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Alam, Talha, Javed, Mazhar, Anik, Abdullah All Mamun and Wahid, Roohi

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High Gain Dipole Tape Antenna for IoT PocketQube/CubeSat, Satellite Applications

Talha Alam
Electronics Engineering
University of Engineering and
Technology Peshawar
Abbottabad, Pakistan
TalhaAlamE.E@gmail.com

Mazhar Javed
Electrical Engineering
Ghulam Ishaq Khan Institute of
Engineering Science and
Technology
Topi, Pakistan
mazharjavedgiki@gmail.com

Abdullah All Mamun Anik
Engineer and PhD Researcher
University of Huddersfield
Queensgate, United Kingdom
abdullahmamunanik28@gmail.com

Roohi Wahid
Electronics Engineering
University of Engineering and Technology Peshawar
Abbottabad, Pakistan
Roohimehak9@gmail.com

Abstract—This paper presents the design and optimization of a high-gain foldable Dipole Tape Antenna tailored for IoT nanosatellite communication platforms. The increasing demand for compact, efficient, and reliable antennas in space-based applications, particularly for CubeSats and PocketQubes, necessitates innovative solutions. The proposed antenna operates at the 433 MHz RF band, addressing critical size and deployment constraints through a foldable design, enabling compact storage and expansion post-launch. Advanced simulation techniques have been employed to optimize gain (5.7 dBi), bandwidth (11.55%), and radiation efficiency, ensuring robust performance. Comparative analysis with existing designs demonstrates superior characteristics in terms of miniaturization, impedance matching, and radiation pattern stability. This research contributes to advancing space-based IoT connectivity, providing an effective solution for nanosatellite communication systems.

Keywords—(Dipole Tape Antenna, Copper, IoT (Internet of Things), PocketQube, CubeSat, nanosatellite, wireless communication)

I. INTRODUCTION

Providing low-cost, scalable access to space-based data through nanosatellite communication is needed to support such applications as IoT and scientific research. Analogous to a hairspray can, the Dipole Tape Antenna is an ultra-compact foldable solution, both minimizing space during launch and ensuring that reliable signal transmission can always be maintained once deployed. It works in the 433MHz band, improves gain and efficiency making it perfect for CubeSat communication needs.

In the past few years, there have been large achievements in antenna design [1], developing compact and high-performance antennas for some special technical applications. Such as crossed dipole Tape Antennas with optimized geometries and folded structures to achieve a space-saving configuration [2]. For

example, by rotating one-half of the dipole arms and further folding them in an E shape, antenna designs have been successfully made small in size without loss of performance [3], as in the progression from T-shaped to folded E-shaped crossed dipoles. Another example of this trend towards compact [4], efficient designs is seen with Folded Dipole Tape Antennas (FDTA), in which not only do the physical dimensions decrease in size, but bandwidth and gain are also increased [5, 6]. In several wideband antenna models, we see these designs aimed at reducing reflector distance to obtain wide impedance bandwidths, uniform radiation patterns, and low cross-polarization levels [7]. Due to the problems encountered in deploying traditional antennas concerning size, weight, and bandwidth constraints, log periodic dipole arrays (LPDAs) have been proposed as deployable antennas in deployable applications [8], indicating the need for structural adaptability in modern antenna designs. Furthermore, the use of transparent wideband dipole and patch antennas is explored for UHD TV broadcasting applications [9], which require omnidirectional and directional radiation patterns to achieve the best possible performance over a wide frequency band. At the same time as these improvements, precise calibration and uncertainty analysis have become essential in validating antenna performance and must be carried out according to rigorous procedures, like those in the Guide to the Expression of Uncertainty in Measurement (GUM) [10]. These methodologies, sometimes buttressed by numerical simulation, equivalent circuit models, and experimental experiments, offer a strong design and optimization methodology for antenna design [11]. These diverse approaches range from COMS radiating aperture and on-demand beam forming for compact deployable solutions that needed enhanced bandwidth and gain [12], to antenna technology that can make IoT and cube Sat communication more compact, as well as antenna technology used to provide traffic for broadcasting [13]. And, while this design innovation and analytical rigor have yielded a progression of high-performance antenna systems that address

the sophisticated issues of contemporary communication platforms [14], the trend will continue.

