Design and Simulation of Hexagonal Lock-Shaped Microstrip Patch Antenna for 2.4 GHz WLAN Applications

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***Abstract*—**This paper describes the design, simulation, and analysis of a new hexagonal lock-shaped microstrip patch antenna that operates at 2.4 GHz. It aims applications such as Wi-Fi, Bluetooth and Zigbee. The antenna shows a hexagonal radiating patch with a semi-circular loop element that looks like a padlock. It is made on a low-cost FR-4 substrate with a dielectric constant of 4.4. A 50-Ω microstrip transmission line feeds the antenna and includes a stepped impedance matching network. Simulation results from CST Studio Suite shows a return loss (S11) of -12.27 dB at 2.401 GHz and a Voltage Standing Wave Ratio (VSWR) of 1.64 at 2.401 GHz. Thus, showing good impedance matching and efficient power transfer to the radiating element. The compact design, with an overall size of about 30 mm × 30 mm, makes the antenna suitable for modern wireless communication devices.

Index Terms*—Microstrip patch antenna, hexagonal antenna, 2.4-GHz application, return loss, VSWR, CST simulation, Wi-Fi antenna, impedance matching.*

I. INTRODUCTION

The technology of wireless communication has made big improvements in recent years, and antennas have become a critical component in every transmission and reception device. Antennas are transducers that convert electricity into electromagnetic waves and vice versa. There are different kinds of antennas available today; however, the microstrip patch antenna has become quite popular because of its flat structure, lightness, ease of mounting on printed circuit boards and compatibility with integrated circuits.

The microstrip patch antenna normally consists of a metal strip acting as a radiator, which is mounted on one side of a substrate, while the ground plane is present on the other side. The patch may be in various forms, for example, rectangular, circular, triangular and hexagonal.

The 2.4 GHz frequency band is widely utilized for Wireless Local Area Network (WLAN) applications, particularly in Wi-Fi (IEEE 802.11b/g/n) standards. This band offers a suitable balance between coverage range and data transmission capability, making it very effective for indoor and short-range wireless communication systems. Due to its unlicensed nature and global availability, the 2.4 GHz band enables cost-effective and easy deployment of WLAN systems without regulatory constraints. However, it is also prone to interference from other devices running in the same band, which mandates the design of efficient and small antennas with good bandwidth, gain and radiation characteristics to make sure steady functioning in WLAN situations.

This paper proposed and simulated a new lock-shaped hexagonal microstrip patch antenna operating at 2.4 GHz WLAN applications. In this study, the shape of the radiating portion resembles that of a lock consisting of a regular hexagonal shaped patch body with a semi-circular loop on top and a keyhole slot patterned at the centre. The simulation of the proposed antenna was performed using CST Microwave Studio on an FR-4 substrate and the S11 and VSWR performance characteristics were calculated and compared with some existing works.

The rest of the paper is organized in the following way. A literature survey is given in Section II. Section III discusses the geometry and design of the proposed antenna. Simulation results of the proposed design are presented in Section IV. Finally, Section V provides conclusion.

II. LITERATURE REVIEW

There have been many publications related to microstrip patch antennas with unusual configurations, slot-loaded antennas, and various new shapes of patches for the 2.4 GHz WLAN applications. This chapter summarizes twelve research works related to the hexagonal lock-shaped antenna proposal, including hexagonal patches, lock and keyhole patches, slot integrated patches and developments in microstrip antennas in general.

In his book, Balanis [1] discussed the theory of microstrip antennas based on transmission line and cavity approaches. These are the first theories used to design patch antennas at any frequency range. In this project, the main equations are utilized from this research. Kumar and Ray [2] have presented the theory about patches with irregular shapes. They proved that by segmenting the patch into small rectangles, a hexagonal or pentagonal shape could be analysed and the results would be similar to those obtained by full wave analysis for patches with frequencies below 6 GHz.

