ISSN (Online) 2394-6849

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)

Vol 12, Issue 04, April 2025

Advanced Polarized Metasurfaces for Small Satellite Communications: Circular, Linear, and Dual Polarization Approaches

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***Abstract*— Metasurface antennas provide a compact and efficient solution for high-performance communication in small satellites, particularly within the X-band (8–12 GHz). This paper explores the design, analysis, and comparison of circular, linear, and dual-polarized metasurfaces, employing a single monopole feed for CubeSat applications. The proposed designs offer polarization diversity while maintaining a space-efficient structure suitable for satellite integration. HFSS simulations are conducted to evaluate key performance metrics, including Gain, S Parameter, and Radiation Pattern. The findings highlight the trade-offs among different polarization states in terms of signal integrity and environmental adaptability, offering valuable insights for optimizing metasurface antennas to enhance link reliability and polarization versatility in small satellite communications.**

Index Terms*— Gain, HFSS, Holography, Metasurface, Phase correction factor, Polarization, S Parameter.

I. INTRODUCTION

Metasurface antennas are emerging as a compact, lightweight, and highly efficient solution for modern communication systems, making them well-suited for CubeSat and SmallSat applications, where size, weight, and power (SWaP) constraints are critical. Their ability to manipulate electromagnetic waves allows for beam shaping, polarization control, and improved radiation performance, addressing the limitations of conventional antennas. These characteristics make metasurfaces particularly advantageous for high-frequency satellite communication, especially within the X-band (8–12 GHz), which is widely used in Earth observation, radar sensing, and deep-space CubeSat missions.

Polarization plays a crucial role in satellite communication, directly impacting signal quality and system performance. Circular polarization (CP) helps mitigate multi-path fading and Faraday rotation, ensuring greater signal stability in space environments. Linear polarization (LP) provides high directivity and efficiency, making it effective for applications requiring focused beam control. Meanwhile, dual-polarization (DP) facilitates the simultaneous transmission of orthogonal wave components, enhancing data capacity and link reliability [1]. However, each polarization state involves trade-offs in Gain, S Parameter, and Radiation pattern, necessitating a comparative analysis to identify the most suitable configuration for CubeSat-based communication systems [2].

This paper presents the design, analysis, and comparative evaluation of circular, linear, and dual-polarized metasurface antennas designed for X-band CubeSat applications. A single monopole feed is employed to achieve a compact and efficient architecture optimized for space-constrained platforms. Performance metrics such as gain, S Parameter, and radiation pattern are analyzed using HFSS simulations, providing key insights into optimizing metasurface antennas for polarization diversity, signal integrity, and reliable CubeSat communication links.

II. METASURFACE

Artificially created materials with desired, useful qualities are called metasurfaces. Materials having desired effective material properties assembled at a sub-wavelength scale are called metamaterials. Material properties that are absent from nature can be attained [3], [4], [5]. In order to produce metamaterials with the necessary bulk properties, small inclusions are often packed into a three-dimensional lattice. Metasurfaces are the two-dimensional equivalents of these volumetric metamaterials. They consist of holes or scatterers arranged along a surface that have distinctive transmission, reflection, or dispersion properties [6].

This meta-unit cell is arranged in a particular way to create a metasurface, as shown in Fig. 1. The desired radiation beams that we are targeting determine how this meta-unit cell is arranged. We have the concept of surface waves produced by a particular feed design, which can be monopole feed, horn feed, aperture coupling [7], etc. The meta-unit cells are positioned in various configurations to produce the appropriate radiation waves using this reference surface wave. The surface's surface impedance determines this configuration. The desired waves are used to determine the

ISSN (Online) 2394-6849

International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)

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surface impedance, which is then used to arrange the meta-unit cells.

