A COMPACT SUPER-WIDEBAND HILBERT SLOT ANTENNA FOR CUBESAT AND SATELLITE MMWAVE APPLICATIONS

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***Abstract* – A compact super-wideband (SWB) Hilbert Slot Antenna (HSA) is designed and simulated in this work for high-frequency satellite and CubeSat communication systems. The proposed antenna provides wide impedance matching at 24.66–62.59 GHz covering the entire 5G Frequency Range 2 (FR2) band and extending into the lower mmWave spectrum suitable for satellite links. The antenna was designed based on a third-order Hilbert fractal curve, achieving electrical miniaturization while maintaining wide bandwidth and high gain. Despite its compact structure (7.31 mm × 7.31 mm× 0.508 mm), the antenna provides a simulated peak gain of 7.35 dBi, stable radiation patterns and a wide impedance bandwidth of ~38 GHz. The antenna is designed on a low-loss semi flexible substrate (Rogers RT/Duroid 5880), to facilitate its integration into deployable structures or curved surfaces in CubeSat missions. The use of a Hilbert fractal geometry allows for antenna miniaturization while supporting broad bandwidth and stable gain, features that align well with CubeSat communication demands where space and weight are limited.**

I. INTRODUCTION

Cube Satellites, or CubeSats, revolutionize satellite technology with 10-centimeter (1U) sides. They are cost effective and very practical for student's projects. They attracted aerospace companies, researchers, institutes, and governments worldwide due to their small size and standard form factors (1U, 2U, 3U, etc.) [1]. They facilitate the process of many scientific, commercial, and educational missions where they can reach orbit quickly and cheaply [2].

CubeSats can communicate with each other and form a swarm to monitor and sense enormous areas. CubeSats need broadband, compact, high-gain antennas to communicate with each other and the ground station. However, CubeSats' limiting size and weight create major antenna design problems. Optimizing radiation performance requires compact, lightweight antennas with high gain and wide bandwidth [1,3].

To achieve the development in millimetre-wave communication systems, efficient compact antennas with super-wideband (SWB) frequency range (all the FR2) capabilities are required. These antennas offer low cost, size, and high performance in terms of high gain and high data rate which is very important for high-speed communication [4,5].

For CubeSat satellite communication systems, antennas play an important role for data transmission between the satellite and ground stations or other spaceborne platforms. CubeSat antennas must be designed to provide wide bandwidth (BW), high gain, compact size, low profile, and mechanical robustness to withstand the harsh space environment [3]. Different antenna types are proposed in the literature for CubeSat communication; details can be found in [3,6,7].

The advantage of using fractal antennas for modern wireless communication systems such 5G, Bluetooth, WLAN, GPS, and CubeSat nanosatellites is explained in [8]. The iteration of fractal geometries improves the BW, multiband operation, performance and compactness. Zhanabaev and Sierpinski carpet fractals are designed and simulated using Ansys HFSS resulting in acceptable matching, gain, and radiation pattern characteristics.

A compact S-band (2.25–2.45 GHz) Koch curve fractal microstrip antenna is designed in [9] for CubeSat communication. The antenna was designed based on second iteration of the Koch snowflake on FR-4 substrate achieving maximum gain of 4.39 dBi and omnidirectional radiation pattern which in turns ensuring reliable communication without the need for attitude control. This makes the proposed antenna a good candidate for CubeSat structural constraints in terms of size, weight, and integration simplicity, demonstrating the effectiveness of fractal geometries for achieving compact, wideband, and efficient antennas in small satellite systems. A square Koch fractal slot antenna for CubeSat UHF telemetry, tracking, and command (TT&C) applications was presented by [10]. The design, fabricated on both FR4-G10 and Cuclad 250 substrates, operates at 458 MHz and fits within the 10 × 10 cm CubeSat face. The FR4-G10 version demonstrated cost-effective and reliable performance with $S_{11} = -16.53$ dB, 22.62 MHz bandwidth, VSWR = 1.35, and directivity = 2.24 dBi. The antenna's second-iteration Koch fractal geometry helps in reducing the size while maintaining omnidirectional radiation and this reflects its compatibility with CubeSat structures and solar panel integration, highlighting the practicality of fractal slot designs for low-cost CubeSat UHF communication systems.

