

Bandwidth Improvement of Optically Transparent Meshed Patch Antennas for CubeSat Applications

by

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A thesis submitted to the Faculty of Graduate and
Postdoctoral Studies of The University of Manitoba
in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

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Abstract

Antennas are essential for satellite communication. With the rapid growth of small satellite platforms, antennas must be miniaturized too, which is often at the cost of gain and link quality degradation. Deployable antennas used in conventional satellites add complexity, cost, and risk of failure. To address these challenges, optically transparent multifunctional antennas have been developed, allowing integration with solar cells to utilize space effectively without sacrificing performance. Among the various approaches for optical transparency, meshed patches offer a high level of transparency and efficiency. However, they suffer from low impedance bandwidth, which is critical for high-data-rate and high-resolution applications, and this thesis addresses these short-comings through novel design approaches.

This thesis explores the impact of geometry changes, transparency level, substrate material, and conductor losses on the radiation properties of square meshed patches. The findings offer guidelines for selecting the optimal mesh line width and number based on desired performance and transparency. To enhance the bandwidth of transparent meshed patch antennas, a stacking technique was applied to a single-layer square meshed patch, achieving around five times greater bandwidth compared to a single-layer antenna with identical dimensions. This led to further exploration of using polymer material between the patches, resulting in a lightweight antenna. Four novel low-profile, optically transparent meshed patch antennas with enhanced bandwidth and full integrability with CubeSat solar cells were designed, and two of them were developed and tested. The first antenna used fused silica glass substrate as dielectric layers to maintain transparency and high integrability with solar cells, resonating at 2.5 GHz, with an impedance bandwidth of 6.2%, a peak gain of 6.5 dBi, and efficiency exceeding 90%. In the second design the upper glass

substrate was replaced with a polymer layer to reduce weight at the cost of lower efficiency. For further weight reduction, the polymer layer was first partially removed and then perforated, resulting in a lightweight stacked meshed patch antenna which compensates for the efficiency and is suitable for direct placement on solar cells without affecting their performance. The glass-glass stacked antenna and glass with a partially removed polymer layer were prototyped and measurement results confirmed simulations.

Overall, this thesis establishes a comprehensive design framework for wideband, lightweight, optically transparent meshed patch antennas, demonstrating that their traditional bandwidth limitations can be effectively mitigated without sacrificing efficiency or integrability. These contributions position transparent meshed patch antennas as a high-performance solution for multifunctional platforms.

Acknowledgments

I would like to express my heartfelt gratitude to Dr. Cyrus Shafai for giving me the opportunity to pursue my research at the University of Manitoba and the Nano System Fabrication Laboratory (NSFL). I am deeply thankful for his continuous support, patience, and encouragement throughout my Ph.D. journey. His vast knowledge and guidance have been invaluable in shaping both my research and the writing of this thesis.

I am very grateful to Dr. Dustin Isleifson for his valuable advice and scientific support throughout my research. His insightful suggestions and constructive feedback have greatly contributed to the quality and rigor of my work.

I would like to thank Dr. Philip Ferguson for his guidance and support throughout my research. His expertise and thoughtful feedback have contributed to the development of this thesis.

I would like to sincerely thank Dr. Lot Shafai for his valuable scientific guidance and support throughout my research. His expertise and insightful advice were critical in overcoming challenges and advancing my work. I also greatly appreciate his willingness to share his knowledge, which has significantly contributed to the successful completion of this thesis.

I am very thankful to James Dietrich for his assistance with antenna measurements. I truly appreciate his willingness to help, which greatly facilitated the experimental part of this research. My sincere thanks also go to Dwayne Chrusch for teaching me practical skills in the cleanroom, Mount-First Ng and Cory Smit for their technical support.

Finally, I would like to thank my family and friends for their constant encouragement and support throughout this journey.

*To my beloved husband, Amirreza,
for his endless love, patience, and encouragement.*

*To my parents, Sorayya and Mohammad Taghi,
for their unwavering support, sacrifices, and faith in me.*

*To my sister, Shiva,
for her kindness, companionship, and constant encouragement.*

*This work is also dedicated to all my friends and loved ones
who stood by me throughout this journey.*

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Notation and Abbreviations

IU	1 Unit
TTC	Telemetry, Tracking and Command
CP	Circular Polarisation
RF	Radio Frequency
TCO	Transparent Conductor Oxide
ITO	Indium Tin Oxide
FTO	Fluorine-doped Tin Oxide
TMPA	Transparent Meshed Patch Antenna
GPS	Global Positioning System
MIMO	Multi Input Multi Output
PET	Polyethylene Terephthalate
IZTO	Indium-Zinc-Tin Oxide
GZO	Gallium-doped Zinc Oxide
LHCP	Left-Hand Circular Polarization
LP	Linear Polarisation
X-pol	Cross Polarisation
PEC	Perfect Electric Conductor
BER	Bit Error Rate
SNR	Signal to Noise Ratio
EIRP	Effective Isotropic Radiated Power
MEMS	Micro-Electro-Mechanical Systems
PDMS	Polydimethylsiloxane
UV	Ultraviolet
PEB	Post Exposure Bake

Chapter 1

Introduction

1.1 Background and Motivation

Small satellites, typically defined as satellites with a mass below 500 kg, have become central to modern space missions due to their lower development costs, shorter lead times, and reduced launch expenses. These advantages contrast with traditional large satellites, which often require multi-year development cycles and substantial financial investment. Among small satellites, the development of CubeSats started in 1999 by California Polytechnic State University and Stanford University to support university-level space research [1], has revolutionized the space industry by significantly reducing launch costs and time, and making space exploration more accessible to the public and academic institutions. CubeSats have now been embraced by space agencies, private companies, and educational institutions worldwide.

A standard CubeSat unit, referred to as "1U", measures just $10 \times 10 \times 10 \text{ cm}^3$ and weighs approximately 1.33 kg. Configurations of 1U, 2U, 3U, or even 6U and 12U are now common, with modular designs [2]. CubeSats have successfully been deployed for a range of applications, including planetary science, solar and space physics, earth science, biological and physical sciences, space weather monitoring, and various technological experiments [3]. Their rapid development cycle and commercial off-the-shelf components have enabled access to space in an unprecedented way.

Despite these advantages, CubeSats face challenges that stem from their limited surface area and strict mass and power budgets. One of the most significant challenges is power availability. Since CubeSats rely on solar panels for energy, maximizing solar exposure is vital. However, surface area is limited, and every component mounted on the exterior, including the antennas, competes with the space needed for solar cells. This creates a fundamental trade-off between communication performance and power generation.

Antennas play an important role in any spacecraft communication system. They are responsible for uplink and downlink of telemetry, tracking, and commands (TTC), high-speed downlink payload data, GPS/GNSS receiver, and potentially inter-satellite links [4]. In CubeSats, commonly used antennas include wire antennas, such as monopoles and crossed dipoles, which are valued for their simple circular polarization (CP) configurations and broad frequency operation. These antennas are often stowed during launch and deployed in orbit using mechanical mechanisms. For example, the Helios antenna [5] was developed as a deployable helical antenna, requiring about one-half of a 1U CubeSat structure to be stowed. Similarly, a deployable mesh reflector antenna designed in [6] to achieve high gain for CubeSat communications. While deployable antennas are effective in many cases, deployment systems are risky due to mechanical failure or incomplete deployment which can lead to mission-ending communication loss.

To mitigate this risk and simplify system architecture, microstrip patch antennas have been explored as alternatives. These antennas are low-profile, planar, and can be fabricated directly onto the surface of the spacecraft, eliminating the need for mechanical deployment. They are known for their robustness, ease of fabrication, and integration with planar structures. However, conventional patch antennas are opaque and occupy surface area that could otherwise be used for solar cells.

This has historically limited their adoption in CubeSat designs, where every available surface must ideally support energy harvesting.

To address this issue, researchers have developed optically transparent patch antennas that can be placed directly on top of solar panels without significantly blocking sunlight [7]. These antennas maintain radio frequency (RF) functionality while allowing light transmission to the photovoltaic cells beneath. To have an optically transparent patch antenna both the top conductor and the dielectric substrate must be optically transparent. Optical transparency of the conductive layer can be achieved using transparent conductive oxides (TCOs), such as indium tin oxide (ITO) [8] or fluorine-doped tin oxide (FTO) [9]. These materials have high sheet resistance compared to opaque metallic conductor. Therefore, the fabricated antenna typically exhibits greater losses than opaque metallic conductors, especially when higher optical transparency is desired. The ITO patch antenna designed in [8] only achieved less than 1 dBi gain at 4.9 GHz and 2 dBi at 26 GHz, the transparency reported as 84% and sheet resistance of $6 \Omega/\text{sq}$.

The other approach to achieve an optically transparent conductor for patch antennas is by employing metallic mesh patterns made from traditional conductors like silver or copper. Meshed metal designs stand out due to their excellent electrical conductivity and the ability to engineer optical transparency and antenna efficiency by controlling mesh geometry [10]. In [11], Neveu et al. designed an S-band patch antenna using metallic meshes for both the top conductor and ground plane. They optimized the mesh line width and spacing to achieve 90% optical transparency, 5.33 dBi gain, and 86% efficiency which is comparable to that of a solid patch. Clasen and Langley investigated meshed patch antennas and reported that increasing mesh transparency generally leads to reduced antenna performance [12]. This conclusion was based on their experiments where the number of mesh lines varied while keeping the line width constant. Later, Turpin [13]

demonstrated that for rectangular meshed patch antennas, performance metrics such as efficiency can be significantly improved by optimizing the mesh line width. These findings suggest that the electromagnetic behavior of meshed antennas is highly dependent on specific geometric parameters. Therefore, more systematic studies are needed to fully characterize and predict mesh antenna performance based on detailed mesh geometry.

While transparent meshed patch antennas (TMPAs) can provide high transparency (over 90%) and efficiency, allowing for seamless integration with solar cells, they suffer from limited impedance bandwidth, similar to conventional solid patch antennas. This limitation can restrict their use in applications that require high data rates and reliable wideband communication.

Moreover, the electromagnetic behavior of TMPAs is strongly influenced by mesh geometry, conductor thickness, and dielectric materials, yet these relationships remain insufficiently characterized in the literature. There is also a growing need for lightweight transparent antennas for small spacecraft, where mass constraints are strict. These challenges motivate a deeper investigation into the fundamental electromagnetic properties of transparent meshed structures and development of antenna configurations that can overcome their bandwidth and mass limitations while preserving transparency.

