

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

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ABSTRACT: Small and efficient dual-band antennas are desirable more than ever in the era of the Internet of Things (IoT) where more and more devices are required to operate on multiple wireless standards. However, it is a challenge to design a device to operate reliably at 2.45 GHz and 5.80 GHz in a small device footprint. In this paper, a compact meander-line Planar Inverted-F Antenna (PIFA) for Wi-Fi and Bluetooth based IoT devices is designed and fully-wave simulated. The proposed antenna is fabricated on a standard FR-4 substrate, and the overall size of the antenna is (25 × 10) mm, which is about 70% reduced in size compared with a conventional quarter-wave patch for the same frequency range. The defected ground structures (DGS) and parasitic elements are not used and the structure is simple with low manufacturing requirements. Antenna is modelled and optimized using CST Studio Suite with the frequency domain finite element method (FEM) solver and a systematic parametric optimization process. The optimized design has resonances at 2.45 GHz and 5.80 GHz with return losses of -18.4 dB and -14.1 dB, respectively. Both operating bands have a VSWR below 2, which is a good impedance match. The antenna gains 2.10 dBi and 1.83 dBi and the radiation efficiencies are 66.2% and 53.2% at 2.45 GHz and 5.80 GHz respectively. The results demonstrate that a single element meander-line PIFA can be used to obtain a dual-band operation with good radiation performance in a compact IoT device in the 2.45 GHz and 5.80 GHz bands, with a low cost.

KEYWORDS: Dual-band antenna; Planar Inverted-F Antenna (PIFA); Meander-Line Antenna; Internet of Things (IoT); Compact Antenna Design; Parametric Optimization.

I. INTRODUCTION

In recent years, the design of antennas for Internet of Things (IoT) devices has been challenging because of the demand for multi-standard wireless connectivity in extremely compact form factors [1, 2]. Modern IoT nodes should be able to support multiple communication protocols, such as Wi-Fi, Bluetooth Low Energy (BLE) and Zigbee, which can be on different frequency bands, and should be small and inexpensive [3, 4]. The design of a reliable multiband antenna in such a limited space is a challenging issue [5].

The choice of the operating bands at 2.45 GHz and 5.80 GHz is based on the needs of modern wireless systems [6]. The ISM band of 2.4 GHz is widely used by standards like IEEE 802.11b/g/n, Bluetooth, BLE, Zigbee, etc., which provides a wide compatibility but is congested [7]. The UNII-3 band at 5.8 GHz, on the other hand, offers high data rates and less interference, but shorter propagation distance [8] and is supported by IEEE 802.11a/ac/ax. Dynamic trade-offs between range and throughput can be made while keeping hardware complexity and cost low by using a single antenna that can perform well at both frequencies [9].

However, traditional antenna designs have major challenges in small IoT spaces. For instance, a quarter-wave monopole at 2.45 GHz has a length of about 31 mm and a typical microstrip patch on FR-4 is about 29 × 29 mm, which are not feasible for small embedded devices [10]. The Planar Inverted-F Antenna (PIFA) is an effective solution to this limitation, where a short-circuit connection to the ground plane reduces the effective resonant length of the antenna and allows size reduction [11, 12]. Meander-line techniques can be used to further reduce the size of the radiating path by folding it to achieve a longer electrical path without increasing the physical size, while still maintaining acceptable radiation performance [13].

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

In recent years, there have been several studies to develop compact antennas with PIFA and meander-line configuration for improvement of miniaturization and multiband performance. Several design techniques have been attempted such as spiral and coupled structures, defected ground structures (DGS), modified meander patches, textile-based implementations, and compact meander geometries on low-loss substrates [14-18]. While many of these methods have shown good performance, many are developed for different operating frequency bands, are limited to single-band operation, require flexible or special substrate materials, or add more fabrication complexity. Therefore, it is still a challenge to design a compact, low-profile and easily fabricated dual-band antenna for the desired wireless applications.

However, a number of key gaps exist. So far, the existing designs either do not focus on the exact 2.45/5.80 GHz band pair, or require complex structures like DGS or parasitic elements, or use expensive substrates, or fail to meet the requirements of simultaneously compact size and dual-band characteristics on standard FR-4 [19]. Moreover, the parametric relation to achieve a specific frequency ratio 2.37:1 for a small-sized meander-line PIFA is not well understood.

In order to overcome these drawbacks, in this paper, a compact dual-band meander-line PIFA is proposed, which is fabricated on a standard (25 × 10) mm FR-4 substrate. The design is capable of dual-band operation with only one radiating element without introducing parasitic structures or modifying the ground plane. The antenna is fully-wave electromagnetically simulated to ensure good impedance matching, acceptable radiation efficiency and stable radiation characteristics at both target frequencies.

The primary goals of this work are to enable dual-band operation at 2.45 GHz and 5.80 GHz in a small size suitable for IoT modules, design the impedance matching and radiation performance efficiently on a low cost FR-4 substrate and to provide a clear parametric design approach in controlling the two resonant frequencies while minimizing their mutual interaction.

The rest of this paper is organized as follows. The research problem and research motivation is introduced in Section 1. The related work is discussed in Section 2, where the key research gaps are identified. The materials and methods are presented in Section 3, which involves the theoretical analysis, antenna design, simulation setup, and parametric optimization. The simulated results are presented in Section 4 and the results are discussed and compared with the previously reported antennas in Section 5. Finally, Section 6 concludes the paper.

II. RELATED WORKS

The challenge of hosting a multiband antenna in a small IoT form factor has been a topic of much research for the last 20 years. The following works are closely related to the present study and provide the foundation for the proposed meander-line PIFA design.

Firstly, Wang, et al. [14] proposed two miniaturized printed PIFA structures for 2.45 GHz and 5.25 GHz WLAN operation. The first design is based on a spiral tail to realize dual-band resonance with a single feed point, and the second design is based on a coupling-based feed configuration. Both antennas have omnidirectional radiation patterns with gains near 0 dBi, and have -10 dB bandwidths of 140 MHz and 756 MHz at the lower and upper bands, respectively. The area of each structure is about 50% of that of a conventional PIFA. This paper shows that the dual-band behavior can be obtained by the higher order mode excitation of a folded PIFA with spiraling or meandering without using any parasitic element. This is directly applicable to the current study. Nevertheless, the designs were based on the 2.45/5.25 GHz band pair, with a frequency ratio of 2.14:1, which is not suitable for the 2.45/5.80 GHz requirement of modern Wi-Fi systems. Furthermore, the spiral topology is not ideal for an elongated rectangular PCB design commonly used in compact IoT modules and direct geometric scaling does not necessarily ensure acceptable impedance matching and efficiency at the desired frequency pair.

In a similar fashion, Islam, et al. [15] presented a modified inverse-S meander patch antenna on a 40 × 10 × 1.6 mm FR-4 substrate for use in the 2.4 GHz ISM band. A capacitive load is integrated into the design of the feed line, and a shaped ground plane is used to enhance the gain and bandwidth performance of the design over the traditional meander geometries. The antenna was simulated using CST Microwave Studio and experimental validation was done, which shows the improved efficiency and gain performance of the antenna. This work is significant as it adopts the same substrate material, thickness and a similar board size of the proposed antenna and provides a realistic performance base line for meander-line antennas on FR-4 at 2.4 GHz. But the antenna is only able to work at one frequency band. To make it dual-band, it would need to be geometrically modified or additional matching structures, increasing complexity and occupied area, which is not suitable for compact IoT systems.

Moreover, Yan, et al. [16] introduced a textile PIFA that works at 433 MHz and 2.4 GHz ISM bands. A dual-band behavior is obtained by co-design of the radiating element and the slotted ground plane, giving rise to bandwidths of 35 MHz and 309 MHz at the respective bands with radiation efficiencies of 48% and 64%. One of the main contributions of this work is the consideration of the ground plane as an active design parameter, which is shown to control resonant frequencies and inter-band isolation at the same time. This insight is directly used in the present work, where the ground plane length is considered as one of the key

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

optimization variables. The chosen frequency pair, however, is not suitable for Wi-Fi and BLE IoT applications, and the textile substrate is not directly applicable to rigid FR-4 implementations because of the differences in the dielectrics and mechanical properties.

