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REGULAR ARTICLE

Design and Simulation of Novel Multi-Band Planar Inverted F-Antenna for Close-range IoT Applications

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Planar inverted F antenna (PIFA) is one of the emerging technologies suited for various mobile applications. Though it is capable of covering a wide range of applications in wireless services, these antennas are designed for multi-band frequencies. To enhance its applications in the areas of wireless communication, an antenna is integrated with IoT (Internet of Things) devices. The compact size and low profile of the PIFA antenna is a notable feature, enhancing its suitability for integration into small devices. In this research paper, we proposed a Multi-Band Planar Inverted F-Shaped Antenna (PIFA) specifically designed for general close-range Internet of Things (IoT) applications. The proposed designed antenna produces an average gain of 2.62 dBi with a return loss of – 20 dB and its operating bandwidths are 2.40 – 2.45 GHz, 3.9 – 4.3 GHz, and 5 – 5.2 GHz covering Zigbee, Bluetooth, and Wi-Fi frequency band applications. Its multi-band frequency response is obtained by inserting an L-shaped slots of various lengths on a radiating patch of PIFA antenna, allowing for precise tuning of operation frequencies. In the design of an antenna, the resonance frequencies for each band are controlled by manipulating the lengths of the corresponding slots. In addition to the desired frequency and gain, the paper evaluates key parameters including bandwidth, directivity, and radiation patterns with the help CST simulation environment and ensures accuracy in predicting the antenna's performance parameters.

Keywords: Planar Inverted-F antenna, Multi-band, Zigbee, CST, Bluetooth, IoT.

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1. INTRODUCTION

In the dynamic landscape of wireless communication, the demand for versatile antennas capable of op-erating at multiple frequencies has fuelled the devel-opment of multi-band solutions. Multi-Band Planar Inverted-F Antenna (PIFA) is designed to operate at different frequency bands [1]. It has garnered significant attention in various applications, notably in wire-less technology. This introduction seeks to illuminate the relevance and importance of these multi-band PIFAs in catering to the diverse communication needs of modern wireless systems [2]. The 2.4 GHz frequency band, a standard in wireless communication, aligns with widely adopted protocols like Zigbee, Bluetooth, and Wi-Fi making it integral for seamless connectivity in everyday devices [3]. Simultaneously, the 5GHz band, associated with higher data rates and improved bandwidth, addresses the growing demand for enhanced performance, especially in Wi-Fi applications.

To address the diverse frequency bands relevant to Internet of Things (IoT) applications, it is imperative to recognize that a single antenna is insufficient, necessi-tating multiple antennas [4]. Despite this, the need for compact and cost-effective devices remains paramount. As a solution to this challenge, incorporating multiband antennas becomes crucial [5]. This approach allows for efficient utilization of various frequency bands, accom-modating the specific requirements of Zigbee, Bluetooth, and Wi-Fi, while simultaneously meeting the constraints of compactness and affordability. The de-sign and implementation of such multiband antennas play a pivotal role in enabling the seamless operation of IoT devices across a spectrum of frequencies [6-9]. Multi-Band PIFAs ensure robust and adaptable com-munication solutions across the 2.4 GHz to 5 GHz spectrum. The subsequent sections will delve into the intri-cacies of their design principles, performance metrics, and the wide-ranging applications that make them indispensable in the ever-evolving landscape of wireless technology [10].

In this paper, The Multi-Band Planar Inverted F-shaped Antenna (PIFA) is an efficient and adaptable solution for close-range Internet of Things (IoT) applications. This

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antenna uses L-shaped slots of different lengths on its radiating patch to achieve a Multi-Band frequency response. It covers the Zigbee, Bluetooth, and Wi-Fi frequency bands with precision-tuned resonance frequencies. The average gain of the PIFA antenna is 2.62 dBi, and it has omnidirectional radiation, which makes it perform excellently. Moreover, its small size and low profile make it an ideal choice for integration into small IoT devices. PIFA antennas offer several advantages, particularly in small devices. Their easy fabrication, simple structure, small volume, and low manufacturing cost make them practical for integrating small electronic devices. Compared to other antenna types, PIFA antennas are easier to conceal within the device, and their minimal backward radiation toward the user's head and body contributes to improved performance. Additionally, PIFA antennas enable reso-nance adjustment by inserting slots in the radiating patch, allowing for compact antenna sizes. Multiband operation is achieved by shaping the patch strategically placing feed plates and shorting pins. [11-13].

