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REGULAR ARTICLE

Design, Fabrication and Measurements of a Single-Layer X-Band Miniaturized Patch Antenna with Metasurface for 0.5U and 1U CubeSat Missions

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In order to satisfy the needs of the smallest cube satellite unit with nearly insignificant air drag altitude, we construct, reduce in size, and optimize an innovative single-layer metasurface antenna in this research. One of the primary goals of this research is to improve antenna performance and therefore enhance data reception time throughout the day while applying a highly efficient energy system. In order to achieve all of this, a new patch antenna shape was chosen, and it was made as small as possible while still maintaining good operating characteristics in line with all of the earlier goals. This eliminated the need for an antenna deployment procedure once the satellite was in orbit. To further improve the final X-band antenna characteristics and, consequently, the overall efficiency of the accomplished cube satellite, a completely new unit cell shape was chosen and optimized to create the metasurface, which is integrated in the same layer as the developed patch antenna. The created metasurface-integrated patch antenna yielded good measured results in X-band for CubeSat communication after being manufactured and validated in an anechoic chamber and with a vector network analyzer. It has an ultra-wide bandwidth of 7.55 to 9.93 GHz (– 10 dB BW of 2.38 GHz), a unidirectional radiation pattern, is lightweight, and has an adequate realized gain of around 7.0 dBi at 8.4 GHz. The total computed and measured findings, and the reduced dimensions and volume demonstrate that the geometrical, mechanical, and electrical criteria of the 0.5U and 1U CubeSat missions at X-band are satisfied by this new single-layer wide-band metasurface antenna.

Keywords: 0.5U and 1U CubeSats, Antenna measurements, CubeSat lifetime, Metasurface, Realized gain.

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1. INTRODUCTION

CubeSat technology advanced dramatically in the last decade, becoming widely used in most countries. Today, we are talking about thousands of CubeSat spacecrafts flying in different orbits around the Earth for a variety of objectives. In addition to commercial and military purposes, these include monitoring the weather, studying climate change, regulating ship traffic in ports, controlling air traffic at airports, and serving as a middleman between integrated missions to speed up the flow of data to Earth [1]. Additionally, the availability and variety of methods that may affordably send these tiny spacecrafts into orbit have caused the conversation to shift to discussing daily launch rates with crucial proportions [2]. The engineering of every instrument of a particular cube satellite mission in accordance with the mission's coordinates and goals has advanced remarkably as a result of this enormous technical growth. For instance, multiple multinational commercial businesses offer all of the components needed to create any CubeSat configuration, with the remaining pieces being appropriately put together in a matter of days or weeks. In this regard, the firms Kongsberg NanoAvionics and GOMspace provide ready-made designs for most devices and parts, which may be joined to form any CubeSat configuration [3, 4].

In Note that a 1U CubeSat weighs around 1.33 kg and provides a few watts to the bulk of its electronics, making inventing and producing these devices rather than obtaining them an asset for space technology researchers [5]. One of the most important aspects in this context is the design and development of CubeSat antennas, which are responsible for transferring signals with earth stations [6]. It is necessary to mention that majority of the successful 1U CubeSat spacecraft launches occurred in low-Earth orbit (LEO), where air causes significant drag on composite spacecraft inter-faces, causing deterioration over time [7]. As a result, the primary goal of any CubeSat mission is to minimize the impact of air resistance on the satellite while in orbit above Earth. Add to this, the need to build earth station-CubeSat transmission links so that data and orders may be transmitted as long as possible during the day, whatever the weather conditions. Thus, the factors impacting the earth

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station-CubeSat transmission quality are heavily dependent on the total performance of the spacecraft antennas [8]. Moreover, the overall loss incurred during data and command exchange includes any signal retention between the CubeSat and the earth station [9, 11]. From another hand, The CubeSat-earth station distance is defined by the orbital height and the angle between the spacecraft and the earth stations [10, 12, 13]. This makes it extremely difficult to determine if a secondary deployment of CubeSat antennae is feasible. One of the most important technological goals for CubeSat engineers going forward is to avoid this secondary deployment [14]. It should be noted that the CubeSat circles the Earth numerous times each day, and the ground stations are immobile and have minimal control on the CubeSat's elevation angle while it is in motion around the Earth. In this circumstance, the goal of this article is to design and construct a metasurface-integrated patch antenna that is lightweight, inexpensive, and has extremely efficient performance for the smallest CubeSats, which are 0.5U and 1U.

This research seeks to build a lightweight and compact single-layer patch antenna with metasurface (MS) for 0.5U and 1U CubeSats by following three main goals. The first uses HFSS's FEM method and QNM package to design, optimize, and evaluate a tiny patch antenna that can cover 40% of a 0.5U CubeSat's smallest face and 20% of a 1U CubeSat's face. The second goal is to employ metasurface (MS) to increase antenna performance at X-band while also enhancing the earth station - CubeSat quality and features. More specifically, we aim to minimize antenna back lobe radiation when improving antenna realized gains and beamwidth angles. The third goal is to build the de-signed metasurface-integrated patch antenna proto-type, measure its characteristics, and compare them to simulation results to determine how well it works for 0.5U and 1U CubeSat missions. As a result, the purpose of this work is to improve a single-layer patch antenna with metasurface (MS) performance suited for 0.5U and 1U CubeSats in X-band (8.4 GHz). Specifically, the authors combine a compact patch antenna and a novel Metasurface on the top face of an inexpensive dielectric material to meet all of the requirements for 0.5U and 1U CubeSat missions while remaining low-cost, lightweight, low-volume, and very rigid.

