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Design and Implementation of Quad Element Planar Monopole MIMO Antenna for Industrial Parameter Monitoring Systems using LoRa WAN

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Abstract

In this manuscript a stair case shaped planar monopole antenna for LoRa WAN application is proposed. The proposed unit element produces peak resonant at 2.41GHz with the operating bandwidth of 150MHz. The proposed structure has been constructed on FR4 substrate of thickness of 1.6mm with the dimension of 15 x24mm^2. The equivalent electrical dimension is 0.12 λ_o x 0.19 λ_o. A quad element MIMO structure has been constructed using the designed unit cell. The physical dimension of the MIMO array is 39 x 39 mm^2 and electrical equivalent is 0.31λ_o x 0.31 λ_o. The mutual coupling between the adjacent elements are <-18 dB. The measured Envelope Correlation Coefficient (ECC) of the antenna is < 0.05, gain is 1.17dBi and efficiency is 76.4%.

Keywords: Monopole Antenna, Quad Element, Industrial Parameter, LoRa, 2.4 GHz

1. Introduction

The New age wireless applications like WLAN, WIFI, and Blue Tooth requires a planar antenna with low cost, electrically small, mechanically rigid and easily integrable configuration [1]. Low profile antennas are attracted towards short range wireless communication applications because of its compact nature. Electrically small antennas can be realized by using meandering line technique, reactive loading, high dielectric substrate and composite left and right handed meta-materials (CLRH). But the limitations of compact profile antennas are increased quality(Q) factor, reduced antenna efficiency and needs complex impedance network [2]. In this work highly sensitive antenna working at 2.45 GHz with good efficiency has been used for human identification [3]. As per industrial Telecommunication Union (ITU) recommendation, 2.4-2.5 GHz band is known as ISM(Industrial, Scientific and Medical) band, can be used for medical and Wireless applications[4-8]. The 2.4 GHz ISM band is globally available for unlicensed use, making it attractive for industrial applications. This means that organizations can deploy wireless devices working at 2.4GHz, without the need for costly spectrum licenses, reducing operational costs. Now a days planar monopole MIMO antennas are widely used in communication applications because of its ability to overcome multipath fading by receiving signals from more than one direction [9-11].

LoRa is an open network standard on the physical layer of LoRa WAN, can be used in several applications such as planning of smart cities, environmental monitoring and smart farming etc [12, 13].In recent years there is a huge surge in the planning of smart cities. Due to this there is a need for wireless connection between the objects. In wireless communication applications maintaining the privacy of the data is an important concern. Industrial machine parameter monitoring systems requires a wireless sensor network (WSN) to transfer data in real time with reliability [14]. There are two major categories of wireless networks are available. One is short range network and another one is long range network (LPWAN) [15].

Short distance network includes WiFi, Zig bee, blue tooth and Z-wave, consumes low power and allows data transfer at lower bit rates. It can able transmit datas, up to 1Km only. Mainly used in indoor applications and home automation systems [16]. Long range networks such as, sigfox, LoRaWAN, can able to transmit datya up to 2Kms, in cities and more than 45 kilometres in the suburban areas. It consumes low power and can able to transmit at a rate of 0.3 to 50 Kilobits per second.

As per UN report, the density of population increases rapidly in the urban areas. Most of the countries are planning for the development of smart cities to address the challenges arising due to urbanization. Throughout the world government official agencies, corporations and municipalities are planning to deploy WAN to extract and analyse data to provide facilities like smart energy distribution, mass transportation, health care, water distribution system, waste management system and E-governance. LoRa will be the suitable solution for migrating towards smart city adoption. LoRa WAN networks can support a large number of devices, making them suitable for industrial applications that require the deployment of numerous sensors and actuators. The network architecture is designed to accommodate scalability while maintaining efficient data transmission.The key advantages of using LoRa is easy to integrate, low power consumption and easy to establish a communication to network server [16]. LoRa is a proven technology that can be used in industry environment due to its low power consumption and immune to interference from other sources [17, 18].

In this research article, a quad element MIMO antenna for industrial parameter measuring system is proposed. This

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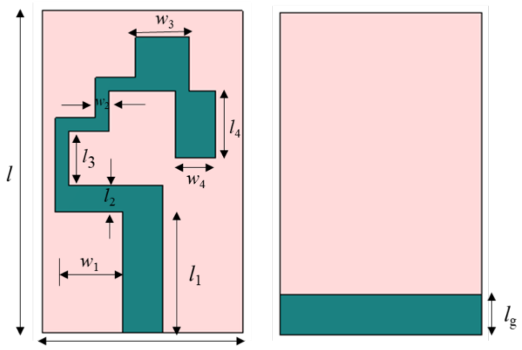
article is divided into five sections. Introduction of this work is given in section 1, Antenna design stages is elaborated in section 2, Obtained results has been discussed in section 3, In section 4 deals real time implementation of the antenna, conclusion of work is given in section 5.