A dual-band (S-band) patch antenna integrated with an optical imaging system for Earth-observation CubeSats was proposed by [11]. The antenna is designed to match the end face of the CubeSat, enabling efficient integration with onboard imaging systems. Based on double-sided FR-4 glass epoxy, the antenna provides gains of 1–4 dBi and 0.85–2.15 dBi at its two resonant frequencies 2.04 GHz and 2.45 GHz, respectively. Its compact size, low cost, dual-band operation, and system integration allow the CubeSat to use a single face for multiple functions, freeing other surfaces for solar energy generation. The consistent simulation and measurement results demonstrate the effectiveness of anisotropic fractal-inspired patch geometries in enhancing CubeSat subsystem efficiency.

In [12], Ismail's entropy which is a generalized version of Shannon, Tsallis, and Rényi entropies that connects information theory and fractal geometry, was proposed. The study emphasized the applicability of this fractal-based model to educational applications and CubeSat technologies, as well as its potential to describe both short- and long-range interactions. This study demonstrated the increasing significance of fractal principle in developing small and effective space communication system designs.

Due to their unique advantages, Hilbert Slot Antennas (HSAs)—including compact geometry, wide operating BW, high radiation efficiency, and ease of integration with CubeSat structures—are excellent candidates for CubeSat communication payloads [8,12,13]. The fractal configuration of Hilbert antennas (HAs) allows significant miniaturization while maintaining stable performance across wide frequency bands, making them ideal for both uplink and downlink communication links in small satellite systems. Furthermore, their design supports mechanical stability and radiation consistency under environmental stresses such as vibration, temperature variation, and launch shock [3]. These characteristics position HSAs as a promising alternative to conventional antenna designs for next-generation CubeSat satellite communication systems.

Several mmWave fractal antennas have been developed for 5G and related applications, demonstrating the advantages of compact size, wide BW, high gain, and multi-band operation. Designs include tree-shaped, Koch, Hilbert, Minkowski, Sierpinski, and circular fractals, implemented as single antennas, arrays, or MIMO systems, and optimized using techniques such as defected ground structures (DGS), substrate-integrated waveguides (SIW), and artificial intelligence algorithms [14–25]. These antennas cover frequencies from 15 GHz to 61 GHz and have been applied in wearables, vehicular communications, IoT devices, and terrestrial 5G networks, achieving gains ranging from 2 to 10 dBi, bandwidths spanning several GHz, and high radiation efficiency. However, no studies have explored mmWave fractal antennas for CubeSat communication, leaving an opportunity to exploit fractal geometries for compact, wideband, high-gain satellite antennas.

In this work, a compact super-wideband (SWB) Hilbert Slot Antenna (HSA) is proposed for high-frequency satellite and CubeSat communication systems using Computer Simulation Technology (CST). The antenna operates across 24.66–62.59 GHz, effectively covering the entire 5G Frequency Range 2 (FR2) spectrum and extending into the lower mmWave bands relevant for emerging satellite links. The antenna provides compact footprint (7.31×7.31 mm^2), super wide BW of 37.93 GHz and peak gain of 7.35 dBi. The semi flexible Rogers RT/Duroid 5880 substrate is used to ensure robust performance and enables potential integration into deployable or conformal CubeSat structures.

In addition to this Section, Section II addresses the design development of the proposed HSA. Section III presents the outcomes, while Section IV provides the conclusion of the work.

II. DESIGN AND ANALYSIS

A Hilbert curve with $n > 1$ promotes electrical compactness by increasing electrical length while retaining exterior dimensions. A meandering line is used, but the iterations' segments excite more resonances, resulting in multi-band operating frequencies and a broader bandwidth. First, divide the unit square into four half-squares to get the Hibert curve [26,27]. Next, scale down, rotate, or reflect the original curve to generate a space-filling curve for each sub-square. Choose reflection and rotation procedures so that the four partial curves can be joined to maintain continuity. Fig. 1 shows the Hibert curve construction from the unit square (n=1) to three-unit squares.

