Design and Analysis of a Compact Meander Line Monopole Antenna with Modified Feeding System for CubeSat Satellite

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Abstract: Many universities were involved in projects related to the design, assembly and operation of nanosatellite (CubeSat) to increase the experience level of researchers and students. The CubeSat is a concept emerged after year 2000 with small size and cubic shape. The antenna is an important component that is used to define the CubeSat size and to provide communication with the ground station. This paper introduces the design and implementation of a miniaturized printed Meander line monopole antenna with modified feeding system having a volume of (80mm×45mm×1.67mm) and operating at 439 MHz center frequency. The antenna is fabricated on FR-4 substrate with dielectric constant of ($\varepsilon r = 4.3$) and thickness of 1.6 mm. The proposed antenna consists of symmetrical meandered lines and thin shorting stubs between these lines to have a maximum size reduction and to be appropriate for the CubeSat size. The comparison between the simulation and measurement results are provided. A reflection coefficient of -16.5 dB and bandwidth of 7 MHz were obtained at 439MHz. The antenna has an efficiency of 80% at this frequency.

1 INTRODUCTION

The small satellites are widely used by the universities especially after the year 2000 to increase the experience of students and space researchers. These satellites are classified into mini, micro, nano and pico satellites. The CubeSat belongs to the picosatellite class. A one unit (1U) CubeSat is the standard size for the CubeSat having a dimensions of 10cm×10cm×10cm and a weight no more than 1.33Kg(S.Gao, 2009). The CubeSats are used for various purposes such as communications, imaging and weather forecasting, military use such as spying and to provide secure communication link (F. EM Tubbal, 2015).

The antenna is one of the most important components for the CubeSat as it provides the connection with the ground station and ensures that the CubeSat does not lost in space. The communication system of CubeSat is a pivotal system as the antenna of this system should realize different tasks such as telemetry, tracking and command (TTC), global positioning system (GPS), global navigation system (GNS), payload data and intersatellite cross links (Y. Yao, 2016).

The Ultra High Frequency (UHF) band is highly used for the CubeSat, especially the frequency range 420-450 MHz, because the International Telecommunication Union has allocated this frequency band as the International satellite band (T. Alam, 2018).

The CubeSat required antenna with wide coverage or near omnidirectional radiation pattern to be suitable for the TTC application of CubeSat. Several types of antennas have been used as CubeSat antennas such as microstrip patch, monopoles, dipoles, helices and PIFA etc. Microstrip patch antennas do not satisfy the omnidirectional radiation pattern and will have a large size at the allocated frequency band for the CubeSat. Monopoles and dipoles are satisfy the omnidirectional radiation pattern required for the TTC application but they are required a deployment mechanism to be released out of the CubeSat. These antennas are rolled around the satellite before the deployment (Mehul K. S, 2016).

The antennas that required mechanical deployment may increase the mission failure if the

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antenna does not released out of the satellite. Several CubeSat missions were failed as a result of antenna deployment failed (Ogherohwo, 2015).

The small size of CubeSat makes it very difficult to design antenna that does not need a mechanical deployment, having a small size to be suitable for the CubeSat size and does not cover all the CubeSat face. The challenges was to design a planer antenna operating at the allocated frequency band (420-450) MHz with maximum size reduction and having a wide coverage radiation or omnidirectional radiation required for the TTC application of CubeSat.

Several miniaturization techniques are used to reduce the antenna size such as: the slots in the radiating patch, the use of high permittivity materials, shorting pins and meander line antennas. Meander line antennas are perfect choice for the CubeSat as it is a transformation for the monopoles and dipoles antennas and it is a one type of the microstrip antennas. By meandering the patch the path of the flowing surface current will be increased and this will lowering the resonance frequency and makes the antenna radiates at lower frequency than the wire antenna of same length (Ogherohwo, 2015).