With the rapid expansion of IoT-based satellite networks, the need for compact, high-performance antennas has become critical. CubeSats and PocketQubes, designed for low-cost space missions, require antennas that balance size, efficiency, and deployment feasibility. Traditional rigid antennas face integration and storage challenges due to limited satellite volume. The proposed foldable Dipole Tape Antenna overcomes these constraints by offering high gain, reduced footprint, and improved radiation characteristics, making it ideal for nanosatellite communication.

This paper introduces a novel foldable Dipole Tape Antenna that optimizes performance for IoT nanosatellites operating at 433 MHz. The key contributions include:

- **Innovative Foldable Design:** Allows compact storage and efficient deployment post-launch.
- **High Gain and Bandwidth Optimization:** Achieves a simulated gain of 5.7 dBi and a bandwidth of 11.55%, improving signal strength and coverage.
- **Material Optimization:** Uses copper for enhanced conductivity, ensuring minimal signal loss.
- **Simulation and Hardware Validation:** The antenna's performance is verified through HFSS simulations and a prototype, confirming its radiation efficiency and impedance matching (73 Ω).
- **Comparative Performance Analysis:** Demonstrates improved results over existing dipole antenna designs, highlighting better efficiency and space utilization.

II. THEORETICAL MODEL

Our design addresses the need for compact and efficient antennas for nanosatellite communication at 434 MHz using a foldable Dipole Tape Antenna. At this frequency, we now have a half wavelength of roughly 34 cm, and this requires a space-efficient solution. The antenna's design, a foldable one, is compactable before deployment, and expands once in space. This approach ensures the antenna fits within the constraints of small satellite systems while maintaining high performance. Advanced materials and simulation techniques were employed to enhance the antenna's gain and efficiency, making it ideal for the demanding requirements of nanosatellite and IoT applications.

A. Transmission Line Impedance Modelling

The input impedance Z_{in} of a lossless transmission line with the characteristic impedance Z_c depends on the distance l to the load Z_L ,

$$Z_{in} = Z_c \frac{Z_L + jZ_c \tan(\beta l)}{Z_c + jZ_L \tan(\beta l)} \quad (1)$$

β is the phase constant defined as

$$\beta = \frac{2\pi}{c} f_{res} \sqrt{\epsilon_r^{eff}} \quad (2)$$

Where $c \approx 3 \times 10^8 \frac{m}{s}$ The speed of light in vacuum and ϵ_{eff} The relative permittivity of the field transmitting line medium is known as the effective relative permittivity of the transmission environment. The effective relative permittivity ϵ_{eff} It is defined as the relative permittivity of a nondispersive homogeneous medium that can be used to model the heterogeneous medium surrounding the transmission line.

By applying Equation (1), one obtains its resonance condition,

$$Z_1 [Z_1 \tan(\beta_1 l_1) + 2Z_2 \tan(\beta_1 l_1)] - Z_2^2 \tan^2(\beta_1 l_1) \tan(\beta_2 l_2) = 0, \quad (3)$$

Where,

Z_1 and Z_2 are the phasor constants, and l_1 , and l_2 represent the lengths of the high- Z_c and low- Z_c sections. Equation (3) designates the relationship between the geometry of the high- Z_c and low- Z_c lines that can be characterized by l and Z_c correspondingly, the dielectric characteristics of the surrounding environment by Z_c , and β and the resonant frequency f_{res} (when $\text{Im}(Z_{in}) = 0$).