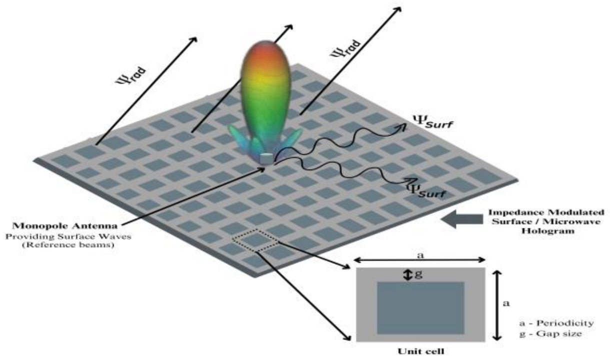

Fig. 1. 2D Metasurface and its unit cell

Finding the impedance matrix, which characterizes the metasurface's reaction to incoming electromagnetic waves, is a crucial step in the construction of a metasurface in HFSS. The size, shape, and material characteristics of the patches or units that comprise the metasurface are among the criteria that are taken into account when computing this matrix using a particular equation. This impedance computation is done using a MATLAB function. The impedance matrix essentially provides the impedance of every patch according to the electromagnetic radiations. Different polarization techniques also make significant changes in the meta unit cell arrangement. The pattern of arranging unit cells in linear polarization is different from circular polarization. More different patterns will be obtained when two polarizations are incorporated together

[8].

III. DESIGN THEORY

The design procedure of Metasurface is based on the technique of Holography.

A. Holographic Patterning

The process of recreating an object's two-dimensional pattern or three-dimensional structure is called holography. Light waves encode detailed spatial information onto a material, and this technique entails recording and recreating the interference patterns they produce [9]. To observe the image, two beams in this notion converge on a photographic plate. A laser beam is scattered from the object to be photographed to create one wave, while the same laser produces a reference plane wave. Photographic film captures the interference pattern created by these two waves [10]. The interference pattern for an object wave φ_{obj} and a reference beam φ_{ref} is proportional to $\varphi_{ref}^{*}\varphi_{obj}$ as illustrated in Fig. 1.

The same approach stated above is employed in hologram design [11]. There are two beams here as well: the reference beam and the targeted beam. A surface wave known as a reference beam is often produced by a source antenna. The object wave matches the required radiation pattern. The surface wave represented by φ_{surf} serves as the reference wave. The object wave is the desired radiation pattern, denoted by φ_{rad}.

From Wave theory, the surface wave generated by the feed is mathematically given by

$$\varphi_{surf} = e^{-jknr} \tag{1}$$

The Object wave / Desired radiation is given by

$$\varphi_{rad} = e^{-jk(x\cos\emptyset y\sin\emptyset)\sin\theta} \tag{2}$$

Here n = effective refractive index r = radial distance from monopole feed θ, ϕ = Desired Elevation and Azimuthal angles. These two angles together provide a complete way to specify the position of an object in a three-dimensional space, relative to a specific point of observation. The Surface Impedance of the Holographic metasurface is:

$$Z(x_t) = j[X + MRe(\varphi_{rad}\varphi_{surf}^{*})] \tag{3}$$

That is,

$$Z(x_t) = j[X + MRe(e^{-jk(x\cos\emptyset + y\sin\emptyset)\sin\theta}.e^{jknr})] \tag{4}$$

Where X_t = Position of the point on the surface concerning the origin Here, X is the average impedance value of the surface. The modulation factor/modulation depth, or "M," is what regulates the beam's width and gain. x_t is the point on the impedance surface with respect to the origin. Here in this case, it will have (x, y) coordinate values as it is 2D. e^{jknr} is the phase correction term. It ensures that the metasurface can effectively control and manipulate electromagnetic waves in the desired manner. For any polarization, the metasurface can be designed by the equation,

$$Z(x_t) = j[X + MRe(\psi_{ext}^{*}.\psi_{rad.}\psi_{surf}^{*})] \tag{5}$$

1) For linear polarization, ψ_{ext} is 0. Hence, Eqn. 5 becomes,

$$Z(x_t) = j[X + MRe(e^{-jk(x\cos\emptyset + y\sin\emptyset)\sin\theta}.e^{jknr})] \tag{6}$$

2) For circular polarization $\varphi_{ext}^{*} = e^{-j(\theta + \frac{\pi}{4})}$

Where $\theta = tan^{-1}(\frac{y-y_0}{x-x_0})$ .Thus, the equation $Z(x_t) =$

$$j[X + MRe(e^{-j\{\tan^{-1}\left(\frac{y-y_0}{x-x_0}\right)+\frac{\pi}{4}\}}e^{-jk(x\cos\emptyset + y\sin\emptyset)\sin\theta}e^{jknr}] \tag{7}$$

3) Hence, for a Dual Polarized Metasurface, the equation becomes

$$Zoverall = 0.5(Zsurf1 + Zsurf2) \tag{8}$$

Where Z_{surf1} corresponds to a Linearly Polarized Surface and Z_{surf2} corresponds to a Circularly Polarized Surface.

