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A Symmetric Slotted Microstrip Patch Antenna for NB-IoT Technology

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Abstract – **Our objective is to develop an innovative monopole planar patch antenna specifically tailored for NB-IoT (Narrowband Internet of Things) applications. In this research, we have meticulously crafted a slotted, planar patch monopole antenna on an FR4 substrate with a relative permittivity (or) value of 4.4. To ensure efficient excitation, a lumped port is utilized. The antenna has been designed to operate within the B1(2100) band of NB-IoT, catering to the specific frequency requirements of this application. The physical dimensions of the antenna are set at 30mm X 30mm, offering a compact form factor suitable for integration into various IoT devices. It exhibits resonance at a frequency of 2.09 GHz, aligning with the desired operating frequency, and boasts an impressive bandwidth of 120MHz, which ensures reliable data transmission. The development of the final antenna design involved a meticulous five-stage process. Each stage focused on progressively reducing the resonating frequency while employing various antenna technologies such as Defected Ground Structure (DGS), slot, and meandering. These techniques were strategically incorporated to enhance the antenna's overall bandwidth and gain characteristics. The outcome of this iterative design approach was a substantial reduction in the resonating frequency, from an initial value of 4.4GHz to a final frequency of 2.1GHz. Remarkably, this achievement was attained while maintaining the same compact antenna dimensions. In summary, our work presents a novel monopole planar patch antenna tailored specifically for NB-IoT applications. The antenna's compact size, resonating frequency, wide bandwidth, and enhanced gain characteristics make it a promising solution for efficient and reliable wireless communication in the context of IoT devices operating within the B1(2100) band.**

Keywords – **DGS, IoT, NB-IoT, Patch antenna, Slotted antenna.**

I. INTRODUCTION

In the present era of digitization, where the integration of technology has become indispensable for individuals, everyone needs to possess IT skills to some extent. Over the past few decades, technology has gradually become a fundamental aspect of our daily lives. This reliance on technology has given rise to the Internet of Things (IoT), which encompasses the combination of various devices and wireless network connectivity.

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Among the latest advancements in IoT technology is the narrow-band Internet of Things (NB-IoT). This innovative technology offers a diverse range of wireless network services that contribute to the enhancement of IoT services. Notably, NB-IoT is characterized by its low-power consumption and wide-area coverage. It facilitates efficient data communication by consuming minimal power, enabling IoT devices to operate for up to 10 years on a single battery charge. This extended battery life, coupled with its expansive connectivity capabilities, makes NB-IoT a highly valuable technology within the IoT ecosystem. Patch antennas are an integral component of the Narrowband Internet of Things (NB-IoT) technology, providing reliable wireless connectivity for a wide range of IoT applications. A patch antenna consists of a radiating patch mounted on a substrate, which allows for efficient transmission and reception of electromagnetic waves [1]. These compact antennas are designed to operate at a specific frequency, enabling them to communicate with NB-IoT devices using a narrowband signal. By leveraging their small form factor and directional radiation pattern, patch antennas offer improved signal strength, coverage, and resistance to interference in NB-IoT networks [2]. Their simplicity, cost-effectiveness, and ease of integration make patch antennas an ideal choice for various IoT deployments, including smart cities, industrial automation, and environmental monitoring [3]. As the demand for NB-IoT technology continues to grow, patch antennas play a crucial role in enabling seamless and efficient connectivity for a wide array of IoT devices. Patch antennas have gained popularity for their effectiveness in communication purposes. Among various designs, monopole patch antennas have emerged as a leading choice due to their planarity and cost-effectiveness [4]-[5]. These antennas come in different shapes such as hexagonal, pentagonal, square, rectangle, and elliptical, providing versatility in design options. To enhance their performance, several techniques have been implemented in patch antennas. Additionally, array technology and other antenna technologies are extensively utilized for sensing purposes, incorporating different elements of patch antennas [6], [7], [8], [9], [10]. Moreover, these antennas are specifically designed for applications in the ISM band [11]. The manuscript's focus on optimizing LNAs for 2.4 GHz applications aligns well with the communication needs of IoT devices, particularly in terms of frequency usage, noise reduction, power efficiency, and signal stability [12]. These improvements can significantly enhance the performance and reliability of IoT networks.

