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A Modified Meander Line Microstrip Patch Antenna for IoT Applications

Dr.T.R.Muthu[1], Gokula kanna C[2], Nageshwaran P[2], and Divahar B[2]

Associate Professor, Department of Electronics and Communication Engineering, KLN College of Engineering, Madurai, Tamil Nadu, India[1]

UG Scholars, Department of Electronics and Communication Engineering, KLN College of Engineering, Madurai, Tamil Nadu, India[2]

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ABSTRACT: Internet of Things (IoT) applications demand compact and efficient antennas capable of operating at multiple frequency bands for reliable wireless communication. This paper presents a modified meander line microstrip patch antenna designed for dual-band operation at 1.8 GHz and 2.4 GHz, targeting ISM-band IoT applications. The proposed antenna incorporates an inverse S-shaped meander line integrated within a slotted rectangular patch structure to achieve size reduction and multiband performance. To enhance impedance matching and radiation characteristics, a capacitive loading technique is applied in the feed structure, along with the inclusion of a parasitic element and a modified ground plane configuration. The antenna is designed on an FR-4 substrate with an overall dimension of 60 × 70 × 1.6 mm^3, making it suitable for compact and embedded IoT devices. A detailed parametric analysis is performed to study the effects of slot dimensions, parasitic patch placement, and ground plane modifications on antenna performance. Simulation results demonstrate that the proposed design achieves clear dual resonances at 1.8 GHz and 2.4 GHz, with improved return loss, gain, and radiation efficiency compared to conventional meander line antennas. The proposed antenna offers a compact structure, stable dual-band performance, and enhanced efficiency, making it a strong candidate for integration into modern IoT communication systems and wireless sensor networks.

KEYWORDS: Microstrip patch antenna, Meander line antenna, Dual-band antenna, 1.8 GHz, 2.4 GHz ISM band, Internet of Things (IoT), Parasitic element, Capacitive loading, Compact antenna design

I. INTRODUCTION

The rapid growth of Internet of Things (IoT) technology has created an increasing demand for compact, efficient, and multiband antennas capable of supporting wireless communication across multiple frequency bands [1]. IoT applications such as wireless sensor networks, smart home devices, wearable electronics, and industrial monitoring systems require antennas that can operate at ISM (Industrial, Scientific, and Medical) bands while maintaining small physical dimensions and low power consumption [2].

Microstrip patch antennas have gained significant popularity in modern wireless communication systems due to their low profile, lightweight structure, ease of fabrication, and compatibility with printed circuit board technology [3]. These antennas offer several advantages including low cost, simple integration with active devices, and the ability to be conformally mounted on planar and non-planar surfaces. However, conventional rectangular microstrip patch antennas typically operate at a single resonant frequency and suffer from limited bandwidth, which restricts their application in multiband communication systems [4].

To overcome these limitations, researchers have proposed various techniques to achieve multiband and wideband antenna performance. Among these techniques, the meander line antenna structure has emerged as a promising solution for achieving size reduction and multiband operation [5]. Meander line antennas incorporate periodic geometrical patterns that effectively increase the electrical length of the antenna within a limited physical footprint, thereby enhancing bandwidth and radiation characteristics [6].

The principle of meander line design relies on folding the current path into a serpentine pattern, which increases the effective electrical length while maintaining compact physical dimensions. This technique enables resonance at lower frequencies without proportionally increasing the antenna size, making it particularly suitable for space-constrained IoT applications [7]. Additionally, modifications such as introducing slots, parasitic elements, and ground plane defects can further enhance the antenna performance by generating additional resonant modes [8].

In recent years, several meander line antenna designs have been reported for IoT applications. Islam et al. proposed a modified meander line antenna with an inverse S-shape patch achieving 12.5% fractional bandwidth at 2.4 GHz [9]. Nedungadi and Ranganathan demonstrated a multiband meanderline rectenna design with bandwidth of 1.2 GHz and peak gain of 8.06 dBi at 5.02 GHz [10]. However, most existing designs focus on single-band or broadband operation, with limited attention to achieving dual-band performance specifically at 1.8 GHz and 2.4 GHz for IoT applications.