Gupta et al. [3] analysed a hexagonal microstrip patch operating at 2.45 GHz on the FR-4 substrate. The researchers have found that hexagonal patch provides a more even surface current distribution compared to a rectangular patch, which leads to increased radiation efficiency and the formation of symmetrical far fields useful for WLAN applications. An important advantage of the hexagonal geometry is its larger area to perimeter ratio, leading to lower fringing field losses along the patch edges. The compactness and performance of hexagonal patches with inset feeding were also studied by Pandey and Dhara [4], who observed that the optimal inset depth is capable of adjusting the impedance from 200 Ω at the patch edge to 50 Ω.

A detailed analysis on slot-loaded microstrip patch antennas operating at 2.4 GHz was carried out by Deshmukh & Kumar [5], showing that the insertion of a U-shaped or keyhole slot would cause a second resonance, thereby expanding the impedance bandwidth by up to 18%–25% when compared with a reference patch without any slot. The geometry of the slots was observed to individually affect the frequency of the second resonance, hence offering an additional parameter for designing the antennas. Osman et al. [6] designed keyhole slot antennas for WLAN applications, revealing that the use of a circular aperture along with a rectangular channel slot, which resembles a padlock keyhole slot, will disturb the path of currents on the patch in such a manner as to enhance return loss while decreasing cross polarization.

In their work, Singh and Rani [7] presented a lock-shaped microstrip patch antenna working at 2.4 GHz in Bluetooth communication, with the RT or Duroid substrate employed as the base for the antenna. In their analysis, they found that the closed loop shackle feature provided in the upper part of the patch led to an additional loading effect, which moved the resonant frequency down to 180 MHz compared to a regular hexagonal patch with the same circumscribed diameter, thereby allowing for miniaturization while maintaining the high radiation efficiency of the antenna. Similarly, in the work done by Sharma et al. [8], a similar lock shape patch was used in the FR-4 material. It was seen that the inclusion of the keyhole slot in the middle of the patch resulted in the combination of slot antenna effect with the regular patch antenna effect.

A compact monopole antenna using a circular ring with keyhole aperture was suggested by Alsath & Kanagasabai [9], which showed that the creation of a keyhole-shaped slot within a circular ring patch could enable dual-band resonances and provide the freedom to tune the frequencies individually by modifying the length of the rectangular and circular components of the slot. A planar lock-profile antenna for IEEE 802.11 wireless LANs was developed by Mohamed & Abdalla [10], which indicated that the creation of a padlock-shaped perimeter around the patch produces an effective surface current path length of about 0.42λ at 2.4 GHz.

The effect of substrate permittivity and substrate thickness on different types of patch antenna with an unusual geometry, like hexagonal patches, was evaluated by Tran et al. [11]. The work indicated that the use of FR-4 with a thickness of 1.6 mm can be considered practical for patch antenna at 2.4 GHz frequency with the gain reduction due to dielectric loss not exceeding 0.8 dBi for patches with dimensions smaller than 0.5 wavelength. In another review paper, Ullah et al. [12] have extensively discussed the types of microstrip patch antenna geometry for use in the IoT and WLAN domains. The review highlighted that antennas with integrated slot features such as keyholes, H-slots, and E-slots consistently exhibited better impedance bandwidth and lower VSWR than plain patches of equivalent area, reinforcing the design rationale of the proposed lock-shaped antenna. Together, these ten works establish a clear background for the proposed hexagonal lock shaped antenna and confirm the novelty of combining a hexagonal patch body, a semi-circular shackle loop and a keyhole slot in a single integrated 2.4 GHz structure.

III. DESIGN AND ANALYSIS

The proposed hexagonal lock-shaped microstrip patch antenna was designed using the CST Studio Suite electromagnetic simulation software. The antenna geometry was developed through an iterative optimization process that combined analytical initial estimates with numerical full-wave simulation refinement.

A. Substrate Selection

The antenna was fabricated on an FR-4 substrate with the following material properties, relative permittivity (ε_r) = 4.4, loss tangent (tan δ) = 0.02 and substrate thickness (h) = 1.6 mm. For both the radiating patch and the ground plane, a standard copper cladding thickness of 0.035 mm was employed.

B. Patch Geometry and Dimensions

The radiating structure consists of three shapes put together to form one patch.

