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Design of 2.4 GHz Circular Polarization Conformal Antenna for RX-450 Sounding Rockets

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Abstract – **Blade antennas are used as transmitters in telemetry system of the sounding rocket RX-450 of Research Center for Rocket Technology – National Research and Innovation Agency to send rocket information to the ground station. For 360º coverage, the rocket needs two blade antennas connected with a splitter device which necessitates provision of additional power on the rocket payload. We designed a circular polarization conformal 2.4 GHz antenna to avoid both aerodynamic disturbances due to antenna shape and data transmission loss due to polarization loss with the ground station. The antenna material is Roger 6010LM and good antenna parameters were determined by simulation. The antenna bandwidth is 71 MHz (2412-2483 MHz). The maximum and minimum gain 7.8 dB at 2.43 GHz and 4.5 dB at 2.47 GHz respectively. Because of its conformal shape, we get an omnidirectional radiation pattern. Further, using the Hilbert curve method with a U-slot on the ground plane, circular polarization with an axial ratio ≤ 2 dB is obtained.**

Keywords – **Sounding rocket, Conformal antenna, Hilbert curve, U-slot.**

I. Introduction

The telemetry system used on a sounding rocket allows one-way communication, where the rocket can send data to the earth station, but the ground station cannot send data to the rocket once it is launched. Therefore, ground stations cannot request re-transmission of data in the event of data corruption or data loss during transmission. Hence, a reliable telemetry system is needed during each process of launching the sounding rocket [1].

At present, blade antennas are used in the telemetry systems of the sounding rockets of the Research Center for Rocket Technology, National Research and Innovation Agency, Indonesia. A blade antenna is a directional antenna in which the radiation beam transmits signals only in a certain direction, hence, more than one antenna should be integrated into one rocket to cover the entire coverage area. Meanwhile, an additional device, namely, a splitter is required to connect multiple blade antennas, and this additional device results in higher power consumption by the rocket telemetry system. In addition, directional antennas have the disadvantage that after the rocket is launched and performs extreme roll, yaw, and pitch motions, the ground station loses the data transmitted by the rocket payload because the ground station is not within the antenna radiation direction.

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Meanwhile, due care must be taken during blade antenna fabrication because its shape resembles a rocket fin. A fabrication error in the angle of the blade antenna to the rocket body can affect the aerodynamic properties of the rocket during the flight test.

To solve the problem of high power consumption, a single telemetry antenna that can cover the trajectory range of the rocket is needed. Such an antenna must have sufficient gain to meet the specification range of the rocket and an aerodynamic shape adapted to the rocket behaviour during flight tests.

In addition, the antenna should have circular polarization to avoid loss of data transmission and polarization interference at the ground station once the rocket is launched.

Patch and conformal antennas are commonly used in rocket telemetry systems. Meanwhile, conformal antennas can provide a wide radiation range, as well a continuous data transmission even if the rocket is rotating or wobbling, and it can maintain the aerodynamic performance of the rocket [2,3]. Several practical variations of conformal antenna mounted on aircraft and spacecraft [4-6]. Rectangular T-junction, rectangular dual feed, and rectangular arrays are often used for missiles or experimental rockets [3,7,8]. Furthermore, the truncated corner antenna is commonly used to obtain circular polarization in patch antennas [9-11]. Circular polarization can also be obtained by using the Hilbert curve method with a single feed on a conformal antenna [12,13]. The performance of microstrip antennas can be enhanced by adding defects on the ground plane of the antenna [14,15].

II. Antenna Design

A. Link Budget Calculation

The link budget was calculated to ensure that the power received by the ground station is greater than the minimum limit. This limit ensures that the received signal can be processed properly. From this calculation, the minimum gain of the transmitting antenna on RX-450 payload can be specified.

This link budget calculation is calculated when the trajectory range of the sounding rocket from the ground station is 142 km. The transmitter and receiver data used for calculation are listed in Table 1.

Therefore, link budget parameters are shown in Table 2. These parameters, form the basis for the design of the RX-450 transmitter antenna. The conformal antenna must be designed to have a minimum gain of -2.25 dB.