In this paper, a printed meander line monopole antenna with modified feeding system is represented to remove the need for deployment mechanism and to increase mission reliability. The antenna designed to fit the size of 1U and 2U Cubesat and cover less than a half of the Cubesat face which has dimensions of 80mm×45mm×1.67mm. The antenna is fabricated on FR-4 substrate with dielectric constant of (εr = 4.3) and thickness of 1.6 mm. The antenna operates at the licensed lower UHF band 435.5 – 442.5 MHz.

2 ANTENNA DESIGN REQUIREMENTS FOR CUBESAT

The CubeSat communication system effectiveness is determined by the link budget and one of the important components is the performance of the antenna. The size of the antenna on the CubeSat structure is dependent on the operating frequency. The CubeSat antenna must realize different functions which are guaranteed in each CubeSat communication mission and these functions are (The CubeSat Program, 2009):

- Transmit a tracking signal which allows the ground stations to follow the position of the satellite.
- Download telemetry data to the ground station and receive commands.

For CubesSat applications the following limitations and requirements should be considered in the design of the CubeSat antenna:

- According to NASA regulations, the dimensions can be selected as 1U CubeSat (10 x 10 x 10 cm3), so the antenna should compact and fit the Cubesat size.
- CubeSat antenna must have wide coverage or omnidirectional radiation for TTC purposes.
- The antenna should not cover all the Cubesat face to provide additional space for the solar panels.

3 FREQUENCY AND ANTENNA TYPE SELECTION

The International Amateur Radio Union (IARU) is an organization which is responsible for regulating the radio spectrum among radio amateurs worldwide for a better use of it and as shown in Table 1. The frequency should be one of the regulated VHF, UHF or S-Band allocated for CubeSat missions (N. Mohi, 2015 and NASA Group, 2014).

Table 1: Frequency allocation for satellite.

	Option 1	Option 2	Option 3	Option 4
Frequency Band (MHz)	144-146	420-450	1260-1270	2400-2450

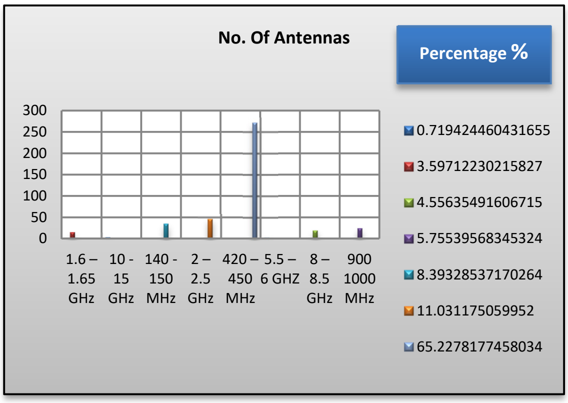

Figure 1: The most frequency band used in Cubesat.

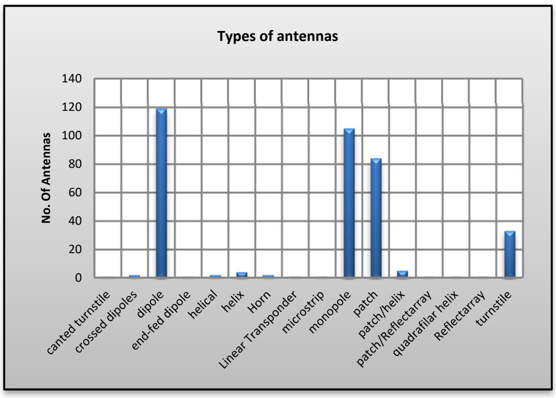

Figure 2: The most antenna type used for Cubesat.

Based on the collected information and standards for the CubeSat deployed in orbit during the period 2000 - 2019, the analysis of these data lead to build the Figs. (1) and (2). These Figures help us to select the frequency band and the antenna type as follows:

- According to Figure 1, most of the Cubesat antenna operates at the licensed lower UHF band (420 – 450 MHz).
- According to Figure 2, most of the Cubesat antenna uses dipole or monopole type.

