Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 9s (2025)

Design and Analysis of Planar Frequency Doubling Reflectenna for IoT Sensor Networks

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Article History:

Received: 12-01-2025

Revised: 15-02-2025

Accepted: 01-03-2025

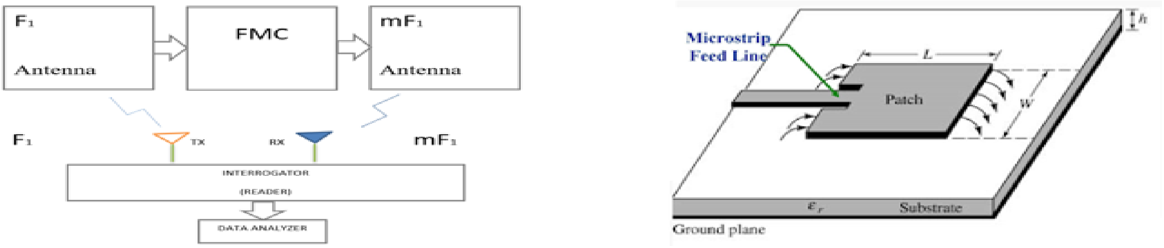
Abstract:

Compact and energy-efficient communication technologies are critical for the development of smart sensor networks in the constantly expanding Internet of Things (IoT) environment. This paper describes the design, analysis, and implementation of a compact planar frequency doubling reflectenna, specifically usefull for IoT sensor networks. The proposed reflectenna utilizes the frequency doubling phenomenon to enhance signal reception and transmission in IoT applications. By leveraging advanced antenna and metamaterial design principles, the reflectenna achieves efficient power conversion, reduced energy consumption, and enhanced wireless communication range. The performance of the reflectenna is analyzed through simulation and practical implementation, showcasing its potential as a fundamental component in the next generation of IoT networks. The gain of F1 antenna is 3.5 dBi and gain of mF1 antenna is 5.1dBi. Output power for frequency doubling reflectenna system observed -20dB, -89dB for distance between Tx and Rx at 100 cm, 1000cm respectively.

Keywords: Frequency Doubling, Reflectenna, Compact Planar Antenna, IoT Sensor Networks, Metamaterials, Wireless Communication, Energy Efficiency etc.

1. Introduction

The introduction of the Internet of Things (IoT) has revolutionized various fields, including smart cities, healthcare, industrial automation, and environmental monitoring [3],[4],[5]. A critical challenge in IoT networks is the need for energy-efficient, compact, and reliable communication systems. IoT devices, particularly sensor nodes, require efficient data transmission to minimize power consumption while maximizing range and reliability [1],[2],[6].



(a) (b)

Figure 1: a) Frequency multiplier reflectenna with Interrogator for Wireless application, b) shows Block diagram of Microstrip antenna with inset-feed line

A promising approach to achieve these objectives is the development of advanced antennas, such as reflectennas, which combine the functionalities of both reflectors and antennas. The concept of frequency doubling within reflectennas can further improve the overall system performance by enhancing the efficiency of signal reception and transmission without increasing the physical size of the system. Figure 1 (a) shows Frequency multiplier reflectenna with Interrogator for Wireless application [9],[10],[11],[12]. This paper aims to design and analyse a compact planar frequency doubling reflectenna that meets the specific requirements of IoT sensor networks, including size constraints, low power consumption, and effective signal propagation [7],[8],[13].

2. Proposed System

IoT sensor networks consist of many wireless devices (nodes) that communicate with each other to collect and exchange data. These networks are typically characterized by the following constraints: 1) Limited power supply: Many IoT devices are battery-operated and must operate for extended periods without recharging or replacing batteries. 2) Limited communication range: To ensure connectivity, efficiency and long-range communication is crucial. 3) Compact size: IoT devices often have small form factors, limiting the space available for antennas. To address these constraints, the design of compact and energy-efficient antennas is key [14],[15],[16]. Frequency doubling refers to the phenomenon where the output signal frequency is twice that of the fundamental frequency signal. This can be utilized in antenna systems to improve performance, particularly in non-linear environments [18],[19],[20]. Equation 1 represents resonant frequency. Equation 2 represents lower cutoff frequency. Equation 3 represents a higher frequency of cutoff. Equation 4 represents α value for parallel LC.