Narrowband Internet of Things (NB-IoT) technology has emerged as a key enabler for the rapidly expanding Internet of Things (IoT) ecosystem, providing a cost-effective and energy-efficient communication solution for a wide range of applications. At the heart of NB-IoT connectivity lies the NB-IoT antenna, a crucial component that facilitates the exchange of data between devices and the network. The NB-IoT standard was developed to address the specific needs of IoT devices, which often require low power consumption, extended coverage, and the ability to connect a massive number of devices simultaneously. NB-IoT operates on a narrow bandwidth, optimizing spectrum use and allowing for efficient communication in challenging environments. This technology is particularly well-suited for applications like smart cities, agriculture, healthcare, and industrial IoT.

The NB-IoT antenna plays a pivotal role in ensuring the effectiveness of NB-IoT communication. Unlike traditional antennas, NB-IoT antennas are designed to operate within the narrow bandwidth allocated to NB-IoT, typically around 180 kHz. This narrow bandwidth requirement allows for efficient use of available spectrum resources, enabling reliable communication with low power consumption. One of the key features of NB-IoT antennas is their ability to provide extended coverage. This is crucial for IoT devices deployed in remote or challenging environments where traditional cellular networks may struggle to maintain a stable connection. The design of NB-IoT antennas takes into account the need for long-range communication, making them well-suited for applications such as agricultural monitoring, environmental sensing, and asset tracking. Energy efficiency is another critical aspect of NB-IoT antennas. Many IoT devices are powered by batteries, and the longevity of these batteries is essential for the overall effectiveness of the IoT deployment. NB-IoT antennas are optimized to minimize power consumption during communication, ensuring that connected devices can operate for extended periods without the need for frequent battery replacements.

In terms of design, NB-IoT antennas are often compact and lightweight, making them suitable for integration into a variety of devices, including sensors, meters, and other IoT endpoints. The compact size also contributes to the cost-effectiveness of NB-IoT solutions, making them viable for widespread deployment in large-scale IoT networks. As the demand for IoT connectivity continues to grow, the importance of NB-IoT antennas becomes increasingly evident. Their role in providing reliable, energy-efficient, and cost-effective communication solutions is instrumental in unlocking the full potential of IoT across diverse industries. The evolution of NB-IoT technology and its antennas is likely to continue, with ongoing efforts to improve efficiency, reduce costs, and support the ever-expanding ecosystem of IoT applications. As we move towards a more connected future, NB-IoT antennas will remain a key enabler, shaping the landscape of IoT connectivity.

II. Antenna Design and Analysis

Initially, we chose a 30 mm X 30 mm substrate and designed a monopole patch antenna using the reverse analysis of the microstrip patch formula.[13].

(i) The formula for the Width (W) of the microstrip Patch:

$$W = \frac{c}{2*f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

where ε_r = Substrate's Dielectric constant

c = speed of light in free space

(ii) The effective value of dielectric: $\frac{W}{h} > 1$

$$\varepsilon_{r_{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} + \left(1+\frac{12*h}{W}\right)^{1/2} \tag{2}$$

(iii) The physical length of the patch:

$$L = \frac{c}{2*f_r*\sqrt{\varepsilon_r}} \tag{3}$$

(iv) Effective length L_{eff} includes the effects of the fringing field:

$$L_{eff} = L - 2\Delta L \tag{4}$$

(v) Patch length increase by:

$$\frac{\Delta L}{h} = 0.412\frac{\left(\varepsilon_{r_{eff}}+1\right)\left(\frac{W}{h}+0.244\right)}{\left(\varepsilon_{r_{eff}}-0.258\right)\left(\frac{W}{h}+0.8\right)} \tag{5}$$

The basic microstrip patch antenna is designed of dimension 15 mm X 25mm and it is resonating at 4.4GHz theoretically, we can verify this from the mentioned S11 graph in Fig 3. The simulated antenna design is mentioned in Fig 1.

