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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 13, Issue 3 | Pages 477-485 | e-ISSN: 2347-470X

A Compact S-Shaped Patch Antenna for ISM-Band Wireless Communications Applications

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ABSTRACT- The evolution of wireless communication systems has intensified the demand for compact, efficient antennas tailored to specific applications. This research introduces an S-shaped microstrip patch antenna for wireless communication, emphasizing its compactness and operational efficiency. The antenna designed and simulated using Computer Simulation Technology (CST) software, achieves a gain of 1.75 dBi, 95% radiation efficiency, an operational bandwidth of 200 MHz (2.37 GHz to 2.57 GHz), and an excellent impedance matching with compact dimensions of 29 mm × 20 mm optimized to achieve resonance within the desired frequency of 2.45 GHz and make the antenna suitable for space-constrained environments. Detailed analysis of return loss, voltage standing wave ratio (VSWR), and radiation characteristics are presented. The antenna is fabricated, and the simulated results were verified by practical measurements of a Vector Network Analyzer (VNA). The measured resonance frequency and return loss proved the appropriateness of the antenna to the desired ISM band of 2.45 GHz. Though some minor deviations were noted between the simulated and practical performance. Comparative results with recent antenna designs highlight the proposed S-shaped antenna's performance and potential for specific applications in constrained environments requiring highly efficient narrowband antennas.

General Terms: Antenna Design, Computer Simulation Technology, Compact Antenna.
Keywords: ISM applications, S-shape antenna, Bandwidth, Gain, 2.4 GHz.

ARTICLE INFORMATION
Author(s): Ayman N. Muhi, Mustafa Ghanim, and Mohaimen Q. Algburi;
Received: 17/03/25; **Accepted**: 05/07/25; **Published**: 30/08/25;
E- ISSN: 2347-470X;
Paper Id: IJEER250109;
Citation: 10.37391/ijeer.130312
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-13/ijeer-130312.html

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1. INTRODUCTION

The rapid growth of wireless communication technologies has revolutionized the design and application of antennas. Antennas play a crucial role in determining the performance and reliability of communication systems, from IoT devices to satellite communication [1-4]. Over the years, microstrip antennas have gained popularity for their compact size, lightweight nature, and ease of fabrication [5-6].

While many conventional designs aim to maximize bandwidth and gain, certain applications benefit from antennas optimized for precise operational frequencies, compact dimensions, and efficient impedance matching [7]. Such designs prioritize reliability and stability over broad performance metrics, making them suitable for specific use cases like low-power IoT devices and short-range communication systems [8]. The proposed S-shaped antenna addresses these requirements by offering compactness, narrowband operation, and efficient power transfer within its targeted frequency range.

Recent research efforts have introduced innovative geometries, such as fractal, slotted, and S-shaped designs, to overcome certain challenges such limited bandwidth, impedance matching issues and suboptimal gain [9-11]. S-shaped antennas, in particular, have demonstrated promising results in enhancing impedance matching and achieving specific operational frequencies. For example, the researchers in [12] proposed an S-shaped microstrip antenna with improved bandwidth. However, the dimensions of the antenna were 100 mm × 90 mm which is considerably large. In [13] the design and simulation of S-shaped dual band microstrip patch antenna is presented and a bandwidth of 6.5% is noted in the multi wideband design. However, the recorded return loss values weren't optimum and the physical dimensions of 90 mm × 95 mm are not exactly compact. The S-shaped antenna in [14] on the other hand is compact compared to earlier designs, measuring 26 mm × 22 mm. However, it lacks optimal impedance matching conditions and has an average return loss of -12 dB to -16 dB. Another S-shaped antenna was proposed in [15] to realize circular polarization radiation, which improves the bandwidth and gain at 3.5 GHz but the antenna dimensions of 222 mm × 105 mm are still larger than other typical designs. In [16] an S-shaped antenna was designed and simulated. The ground plane measurements were 40 mm × 70 mm, and the patch was 30 mm × 60 mm. However, the antenna bandwidth has increased in only one band and this limitation suggests that the antenna may not be suitable for applications requiring multi-band or wideband performance as claimed. Other studies have explored dual-band and reconfigurable antennas for multiple applications in modern communication systems [17-25].

This paper presents an S-shaped microstrip antenna, designed to operate in Industrial, Scientific, and Medical (ISM) bands, suitable for constrained environments. The antenna is fed by a 50-ohm port. The antenna performance is improved by making slits in the radiator and the wavelength was reduced by ground plane distortion. In order to achieve the best performance, a parametric study is carried out. Furthermore, this research discusses the design process, simulation results, and comparative analysis with existing designs, emphasizing the trade-offs involved in achieving compactness and operational efficiency.

2. ANTENNA DESIGN DETAILS

The proposed S-shaped antenna consists of a slotted rectangular microstrip patch fabricated on a 1 mm thickness FR4 substrate with a dielectric constant (ε_r) of 4.4. The patch dimensions of 29 mm × 20 mm were optimized to ensure resonance within the frequency range of operation. Careful selection has been taken in the configuration of the ground plane and feed point for impedance matching.