1.2 Research Contribution

This thesis first advances the scientific understanding of transparent meshed patch antennas by investigating how mesh geometry, specifically the line width and density, affects the key antenna performance metrics, including impedance bandwidth, gain, efficiency, and cross polarization. These results clarify the fundamental trade-offs inherent to meshed conductors and

provide predictive guideline for selecting mesh geometries based on the performance and transparency requirements (Chapter 3).

Second, building on this understanding, the research addresses the low impedance bandwidth of TMPAs by introducing stacking technique to meshed radiators. A detailed investigation of the effect of dielectric thickness, material properties, and interlayer coupling provides design principles that extend to other transparent multilayer antenna architectures (Chapter 4)

The thesis further explores polymer based transparent dielectrics, specifically SU-8 an epoxy-based negative photoresist, in full, partially removed, and perforated forms. The results show how polymer geometry influences effective permittivity, dielectric loss, and coupling strength, enabling mass reductions of up to 68% while maintaining high radiation performance. These findings provide new insight into how polymer materials can be engineered to create lightweight transparent antennas suitable for mass-constrained spacecraft (Chapter 5).

Finally, the proposed architectures are validated experimentally through the fabrication and measurements of three prototypes. The close agreement between the simulation and measurement results confirms the practical feasibility of the stacked TMPA concepts and demonstrates the potential of using SU-8 or other polymer-based materials as main dielectric substrate for lightweight transparent antennas (Chapter 6).

This thesis is guided by the following research questions:

1. How do mesh geometry parameters such as line width, mesh density, and transparency level affect the radiation properties of the meshed patch antenna?
2. What physical properties fundamentally limit the bandwidth of single-layer transparent meshed patches?

3. How can stacking technique overcome the inherent bandwidth limitations of single-layer TMPAs?
4. How do transparent dielectric materials, including fused silica and polymer-based substrates, influence electromagnetic coupling and overall antenna performance?
5. To what extent can polymer or perforation techniques be used to reduce antenna mass while preserving transparency and radiation performance?

Overall, these contributions advance the state of the art and strengthen the foundation for future transparent and multifunctional antenna systems.

1.2.1 Contributed Research Publications

The following publications were published and are directly related to the topic of this thesis. The paper presented at the ANTEM 2025 Symposium received First Place in the Women in Engineering Best Paper Award.

[Conference Proceedings]

1. **S. Ramezanzadehyazdi**, C. Shafai, D. Isleifson, and L. Shafai, “Bandwidth improvement of transparent meshed patch antennas using stacking technique,” *Proc. IEEE 19th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM)*, Winnipeg, MB, Canada, 2021, pp. 1-2.
 - Extended the stacking technique to transparent meshed patch antennas, demonstrating that stacking can effectively overcome their inherently narrow impedance bandwidth while preserving high optical transparency.
 - Introduced a systematic design method for creating stacked meshed patch antennas with closely spaced resonances, providing a practical step-by-step procedure for achieving wideband performance.

- Proposed a new stacking approach that eliminates the need for air or foam substrates.

This results in a more mechanically stable structure for space applications.

2. V. Platero, **S. Ramezanzadehyazdi**, D. Isleifson, C. Shafai, and P. Ferguson, “Fabrication of an embedded multifunctional structural antenna for spacecraft applications,” *Proc. IEEE 19th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM)*, Winnipeg, MB, Canada, 2021, pp. 1-2.

- Fabricated a multifunctional embedded structural antenna by integrating a copper microstrip patch directly onto a hybrid composite panel using SU-8 as the dielectric layer.
- Developed and implemented modified SU-8 deposition and curing procedures to work within the strict thermal limits of the hybrid composite, preventing delamination while achieving a stable thick polymer layer.
- Adapted the copper sputtering process to deposit a uniform conductive patch without exceeding composite temperature constraints.

3. **S. Ramezanzadehyazdi**, C. Shafai, D. Isleifson, P. Ferguson, and L. Shafai, “An SU-8/glass meshed patch antenna for integration with solar cells”, *Proc. 16th European Conference on Antennas and Propagation (EuCAP)*, Madrid, Spain, 2022, pp. 1-5.

- Introduced SU-8 negative photoresist as the upper dielectric layer in a stacked structure, provided adjustable thickness, strong adhesion, mechanical robustness, and lower mass than glass.
- Showed that depositing SU-8 on glass avoids fabrication challenges associated with thermal mismatch and temperature limits observed in previous SU-8/composite implementations.

- Characterized stacked meshed patch antennas, including over-coupling the lower patch, tuning the feed location, selecting substrate heights, and defining upper and lower patch lengths to maximize the antenna bandwidth.
4. **S. Ramezanzadehyazdi**, C. Shafai, D. Isleifson, P. Ferguson, and L. Shafai, “An optically transparent meshed patch antenna with enhanced bandwidth for cubesat applications”, Proc. IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), Winnipeg, MB, Canada, 2022, pp. 44-48.
- Designed a lightweight stacked antenna by partially removing the polymer layer, achieving a 72% mass reduction (from 110 g to 31 g) compared to the glass–glass stacked antenna presented in previous work, while maintaining improved bandwidth of 5.5% and comparable gain.
 - Established a design path for transparent stacked antennas that simultaneously enhance bandwidth and dramatically reduce weight, enabling integration into multi-unit CubeSat arrays where mass budgets are tightly limited.
5. **S. Ramezanzadehyazdi**, P. Ferguson, D. Isleifson, L. Shafai, C. Shafai, “Stacked transparent meshed patch antenna for CubeSats”, Proc. IEEE 20th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM), St. John’s, NL, Canada, 2025, pp. 1-4. (Received First Place in the Women in Engineering Best Paper Award)
- A proximity-coupled feeding mechanism was applied to the stacked mesh patch antenna to eliminate the need for substrate and solar cell drilling, and improved manufacturability and compatibility with CubeSat solar-panel surfaces.

- Prototyped the proposed stacked meshed patch antenna using glass dielectric substrates with dimensions compatible with 1U CubeSat.
- Achieved a measured impedance bandwidth of 6.5% while preserving 94% optical transparency, demonstrating the effectiveness of closely spaced coupled resonances for bandwidth enhancement.
- Investigated array scalability through a 1×5 linear array study, showing that the antenna maintained acceptable active impedance behavior and achieved a broadside array gain of 13 dBi, supporting its applicability to multi-unit CubeSat communication systems.

[Journal Paper]

6. **S. Ramezanzadehyazdi**, D. Isleifson, P. Ferguson, L. Shafai, and C. Shafai, “Low profile enhanced bandwidth optically transparent and semi-transparent meshed patch antennas for integration with solar cells”, *IEEE Open Journal of Antennas and Propagation*, vol. 6, no. 4, pp. 1237-1247, Aug. 2025.
 - Introduced a novel stacked transparent antenna configuration employing a meshed copper radiator on a meshed SU-8 substrate, which enhances the bandwidth, gain, and transparency of the previous stacked TMPA designs while maintaining light weight; this architecture achieved bandwidth of 11.8%, and gain of 8.2 dBi, performance comparable to suspended-patch implementations.
 - Designed and experimentally validated three low-profile stacked TMPA architectures using combinations of fused silica glass and SU-8/polymer substrates, demonstrating practical manufacturability through copper foil and sputtered-metal fabrication.

The following publication were published and are indirectly related to the topic of this thesis:

7. M. Allameh, **S. Ramezanzadehyazdi**, C. Shafai, “Thermal stress analysis and stabilization of metal and SU-8 coatings for Tri-layer mirror,” *Proc. Canadian Conference of Electrical and Computer Engineering (CCECE)*, ON, Canada, 2021, pp. 1-5.
 - Investigated a tri-layer metal/SU-8/metal structure to determine the fabrication conditions required to achieve stable tensile stress for flat-surface micromirrors.
 - Examined the influence of SU-8 hard-bake temperature and duration on thermal stress behavior.
 - Evaluated the effects of different metal selections (Cr and Al) and deposition techniques (sputtering and thermal evaporation) on the final mirror stress.
 - Identified the processing requirements necessary to obtain a mechanically stable SU-8 layer suitable for reliable mirror fabrication.

[Future Publication]

Future publication will investigate advanced mesh optimization strategies, including non-uniform grids to further improve antenna performance. Optimization techniques, such as genetic algorithms and machine-learning-based solvers, will be explored to simultaneously maximize transparency, bandwidth, and radiation efficiency.

1.3 Thesis Outline

This thesis is structured into seven chapters, each addressing different aspects of the research:

- **Chapter 1** is the introduction of this thesis.
- **Chapter 2** summarizes the background of the research.

- **Chapter 3** describes the study performed on characterization of the performance of the TMPAs. The effect of the mesh geometry, transparency percentage, and conductor thickness on the antenna bandwidth, gain, and cross-polarization is investigated and compared with its solid counterpart.
- **Chapter 4** presents the novel stacked TMPA with enhanced bandwidth, constructed from two layers of glasses as the substrate dielectrics. The parametric study in this chapter aids in better understanding the performance of a double-layer meshed patch antenna.
- **Chapter 5** demonstrates the performance of the three novel lightweight stacked TMPAs. The feasibility of using SU-8 as the second dielectric layer of the stacked antenna and its radiation properties are studied in three different structures, full layer, partially removed, and perforated. Then, the performance of the proposed antennas is compared to each other and a suspended meshed patch antenna.
- **Chapter 6** presents experimental results and verification of the models.
- **Chapter 7** is the conclusion and future work recommendations.

Chapter 2

Background Study of Transparent Meshed Patch Antennas

2.1 Introduction

Integrating antennas with solar cells has been a key focus in designing multifunctional devices for space applications, particularly in CubeSats and microsatellites. In 1994, Tanaka et al. introduced the initial concept of integrating the antenna with solar cells by placing solar cells on top of a high-gain patch antenna for installation on microsatellites' body [14]. This approach highlighted the need for compact, multifunctional solutions as satellites became smaller and more constrained in terms of size and weight. Integrating solar cells with antennas offers a valuable way to optimize space and performance by combining energy harvesting and communication functionalities in a single device. Several techniques have been proposed to achieve this integration, each offering unique trade-offs between transparency, antenna performance, and structural complexity.

In this chapter, these different methods of integration are briefly reviewed, and TMPAs are studied in greater detail due to their promising balance of transparency and RF performance.