TABLE 1
TRANSMITTER AND RECEIVER PARAMETER FOR THE LINK BUDGET CALCULATION

Parameter	Value
Frequency	2.4-2.48 GHz
Transmitted power	30 dBm
Effective isotropic radiated power (EIRP)	6 dBm
Total loss in receiver	-1.388 dB
Receiver gain	31.5 dBi
Receiver sensutuvuty	-105 dBm
Total loss in receiver	-5.06 dB

TABLE 2
LINK BUDGET PARAMETER

Parameter	Value
Free Space Loss (FSL)	143.1 dB
Fade margin	14.7 dB
Received power	-90.3 dBm
Antenna transmitter gain minimal	-2.25 dB

B. Design of the Conformal Antenna

Several types of fractal geometries are employed in antenna manufacturing. The term fractal was coined by Mandelbrot in the 1970s based on his research on some fragmented and irregular geometries that occur naturally and do not conform to conventional geometries. Mandelbrot found that special properties that can be grouped based on these irregular geometries and made formulations based on his findings [16].

Hilbert curve is the fractal geometry used in antenna manufacturing applications. Iterations on Hilbert curves are shown in Fig. 1. Each iteration stage is four times a copy of the previous iteration with the addition of a line segment as a connecting line, depicted by dotted lines in the figure. The Hilbert curve has a self-separating property, where no line segment intersects each other.

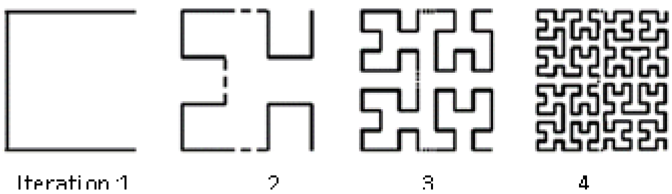


Fig. 1. First four iterations of Hilbert curve

In addition, this geometry is also simpler than other types of fractals because each curve can be drawn with a single stroke of the pen. The line length of each segment d can be calculated using Eq. (1). Meanwhile, the diameter of the Hilbert curve in each segment b can be calculated using the characteristic impedance η equation with an impedance antenna Z_0 of 50 Ω, shown in Eq. (2). The composition of the Hilbert curve antenna geometry shown in Fig. 2.

$$d = L / \left(2^n - 1\right) \tag{1}$$

$$Z_0 = \eta / \pi \log\left(2d / b\right) \tag{2}$$

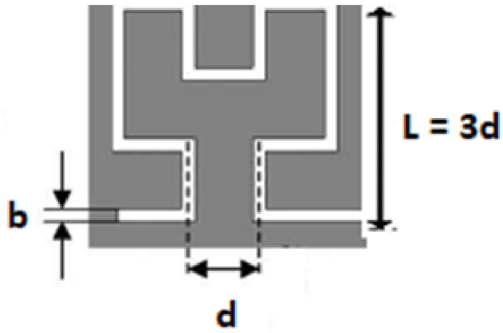


Fig. 2. Hilbert curve geometry

In this study, we used Roger 6010LM as the antenna substrate. This type of substrate is widely used in aeronautical communication systems, satellites, and ground radar warning systems applications. This substrate material was used because it can provide the flexibility required by conformal antennas. In addition, this substrate material has high heat resistance, making it suitable for application to the outer side of the rocket body. The maximum temperature experienced by the outer structure of the RX-450 rocket is 335ºC [17]. Roger 6010LM substrate has a permittivity ε_r of 10.2, a dielectric loss σ of 0.0023, a thickness h of 0.13 mm, 0.035-mm-thick copper cladding, and heat distortion temperature T_d of 500º C.

This conformal antenna uses SubMiniature version A (SMA) bulkhead female solder type connector as the feed point with a pin radius of 1.3 mm, Teflon radius of 4.2 mm, and coaxial outer radius of 6.35 mm. Dimensions of the initial antenna design are listed in Table 3.

TABLE 3
DIMENSIONS OF THE INITIAL ANTENNA DESIGN

Parameter	Dimensions (mm)
Length (L)	470
Width (W)	80
Length of Hilbert curve	20.83
Width of Hilbert curve	15.9

After completing the antenna model design process and obtaining the desired antenna dimensions, the simulation was performed using CST Studio Suite software. The conformal antenna geometry is shown in Figs. 3(a) and (b), and antenna simulation models, along with the cylindrical payload structure of the RX-450 sounding rocket is shown in Fig. 3(c).