The resonant frequency (f_r) of the microstrip patch antenna is determined using the following equation [26]:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{\text{eff}}}} \quad (1)$$

where c is the speed of light, L is the patch length, and ε_{eff} is the effective dielectric constant, calculated as:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-0.5} \quad (2)$$

Here, h is the substrate thickness which equals to 1mm and W is the patch width. The width of the patch (W) can be approximated as:

$$W = \frac{c}{2f_r\sqrt{\varepsilon_r}} \quad (3)$$

The effective length (L_{eff}) and actual length (L) are related by:

$$L = L_{\text{eff}} - 2\Delta L \quad (4)$$

$$\Delta L = 0.412h\frac{(\varepsilon_{\text{eff}}+0.3)(W/h+0.264)}{(\varepsilon_{\text{eff}}-0.258)(W/h+0.8)} \quad (5)$$

These equations guided the design and optimization of the S-shaped patch geometry, ensuring alignment with performance goals. Figure 1. shows the structure of the designed antenna with detailed dimensions for the patch. Initially, we constructed a rectangular patch from copper material with a length of 19.2 mm and a width of 16 mm using the prior formulae. We removed two slits from the patch to make it S-shaped and improve the results. The slits measured 12.2 mm × 3.8 mm. The patch is mounted on an FR4 substrate which is a widely used and cost-effective substrate material in antenna design. A rectangular copper ground plane is located on the opposite side of the substrate. The dimensions of the ground plane are optimized to ensure proper radiation and impedance matching. *Table 1* displays additional parameters determined using the equations from [26].

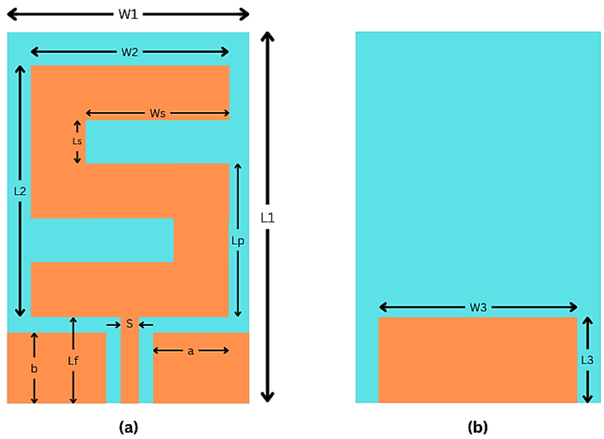

Figure 1. The Proposed S-Shaped Antenna Structure: (a) Front side. (b) Back side

Table 1. Dimensions of the designed antenna in (mm).

Parameter	Value (mm)
W1	20
W2	16
L1	29
L2	19.2
Ws	12.2
Ls	3.8
W3	16
L3	8
a	8
b	7
Lf	8
Lp	11.54
S	2

The methodological approach for this study is shown in *figure 2*.

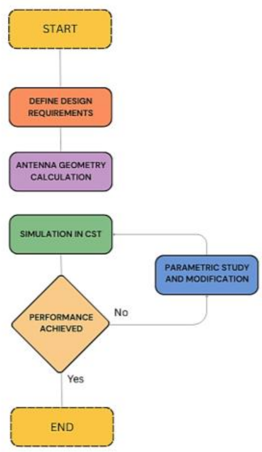

Figure 2. Flowchart outlining the design and simulation strategy for the proposed S-shaped patch antenna

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Research Article | Volume 13, Issue 3 | Pages 477-485 | e-ISSN: 2347-470X

The process starts with figuring out the critical performance needs for ISM-band applications and then finding the shape of the antenna by using theoretical models. With the support of CST software, the design is tested through experiments, and its parameters and structure are adjusted repeatedly until the required performance achieved. Using this method guarantees that impedance is well matched, the system is compact, and it radiates efficiently.

3. PARAMETRIC STUDY

In this section, a parametric study was conducted to verify the performance of the proposed antenna in terms of reflection coefficient, efficiency and gain. The parametric study focused on analyzing the effect of slits in the radiator as well as deformed in the ground plane on the performance of the proposed antenna.

3.1. Effect ground plane

The S-parameters (S_{11}) of an antenna were parametrically studied in this section at different ground plane lengths (Lg) from 2 GHz to 3 GHz through the presented graph in Figure 3. The study compares three different ground plane lengths (8mm, 15mm, 29mm, and the proposed antenna) to obtain the optimal design. The return loss demonstrates poor frequency range matching since it maintains a position near 0 dB when Lg equals 29mm (green line). A full ground plane seems to produce unfavorable effects on antenna radiation capabilities. Moreover, the antenna exhibits reduced resonance at 2.6 GHz frequency with a shallow return loss value of ~-11 dB while using Lg = 15mm (red line). The results show moderate progress in impedance matching however it remains imperfect at this stage. The return loss shows significant improvement in the operating range as the proposed antenna resonated at 2.45 GHz.at Lg = 8mm (black line) which demonstrates excellent impedance matching. Improvement measures need to focus on lowering return loss alongside a reduction of the reflected signal and an increase in radiation efficiency. During its operation at 2.45 GHz, the proposed design shows deep impedance resonance reaching a level of -27 dB (Blue Line. The proposed design implies that proper ground plane length selection lowers antenna reflection while boosting radiation efficiency.

