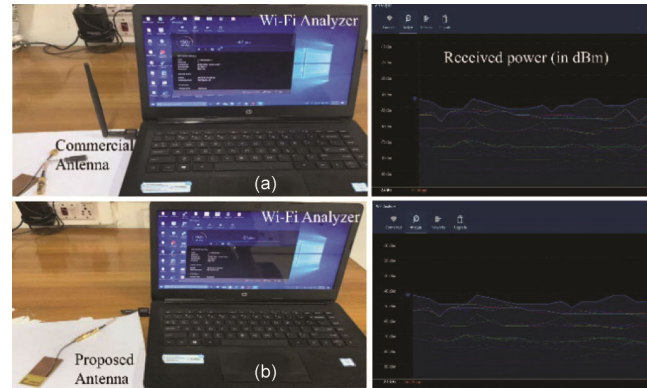


Fig. 12 — Experimental setup with real hardware and software

received signal strength measured using the existing antenna was around -16 dBm. When the proposed antenna was connected to the dangle, the received signal strength improved to approximately -12 dBm. The stronger received signal observed in this case indicates that the proposed antenna performs effectively in short-range wireless communication environments.

Overall, the experimental observations confirm that the proposed antenna maintains reliable wireless performance when connected to a practical Wi-Fi dangle. Even in the presence of the dangle PCB and surrounding circuitry, the antenna continues to operate effectively within the 2.4 GHz WLAN band, demonstrating its suitability for integration in compact wireless communication devices.

6 Conclusion

A compact printed antenna operating in the 2.4 GHz WLAN band has been designed, fabricated, and experimentally evaluated. The antenna is implemented on an FR4 substrate, providing a low-cost and easily manufacturable structure suitable for portable wireless devices. Parametric analysis was used to optimize the antenna geometry and achieve good impedance matching near 2.45 GHz. The fabricated prototype shows good agreement with simulation results, with satisfactory return loss, bandwidth, and radiation characteristics. The antenna achieves a measured return loss of -38 dB, an impedance bandwidth of approximately 350 MHz, and a gain of 2.2 dBi at 2.45 GHz. Integration of the antenna with a Teconica USB Wi-Fi dangle confirmed reliable wireless performance under both short-range and moderate-distance conditions. These results demonstrate that the proposed antenna is suitable for compact WLAN communication systems.

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