2.2 Integrated Patch Antenna with Solar Cell

The first method, as stated earlier, involves mounting solar cells directly on top of the radiating patch antenna. One notable example is the work by Jones et al. [15], where an aperture-coupled patch antenna was integrated with commercial solar cells for CubeSat applications. In their design, the radiating patch is placed beneath a solar cell and is excited through a slot in the ground plane, ensuring minimal disturbance to the radiated fields. The use of aperture coupling provides DC-RF isolation, allowing independent operation of the antenna and the solar cell. To evaluate the concept, a linearly polarized patch antenna was fabricated and tested with and without a solar cell mounted on top. Experimental results showed that the addition of the solar cell had negligible effect on the S_{11} and radiation characteristics of the antenna if the solar cell and its lead lines were placed appropriately. Fig. 2.1 shows an example of a patch antenna mounted below the solar cells.

Studies demonstrated that solar cells could be placed directly above the patch without significantly degrading antenna performance. However, this approach still requires careful consideration of the number, size, and arrangement of the solar cells to avoid disturbing the fringing fields of the patch antenna, and an insulation layer is typically required between the solar cells and the antenna. Moreover, precise material selection is needed to ensure the antenna size is slightly larger than the solar cell to minimize its impact on antenna performance. Otherwise, custom-sized solar cells must be used, which adds additional cost and complexity. While this method is straightforward, it can impose significant limitations on both the antenna design and solar cells placement. Therefore, other methods have been investigated, such as use of slot antennas which are studied in next section.

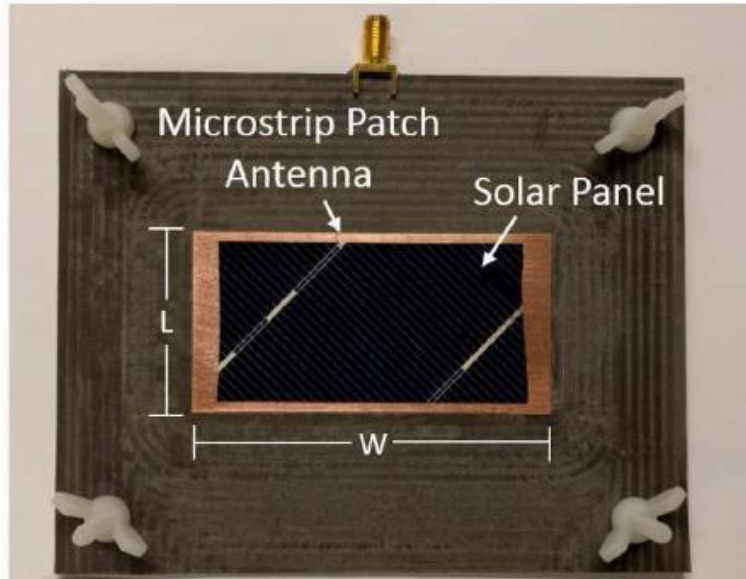
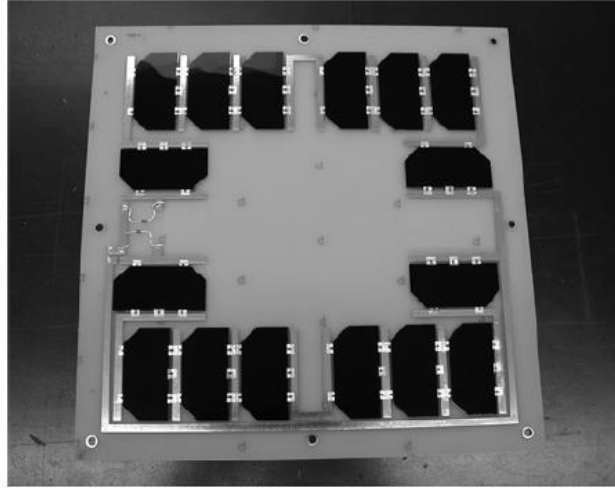


Fig. 2.1: Integrated patch antenna with solar cell by placing the solar cell on top of the patch [15].

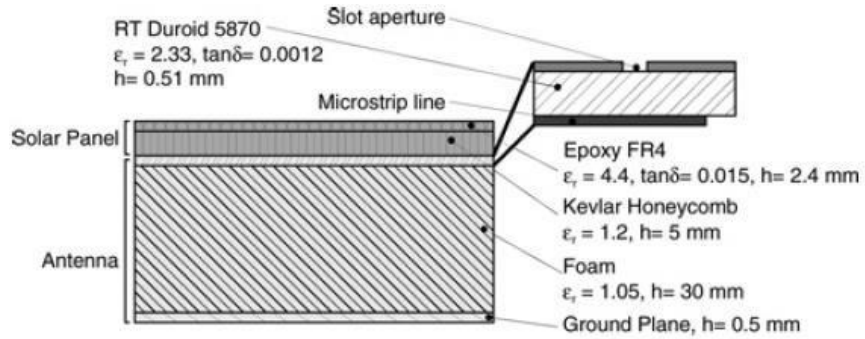
2.3 Integrated Slot Antenna with Solar Cell

An alternative approach for integrating antennas with solar cells involves placing slot antennas between or underneath the cells. Slot antennas are typically cut into a metallic ground plane and excited by a microstrip line. Since the antenna lies flat, solar cells can be mounted directly on top or around it. The initial concept of combining slot antennas with solar cells was introduced by Vaccaro et al. in 2000 [16], where custom-made amorphous silicon (a-Si:H) solar cells were directly deposited onto a stainless steel ground plane that also served as the slot antenna. Later works further advanced this integration. In [17], slot antennas for Global Positioning System (GPS) at 1.575 GHz and S-band communication were embedded beneath GaAs solar cells within a layered composite panel. The GPS antenna employed a circularly polarized four-slot configuration, while the S-band unit consisted of a four-element array that achieved a gain of 5 dBi across its operating bandwidth of 2.4 GHz to 2.45 GHz. Fig. 2.2a shows the S-band antenna configuration. As seen in the figure, a special arrangement of solar cells is required to minimize

their impact on the radiation characteristics of the slot antennas, which are placed on the center of the module.



(a)



(b)

Fig. 2.2: Slot antennas are placed below the solar cells. a) Final design top view. b) Layer's structure [17].

Moreover, the custom composite structure used for integration has a thickness exceeding 3 cm, which occupies a significant portion of the available payload volume. This increased height is primarily due to the need for a ground reflector beneath the slot antenna. Slot antennas inherently radiate in both forward and backward directions, and without a reflector, a considerable portion of energy is lost toward the backside of the panel. To mitigate this, a cavity or metallic reflector is

placed behind the slot, typically separated by a quarter-wavelength or a reduced air-filled gap, to redirect radiation forward and improve gain and efficiency [18]. While this approach improves radiation performance, it adds bulk to the design, making it less suitable for highly space-constrained platforms like CubeSats. To overcome this challenges use of transparent antennas have been proposed in literature which is discussed in next section.

2.4 Transparent Antennas

The third approach involves using transparent planar microstrip antennas placed directly on top of the solar cells. To enable this, the conventional opaque conductors used in microstrip antenna design must be replaced by a transparent material, and the dielectric substrate should be transparent too. An example of this method is demonstrated in [19], where a transparent patch antenna was fabricated using ITO films as the radiating material, and glass as the substrate. The antenna, designed for a center frequency of 4.9 GHz, and achieved 2.3 dBi of gain, which is lower than that of a conventional patch antenna gain. Fig. 2.3 shows the fabricated ITO patch antenna.

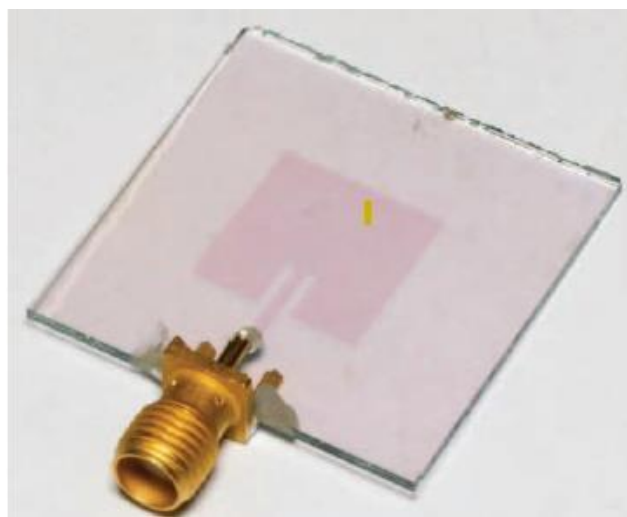


Fig. 2.3: Transparent ITO patch on a glass substrate [19].

The use of transparent conductors such as ITO introduces a fundamental trade-off between optical transparency and RF efficiency. Increasing the transparency of ITO typically involves making the conductive film thinner which reduces its electrical conductivity and degrades antenna performance [20]. Therefore, achieving acceptable antenna gain while maintaining high transparency remains a key design challenge for optically transparent antennas using transparent conductors. To address this, researchers have explored alternative transparent conductive materials as well as doping techniques.

In [21], Desai et al. presented a flexible, transparent 4-port MIMO antenna realized using AgHT-4, a silver oxide-based transparent conductive film, patterned on a polyethylene terephthalate (PET) substrate. This material choice offered optical transparency of approximately 70% and electrical conductivity of $4 \Omega/\text{sq}$. The antenna achieved maximum radiation efficiency of 40%. In another study, Haraty et al. investigated the deposition of a thin gold layer on ITO to improve its efficiency. Their studies showed that depositing 7 nm of gold on ITO can improve the antenna efficiency from 27% to 75% however the transparency decreased from 88% to 55% [22]. Indium-Zinc-Tin Oxide (IZTO) / Ag / IZTO multilayer structure, and gallium-doped zinc-oxide (GZO) were also studied in [23] and [24]. A compromise is always needed between the transparency and efficiency.

Another technique to achieve transparent planar antennas is by meshing the metallic conductors instead of using transparent materials. This method forms the focus of this thesis. These antennas can achieve transparency levels exceeding 90% while maintaining high efficiency, making them an attractive option for CubeSat installations, where space and performance are critical [25]. Compared to other transparent antenna technologies, TMPAs offer a unique balance between optical clarity and RF performance, without requiring specialized materials or complex

fabrication techniques. The next section explores the operating principles of meshed antennas, provides a review of prior works, and compares their performance in terms of transparency, gain, bandwidth, efficiency, and integrability.