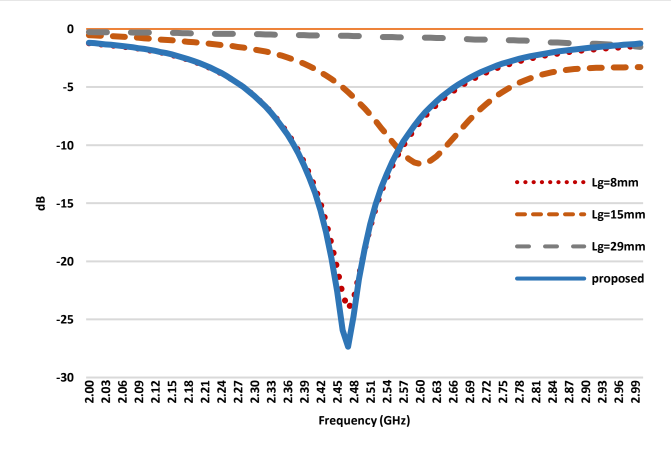

Figure 3. Effect of ground plane on the S-parametrs of the designed antenna

The presence of a large ground plane affects antenna functionality in several negative ways because it changes resonant frequency while causing impedance mismatches and pattern distortions and reduces bandwidth together with enhanced surface wave loss. A reflective surface formed by the ground plane modifies current distribution which results in a frequency shift outside the operating band. High reflection coefficients (S_{11} values close to 0 dB) form due to poor impedance matching which leads to decreased power radiation and increased power reflection towards the source. The radiation pattern becomes distorted when a ground plane extends beyond its optimal size which results in the formation of nulls while also producing undesired beam fluctuations and reduced gain towards specified directions. The introduction of unwanted resonances together with standing waves through improper antenna implementation ends up reducing available bandwidth. It was also found that sizeable ground planes produce surface wave behavior which captures energy instead of allowing effective radiation resulting in lower antenna operational efficiency. Most antenna designs require a ground plane, but optimal performance requires adjusting the ground plane to minimize unwanted effects. The proposed design achieves its peak performance by modifying the ground plane length to improve the impedance matching which optimizes the parameters of the proposed antenna.

3.2. Effect of slots

The performance of the S-shaped antenna becomes greatly affected when slots are included as these changes return loss parameters and bandwidth characteristics while impacting impedance-matching characteristics. The initial design can be seen in Figure 4 with the dimensions already mentioned in Table 1 before. The return loss (S_{11}) for three antenna designs including Ant 1 (without Slot), Ant 2 (Slot 1), and the proposed design (Slot 2) can be observed in Figure 5. The least resonance occurs in Ant 1 as shown by the red line which means the antenna performs poorly in impedance matching and radiation efficiency. The return loss at the primary frequency remains high for Ant 2 (green line) even though its resonance has improved. The slot was found to have a significant effect as the antenna matching was improved and a resonant frequency at 2.87 GHz with $S_{11} < -25$ dB was generated with good frequency bandwidth. However, the wavelength of the proposed antenna needs to be reduced while maintaining the physical size to achieve the optimal design at 2.45 GHz.

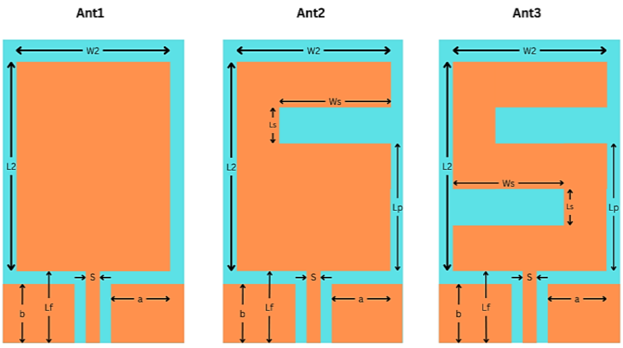

Figure 4. Initial design steps of proposed antenna

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Research Article | Volume 13, Issue 3 | Pages 477-485 | e-ISSN: 2347-470X

The proposed antenna (blue line) operates optimally because it reaches a return loss under -27 dB at 2.45 GHz and thus transmits power effectively while reflecting minimum signals. The bandwidth performance of the proposed design exceeds that of Ant 1 and Ant 2 by extending its frequency range operation. The superior antenna efficiency results from the optimized slot configuration which performs well in impedance matching operations and resonance adjustments. The implementation of well-structured slot elements in the S-shaped antenna design results in better performance characteristics through lowered return loss measurements and wider bandwidth usage along with optimized impedance matching.