This study is organized as follows: Section 2 de-scribes the geometrical specifics of the proposed single-layer MS antenna design, its fabrication and measurement block. It also illustrates and explains the geometrical features and measuring procedure of the suggested antenna approaches. In section 3, the suggested techniques are discussed and analyzed in terms of simulated results and achieved improvements based on their effectiveness for 0.5U and 1U CubeSats. Additionally, the effectiveness and advantages of the proposed metasurface-integrated patch antenna and its optimization for 0.5U and 1U CubeSats in X-band are also demonstrated based on the summarized data. The measured outcomes acquired within the anechoic chamber and using the vector network analyzer are presented in Section 4, along with a brief analysis of the overall results obtained for 0.5U and 1U CubeSat standards. A thorough comparison of the created single-layer MS antenna design with twenty X-band metasurface and AMC antenna ideas put forth by the scientific community is presented in Section 4, along with a com-parison of each design's suitability for utilization on 0.5U and 1U CubeSats. Section 5 concludes by summarizing our contributions to this research project.

2. ANTENNA DESIGN, FABRICATION AND MEASUREMENT BLOCK

This paper proposes to design an X-band (8.4 GHz) single-layer patch antenna with metasurface developed and optimized using ANSYS HFSS for optimal operation on a 0.5U CubeSat [15] in order to combine the characteristics of the smallest size and the highest performance, making it suitable for all CubeSat standards. The developed patch antenna and metasurface are both printed on the top face of the same FR4 dielectric ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$ and $h = 1.6$ mm) which considered as substrate material because of its low cost and wide availability in the market and high reliability characteristics for CubeSat applications at frequencies below 10 GHz [16, 17]. Fig. 1 depicts the design evolution of proposed metasurface integrated patch antenna system and shows that it is feed using a 50-Ω feed-line having dimensions of 14×2.4 mm^2. All antenna dimensions are estimated using the HFSS FEM method and optimized using a special QNM (Quasi Newtonian Method) approach. Its purpose is to construct a tiny and light-weight single-layer metasurface antenna suited for 0.5U and 1U CubeSats and then all other forms, with a realized gain more than 7.0 dBi and a broad – 10 dB BW at X-band (8.4 GHz). To obtain the desired return loss and realized gain at 8.4 GHz while preserving size and volume suitability for 0.5U and 1U CubeSat forms, the antenna dimensions are optimized using the QNM technique, which requires varying their initialization values over 1000 rounds. We propose a new MS array, as shown in Fig. 2, to further enhance the realized gain, return loss, and impedance bandwidth while pre-serving good impedance matching at 8.4 GHz. As seen in Fig. 2, this MS architecture is composed of a collection of square unit cells. The improved design looks to be very sturdy, lightweight, and compact, making it perfect for use with 0.5U CubeSat spacecrafts. It also covers approximately 41% of the smallest face (5×10 cm^2) of the 0.5U CubeSat.

The antenna manufacturing process of the created single-layer MS antenna system was then performed to support the simulation findings and analyze the physical performance and efficacy of the proposed antenna approach. The vector network analyzer's 50Ω port was used to examine the $|S_{11}|$ parameter as a function of frequency, as well as the 2D radiation pattern features of the prototype metasurface integrated patch antenna. Figs. 3 and 4 demonstrate the manufacture and testing method, with the antenna connected coaxially to the vector network analyzer (VNA) port. It should be noted that the features of the transmission connection, the date rate of

CubeSat-to-Earth and earth-to-CubeSat transmissions, and, ultimately, the mission's lifetime are governed by the sending antenna's power and gain, as well as the receiving antenna's power and gain. Furthermore, the whole MS-integrated patch antenna occupies a little area on the smaller sides of the 0.5U and 1U CubeSats, whereas solar panels consume practically all of the available space to produce energy, which is highly limited on these CubeSat designs. Together with the performance requirements based on the desired wavelength, CubeSat configuration, frequency, and orbit radius, as well as the CubeSat lifetime itself, this paper shows how to compute the limits of physical area and volume that any CubeSat antenna can occupy simultaneously.

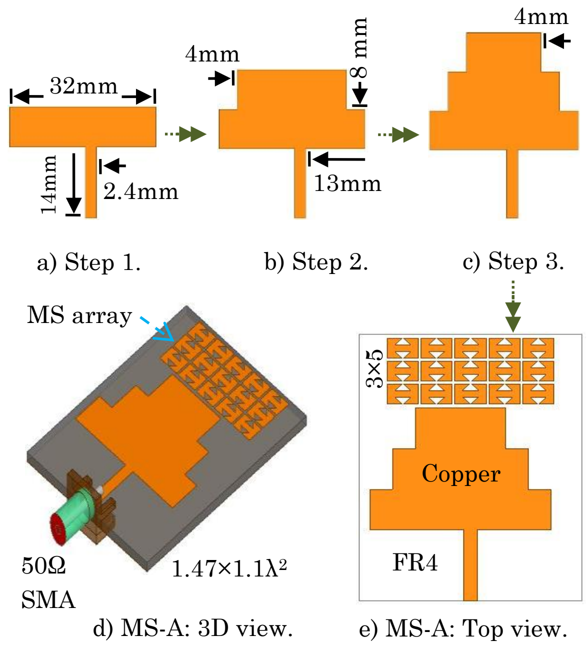


Fig. 1 – Configuration, evolution and dimensions of proposed MS-integrated antenna

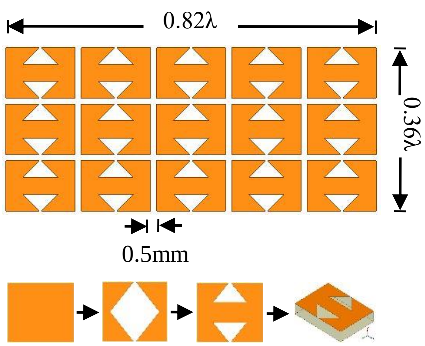


Fig. 2 – Configurations of developed Unit cell and metasurface.