4 MEANDER LINE ANTENNA

The meander line antenna can be designed by a set of horizontal and vertical lines and the combination of these lines will form the turns of meander line antenna as shown in Fig.3. The meander line antenna is a transformation of monopole and dipole antenna and was proposed to reduce antenna size by bending the monopole into right angle pends and these pends will form the antenna. The idea of a meander line antenna is to fold the conductor back and forth to make the antenna size smaller (Ogherohwo, 2015 and M. J. Ma, 2010).

Figure 3: Meander Line Structure.

5 PRIMARY DESIGN OF THE PROPOSED MEANDER LINE ANTENNA

The primary design of printed meander line antenna was designed using CST microwave studio. The antenna was designed depending on the equations (1), (2), (3) and the parametric study on the antenna.

The height of the substrate was found by:

$$h_s \leq \frac{0.3c}{2\pi f\sqrt{\varepsilon_r}} \tag{1}$$

The length of the patch was calculated for the equation:

$$L_p = \frac{c}{2f\sqrt{\varepsilon_{eff}}} \tag{2}$$

Where ε_{eff} the effective dielectric constant.

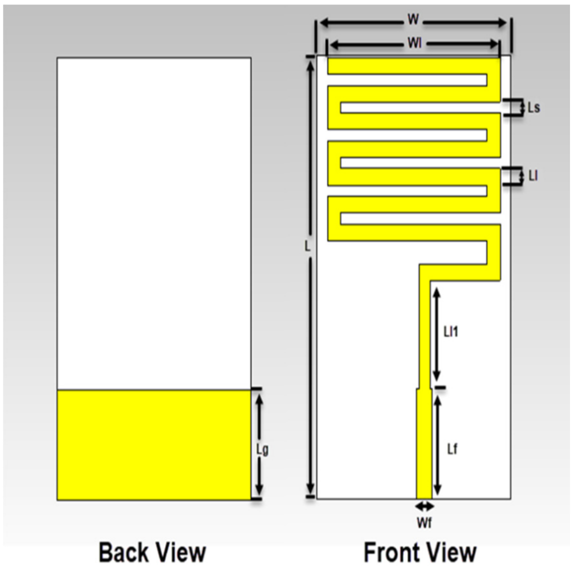

Figure 4: The primary design of meander line monopole antenna.

The antenna printed on FR-4 substrate ($\varepsilon_r = 4.3$) of a thickness h=1.6 mm and area of W×L. The feed line was chosen to have a length of Lf and width of Wf to provide the 50Ω impedance matching as shown in Fig.4.

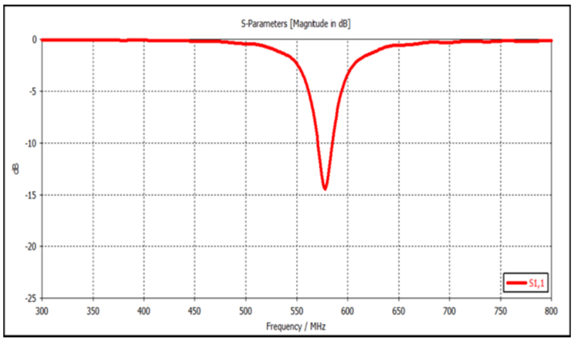

Figure 5: The return loss of the primary designed antenna.

The antenna size was appropriate for the CubeSat size as it has dimensions of 80×45 mm which is suitable and covering less than a half of the CubeSat face. The antenna operates at 578 MHz with return loss of -14.4 dB as shown in Fig. 5. The operating frequency was inappropriate for the TTC application of CubeSat which required being in the range of the licensed band (420-450) MHz. The radiation efficiency was about 87% which is suitable value for the antenna. The values of the antenna dimensions are chosen using the above equations and are shown in Table 2.