IV. METHODOLOGY

A. Unit cell design

A unit cell is the fundamental building block of metasurface design. The square patched unit cell is most common, which is shown in Fig. 2. These are designed to interact with electromagnetic waves in a controlled manner. Here, the substrate used is Rogers RT/Duroid 5880 with 1.575 mm thickness and a periodicity of 5 mm. It is designed with a resonating frequency of 10 GHz.

ISSN (Online) 2394-6849
International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
Vol 12, Issue 04, April 2025

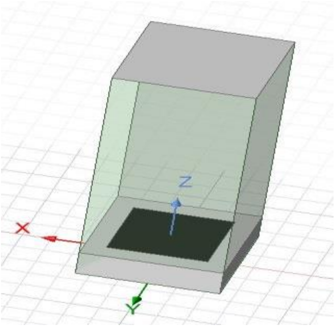

Fig. 2. Unit cell with square patch

B. Monopole Feed

This design utilizes monopole feeding, a mechanism in which a monopole antenna is energized through a single, centrally located feed point, typically positioned at its base. The monopole (Fig. 3) is constructed by using 2 cylinders of PEC (Perfect Electric Conductor) material, the outer cylinder of radius 0.6 mm and the inner cylinder of radius 0.3 mm. Both have a height of 3 mm.

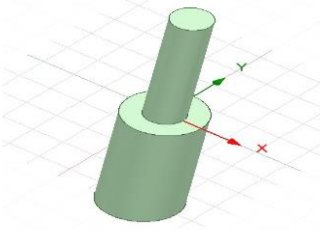

Fig. 3. Monopole feed

In monopole feeding, a coaxial cable is frequently used to link the antenna to the feed directly. The outside conductor serves as the ground plane, and the inner conductor provides the monopole with the signal. The most popular technique is coaxial feeding, in which the antenna is directly connected to the coaxial cable. The patch was taken out of the spot where the monopole feed was supposed to be placed. In this case, the monopole feed was placed in the middle of the surface.

C. Design Procedure of Metasurface

Eigen mode analysis is performed on the unit cell to generate the dispersion plot, which illustrates the relationship between the wave vector and the operating frequency. From this plot, the phase values corresponding to 10 GHz are extracted, and the corresponding gap values are determined. The dispersion curve, derived from Eigen mode analysis, serves as the basis for further calculations, and the obtained gap values are compiled into an Excel sheet. A gap vs impedance plot is then created by mapping each unit cell's impedance to its respective gap value. This plot is refined using MATLAB's curve fitting tool to ensure a smooth and accurate representation. The impedance is interpolated across all gap values, and an Excel sheet containing the interpolated gap and impedance values is generated, forming the Gap Matrix.

This Gap Matrix is then imported into a Python script for metasurface synthesis. The Python script is executed within HFSS to generate the metasurface design, ensuring accurate phase compensation and performance optimization. Design equations are adjusted and modified to create Linear, Circular, and Dual Polarized Metasurfaces.

D. Linear Polarization and Circular Polarization

A polarized metasurface manipulates electromagnetic waves to control beam direction and wave shaping. A linear polarized metasurface maintains a fixed polarization for applications like antennas and wireless communication, while a circular polarized metasurface handles [12] rotating electric fields to enhance signal stability, making it ideal for satellites and radar systems. A linear polarized metasurface is made by using Eqn.6, and a circular polarized metasurface is made by Eqn. 7. Fig. 4 depicts linear and circular metasurface designed in HFSS.

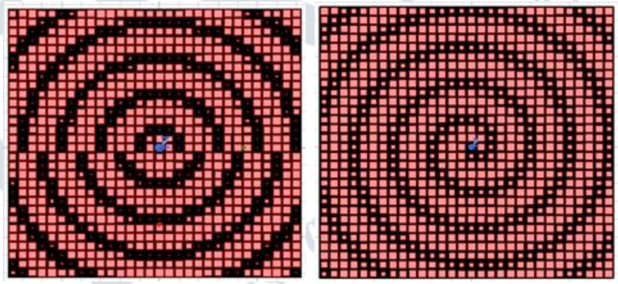

Fig. 4. Linear and Circular Polarized Metasurface

E. Dual Polarization

A dual-polarized metasurface controls electromagnetic waves in two orthogonal polarization states, supporting both linear and circular polarization for efficient signal transmission [13]. It enhances bandwidth, enables polarization diversity [14], and reduces interference, making it ideal for antennas, MIMO systems [15], base stations [16], radar, and satellite communication. Proper design helps suppress cross-polarization effects, ensuring high signal purity and minimizing unwanted polarization leakage [17]. A Dual-polarized metasurface is made by using Eqn. 8. The Dual-polarized surface designed in HFSS is shown in Fig. 5. Dual-polarized metasurfaces commonly provide better efficiency but have a complex design.