The characteristic impedance of a general TEM transmission line with negligible losses is expressed as,

$$Z_c = \sqrt{\frac{R + j\omega l}{G + j\omega C}} \approx \sqrt{\frac{L}{C}} \quad (4)$$

The inductance L and capacitance C (per unit length) may be represented through the phase velocity v_p ,

$$V_p = \sqrt{\frac{1}{LC}} = \frac{1}{\sqrt{\mu_{eff} \epsilon_{eff}}} \rightarrow \sqrt{\frac{L}{C}} = \frac{1}{V_p} = \frac{r \cdot \sqrt{\mu_{eff} \epsilon_{eff}}}{c} \quad (5)$$

Substituting (4) and (5) gives the following expression for the characteristic impedance,

$$Z_c = \frac{\mu_{eff} \epsilon_r^{eff}}{cC}. \quad (6)$$

As neither the capsule environment nor the biological tissues exhibit ferromagnetic properties, we can assume that $\mu^{eff} = 1$.

The capacitance C can be determined using the energy formulation,

$$C = \frac{2W_e}{V^2}, \quad (7)$$

Where W_e is the total electrical energy stored in the system and V stands for the electrical potential difference.

III. DESIGN AND MATERIAL

TABLE 1, Materials and their behavior,

Table 1: Material and Behavior

In this research endeavor, the focus lies on the meticulous design and optimization of a Dipole Tape Antenna intended for operation within the 433 MHz to 440 MHz frequency band.

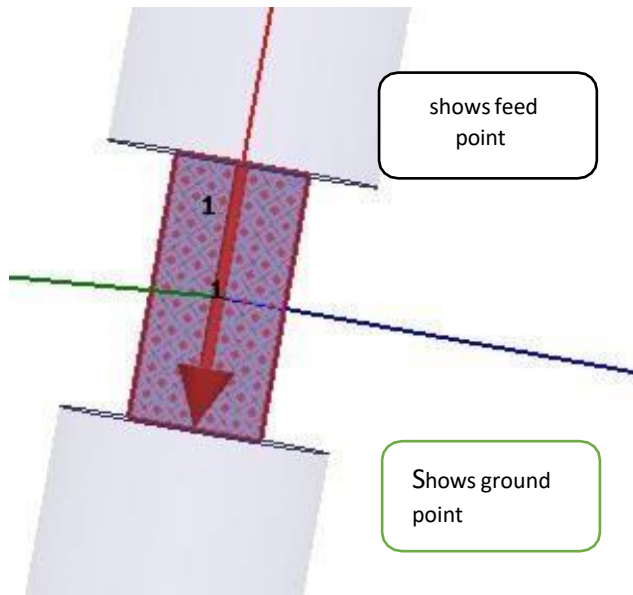


Fig. 1. Connection Gap Between Both Elements of Dipole Tape Antenna

Leveraging HFSS software, renowned for its proficiency in antenna design, the antenna's specifications are meticulously tailored to meet the unique requirements of this frequency range. The calculated gain of the Dipole Tape Antenna stands at approximately 4.65 dBi, Eq[22], demonstrating its efficacy in transmitting and receiving signals within the designated frequency band.

But the overall Design Gain is positive 5.7dBi.

TABLE [2], Angle and Gain parameters for 1MHz to 1GHz frequency band,

S/N o	Material	Relative Permittivity	Conductivity	Mass Density
1.	Copper	1	58×10^8 <i>si. e. iemens/m</i>	8933
2.	Aluminium	1	38×10^8 <i>si. e. iemens/m</i>	2689
3.	Silver	1	61×10^8 <i>si. e. iemens/m</i>	10500
4.	Steel_ Stainless	1	11×10^5 <i>si. e. iemens/m</i>	8055
5.	Iron	1	103×10^5 <i>i. e. iemens/m</i>	7870