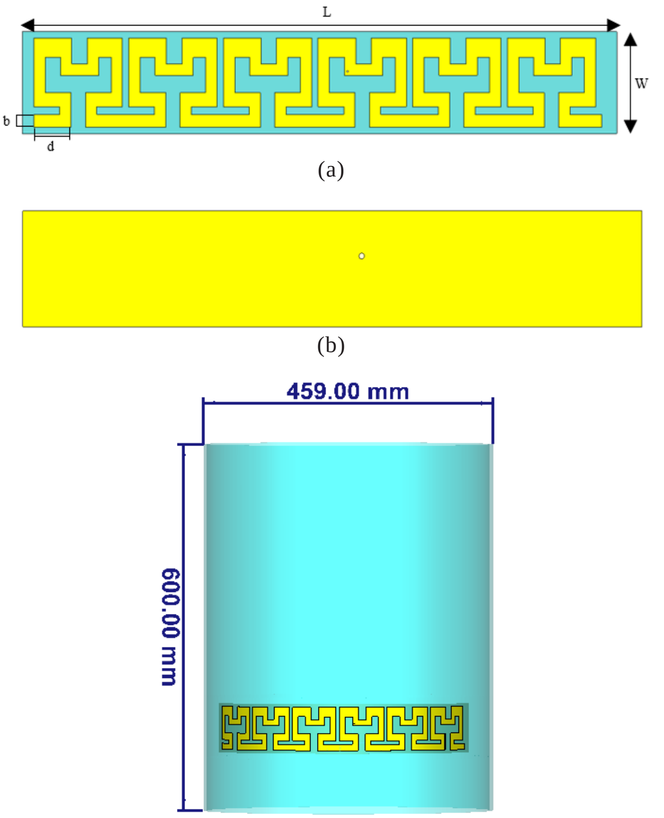


Fig. 3. Hilbert curve conformal antenna design : (a) Front view of the antenna, (b) Ground plane of the antenna, (c) Antenna integrated with a cylindrical payload structure

The simulation was performed to determine the initial performance of the conformal antenna model design. Furthermore, the antenna simulation was optimized to obtain the final dimensions of the Hilbert curve conformal antenna. To increase the bandwidth and gain of the antenna, a U-slot geometry was added on the ground plane as shown in Fig. 4. Dimensions of U-slot can be calculated using Eq. (3) through Eq. (5), f_l signifies the low frequency and f_c signifies the center frequency. Thus, the U-slot dimensions for this conformal antenna are obtained as thickness E is 2 mm, length A 35 mm, and width C 65.1 mm.

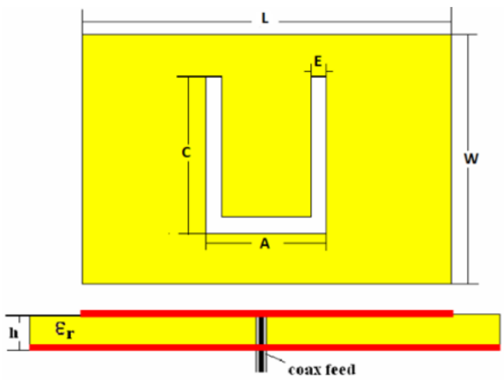


Fig. 4. U-slot on the ground plane of the antenna

$$E = f_c / 60 \tag{3}$$

$$A = C / \left(f_l \sqrt{\varepsilon_{reff}} \right) - 2\left(L + 2\Delta L - E\right) \tag{4}$$

$$C / W \geq 0.3 \text{ and } C / A \geq 0.75 \tag{5}$$

III. Result and Discution

A. Simulation Result

The simulation results of the initial antenna design integrated with the RX-450 payload structure for S11 parameter is shown in Fig. 5. A return loss of ≤ -10 dB is obtained in the operating frequency range, except at frequency of 2.43 GHz.

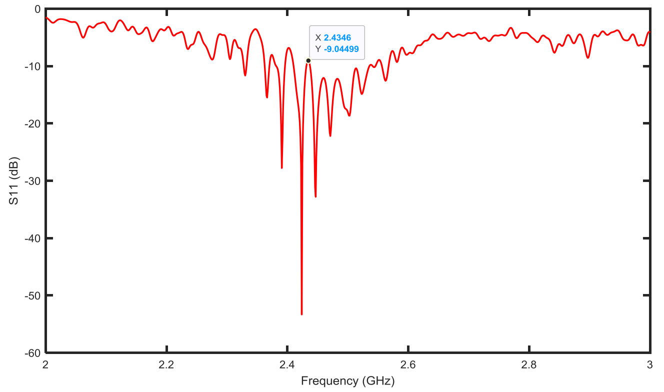


Fig. 5. S11 parameter simulation result for the initial antenna design.