Table 2: The dimensions of the primary designed antenna.

Dimension	Description	Value(mm)
L	Total antenna length	80
W	Total antenna width	45
Ll	The meandered line width	3
Ls	The spacing between turns	2
Wl	The meandered line length	40
Ll1	The length of the line between the feed line and the antenna	22.5
Lf	The feed line length	20
Wf	The feed line width	3.14
Lg	The ground plane length	20

In order to reduce the operating frequency of the antenna to be appropriate for TTC application of CubeSat the antenna required to be modified.

6 MODIFIED MEANDER LINE ANTENNA AND THE PARAMETRIC STUDY

Some modifications were applied on the primary design in order to reduce the operating frequency to be suitable for the CubeSat application. These modifications are discussed in the below subsections:

6.1 Ground Plane Modification

In order improve the antenna radiation, radiation efficiency and to reduce the coupling between the antenna and the CubeSat structure, some modifications were applied on the ground plane. The effect of changing the ground plane dimensions are shown in Fig. 6 and 7.

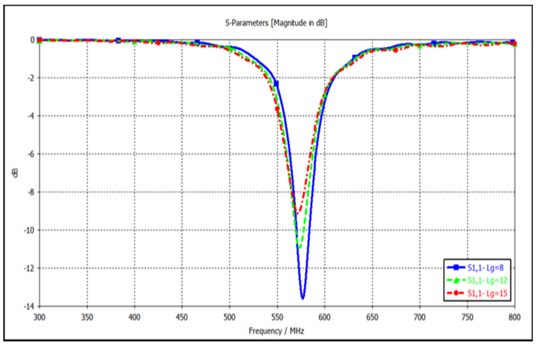

Figure 6: The effect of the ground plane length on the return loss.

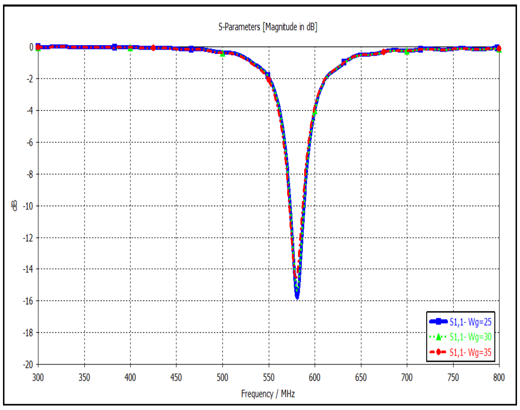

Figure 7: The effect of the ground plane width on the return loss.

6.2 Meander Lines and Feed Line Modifications

The modifications on the number of turns, the spacing between turns, the line width and the feed line were applied in order to reduce the operating frequency. Also, a thin conducting pin was added between the lined to reduce the path of the surface current and this will leads to reduce the operating frequency. The parametric study on all of these modifications was done as shown in Fig. 8, 9 and 10.

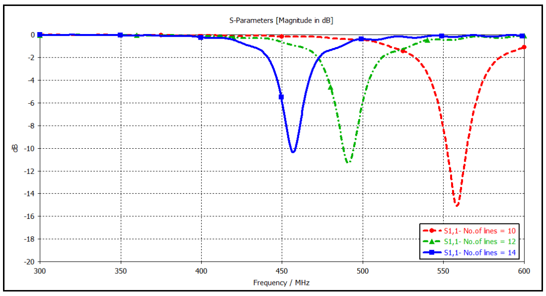

Figure 8: The effect of increasing the number of lines on the return loss.

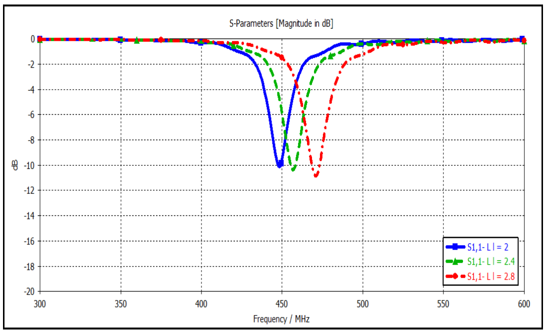

Figure 9: The effect of changing the line width on the return loss.