2. Antenna Design

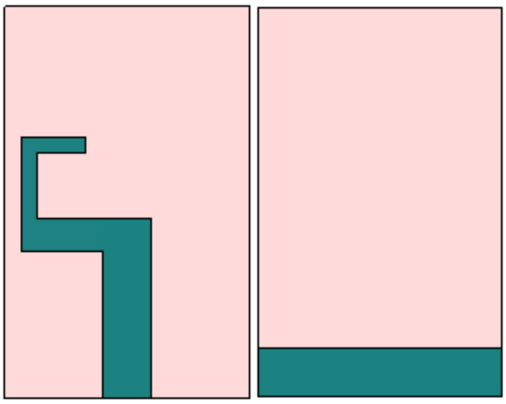
The proposed narrow band monopole antenna has been designed on FR4 dielectric substrate with the height of 1.6mm, relative permittivity ε_r= 4.3, and the radiator in the front plane is fed by microstrip line having width 3mm to match 50 ohm impedance. The proposed unit element antenna has the dimension of 15 mm x 24 mm x 1.6 mm as depicted inn figure 1.

The final structure of the antenna has been obtained after four stages of evolution as shown in figure 2. The reflection coefficient characteristics for various stages of evolution is plotted in figure 3. In stage 1 "C" shaped stub line is used as primary radiator in the front plane and rectangular shaped partial ground structure in the rear side. With this configuration antenna does not produces any resonance frequency. In the second stage of evolution inverted "7" shaped stub is appended on the top of fundamental radiator, thereby antenna produces resonance at 3.5 GHz. The resonance frequency will be shifted to lower side by increasing the circumference of the current path. At the end of 3rd stage of evolution antenna produces peak resonance at 2.8GHz. Further the resonant frequency is shifted to bottom side increasing the inductive loading of the radiator. In fourth stage of evolution inductive loading is achieved by adding the rectangular shaped patch to the radiator, thereby antenna resonates at 2.41 GHz.

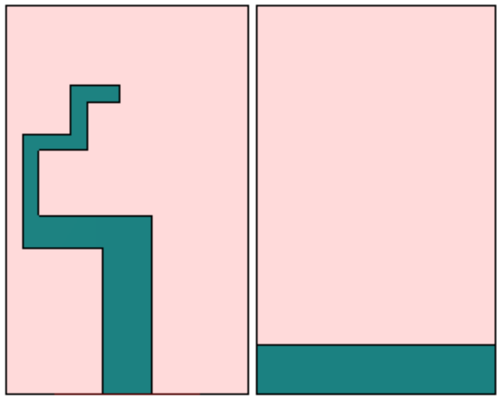


(a) (b)

Fig. 1. Proposed Compact Monopole Antenna. (a) Radiator (b) Ground. l= 24mm, w=15mm, l_1=11mm, l_2= 2mm, l_3=7mm , l_4= 5mm, l_g=4mm , w_1= 4mm, w_2= 1mm, w_3=4mm , w_4= 3mm.



(a)



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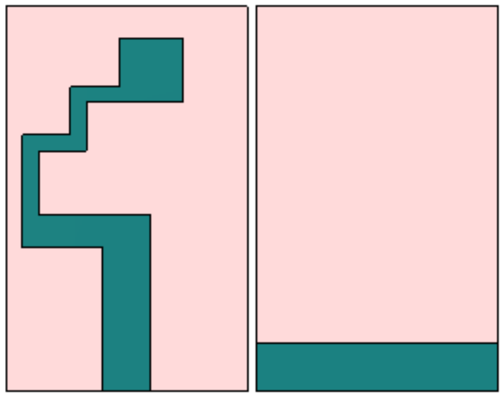
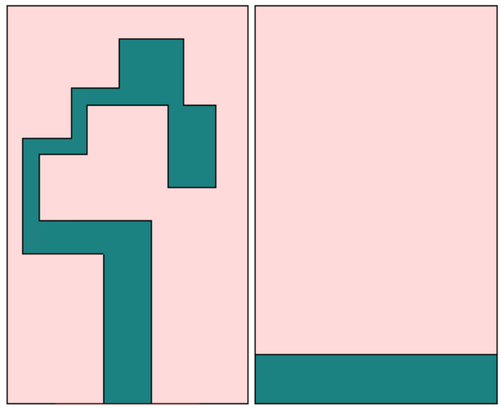