The organization of the paper is, Section 2 gives the proposed methods for the antenna design, Section 3 represents the simulation results and its discussions followed by conclusion in Section 4.

2. PROPOSED METHODS FOR THE ANTENNA DESIGN

The proposed Planar Inverted F-shaped Antenna (PIFA) operates at multi-band frequencies as shown in Fig. 1. It encompasses a rectangular planar element positioned above the FR-4 substrate and a copper ground plane, featuring a shorting pin and feeding pin, a coaxial feed is given between the ground plane and the patch element. The radiating patch plane is folded at one edge of a patch and shortened to the ground plane to decrease the antenna length. The dimensions of a patch antenna are determined using empirical equations based on the substrate's dielectric constant, height, and frequency of operation. These dimensions are vital in determining the antenna's impedance matching, radiation pattern, and overall performance.

According to the fundamental theory of the PIFA antenna, the shorting pin causes the antenna to resonate at a quarter-wavelength. The following Eq. (1) and (2) are used to determine the size of the patch of an antenna.

$$L_p + W_p - W_{sp} = \frac{\lambda}{4} \tag{1}$$

$$\lambda = \frac{c}{f_r} \tag{2}$$

Where, W_p – Width of the patch, L_p – Length of the patch, c – Speed of light, ε_r – Relative permittivity, f_r – Resonant frequency, W_{sp} – Width of the shorting pin.

Parameters of the PIFA antenna will be half of the parameters of the microstrip antenna which is resonant at half wavelength. The parameters of the PIFA to be calculated are as follows:

Width (Wp): The Eq. (3) used to calculate the width of the patch is as follows:

$$W_p = \frac{C}{4fr}\sqrt{\frac{2}{\varepsilon r+1}} \tag{3}$$

Effective refractive index (ε_{eff}): This value is determined using the following Eq. (4):

$$\varepsilon_{eff} = \frac{\varepsilon r+1}{4} + \frac{\varepsilon r-1}{4}\left[\frac{1}{1+6\left[\frac{h}{w}\right]}\right] \tag{4}$$

Length (L_p): When a patch antenna's edges have fringing, the antenna's size increases by an amount (ΔL). The actual increase in length of the patch (ΔL) can be calculated using the following Eq. (5):

$$\Delta L = 0.412h\left[\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{w}{h}+0.264\right)}{\left(\varepsilon_{eff}-0.258\right)\left(\frac{w}{h}+0.8\right)}\right] \tag{5}$$

Where 'h' – height of the substrate.

The length (L) of the patch can be calculated using the following Eq. (6):

$$L_p = \frac{C}{4fr\sqrt{\varepsilon \mathrm{eff}}} - 2\Delta L \tag{6}$$

Now the dimensions of a patch are known. The length and width of a substrate are equal to that of the ground plane. The Eq. (7) and (8) for calculating the length (L_g) and width (W_g) of a ground plane are as follows:

$$L_g = 6h + L_p \tag{7}$$

$$W_g = 6h + W_p \tag{8}$$

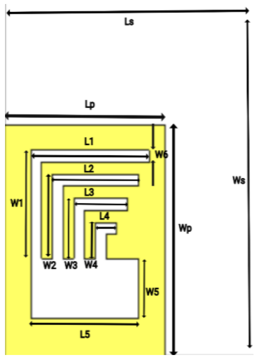
Impedance Matching: Impedance (Z_0) calculation Eq. (9) using coaxial cable:

$$Z_0 = \frac{(138\times\log\left(\frac{D}{d}\right))}{\sqrt{\varepsilon_r}} \tag{9}$$

Where D – Outer Diameter, d – Inner Diameter.