Theta [deg]	dB(GainTotal) Setup1_LossAdaptive Freq=0.433GHz Phi=0deg	dB(GainTotal) Setup1_LossAdaptive Freq=0.433GHz Phi=10deg	dB(GainTotal) Setup1_LossAdaptive Freq=0.433GHz Phi=20deg	dB(GainTotal) Setup1_LossAdaptive Freq=0.433GHz Phi=30deg	dB(GainTotal) Setup1_LossAdaptive Freq=0.433GHz Phi=40deg	dB(GainTotal) Setup1_LossAdaptive Freq=0.433GHz Phi=50
1	-48.550064	-48.550064	-48.550064	-48.550064	-48.550064	-48.550064
2	-21.626466	-21.666630	-21.708660	-21.751059	-21.792427	-21.831046
3	-16.441877	-16.460955	-16.481838	-16.501516	-16.521295	-16.539375
4	-13.543741	-13.548938	-13.556738	-13.566225	-13.573008	-13.579442
5	-10.027879	-10.021489	-10.016850	-10.013888	-10.012267	-10.011616
6	-5.582346	-5.582163	-5.572390	-5.566797	-5.562619	-5.560686
7	-1.616784	-1.606158	-1.597866	-1.591538	-1.587772	-1.586269
8	1.290721	1.296712	1.306866	1.311979	1.316059	1.319187
9	3.033363	3.040633	3.046430	3.050687	3.053133	3.054141
10	3.618217	3.623945	3.628554	3.631902	3.634026	3.634985
11	3.065341	3.067307	3.061449	3.054119	3.046650	3.038714
12	1.331953	1.335494	1.338389	1.340488	1.341776	1.342348
13	-1.556961	-1.554002	-1.551632	-1.550098	-1.549411	-1.549455
14	-5.544238	-5.541532	-5.539571	-5.538690	-5.539226	-5.540115
15	-10.105169	-10.101990	-10.100051	-10.098755	-10.101162	-10.104072
16	-13.861196	-13.855015	-13.850893	-13.848666	-13.850885	-13.854076
17	-16.843782	-16.831346	-16.822434	-16.817019	-16.817254	-16.821487
18	-21.945113	-21.919689	-21.901427	-21.891161	-21.889465	-21.896722

Table 2: Angle and Gain Behavior at different Frequencies (1MHz to 1GHz)

Copper is selected as the primary material for constructing the antenna due to its exceptional electrical conductivity, making it well-suited for high-frequency applications such as this. The dimensions and configuration of the Dipole Tape Antenna are intricately crafted to ensure optimal performance, with careful consideration given to factors such as radiation pattern, impedance matching, and overall efficiency. By focusing on the design intricacies and material selection specific to the 433 MHz frequency band, the Frequency plot with overall Gain at different frequencies is shown in Fig. 3.

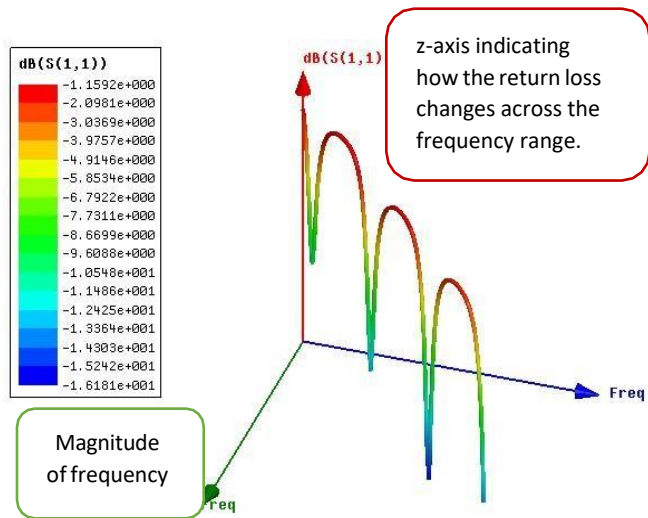


Fig. 2. Frequency Plot

This research aims to contribute to the advancement of Dipole Tape Antenna technology for applications ranging from telecommunications to IoT and beyond.