From another perspective, the air resistance on the CubeSat structure impacts its longevity. Furthermore, the atmospheric drag is greater close to the Earth's surface compared to altitudes above 1000 km. The CubeSat's size and consequently the area of its interface influence the values of air drag effects. Additionally, it seems that the lifespan of a CubeSat can become indefinite, meaning it is not influenced by the effects of air, if it possesses a compact interface or if it orbits the Earth at altitudes greater than a thousand kilometers. In terms of lengthy lifespan, CubeSats outperform others due to their designs and resistance to air effects, especially when aiming altitudes more than a thousand kilometers or using the smallest CubeSat configurations, which minimizes the effects of air drag. Based on that, this study proposes an X-band metasurface-integrated patch antenna for 0.5U and 1U CubeSats, which will provide multiple options for research and development.

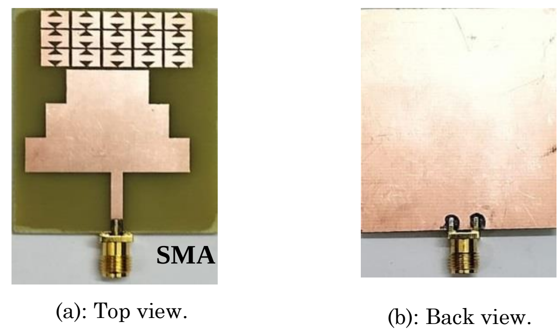


Fig. 3 – Prototype of the fabricated metasurface antenna: Top and back views.

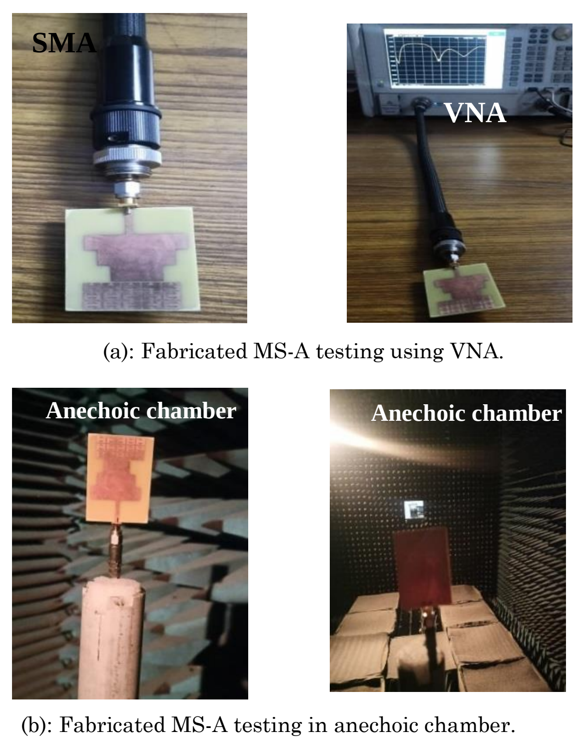


Fig. 4 – Measurement and testing blocks of the manufactured MS-integrated patch antenna

This project will help students comprehend the need of reducing energy consumption for spacecraft antenna systems and other instruments for supplying power to other devices, as well as reducing pressure on the satellite's electricity-generating system. Additionally, size reduction is highly desirable for CubeSats because to their restricted physical area/volume according to the required standards. Moreover, antenna performance should be improved in order to improve the transmission quality of the earth station-CubeSat and hence the whole CubeSat mission.

3. SIMULATION RESULTS, DISCUSSION, AND ANALYZIS

As previously stated, this metasurface antenna approach is built around the unique antenna parameters that effect a 0.5U CubeSat mission while still meeting consumer requirements. The analysis of all simulated and measured results will now be done in terms of a CubeSat mission under development by engineers and consumers inside the laboratory, taking into account the entire CubeSat lifetime from design to the end of its lifetime in orbit around Earth. Fig. 5 shows the results of simulated reflection coefficients for both the patch alone and the MS-integrated patch antenna. It is found that both designs provide wide effective bands at the X-band of 600 MHz (8.0 – 8.6 GHz) for the first one and 700 MHz (7.9 – 8.6 GHz) for the single-layer MS-integrated antenna demonstrating bandwidth enhancement of about 16% (100 MHz) using the proposed metasurface. Moreover, the lowest values of $|S_{11}|$ for both designs are – 20 and – 35 dB close to 8.4 GHz, respectively. This means that the used metasurface improved both impedance bandwidth and the reflection coefficient around 8.4 GHz without increasing the physical sizes or antenna volume as well as the excitation power.