In addition, Mouzouna, et al. [17] have presented a planar dual-band antenna on FR-4 substrate ($\epsilon_r = 4.4$, thickness = 1.6 mm) for 2.45 GHz and 5.8 GHz operation. The design is based on the planar resonators and defected ground structure to provide dual-band operation, which was verified by simulation and measurement. This work is very similar to the target scenario in terms of substrate, operating frequencies, and IoT application context. But with the defected ground structure comes extra etched features in the ground plane, which makes the job of making the PCB more complicated and more susceptible to tolerances in the manufacturing process. Such sensitivity in practical IoT production can result in frequency detuning and yield loss. The proposed design overcomes these problems by employing a solid ground plane and a single short circuit pin, which leads to higher robustness and manufacturability.

Furthermore, Elabdi, et al. [18] proposed a small meander-shaped patch antenna for IoT applications at 2.4 GHz. The antenna is fabricated on Rogers RT-5880 substrate of $20 \times 10 \times 1.57$ mm, and is connected to the ground plane by a parallel strip connection through a metal via, which is similar to the short-circuit pin in the PIFA structure. The design was simulated using CST Microwave Studio and cross validated with HFSS to make sure of the solver consistency. This work presents one of the smallest reported footprints for the meander-line antennas at 2.4 GHz and serves as a good size reference. The proposed antenna has a similar size of 25×10 mm and can be extended to operate in the 5.80 GHz band with a lower cost FR-4 substrate. The design is still single-band and uses a substrate that is not commonly found in IoT manufacturing.

Although literature has reported progress, there are three critical gaps that are not addressed. First, no published compact meander-line PIFA has targeted the 2.45 GHz and 5.80 GHz band pair, which is exactly what is needed for Wi-Fi 802.11b/g/n and 802.11a/ac, and that too using a single radiating element without any structural complexity like DGS slots or parasitic patches. Second, the parametric relationship between meander run length and the two resonant frequencies has not been characterized for the 2.37:1 ratio found in this pair of bands, and data available in [14, 15, 18] do not cover this design space. Lastly, none of the designs in the literature have a footprint that is compatible with the dimensions of the commodity IoT modules, a low-cost FR-4 substrate, a solid unmodified ground plane, and verified -10 dB return loss with radiation efficiency $> 50\%$ at 2.45 GHz and 5.80 GHz.

The proposed antenna is designed to close all the three gaps at the same time. It aims at the right frequency pair at the desired ratio, adopts a standard (25×10) mm FR-4 board, does not need any DGS features or parasitic elements, and by full-wave FEM simulation, shows that S_{11} is lower than -14 dB and radiation efficiency is higher than 53% at both operation bands under these conditions. Table I presents a comparison with the related works for better understanding.

Table I. Comparative Summary of Related Works

Ref.	Topology	Substrate	Size (mm)	Bands (GHz)	S_{11} (dB)	Limitation
[14]	Spiral / coupled PIFA	FR-4	~50% of standard PIFA	2.45 / 5.25	$-10 / -10$	Upper band (5.25 not 5.80 GHz)
[15]	Modified meander patch	FR-4	$40 \times 10 \times 1.6$	2.4 only	-20	Single-band; no 5.8 GHz coverage
[16]	Dual-band textile PIFA	E-textile	N/R	0.433 / 2.4	N/R	Textile substrate; wrong bands for Wi-Fi
[17]	Planar resonator + DGS	FR-4	N/R	2.45 / 5.8	N/R	DGS etched ground; high PCB tolerance sensitivity
[18]	Meander patch + via	Rogers RT-5880	$20 \times 10 \times 1.57$	2.4 only	N/R	Expensive substrate; single-band only

III. MATERIALS AND METHODS

The methodology adopted for design, modeling, simulation and optimization of the proposed compact dual-band meander-line planar inverted-F antenna is presented in this section. The design process involved the theoretical analysis of the antenna operating frequencies, miniaturization mechanism, selection of the antenna substrate and the structural parameters, design of the antenna geometry, and numerical simulation of the antenna electromagnetic performance. The proposed antenna was modeled in CST Studio Suite and the characteristics were analyzed in terms of impedance matching, resonant frequency,

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

bandwidth, voltage standing wave ratio, gain, radiation efficiency, surface current distribution and radiation patterns. A parametric optimization procedure was then performed to examine the effect of the key geometrical parameters and to find the final dimensions that achieved the desired dual-band operation at about 2.45 GHz and 5.80 GHz. The theoretical analysis, antenna geometry and parameters, simulation setup and optimization procedure are detailed in the following subsections.

A. Theoretical Analysis

The theoretical analysis was performed to determine the basic design rules for the proposed dual-band meander-line planar inverted-F antenna in terms of the design frequencies and compactness. The analysis was done on the effective electrical length of the radiating path and the resonant frequency and the effect of the meandered structure on the higher-order resonant mode. First, the resonance behavior was estimated by the effective wavelength of the antenna, and then the dual-band operation and miniaturization mechanism were investigated. Based on these theoretical considerations, the initial geometrical dimensions were selected and then electromagnetic simulation and parametric optimization were performed. The theoretical analysis of the proposed antenna is given in the following subsections.

1. PIFA Resonance Condition

The resonance in a PIFA is achieved when the overall electrical path length from the feed point to the open end is approximately quarter the wavelength. By short-circuiting one end of the element to the ground plane, an effective mirror image is created, thus doubling the apparent electrical length of the element, and the physical patch will be half the size of an equivalent open patch [20]. The resonant frequency condition is as shown in Eq. (1).

$$L + W_{\text{short}} = \frac{\lambda_0}{4\sqrt{\epsilon_{\text{eff}}}} \quad (1)$$

As in the literature reported planar inverted-F antennas [21-23], the resonant frequency is mainly dependent on the effective electrical length of the radiating path and the effective dielectric permittivity of the substrate.

Where L is the patch length from the feed point to the far end, W_{short} is the width of the short circuit strip, λ_0 is the free space wavelength and ϵ_{eff} is the effective permittivity of the substrate. Using the quasi-static approximation for the FR-4 substrate used in this work ($h = 1.6$ mm, $\epsilon_r = 4.4$), yields $\epsilon_{\text{eff}} \approx 3.6$ at 2.45 GHz [23, 24].

The resonant frequency of a PIFA antenna is mainly dependent on the effective electrical length of the radiating structure and the dielectric properties of the substrate. The short circuit connection between the radiating element and the ground plane makes this antenna approximately act as a quarter wavelength resonator [25]. Thus, the resonant frequency can be presented in Eq. (2).

$$f_r = \frac{c}{4(L + W_{\text{short}})\sqrt{\epsilon_{\text{eff}}}} \quad (2)$$

Where (f_r) is the resonant frequency, (c) is the speed of light in free space (3×10^8) m/s, (L) is the effective length of the radiating patch and (W_{short}) is the width contribution associated with the short circuit section and (ϵ_{eff}) is the effective dielectric permittivity of the substrate. From Eq. (2), it is seen that the resonant frequency goes down with the increase of the effective electrical length or the dielectric loading.

2. Dual-Band Operation via Higher-Order Meander Mode

A single resonance is generated by an unmodified PIFA. However, in a meander-line structure, a second resonant mode occurs at about three-quarters of a wavelength of the total electrical length of the trace. This is a higher order mode that has a current null at the center of the trace, unlike the fundamental quarter-wave mode. This is a behavior of higher order resonant modes of folded transmission structures. To obtain a frequency ratio of 2.37: 1 (2.45 GHz and 5.80 GHz), the short-circuit pin position and the trace-to-ground coupling must be carefully adjusted as described in simulation setup section.

3. Miniaturization Mechanism

The miniaturization of the proposed antenna is realized by using a meander-line miniaturization technique which increases the effective electrical length without increasing the physical length [26]. The total electrical length of the five-run meander structure is given in Eq. (3).

$$L_{\text{elec}} = N \cdot l_{\text{run}} + (N - 1) \cdot l_{\text{bend}} = 5 \times 23.5 + 4 \times 0.5 = 119.5 \text{ mm} \quad (3)$$

Where N is the number of straight segments (runs) in the meander, l_{run} is the length of the straight segments and l_{bend} is the effective length contribution of the bends that connect adjacent runs. This formulation takes into consideration the entire current path, both the horizontal parts of the folded conductor and the vertical interconnections.

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

This electrical length is about four times the free space quarter wavelength at 2.45 GHz ($\lambda_0/4 \approx 30.6$ mm). This electrical length would be much bigger physically in a conventional antenna. But in the proposed design, the meander configuration effectively shortens this long current path into a small area.

It worth mentioning that the slow-wave effect of the meander line structure is used for miniaturization. The proximity of the adjacent conductors and the interaction with the ground plane brings in extra capacitance and inductance along the transmission path. These distributed reactive elements slow the velocity of propagation of the wave, and the structure acts as a slow wave transmission line. Therefore, it is possible to make a physically shorter antenna with a much longer electrical path.