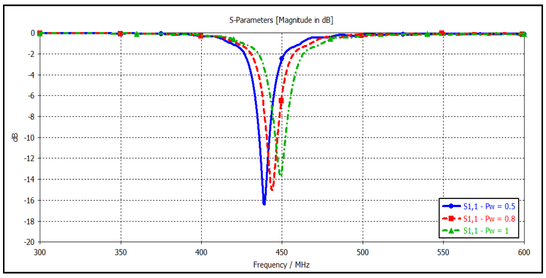

Figure 10: The effect of changing the thin pins width on the return loss.

7 PROPOSED PRINTED MEANDER LINE MONOPOLE ANTENNA WITH MODIFIED FEEDING SYSTEM

The final design for the modified printed meander line monopole antenna which composed of symmetrical meandered lines and thin conducting pins between these lines is shown in Fig. 11.

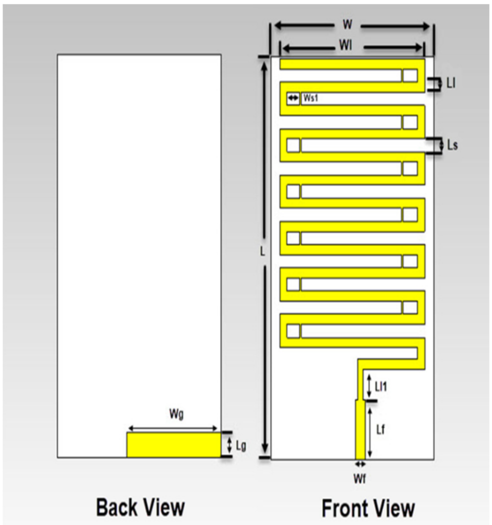

Figure 11: Proposed meander line monopole antenna.

The values of the final dimensions for the proposed antenna are shown in Table 3. From the table it can be seen that the antenna dimensions are suitable for the CubeSat size which are 80×45 mm. This size will leave additional space for the solar cells and cover less than a half of the CubeSat face.

Table 3: The final dimensions of the proposed antenna.

Dimension	Description	Value(mm)
L	Total antenna length	80
W	Total antenna width	45
Ll	The meandered line width	2
Ls	The spacing between turns	2
Ws 1	The spacing between the pins and the meandered lines	3
Wl	The meandered line length	40
Ll 1	The length of the line between the feed line and the antenna	8
Lf	The feed line length	12
Wf	The feed line width	3.14
Lg	The ground plane length	8
Wg	The ground plane width	25
Wp	The thin pins width	0.5
h	The substrate height	1.6

7.1 Simulation Results

All the simulation results of the proposed antenna were in the regulated and accepted ranges for the CubeSat application. The operating frequency and the return loss for the proposed antenna are shown in Fig.12. The proposed antenna operates at 439 MHz with a return loss of – 16.5 dB.

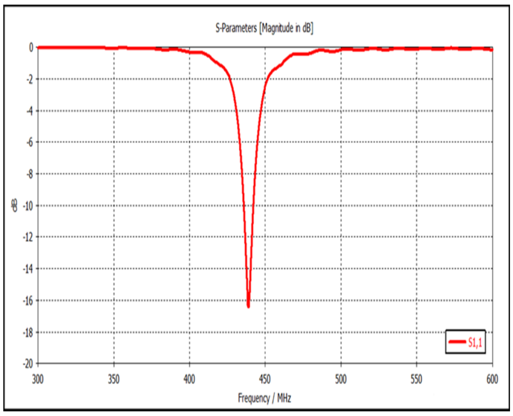

Figure 12: The return loss and operating frequency of the proposed antenna.