To realize the required operating bandwidth, U-slot is added to the ground plane antenna. The addition of the U-slot results in a frequency shift, hence it is necessary to optimize the length of the U-slot. The lengths of the U-slot for different A (33, 35, 36, and 37 mm) were simulated. S11 simulation result of antenna design was obtained after addition of the U-slots and optimization is shown in Fig. 6. The best dimension of U-slot is obtained when the value of A is 37 mm and the antenna bandwidth improves to 75 MHz (2408-2483 MHz) while the bandwidth of initial antenna design was only 43 MHz (2437-2480 MHz).

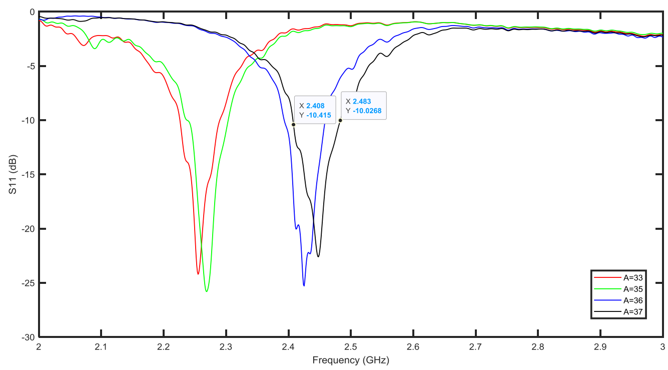
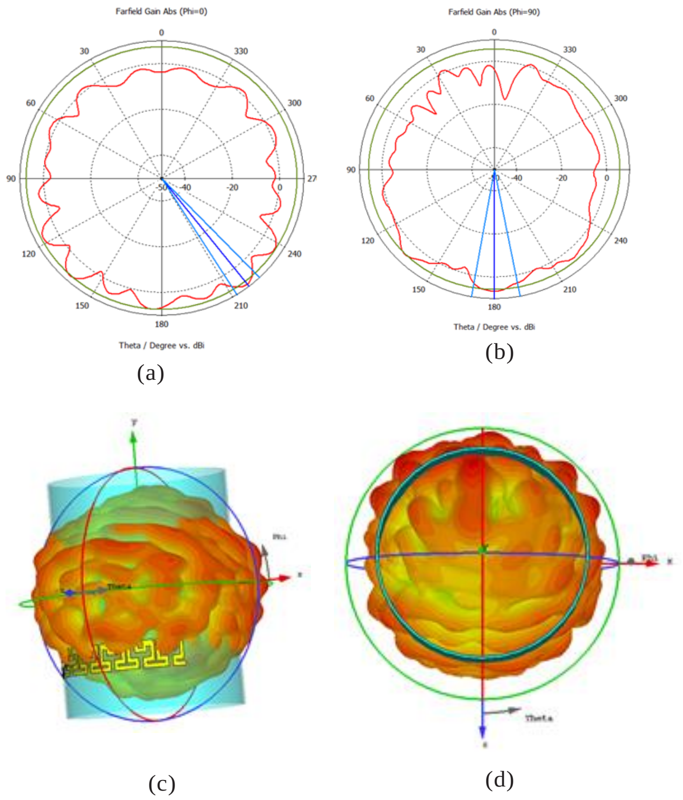


Fig. 6. S11 parameter simulation result for variation length A

The radiation characteristic of the conformal antenna is shown in Fig. 7. At horizontal (phi = 0º) and vertical (phi = 90º) pattern, this proposed antenna exhibits omnidirectional radiation pattern. This simulation result is desirable, since omnidirectional antenna is essential for telemetry system to cover wide range area and to guarantee a reliable radio communication during flight test as aircraft maneuvering and/or rotating as stated in [5,18].



(a) (b) (c) (d)

Fig. 7. Simulation result of the radiation pattern conformal antenna: (a) Phi=0°, (b) Phi=90°, and 3D plots of the (c) Front, and (d) Top

At the initial antenna dimensions, a maximum gain of 3.71 dB can be obtained at frequency of 2.45 GHz. After optimization and addition of the U-slot, the gain increases remarkably. The maximum gain value of 6.73 dB was obtained at frequency of 2.45 GHz, and the minimum gain value was 6.04 dB at frequency of 2.48 GHz. The gain values of the initial and optimized designs are listed in Table IV.