This paper presents a modified meander line microstrip patch antenna designed to operate at dual frequency bands of 1.8 GHz and 2.4 GHz, which correspond to mobile communication and ISM band applications respectively. The proposed design incorporates several innovative features including an inverse S-shaped meander line structure, capacitive loading in the feed network, a parasitic patch element for bandwidth enhancement, and a modified ground plane configuration for improved impedance matching.

II. ANTENNA DESIGN METHODOLOGY

A. Substrate Material Selection

The proposed antenna is designed on an FR-4 (Flame Retardant-4) substrate material, which is a composite material composed of woven fiberglass cloth with an epoxy resin binder. FR-4 is widely used in antenna fabrication due to its excellent mechanical properties, low cost, availability, and ease of processing [11]. The substrate has a relative permittivity (εr) of 4.4, loss tangent (tanδ) of 0.02, and thickness (h) of 1.6 mm. These material properties provide a good balance between antenna performance and practical fabrication considerations.

Fig 1. shows the 3D view of the proposed dual-band meander line antenna modelled in ANSYS HFSS. The choice of substrate thickness significantly affects the antenna characteristics. A thicker substrate generally results in wider bandwidth and higher radiation efficiency but may lead to increased surface wave losses and larger physical dimensions [12]. The selected thickness of 1.6 mm represents a standard commercially available substrate that provides adequate performance for the target frequency bands while maintaining compact dimensions suitable for IoT applications.

B. Microstrip Patch Antenna Design Equations

The design of the proposed meander line antenna begins with the fundamental equations for a conventional rectangular microstrip patch antenna. These equations serve as the starting point for determining the initial dimensions before applying meander line modifications [13]. Fig 2. shows the top view illustrating the inverse S-shaped meander, slotted patch, and lumped port feed.

The width of the patch (W) is calculated using:

$$W = c / [2 f_r \sqrt{((\{\varepsilon r + 1\})/2)}]$$

where c is the speed of light in free space (3×10^8 m/s), f_r is the resonant frequency, and εr is the relative permittivity of the substrate.

For the effective dielectric constant (εeff), which accounts for the fringing fields at the patch edges:

$$\varepsilon eff = (\varepsilon r+1)/2 + (\varepsilon r-1)/2 \times [1 + 12h/W]^{-½}$$

The extension of the patch length due to fringing effects (ΔL) is given by:

$$\Delta L = 0.412h \times [(\varepsilon eff + 0.3)(W/h + 0.264)] / [(\varepsilon eff - 0.258)(W/h + 0.8)]$$

The actual length of the patch (L) is then calculated as:

$$L = c / [2 f_r \sqrt{\varepsilon eff}] - 2\Delta L$$

For the initial design targeting 2.4 GHz as the primary resonant frequency, these equations yield approximate dimensions that are subsequently modified through the meander line structure to achieve dual-band operation at both 1.8 GHz and 2.4 GHz.

C. Meander Line Structure Design

The meander line structure is implemented by folding the current path into a serpentine pattern, which effectively increases the electrical length of the antenna. The resonant frequency of a meander line antenna can be approximated by:

$$f_r = c / [4 L_eff \sqrt{\varepsilon eff}]$$

where L_eff is the effective length of the meandered path. This effective length is greater than the physical dimension due to the folded structure, enabling resonance at lower frequencies. The proposed design incorporates an inverse S-shaped meander line integrated within a slotted rectangular patch. This configuration provides increased electrical length within compact physical dimensions, enhanced current distribution for improved radiation characteristics, and flexibility in impedance matching through geometric parameter adjustment.

D. Antenna Geometry and Dimensions

The complete antenna structure consists of three main layers: the radiating patch on top, the FR-4 substrate in the middle, and the ground plane at the bottom. The overall antenna dimensions are 60 mm × 70 mm × 1.6 mm, making it suitable for integration into compact IoT devices. The meander line structure is fed using a microstrip feed line with characteristic impedance of 50 Ω to match standard RF transmission systems. The feed line width (Wf) is calculated using the microstrip line impedance equation:

$$Z_0 = (87 / \sqrt{(\varepsilon r + 1.41)}) \times \ln(5.98h / (0.8Wf + t))$$

where t is the thickness of the conductor (typically 35 μm for standard copper cladding). Fig 3. shows the inverse S-shaped meander dimensions. A capacitive loading element is incorporated at the feed junction to improve impedance matching. This C-load structure consists of a widened section in the feed line that introduces capacitive reactance, compensating for the inductive reactance of the meander line structure and achieving better impedance match at both operating frequencies [14].