IV. RESULTS AND DISCUSSIONS

The performance of the Dipole Tape Antenna designed for operation within the center frequency 433 MHz frequency band is comprehensively analyzed and evaluated. The key parameters such as gain, radiation pattern, impedance matching, and bandwidth are scrutinized to assess the antenna's effectiveness and suitability for its intended application. Fig. 5, frequency sweep graph, Y-Axis in dB and X-Axis is the frequency,

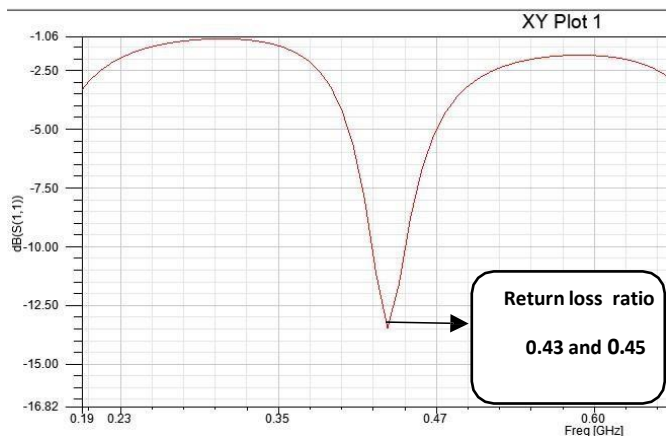
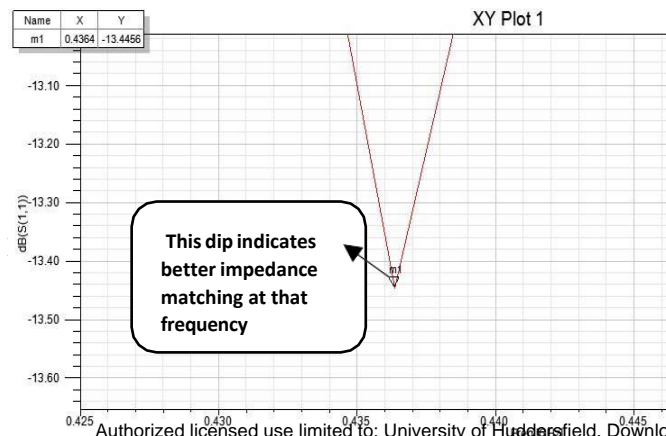


Fig. 4. Frequency sweep and Graph behavior



A. Gain Analysis

The calculated gain of the Dipole Tape Antenna, approximately 5.7 dBi, is compared with simulated results (5.5 dBi) to validate the design's efficacy. Any disparities between simulated and calculated gains are explored, and potential reasons for such deviations are discussed. The achieved gain is also compared with industry standards as well as requirements to ensure the appropriate performance of the antenna. Overall gain in dB scale in fig. 6 is shown.

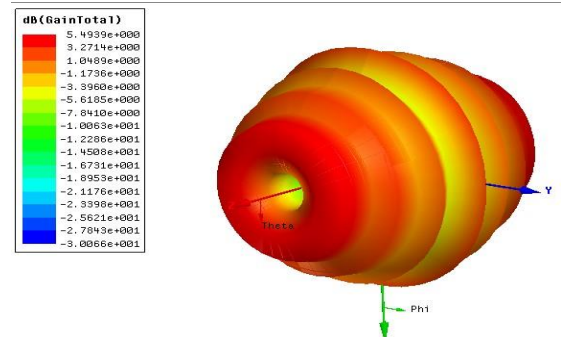


Fig. 6. 3D Rectangular Plot

B. Radiation Pattern

In the analysis of the radiation pattern, we focused on how the Dipole Tape Antenna performed concerning directionality and coverage. To understand how efficiently the antenna radiates in desired directions while suppressing any unwanted radiation in particular directions, we set up a vacuum cube and observed how transmission properties Fig. 7.