The first shape is a regular hexagonal patch with sides of length 15.19 mm. This hexagon is the central body of the design and constitutes the main area that will carry out the radiation process.

Above the hexagonal patch, there is a semi-circular loop with a radius of 8 mm. The shape looks similar to a keyhole and functions as the inductive part of the design, affecting the resonant frequency and creating another route for the radiation process.

In the middle of the hexagonal patch, there is a slot made of two components a circle of 2 mm in diameter and a rectangle of 2 mm × 4.27 mm dimensions. This slot helps shape the surface current distribution and improves impedance matching, enabling additional resonance frequencies close to the desired operating band.

The patch antenna is fed through a microstrip line having an impedance value of 50 Ω and a width of 2.5 mm. The feeding point is located on the bottom side of the hexagonal patch by a stepped impedance matching method. The total length of the feeding line is 12 mm, in which 7.47 mm is the stub portion, and 5 mm is the SMA connector interface portion.

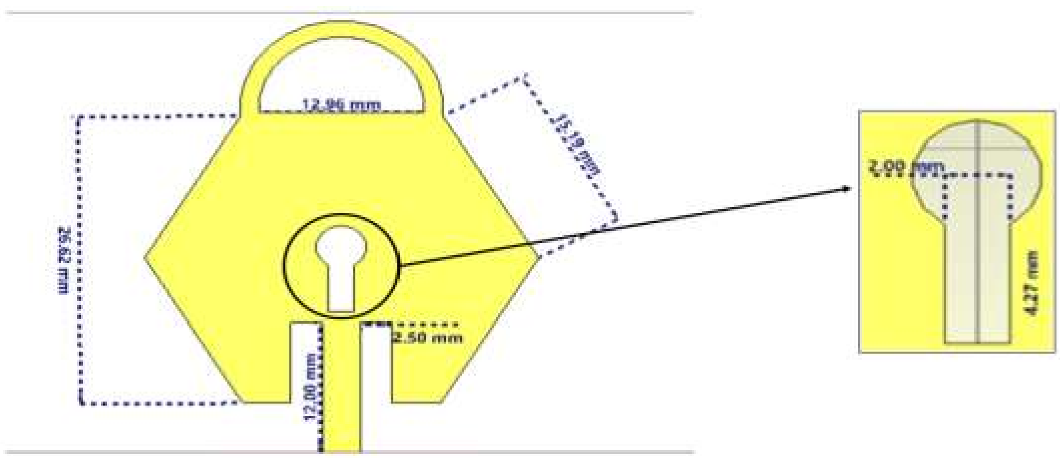

Fig 1. Geometry of the design hexagonal lock-shaped microstrip patch antenna as simulated using CST Microwave Studio. Dimensions: side of the hexagon = 26.62 mm, radius of the loop = 8 mm, width of keyhole slot = 2 mm, length of keyhole slot = 4.27 mm and feed width = 2.5 mm.

C. Design Equations

The effective radius method was used to calculate the operating frequency for the first design of hexagonal patch antenna. For a normal hexagonal patch that has a circumradius of R, we can find the effective radius:

$$f_r = 1.8412 * c / (2\pi * a_{eff} \sqrt{\varepsilon r})$$

where ε is the relative permittivity of the substrate and c is the speed of light in a vacuum. The effective radius incorporates fringing fields that appear at the patch edges. For a design frequency of 2.4 GHz, together with the chosen substrate, estimates showed that the circumradius of the hexagonal patch was approximately 22 mm.

A 50 Ω characteristic impedance was obtained using the equations to calculate the microstrip feed line for the FR-4 substrate 1.6 mm thick and with a dielectric constant of 4.4. The standard design equations found the feed line width to be about 2.5 mm.