Following the design procedure in [13], The proposed

HSA was designed using the third-order Hilbert fractal geometry to achieve compactness and broad impedance bandwidth across the 24–64 GHz range.

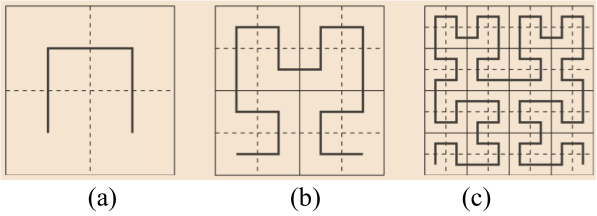


Fig. 1. Geometry of Hilbert curve (a) n=1, (b) n=2 and (c) n=3[27]

The final optimized design is shown in Fig. 2, integrates a modified ground plane, an etched matching slot, and extended patch edges to achieve superior performance. Results are discussed in the next section.

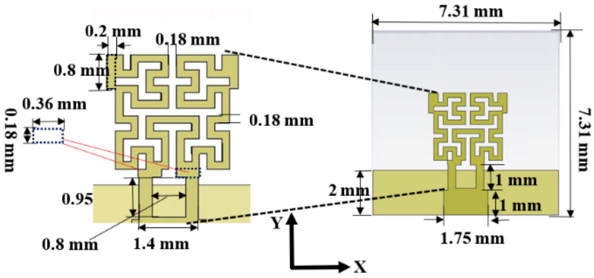


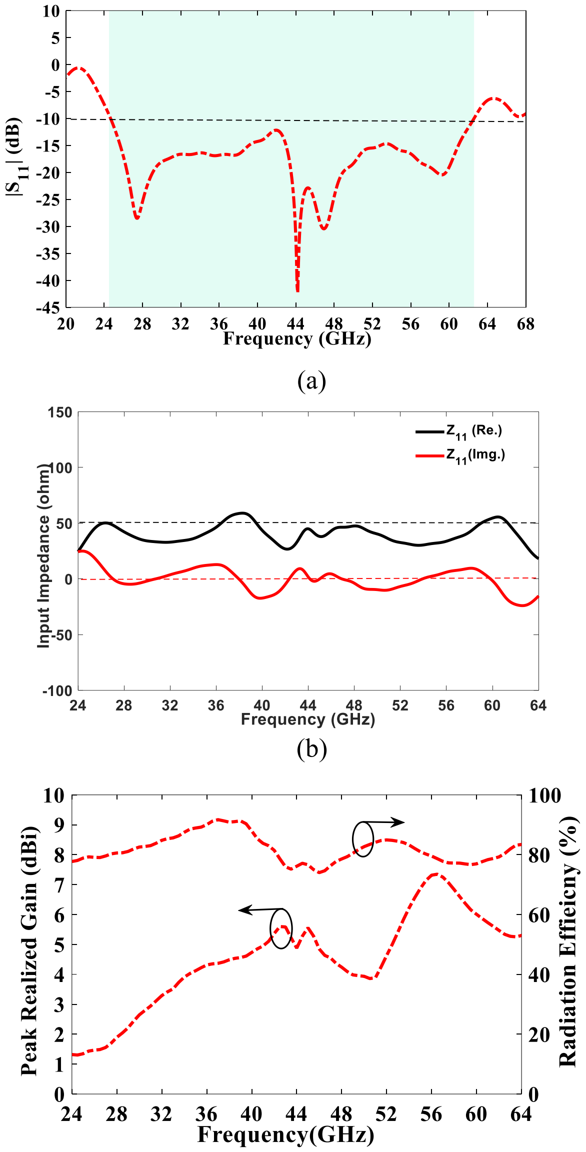
Fig. 3. The proposed SWB HAS with its optimized dimensions