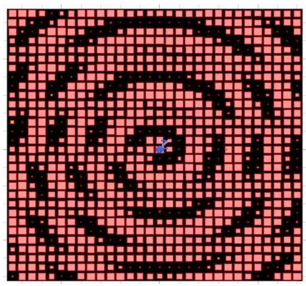

Fig. 5. Dual Polarized Metasurface

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International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
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V. RESULTS AND DISCUSSION

After completing the validation check, analysis was performed to find parameters such as Return loss, Gain, Directivity, Radiation pattern, and Efficiency.

A. S parameter

S_{11}, sometimes referred to as the reflection coefficient, aids in determining the return loss of an antenna. It indicates how much of the signal is reflected into the antenna due to impedance mismatches between the antenna and the feed line.

A return loss below -10 dB signifies efficient power rejection and desirable radiation characteristics.

1) ***Linear Polarization:*** The S-parameter (S_{11}) reaches its minimum value of -11.7067 dB at 14 GHz. Return loss is found to be less than -10 dB from 13.75-14.25 GHz, as depicted in Fig. 6.

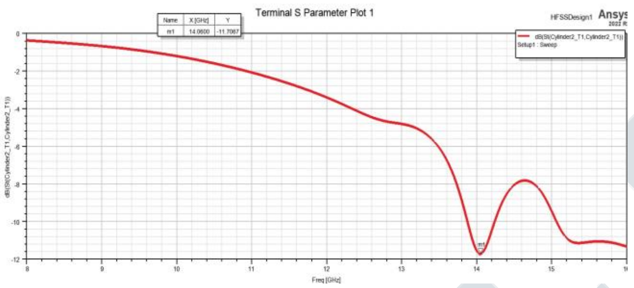

Fig. 6. S-parameter plot for Linear polarized metasurface

2) ***Circular Polarization:*** The lowest value of the S-Parameter (S_{11}) is -13.8841 dB at 14 GHz, which can be observed from Fig. 7. From 15 GHz, the return loss was less than -10 dB.

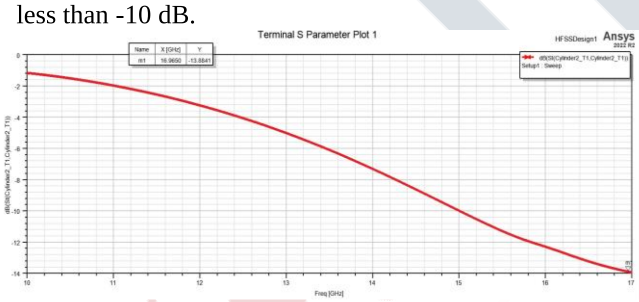

Fig. 7. S parameter plot for circular polarized surface

3) ***Dual Polarization:*** At 16 GHz, the S-parameter (S_{11}) drops to a minimum of -12.31531 dB. It is discovered that the return loss is less than -10 dB from 15 GHz (Fig. 8).

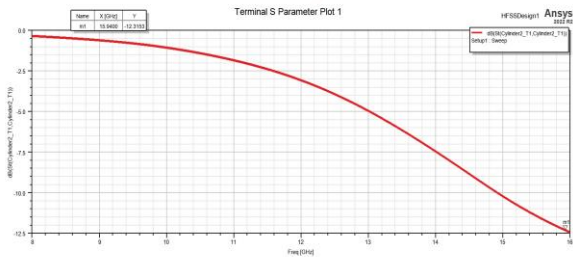

Fig. 8. S parameter plot for Dual polarized metasurface

B. Gain

The gain of a metasurface antenna defines its ability to direct electromagnetic energy compared to a reference antenna. Gain of antenna is influenced by its polarization, design of the unit cell, operating frequency, etc.

1) ***Linear Polarized Surface:*** Here, θ and Φ both are set at 0; thus, the gain peak is obtained (Fig. 9) at the (0, 0) position. The gain obtained here is 19.6527 dB. Fig. 10 shows the 3D gain plot.