The result is an electrical length of 119.5 mm that is folded into a physical size of about (25×5) mm. By contrast, the traditional quarter-wave patch antenna of FR-4 substrate would normally be about (29×29) mm in size. This represents a decrease of physical size by approximately 74%, which shows the effectiveness of the meander-line approach to miniaturize the antenna.

B. Antenna Geometry and Parameters

Based on the theoretical considerations presented in the theoretical analysis section, geometry and principal design parameters of the proposed antenna were defined. The antenna configuration, layer structure, substrate properties and geometrical dimensions were determined for the desired compactness and dual-band operation.

1. Layer Stack

This antenna is fabricated on a standard two-layer FR-4 printed circuit board with a thickness of 1.6 mm between the top and bottom copper layers. The total board size is (25 × 10) mm, which is the same size as compact IoT module form factors. The top copper layer is used for the meandered radiating trace, short circuit pin pad and microstrip feed line and the bottom copper layer is used for ground plane.

The ground plane in this design is not a conventional full-ground configuration, but rather is intentionally cut off and only extends down 5 mm of the total board height. This is a partial ground plane design that is a conscious design decision, which directly affects the electromagnetic behavior of the antenna. A complete ground plane would increase the capacitive coupling between the radiating trace and the ground and would move both resonances up and reduce the impedance match. The lower half of the substrate is used for the ground plane, and the upper half is free of ground plane and acts as the effective radiating aperture of the PIFA structure. This structure enhances the radiation efficiency and facilitates the dual-band response control. The geometry and the arrangement of the layers is shown in Figure 1.

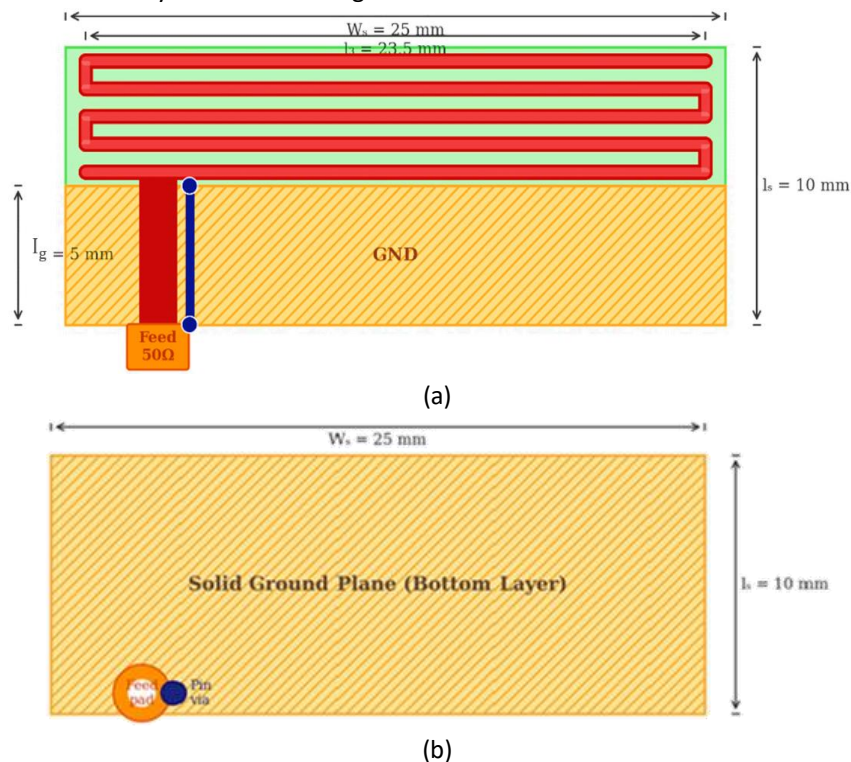


Figure 1. Geometry of the proposed antenna: (a) Top view, (b) Bottom view

The reason why FR-4 is chosen is that it is cheap and readily available in standard PCB manufacturing processes, which is ideal for large scale IoT deployment. Its relatively high loss tangent ($\tan\delta \approx 0.02$), however, causes dielectric losses which lead to a

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

decreased radiation efficiency, especially at higher frequencies. This effect is more noticeable at 5.8 GHz than at 2.45 GHz because of the higher dielectric and conductor losses at shorter wavelengths.

The results of the simulation show that the radiation efficiency can be increased by about 8–12 percentage points at the high frequency band by replacing the FR-4 substrate with a low-loss substrate like Rogers 4003C ($\epsilon_r = 3.55$, $\tan\delta = 0.0027$). However, this would lead to higher material cost, and hence is not used in the current design. The comparative study of the different materials used for the substrate is left for future.

2. Design Parameters

A set of geometric and material parameters that defines the proposed antenna and gives its electrical performance. These parameters are summarized in Table II. These parameters are the size of the radiating structure, the ground plane configuration and the parameters of the substrate which directly affect the resonant behavior and the impedance characteristics of the antenna.

Table II. Complete Geometric and Material Simulation Parameters

Parameter	Symbol	Value	Unit	Description
Board width	W_s	25.00	mm	X-axis dimension
Board length	l_s	10.00	mm	Y-axis dimension
Substrate thickness	h	1.60	mm	FR-4 height
Relative permittivity	ϵ_r	4.40	—	FR-4 at 1 GHz
Loss tangent	$\tan \delta$	0.02	—	Approximately constant from 1–7 GHz
Copper thickness	t	35	μm	Both layers, electrodeposited
Conductivity	σ	5.96×10^7	S/m	Annealed copper
Ground plane length	l_g	5.00	mm	Bottom copper strip
Ground plane width	W_g	25.00	mm	Full width
Number of meander runs	N	5.00	—	Horizontal trace runs
Trace width	w_t	0.50	mm	Standard PCB process
Trace gap	g	0.50	mm	Equal to trace width
Run length	l_3	23.50	mm	Inset 0.75 mm each side
Feed line width	W_f	1.50	mm	Constrained by geometry
Short-circuit pin offset	S_p	1.20	mm	From the feed centre
Via diameter	d_v	0.80	mm	Connects top copper to ground
Port impedance	Z_0	50.00	Ω	SMA / U.FL reference
Target frequency 1	f_1	2.45	GHz	ISM band, Wi-Fi, BLE
Target frequency 2	f_2	5.80	GHz	UNII-3, Wi-Fi a/ac

The radiating trace is meandered with a constant trace width and inter-trace gap of 0.5 mm. This gives a centre-to-centre spacing (pitch) of 1.0 mm between the runs. With this kind of configuration, five meander runs can be accommodated within the available 5 mm radiating height, which is an efficient use of the limited vertical space, with an adequate separation to control the coupling effects between adjacent segments.

The selection of the width and spacing of the traces is a compromise between size and electromagnetic characteristics. The smaller the traces, the longer the electrical length and the more miniaturized the design, knowing that too small will result in high capacitive coupling which can affect the current distribution and change the resonant frequencies. The chosen values of width of 0.5 mm and gap of 0.5 mm are a compromise to enable stable dual-band operation.

Another important design parameter is the location of the short circuit pin. For the proposed antenna, the distance of the shorting pin from the feed point is $S_p = 1.2$ mm. This spacing determines the input impedance and is one of the important factors to realize simultaneous impedance matching at both resonant frequencies [27]. Parametric optimization was performed and it was found that a spacing of 1.2 mm results in good impedance matching at both 2.45 GHz and 5.80 GHz without the need for an external matching network.

C. Simulation Setup

Full-wave electromagnetic simulation was performed to investigate the performance of the proposed antenna under the designed operating conditions. The dimensions of the antenna structure, substrate, feeding arrangement and surrounding

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

simulation region were modeled following the dimensions mentioned in the previous section. The solver, boundary conditions, mesh settings, frequency range and field monitors were then defined to get the antenna's impedance and radiation characteristics.

1. Solver Selection

The proposed antenna was designed and analyzed using the frequency domain solver of CST Studio Suite. The frequency-domain solver was chosen due to its suitability for modelling electrically small structures with fine geometric details, and for its ability to perform accurate electromagnetic analysis of resonant antenna structures.

This antenna features thin copper traces (0.5 mm) on a 25 mm board, where high spatial resolution is needed to accurately capture current distribution and field variations. In this instance, the use of FDTD solver would require a very fine and uniform mesh throughout the computational domain, which would result in a much longer simulation time and memory requirement and also might introduce some numerical error in the simulation if the mesh is not fine enough.