$$\omega_0^2 = \frac{1}{LC} \qquad (1)$$

$$\omega_{c1} = -\alpha + \sqrt{a^2 + \omega_0^2} \qquad (2)$$

$$\omega_{c2} = \alpha + \sqrt{a^2 + \omega_0^2} \qquad (3)$$

$$\alpha = \frac{1}{2RC} \qquad (4)$$

Reflectennas, which combine the properties of reflectors and antennas, offer a novel solution for compact antenna designs. By using frequency doubling, a reflectenna can operate at higher frequencies while keeping its physical size small, making it an attractive solution for IoT sensor networks. Use equation 5 to determine the antenna width 'W'. Utilizing equation 6, to get the effective dielectric constant. In this case, 'εr' represents the material's relative dielectric constant. W is the patch's width determined by equation 5, and 'h' is the substrate's height. Utilizing the formula found in equation 7, to determine ΔL. Equation 8 is the speed of light in open space, to get the patch's length. Utilizing equation 9, determine the patch's input impedance. where G1 and G2 represent the conductance of the patch antenna's slots #1 and #2. The odd resonant voltage distribution between the slots and underneath the patch is denoted by a + sign, while the even resonant voltage distribution is denoted by a - sign [21],[22]. Equation10 is used calculate y0 by assuming Rin(y=y0) as 50Ω and Rin(y=0). L is the length of the patch. The calculated value of y0 will be between 0 and L/2. We can calculate the width of 50Ω feedline using formula for the microstrip line. If W/h ≤ 1 we use equations 11.1 and 11.2. If W/h ≥ 1 we use equations 12.1 and 12.2. Figure 1 (b) shows Block diagram of Microstrip antenna with inset-feed line [23],[24],[25].

$$W = \frac{v_0}{2fr}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{5}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \tag{6}$$

$$\frac{\Delta L}{h} = 0.412\,\frac{(\varepsilon_{reff}+0.3)\,(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)\,(\frac{W}{h}+0.8)} \tag{7}$$

$$L = \frac{v_0}{2fr\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{8}$$

$$R_{in} = \frac{1}{2(G_1 \pm G_{12})} \tag{9}$$

$$R_{in}(y = y_0) = R_{in}(y=0)\,cos^2(\frac{\pi}{L}y_0) \tag{10}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\left(1+12\frac{h}{W}\right)^{-0.5} + 0.04\left(1-\frac{W}{h}\right)^2\right] \tag{11.1}$$

$$Z_c = \frac{\eta}{2\pi\sqrt{\varepsilon_{reff}}}\ln\left(\frac{8h}{W}+0.25\frac{W}{h}\right) \tag{11.2}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-0.5} \tag{12.1}$$

$$Z_c = \frac{\eta}{\sqrt{\varepsilon_{reff}}}\left[\frac{W}{h}+1.393+0.677\,ln\left(\frac{W}{h}+1.444\right)\right]^{-1} \tag{12.2}$$

3. Implementation Techniques

Frequency Doubling Reflectenna design consists of F1 antenna, Frequency multiplying refelectenna (FMC) and mF1 reflectenan with frequency doubling capabilities. Different structure for 433MHz frequency designed and simulated. Figure 2 (a) shows 3-D gain (dBi) radiation pattern and current distribution distribution of Meander Line Monopole Antenna of 433MHz. Figure 2 (b) represents 3-D gain (dBi) radiation pattern and current distribution distribution of Meander Line Antenna of 433MHz. Figure 2 (c) shows 3-D gain (dBi) radiation pattern and current distribution distribution of Microstrip

Antenna with Cohen-Minkowski Fractal of 433MHz. Figure 2 (d) represents 3-D gain (dBi) radiation pattern and current distribution distribution of Microstrip Antenna with Triangle Fractal of 433MHz. Figure 3 shows simulation of Microstrip antenna, radiation pattern and gain of F1 Microstrip antenna for 433 MHz. After comparison of different Structure of 433 MHz antennas gain, we observed that gain of Microstrip Patch Antenna is more.