The proposed antenna has a good radiation efficiency of 80% at 439 MHz as shown in Fig.13. The gain of the proposed antenna was recorded as a positive value of 0.3 dB at 439 MHz for the proposed antenna. This value of gain is acceptable value as the TTC application does not required an antenna with high gain.

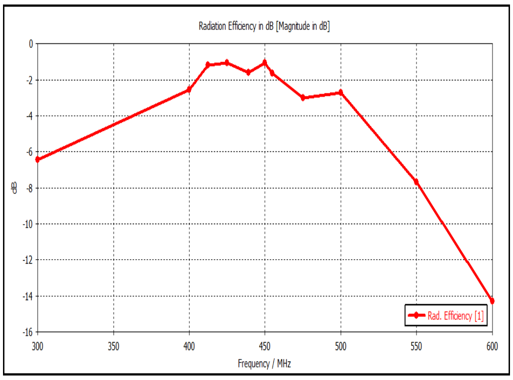

Figure 13: The radiation efficiency of the proposed antenna.

Fig. 14 shows the 2-D pattern of the far field directivity for the proposed meander line monopole antenna and Fig. 15 shows the 3-D pattern of the far field directivity for the proposed antenna. The proposed antenna has achieved wide coverage or near Omni-directional radiation pattern at the required frequency. The surface current of the proposed meander line antenna is shown in Fig. 16.

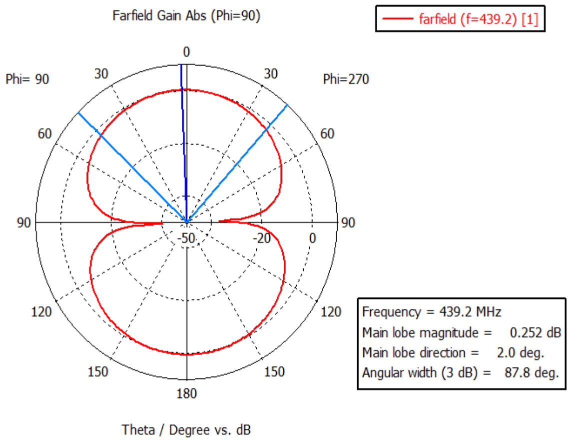

Figure 14: 2-D pattern of the far field directivity of the proposed antenna.

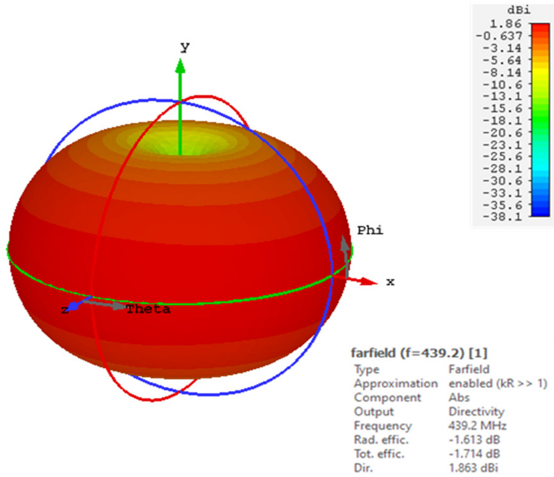

Figure 15: The 3-D pattern of the far field directivity for the proposed antenna.

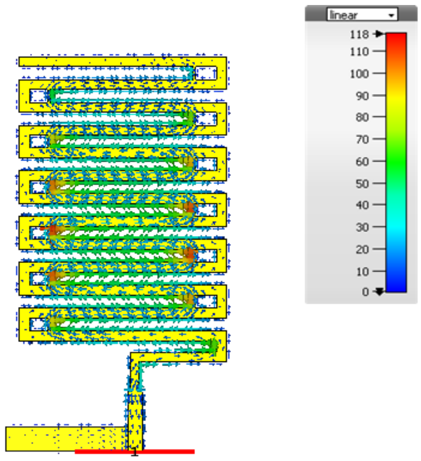

Figure 16: The surface current of the proposed antenna.