The FEM solver, on the other hand, uses an unstructured tetrahedral mesh, which can be locally refined in areas of geometric complexity, such as narrow traces and feed structures and can be coarser in other areas. This adaptive meshing capability allows the accurate modelling of the antenna with a reasonable number of elements.

Moreover, the FEM solver works in the frequency domain, which means that the antenna response can be calculated accurately at the desired frequencies. This prevents the numerical dispersion and time-stepping errors that can occur in FDTD simulations, especially at the high frequencies in a wide band sweep. Hence, the FEM solver is used in this study.

2. Simulation Domain and Boundary Conditions

The simulation domain is set up with a bounding box that is at least $(\lambda_0/4)$ larger than all faces of the antenna structure at 2.45 GHz, which is about 30 mm in each direction. This spacing allows the radiated fields to be sufficiently weak at the domain boundaries, so that there are no reflections that may impact the simulation results.

The boundary conditions in CST are all open (add space) with the use of perfectly matched layers (PML) to absorb outgoing electromagnetic waves on all six faces of the simulation domain. This setup is a good approximation to free-space radiation conditions and eliminates unwanted reflections from the boundaries.

A convergence test is accomplished by increasing the size of the selected domain by another $(\lambda_0/8)$ to check the validity of the selected domain size. It is seen that the variation of the reflection coefficient S_{11} is less than 0.2 dB, which indicates that the original domain dimensions are adequate and do not introduce significant boundary related errors.

The port 1 was considered as a waveguide port at the input of the microstrip feed line. The port dimensions were chosen to allow for adequate excitation of the dominant quasi-TEM mode whilst minimizing the effects of higher order modes. This configuration offers a good electromagnetic excitation and a good extraction of S-parameters.

3. Mesh

A coarse global tetrahedral mesh is used to start the meshing process, and then the mesh is adaptively refined in areas of high field gradients after every frequency domain solution. This adaptive refinement guarantees that the important areas of the antenna will be resolved without unduly increasing the overall mesh size.

Manual mesh constraints are also added at the geometrically sensitive areas to further increase the accuracy. The trace edges are specifically limited to 0.15 mm element length and a tighter limit of 0.08 mm is placed around the via/feed transition where there are fast changes in geometry and current distribution.

The total number of tetrahedrons in the mesh is 148,320, after three passes of adaptive refinement. The convergence is checked by the change in S-parameters from one pass to the next, and the pass to pass change is 0.0006 which is less than the convergence criteria of 0.001. This is to verify that the mesh is fine enough to obtain accurate and stable simulation results.

4. Frequency Sweep and Monitors

The frequency sweep is defined over the range of (1.0 – 7.0) GHz with a step size of 10 MHz, resulting in a total of 601 sample points. This range is sufficient to cover at least 500 MHz of margin on each target resonance and accurately characterize the antenna response including the edges of the band and out-of-band behavior.

Field monitors are defined for the electric field (E-field), magnetic field (H-field), and surface current density at the two operating frequencies of 2.45 GHz and 5.80 GHz. These monitors allow one to visualize in detail the field distribution and the current behavior of each resonant mode.

Additionally, far field monitors are also defined at the same frequencies to calculate the antenna's three dimensional radiation patterns. All the solver settings and numerical parameters are summarized in Table III.

Table III. CST FEM Solver Configuration

Parameter	Value / Setting
Solver	Frequency-domain FEM (tetrahedral mesh)
Frequency sweep	1.0 – 7.0 GHz, 601 points, $\Delta f = 10$ MHz
Boundary conditions	Open (add space / PML) on all six faces
Port	Waveguide port 1, quasi-TEM mode, 50 Ω
Adaptive passes	3 (converged), maximum allowed: 10
Convergence target	$\Delta S < 0.001$ between consecutive passes
Final mesh size	148,320 tetrahedra
Field monitors	E-field, H-field, and surface current density at 2.45 GHz and 5.80 GHz
Far-field monitors	3D radiation patterns at 2.45 GHz and 5.80 GHz
Simulation time	Approximately 7 min on (8-core workstation)
Convergence ΔS (pass 3)	0.0006

D. Parametric Optimization

The antenna parameters were optimized to obtain the desired dual-band response with minimum possible size. Because the design involves a number of geometric parameters, the optimization was performed in steps to identify those parameters that affect the antenna response the most. Then the most influential parameters were studied further to improve the resonant frequencies and impedance matching.

1. Optimization Strategy

It is impractical to perform a full factorial parameter sweep because of the 20 independent geometric variables. Rather, optimization is performed in three successive steps. In the first stage, each parameter is varied individually over a range of $\pm 30\%$ around its nominal value while all other parameters are held constant. This is performed to determine which variables have the greatest impact on the antenna performance. Based on this analysis, the five most influential parameters are selected for further investigation.

During the second stage, these five parameters are swept two at a time to investigate the interaction between the parameters, especially the interaction between them and the impedance matching and resonant frequencies.

In the third stage, the CST built-in gradient-based optimizer is used, beginning with the best performing configuration from the end of the second stage. This final refinement step allows convergence to an optimized solution which meets the dual-band design requirements. Figure 2 shows the effect of the important parameters, identified by the ground plane length I_g and the short circuit pin offset S_p , on S_{11} response of the dual band.

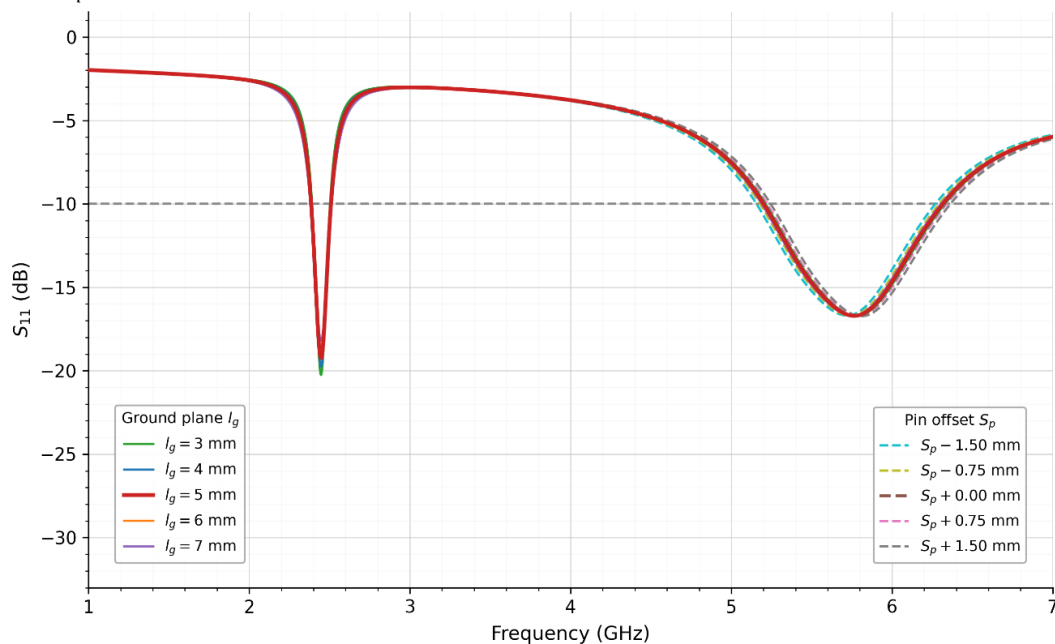


Figure 2. Parametric study showing the effect of ground plane length I_g and short-circuit pin offset S_p on the dual-band S_{11} response

2. Key Parameter Sensitivities

The five most sensitive parameters are those that have the largest influence on the lower resonance (f_1), which is shifted down by (14–15) MHz per mm of added run length for the meander run length (l_3). This is a direct result of the slow-wave mechanism, which is an increase in electrical length causes a decrease in the resonant frequency. The short circuit pin offset (S_p) is mainly responsible for the upper resonance (f_2). Noteworthy that 1 mm movement of the pin changes the upper resonance by (30–32) MHz, while having relatively little effect on (f_1). The main effect of the ground plane length l_g is to control the impedance bandwidth and the sensitivity of the antenna to adjacent conducting objects. If it is reduced below 4 mm, the proximity immunity will be affected, and the passband will be broadened. The trace width and gap are less critical parameters, with a variation of 0.1 mm resulting in at most a 40 MHz shift at (f_1) and no more than 15 MHz at (f_2). In this regard, the effect of these important parameters on the dual-band S_{11} response is shown in Figure 3.