2.5 Transparent Meshed Patch Antennas

Transparent Meshed Patch Antennas, also referred to as “see-through antennas,” firstly were introduced in [26] for automotive applications. Later, their ability to seamlessly integrate with solar cells caused them to find applications in other industries, such as the space and renewable energy sectors. TMPAs replace solid metal surfaces with patterned conductor grids, allowing visible light to pass through the open areas while maintaining the radiating function at microwave frequencies. They combine high transparency and efficiency, making them ideal for integrating with solar cells in space applications. Fig. 2.4a shows a simple rectangular meshed patch antenna and a scheme of a rectangular meshed patch antenna mounted on the 1U CubeSat body is demonstrated in Fig. 2.4b.

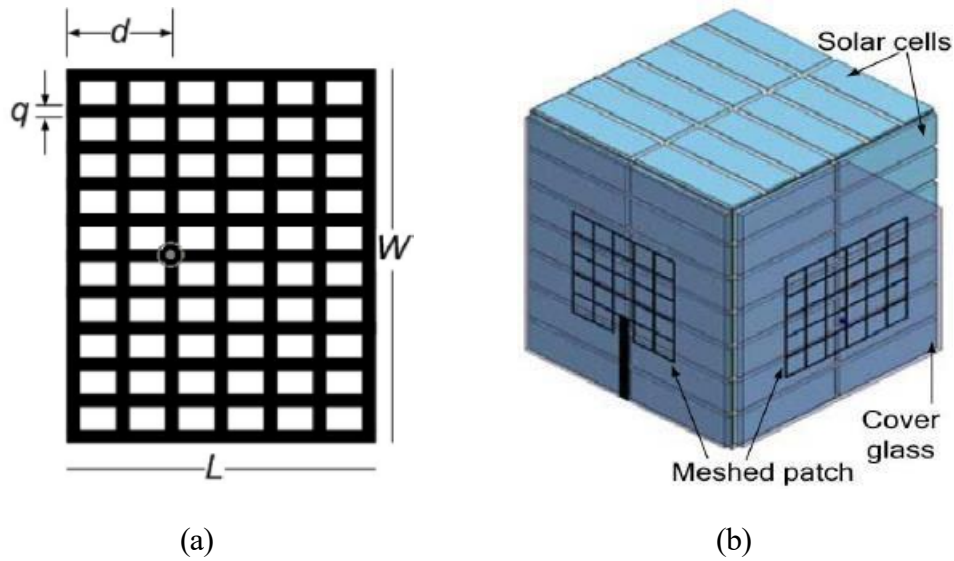


Fig. 2.4: Rectangular transparent meshed patch antenna. a) TMPA mounted on the 1U CubeSat body. b) Geometry of a rectangular TMPA [27].

2.5.1 Mesh Geometry

The geometry of the meshed patch plays an important role in determining the electromagnetic performance of TMPAs. Specifically, key parameters such as the number of lines, their spacing, and the line width directly affect the resonance frequency, bandwidth, gain, and radiation efficiency of the antenna. A few studies have investigated the effect of mesh geometry on antenna performance. In [12], Clasen and Langley initially demonstrated that increasing the mesh transparency by reducing the number of lines or refining the line widths led to a decrease in gain and an increase in cross polarisation level. They also showed that the dominant current flows along the vertical lines, and that radiation is maintained when enough vertical current paths are provided. Moreover, it was shown in [12] that meshing the patch antenna shifts the resonance frequency towards the lower range because the surface current passes across the horizontal lines in junctions, resulting in a longer path. Additionally, the input impedance of the patch increases after meshing and the probe feed must be positioned closer to the meshed patch center. They concluded that increasing the transparency level, either by reducing the number of lines or decreasing the line width, shifts the resonance frequency to lower bands, and degrades antenna efficiency, gain, directivity, and input impedance matching.

Turpin and Baktur [28] confirmed these trends, reporting that higher transparency resulted in reduced gain, bandwidth, and radiation efficiency. They attributed the gain loss after meshing to conductor losses due to high current densities at the edges of each mesh line. Additionally, in [29] they introduced the effect of grid width as a new parameter for optimization. Their results showed that, at a fixed transparency level, reducing the line width, which effectively means increasing the number of lines and making each line narrower, significantly improved gain, bandwidth, and efficiency. This finding highlighted the possibility of simultaneously achieving

both high transparency and improved antenna performance by carefully designing the mesh geometry. However, the conductor loss may limit the design. These conclusions were further supported in a comprehensive parametric simulation study by Dao et al. [30], who investigated TMPAs at 24 GHz.

To have a transparent microstrip antenna, both substrate and conductor layers (radiator patch and ground layer) must be transparent. Therefore, the effect of meshing the ground plane on the antenna performance has been studied in [31] and [32]. The results in [31] suggested that meshing the ground plane decreases front-to-back ratio and increases backward radiation. In [32] the performance of a circular meshed patch antennas with meshed ground plane was investigated and it was discovered that, a properly designed ground mesh could improve both bandwidth and gain, while some degradation in cross polarization level was observed with coarser meshes. These findings suggest that with careful control of mesh geometry, such as grid spacing, orientation, and alignment between the patch and ground, it is possible to maintain or even enhance performance while achieving high transparency.

Beyond the commonly used rectangular grids, Sharifi et al. [33] proposed a honeycomb-shaped metal mesh for millimeter-wave patch antennas at 77 GHz. Their measurements showed that the radiation characteristics of the honeycomb-grid patch closely matched those of its solid-metal counterpart, while also offering higher than 70% optical transparency. This highlights the feasibility of non-orthogonal mesh patterns for transparent antenna designs, offering smooth current paths and strong support of characteristic modes.

A detailed parametric study of these trade-offs, supported by simulation, is presented in Chapter Three of this thesis. The following section reviews selected TMPA designs, their applications, and their performance metrics.

2.5.2 Review of Reported TMPA Designs

Various studies were conducted on designing TMPAs from 900 MHz to 80 GHz for installation on CubeSats or using them in sensors and WLAN applications. In this section, some of them are reviewed, and their performance is summarized in Table 2.1.

Yasin and Baktur proposed two circularly polarized (CP) mesh patches for installation on CubeSats. Their first design in [34], is a nearly squared meshed patch excited with a coplanar Y-shaped coupling feed, and the second one is two squared meshed patches which are placed orthogonal and excited by a coplanar proximity feed [35]. Both antennas were fabricated and tested on a non-transparent substrate and resonance close to 2.4 GHz. The transparency of the first design was 60% with a 10 dB impedance bandwidth of 2% and a gain of 4.7 dBi. The second design had a transparency of 70% with 5.15 dBi gain and 2% bandwidth. As the horizontal lines in a meshed patch do not carry the current flow [31], they increased the transparency of their second design by minimizing the number of horizontal lines without significantly affecting the performance.

Another CP meshed patch antenna resonating at 2.45 GHz was proposed by Podilchak et al. for integration with CubeSats' solar cells [36]. They employed a 3.175 mm thick borosilicate glass as the transparent antenna substrate and mounted it directly on the solar cell. The antenna was excited using two orthogonal feed points with a 90-degree phase difference. The overall thickness of the proposed integrated antenna prototype was 7.4 mm, primarily due to the complex feeding network required to excite the patch with two 90-degree out-of-the-phase signals. The final fabricated prototype demonstrated a measured 10 dB impedance bandwidth of approximately 100 MHz centered at 2.45 GHz, a peak gain of 3 dBi, and a cross-polarisation level 10 dB lower than the co-polarised maximum at broadside. This work demonstrates the feasibility of integrating a

transparent meshed antenna directly mounted on a functional solar panel, with only a 10% reduction in solar cell efficiency.

In another work, X. Liu et al. in [37], introduced a broadband circularly polarized transparent meshed patch antenna for CubeSats, operating in the 2.4 GHz ISM band. The antenna was designed using a wire mesh structure for both the patch and ground plane, achieving 80-90% optical transparency. The Antenna was designed on a 2.25 mm thick quartz substrate, and a cross-shaped slot was embedded within a nearly square patch and excited using a 90° hybrid coupler to enhance the bandwidth and produce left-hand circular polarization (LHCP). The antenna simulation results yielded a 5.4% impedance bandwidth and a gain of 4.4 dBi. Although the design shows promise for transparent CubeSat integration, measurement results were not reported in this study.

The potential of TMPAs also extends beyond CubeSat and solar cell integration, with promising applications in wearable devices, RFID sensors, and smart lighting systems. For instance, in [38] and [39], Dao et al. developed a transparent meshed patch antenna operating at 24 GHz for an RFID sensor tag, achieving 75% transparency and 49% efficiency. The antenna employed ultra-thin metal grid lines to balance high-frequency RF performance with visual transparency. In another study [40], El Halaoui et al. designed and compared full-ITO and meshed-ITO transparent patch antennas integrated into OLED lighting systems for WLAN applications. Using meshed ITO can help with transparency. Their design achieved 78% theoretical transparency and exhibited slightly reduced gain (4.33 dB vs. 4.41 dB) due to increased sheet resistance. Nonetheless, it provided improved optical transparency and compatibility with OLED integration, validating its effectiveness for smart city and wearable applications.

Table 2.1 summarizes the comparison of the performance of transparent antennas in previous research.

Table 2.1: Summary of the performance of transparent antennas in previous research.

Ref. No	Freq. (GHz)	Gain (dBi)	BW (%)	Pol.	Eff.	Tr. (%)	Height (mm)	ϵ_r	Technique
[11]	2.4	5.33	1.65	LP	85.9	90	2.25	3.9	Meshed
[34]	2.34	4.7	2	CP	-	60	1.524	3.55	Meshed
[35]	2.47	5.15	2	CP	-	70	1.524	3.55	Meshed
[36]	2.45	4	1.45	CP	-	>70	1.6	4.4	Meshed
[37]	2.4	4.4	5.4	CP	-	89	2.25	3.9	Meshed
[38]	24	4	1.87	CP	49	92	0.254	2.2	Meshed
[40]	5.47	4.33	2.7	LP		>78	1.1	5.5	Meshed ITO
[33]	77	-	2.6	-	-	>70	0.125	2.9	Meshed
[41]	0.9	5.82	1	CP	-	-	22	2.2	Meshed
	5.8	13.75	1.4	CP	-	-	22	2.2	Meshed

The performance summary presented in this table demonstrates that meshed patch antennas offer a promising approach for achieving optical transparency while maintaining acceptable gain and compact form. Nevertheless, further efforts are required to enhance radiation efficiency and transparency simultaneously. In addition, improvements in impedance bandwidth remain necessary, particularly for applications demanding higher data rates. The next section reviews a few studies that have explored bandwidth enhancement of TMPAs specifically for CubeSat applications.