The polarization characteristics of antenna based on the current distribution simulation are shown in Fig. 8. In the visualization of the antenna simulation, it is known that the current shifts clockwise for every 90° phase angle, hence the antenna polarization is left-hand circular polarized. From the simulation, the axial ratio (AR) bandwidth as 1732 MHz in the frequency range of 1261–2993 MHz as shown in Fig. 9.

The simulation results that have been shown demonstrate that the proposed conformal antenna is compatible for telemetry purpose operating at frequency of 2.4 GHz. Furthermore, this proposed antenna with the Hilbert curve is easy to manufacture, and its conformal shape ensures the aerodynamic movement of the rocket during flight tests. As a result, this proposed conformal antenna is more favourable than previous blade antenna for sounding rocket telemetry system purposes. Eventually, the proposed conformal Hilbert curve antenna was fabricated and measured in the anechoic chamber.

TABLE 4
COMPARISON OF SIMULATED GAIN OF THE INITIAL DESIGN AND OPTIMIZED ANTENNA

Frequency (GHz)	Gain at initial design (dB)	Gain after optimization (dB)
2.4	0.14	6.57
2.41	1.87	6.13
2.42	-0.34	6.21
2.43	-0.08	6.07
2.44	2.64	6.45
2.45	3.71	6.72
2.46	1.05	6.55
2.47	2.62	6.44
2.48	1.58	6.04

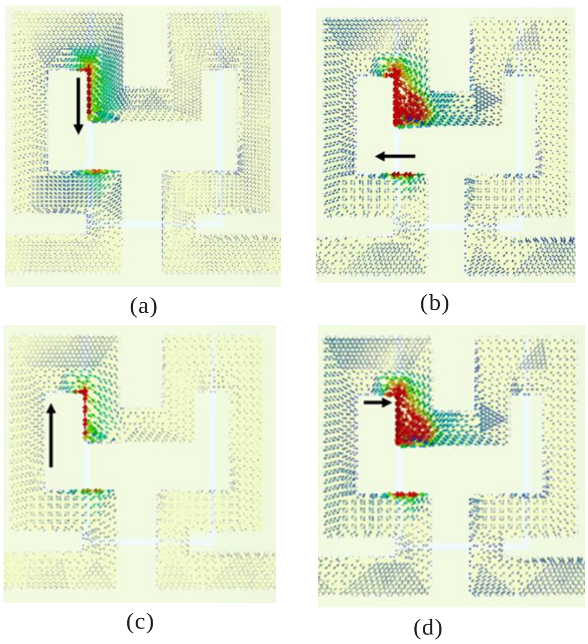

(a) (b) (c) (d)

Fig. 8. Simulation result of the current distribution: (a) Phase=0°, (b) Phase=90°, (c) Phase=180°, (d) Phase=270°

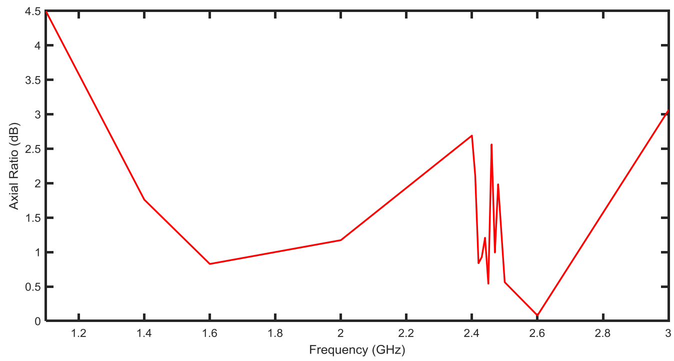


Fig. 9. Simulation result of the axial ratio bandwidth antenna

B. Measurement Result

The optimum antenna design comprises the Hilbert curve patch and U-slot ground plane are listed in Table V. The Hilbert curve conformal antenna was fabricated using Roger 6010LM material. The antenna attached to the SMA connector was mounted on the outer structure of the RX-450 payload as shown in Fig. 10 for further testing in anechoic chamber.