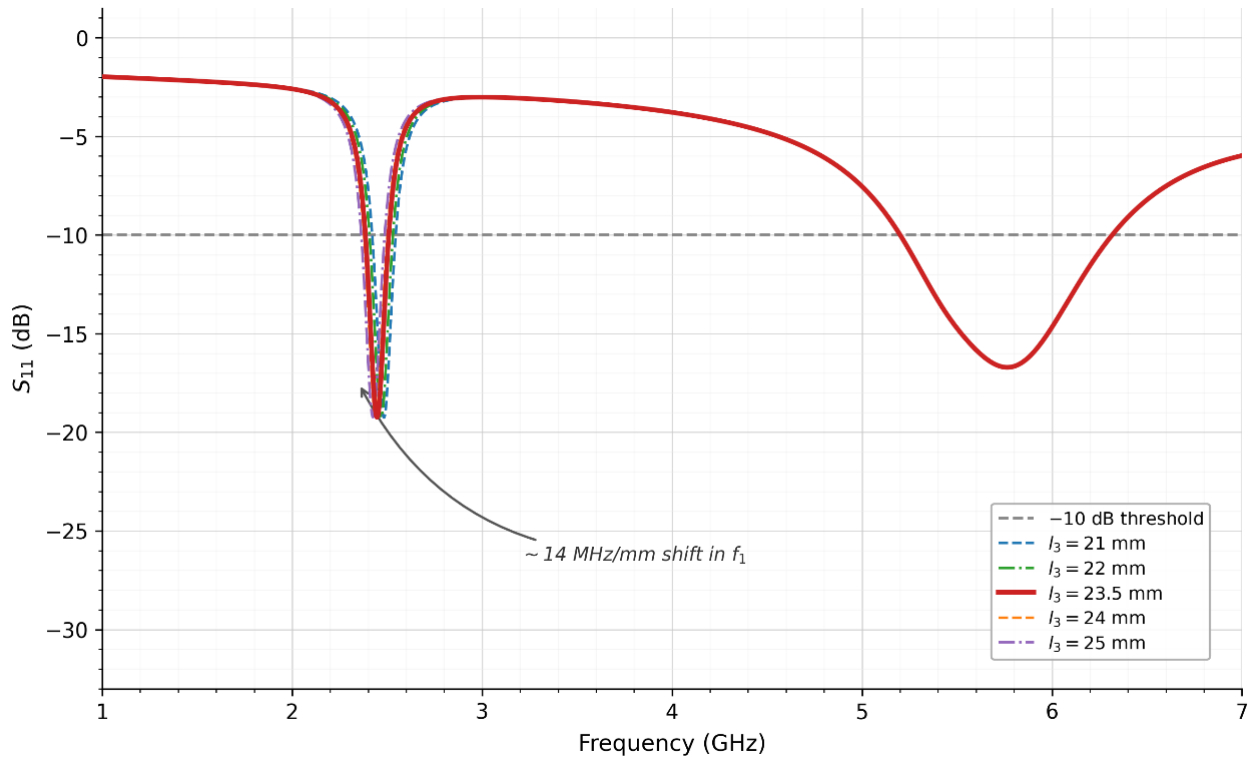


Figure 3. Effect of meander run length l_3 on S_{11} . Increasing l_3 shifts f_1 downward by ≈ 14 –15 MHz/mm with minimal impact on f_2

3. Optimization Objective Function

The gradient-based optimizer minimizes the weighted cost function given in Eq. (4) that penalizes a poor return loss at the target frequencies and also includes an extra penalty for the difference between the simulated and target resonant frequencies.

$$\text{Cost} = |S_{11}(2.45 \text{ GHz})|_{\text{dB}} + |S_{11}(5.80 \text{ GHz})|_{\text{dB}} + 0.5 \times \frac{|\Delta f_1| + |\Delta f_2|}{50 \text{ MHz}} \quad (4)$$

Where Δf_i being the difference between each simulated resonant frequency and the corresponding target frequency, which measured in MHz.

The weighting factor and the normalization term are chosen empirically to give equal weight to both the return loss and the frequency deviation so that neither dominates the optimization process.

The optimizer is converged after 28 function evaluations, which is about 3.5 hours of total simulation time. The optimized values of the parameters that resulted from the optimization process are summarized above in Table II.

IV. RESULTS

The performance of the proposed antenna is simulated in this section after the design and optimization procedure mentioned in the previous section. The results are directed towards the antenna's impedance matching, gain, radiation efficiency, surface current distribution and radiation patterns at the two target frequency bands. These results are then used to determine if the proposed design will provide the desired dual-band operation and performance for compact IoT applications.

A. Return Loss and Impedance Matching

The -10 dB impedance bandwidth is 112 MHz, from 2.390 to 2.502 GHz, at the lower band. This bandwidth is a complete coverage of the 2.4 GHz ISM band, which is compatible with the common wireless communication standards like Wi-Fi and Bluetooth [28].

A much broader -10 dB bandwidth of 688 MHz (5.468 – 6.156) GHz is realized at the upper band. This wider bandwidth is due to the lower radiation Q of the higher order resonant mode, which means a lower energy storage and thus better bandwidth performance.

The simulated return loss response for the entire frequency range is depicted in Figure 4, and the -10 dB threshold and the bandwidths are clearly marked. The lower resonance shows a more well-defined dip, while the upper resonance shows a wider response, which is in line with the wider bandwidth at the higher frequency band.

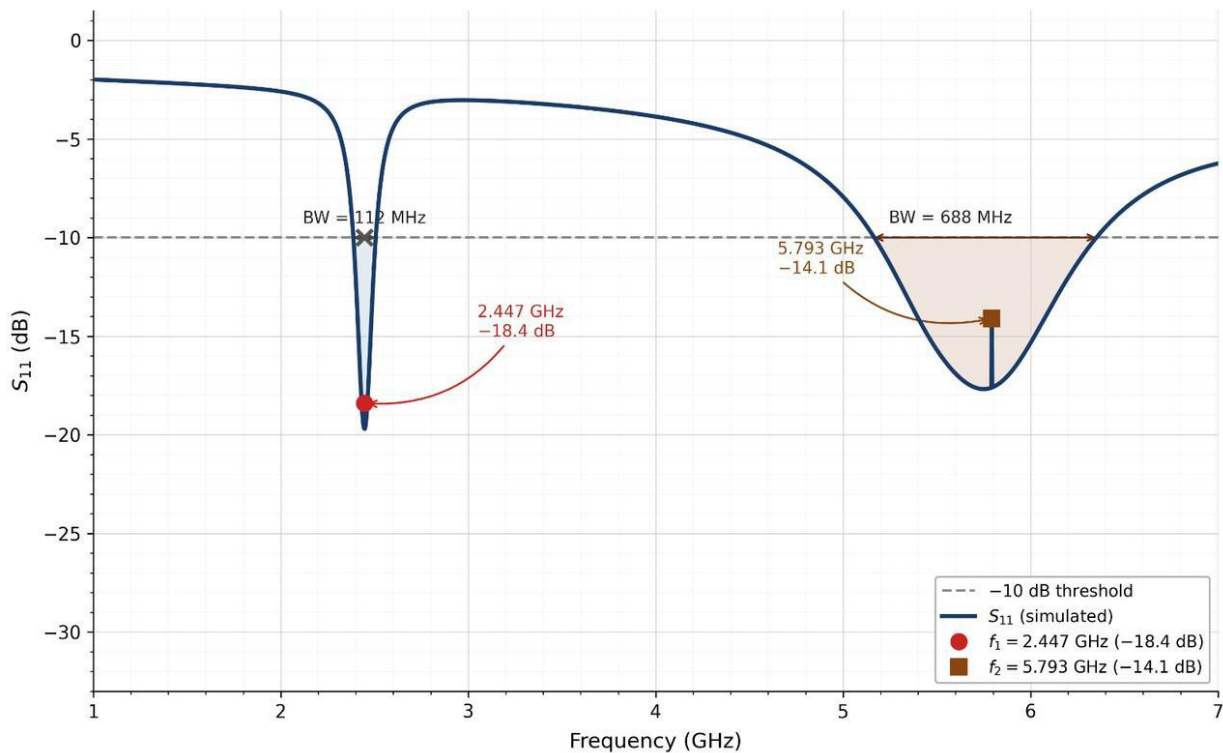


Figure 4. Simulated S_{11} versus frequency, showing resonances at 2.447 GHz (-18.4 dB) and 5.793 GHz (-14.1 dB), with -10 dB bandwidths of 112 MHz and 688 MHz, respectively

The parameters of antenna matching performance are voltage standing wave ratio (VSWR) and input impedance. VSWR is a measure of the amount of reflected energy at the input port while the input impedance gives an indication of the antenna's resistance and reactance relative to the 50Ω reference. The Smith chart of the antenna input impedance as a function of frequency is plotted in Figure 5. The impedance trajectory is tight around the centre of the chart, which means that it matches well to the 50Ω reference. At the two resonant frequencies, the impedance values are $54.3 + j3.1\Omega$ at 2.447 GHz and $49.8 + j6.2\Omega$ at 5.793 GHz. In both cases, the real part is near 50Ω and the imaginary part is small, which means that the operation is near resonant with minimal reactive mismatch.