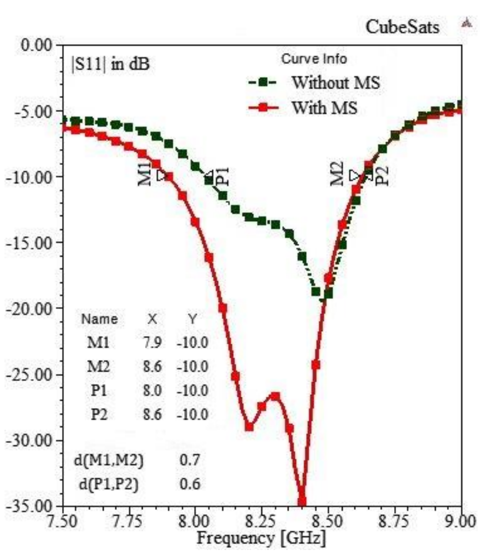


Fig. 5 – Measured and Simulated $|S_{11}|$ of proposed Cross-Patch antenna

Thus, these achievements allow earth stations and other spacecrafts to connect with the developed CubeSat antenna via a wide effective band and at low power consumption. To be more beneficial, because the bilateral transmission between a CubeSat and Earth stations takes just a few minutes each day, it is prefer-able to maximize the acquired performance in accordance with the geometrical, mechanical, and electrical requirements of every CubeSat mission. In this sense, this antenna approach creates an optimal metasurface of 3×5 unit cells with the current distribution shown in Fig. 6. It exhibits practically uniform current distribution as a result of the extremely powerful optimization applied to the novel form of metasurface unit cell as shown in Fig. 2.

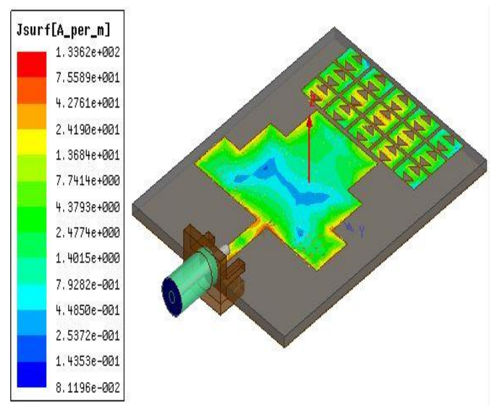


Fig. 6 – Current distribution of developed MS-A at 8.4 GHz.

The findings of VSWR coefficients and input impedance, shown in Figs. 7 and 8, clearly demonstrate these achievements. As seen in Fig. 7, the produced metasurface-integrated patch antenna provides a significant VSWR increase, two X-band bandwidths, and a VSWR close to one at 8.4 GHz, whereas the patch antenna alone provides a VSWR bandwidth ranging from 8.0 to 8.64 GHz. The MS antenna's first VSWR bandwidth, which covers from 7.88 to 8.64 GHz, and second, which ranges from 9.44 to 9.66 GHz, demonstrate that the VSWR bandwidth has been increased and that the impedance matching at 8.4 GHz is satisfactory.

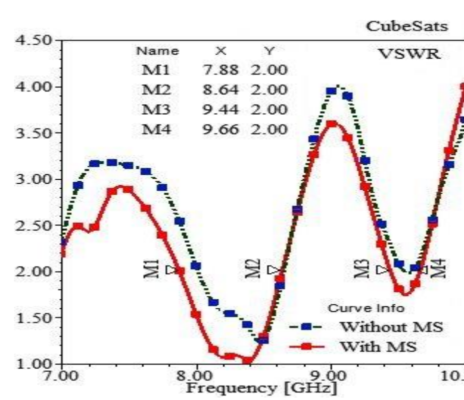


Fig. 7 – VSWR coefficient vs Frequency

The patch antenna without metasurface has an in-put impedance of 59.8-j14.5 Ω and about 62.8+j22 Ω at 8.2 and 8.4 GHz, respectively, see Fig. 8. This implies that it is preferable to optimize impedance matching with the feeding system in order to reduce temperature in the excitation port and so limit the possibility of the court circuit of electronic instruments within the CubeSat box. Furthermore, the feed line can provide significant electric power to the patch and metasurface array, improving antenna gain at $\theta = 0°$. As seen in Fig. 8, these goals are successfully satisfied with the produced metasurface.