TABLE 5
DIMENSION OF THE PROPOSED ANTENNA

Parameter	Dimension (mm)
Length (L)	470
Width (W)	80
Length of Hilbert curve (d)	20.83
Width of Hilbert curve (b)	15.9
Thickness of U-slot (E)	2
Length of U-slot (A)	37
Width of U-slot (C)	57

(a)

(b)

(c)

Fig. 10. Hilbert curve conformal antenna: (a) The front view of the antenna, (b) The ground plane with SMA connector, (c) Antenna integrated on the RX-450 payload structure

In this study, the antenna bandwidth was measured for reflection coefficients less than -10 dB. From the simulation results, the bandwidth is 75 MHz in the frequency range of 2407-2482 MHz. The minimum reflection coefficient obtained at a frequency of 2448 MHz is -22.60 dB. Meanwhile, the measured bandwidth is 71 MHz in the frequency range of 2412-2483 MHz. The minimum reflection coefficient of the antenna measurement -18.54 dB at a frequency of 2452 MHz is. The difference between the simulation and measurements results may be attributed to the addition of sealant when installing the antenna connector. The addition of this sealant causes a change in the effective permittivity of the material, resulting in a frequency shift. This effect agrees with the result of the previous study [19], in which a frequency shift was observed when an antenna was mounted on unmanned platform and coated with a sealant. The simulated and measured S11 parameters are shown in Fig. 11 for comparison.

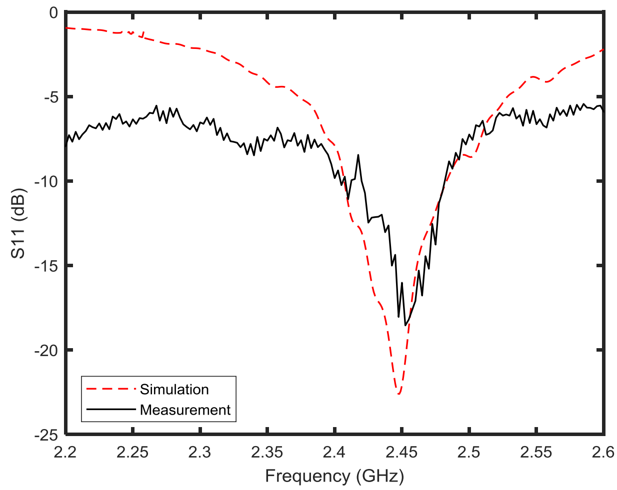
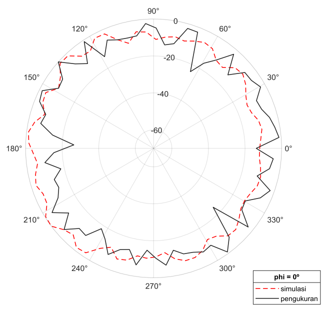
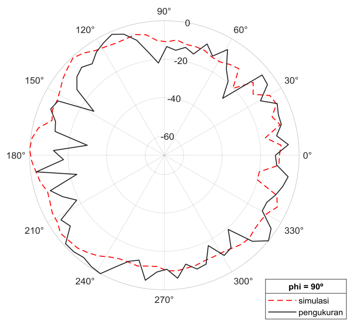


Fig. 11. Comparison between the simulated and measured S11 parameter values



(a)



(b)

Fig. 12. Comparison between simulated and measured radiation pattern at: (a) Phi = 0º, (b) Phi = 90º

To determine the radiation characteristics of the antenna, the radiation patterns were measured and compared with the antenna simulation results. The radiation patterns were measured at phi = 0° and phi = 90°, each with 5° intervals. The simulated and measured antenna radiation patterns for a central frequency of 2.44 GHz are shown in Fig. 12 for comparison. The two graphs show that this conformal antenna has an omnidirectional radiation pattern. Next, the antenna gain was measured. Table VI lists the simulated and measured antenna gain, for comparison. From the simulation results, the maximum and minimum gain are 6.73 dB at 2.45 GHz and 6.04 dB at 2.48 GHz, respectively. Meanwhile, from the measurement results, the maximum and minimum gain are 7.86 dB at 2.43 GHz and 4.59 dB at 2.47 GHz, respectively.