(c)



(d)

Fig. 2. Stages of Evolution of Proposed Monopole Antenna. (a) Stage1 (b) Stage 2 (c) Stage 3 (d) Stage 4

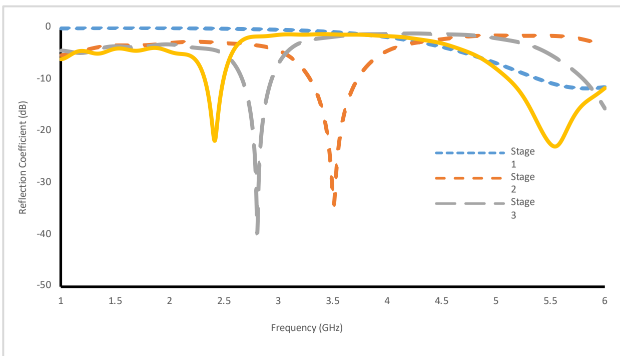


Fig. 3. Reflection Coefficient Characteristics of various stages of Evolution

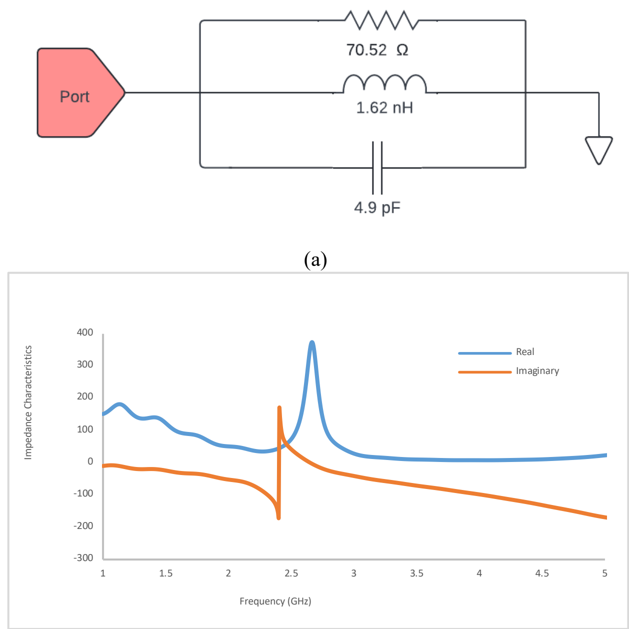


Fig. 4. (a) Equivalent Circuit (b) Impedance Characteristics

To get the insight view of theoretical background of the antenna, an electrical equivalent circuit model has been developed and impedance characteristics are plotted. Fig 4 (b) shows the real and imaginary impedance characteristics of the antenna [19, 20]. Exactly at resonance frequency (2.4 GHz) the real impedance value is 50 Ω and imaginary impedance is closer to zero and then moves from low to high, resulting an equivalent circuit with parallel RLC combination. The R, L & C values are expressed in terms of resonance frequency and characteristics impedance is given in (1), (2) & (3).

$$R = \frac{2Z_o}{\sqrt{\frac{1}{|S_{11}|^2}\left(2Z_0\left(C\omega_0 - \frac{1}{L\omega_0}\right)\right)^2 - 1}} \quad (1)$$

$$C = \frac{\omega_c}{2Z_o(\omega_o^2 - \omega_c^2)} \quad (2)$$

$$L = \frac{1}{\omega_o^2 C} \quad (3)$$

The gain and efficiency plot of the antenna is shown in figure 5. It is observed that, at resonance frequency the gain of the antenna is 1.17dBi with an efficiency 76.4%.

2.1. MIMO Antenna Design

A quad element MIMO antenna has been constructed for the effective reception of signals from all directions. The MIMO antenna consists of four unit elements placed orthogonal to each other and has the dimension of 39x39 mm^2 as shown in figure 6. The inter-element spacing between the antennas is 4.9mm (0.08 λ_o electrical equivalent). When the unit elements are placed closer problem of mutual coupling arises, which may lead to higher ECC. It is necessary to maintain the ECC value below the threshold level of 0.5. For this proposed MIMO antenna the measured mutual coupling value is less than 0.05 at the resonant frequency.