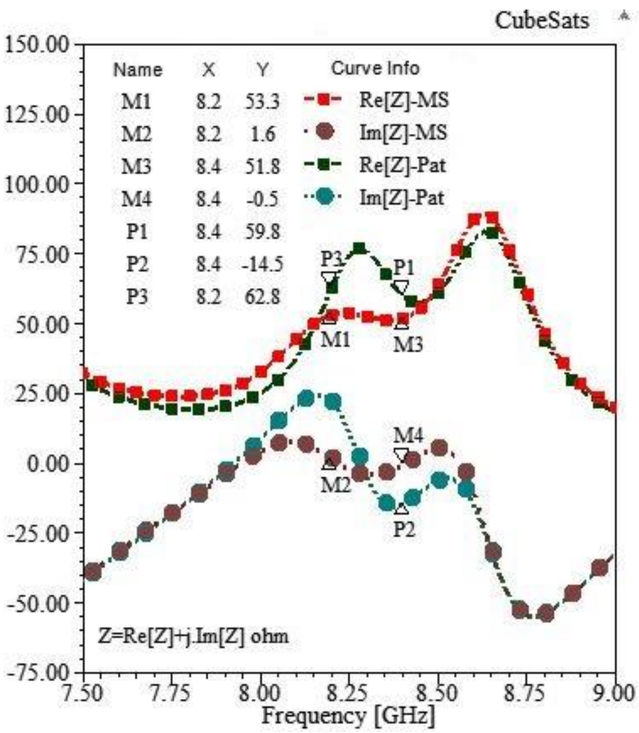
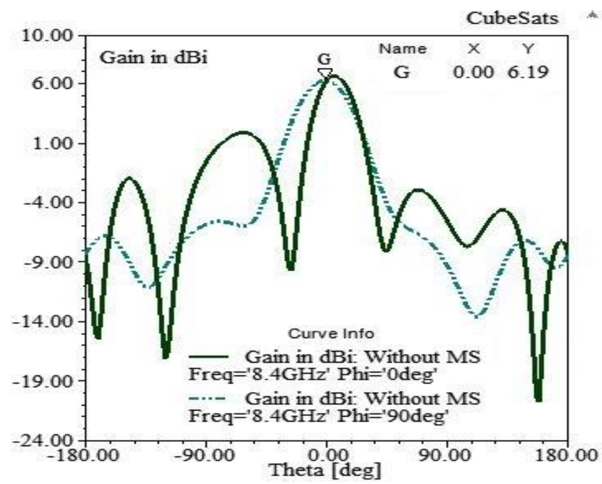
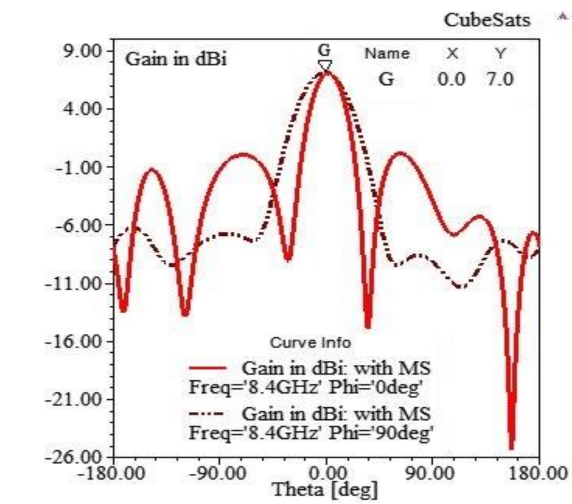


Fig. 8 – Zin plot of proposed Patch antenna with and without MS

The metasurface antenna has input impedances of 53.3+j1.6 Ω and 51.4-j0.5 Ω at 8.2 and 8.4 GHz, respectively. This results in good impedance matching and more electrical energy to the radiating elements, including the metasurface unit cell, increasing radiation outside the CubeSat box. Fig. 9 demonstrates that the improved metasurface raises antenna gain by roughly 16% (about 1.0 dBi) at the same operating frequency while occupying the exact same area on the CubeSat box and with the same electric energy. The patch de-sign alone produces a peak gain of roughly 6.1 dBi, whereas the metasurfaced antenna produces a peak gain of around 7.0 dBi. As a result, both designs are best suited for use on tiny CubeSat configurations like 0.5U and 1U. As a result, in terms of impedance band-widths, gain, and impedance matching, the entire metasurface antenna exhibits very efficient electrical characteristics for small-sized CubeSat configurations such as 0.5U and 1U.



a). Simulated Gain: Patch antenna without MS



b). Simulated Gain: MS-integrated Patch antenna.

Fig. 9 – Gain plots of proposed Patch antenna with and without MS: 8.4 GHz.

Consequently, the developed single-layer MS antenna meets all geometrical and mechanical requirements of CubeSat missions with low power consumption and no need for any deployment operation after CubeSat launch. The acquired outcomes maintain high data rate transmission with CubeSat/earth stations, hence increasing the overall CubeSat mission efficacy.

4. MEASUREMENTS, DISCUSSION, AND SAMMARY OF ACHIEVED RESULTS

As shown in Fig. 4, the developed MS antenna is carefully constructed, evaluated with a vector network analyzer, and placed inside the anechoic chamber to validate the outcomes of the simulations. Fig. 10 depicts the measured re-flection coefficient, which shows an ultra-wide bandwidth ranging from 7.55 to 9.93 GHz (– 10 dB BW of 2.38 GHz) and a low of – 44.27 dB at 8.59 GHz.

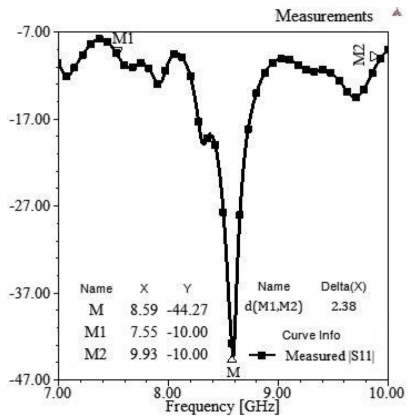
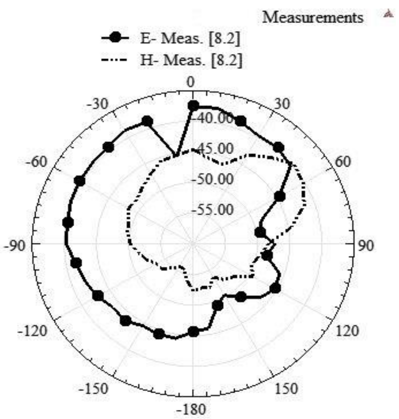
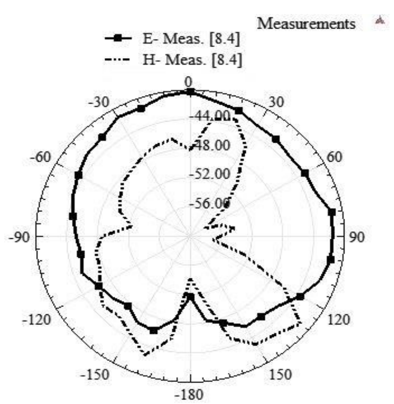


Fig. 10 – Measured $|S_{11}|$ coefficient of fabricated MS antenna



a). Measured 2D RP of fabricated MS antenna at 8.2 GHz.



b). Measured 2D RP of fabricated MS antenna at 8.4 GHz.