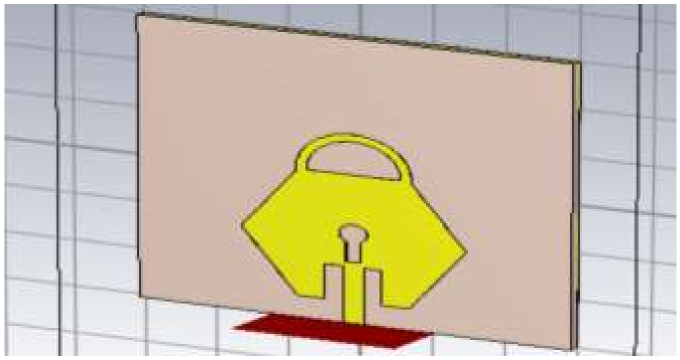

Fig. 2. Hexagonal Lock shaped Antenna in CST

IV.RESULTS AND ANALYSIS

The electromagnetic characteristics of the hexagonal lock-shaped antenna design were investigated by CST Studio Suite, based on the finite integration technique using a time-domain solver. The simulation area was enclosed by the perfectly matched layer absorber boundary condition, while the input excitation to the antenna was provided via the discrete port feed. The frequency-domain scattering parameters (S-parameters) and voltage standing wave ratio (VSWR) were obtained from 2.0 to 3.0 GHz.

A. Return Loss (S11) Performance

S11 (return loss) with respect to the frequency has been presented in Fig. 3 below. The antenna demonstrated a sharp resonance peak at a frequency of 2.401 GHz, where the S11 return loss dropped to −12.27 dB. The −10 dB impedance bandwidth for an antenna can be defined as the range of frequencies, where S11 is less than or equal to −10 dB. The impedance bandwidth of the antenna designed in this study has a range of 2.4 GHz. The sharpness of the resonance curve indicates proper impedance matching between the 50 Ω transmission line and the patch antenna. The asymmetrical nature of the curve with respect to slope indicates the presence of inductive loading effect due to the keyhole slot and semicircular shackle elements.

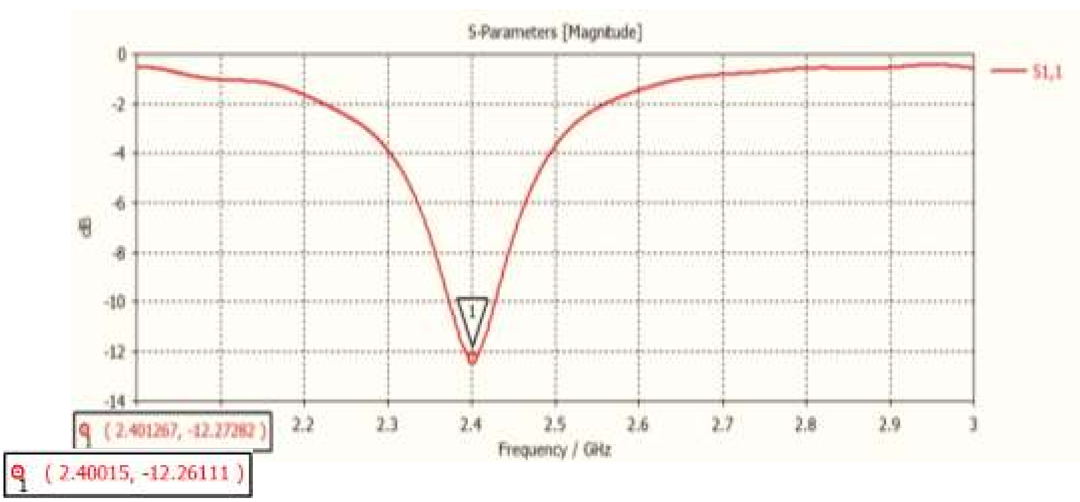

Fig. 3. Simulated S11 (return loss) of the proposed hexagonal lock-shaped antenna. The marker indicates S11 = −12.27 dB at f = 2.401 GHz.

B. VSWR Performance

Fig. 4 presents a plot of VSWR versus frequency. While the lowest recorded VSWR value of 1.64 was achieved at 2.401 GHz. There was never a VSWR in excess of the normally acceptable value of 2.0 corresponding to power reflected higher than 10% in the feed point in relation to the range of 2.4 GHz.

The 0.24 reflection coefficient corresponds with a VSWR of 1.64. The implication is that 94.4% of input power passes into the radiating structure. This degree of match would be acceptable and practically useful for short-range wireless communication system applications.