The configurations of PIFA are shown in Fig. 1. Using the above equations, the dimensions of the patch are 14.9 mm × 19.2 mm × 0.01 mm. The ground dimensions are 24 mm × 30 mm × 1 mm are shown in Fig. 1. The PIFA has a relative permittivity of 4.3 with dimensions of 24 mm × 30 mm × 1.57 mm and it is fed with a coaxial feeding system with a characteristic impedance of 50 ohms by using the materials of Copper, Teflon, and Dielectric. The coaxial feeding has an inner radius (d) of 0.45 mm and an outer radius (D) of 1.6 mm. This design involves incorporating slots on the patch, allowing for enhanced bandwidth and frequency coverage. These slots help in improving various characteristics of the antenna such as impedance matching, bandwidth, radiation pattern, frequency, and overall performance.

The slots are carefully positioned and optimized to achieve the best results, which involves simulations and analysis to assess the impact of different slot dimensions and positions on the antenna's performance.



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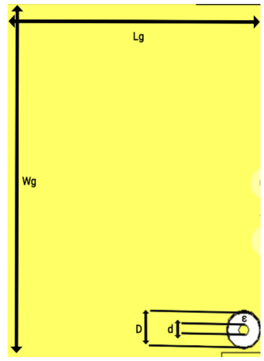

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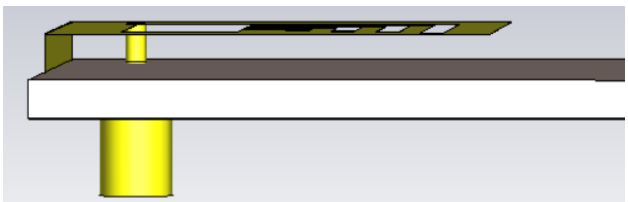


c

Fig. 1 – Top view (a), bottom view (b), side view of antenna (c)

Table 1 – Parameters of the proposed Antenna

Parameters	Value(mm)
Patch length (L_p)	14.9
Patch width (W_p)	19.2
Patch height (h_p)	0.01
Substrate height (h_s)	1.57
Substrate length (L_s)	24.3
Substrate width (W_s)	28.6
Ground length (L_g)	24.3
Ground height (h_g)	0.01
Ground width (W_g)	28.6
Coaxial outer radius (D)	1.6
Coaxial inner radius (d)	0.4
Shorting pin width (W_{sp})	3
Slot width (W_5)	1

Table 2 – Slot dimensions of the proposed antenna

Parameter	Value(mm)	Parameter	Value(mm)
L_1	11	W_1	9
L_2	8	W_2	7
L_3	5	W_3	5
L_4	2	W_4	3
L_5	10	W_5	5

3. RESULT AND DISCUSSION

This section describes and discusses the various parametric analyses of the optimized design, including antenna S-parameters, and 2D radiation characteristics.

To achieve single, dual, and triple-band frequencies while maintaining a reasonably low return loss of – 25 dB, various configurations of L-shaped slots on a radiating patch are employed.

For a single-band frequency at 2.4 GHz covering Zigbee and Bluetooth protocols shown in Fig. 2, two L-shaped slots of specific lengths are inserted, producing a gain of 2.65 dB at the resonating frequency shown in Fig. 3.

For dual-band frequencies at 2.4G Hz and 5 GHz covering Bluetooth and Wi-Fi shown in Fig. 2, three L-shaped slots of different lengths are inserted on the same antenna. This configuration achieves gains of 2.6 dB and 4.57 dB at the respective frequencies shown in Fig. 3.

For triple-band frequencies at 2.4 GHz, 4.2 GHz, and 5 GHz covering various Wi-Fi applications shown in Fig. 2, four L-shaped slots of varying lengths are inserted on the same antenna. This setup yields gains of 2.52 dB, 4.9 dB, and 5.35 dB at the lower, central, and higher frequencies, respectively shown in Fig. 3.