Fig. 11 – Measured 2D radiation patterns of fabricated MS antenna at X-band: 8.2 and 8.4 GHz

These achievements confirm the simulation results and the improvements obtained using the proposed metasurface. Additionally, Fig. 11 shows the measured radiation patterns at 8.2 and 8.4 GHz. The measured radiation patterns feature high beamwidth angles that are appropriate for 0.5U and 1U CubeSats since the majority of electromagnetic energy is released outside the CubeSat box and the CubeSat is capable of connecting with earth stations and other spacecraft while in motion around the planet. Furthermore, the broad beamwidth angle conserves transmission for varied CubeSat elevation angles, which ended in the obtained realized gain, and this ensures transmission for an extended period of time during CubeSat motion. These two aspects are one of the most significant successes of this antenna approach since they allow for high data rate transmission between the planned CubeSat and Earth stations or other spacecraft while orbiting the earth at high speeds. Tables 1 and 2 provide numerical descriptions of all of these accomplishments, as well as the geometrical and mechanical properties of the developed Single-layer metasurface antenna.

Table 1 – Physical and electrical characteristics of the fabricated metasurfaced antenna at X-band (8.4 GHz)

Characteristics	**Proposed Single-Layer MS antenna**
Dielectric constant (FR4)	4.4
Dielectric thickness (FR4)	1.6 mm
Physical size	1.47 λ_0 × 1.1 λ_0
Operating frequency	8.4 GHz
Return Loss	44.27 dB (8.59 GHz)
VSWR	Very Close to one
Beamwidth angle	Very wide
Radiation Pattern	Unidirectional
Back lobes	minimum
Realized Gain	~7.0 dBi

Table 2 – Suitability and Geometrical / mechanical Analysis according to all CubeSat standards: 0.5 U, 1U, 2U, 3U and 6U

Characteristics	Single-Layer MS antenna
Surface / 0.5U CubeSat's smallest face (10×5 cm²)	41.16 %
Volume / 0.5U CubeSat's volume	0.66 %
Surface / 1U CubeSat's top face (10×10 cm²)	21.3 %
Volume / 1U CubeSat's volume	0.33 %
Surface / 2U CubeSat's top face (10×20 cm²)	10.65 %
Volume / 2U CubeSat's volume	2.16 ‰
Surface / 3U CubeSat's top face (10×30 cm²)	6.94 %
Volume / 3U CubeSat's volume	1.11 ‰
Surface / 6U CubeSat's top face (20×30 cm²)	3.47 %
Volume / 6U CubeSat's volume	0.55 ‰
Power consumption	Very low
Radiation Pattern	Unidirectional
Beamwidth Angle	Very wide
EM Interferences with CubeSat subsystems	Minimum
Power dissipation	Negligible
Realized Gain	~7.0 dBi
Cost	Very low (< 40 USD)
Mass	Lightweight
Suitability for 0.5U and 1U CubeSat Standards	**Very suitable**

This indicates that the created 0.5U CubeSat spacecraft may be launched at altitudes with minimal air drag because to the obtained realized gain, small sectorial area, and high stiffness of the suggested single-layer MS antenna. On the other hand, the achieved large effective band and wide HPBW make the entire configuration suitable for communicating simultaneously with several earth stations located in different places. This improves the quality of bilateral transmission between the earth station and the CubeSat throughout the day, even though the CubeSat moves positions quickly.

5. DETAILED COMPARISONS WITH LITERATURE WORKS.

As previously stated, the X-band is often selected for space applications which include CubeSats because to its ability to create high-performance small and light-weight antenna systems. Tables 3, 4, and 5 compare the geometrical, mechanical, and electrical efficacy of the developed single-layer metasurface antenna with 20 comparable X-band metasurface/AMC antenna designs that may be employed for CubeSats. It is important to remember that any antenna system's appropriateness for a CubeSat mission is evaluated based on its overall geometrical, mechanical, and electrical requirements. Accordingly, every potential antenna system has the following prospects: (1) it may be used for communication between Earth and CubeSats; (2) it can be used for communication between CubeSats; or (3) unsuitable for any CubeSat uses. In this regard, the purpose of this study is to achieve an acceptable balance between the radiating characteristics of the examined MS/AMC antenna systems while maintaining geometrical/mechanical appropriateness for 0.5U and 1U structures at the same time using low power and cost. Apart for designs [22], [24], and [36], all antenna approaches indicated in Tables 3, 4, and 5 fulfill all geometrical and mechanical criteria of 0.5U and 1U CubeSat spacecrafts, implying that their overall appropriateness for the CubeSat mission is controlled by their electrical qualities. They are tiny, lightweight, consume little electric energy, and do not require a second deployment procedure following the CubeSat launch. In order to demonstrate how accurate and realistic the entire contribution is in terms of its utility for a 0.5U/1U CubeSat mission, these X-band MS/AMC antenna designs are carefully analyzed in terms of physical dimensions, materials, operating frequency, band-widths, polarization, forms of realized radiation patterns, and electromagnetic interference with other instruments.