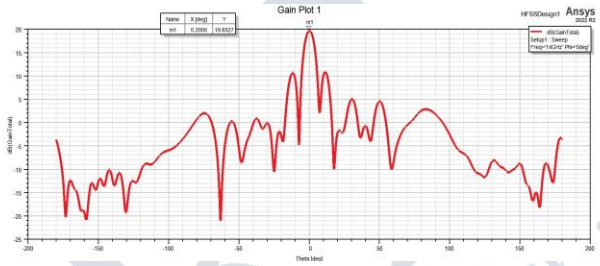

Fig. 9. Gain plot for linear polarized metasurface

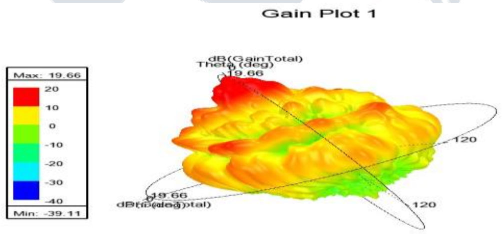

Fig. 10. 3D Gain plot

2) ***Circular Polarized Surface:*** Here, polarization is changed from linear to circular θ and Φ are still 0, thus the gain peak is obtained at position (0, 0). The gain obtained here is 19.1420 dB (Fig. 11). Fig. 12 shows the 3D plot.

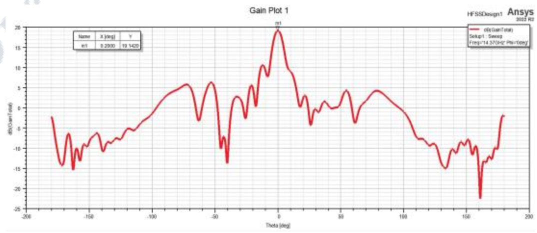

Fig. 11. Gain plot for Circular polarized metasurface

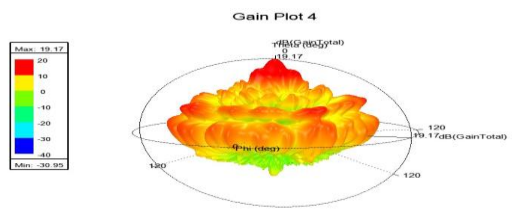

Fig. 12. 3D Gain plot

3) ***Dual Polarized Surface:*** Since this is a dual-polarized surface, it represents the combined gain of both polarizations (linear or circular). The highest gain observed here is 15.37 dB at 14 GHz. Gain reduction is observed in

ISSN (Online) 2394-6849
International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)
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Fig. 13 due to the combination of 2 polarizations. 3D gain plot of the same is in Fig. 14 which consists of 2 beams.

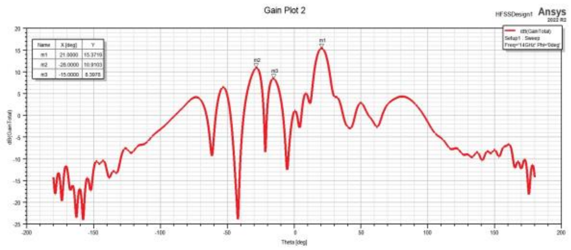

Fig. 13. Gain plot for dual-polarized metasurface

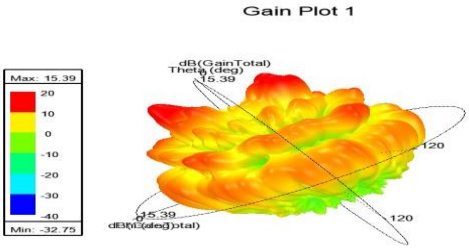

Fig. 14. 3D Gain plot

C. Radiation pattern

The radiation pattern of an antenna describes how it effectively radiates energy into space. Directional antennas usually have their radiation in a particular direction.

1) Linear Polarized Surface: The beam is directional, indicating the surface is radiating energy in a specific direction rather than isotropically. The main lobe is centred around 0 degrees with a peak gain above 10 dB can be viewed in Fig. 15. There are multiple side lobes around ±30 degrees to ±90 degrees. A small back lobe is also present, indicating very little backward radiation.