III. RESULTS AND DISCUSSION

As shown in Fig. 4(a), the proposed SWB HAS provides broad impedance matching across the operational mmWave spectrum (S_{11} < -11.34 dB at 15.96–<-12.18, 24.66– 62.59=37.93 GHz) although of it its small size (7.31 mm × 7.31 mm). This matching can be explained in Fig. 4(b) where the real and imaginary components oscillate around 50 Ω and 0 Ω, respectively. As shown in Fig. 4(c), the simulated gain increases steadily with frequency, reaching 3.9 dBi at 34 GHz and peaking at 7.35 dBi at 56.5 GHz, indicating excellent radiation performance. The simulated radiation efficiency ranges from 74.38% to 97.17%.

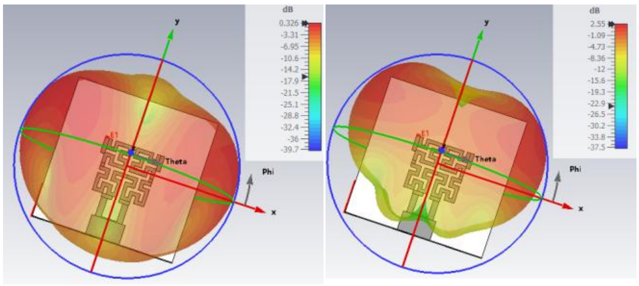
Because of the semi flexible Rogers RT/Duroid 5880 substrate, the proposed HAS is easily integrated into compact or curved CubeSat structures. In addition to that, its super BW (37.93 GHz), compactness, and high gain ensure efficient power transfer and reliable signal transmission. This making it good candidate for CubeSat communication systems, where space and weight constraints are critical design considerations.

The 3D radiation patterns of the proposed antenna at 28 GHz, 38 GHz, 48 GHz and 58 GHz are shown in Fig. 5(a), 5(b), 5(c) and (d), respectively. The antenna provides quasi-directional patterns with stable main lobes oriented along the z-axis which in turns ensures reliable communication links for CubeSat applications, maintaining efficient transmission toward the ground station despite satellite attitude variations.

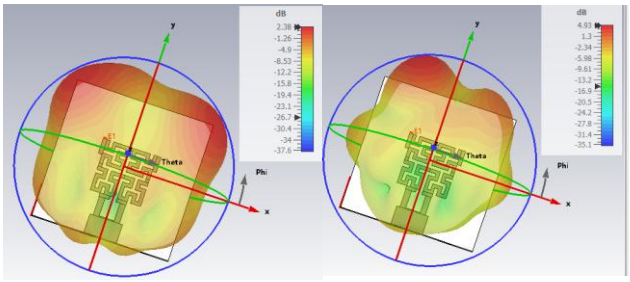


(c)

Fig. 4. The simulated (a) S_{11}, (b) input impedance, and (c) maximum realized gain with radiation efficiency of the proposed SWB HAS.



(a) (b)



(c) (d)

Fig. 5. The simulated 3D radiation patterns of the proposed SWB HAS at (a) 28 GHz, (b) 38 GHz, (c) 48 GHz, and (d) 58 GHz.

IV. CONCLUSIONS

In this study, a 5G FR2 compact super-wideband (SWB) Hilbert Slot Antenna (HSA) was effectively designed and simulated using CST for high-frequency satellite and CubeSat communication systems. The proposed HSA provides super wide impedance matching of the 24.66–62.59 GHz, compact dimension (7.31 mm × 7.31 mm × 0.508 mm), stable radiation patterns, and high peak gain of 7.35 dBi. The low-loss Rogers RT/Duroid 5880 substrate guarantees compatibility with flexible or curved CubeSat surfaces, while the utilization of a third-order Hilbert fractal geometry facilitated substantial miniaturization without sacrificing performance.

For future work, the antenna will be fabricated and its results will be measured to validate the simulated ones. Further optimization can also explore array configurations and integration with CubeSat communication modules to enhance link reliability and coverage.

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