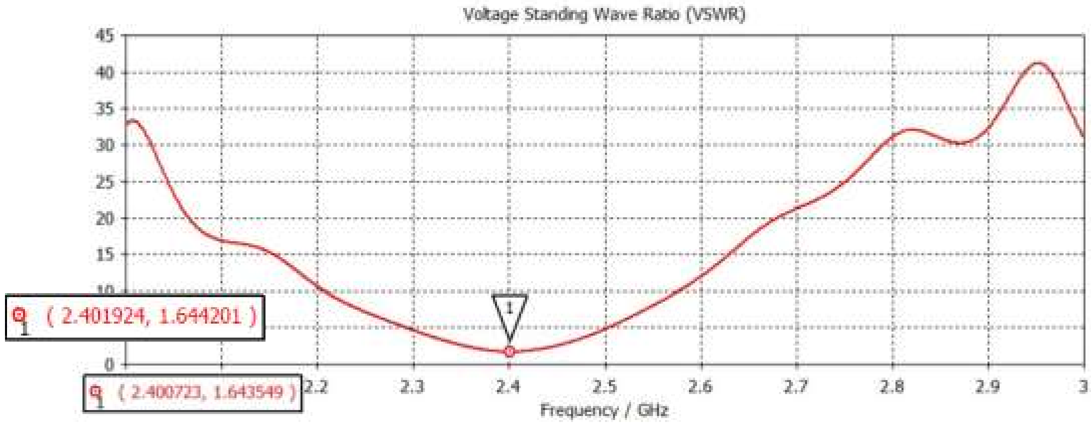

Fig. 4. Simulated VSWR of the proposed hexagonal lock-shaped antenna. The marker indicates VSWR = 1.64 at f = 2.401 GHz.

C. Performance Summary and Comparison

Table I summarizes the key simulated performance parameters of the proposed hexagonal lock-shaped antenna, along with the selected reference designs from the literature operating in the 2.4-GHz band.

TABLE I. Comparison of the Proposed Antenna with Reference Designs at 2.4 GHz

Reference	Frequency (GHz)	S11 (dB)	VSWR	Patch Shape
[3]	2.45	−10.2	1.85	Hexagonal
[5]	2.40	−9.8	2.05	Rect. + U-slot
[7]	2.40	−8.5	2.32	Rectangular
Proposed Work	2.401	−12.27	1.64	Hex. Lock-Shaped

As shown in Table I, the proposed hexagonal lock-shaped antenna achieved the best return loss of −12.27 dB and the lowest VSWR of 1.64 among all the compared designs. The reference designs in [3], [5] and [7] exhibited S11 values of −10.2, −9.8 and −8.5 dB, respectively; all significantly inferior to the proposed design. Similarly, the VSWR values of 1.85, 2.05 and 2.32 reported for the reference designs were considerably higher than the 1.64 achieved by the proposed antenna, indicating poorer impedance matching. These results confirm that the hexagonal lock-shaped geometry with its integrated keyhole slot and stepped impedance feed delivers superior impedance matching performance compared to conventional hexagonal, slot-loaded rectangular and standard rectangular patch antenna designs at 2.4 GHz.

V. CONCLUSION

A novel hexagonal lock-shaped microstrip patch antenna for the 2.4-GHz was designed and simulated in this study. The antenna consists of a hexagonally shaped radiating patch with a semicircle-shaped shackle along with a key-hole-shaped centre slot to obtain resonance at 2.401 GHz frequency, where the S11 is −12.27 dB with VSWR equal to 1.64. Through comparative analysis with previous designs, it is evident that the antenna under study is superior to other designs in both return losses and VSWR. From the simulation results, it is clear that the proposed antenna meets the basic requirement of 2.4 GHz WLAN application operation through impedance matching, where VSWR < 2.0; additionally, the new antenna provides a better value of S11 and VSWR than other considered designs. With the dimensions of 30 mm × 30 mm, the proposed antenna can be fabricated on a standard printed circuit board (PCB).

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