7.2 Fabrication Results

The proposed printed meander line monopole antenna with modified feeding system was fabricated on FR-4 substrate of dielectric constant $\varepsilon_r = 4.3$ of a thickness 1.6 mm as shown in Fig.17. The return loss of the fabricated antenna was measured using Vector Network Analyzer (VNA). The antenna was firstly tested without the CubeSat and then tested when located on the fabricated structure of CubeSat. Fig.18 shows the fabricated antenna when located on 1U CubeSat structure.

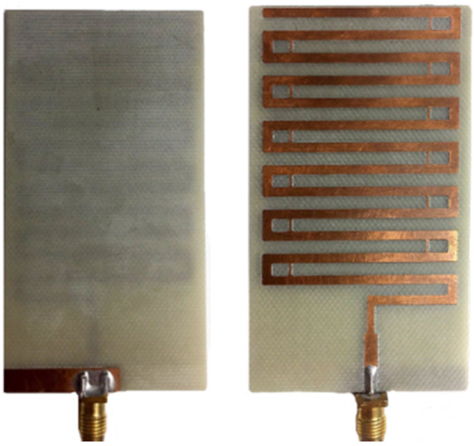

Figure 17: The fabricated antenna (Front view and Back view).

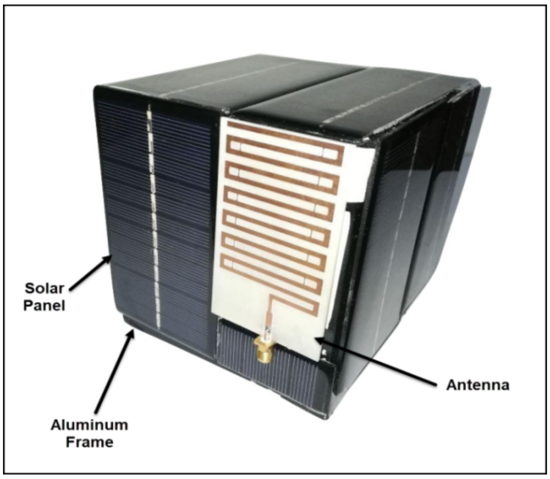

Figure 18: The fabricated antenna with 1U CubeSat.

The return loss and the operating frequency of the fabricated and simulated design of the proposed antenna when tested with and without the CubeSat structure are shown in Fig. 19. It can be seen from the figure that the fabricated antenna resonates at lower frequency than the simulated design. The fabricated antenna radiates at 423 MHz when tested without the CubeSat which is in the range of the licensed band (420-450 MHZ). The value of S11 in VNA was -11.5 dB at 423 MHz. The measured band width is 11 MHz at -10 dB which is suitable for the application of TTC of CubeSat.

The return loss of the antenna was -12.8 dB at 419 MHz when the antenna located on the CubeSat, That's mean the antenna resonate at lower frequency when located on the CubeSat as shown in Fig. 19. The band width was increased to 15 MHz compared to the bandwidth of the antenna without the CubeSat. From the collected measurements of the fabricated antenna, the results of the fabricated antenna are all in the acceptable ranges and suitable for real-time applications of TTC of CubeSat.

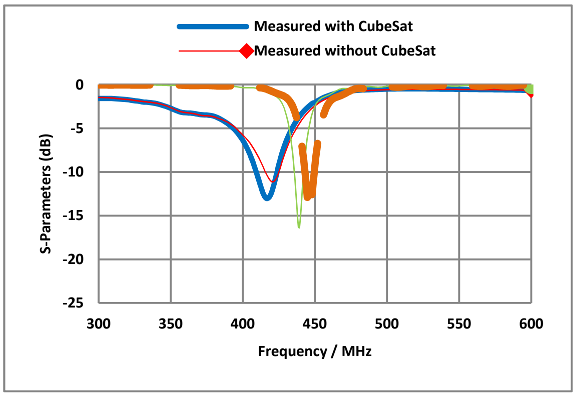

Figure 19: The fabricated and simulated results of the proposed antenna.