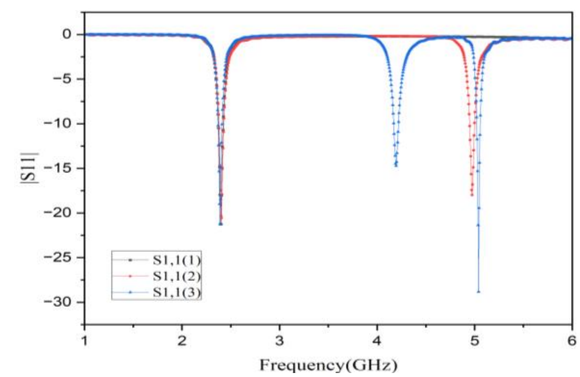
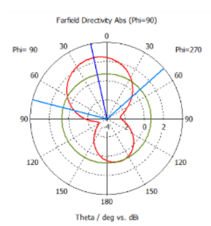


Fig. 2 – Simulated $|S_{11}|$ values (dB) of the Triple -band antenna versus frequency



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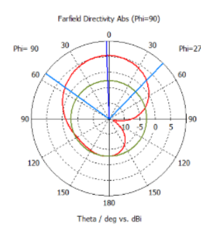

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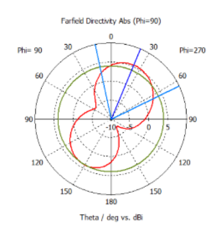

c

Fig. 3 – Simulated Radiation Pattern (dB) at 2.4 GHz (a), 4.2 GHz (b), and 5 GHz (c) respectively

a

b

Fig. 4 – Top (a) and bottom (b) view of the proposed and fabricated antenna

The results of the simulation were confirmed by constructing and testing a prototype that was designed with the same dimensions shown in Fig. 1. A prototype of the Top and bottom sides of the proposed antenna that was fabricated is shown in Fig. 4. This antenna is highly compact and can be effortlessly integrated into small devices.

4. CONCLUSION

In this paper we have successfully proposed, designed, simulated and fabricated the PIFA antenna, which is mainly for the IoT applications. This multi-band PIFA antenna is effectively used for close-range IoT applications. Its design features are L-shaped slots which are having varying lengths on the radiating patch, and it allows precise tuning across the 2.4 GHz, 4.2 GHz, and 5 GHz frequency bands. With maximum gains of 2.52 dB and 5.35 dB at lower and higher resonating frequencies, the PIFA stands out for its efficiency and bandwidth. The antenna has a very compact size of 14.9 mm × 19.2 mm × 0.01 mm. It is therefore considered a suitable candidate for future mobile communications. As a compact and low-profile solution, the Multi-Band PIFA not only meets the challenges of IoT integration but also exemplifies a versatile and cost-effective approach to address the diverse communication needs in the ever-evolving landscape of wireless technology.

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Проектування та моделювання багатодіапазонної планарної інвертованої F-антени для додатків IoT малого радіусу дії

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Планарна обернена F-антена (PIFA) є однією з нових технологій, що підходить для різноманітних мобільних додатків. Незважаючи на те, що ці антени здатні охоплювати широкий спектр застосувань у бездротових службах, вони розроблені для багатодіапазонних частот. Щоб покращити застосування в області бездротового зв'язку, антену інтегровано з пристроями IoT (Інтернет речей). Компактний розмір і низький профіль антени PIFA є помітною особливістю, що підвищує її придатність для інтеграції в невеликі пристрої. У цьому дослідницькому документі ми запропонували багатодіапазонну планарну перевернуту F-подібну антену (PIFA), спеціально розроблену для загальних додатків Інтернету речей (IoT) на близькій відстані. Запропонована розроблена антена забезпечує середній коефіцієнт посилення 2,62 дБі із зворотними втратами – 20 дБ, а її робочі смуги смуг 2,40–2,45 ГГц, 3,9–4,3 ГГц і 5–5,2 ГГц охоплюють смугу частот Zigbee, Bluetooth і Wi-Fi. програми. Його багатодіапазонна частотна характеристика досягається шляхом вставки *L*-подібних прорізів різної довжини на випромінювальну ділянку антени PIFA, що дозволяє точно налаштовувати робочі частоти. У конструкції антени резонансні частоти для кожного діапазону контролюються шляхом маніпулювання довжиною відповідних щілин. Окрім бажаної частоти та підсилення, у статті оцінюються ключові параметри, зокрема смуга пропускання, спрямованість і діаграми спрямованості за допомогою середовища моделювання CST, і забезпечується точність прогнозування параметрів ефективності антени.

Ключові слова: Планарна інвертована F-антена, Багатодіапазонна, Zigbee, CST, Bluetooth, IoT.