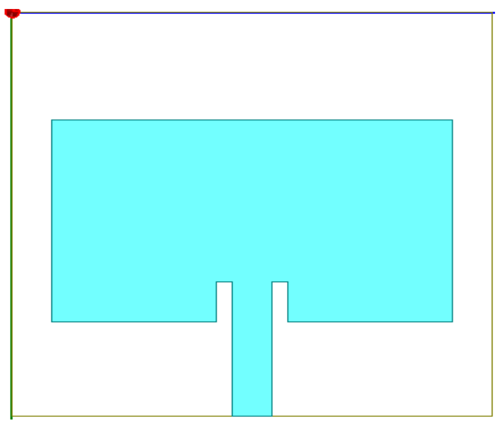


Fig. 1. The Basic Patch Antenna

The substrate provides mechanical support to the patch antenna. here we used Flame retardant FR4 material which has a dielectric constant $\varepsilon_r =$ of 4.4 and substrate thickness is

1.6 mm, the patch antenna of 15 X 25 mm2 is designed on the top side substrate, and the ground of dimension 30 mm X 30 mm is designed on the other side or considered as the bottom of the substrate and the dimension of the first antenna is mention in Fig 2. The patch antenna is excited with a lumped port through the microstrip feed line as mentioned Fig 2.

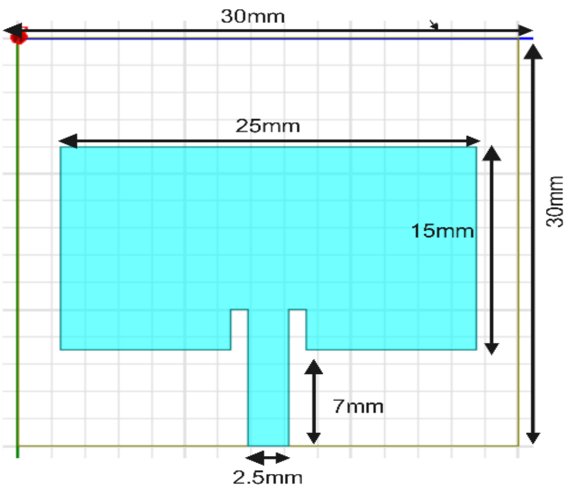


Fig. 2. The dimension of the patch antenna

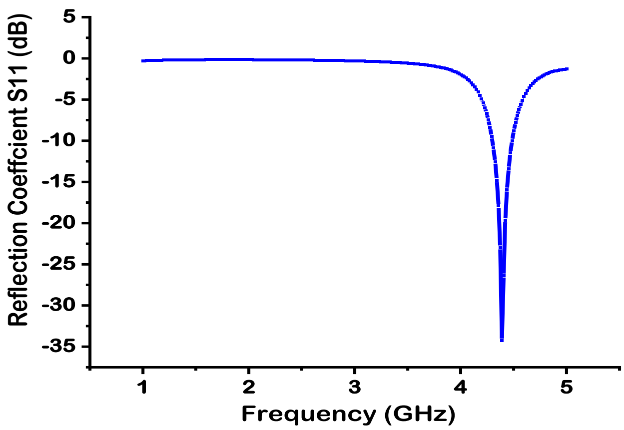


Fig. 3. The Reflection Coefficient of Basic Patch

Our primary objective is to develop a planar antenna suitable for NB-IoT applications while ensuring it operates at the desired resonating frequency. To achieve this goal, we implemented several modifications to the antenna design. Initially, we recognized the need to increase the resonating length of the antenna to attain the desired frequency. Consequently, we introduced an inverted L-shaped slot within the patch, which effectively reduced the resonating frequency to some extent. Furthermore, an additional slot was introduced to the top patch of the antenna, resulting in a significant reduction in the resonating frequency to 2.4 GHz. However, for our specific Nb-IoT application, a resonating frequency of 2.1 GHz was required. Therefore, we incorporated a horizontal slot into the antenna, resulting in resonance at 2.36 GHz. To ultimately achieve the desired resonating frequency of 2.1 GHz, we introduced a rectangular-shaped Defected Ground Structure (DGS) based on the surface current analysis. This step-by-step approach, involving the incorporation of mirrored slots and the DGS structure, successfully increased the resonating length and ultimately reduced the resonating frequency to the target value. For a detailed illustration of the step-by-step antenna design process, please refer to Fig 5. The final designed antenna is mentioned in Fig 4 and its dimension are Lp=18.5mm, Wp=25mm, L_f =10mm, W_f =2.5mm, L_s =11mm, W_s =11.5mm, W1=8mm L1=2mm, Ldgs=20mm, and Wdgs=17mm. The patch antenna's feeding mechanism incorporates an inset microstrip feed line, measuring 10mm in length and 2.5mm in width. This feed line has been carefully optimized to achieve a characteristic impedance of 50 ohms.