2.5.3 Broadbanding of TMPAs

Several broadbanding techniques traditionally used in microstrip antennas may also be applied to TMPAs to address their inherently narrow impedance bandwidth. These techniques include increasing the dielectric layer thickness, employing aperture-coupled or proximity feeding, exciting multiple resonant modes (multimoding), and utilizing coplanar or stacked parasitic elements. In the following sections, a review of relevant literature is provided on the use of coplanar parasitic elements, multimoding, suspended patch configurations, and stacking techniques for bandwidth enhancement, with emphasis on their trade-offs in terms of size, transparency, and radiation performance.

2.5.3.1 Coplanar Elements

T. Yasin et al. in [42], enhanced the bandwidth of the TMPAs by using coplanar parasitic elements to introduce multiple resonances. In their design, shown in Fig. 2.5, three patches with slightly varying sizes and resonance frequencies were capacitively coupled via proximity feeding along a straight microstrip line. This approach achieved a 2.5-fold improvement in bandwidth but resulted in a 5 dB gain variation within the -10 dB impedance bandwidth and approximately a 30-degree rotation in the radiation pattern. In addition, the proposed antenna occupied three times more space, reducing overall transparency.



Fig. 2.5: Bandwidth enhancement of TMPAs using three proximity-fed meshed patches [42].

2.5.3.2 Multimoding Technique

X. Liu et al. developed a dual band meshed patch antenna, depicted in Fig. 2.6, by exciting the (1,0) and (0,1) modes to enhance the TMPAs' bandwidth [25]. To achieve circular polarization, two slightly different patches were positioned diagonally on the substrate and driven by two signals with a 90-degree phase difference. Their design demonstrated nearly a three-fold improvement in bandwidth. Similar to the coplanar elements' method, bandwidth enhancement came at the cost of increasing the required area, which is not ideal for CubeSat applications.

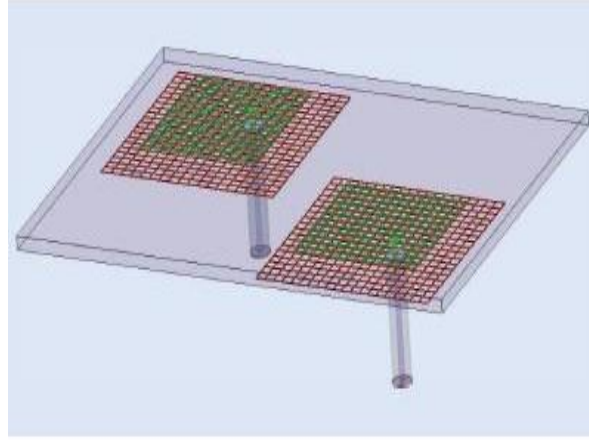


Fig. 2.6: CP broadband transparent antenna, the green meshes are the two patches, and red grids are the ground planes [25].

2.5.3.3 Suspended Patch

A broadband-suspended meshed patch antenna was proposed in [43] for Ku-band satellite communications, covering both uplink and downlink operations. The antenna structure is shown in Fig. 2.7. The design used plexiglass for the lower patch substrate and air as the upper substrate. The ground plane was also meshed in this study. They achieved a 17 dB bandwidth of 880 MHz for downlink (11.7 GHz to 12.22 GHz) and 500 MHz for uplink (14.0 GHz to 14.5 GHz). The solar cell cover glass was not incorporated into the structure, and the overall antenna height was not reported.

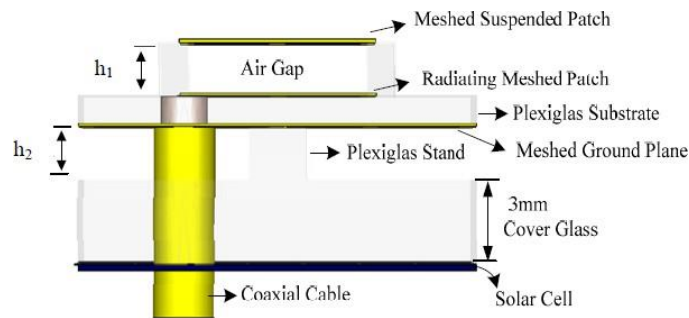


Fig. 2.7: Suspended meshed patch antenna side view [43].

2.5.3.4 Stacking Technique

Another approach to introducing multiple resonances to conventional patch antennas is through the stacking technique [44]. Compared to using coplanar parasitic elements [42] or multimoding techniques [25] this method's key advantage is its consistent physical size and transparency. This is particularly valuable for CubeSat applications, where available space is highly constrained. A wideband transparent dual-polarized stacked patch antenna was proposed in [45]. This design consisted of two circular meshed patches stacked to achieve a 19% bandwidth, covering the frequency range from 2.4 GHz to 2.9 GHz. The metal layers, including the two patches and the ground plane, were fabricated from a transparent conductive film with a sheet resistance of $0.5 \Omega/\text{sq}$, printed on polyethylene terephthalate (PET) with an overall thickness of 0.1 mm. These conductive films adhered to polymethyl methacrylate (PMMA) plates with 4 mm and 5 mm thicknesses, which served as the primary substrate layers. The main drawbacks of this design are its low optical transparency and efficiency. The optical transparency of the ground plane is less than 70%, a limitation inherent to the choice of conductor material. Additionally, the antenna efficiency is approximately 75%, impacted by the sheet resistance of the metal mesh. The main portion of the wideband performance was attributed to using two circular feeding disks, connected to the probes and coupled to the lower patch rather than the stacking technique. M. A. Ahmad et al. also studied applying the stacking technique to TMPAs [46]. They used low-temperature co-fired ceramic (LTCC) with a dielectric constant of 7.1 and a loss tangent of 0.001. The overall thickness of the proposed antenna was 2.8 mm. They achieved 1.5% bandwidth at 2.5 GHz and -0.12 dBi gain.

This thesis extends the exploration of stacking techniques to enhance the bandwidth of TMPAs while maintaining high transparency and efficient use of surface area on 1U CubeSats.

The detailed design methodology and simulation results of the stacked TMPAs developed in this thesis are presented in Chapters Four and Five.

2.6 Summary and Conclusion

In summary, TMPAs exhibit performance metrics comparable to their solid-metal counterparts, particularly in terms of gain and radiation characteristics. Reported TMPAs achieve gains ranging from 4 dBi to over 5 dBi, with slightly reduced gain attributed to additional losses introduced by the meshed conductor structure. Their impedance bandwidths remain narrow, around 2%, similar to traditional patch antennas, and thus bandwidth enhancement is still required to meet the demands of high data rate applications. Additionally, performance is closely tied to material characteristics such as the substrate dielectric constant (ϵ_r), which influences resonance and efficiency.

A comparative study by Nogi and Kuwahara [47] evaluated transparent antenna solutions suitable for CubeSat integration, examining three implementations: standard copper, ITO, and meshed copper patches, all designed to operate at 437 MHz. The solid copper patch served as the baseline, achieving a gain of 3.06 dB, and an efficiency of 58.9% with no transparency. Their simulation results demonstrated that although the meshed design yielded lower efficiency and gain than the solid patch, it outperformed ITO in terms of realized gain, and efficiency. The meshed structure achieved 1.30 dBi gain, 39.2% efficiency, and 86.8% transparency, compared to ITO's -1.06 dBi gain and 22.7% efficiency. These findings reinforce the conclusion that meshed conductors offer a more balanced trade-off between transparency and RF performance compared to alternative transparent conductors like ITO.

Taken together, the literature review indicates that increasing transparency in TCO based antennas by thinning the conductive film leads to reduced conductivity and degraded gain and efficiency as reported in [20], and conversely improving the conductivity by doping or multilayer film deposition can enhance the antenna performance significantly but at the cost of reduced transparency [21-24]. These trends illustrate an inherent transparency performance trade-off in TCO based patches, motivating the exploration of meshed metallic structures.

Early studies on TMPAs [12] and [28] reported that increasing transparency by reducing the number of lines or their width leads to lower gain and reduced efficiency as insufficient current paths limit radiation performance. Subsequent works changed this understanding by demonstrating that, for a fixed transparency level, increasing the number of mesh lines while narrowing their width can improve gain, bandwidth, and efficiency. Therefore, TMPAs have the potential to simultaneously provide high optical transparency and strong RF performance when their geometry is appropriately engineered. The next chapter investigates these trade-offs through a parametric study, offering design insights on selecting the appropriate mesh line width and density to maximize antenna performance.

Chapter 3

Characterization of Transparent Meshed Patch Antennas

3.1 Introduction

TMPAs offer low profile, low cost, high reliability, and robustness similar to the conventional microstrip antennas. However, their gain, bandwidth, efficiency, and radiation pattern depend on their mesh geometry (line width and pitch), and transparency level. This chapter investigates the effect of mesh density, line width, and transparency of a square meshed patch antenna on a solid ground plane on its radiation properties through simulations, aiming to establish practical guidelines for selecting the number of lines and their width based on the desired performance.

3.2 Characterization of Square Meshed Patch Antennas

As discussed in Chapter Two, introducing a mesh into the patch geometry shifts the antenna's resonance frequency downward due to the longer current paths across the mesh lines. To characterise the meshed antenna and compare different mesh configurations, the antenna must be evaluated at a fixed operating frequency. Therefore, in this study, the dimensions of the meshed patches were carefully adjusted in each case to maintain the same target resonance frequency, ensuring a consistent basis for comparison. All designs in the following sections employed an FR4

epoxy substrate with a relative dielectric constant of 4.4, a loss tangent of 0.02, and a thickness of 1.6 mm backed by a solid ground plane unless otherwise specified. ANSYS HFSS 2020.R1 was used to model the antennas.