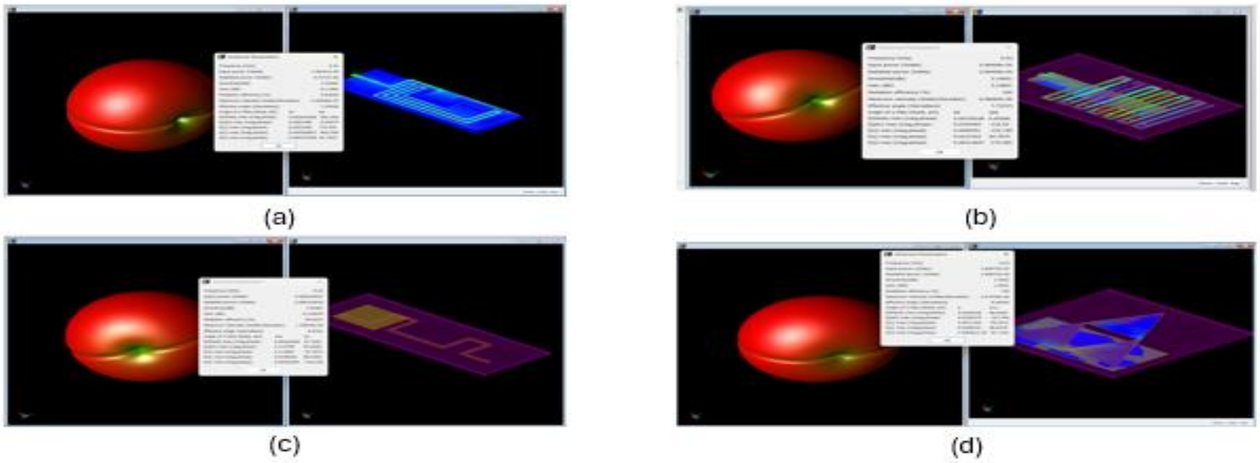


Figure 2: 3-D gain (dBi), radiation pattern and current distribution distribution of a) Meander Line Monopole Antenna, b) Meander Line Antenna, c) Microstrip Antenna with Cohen-Minkowski Fractal, d) Microstrip Antenna with Triangle Fractal of 433MHz

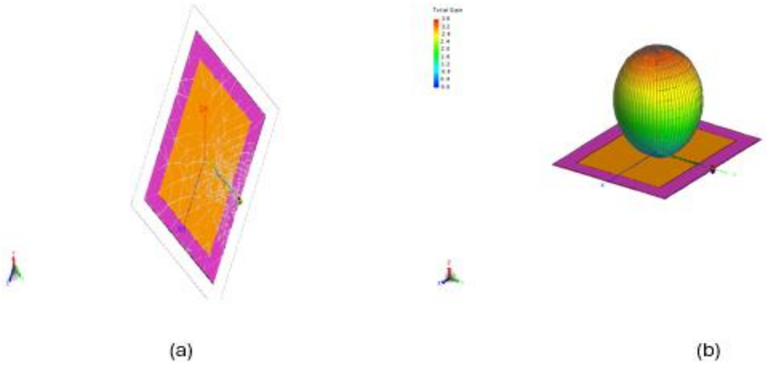


Figure 3: Simulation of a) F1 Microstrip antenna, b) radiation pattern and gain of F1 Microstrip antenna for 433 MHz

The table I represents gain of different structures of Microstrip Patch Antenna of 433MHz. The planner microstrip antenna is designed to operate at a fundamental frequency and exhibit a second-order nonlinearity, which is the key to achieving frequency doubling. F1 microstrip patch antenna serves as the primary radiating element, designed to operate at a fundamental frequency of F1. Different structure for 866 MHz frequency designed and simulated. Figure 4 (a) shows 3-D gain (dBi) radiation pattern and current distribution distribution of Meander Line Monopole Antenna of 866 MHz. Figure 4 (b) represents 3-D gain (dBi) radiation pattern and current distribution distribution of Meander Line Antenna of 866 MHz. Figure 4 (c) shows 3-D gain (dBi) radiation pattern and current distribution distribution of Microstrip Antenna with Cohen-Minkowski Fractal of 866 MHz. Figure 4 (d) represents

3-D gain (dBi) radiation pattern and current distribution distribution of Microstrip Antenna with Triangle Fractal of 866 MHz.