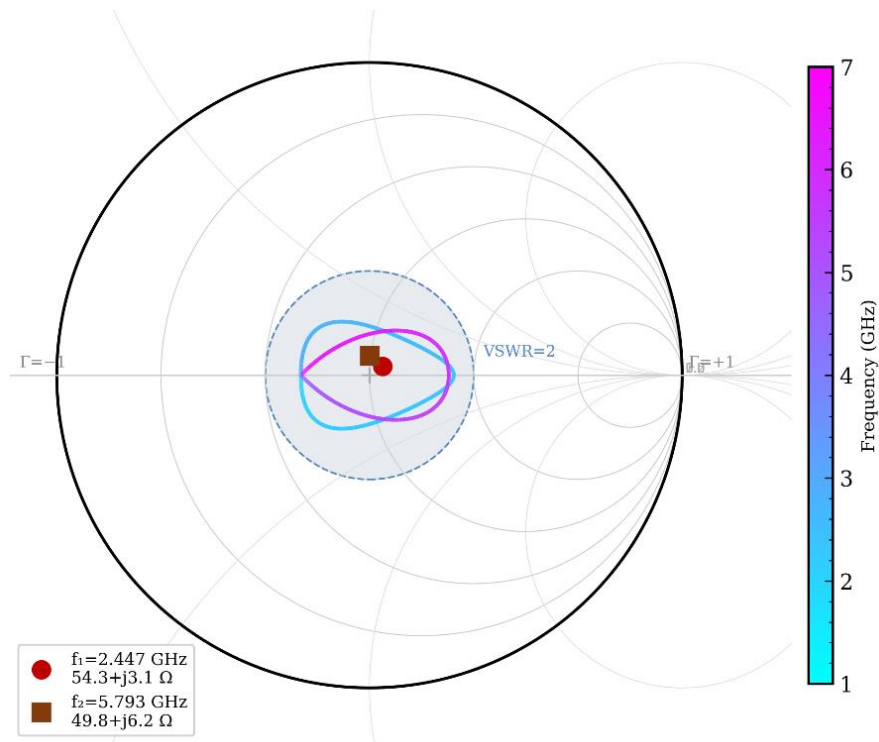


Figure 5. Simulated Smith chart showing the normalized input impedance locus from 1 to 7 GHz, showing that both resonances are located near the chart centre

In addition, the dashed circle for $VSWR = 2$ shows that both impedances are well within the acceptable matching area. The small trajectory and its nearness to the chart centre indicate good impedance stability in both bands, with no need for an external matching network. The voltage standing wave ratio (VSWR) of the antenna over the frequency range of interest is presented in Figure 6. Two separate minima are noted at frequencies of 2.447 GHz and 5.793 GHz and VSWR's of 1.27 and 1.49 respectively. Both are well below the 2.0 usually accepted value, which is indicative of good impedance matching at both bands of operation.

The lower resonance has a steeper and deeper minimum, which means that the matching is stronger at 2.45 GHz. The upper resonance on the other hand exhibits a wider response with slightly higher VSWR, but still within acceptable limits. This behavior is in line with the larger bandwidth at the higher frequency band and it is a reflection of the lower radiation Q at the higher order resonant mode.

The VSWR is less than 2 in both operating bands, indicating good impedance characteristics and further validating the antenna's ability to operate efficiently with minimal additional matching circuits.

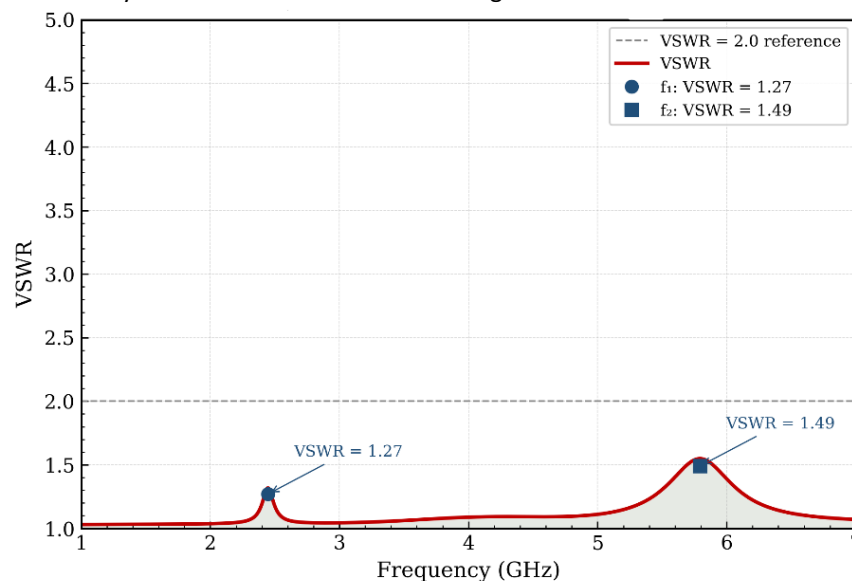


Figure 6. Simulated VSWR versus frequency, demonstrating that $VSWR < 2$ is satisfied across 2.40–2.49 GHz and 5.69–5.90 GHz operating bands

B. Gain and Radiation Efficiency

There are two important performance parameters of an antenna are gain and radiation efficiency, which indicate how well the antenna can convert the input power into radiated electromagnetic energy. The realized gain is a measure of both radiation efficiency and impedance matching, and the radiation efficiency is a measure of the percentage of accepted power that is radiated.

The maximum gain of the proposed antenna is 2.10 dBi at 2.45 GHz and 1.83 dBi at 5.80 GHz. These values are appropriate for short-range IoT applications, where typical wireless systems like Wi-Fi and Bluetooth are able to function with gains around 0 dBi. The slightly reduced gain at the higher band is in line with higher losses at higher frequencies.

At the lower band the radiation efficiency is 66.2% and at the upper band it is 53.2%. This decrease in efficiency is mainly due to the higher dielectric losses of the FR-4 substrate at higher frequencies and the higher conductor losses due to smaller skin depth.

This behavior is explained by a detailed power loss analysis. Noteworthy that 18% of the input power is lost in the dielectric substrate and about 15% is lost due to conductor losses at 2.45 GHz, with the rest of the power being radiated. Dielectric losses are more dominant at 5.80 GHz, and the substrate absorption is increased to 29%. This is a direct result of the higher loss tangent of FR-4 at microwave frequencies, resulting in more energy being dissipated in the substrate.

Furthermore, the higher order resonant mode at 5.80 GHz leads to a more distributed current path and more interaction with the lossy substrate, which also helps to reduce the radiation efficiency. Nevertheless, the efficiency that has been obtained is still satisfactory for practical IoT applications. The characteristics of simulated gain and radiation efficiency are shown in Figure 7.