3.2.1 Effect of Line Width and Mesh Density

In this section, two sets of square meshed patch antennas were designed and analyzed to systematically evaluate the impact of mesh geometry on antenna performance. The first set includes four antennas with approximately 56% transparency; while in the second set, the transparency level was increased to approximately 82%. Within each set, the line widths and mesh densities were varied, and the results were compared to a solid patch antenna. In the second set, the number of grid lines (mesh density) was kept constant, and only the line width was reduced to achieve higher transparency. Together, these two sets allow us to assess both the role of mesh density at fixed transparency and the impact of increasing transparency at fixed density. Transparency was calculated using Equation (3.1), and the dimensions of the meshed patches were adjusted to maintain approximately the same resonance frequency as the solid patch antenna. The transparency throughout this chapter represents the fraction of the patch area that is not occupied by metal.

$$Tr = 1 - \left(\frac{\text{Meshed patch metal area}}{\text{Solid patch metal area}} \right) \quad 3.1$$

Table 3.1 provides a summary of the antennas' geometry in the first set, including their resonance frequency, dimensions, and transparency level. Here, N_v represents the number of vertical lines (parallel to radiating edges), and N_h indicates the number of horizontal lines. A perfect electric conductor (PEC) was used for the metal to eliminate the influence of conductor loss on the study. The geometry of the antennas is illustrated in Fig. 3.1, where d denotes the line width, and g represents the gap between the lines. The specifications and geometry of the second

set of antennas, with approximately 82% transparency, are presented in Table 3.2 and graphically illustrated in Fig. 3.2. Additionally, an extra antenna, labeled Ant-0, was introduced to this group to illustrate the overall performance trend more clearly.

Table 3.1: Mesh geometry of four PEC squared meshed patches with 56% transparency and 2.45 GHz resonance frequency.

	d (mm)	g (mm)	N_v & N_h	Dimension (mm)	Frequency (GHz)	Tr (%)
Ant-1	1.5	4.3	5*5	24.7	2.45	58.1
Ant-2	0.85	2.22	9*9	25.45	2.435	55.9
Ant-3	0.41	1.26	17*17	27.2	2.445	55.6
Ant-4	0.2	0.65	33*33	27.44	2.4525	57.5
Solid Patch	-	-	-	27.4	2.445	0

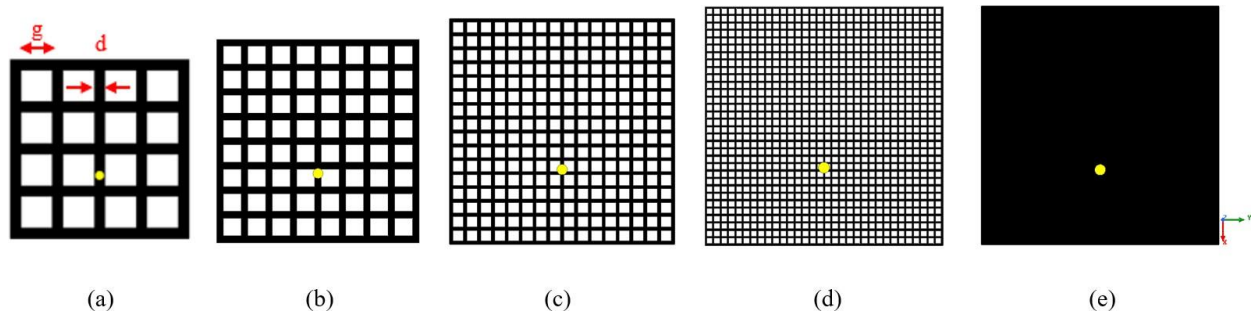


Fig. 3.1: Mesh geometries of four PEC square meshed patches with 56% transparency and resonance frequency of 2.45 GHz. a) Ant-1. b) Ant-2. c) Ant-3. d) Ant-4. e) Solid patch.

Table 3.2: Mesh geometries of five PEC square meshed patches with 81% transparency and 2.45 GHz resonance frequency.

	d (mm)	g (mm)	N_v & N_h	Dimension (mm)	Frequency (GHz)	Tr (%)
Ant-0	1	9.7	3*3	22.4	2.44	83.2
Ant-1	0.6	5.05	5*5	23.2	2.4375	82.7
Ant-2	0.35	2.74	9*9	25.05	2.4475	80.3
Ant-3	0.15	1.52	17*17	26.9	2.4475	82.6
Ant-4	0.075	0.78	33*33	27.475	2.445	82.7
Solid Patch	-	-	-	27.4	2.445	-

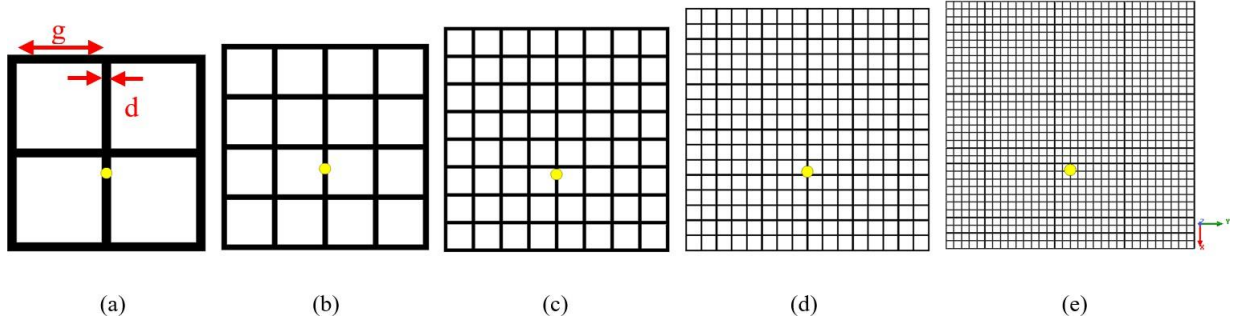


Fig. 3.2: Mesh geometries of five PEC square meshed patches with 81% transparency resonating at 2.45 GHz. a) Ant-0. b) Ant-1. c) Ant-2. d) Ant-3. e) Ant-4.

Fig. 3.3 compares the bandwidth, gain, efficiency, and cross-polarization of the antennas listed in Table 3.1 and Table 3.2. Impedance bandwidth in this work is calculated using Equation (3.2).

$$BW = \frac{f_H - f_L}{f_c} \quad (3.2)$$

Where f_H is the highest frequency at which the input return loss is greater than 10 dB, f_L is the lowest frequency at which the input return loss is greater than 10 dB, and f_c is the center frequency.

As anticipated from the literature review, the results demonstrated that for both transparency levels (56% and 82%), the gain, bandwidth, and efficiency of the meshed patch antenna approached those of the solid patch as the number of lines increased and their width was refined. The bandwidth plot (Fig. 3.3a) indicates that for a grid density lower than 9×9 (Ant-2), the antenna with higher transparency exhibited lower impedance bandwidth. However, beyond that mesh density, the bandwidth became the same or even higher. The gain for both antenna sets eventually reached the gain of the solid patch, with a significant reduction in gain difference observed for antennas with N_v and N_h larger than 9. Similarly, the efficiency of both antenna sets followed the same trend, and no consistent pattern was observed for cross-polarization, though it remained

better than -20 dBc in all cases.

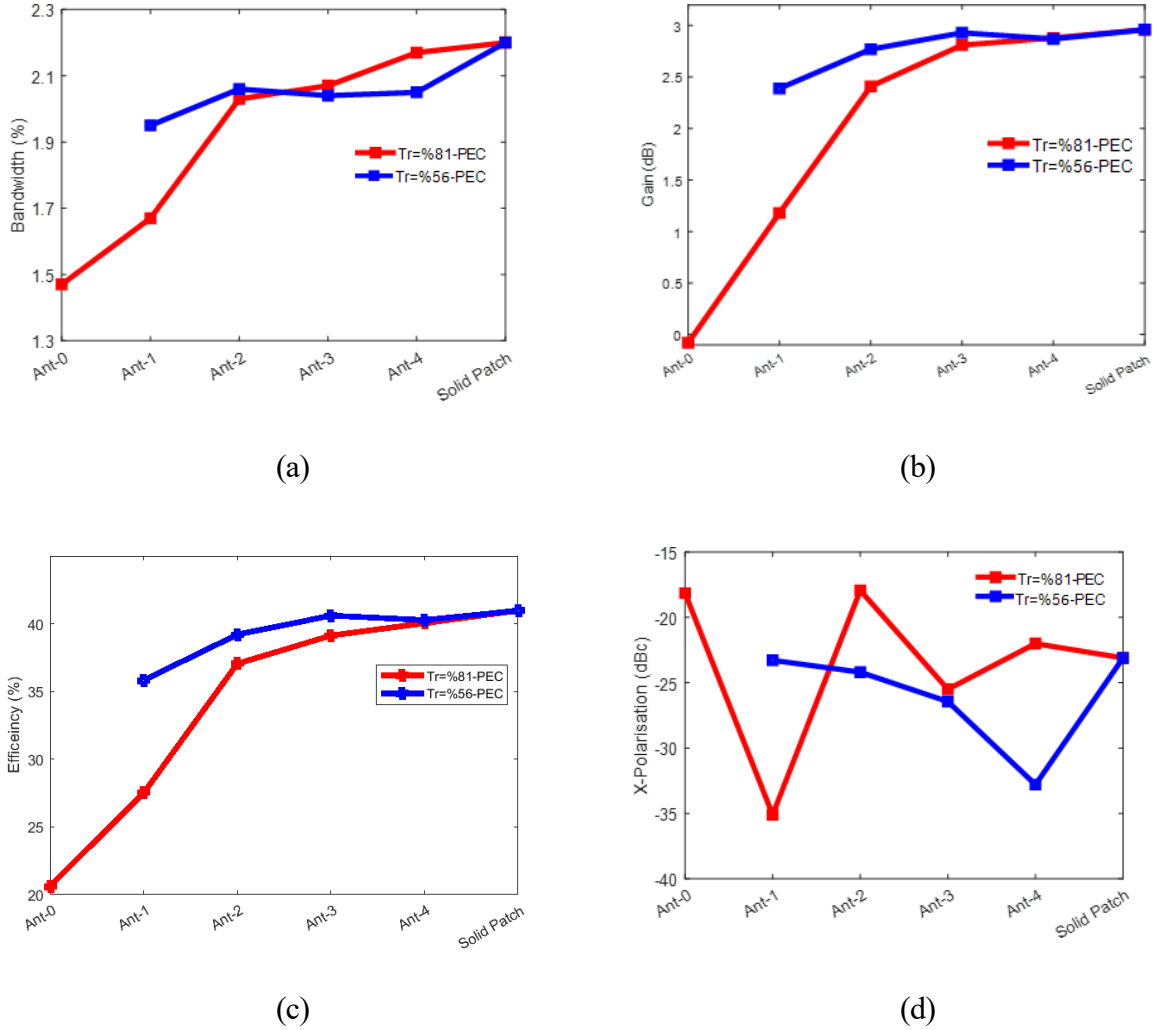


Fig. 3.3: Comparing the performance of meshed patch antennas with 56% and 81% transparency resonating at 2.45 GHz with different mesh geometries on FR4 substrate. a) Bandwidth. b) Gain. c) Efficiency. d) X-pol.