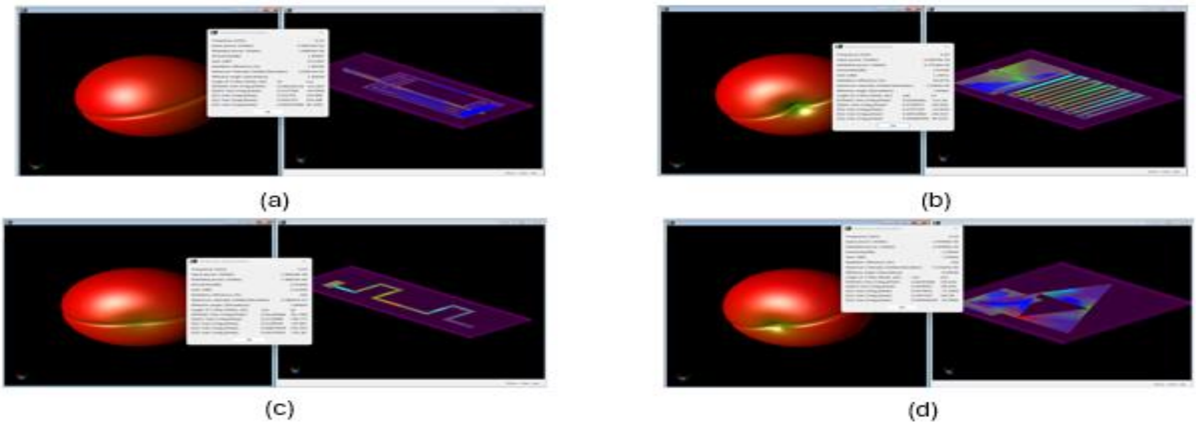


Figure 4: 3-D gain (dBi), radiation pattern and current distribution distribution of a) Meander Line Monopole Antenna, b) Meander Line Antenna, c) Microstrip Antenna with Cohen-Minkowski Fractal, d) Microstrip Antenna with Triangle Fractal of 866 MHz

Table I: Represents gain of different structures of Microstrip Patch Antenna of 433MHz

Antenna Structure	**Gain (dBi)**
Meander Line Monopole Antenna	2.52
Meander Line Antenna	2.11
Microstrip Antenna with Cohen-Minkowski Fractal	1.94
Microstrip Antenna with Triangle Fractal	1.93
Microstrip Patch Antenna	3.50