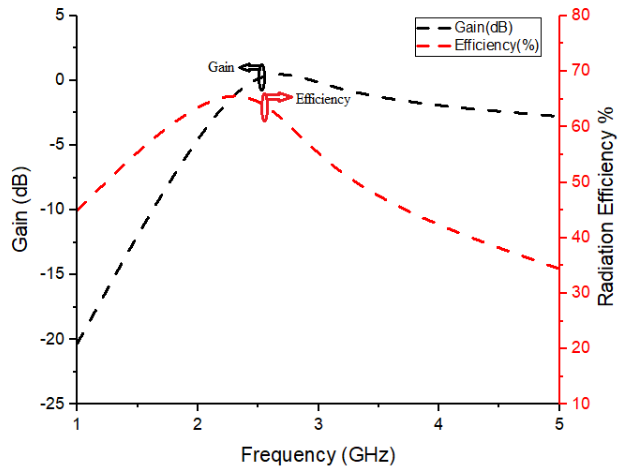


Fig. 5. Measured Gain and Efficiency of the antenna

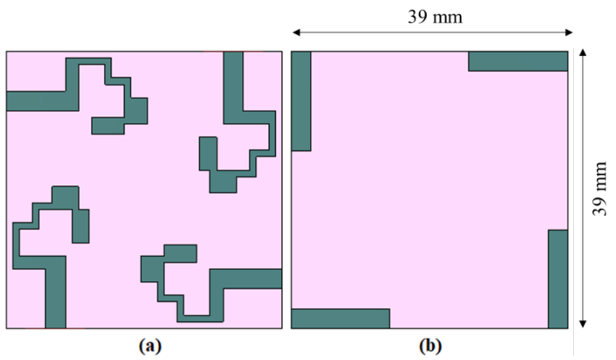
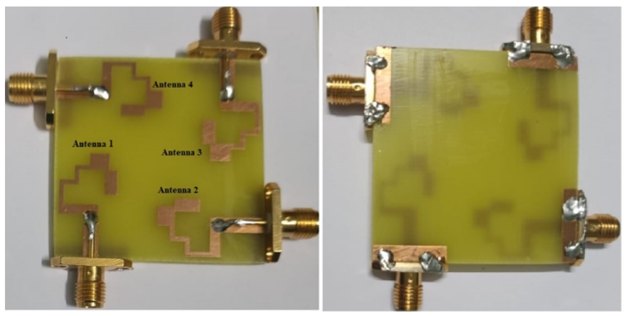


Fig. 6. Quad Element MIMO Antenna (a) Front View (b) Rear View

3. Results and Discussion

To ensure the reliability of the proposed antenna, a four port MIMO antenna has been fabricated as shown in fig. 7 and its performance was tested using vector network analyser. The measured mutual coupling characteristics of the fabricated prototype are shown in fig. 8. At the peak resonant frequency the mutual coupling between the antenna elements are less than the -18db.



(a) (b)

Fig. 7. Fabricated Quad Element MIMO Antenna (a) Front View (b) Rear View

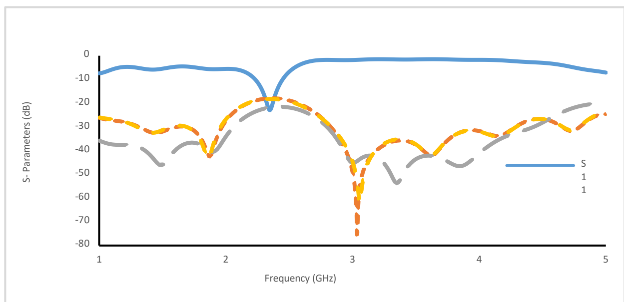


Fig. 8. Measured Reflection (S_{11}) and Mutual Coupling Coefficient (S_{12}, S_{13}, S_{14}) Characteristics

3.1. Radiation Pattern

The radiation pattern reveals the antenna's directivity, which is a measure of how well an energy is concentrated in a particular direction. The radiation characteristics of the antenna is measured in anechoic chamber as shown in fig. 9. Figure- 10 illustrates the radiation characteristics of the MIMO antenna at 2.4 GHz. From the E-plane and H-plane radiation characteristics of the antenna, it is evident that antenna produces omnidirectional radiation pattern. The orthogonal placement of the unit elements ensures the polarization and pattern diversity. Due to orthogonal placement of antenna elements, loss occurred in one direction is equalized by another antenna in the MIMO configuration.