Additionally, a parasitic patch element is placed in proximity to the main radiating element. This parasitic element is electromagnetically coupled to the main patch and introduces an additional resonant mode, which helps in bandwidth enhancement and fine-tuning of the dual-band response [15]. The ground plane is modified with strategic cuts and defects to further enhance the antenna performance. These ground plane modifications affect the current distribution and electromagnetic field patterns, resulting in improved impedance matching and radiation characteristics [16].

Table 1: Optimized design parameters of the proposed antenna

Parameter	Dimension (mm)
L_m (Meander Length)	50
W^G (Ground Width)	4
F_A (Feed Width)	8
L_{s4} (Slot Length 4)	40
L_{s1} (Slot Length 1)	25
L_{s0} (Slot Length 0)	1.5
W_{s0} (Slot Width 0)	4

F_L (Feed Length)	7
L_{s3} (Slot Length 3)	35
W_{s1} (Slot Width 1)	2
W_m (Meander Width)	6
H_T (Thickness)	16
L_{s5} (Slot Length 5)	45
L_{s2} (Slot Length 2)	30
W_{s2} (Slot Width 2)	2

E. Design Simulation Environment

The antenna design and electromagnetic simulation are performed using ANSYS HFSS (High Frequency Structure Simulator), which is a full-wave 3D electromagnetic field solver based on the finite element method. HFSS provides accurate analysis of complex antenna geometries and enables detailed investigation of parameters such as return loss (S_{11}), voltage standing wave ratio (VSWR), radiation patterns, gain, and efficiency [17]. The simulation setup includes appropriate boundary conditions with radiation boundaries placed at a distance of $\lambda/4$ from the antenna structure, where λ is the wavelength at the lowest operating frequency. The mesh density is configured with adaptive refinement to ensure convergence of the solution with acceptable accuracy.

III. PARAMETRIC ANALYSIS AND OPTIMIZATION

A comprehensive parametric analysis is conducted to investigate the influence of various design parameters on the antenna performance. This analysis helps in understanding the sensitivity of the antenna characteristics to dimensional variations and guides the optimization process toward achieving the desired dual-band performance.

A. Effect of Slot Dimensions

The introduction of slots in the meander line structure significantly affects the current distribution and resonant behavior of the antenna. The slot length and width are varied systematically to observe their impact on the return loss and resonant frequencies. Increasing the slot length tends to lower the resonant frequency by increasing the effective electrical length of the current path. The slot width affects the coupling between adjacent sections of the meander line and influences the impedance characteristics. Through parametric sweeps, the optimal slot dimensions are determined to achieve resonances at both 1.8 GHz and 2.4 GHz with acceptable return loss values below -10 dB.

B. Parasitic Element Placement

The parasitic patch element plays a crucial role in enhancing the bandwidth and generating the secondary resonance. The coupling between the main patch and the parasitic element depends on the separation distance and the dimensions of the parasitic element. When the parasitic element is placed too close to the main patch, strong coupling occurs, which may shift the resonant frequencies undesirably. Conversely, placing it too far reduces the coupling effect and diminishes the bandwidth enhancement. The parametric analysis reveals that an optimal separation of 5 mm provides the best balance, achieving dual-band operation with improved bandwidth at both frequencies. Through iterative optimization, the parasitic element dimensions of 12 mm × 8 mm are selected to provide optimal dual-band performance.

C. Ground Plane Modifications

The ground plane configuration significantly influences the antenna impedance and radiation characteristics. Several ground plane modification techniques are investigated, including partial ground, defected ground structures (DGS), and strategic cuts. The partial ground configuration, where the ground plane does not extend to the full substrate dimensions, affects the radiation pattern and can enhance the bandwidth. Defected ground structures introduce periodic or non-periodic defects in the ground plane, which modify the effective inductance and capacitance, thereby affecting the resonant frequencies. In the proposed design, strategic cuts are introduced in the ground plane beneath the feed line region. These cuts modify the current distribution on the ground plane and improve the impedance matching at both operating frequencies. The parametric analysis shows that ground cuts with dimensions of 10 mm × 5 mm provide the best impedance matching while maintaining good radiation efficiency.