In conclusion, for grid densities greater than 9×9 , the performance of the 56% transparent antenna matches that of the 81% transparent one. Therefore, it can be stated that for PEC conductor, the TMPAs' performance at a particular frequency is independent of its transparency and the line width if enough lines are chosen. These results directly quantify the transparency-performance trade-off, showing that higher transparency does not necessarily degrade the antenna performance when mesh density is sufficiently high.

3.2.2 Effect of Conductor Loss

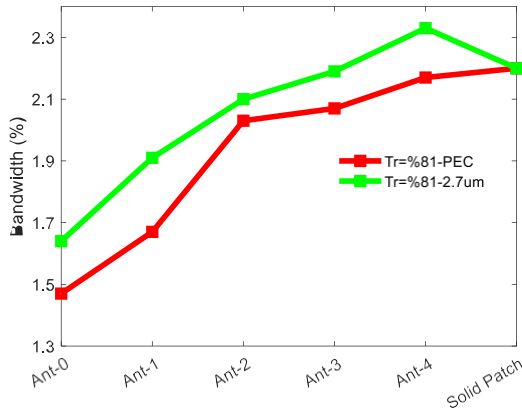
A new set of meshed antennas with 2.7 μm thick copper and 82% transparency designed on 1.6 mm thick FR4 substrate was modelled and compared with the PEC antennas, in order to study the effect of conductor loss on the performance of a meshed patch antenna when the lines get thinner. The conductor thickness was selected to be approximately twice the skin depth of copper at 2.45 GHz which is 1.32 μm calculated by

$$\delta_s = \sqrt{\frac{2}{\omega * \mu * \sigma}} \quad (3.3)$$

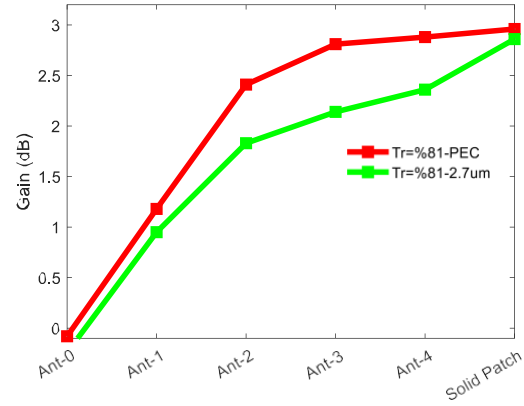
In the formula above, ω represents the radian frequency, μ is the permeability ($4\pi * 10^{-7}$ H/m), and σ denotes the conductivity (s/m). The specifications of this new set of antennas are provided in Table 3.3, with the corresponding results shown in Fig. 3.4. It is seen that the thin copper layer used for the patch conductor introduced losses, leading to reductions in the gain and efficiency of the meshed antenna. This degradation became significant for antennas with line widths narrower than 0.35 mm. The deviation of the two graphs was approximately linear when the lines got narrower and denser. The gain deviation was 0.58 dBi for Ant-2 and 0.52 dBi for Ant-4, while the efficiency dropped by 5.5% and 4.6%, respectively. The bandwidth slightly increased due to conductor loss, and the cross-polarization remained better than -20 dBc in all cases.

Table 3.3: Mesh geometry of five 2.7 μm thick square meshed patches on FR4 substrate with 81% transparency resonating at 2.45 GHz.

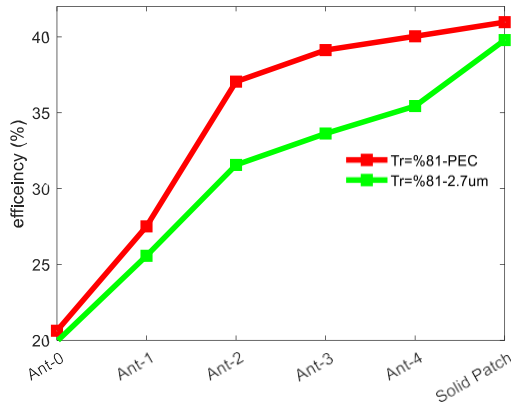
	d (mm)	N_v & N_h	Dimension (mm)	Frequency (GHz)	Tr (%)
Ant-0	1	3*3	22.1	2.445	82.3
Ant-1	0.6	5*5	23.8	2.44	80.9
Ant-2	0.35	9*9	25.53	2.435	79.6
Ant-3	0.15	17*17	26.65	2.4475	81.5
Ant-4	0.075	33*33	27.625	2.4475	81.4
Solid Patch	-	-	26.5	2.4375	0



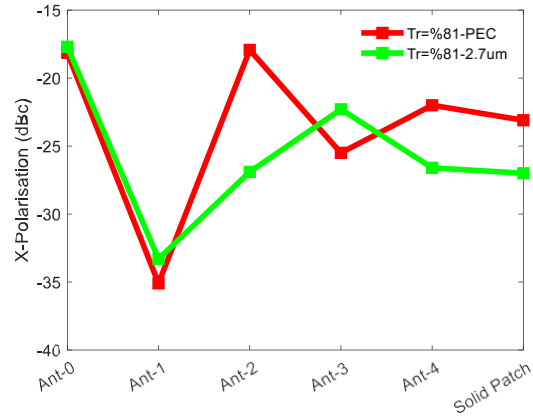
(a)



(b)



(c)



(d)

Fig. 3.4: Comparing the performance of PEC and 2.7 μm thick copper meshed patch antennas with 81% transparency at 2.45 GHz with different mesh geometries. a) Bandwidth. b) Gain. c) Efficiency. d) X-pol.

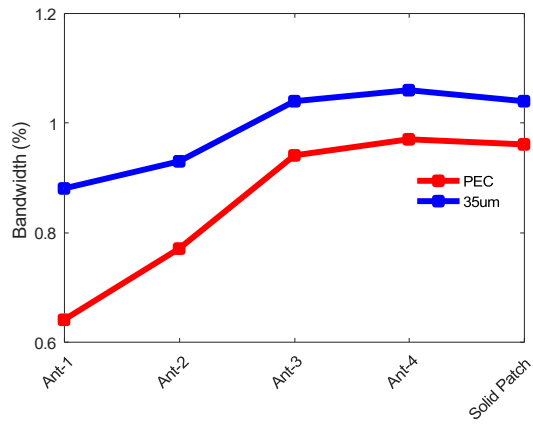
3.2.3 Effect of Substrate

A 1.6 mm thick fused silica glass with a dielectric constant of 3.8 and loss tangent of 0.00002 [48] was used to investigate the effect of substrate. The same as the previous sections, four antennas with the same transparency of 56%, but different line widths and densities were simulated. The simulations were repeated with PEC, and 35 μm thick copper as the patch conductor. The antennas' dimensions are summarized in Table 3.4, and the results are reported in Fig. 3.5.

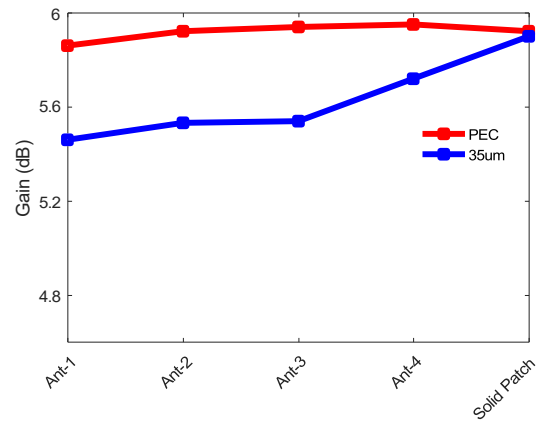
A performance comparison of Ant-1 through Ant-4, between the PEC conductor and 35 μm -thick copper patches, indicated a maximum gain reduction of 0.4 dBi and a minimum gain reduction of 0.23 dBi for Ant-4 with 33 vertical and horizontal lines. For the 35 μm copper designs, the lowest gain observed was 5.4 dBi for Ant-1 with 5×5 vertical and horizontal line configuration. Increasing the number of lines to 33 in each direction and reducing the line width improved the gain to 5.7 dBi, highlighting the positive impact of higher mesh density and finer conductor traces on radiation performance. The radiation efficiency of the meshed patches fabricated with 35 μm -thick copper reached 90% when the mesh density exceeded 17×17 lines, demonstrating the strong potential of meshed antennas to maintain high efficiency when their geometry is carefully optimized and combined with a low-loss substrate. The simulated impedance bandwidth was approximately 1%, which is about half that of the FR4-based antennas presented in Section 3.2.1. This reduction is attributed to the lower loss tangent of the substrate used in the present designs, which influences the stored energy and radiation characteristics of the antenna [49].

Table 3.4: Specifications of the four square meshed patches with 56% transparency and 2.45 GHz resonance frequency on a 1.6 mm thick fused silica glass substrate.

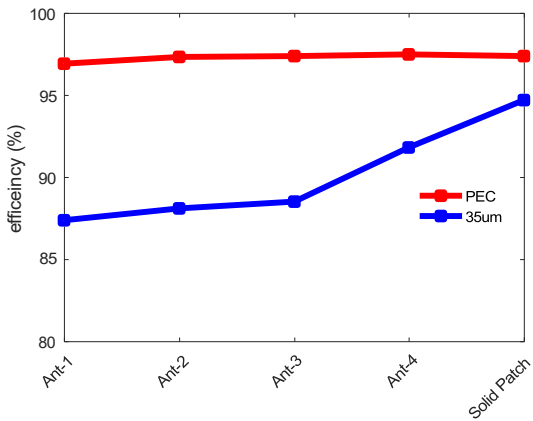
	d (mm)	N_v & N_h	Dimension (mm)		Frequency (GHz)		Tr (%)	
			PEC	35 μ m	PEC	35 μ m	PEC	35 μ m
Ant-1	1.5	5*5	25.6	26.1	2.44	2.45	56.6	55.6
Ant-2	0.8	9*9	27.3	27.4	2.4425	2.4425	55.8	55.4
Ant-3	0.4	17*17	28.6	28.5	2.4425	2.4425	55.5	54.4
Ant-4	0.2	33*33	29.3	29.4	2.44	2.445	55.4	54.4
Solid Patch	-	-	29.5	29.7	2.45	2.435	0	0



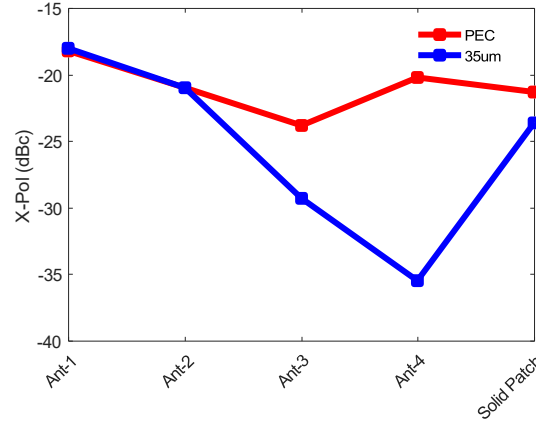
(a)



(b)



(c)



(d)

Fig. 3.5: Performance of meshed patch antennas on fused silica glass substrate with 56% transparency at 2.45 GHz with different mesh geometries. a) Bandwidth. b) Gain. c) Efficiency. d) X-pol.