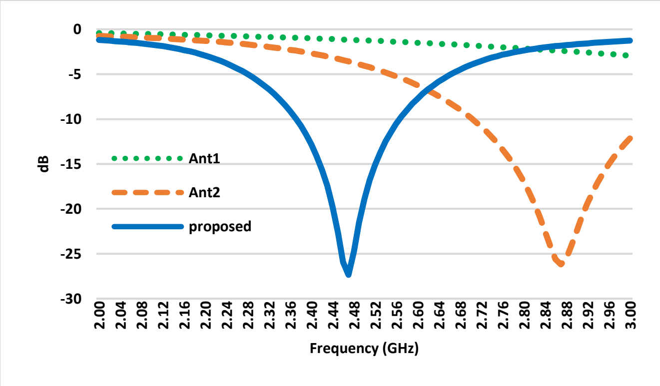


Figure 5. Effect of slots on the S_{11} of the designed antenna

3.3. Effect of CPW

In this section, the effect of introducing CPW on the performance of the proposed antenna in terms of return loss, radiation efficiency, and operating range is analyzed. It is found that CPW affects the performance of the antenna. The antenna resonance characteristics depend significantly on coplanar waveguide (CPW) feeding. *Figure 6* shows the S-parameter (S_{11}). The center frequency was moved to 2.5 GHz and the return loss S_{11} < -40 dB without introducing CPW in the proposed design (red line), however, When CPW was introduced into the proposed antenna structure (blue line), a reduction in wavelength was achieved as the antenna resonated at 2.45 GHz making the spectrum ideal for ISM band applications. The CPW feeding system causes a frequency change because it affects both impedance-matching functions and effective electrical length properties.

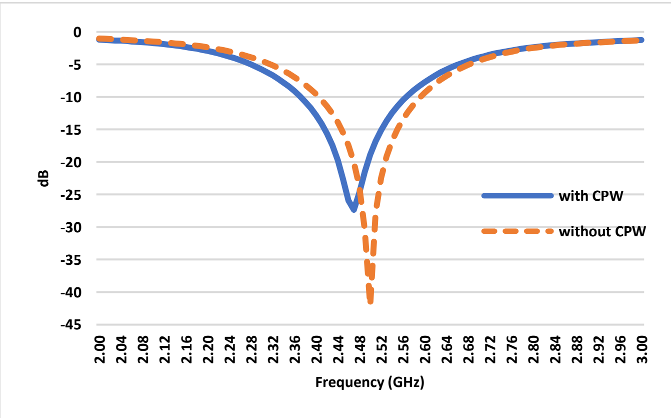


Figure 6. Effect of CPW on the S_{11} of the designed antenna

The benefits of CPW feeding include reduced radiation loss together with better impedance control and enhanced surface wave suppression which ultimately cause this frequency shift. The CPW structure changes substrate effective permittivity which results in modifications of the guided wavelength. A change in effective permittivity affects antenna resonance by making the frequency lower because the frequency directly varies with electrical length. The antenna obtains superior bandwidth characteristics and impedance matching from CPW feeding since it shows a smooth wide return loss curve in the blue plot instead of the red curve's sharp resonance point.

The transition from 2.5 GHz to 2.45 GHz represents advantages because the widely used 2.45 GHz frequency from the ISM band meets the requirements for Wi-Fi, drone, and RFID communication systems. A CPW-fed design operates as an improvement method because it decreases reflection losses and improves signal transmission capability. When CPW is implemented, it produces two changes to the antenna: first, it alters its electrical characteristics and second, it produces frequency resonance while obtaining better impedance correspondence which enables more effective ISM-band performance.

4. RESULTS AND DISCUSSION

This section presents the obtained results and discusses them comprehensively. It is seen that good tuning performance was achieved, displaying an accurate resonance frequency of 2.45 GHz achieved. The antenna with compact dimensions of 29 mm × 20 mm is suited for space-constrained wireless communication devices in embedded systems and portable devices.

From *figure 7*, the proposed S-shaped antenna return loss (S_{11}) is much below -10 dB and extends up to -27 dB within the operational frequency. This shows excellent impedance matching, which minimizes signal reflection and maximizes power transferred from the feedline to the radiating element. This strong impedance match ensures good reliability in communication systems, especially where power efficiency is of crucial concern.