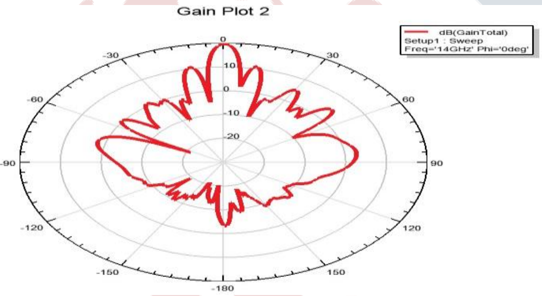

Fig. 15. Gain plot

2) Circular Polarization: Pattern exhibits symmetry which is a characteristic feature of circular polarization as it radiates uniformly in a plane. Here also the pattern is directional with main lobe centred on 0 degrees. The magnitude of side lobe and back-lobe radiation is considerably lower compared to the main lobe (Fig. 16). The gain distribution is smoother and more uniform, which is typical for circular polarization.

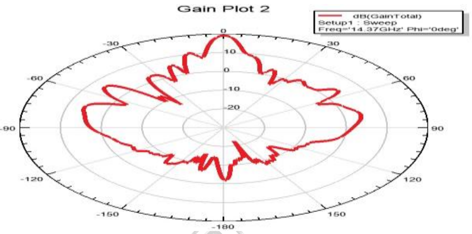

Fig. 16. Gain plot

3) Dual Polarization: Compared to the linear and circular polarization pattern, the dual polarization radiation pattern exhibits a more balanced response. The pattern (Fig. 17) suggests improved coverage and polarization diversity [15]. The gain variations are more pronounced reflecting the influence of both polarizations. The slight asymmetry is due to variations in polarization efficiency across different angles.

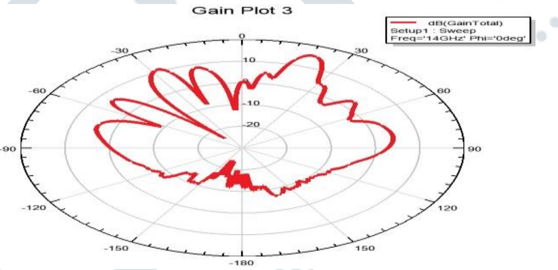

Fig. 17. Gain plot

D. Comparison

Table I: Comparison Table

Sl.no	Parameters	LP	CP	Dual
1	S-parameter	-11.706 dB	-13.88 dB	-12.315 dB
2	Gain	19.6527 dB	19.142 dB	15.37 dB
3	Beams	One beam	One beam	Two beams

Table I shows the comparison between LP, CP and dual polarised metasurface design. Linear polarized (LP) antennas radiate waves in a single plane, offering high gain (6-12 dBi), wide bandwidths (10-20%), and high efficiency (>80%), making them ideal for wireless communication and radar. Circular polarized (CP) antennas ensure stable signal reception regardless of orientation but have moderate efficiency (70-85%) and narrower bandwidths (5-15%) due to axial ratio constraints. Dual-polarized (DP) antennas support both LP and CP, providing high efficiency (70-90%), wide bandwidths (10-25%), and enhanced performance in 5G, radar, and satellite communication, though their complex designs ensure polarization separation. Cross polarization and side lobe suppression is observed in dual polarization [18], [17].

VI. CONCLUSION

Each polarization technique offers distinct advantages

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International Journal of Engineering Research in Electronics and Communication Engineering (IJERECE)

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depending on the specific communication requirements and environmental conditions. Linear polarization (LP) metasurfaces provide high gain, efficiency, and wide bandwidth, making them well-suited for applications where satellite orientation is fixed and precise beam directionality is required. However, their susceptibility to polarization mismatch limits their effectiveness in dynamic environments. Circular polarization (CP) metasurfaces, in contrast, offer better signal stability and robustness against polarization misalignment, making them ideal for satellite-based applications.

Dual-polarized (DP) metasurfaces emerge as the most versatile option, combining the strengths of both LP and CP antennas. By supporting multiple polarizations, DP antennas enhance spectrum efficiency, maximize data throughput, and improve link reliability, making them highly suitable for MIMO systems, and high-capacity satellite links [1]. Despite their more complex design requirements, their ability to support multiple signals and polarization diversity makes them a crucial technology for next-generation satellite communications, like CubeSat applications.

This research can be expanded to include the construction of metasurfaces with various feeding methods, such as horn feeding, and dual feed antennas for CubeSat applications. By altering the feeding methods and substrate composition, numerous comparison studies may be conducted.

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