Table 3 – Geometrical comparison with various metasurface and AMC-Based Antenna Designs for CubeSats at X-band

References	Total antenna size	Operating Freq. [GHz]	Materials
[19]	5×26×0.5mm³	6.9 - 8.8	Jeans textile, Copper
[20]	25.2×23.7×10mm³	8.30	RT/duroid 5880 (0.5 mm-thick), Copper
[21]	12×12×3.58mm³	8.95-10.68	Rogers RT5880; Rogers RO4030; Copper
[22]	140×140mm²	8.82, 9, 9.25, 9.43, and 10.1	FR4; copper
[23]	~31.2×31.2×4.5mm³	7.47-11.65	Rogers 4350B; Rogers RT5880 ; Copper
[24]	62×62× 22.2mm³	8.28 -8.88	RO3003, Copper
[25]	29×29×2 mm³	8.4	Rogers RO 4003, copper
Proposed Single-Layer MS antenna	52.6×39.6×1.6	8.4	FR4; copper

Table 4 – Electrical comparison with various metasurface and AMC-Based Antenna Designs for CubeSats at X-band

References	Operating Freq. [GHz]	Gain [dBi]	Bandwidths [GHz]	Polarization	Radiation Pattern	Interferences
[19]	6.9 - 8.8	6.17	6.9-8.8	Circular	semi-omnidirectional	Medium
[20]	8.30	1.70	~8.0-10.0	Linear	bidirectional	High
[21]	8.95-10.68	5.85	IBW: 8.95-10.68 ARBW: 10.62-11.87	Circular	Unidirectional	Minimum
[22]	8.82, 9, 9.25, 9.43, and 10.1	Not assigned	8.5 - 10.5	Linear	Unidirectional	negligible
[23]	7.47 - 11.65	H: 6.58 - 7.68 V: 5.85 - 7.28	43.72%: Port H 38.65%: Port V	Linear	Quasi-omnidirectional	Low
[24]	8.28 - 8.88	7.0	-10dB BW : 8.0-9.5 3dB ARBW: ~8.3-8.8	LHCP	Unidirectional	Low
[25]	8.40	5.80	8.28-8.59	Linear	Unidirectional	Low
Proposed Single-Layer MS antenna	8.40	~7.0	3dBi GBW > 1.0 IBW > 1.31	Linear	Unidirectional	Low

The physical dimensions of the design presented in [20] allow it to be used for both 0.5U CubeSats and FemtoSats. However, it's extremely low gain of only 1.7 dBi and its bidirectional radiation pattern restrict its use for any CubeSat configuration or FemtoSat because of the high level of electromagnetic interferences that are resulted with other instruments. Similarly, the antenna designs shown in [28–35] are small, light, and low profile, and they satisfy all geometrical and mechanical requirements for 0.5U and 1U CubeSat standards. However, their bidirectional radiation patterns exhibit extremely high back lobe radiations, which result in severe electromagnetic interference with other CubeSat electronics. Additionally, they have very massive losses, which can raise the failure rate and, as a result, restrict their appropriateness for use on CubeSats. Moreover, the majority of them exhibit low return loss at their working frequencies, which prevents impedance matching and raises the temperature in the excitation port, potentially harming other circuits within the CubeSat. However, if additional improvements are made to reduce back lobe radiation and the reflection coefficient, radiation outside the CubeSat chassis will increase, resulting in higher value realized gains, beamwidth angles, and impedance bandwidths, which are extremely beneficial for CubeSat applications. With respect to the design presented in [22] and [37], they are wideband and have a unidirectional radiation pattern, making them at least appropriate for communication between CubeSats or, in the event that the earth station has a very high gain based on the orbit coordinates, between CubeSats and Earth.

Table 5 – Comparison with some similar works which use Patch antennas at X-band

Reference	F_0 [GHz]	Volume [mm³]	Dielectric Material	Feeding System	RL [dB]	Radiation Pattern	Gain in dBi	Power Losses
[26]	9.6	27.5×42.5×1.57	FR4	50Ω strip line	~ 40	Multi-Lobes	~4.0	High
[27]	9.7	50×30×1.6	FR4	50Ω strip line	~ 25	Multi-Lobes	2.09	High
[28]	8.2	40×40×3.2	FR4	50Ω strip line	~ 28	Bidirectional	7.023	High
[29]	8.94	50×30×1.6	FR4	50Ω strip line	~ 30	Bidirectional	~5.5	High
[30]	10	46.7×46.7×3.2	FR4	4 Apertures	~ 30	Bidirectional	2.5 dBic	Very High
[31]	10	13.39×9.16×4.4	Rogers RO3003	50Ω CPW line	26	Bidirectional	6.72	High
[32]	8.95	34×36×1.6	FR4	50Ω strip line	15	Bidirectional	2.63	Very High
[33]	11	32×32×1.6	FR4	50Ω strip line	~ 15	Bidirectional	2.2	High
[34]	9	25×26×1.6	FR4	50Ω strip line	~ 25	Bidirectional	6.2	High
[35]	8.15	37×35×3.4	Laminate	Aperture	~ 22	Bidirectional	5.33	High
[36]	8.19	80×36×1.575	RT-Duroid 5880	50Ω SIW line	~ 25	unidirectional	9.6	Medium
[37]	9	20×20×2.5	FR4	50Ω coaxial probe	low	unidirectional	Not assigned	high
[38]	10.5	22.5×22.5×2	Mg-Nd-Cd ferrite	50Ω coaxial probe	~ 30	unidirectional	0.46	Low
Proposed Single-Layer MS antenna	8.4	52.6×39.6×1.6	FR4	50Ω strip line	44.27	unidirectional	~7.0	Minimum