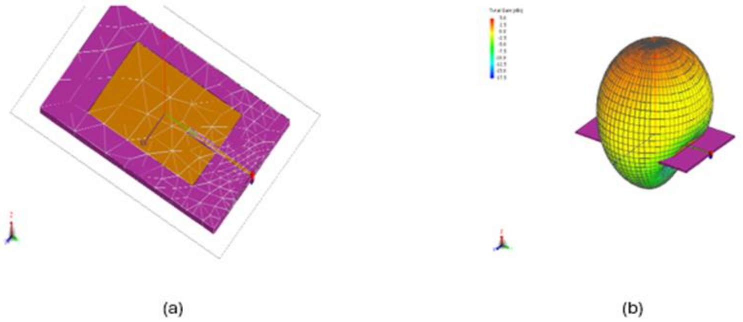


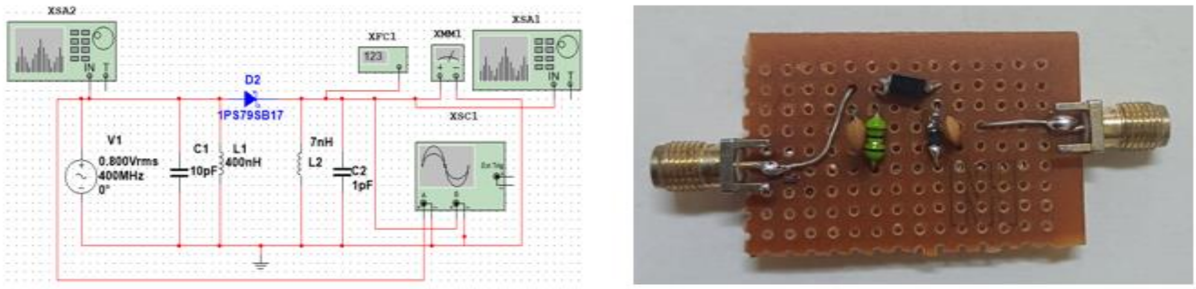
Figure 5: Simulation of a) Microstrip antenna for 866 MHz, b) Radiation pattern and gain of mF1 Microstrip antenna for 866 MHz by simulation

Figure 5 shows simulation of Microstrip antenna, radiation pattern and gain of F1 Microstrip antenna for 866 MHz. After comparison of different Structure of 866 MHz antennas gain, we observed that gain of Microstrip Patch Antenna is more. The following table II represents the gain of different structures of Microstrip Patch Antenna of 866 MHz. mF1 Reflectenna is used to enhance the radiation pattern and redirect the radiated signal, improving the efficiency of signal transmission.

Table II: Represents gain of different structures of Microstrip Patch Antenna of 866MHz

Antenna Structure	Gain (dBi)
Meander Line Monopole Antenna	1.99
Meander Line Antenna	1.53
Microstrip Antenna with Cohen-Minkowski Fractal	2.01
Microstrip Antenna with Triangle Fractal	1.93
Microstrip Patch Antenna	5.10

The design parameters, including patch dimensions, metamaterial properties, and reflecting surface characteristics, are optimized for maximum performance in IoT sensor networks. The performance of the frequency doubling reflectenna is evaluated using electromagnetic simulation software, such as ADS, CADFEKO. The following metrics are considered: Frequency Doubling Efficiency, Bandwidth, Radiation Pattern, Return Loss, Size and Compactness etc.



(a) (b)

Figure 6: a) Simulation circuit diagram of frequency doubling system using Schottky diode, b) Hardware implementation of frequency doubler using Schottky diode

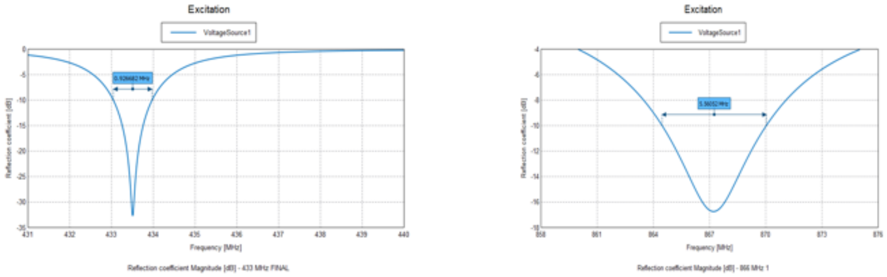
(a) (b)

Figure 7: Hardware implementation of a) F1 Microstrip antenna for 433 MHz, b) mF1 Microstrip antenna for 866 MHz

FMC Converting the fundamental frequency to the doubled frequency. Figure 6(a) shows simulation circuit diagram of frequency doubling system using Schottky diode. Figure 6(a) are implemented in NI Multisim. Figure 6(b) Shows Hardware implementation of frequency doubler using Schottky diode. Figure 7 (a) represents Hardware implementation of F1 Microstrip antenna for 433 MHz. Figure 7 (b) represents Hardware implementation of mF1 Microstrip antenna for 866 MHz.