Fig. 9. Radiation Pattern Measurement in Anechoic Chamber

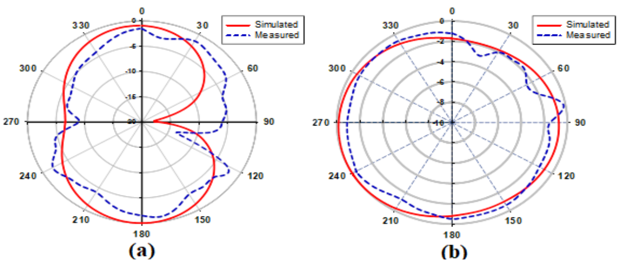


Fig. 10. Radiation Pattern of the proposed antenna (a) E- plane Pattern (b) H- plane Pattern

3.2. Envelope Correlation Coefficient (ECC)

The envelope correlation coefficient (ECC) is an important parameter in multiple-input, multiple-output (MIMO) antenna systems. MIMO systems use multiple antennas at both the transmitter and receiver to improve communication performance by exploiting spatial diversity and to mitigate the effects of multipath fading. The ECC quantifies the correlation between the envelopes of the signals received by different antennas in a MIMO system. In general the minimum and the maximum range of ECC lies between 0 and 1. However effects of ECC can be tolerated till 0.5.ECC values of the MIMO antenna is plotted in fig 11. In this MIMO configuration port1 is kept as reference port and ECC values of the other ports (2,3,4) are measured with respect to port1. The ECC of the proposed antenna is calculated using far field equation (4). At the resonant frequency the ECC value is quite low (<0.05), than the permitted level(<0.5). From the lower ECC value it is clear that MIMO antenna performance metrics such as channel capacity, diversity gain are not affected the by mutual coupling effect.

$$\rho_e = \frac{\left|\iint\left[\vec{F_1}(\theta,\varphi).\vec{F_2}(\theta,\varphi)\right]d\Omega\right|^2}{\iint\left|\vec{F_1}(\theta,\varphi)\right|^2 d\Omega \iint\left|\vec{F_2}(\theta,\varphi)\right|^2 d\Omega} \quad (4)$$

The MIMO configuration of the antenna increases the Signal to Noise Ratio (SNR) of the system. The SNR improvement is measured by the parameter called diversity gain (DG) and it is estimated as 9.75dB.

$$DG = 10 \text{ x } \sqrt{1-|\rho_e|^2} \quad (5)$$

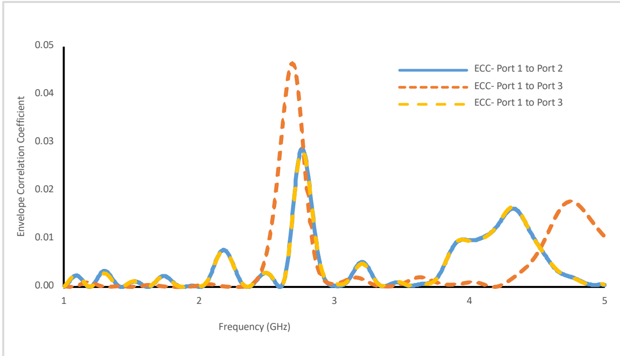


Fig. 11. Measured Envelope Correlation of the proposed antenna

4. Real Time Implementation of Quad Element MIMO Antenna

LoRa WAN finds space in many hot areas such as asset tracking, smart home, cold chain monitoring, equipment tracking, irrigation management, leak detection, logistics management, parking space management, pest monitoring, environmental monitoring, soil water monitoring, temp monitoring etc.

In smart home applications, the light intensity and temperature inside the home are to be monitored and obtained values to be transmitted to the controller unit. Based on the received values further action will be initiated. Similarly in agricultural fields it is necessary to maintain soil moisture and PH level. These parameters can be monitored and controlled with the help of LoRa WAN enabled network.

The temperature, pressure and light intensity are the crucial parameters in the industry environment. These parameters should be maintained in the certain level for the proper operation of the machineries.