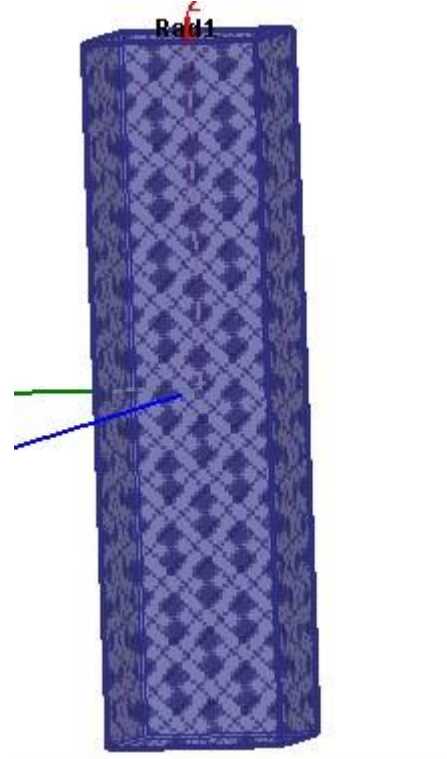


Fig. 7. Radiation Boundary

Any asymmetry irregularities within the radiation pattern were paid close attention to, and we sought to understand how these items may impact the antenna's performance, Fig. [9]. Through radiating pattern analysis of this type, we learn about the behavior and suitability for a given application within the 433 MHz frequency band.

Fig. 8 Radiation Pattern,

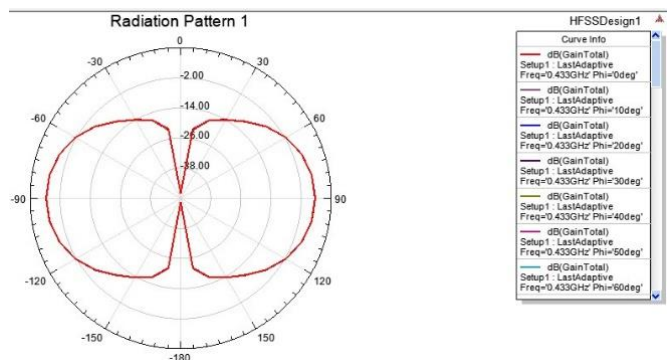


Fig. 8. 2D Radiation Pattern

C. Impedance Matching and Bandwidth

We also analyzed the Dipole Tape Antenna's capacity to transfer the power efficiently at 433MHz, having an impedance of 73 ohms. We also measured the bandwidth of the antenna, that is, the frequency range over which it can operate effectively. Our calculated bandwidth for this antenna is 11.55 %, which is indicative of the antenna's capacity to span a fair part of the spectrum around the frequency being targeted. Through our analysis, we found challenges when trying to optimize impedance matching and having enough bandwidth, so in these cases, we looked at potential solutions and optimizations for them. We address these considerations to improve the overall performance and effectiveness of the Dipole Tape Antenna in the 433 MHz operating band.

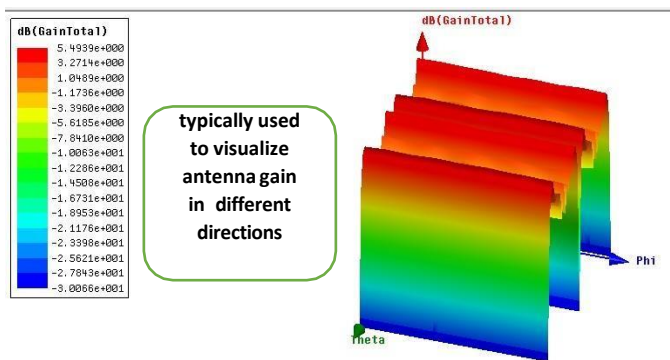


Fig. 9. Polar Plot

D. Material Selection and Fabrication Considerations

Like Table 1, agreeing that choosing Cu as the main material of the Dipole Tape Antenna, due to its electrical conductivity, durability, and suitability for high frequency application and achieving a high range to gain a better performance. As with any

fabrication process, whether its machining or additive manufacturing, it is considered how to avoid such constraints.

V. HARDWARE DESIGN

As shown in Table 1, we agree that from making Cu is the preferred material for the main part of the Dipole Tape Antenna, since, its electrical conductivity and durability, and is suitable for high frequency applications, and has a high range to gain a better performance. Similar to any fabrication process — be it machining or additive manufacturing — a criterion to avoid such constraints is considered.



Fig. 10. Hardware Dipole Tape Antenna

Like software, this hardware outcome is highly effective in signal transmission and reception. The design and implementation of the antenna yield favorable results, resulting in reliable connectivity required for nanosatellite and CubeSat missions. The hardware performance matches expected criteria in a very meticulous testing and analysis, confirming the hardware is compatible with the desired applications. Overall, the performance of the antenna is shown to be suitable for establishing efficient communication links over the range of frequency under consideration, and hence helping to improve the overall functionality and the mission success of IoT nanosatellites and CubeSats.