8 COMPARISON WITH OTHER WORKS

Several types of CubeSat antennas were designed in the last few years. These designs are different in dimensions, lower edge frequency, upper edge frequency and bandwidth. This section presents a comparison between the designed antenna and different antennas were designed for the CubeSat applications in terms of size, operating frequency, bandwidth, and compatibility of CubeSat. The comparison also includes the factor Bandwidth to Dimension Ratio (BDR) in order to provide an equitable comparison between models in different bands. The BDR was calculated depending on below equation (3) and (4). Table 4 presents the comparison between the designed antenna and other CubeSat antennas.

$$BDR = \frac{BW\%}{\lambda length \times \lambda width} \quad (3)$$

$$BW\% = \frac{2(fh - fl)}{(fh + fl)} \times 100\% \quad (4)$$

Where λ is the wavelength of the lower end resonance frequency, $BW\%$ *is* the percentage bandwidth, fh is the higher end resonance frequency and fl is the lower end resonance frequency.

Table 4: Comparison with other works.

Antenna	Dimensions	Bandwidth	BDR	Compatibility of CubeSat
Inverted F Antenna (T. Alam, 2018)	100 × 100 mm 0.149λ × 0.149λ	447.5 – 453.5 MHz 1.33%	59.9	Compatible with CubeSat But cover all the CubeSat face and have design complexity
Patch Antenna (Y. Yao, 2016)	110 × 110 mm 0.57λ × 0.57λ	1575 - 1721 MHz 8.85%	27.2	Not compact enough. Does not cover the licensed lower UHF band (420-460 MHZ)
Dipole Antenna (Mehul K. S, 2016)	200 mm 0.14λ	220 - 267 MHz 19.3%	137.8	Compatible with CubeSat but need complex deployment mechanism
Monopole Antenna (E. Pittella, 2013)	175 mm 0.25λ	435-438 MHz 0.68%	2.7	Compatible with CubeSat but have Deployable complexity
Microstrip Patch (G. Kakoyiannis, 2008)	120 × 170 mm 0.17λ × 0.25λ	435 - 437 MHz 0.45%	10.5	large and not compatible with 1U CubeSat
Meander line monopole (J. Fan, Z. Lei, 2014)	155 × 52 mm 0.22λ × 0.074λ	426-436 MHz 2.3%	143.74	Too large and not compatible with 1U CubeSat
Proposed Design	80 × 45 mm 0.11λ × 0.06λ	434 - 444 MHz 2.2%	333.3	Compatible with 1U and 2U CubeSat and free from deployment complexity

9 CONCLUSION

The small size of CubeSat and the low operating frequency represent the major challenge to design a miniaturized antenna with acceptable performances. This paper presents antenna design geometry for CubeSats. The proposed antenna topology is based on the meander line type. The antenna was simulated, implemented and tested successfully. The size of the designed antenna (80mm×45mm) was suitable for the CubeSat size and cover less than a half of the CubeSat face which gives additional space for the solar panels and other components. Finally, the antenna have been designed on FR-4 substrate using CST software, also it has been implemented, and the measurements of the implemented antenna match the results of the design with insignificant errors due to the limited ability of the fabrication machine and other limitations.The work in this thesis can be extended in the future by using high dielectric constant substrate can be used to increase the miniaturization level. More than one miniaturization techniques can be used to increase the miniaturization level. Gain and bandwidth enhancement of a miniaturized meander line so that the antenna can be used for both TTC application and payload data communication. Lowering the effect of the CubeSat structure on the antenna.

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