Although the antenna configurations suggested in [26] and [27] meet all geometrical and mechanical requirements for 0.5U and 1U CubeSat configurations, their multi-lobe radiation pattern is a major drawback that restricts their usefulness for space applications. This is due to their extremely high interferences with other circuits within the satellite box, as well as their realized gains of less than 2.0 dBi at X-band. Compared to the antenna strategy provided in [36], it employs a substrate-integrated waveguide as a feeding system and exhibits low impedance matching at X-band, resulting in a high temperature in the substrate-integrated waveguide, which is structured across a large portion of this antenna system. As a result, despite its high gain, our design is more effective due to its extremely high return loss, negligible EM interferences, and high return loss at the X-band. All other designs fulfill the mechanical and geometrical criteria of 0.5U and 1U CubeSat shapes, as well as having adequate electrical features such as large impedance bandwidths, unidirectional radiation patterns, and achieved gains ranging from 5.8 to 7.0 dBi at X-band. They can be used for CubeSat-to-earth or CubeSat-to-CubeSat communications without the risk of electromagnetic interference or other issues such as excessive temperatures in the excitation port. Compared to all of them, our designed single-layer metasurface antenna provides greater gains while maintaining the smallest volume, consuming very little electric energy, and being a very low-cost CubeSat antenna system. As a consequence, our single-layer metasurface antenna approach outperforms all other listed antenna techniques in terms of CubeSat criteria.

6. CONCLUSIONS AND PERSPECTIVES.

This research project creates a compact single-layer patch antenna design based on experimental data for the smallest CubeSat builds, 0.5U and 1U. This metasurface-integrated patch antenna is lightweight, consumes very little electricity, and has mechanical, geometrical, and electrical properties that make it ideal for all CubeSat designs, including 0.5U and 1U configurations. Simulations and real-world experiments demonstrate strong agreement that both the patch antenna alone and the metasurface-integrated patch antenna radiate unidirectionally and function over wide impedance bandwidths in the X band. Additionally, the second one shows improvement in both bandwidth and return loss (RL), with an RL exceeding 44 dB and a – 10 dB BW of 2.38 GHz at X-band. Besides that, despite its compact size, the metasurface-integrated patch antenna exhibits outstanding performance for 0.5U and 1U CubeSat missions, measuring a broad beamwidth angle at 8.4 GHz with a realized gain of about 7.0 dBi and a gain improvement of about 1.0 dBi.

As a starting point for future research, we could build an AMC layer beneath the developed metasurface-integrated patch antenna and a multilayer Fabry-Perot antenna on top of it, using the same array of unit cells or new unit cell configurations, to increase the antenna gain to more than 20 dBi at the same CubeSat frequency, making the developed 0.5U and 1U CubeSats suitable for advanced CubeSat projects. Additionally, this would increase the transmitted date between the spacecraft and the earth stations while also reducing the amount of antenna gain needed the deployed earth station to keep in touch with the CubeSat in its orbit while circling the planet at high speeds several times a day.

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Проектування, виготовлення та вимірювання одношарової мініатюризованої патч-антени X-діапазону з метаповерхнею для місій CubeSat 0.5U та 1U

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Для задоволення потреб найменшого кубічного супутникового блоку з майже незначним опором повітря на висоті, ми в цьому дослідженні конструюємо, зменшуємо в розмірах і оптимізуємо інноваційну одношарову метаповерхневу антену. Однією з основних цілей цього дослідження є покращення роботи антени та, відповідно, зменшення часу прийому даних протягом дня при використанні високоефективної енергетичної системи. Для досягнення всього цього була обрана нова форма патч-антени, яка була зроблена якомога меншою, зберігаючи при цьому хороші експлуатаційні характеристики відповідно до всіх попередніх цілей. Це усунуло необхідність процедури розгортання антени після виходу супутника на орбіту. Щоб ще більше покращити характеристики остаточної антени в X-діапазоні та, відповідно, загальну ефективність завершеного кубічного супутника, була обрана і оптимізована абсолютно нова форма одиничної клітини для створення метаповерхні, яка інтегрована в той же шар, що й розроблена патч-антена. Створена метаповерхня-інтегрована патч-антена показала хороші виміряні результати в X-діапазоні для зв'язку CubeSat після виготовлення та валідації в безехо-камері та за допомогою векторного мережевого аналізатора. Вона має надширокий діапазон частот від 7.55 до 9.93 ГГц (– 10 дБ BW 2.38 ГГц), односторонній радіаційний малюнок, є легковажною і має адекватний реалізований підйом близько 7.0 дБ на 8.4 ГГц. Загальні обчислені та виміряні результати, а також зменшені розміри та об'єм демонструють, що геометричні, механічні та електричні критерії місій CubeSat 0.5U та 1U в X-діапазоні задовольняються цією новою одношаровою широкосмуговою метаповерхневою антеною.

Ключові слова: 0.5U та 1U CubeSats, Вимірювання антени, Тривалість життя CubeSat, Метаповерхня, Пікове підсилення.