TABLE 6
COMPARISON OF THE SIMULATED AND MEASURED GAIN ANTENNA

Frequency (GHz)	Gain Simulation (dB)	Gain Measurement (dB)
2.4	6.57	6.34
2.41	6.13	7.22
2.42	6.21	7.19
2.43	6.07	7.86
2.44	6.45	6.12
2.45	6.72	6.60
2.46	6.55	6.06
2.47	6.44	4.59
2.48	6.04	6.58

The simulated and measured antenna gain were different. Further, the antenna gain also decreased above a frequency of 2.44 GHz likely because of power loss in the material. Power loss might be caused by the poor connection of the coaxial connector with the antenna because of the thickness of the substrate material. Furthermore, this loss might also originate from the electromagnetic loss of metal material of the payload, this electronic loss increases with increasing frequency because of the surface resistivity of the metal (see Fig. 13), in accordance with Eq. (6) [20]. However, the gain measurement results satisfied the minimum gain requirement (-2.25 dB in a frequency range of 2.4-2.48 GHz) of the sounding rocket RX-450 telemetry system.

$$R_s = 1/\delta\sigma = \sqrt{(\pi f \mu_0 \mu_r)/\sigma} \qquad (6)$$

The polarization characteristics of the antenna were obtained by measuring the AR. It is the ratio of the major and minor axes of the elliptical polarization and is generally expressed in dB values. The AR was calculated from the difference between the co-field and cross-field antennas. The simulated and measured AR values were less than 2 dB, as shown in Fig. 14. Thus, it is established that this conformal antenna has circular polarization.

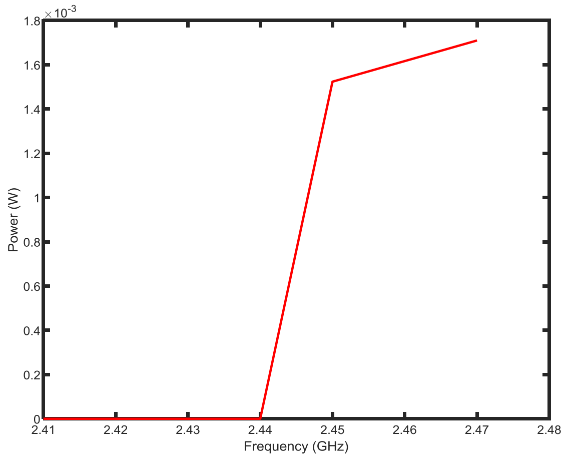


Fig. 13. Power loss simulation result of the metal material of the RX-450 payload structure

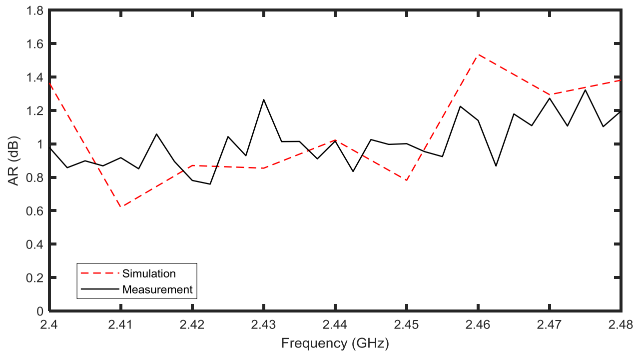


Fig. 14. Comparison of the simulated and measured axial ratio (AR)

IV. CONCLUSION

In this study, a conformal Hilbert curve antenna was designed, fabricated, and its characteristics were measured in an anechoic chamber integrated on the payload structure of RX-450 sounding rocket. The measurement results of the conformal antenna fabricated from Roger 6010LM material (ε_r = 10.2) showed that the bandwidth was 71 MHz in a frequency range of 2412-2483 MHz.

The simulation results indicate that the addition of a U-slot on the ground plane can widen the bandwidth while increasing the antenna gain. The maximum measured gain was 7.86 dB at frequency of 2.43 GHz and the minimum gain was 4.59 dB at a frequency of 2.47 GHz. The conformal antenna gain satisfies the minimum link budget calculation (the minimum gain required is -2.25 dB). Thus, the proposed antenna is suitable for use as a transmitter on the RX-450 sounding rocket telemetry system.

The simulated and measured antenna radiation patterns show that the antenna has an omnidirectional radiation pattern, that it is expected to cover the entire range of the RX-450 sounding rocket. In addition, since the AR<2, this conformal antenna exhibits circular polarization characteristics that help avoid polarization loss during data transmission of the payload to the ground station. In addition to meeting measurement results, ease of manufacturing, lightweight design, and the conformal shape that ensures aerodynamic movement make this conformal antenna more desirable compared to the previous blade antenna.

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