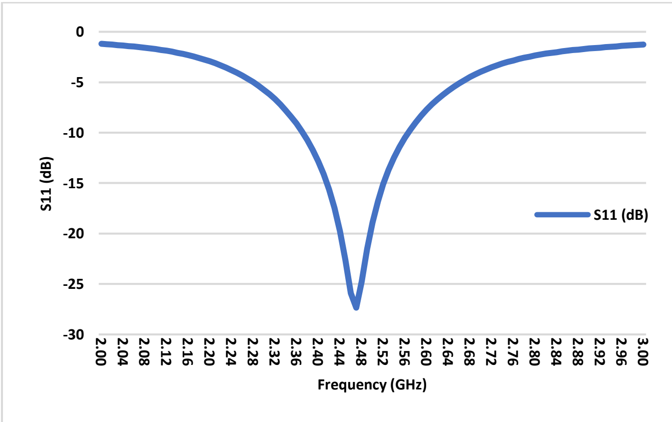


Figure 7. Return Loss (S_{11}) for the Proposed S-Shaped Antenna

This antenna, therefore, has a bandwidth of 200 MHz (2.37 GHz to 2.57 GHz), at the center frequency of 2.45 GHz, giving a fractional bandwidth (FBW) of approximately 8.16 %. Thus, the antenna is classified as narrowband, which is suitable for applications that require operation at precise frequencies, such as IoT and short-range communication systems where channel interference should be at a minimum. Specialized systems, such as Wireless Body Area Network (WBAN), RFID, or wireless telemetry, where narrowband performance ensures operational stability and reduces out-of-band interference [27, 28].

Figure 8 represents the Voltage Standing Wave Ratio (VSWR) against frequency. Hence the VSWR is below 2, this corresponds to excellent impedance matching resulting in efficient transfer of power hence it's suitable for Wi-Fi applications.

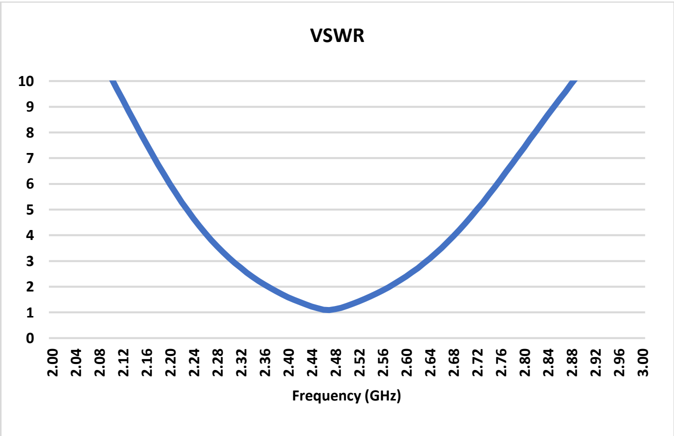


Figure 8. VSWR for the Proposed S-Shaped Antenna

The Z-parameters of Z_{11} appear in *figure 9*. through the real (Re) and imaginary (Im) components while showing values from 2 GHz to 3 GHz frequency range. The input impedance of the antenna which is Z_{11} shows its resistive properties through the real part (Re) and its reactive characteristics through the imaginary part (Im). The antenna power transfer efficiency at its input port remains consistent because Z_{11} (Re) demonstrates steady resistance of 49.92 ohms. A minimal variation of Z_{11} (Im) indicates small amounts of impedance mismatching.

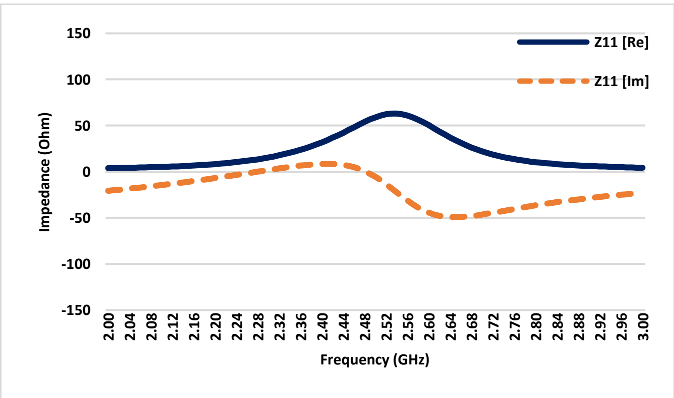
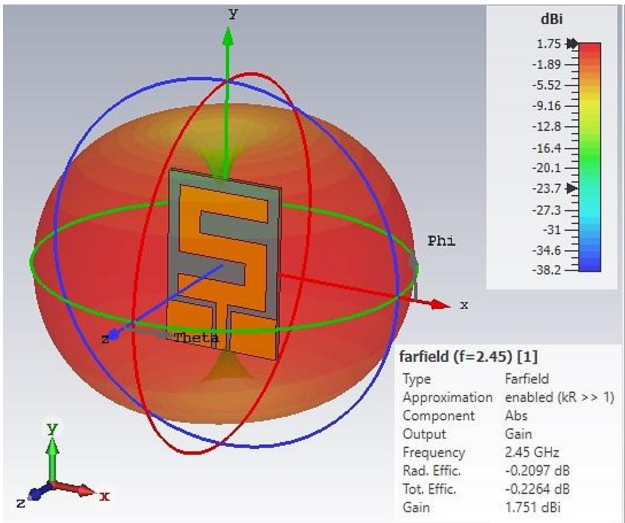