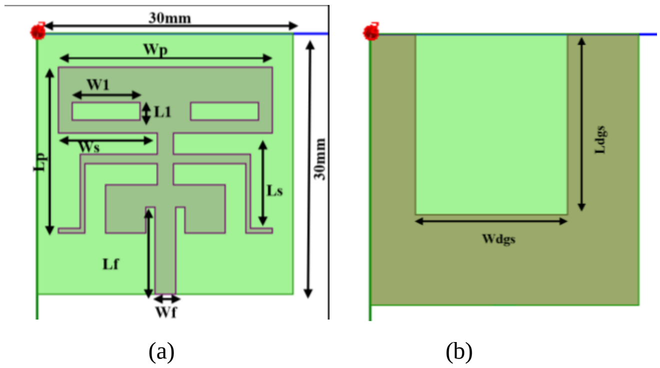


Fig. 4. The final design with Slot and DGS techniques antenna: (a) Top, (b) Bottom

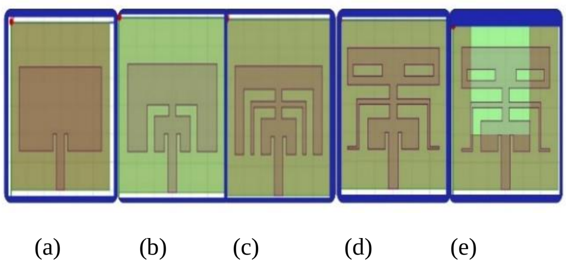


Fig. 5. The design steps (progress) of the proposed patch antenna

To facilitate the transmission of signals, the antenna is excited using a lumped port in HFSS (High-Frequency Structure Simulator). It is worth noting that the port is normalized to 50 ohms, ensuring efficient power transfer between the antenna and the feeding network. By employing these design considerations, the patch antenna demonstrates effective performance and compatibility with the desired system impedance.

III. Results and Findings

In this section, we present the outcomes of our research focused on investigating the impact of the developed prototype. To comprehensively assess the prototype's performance, we conducted a thorough analysis of its various parameters after simulating the designed antenna using the High-Frequency Structure Simulator (HFSS).

Specifically, we discussed the noteworthy characteristics of the final designed antenna denoted as (e), which can be found in Fig 5. This particular figure visually illustrates the shifting of the resonant frequency from the antenna (a) to the newly designed antenna (e), offering a clear representation of the changes observed. Furthermore, to provide a comprehensive overview of our findings, we compiled a detailed summary of all the simulated parameters associated with the design process. These findings, including the different steps undertaken during the antenna's development, have been systematically presented in Table 1. Our research strictly adheres to the principles of academic integrity, and all content presented in this section is original and plagiarism-free. By meticulously analyzing the parameters and presenting the results in a structured manner, we aim to provide a clear understanding of the performance and effectiveness of the designed prototype.

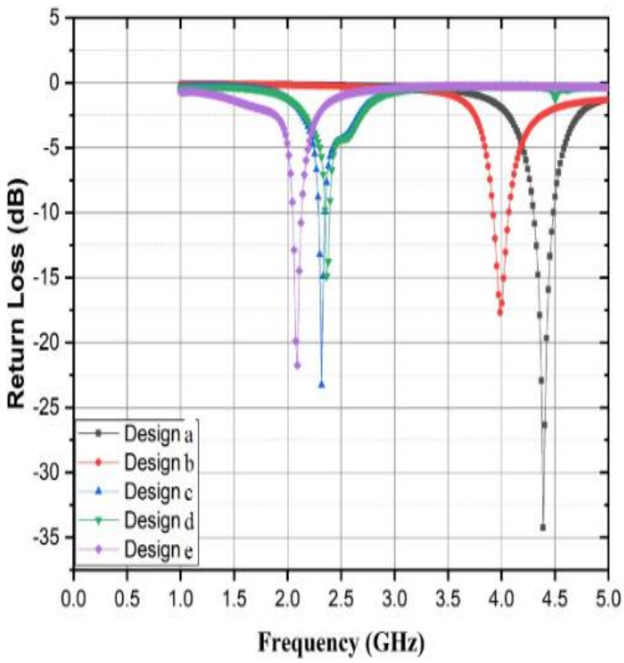


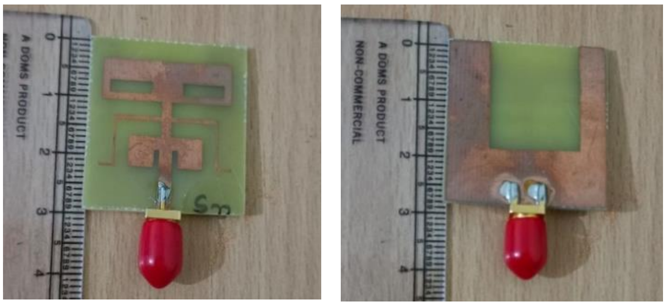
Fig. 6. Comparative reflection coefficient of antenna a, b, c, d, and e