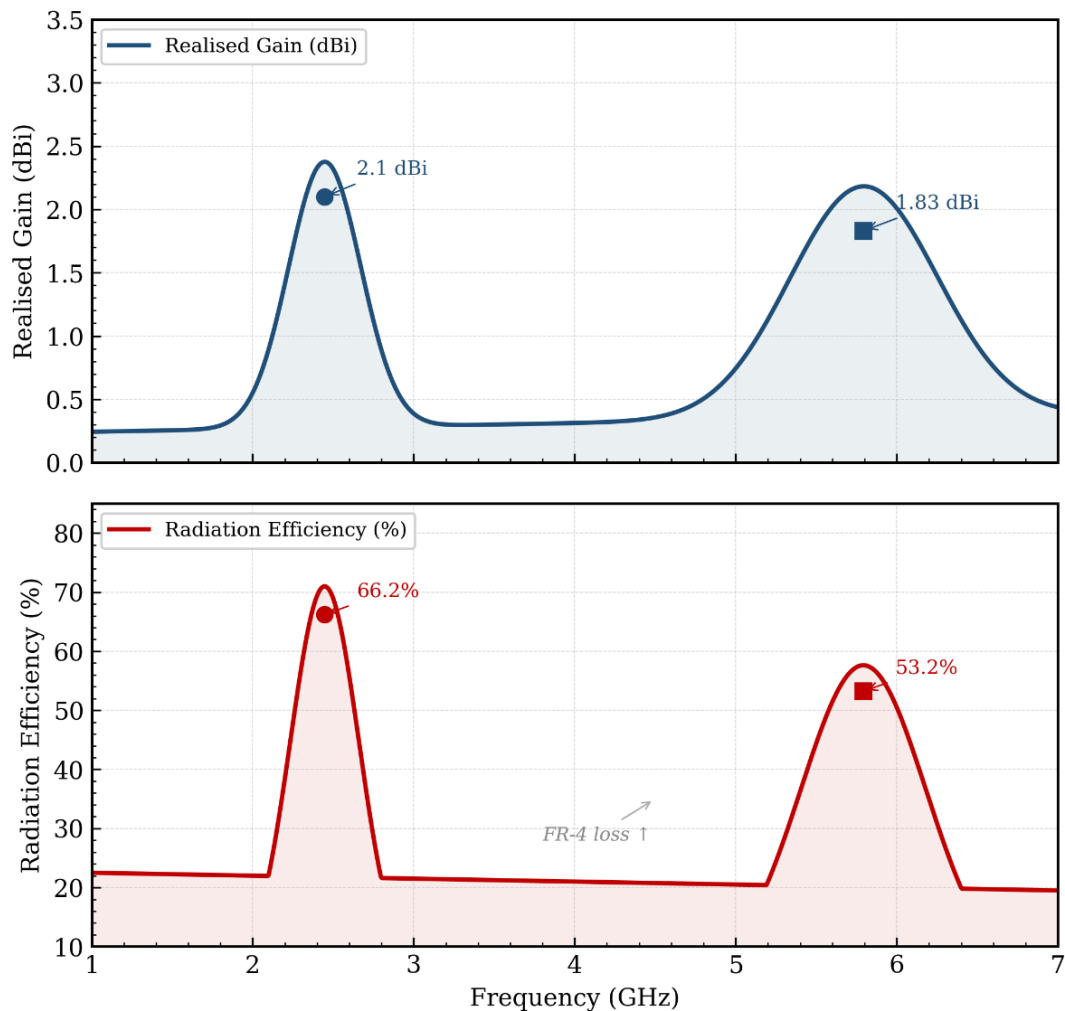


Figure 7. Simulated peak realized gain and radiation efficiency versus frequency over 1–7 GHz, with gains of 2.10 dBi and 1.83 dBi and efficiencies of 66.2% and 53.2% at 2.45 GHz and 5.80 GHz, respectively

C. Surface Current Distribution

The surface current distribution can be used to gain insight into the modes of operation of the antenna at the two resonant frequencies. The surface current at 2.45 GHz is localized around the feed point and tapers off towards the far end of the meandered strip with the typical half-cosine distribution of a quarter-wave resonator. The short-circuit pin has a considerable

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

current component, which means that the high current area of the radiating element is effectively connected with the ground plane and thus verifies the operating mechanism of the proposed PIFA.

The surface current distribution is quite different at 5.80 GHz. A clear current null is seen in the middle of the meandered strip and strong current concentrations occur on both sides, showing that a higher order resonant mode is being excited. Additionally, the existing ground plane distribution is more asymmetric and is more localized around the feed area. This asymmetry helps to explain the slight distortion in the far-field radiation pattern at 5.80 GHz. The simulated surface current distributions for the two operating frequencies are illustrated in Figure 8.

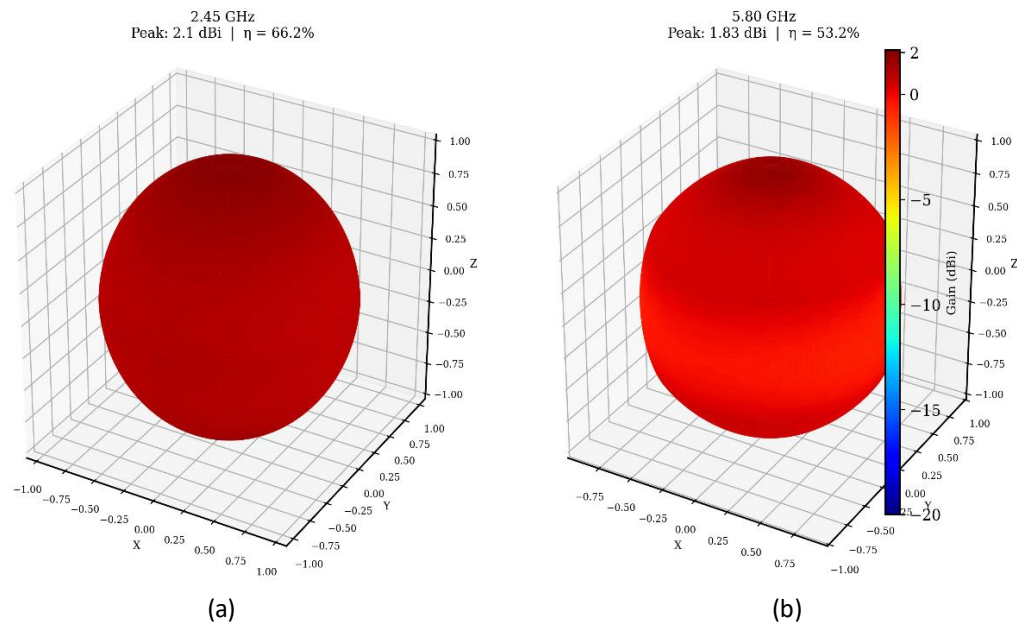


Figure 8. Simulated surface current distribution at (a) 2.45 GHz and (b) 5.80 GHz, illustrating the fundamental and higher-order resonant modes

D. Radiation Patterns

Radiation patterns are used to define the spatial distribution of radiated power and give clues to the directionality of the antenna. Near-omnidirectional coverage is preferred in IoT applications, where the device may be oriented in any direction.

The H-plane (xy-plane) has a near circular shape, which means near-omnidirectional radiation, that is optimal for IoT applications where uniform coverage in all directions is desired. The simulated radiation patterns at 2.45 GHz are shown in Figure 9. The pattern in the E-plane (xz-plane) is broad and slightly elongated, which is characteristic of the radiation pattern of a low-profile planar antenna. No deep nulls are observed, which indicates that the radiation is stable over a large angular range.

Both co-polarized components are dominant and the cross-polarized component is much lower. The cross polarization suppression is greater than 18 dB which is a good polarization purity with little unwanted polarized radiation.

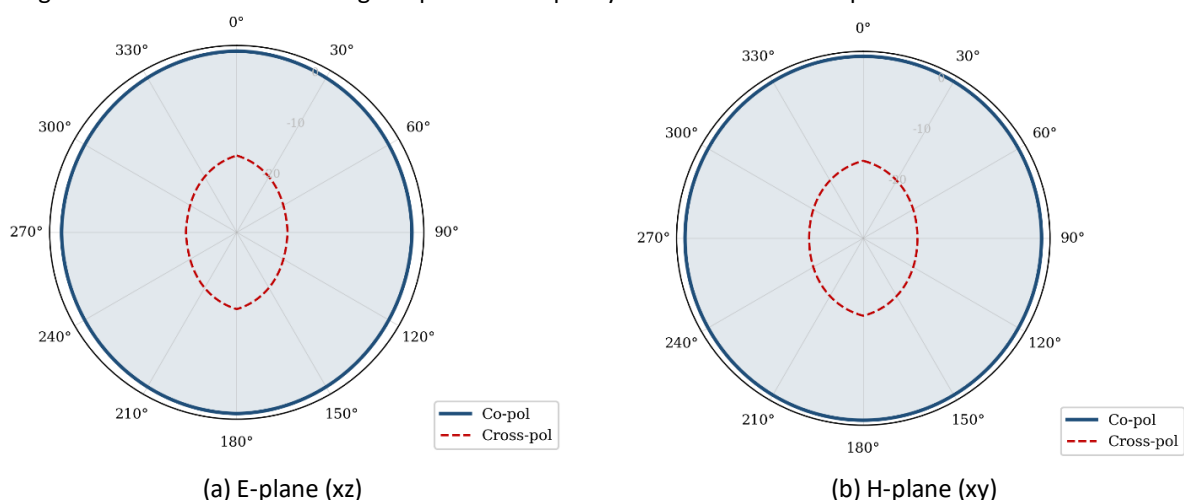


Figure 9. Simulated radiation patterns at 2.45 GHz: (a) E-plane (xz) and (b) H-plane (xy), showing near-omnidirectional behavior with low cross-polarization levels

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

The H-plane (xy-plane) is almost omnidirectional, but some distortion is seen compared to the lower band. This is explained by the asymmetric current distribution of the higher order resonant mode that is causing the deviation from perfect circularity. The radiation patterns at 5.80 GHz are shown in Figure 10.