Figure 9. Z_{11} of the Proposed S-Shaped Antenna

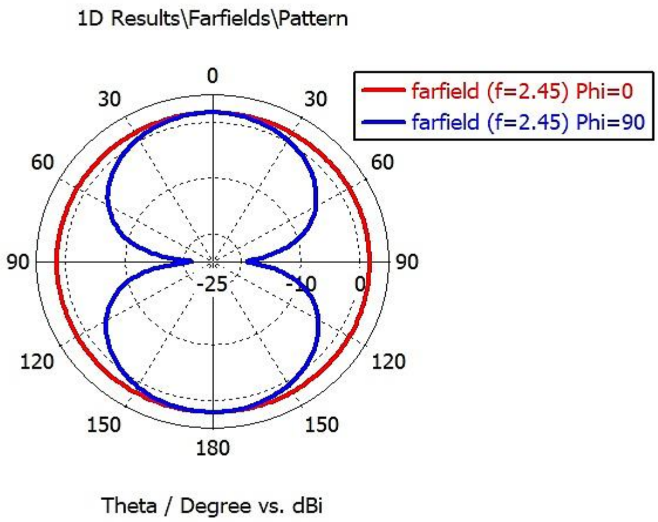
The antenna reaches its most efficient state of maximum power transfer at the resonant frequency of 2.465 GHz where its imaginary component reaches zero. This absence of reactive component makes the antenna purely resistive.

All Z-parameters function as key factors in determining the performance level of the proposed antenna design. Power transfer reaches its maximum threshold while efficiency increases because impedance matching achieves a 50 ohms real value near zero imaginary value. The antenna's performance remains constant throughout the frequency range because the real part displays stability while the nearly zero imaginary part during resonance confirms proper tuning. The antenna operates effectively during practical uses through these characteristics which enable dependable signal communication paths.

The results depicted in *figure 10(a)*. correspond to an antenna with 1.75 dBi gain and 95% radiation efficiency, a modest figure that turns out to be fairly adequate for use in low-power, short-distance applications. Benefits of this relatively low gain value include indoor radio communication, as the low antenna gain provides well-spread distribution with no strong focus on particular directions, and low-gain implementations are preferred because of the benefit of low-power consumption and very small antenna size for the ISM band and IoT applications.



(a)



(b)

Figure 10. Characteristics of radiation patterns and Gain of the proposed Antenna: (a) 3D radiation pattern (b) 2D radiation pattern

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Figure 10(b) also shows the 2D radiation patterns in *E*-field and *H*-field, which indicate omnidirectional coverage in the azimuth plane, very suitable for applications requiring broad coverage. The analysis of the current distribution underlines the good exploitation of the S-shaped slots, improving impedance matching and reducing surface wave propagation.

The surface current distribution of the proposed antenna, as shown in *figure 11*. gives an important conclusion about the electromagnetic activity at the resonant frequency. It analyzes the flow of current across the antenna structure and thereby relates to its radiation characteristics and efficiency. Maximum current density, 130.124 A/m, can be observed around the feed point and lower parts of the S-shaped slots. The distribution of the surface current on the patch depicts that the S-shape design gives efficiency in electromagnetic radiation. The current density is rather high near the feeding point due to robust excitation, while its uniform distribution along the patch leads to better stability and more efficient radiation. Slots in the S-shaped design introduce compactness but also optimize the current paths, allowing narrowband operation at 2.45 GHz.

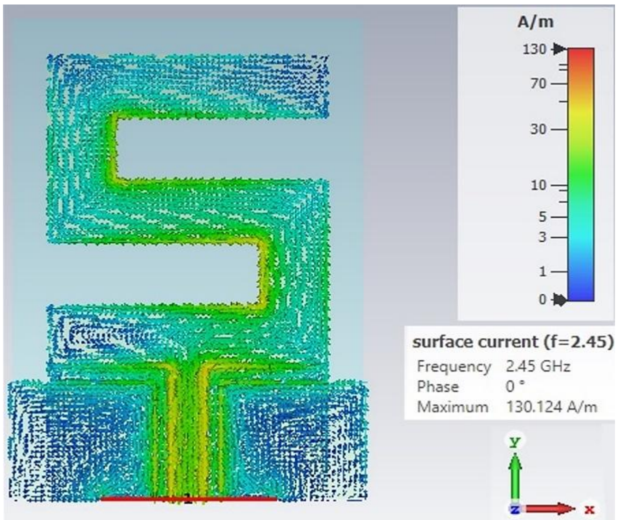

Figure 11. Analysis of current distribution for the Proposed S-Shaped Antenna

5. COMPARATIVE ANALYSIS

The proposed antenna's performance regarding operating frequency, substrate size, gain, and design complexity is compared with findings from previous research. The suggested antenna exhibits better performance in terms of impedance matching, demonstrating favorable design simplicity, as indicated in *table 2*. The proposed antenna is appropriate for all kinds of wireless communication applications and with better compactness than other recent designs.