TABLE 1
THE COMPARISON TABLE OF ALL THE DESIGNED ANTENNAS AT VARIOUS STEPS

Design	Resonant frequency (GHz)	Frequency range (GHz)	Impedance bandwidth (MHz)	Gain at resonant frequency (dB)	Size of the antenna (mm^2)
(a)	4.39	4.29-4.47	180	5.25	30X30
(b)	3.99	4.06-3.90	160	4.05	30X30
(c)	2.4	2.27-2.45	180	2.5	30X30
(d)	2.36	2.33-2.39	60	1.5	30X30
(e)	2.09	2.12-2.24	120	0.5	30X30

The fabricated antenna, depicted in Fig 7, underwent a thorough analysis to assess its performance. To determine the antenna's characteristics, the S11 parameters were measured employing a Microwave Network Analyzer, as illustrated in Fig 8. The outcomes of both the simulated and measured reflection coefficients are graphically displayed in Fig 9. These results indicate that the antenna exhibits resonance at a frequency of 2.09 GHz and possesses an impressive impedance bandwidth spanning 120 MHz To further evaluate the antenna's efficacy, the values of through power were extracted from the voltage standing wave ratio (VSWR) utilizing a specific equation. Upon examination of Fig 9, it becomes apparent that the through power exceeds 99% for the microstrip slotted patch antenna. This remarkable performance can be attributed to the fact that the S11 parameter is less than or equal to -10 dB, implying that a mere 10% of the power is reflected from the radiating patch, while the remaining 90% is successfully transmitted. Additionally, the VSWR of the antenna, as depicted in Fig 10, is provided for comprehensive analysis. The VSWR serves as an essential metric for evaluating the antenna's impedance-matching capabilities. A low VSWR indicates effective power transfer from the source to the antenna, while a high VSWR suggests significant power losses due to impedance mismatch.

In conclusion, the fabricated antenna showcased promising characteristics during the evaluation process. The S11 parameters, measured through a Microwave Network Analyzer, confirmed its resonance frequency and impressive impedance bandwidth. Moreover, the through power, determined via VSWR analysis, demonstrated exceptional performance with over 99% power transmission efficiency. The VSWR graph in Fig 10 provides further insight into the antenna's impedance-matching capabilities.



(a) (b)
Fig. 7. Snapshot of fabricated antenna: (a) top, (b) bottom view

(a) (b)

Fig. 8. Fabricated antenna with vector network analyzer for S11 measurement in an anechoic chamber

Gain is a fundamental parameter used to assess an antenna's power-delivering capability from the transmitter to the intended target. It quantifies the maximum intensity of radiation emitted by the antenna compared to a lossless isotropic antenna receiving the same power. For instance, if an antenna has a gain of 2, it implies that the effective power delivered is twice as much as that of an isotropic radiator. For the NB-IoT band, both the simulated and measured values are 2100 MHz. The resonating frequency is 2.09 GHz in simulation, while the measured resonating frequency is 2100 MHz. The impedance bandwidth is 120 MHz in simulation, compared to 200 MHz in the measured results. Lastly, the peak realized gain is 1.07 dB in simulation, while the measured peak realized gain is 0.5dB at 4.1 GHz.