Fig. 11. SMA Brass Connector (female to female)

VI. ELECTRIC FIELD ANALYSIS

A Dipole Tape Antenna was designed for CubeSat applications at RF frequencies of 1MHz to 1GHz by careful analysis of the vector field electric field domain. Here, the purpose is to gain a deeper understanding of the distribution and polarization of the electric field at the antenna structure. This includes witnessing back radiation pattern, impedance matching, and the efficiency over the frequency band of interest. Engineers can understand the

performance of the antenna by comprehensively analyzing the vector field, optimizing the antenna's performance to optimize specific requirements of CubeSat communication systems in satellite communications and guarantee reliable transmission and reception of satellite signals that work in designated frequency bands and meet the subject space and weight limitations of CubeSat platforms. Fig. 12 shows E-Field analysis in HFSS,

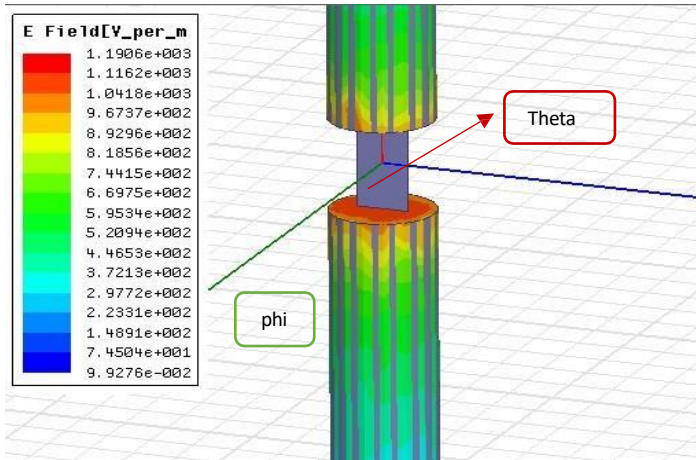


Fig. 12. E-Field Analysis (Vector)

VII. COMPARATIVE ANALYSIS AND FUTURE DISCUSSION

CubeSats and PocketQubes are both promising trajectories for the future of satellite technology. With their small size, light weight, and affordability, they afford unprecedented possibilities for scientific and Earth observation research as well as for communication. These nano-satellites rely on this Dipole Tape Antenna as a cornerstone component that will help transmit critical data from space to ground stations. For future advancement of Dipole Tape Antenna technology, CubeSats and PocketQubes will still depend on improving the capabilities and reliability of the radio. The designs of the Dipole Tape Antenna will be refined further for gain, bandwidth, and radiation efficiency in further work. Antenna technology is being explored on the boundaries of antenna geometries, materials, and fabrication techniques. By integrating advanced signal processing methods, including beamforming and polarization diversity, Dipole Tape Antennas can be adapted to multiple environments and combat signal interference to improve reliability and overall data throughput. Collaboration among academia, industry, and space agencies is key to a cooperative effort to develop standardized Dipole Tape Antenna designs and accommodate future CubeSat and PocketQube platform evolution. By fostering innovation and accelerating CubeSat-based mission adoption in domains such as telecommunications, remote sensing, and scientific exploration, this collaborative approach promotes CubeSat-based missions. With increasing CubeSat and PocketQube missions, we need to develop robust ground station networks and communication protocols to collect and downlink data that accumulates on Dipole Tape Antennas. Such a holistic approach will provide the greatest

utility to nano-satellite constellations and open a new age of space exploration and research.

Table [2] shows the Gain comparison,

Reference	Gain	Frequency
[2]	2.15dB	1GHz
[1]	2.91dB	450MHz to 950MHz
[6]	3.7dB	6.6GHz
This paper results	5.49dB	1MHz to 1GHz (Maximum Directivity for 400MHz to 440MHz)

Table 3: Results Comparison

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