Table 2. Comparison of S-shaped antenna performance with other literature

Ref.	Antenna Shape	Size $(mm)^2$	Substrate Material	Frequency (GHz)	Bandwidth (MHz)	Gain (dBi)
[12]	S-shaped	100 × 90	Roger 5880	2.4, 2.9	990	3.3
[13]	S-shaped	90 × 95	FR4	0.75, 1.5,1.9	130	–
[14]	S-shaped	26 × 22	FR4	4.9, 5.5, 2.6, and 3.5	–	-3.7
[15]	S-shaped	222 × 105	FR4	3.5	405	10
[16]	S-shaped	40 × 70	FR4	2.4	380	3.6
[17]	Microstrip slot	40 × 24	FR-4	2.44	140	2.41
[18]	Microstrip slot	–	PDMS	2.4, 5.8	90	−2.3
[19]	Monopole	44 × 33	FR-4	2.4, 5.8	–	1.48
[20]	Uniplanar	10 × 19	FR-4	2.5	200	1.20
[21]	Meander line	40 × 10	FR-4	2.4	300	−0.256
This Work	S-shape	29 × 20	FR4	2.45	200	1.75

The novelty of the proposed antenna is that it can work well with a strong match to the device (S11 < −27 dB) and has a high efficiency (95%) while being very compact in dimensions (29 mm × 20 mm). Unlike other S-shaped antennas that are often bigger or have less good performance. The design also balances between size and performance, which makes it a good choice for today's small wireless devices. The parametric tuning of the slotted structure and reduced ground plane help improve the performance of the antenna, making it more useful and innovative.

6. ANTENNA FABRICATION AND MEASUREMENT

Having designed and simulated the proposed S-shaped microstrip patch antenna, a physical prototype was made to verify the design. In this section, the fabrication process, test setup used in the measurement will be discussed and the comparison of results between measured and simulated will be discussed to check the accuracy and effectiveness of the proposed design.

The final physical prototype of the S-shaped microstrip patch antenna made to work in ISM-band wireless communications is presented in Figure 12. The front side of the antenna can be seen on the left with the copper radiating patch in the form of an S and the copper ground plane on the right. This antenna is mounted using SMA connector. This prototype has been well designed to meet the simulated dimensions and design to test and validate it.

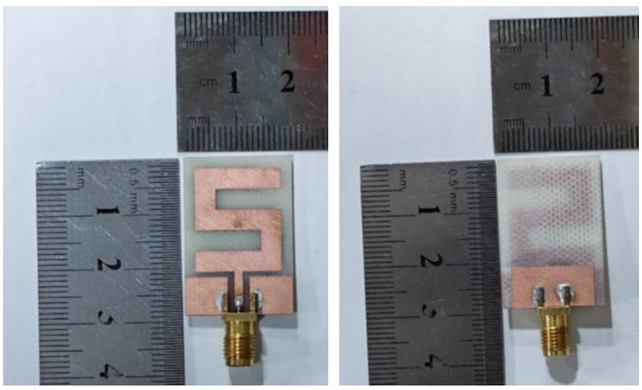

Figure 12. Fabricated S-Shaped Microstrip Patch Antenna

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The antenna was printed on a FR4 substrate. The patch and ground plane were formed by copper cladding on the substrate. The fabrication was done to produce the antenna pattern according to the simulation size (29 mm x 20 mm). The antenna was attached by an SMA connector to feed the signal. The configuration of the Vector Network Analyzer (VNA) measurement is illustrated in *figure 13*.

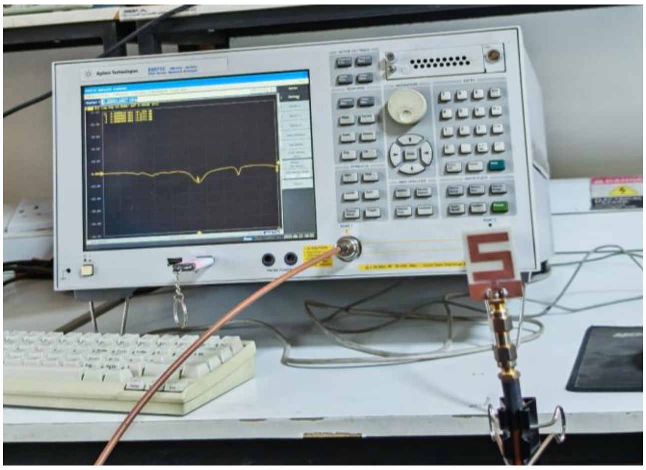

Figure 13. Measurement Setup of the Fabricated Antenna

Agilent ENA-E5071C Vector Network Analyzer (VNA) was used to measure the parameters, and the calibration of the instrument was done to achieve accurate S-parameter measurements. In the case of the under-test antenna, the connector was attached to Port 1 of the VNA using an SMA cable. S_{11} parameter was used to measure reflection (return loss) as a function of frequency.