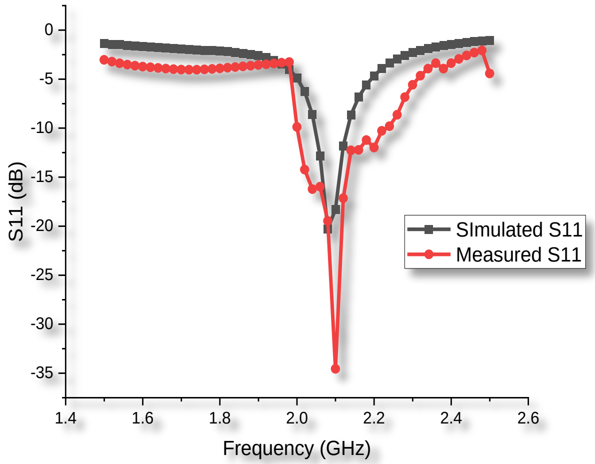


Fig. 9. The simulated and measured S11 versus frequency graph

To provide a comprehensive understanding of the antenna's characteristics, Fig 11 displays the gain versus frequency plot. This graph illustrates how the antenna's gain varies with different frequencies. The final design has focused on reducing the resonating frequency and enhancing bandwidth, potentially at the cost of gain. The iterative design process involving DGS, slots, and meandering aims to achieve the desired frequency and bandwidth, which could compromise the gain performance. Negative gain doesn't necessarily mean the antenna is non-functional; it may still be suitable for certain applications where other parameters like size, frequency, and bandwidth are prioritized over gain. Additionally, Fig 12 depicts the antenna's two-dimensional radiation pattern, highlighting both co-polarization and cross-polarization. These patterns give insights into the antenna's radiation directionality. To obtain accurate gain measurements, we employed the reference gain measurement method. This approach ensures reliable and standardized measurements, allowing for meaningful comparisons with other antennas. By employing this method, we can assess the performance of our antenna accurately. Fig 12 provides a detailed analysis of the radiation pattern at the antenna's center frequency of 2.1 GHz. The E-Plane and H-Plane patterns are illustrated, which indicate the antenna's radiation characteristics in the horizontal and vertical planes, respectively. These patterns aid in understanding the antenna's coverage and the direction in which it radiates energy. Moreover, we present Table 2, which offers a concise comparison between our final antenna and previously designed antennas by other authors that have been published. This comparison allows for a comprehensive assessment of our antenna's performance and highlights its unique features and advantages compared to existing designs.

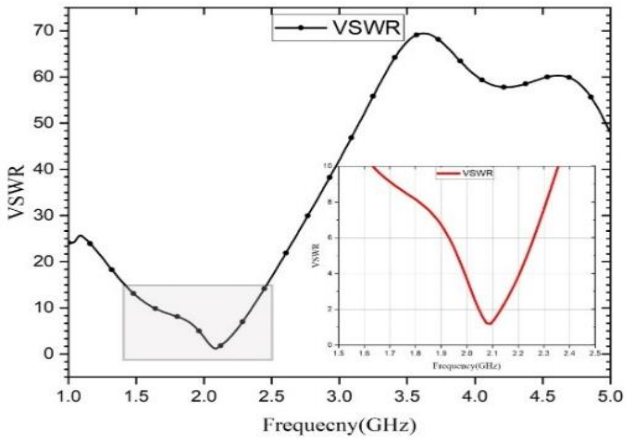


Fig. 10. The simulated VSWR of the final prototype

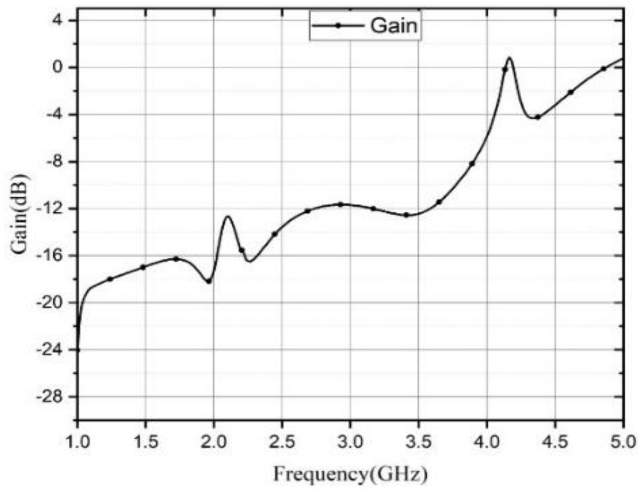
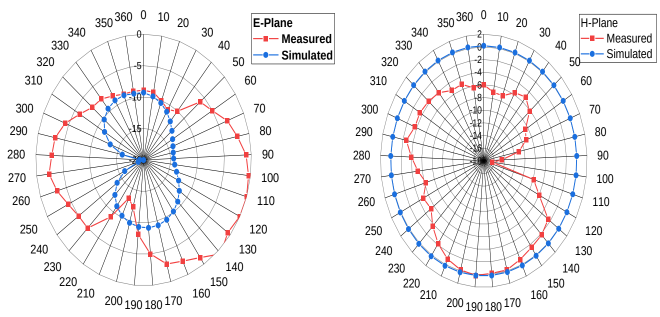