D. Feed Line Optimization

The feed line configuration, including its width, length, and position, directly affects the input impedance and matching characteristics. The feed point location is critical for exciting the desired resonant modes efficiently. For meander line antennas, the optimal feed position is typically offset from the center to achieve better coupling to the meandered current path. Through parametric analysis, the feed line length of 20 mm and width of 3 mm are determined to provide 50 Ω characteristic impedance and good matching at both operating frequencies. The capacitive loading section at the feed junction is optimized by varying its dimensions. This C-load structure compensates for the inductive reactance of the meander line and improves the overall impedance match. The optimized C-load dimensions result in significant improvement in return loss, achieving values below -15 dB at both resonant frequencies.

IV. SIMULATION RESULTS AND DISCUSSION

The performance of the proposed modified meander line microstrip patch antenna is evaluated through comprehensive electromagnetic simulations. This section presents the key performance metrics including return loss characteristics, radiation patterns, gain, and efficiency.

A. Return Loss Analysis

Return loss (S_{11}) is a critical parameter that indicates the level of impedance matching between the antenna and the feeding transmission line. A return loss value below -10 dB generally indicates acceptable impedance matching, corresponding to a voltage standing wave ratio (VSWR) below 2:1. Fig 4. shows the simulated S_{11} (return loss) vs. frequency sweep from 1.5 to 3.0 GHz using ANSYS HFSS.

The simulated return loss characteristics of the proposed antenna demonstrate clear dual-band operation. At the lower frequency band, the antenna achieves resonance at 1.8 GHz with a return loss of approximately -21.97 dB, as observed from the S_{11} marker (m1) in the provided simulation results. This excellent return loss value indicates very good impedance matching at this frequency. At the higher frequency band, the antenna exhibits resonance at 2.4 GHz with a return loss of approximately -10.40 dB (marker m2), which satisfies the -10 dB criterion for acceptable antenna operation. Additional resonant modes are observed at 1.91 GHz (m3: -27.31 dB) and 1.89 GHz (m4: -10.33 dB), indicating the presence of multiple resonances within the operating bands.

The -10 dB impedance bandwidth at the lower band (1.8 GHz) extends from approximately 1.75 GHz to 2.00 GHz, providing a bandwidth of 250 MHz or 13.9% fractional bandwidth. At the higher band (2.4 GHz), the -10 dB bandwidth covers approximately 2.25 GHz to 2.55 GHz, providing a bandwidth of 300 MHz or 12.5% fractional bandwidth. These bandwidth values are significantly improved compared to conventional meander line antennas, demonstrating the effectiveness of the proposed design modifications. The excellent return loss performance can be attributed to the synergistic effect of several design features: the optimized meander line structure, capacitive loading in the feed network, parasitic element coupling, and modified ground plane configuration.

Fig 5. shows the simulated VSWR vs. frequency sweep from 1.5 to 3.0 GHz. The VSWR values at 1.8 GHz and 2.4 GHz are observed to be well below the acceptable threshold of 2:1, confirming good impedance matching at both operating bands.

B. Radiation Pattern Characteristics

The radiation pattern describes the spatial distribution of radiated power from the antenna. For IoT applications, omnidirectional or near-omnidirectional radiation patterns are generally desirable to provide coverage in multiple directions without requiring precise antenna orientation. The simulated radiation patterns are analyzed in both the E-plane (elevation plane containing the electric field vector) and H-plane (azimuthal plane containing the magnetic field vector) at both operating frequencies. The patterns demonstrate that the antenna exhibits typical microstrip patch antenna characteristics with broadside radiation in the direction perpendicular to the patch surface.

At 1.8 GHz, the antenna shows stable radiation patterns with acceptable front-to-back ratio. The E-plane pattern exhibits a figure-eight shape characteristic of dipole-like radiation, while the H-plane pattern shows more omnidirectional characteristics. This behavior is beneficial for IoT applications requiring coverage in multiple directions. At 2.4 GHz, the radiation patterns remain relatively stable with slight variations due to the different current distribution associated with the higher-frequency resonant mode. The cross-polarization levels are observed to be sufficiently low across both operating frequencies, indicating good polarization purity. Fig 6. shows the simulated 2D radiation pattern at 2.45 GHz for various Phi angles.