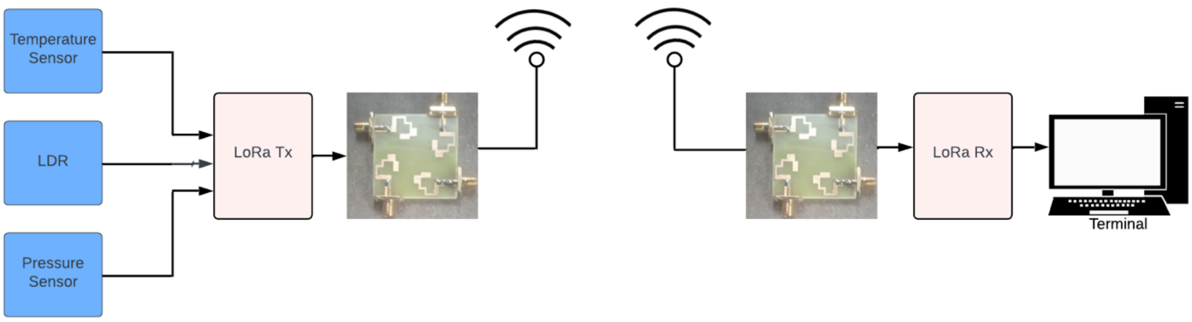


Fig. 12. System Architecture for the proposed industrial parameter Measurement Application

The industrial parameter measurement setup is shown in fig. 13. The setup has three transmitting antennas and one receiving antenna. The transmitting antennas are connected with three different sensors (Temperature, Light Intensity and Pressure) through LoRa transmitter and the single receiving antenna is connected to the monitor through LoRa receiver. The measured parameters are continuously monitored and if there is abnormality witnessed, then the immediate action will be taken to keep the parameters in the required level or switching off the machineries for a particular time period till the parameter comes to permitted level.

As the antenna is fabricated on FR4 substrate it can work optimally from -41°C to 130°C and also it is working at 2.4GHz unlicensed band, the interference from other electromagnetic sources may affect the antenna's performance. If we use the unit element antenna for LoRa WAN applications, the range of coverage may be comparatively less. By deploying the MIMO configuration, the line of sight limitation and range of coverage is significantly improved.

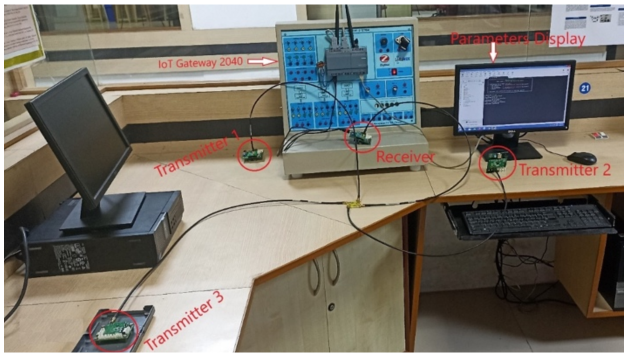


Fig. 13. Experimental Setup for Industrial Parameter Measurement

Table 1. Comparison of reported antennas with proposed antenna in terms of performance metrics

Ref	No of elements	Dimension (mm², λo x λo)	Inter-element spacing (mm, λo)	Isolation (dB)	ECC	DG (dB)	Real Time Implementation
[5]	2	76.8 x 57.8, 0.63λo x 0.47λo	5.75, 0.046 λ	> 15	< 0.000027	9.9	×
[6]	2	40 x 38.5, 0.39λo x 0.32λo	12.9, 0.105 λ	> 25	< 0.3	-	×
[7]	2	38.2 x 95.994 0.31λo x 0.78λo	17, 0.14 λ	> 24	< 0.019	9.996	×
[8]	2	65.25 x 65.25, 0.53λo x 0.53λo	-	> 17	< 0.01	10	×
[9]	4	44 x 24, 0.36λo x 0.2λo	-	> 10	< 0.015	8.85	×
[10]	4	70 x 70, 0.57λo x 0.57λo	-	> 21	< 0.034	9.92	×
Proposed	4	0.39 x 0.39, 0.31λo x 0.31λo	7.9, 0.064 λ	> 18	< 0.05	9.75	✓

5. Conclusion

The quad element planar MIMO antenna for wireless application has been presented. The designed antenna produces peak resonance at 2.4GHz. The proposed antenna delivers gain of 1.17dB with the efficiency of 76.4%. A four port MIMO antenna has been constructed by placing unit elements orthogonal to each other. The mutual coupling between the antenna elements is less than -18db, ECC <0.05 and DG is 9.75dB. The designed antenna produces nearly omni directional radiation pattern at 2.4 GHz. To verify the practical usage of the antenna, it has been used in LoRa WAN as transmitter and receiver and the data are received successfully. So, this antenna can be used in LoRa WAN for industrial parameter measurement applications.

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