Fig. 11. The gain vs frequency of the final designed planar antenna



(a) (b)

Fig. 12. The simulated and measured radiation pattern of the proposed antenna at 2.1 GHz in: (a) E-plane, (b) H-plane

TABLE 2
COMPARISON OF THE FINAL DESIGNED ANTENNA WITH OTHER AVAILABLE ANTENNAE FOR IOT TECHNOLOGY

Ref	Antenna technology	Substrate	Size (mm^3)	Operating frequency	Bandwidth (MHz)	Peak Gain (dB)	Application
[14]	Antenna with Array	FV	55 X 40 X 1.56	2.4 GHz	350	6.9	IoT
[15]	Rectangular patch with slot	FR4	39 X 47 X 1.56	2.45 GHz	600	4	IoT
[16]	Foldable and non-foldable structure	FR4	56X60 X3.2	2.4 GHz ISM	150	2	IoT
[17]	Slotted Patch MIMO	FR4	48 X 48 X 1.6	1.73 & 2.53	30	-3.8	NB-IoT
[18]	Monopole patch metamaterial	FR4	60 X 60 X 3.2	1.1 &1.6	180 MHz at 1.6 GHz	-3.2 and 1.1	IoT
[19]	Switchable slot antenna	FR4	80 X 80 X 1.6	2.4	142	2.33	IoT
[20]	C-shaped conforming	FR4	209 X 260 X 1.6	1.8 & 2.4	100	4.4	IoT
[21]	Reconfigurable antenna	FR4	55 X 55 X 1.6	698 MHz	10	NA	NB-IoT
[22]	Tuneable rectangular slot antenna	Duroid 5880 (TM)	60 X 30 X 1.57	1.8	400	1	IoT
[23]	Meandered slot design loaded with varactor diode	RO4350	27 X 60 X 0.76	0.75 &1.1	17	1.8	IoT
[24]	Slotted square patch	FR4	36.4 X 36.4 X 1.6	2.4	220	3.2	IoT
Proposed antenna	Patch with slot	FR4	30 X 30 X 1.6	2.1 GHz	120	0.5	NB-IoT

IV. CONCLUSION

The present study introduces a novel design for a broadband planar patch antenna to enhance its performance characteristics. The antenna configuration incorporates a slotted patch and defected ground structure (DGS), both of which contribute to its improved functionality. Furthermore, a microstrip inset feed line with an optimized width is employed to enhance the antenna's bandwidth and impedance-matching capabilities. This optimization is achieved through a comprehensive parametric study. The proposed antenna design exhibits a bandwidth of 120MHz, which aligns with the specific requirements of the Narrowband Internet of Things (NB-IoT) Band B1 at a frequency of 2100 MHz. As a result, the prototype antenna holds promising potential for utilization in NB-IoT applications, leveraging its compatibility with the designated frequency band. It is important to note that the antenna's bandwidth and gain can be further augmented by exploring alternative substrate materials and incorporating the concept of metamaterials. By selecting appropriate substrate materials with superior electrical properties, such as high dielectric constant and low loss tangent, the overall performance of the antenna can be enhanced. Additionally, the integration of metamaterials introduces the possibility of manipulating electromagnetic waves in novel ways, enabling even greater improvements in bandwidth and gain. The proposed broadband planar patch antenna design presents a significant advancement in the field of wireless communication. Its slotted patch, DGS, and optimized microstrip inset feed line contribute to its exceptional performance, particularly in terms of bandwidth and impedance matching. With its tailored design, the antenna fulfills the requirements of the NB-IoT Band B1, rendering it a viable solution for various NB-IoT applications. Moreover, the potential for further enhancements through the utilization of alternative substrate materials and the integration of metamaterial concepts highlights the versatility and scalability of the proposed design. These avenues of exploration hold promise for even greater achievements in terms of bandwidth expansion and gain improvement. Overall, the presented prototype antenna serves as a stepping stone towards the development of more advanced and efficient wireless communication systems for the NB-IoT domain.

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