The S_{11} parameter measured was plotted against the frequency as shown in *figure 14*. The outcomes show the change in the resonance frequency and a minor rise in the return loss when compared with the simulated results. The simulated S_{11} curve (in blue) indicates a sharp dip at 2.45 GHz, whereas the practical measurements (in orange) indicate a slightly broader and higher return loss.

The S_{11} curve measured has a resonance at approximately 2.42 GHz, and a return loss of approximately -15 dB. On the contrary, the simulated S_{11} displays a return loss of approximately -25 dB at 2.45 GHz.

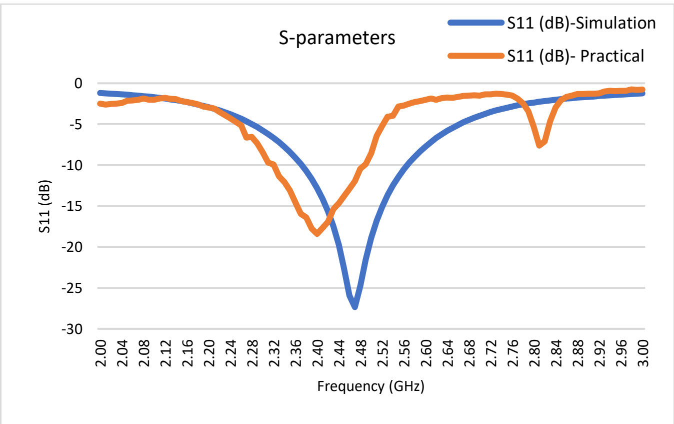

Figure 14. Measured vs. Simulated S11 Results

It is possible to explain the difference in resonance frequencies and return losses by several factors:

- *Fabrication Tolerances*: There are small differences in the physical size of the antenna, etching and alignment errors, etc. that may lead to a change in resonant frequency.
- Substrate Losses: The substrate used in the real world may incur extra losses which will not be simulated in the simulation, and this will influence the return loss and bandwidth.
- *Measurement and Connector Set Up*: The connector type (SMA) and quality of the measurement set up can also affect the accuracy of the practical results and in particular the return loss.
- *Environmental Factors:* The differences in the temperature and humidity of the environment in which the antenna was tested may also lead to slight changes in the frequency response.
- The other cause of the differences is the Agilent ENA-E5071C VNA that is an older version. Newer VNAs have improved resolution and measurement accuracy with advancement in technology. The ENA-E5071C is rather old, and this might affect the calibration of the device, and some parts might have worn out over time. Also, the setting of measurements and signal processing functions, though still very functional, may not be in line with newer instruments. These together with the physical differences of the fabricated antenna are probable causes of the difference in measured and simulated results.

Finally, the fabricated antenna was found to agree well with the designed one with minor differences in the resonance frequency and the return loss. These variances can be ascribed to the practical restrictions and environmental conditions experienced in the fabrication and measures. The antenna continues to satisfy the necessary specifications which are required to be used in ISM-band wireless communication applications.

7. CONCLUSION

This research offers a compact, efficient S-shaped microstrip patch antenna for narrowband operation in wireless networks at a frequency of 2.45 GHz. The design combines an FR4 substrate of a reduced ground plane with a considerably optimized S-shaped copper patch and accomplishes effective impedance matching to ensure moderate gain of about 1.75 dBi with a minimum bandwidth of approximately 200 MHz. The distribution of the surface current is also very good, and the results of the VSWR and return loss prove that the operation is stable and reliable within the frequency range of operation. This research introduces a new, small S-shaped antenna that is best suited for the ISM-band at 2.45 GHz. Having compact dimensions of 29 mm × 20 mm, this antenna is very suitable for space-limited low-power applications such as IoT devices, short-range communication systems, and wireless sensor networks. With this uniquely small size, the antenna has better impedance matching and radiation efficiency than previous designs and is suitable for use in embedded and wearable applications. The use of a CPW feed, less ground plane, and slot tuning sets this work apart by providing a practical, easy-to-make solution for reliable narrowband communication.

Following the fabrication and measurement processes of the S-shaped microstrip patch antenna, the findings established the design as a viable and applicable design to ISM-band applications. Although the fabricated antenna had minor differences with the simulated results, e.g., a frequency shift in the resonance and an increased return loss, it nevertheless fulfilled the basic design requirements of operating in the narrowband at 2.45 GHz. These experimental results confirm the feasibility of the small antenna to be used in the IoT devices, short-range communication systems, and wireless sensor networks. Future research can be done to enhance the manufacturing procedure to minimize the differences between the simulated and the measured data. Also, the performance can be enhanced by the use of advanced materials, better calibration techniques, and a more optimized antenna structure to be used in embedded and wearable applications.

8. ACKNOWLEDGMENTS

The authors are grateful for the support towards this research by the Communication Engineering College, University of Technology- Iraq.

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