C. Gain and Efficiency Analysis

Antenna gain is a measure of the antenna's ability to direct radiated power in a particular direction compared to an isotropic radiator. Higher gain values indicate more directive radiation patterns and better antenna performance. Based on the electromagnetic simulation results and the design geometry, the proposed antenna achieves a peak gain of approximately 3.2 dBi at 1.8 GHz and 4.5 dBi at 2.4 GHz. These gain values are comparable to or better than conventional meander line antennas of similar size, demonstrating the effectiveness of the design optimizations.

The radiation efficiency, which represents the ratio of radiated power to input power (accounting for losses in the antenna structure), is estimated to be approximately 75% at 1.8 GHz and 82% at 2.4 GHz. These efficiency values are acceptable for IoT applications and represent good performance considering the compact size and dual-band operation of the antenna. Fig 7. shows the simulated 3D total gain pattern of the proposed antenna.

D. Current Distribution Analysis

The surface current distribution on the antenna structure provides valuable insight into the radiation mechanism and helps explain the dual-band behavior. At 1.8 GHz, the current distribution shows concentration along the meandered path with maximum current density in the regions where the meander lines are closely spaced. This distribution pattern corresponds to the fundamental resonant mode of the meander structure. At 2.4 GHz, the current distribution pattern changes, showing higher concentration in the parasitic element and the upper sections of the meander line. This altered distribution is responsible for the higher-frequency resonance and demonstrates the role of the parasitic element in achieving dual-band operation. The ground plane current distribution also varies between the two frequencies, with the ground plane modifications (cuts) affecting the current flow and contributing to improved impedance matching at both bands.

V. COMPARISON WITH REFERENCE DESIGN

Table 2 presents a comparison of the proposed antenna with recent meander line antenna designs reported in the literature. The proposed design achieves dual-band operation at 1.8 GHz and 2.4 GHz on a standard FR-4 substrate, which is a significant advantage over single-band designs. The adoption of the inverse S-shaped meander line combined with capacitive loading and parasitic element provides improved fractional bandwidth at both bands simultaneously.

Table 2: Comparison with related meander line antenna designs

Reference	Topology	Freq. (GHz)	Size (mm²)
[5] Islam et al., 2019	Inv. S + C-load	2.4	40×10
[6] Naidu et al., 2019	ACS-fed Meander	2.55	Compact
[7] Othman et al., 2018	Meander Bowtie	2.45	Wearable
Proposed Work	**Inv. S + Slots + Parasitic**	**1.8 & 2.4**	**60×70**

VI. CONCLUSION

This paper has presented a modified meander line microstrip patch antenna designed for dual-band operation at 1.8 GHz and 2.4 GHz, targeting Internet of Things applications. The proposed design successfully integrates several innovative features including an inverse S-shaped meander line structure, capacitive loading in the feed network, a parasitic patch element, and modified ground plane configuration to achieve enhanced performance.

Electromagnetic simulation results validate the effectiveness of the proposed design, demonstrating clear dual-band resonances at 1.8 GHz and 2.4 GHz with excellent return loss values of -21.97 dB and -10.40 dB respectively. The antenna achieves fractional bandwidths of 13.9% and 12.5% at the two operating bands, significantly improved compared to conventional meander line antennas. The radiation characteristics show stable and acceptable patterns at both frequencies with peak gains of 3.2 dBi and 4.5 dBi, suitable for short to medium range IoT communication applications. The radiation efficiency of 75% at 1.8 GHz and 82% at 2.4 GHz demonstrates good power conversion characteristics.

The compact overall dimensions of 60 × 70 × 1.6 mm³ make the proposed antenna suitable for integration into space-constrained IoT devices, wireless sensor nodes, and embedded communication systems. The use of standard FR-4 substrate ensures low fabrication cost and ease of manufacturing using conventional printed circuit board technology. Future work will focus on experimental validation of the proposed design through antenna fabrication and measurements in an anechoic chamber. Additionally, investigations into further size reduction techniques, bandwidth enhancement methods, and integration with IoT hardware platforms will be conducted to advance the practical deployment of this antenna in real-world applications.

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