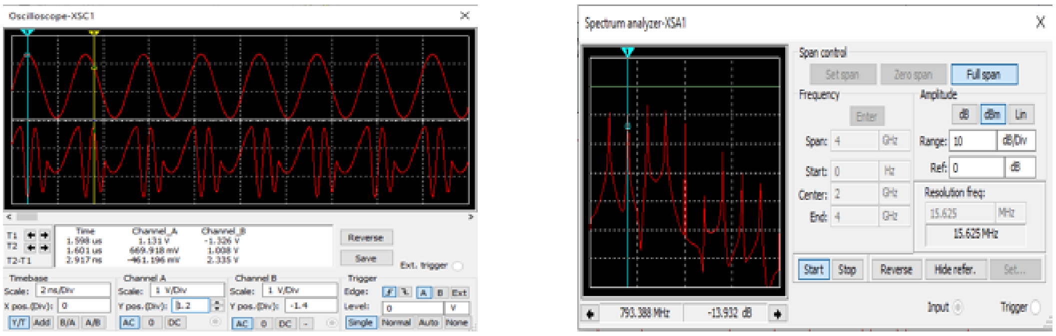
4. Result and Analysis

Simulation results show that the proposed frequency doubling reflectenna exhibits key characteristics. Frequency Doubling reflectenna effectively doubles the input frequency. The antenna maintains a directional radiation pattern with a gain of 5.1 dB for the doubled frequency. The antenna provides a broad bandwidth for both the fundamental and doubled frequencies, ensuring reliable communication. A return loss of below -10 dB is achieved at both frequencies, indicating efficient signal transmission. The antenna dimensions are suitable for integration into IoT sensor nodes. Figure 11(a) shows hardware fabrication and implementation of frequency multiplying Reflectenna. Figure 8(a) represents simulated reflection coefficient of F1 Microstrip antenna for 433 MHz. Figure 8(b) represents simulated reflection coefficient of mF1 Microstrip antenna for 866 MHz. Figure 9(a) shows Input and Output waveform of frequency Doubler system using Schottky diode. Figure 9(b) shows output power -13.932 dBm of frequency doubler system using Schottky diode.



(a) (b)

Figure 8: Reflection coefficient of a) F1 Microstrip antenna for 433 MHz, b) mF1 Microstrip antenna for 866 MHz by simulation



	Time	Channel_A	Channel_B
T1	1.598 us	1.131 V	-1.326 V
T2	1.601 us	669.918 mV	1.008 V
T2-T1	2.917 ns	-461.196 mV	2.335 V

Timebase
Scale: 2 ns/Div
X pos.(Div): 0

Channel A
Scale: 1 V/Div
Y pos.(Div): 1.2

Channel B
Scale: 1 V/Div
Y pos.(Div): -1.4

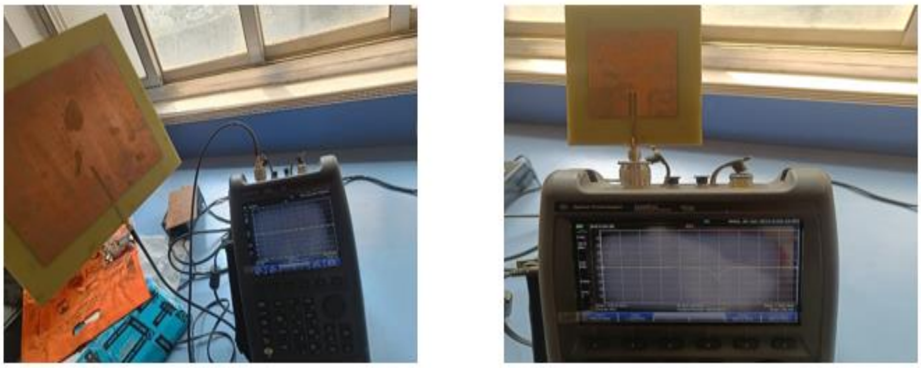
Trigger
Level: 0 V

Span: 4 GHz
Start: 0 Hz
Center: 2 GHz
End: 4 GHz
Range: 10 dB/Div
Ref: 0 dB
Resolution freq: 15.625 MHz
15.625 MHz
793.388 MHz -13.932 dB

(a) (b)