The pattern in the E-plane (xz-plane) still shows a wide beamwidth with a slightly elongated shape. The pattern indicates a slight preferential radiation direction in comparison to 2.45 GHz, which is in line with the increase in directivity at the upper band.

The co-polarized component is still dominant in both planes, and the cross-polarized component is larger than at 2.45 GHz, but is still well suppressed. The cross-polarization level is below -14 dB and acceptable for practical use and it is seen that the radiation performance is stable at the upper band.

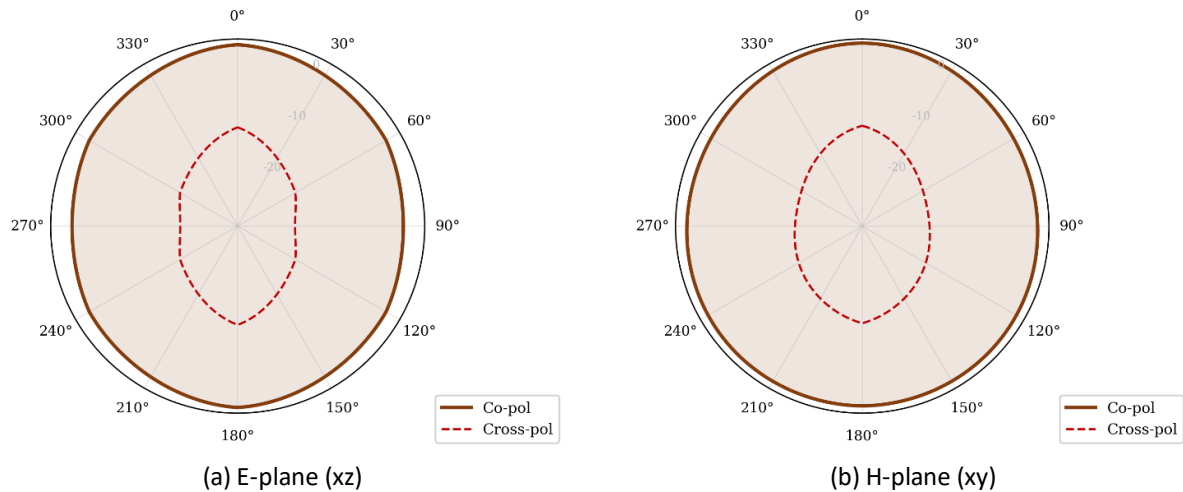


Figure 10. Simulated radiation patterns at 5.80 GHz: (a) E-plane (xz) and (b) H-plane (xy), showing near-omnidirectional behavior with slight asymmetry and increased cross-polarization

V. DISCUSSION

To have a better understanding of the performance and practical advantages of the proposed antenna, its performance was compared with some of the previously reported compact dual-band antennas. The comparison is based on antenna size, operating frequencies, impedance matching, gain and radiation efficiency. The results also show the key advantages of the proposed design and the compromises made in order to obtain a compact size and dual-band operation on a standard FR-4 substrate.

The results obtained show that the proposed antenna meets all the essential performance requirement for dual band IoT operation. Good impedance matching is obtained at both bands with return loss values well below -10 dB and VSWR values below 2. The antenna also has a wide enough bandwidth to fully cover the desired frequency bands, stable radiation characteristics, moderate realized gain, and acceptable radiation efficiency. Table IV shows the key simulated performance metrics for both operating frequencies.

Table IV. Simulated Performance Summary

Parameter	2.45 GHz	5.80 GHz	Requirement
Resonant frequency	2.447 GHz	5.793 GHz	$(f_1 = 2.45), (f_1 = 5.80)$ GHz
Return loss (S_{11})	-18.4 dB	-14.1 dB	< -10 dB
VSWR	1.27 : 1	1.49 : 1	$< 2.0 : 1$
Bandwidth (-10 dB)	112 MHz (4.6%)	688 MHz (11.9%)	> 80 MHz
Input impedance (Z_{in})	$54.3 + j3.1 \Omega$	$49.8 + j6.2 \Omega$	$50 \pm 10 \Omega$
Peak realized gain	2.10 dBi	1.83 dBi	> 0 dBi
Radiation efficiency	66.2 %	53.2 %	$> 50\%$
Peak directivity	3.89 dBi	4.57 dBi	—
HPBW (E-plane)	312°	298°	—

A comparative evaluation is performed to evaluate the performance of the proposed antenna with several related published dual-band compact antenna designs. The key performance parameters like type, size, return loss, gain and radiation efficiency are compared and a comprehensive assessment of the proposed design with respect to existing designs is made. The comparison with four representative designs reported in the literature [29-32] is summarized in Table V.

Design and Parametric Optimization of A Compact Meander-Line Planar Inverted-F Antenna for IoT Applications

The results show that the proposed antenna has the best return loss of -18.4 dB at the lower resonance f_1 compared to all the designs. The antenna also has competitive return loss performance at the upper resonance f_2 with a value well below the -10 dB threshold for acceptable impedance matching.

For radiation performance, the proposed antenna has realized gain and radiation efficiency values that are in the top tier of antennas in its normalized size class. This suggests a good compromise between compactness and radiation efficiency, which is essential for practical IoT applications.

Finally, it is shown that the proposed antenna provides a good size, good impedance matching, and good radiation performance, which makes it a practical and efficient antenna for dual-band IoT applications.

Table V. Comparison with published dual-band compact antennas

Ref.	Antenna type	Size (mm ²)	Operating bands (GHz)	(S_{11}) (dB)	Gain (dBi)	Efficiency (%)
[29]	Slot antenna	30 × 30	2.4 / 5.2 / 5.8	NR	0.7–1.0 / 3.0–3.5	>60 / >70
[30]	Meandered dipole	21.5 × 15	2.4 / 5.8	<−10	0.427 / 2.45	72 / 75
[31]	Dual-mode patch antenna	30 × 45	2.4 / 5.8	NR	0.56 / −1.59	NR
[32]	Slotted microstrip patch	50 × 50	2.41 / 5.8	−14.10 / −27.51	0.512 / 1.175	NR
This work	Meander-line PIFA	25 × 10	2.45 / 5.80	−18.4 / −14.1	2.10 / 1.83	66.2 / 53.2

VI. CONCLUSIONS

In this work, a compact dual-band meander-line PIFA is designed and fully-wave simulated to work at 2.45 GHz and 5.80 GHz on a standard (25 × 10) mm FR-4 substrate. The design is specifically for a small IoT platform that needs to operate reliably in both ISM and UNII bands in a very small footprint.

The simulation results show that the proposed antenna has a good impedance matching performance at both bands with return loss better than -14 dB and VSWR less than 2. The antenna also has a wide bandwidth to cover the desired frequency bands, stable radiation characteristics, near omnidirectional radiation patterns, realized gain of up to 2.10 dBi, and radiation efficiency of greater than 53% at both frequencies.

One of the important aspects of this work is that the single-element meander-line PIFA, which is fabricated on a low-cost FR-4 substrate and has a simple solid ground plane without DGS or parasitic elements, can be designed to achieve compact size, dual-band operation at the desired frequency ratio of 2.37:1, and competitive RF performance. The parametric analysis also reveals that the two resonances can be tuned with a certain degree of cross-coupling, which makes the design and optimization process easier.

The proposed antenna provides a practical and manufacturable solution for compact IoT devices, where cost, size, and integration are important factors. The obtained results demonstrate that FR-4 based implementations are able to satisfy the requirements of modern dual-band wireless systems without using expensive substrate or complex geometry.

The drawback of the present design is that the radiation efficiency at the upper band is decreased due to the higher dielectric loss of FR-4 at 5.80 GHz. Future research will involve experimental validation of the fabricated and measured prototype, and exploring other low-loss substrates like Rogers 4003C to further enhance the efficiency. Further investigations will also be carried out to understand the integration effects in real IoT device environments and to optimize the radiation pattern for better system level performance. Finally, the proposed antenna has the advantages of compactness, simplicity, and dual-band performance, which makes it a promising antenna for next-generation IoT wireless applications.

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