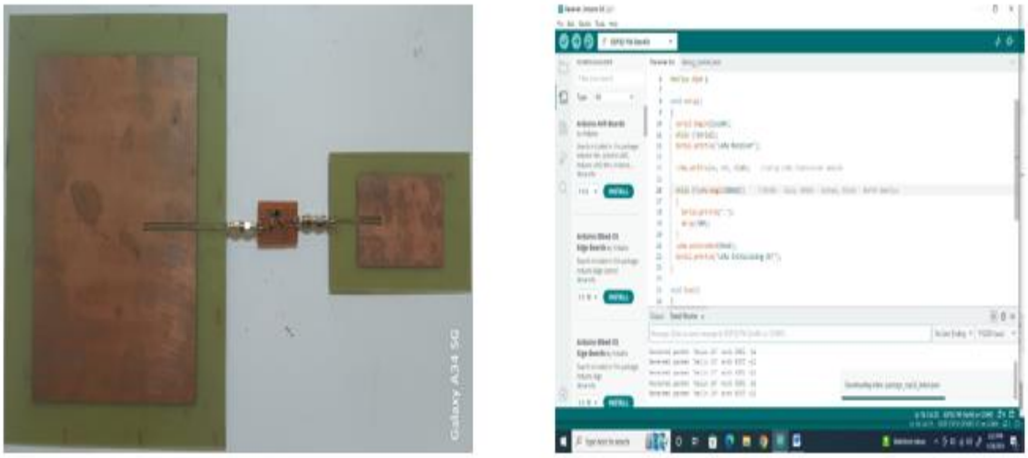
Figure 9: a) Input and Output waveform of frequency Doubler system using Schottky diode, b) Output power (dBm) of frequency Doubler system using Schottky diode.

A prototype of the frequency doubling reflectenna is fabricated and tested to validate the simulation results. The practical measures align with the simulation, demonstrating that the reflectenna provides enhanced signal strength and frequency doubling capabilities. The measured gain at the doubled frequency is approximately 5.1 dBi, with an efficiency of 83% in converting the signal. The proposed frequency doubling reflectenna outperforms traditional single-frequency antennas in terms of signal strength, bandwidth, and compactness. It also offers better energy efficiency by reducing the need for multiple frequency channels in IoT networks, thereby conserving power and enhancing the longevity of battery-operated devices. Figure 10(a) shows fabricated reflection coefficient of F1 Microstrip antenna for 433 MHz. Figure 10(b) shows fabricated reflection coefficient of mF1 Microstrip antenna for 866 MHz. Figure 11(b) shows ESP32 With 866MHz RFM95W Lora Output. Table III represent Hardware output power for frequency doubling reflectenna system.



(a) (b)

Figure 10: Fabricated reflection coefficient of a) F1 Microstrip antenna for 433 MHz, b) mF1 Microstrip antenna for 866 MHz



(a) (b)

Figure 11: a) hardware fabrication and implementation of frequency multiplying Reflectenna , b) ESP32 With 866MHz RFM95W Lora Output

Table III: Hardware output power for frequency doubling reflectenna system

Operating Frequency at F1 Antenna	Distance between Tx and Rx	Operating Frequency at mF1 Antenna	Output Power
433MHz	100cm	866MHz	-20dB
433MHz	200cm	866MHz	-28dB
433MHz	300cm	866MHz	-36dB
433MHz	400cm	866MHz	-45dB
433MHz	500cm	866MHz	-55dB
433MHz	600cm	866MHz	-61dB
433MHz	700cm	866MHz	-70dB
433MHz	800cm	866MHz	-78dB
433MHz	900cm	866MHz	-86dB
433MHz	1000cm	866MHz	-89dB

5. Conclusion

This paper describes the design, analysis, and implementation of a compact planar frequency doubling reflectenna for IoT sensor networks. The proposed reflectenna achieves efficient signal conversion, broad bandwidth, and directional radiation, making it an ideal candidate for future IoT communication systems. The integration of frequency doubling with a compact reflectenna design offers a significant advancement in antenna technology, improving energy efficiency and communication range in IoT networks. The gain of F1 antenna is 3.5 dBi and gain of mF1 antenna is 5.10dBi. Output power for frequency doubling reflectenna system observed -20dB, -89dB for distance between Tx and Rx at 100 cm, 1000cm respectively. Future work will focus on further optimization of the reflectenna design and the exploration of additional nonlinear materials to enhance the overall performance. Further integration of the reflectenna with practical IoT sensor nodes and real-world network deployment to validate its performance in dynamic environments. Exploring methods to reduce the size further while maintaining performance, making the antenna more suitable for ultra-compact IoT devices.

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