3.3 Summary and Conclusion

This chapter reviewed the performance of meshed patch antennas, considering variations in line width and number, substrate materials, and copper thickness. It can be concluded that, with an optimal selection of line count and width, the performance of a transparent meshed patch antenna can closely match that of a solid patch antenna. Furthermore, TMPAs have the potential to achieve 90% transparency and 90% efficiency with an appropriate choice of dielectric layer. Also, the comparison between FR4 and fused silica substrates demonstrated the trade-offs between bandwidth, gain, and efficiency. Antennas implemented on fused silica achieved higher gain and efficiency, though with a narrower impedance bandwidth due to its lower loss factor. This highlights the importance of substrate selection in balancing efficiency, gain, and operational bandwidth for transparent meshed patch antennas.

The findings of this chapter along with background study in Chapter 2, indicate that TMPAs can simultaneously provide high transparency and strong electromagnetic performance when their geometry is properly engineered which means increasing mesh density and reducing line width at a fixed transparency level. Such a geometric refinement can be limited by fabrication capabilities. The minimum achievable line width and pitch depend heavily on the selected manufacturing process such as inkjet printing, photolithography, physical vapor deposition, or electroplating. Each method imposes limits on pattern resolution, edge definition, and metal thickness [50], [51]. For instance, inkjet printing often suffers from ink spreading and line width variability, which increase conductor loss, while sputtered or evaporated films may achieve finer features but tend to produce very thin metallic layers that are insufficient compared to the RF skin depth, leading to higher ohmic losses at microwave frequencies [52]. Additionally, the fabrication nonuniformities such as line edge roughness and under etching can increase sheet resistance beyond the ideal

predicted values. These practical constraints indicate that TMPA performance improves with finer meshes but achievable transparency-performance balance is ultimately bounded by the fabrication process. However, they still outperform the TCO based antennas [53].

Chapter 4

Bandwidth Improvement of Transparent Meshed Patch Antennas

4.1 Introduction

Meshed patches stand out for their high efficiency and transparency among the various planar optically transparent antennas. They can be directly placed over solar cells without impacting their performance. However, a significant drawback of meshed patch antennas is their inherently narrow impedance bandwidth, similar to conventional patch antennas.

In this thesis, a stacking technique was used to improve the bandwidth. The proposed antenna offered approximately five times wider bandwidth than a single-layer meshed patch, with efficiency exceeding 80% across the entire frequency range, while maintaining a normal transparency of about 95%. The design procedure along with simulations are presented in the following sections.

4.2 Antenna Design and Simulation

The schematic of the stacked meshed patch antenna designed in this work and placed on top of a solar cell is shown in Fig. 4.1. The bandwidth enhancement in this design comes from two squared meshed patches which resonate close to each other. In this stacking technique, the lower patch, called the active patch, must be excited directly and the upper patch is parasitically coupled

to the lower one and excited with the field coupling between the patches [44]. Therefore, the performance of the stacked patch antennas is highly dependent on the dielectric constant and height of each substrate layer. The same as solid stacked patches the active meshed patch layer can be excited by any method, such as a 50-ohm coaxial probe feed [54], microstrip line, proximity coupling [55], or aperture coupling [56].

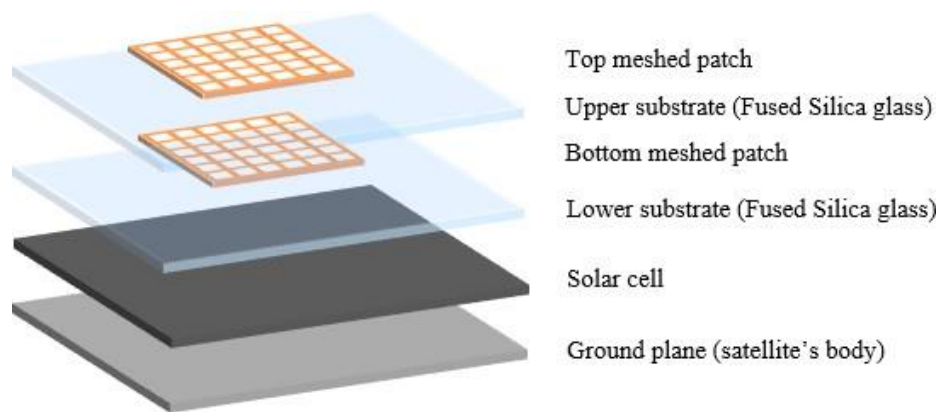


Fig. 4.1: Stacked antenna assembly.

4.2.1 Material Selection

A lot of research has been conducted on material selection for stacked microstrip antennas. It has been shown that combining materials with high and low dielectric constant results in the widest impedance bandwidth [55]. Then, in most of the previous works, a foam substrate with $\epsilon_r = 1.07$ is used as the upper dielectric layer to get the largest bandwidth, and the second patch is etched on a thin dielectric layer. In this work, the goal was to make the stacked meshed patch antenna compatible with solar cells' integration and CubeSats applications. Therefore, a compromise must be achieved between the antenna bandwidth and its transparency, robustness, and easy integration with the solar cells. To achieve this, a fused silica glass substrate with a transparency of 92% was selected for both upper and lower dielectric layers. The first glass layer, as shown in Fig. 4.1, can act as both a cover layer for solar cells to protect them from space

radiation and the active antenna substrate layer. Also, the satellite body would be the ground layer of the proposed stacked antenna. However, in the following simulations, for simplicity purposes, a solid ground plane was considered as the antenna's ground plane.

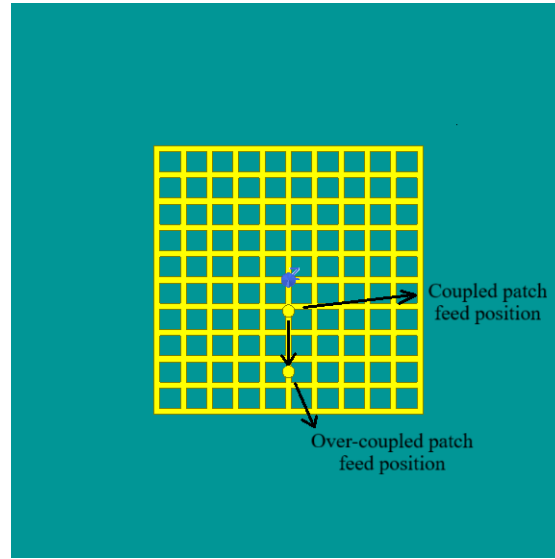
4.2.2 Design Procedure

The principle of designing stacked patch antennas is moving the impedance loci of an over-coupled active patch (bottom patch) from the capacitive region to the matched condition and creating the resonance loop in the impedance locus by placing the parasitic patch on top of the lower patch [54], [56]. Different parameters, including height and dielectric constant of each layer, active and parasitic patch dimension, and feed location, affect the antenna's performance and must be designed carefully to achieve good performance for a stacked transparent meshed patch antenna.

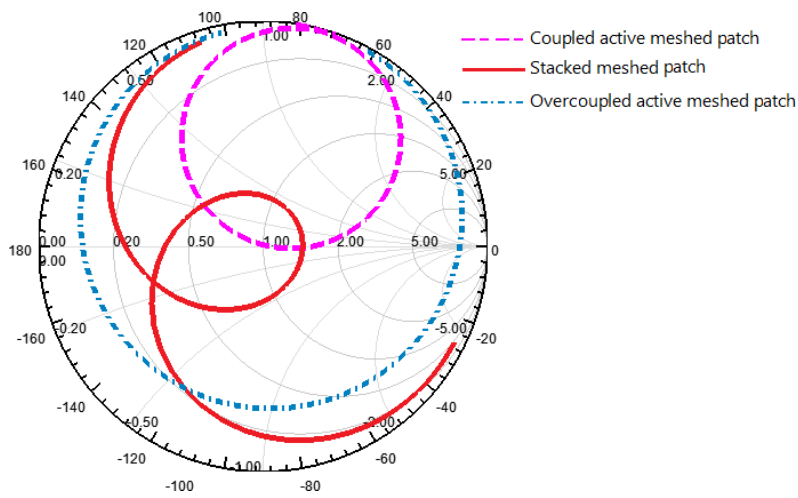
To start designing the stacked TMPA, first, a single-layer meshed patch (active patch) was designed at the higher end of the desired frequency bandwidth (2.51 GHz). Next, the feed was moved towards the edge of the antenna to create an over-coupled patch. The impedance locus of the over-coupled patch needs to be outside the VSWR circle of 2.5:1 and have an input impedance close to 250 Ohm [54]. Finally, by putting the parasitic element the resonance loop will be created in the Smith chart. Fig. 4.2a illustrates the feed movement to create the over-coupled antenna and Fig. 4.2b shows the changes in the impedance locus.

Based on the study in Chapter 3, Fig. 3.3, if a TMPA with 56% transparency has 9 vertical and 9 horizontal lines or more, the antenna performance with a good approximation is regardless of the line width and number. Therefore, a squared meshed patch antenna with a line width of 0.6 mm and 11 equally spaced horizontal and vertical lines was chosen here for applying the stacking technique. The initial dimensions of the TMPA could be calculated with well-known equations for

designing conventional microstrip antenna, Equations (4.1) to (4.5) [49]. Once the patch length (L) is calculated, the width (W) is set to be equal to that to have a square patch.



(a)



(b)

Fig. 4.2: Stacked TMPA design process. a) Feed movement to create the over-coupled antenna. b) Impedance locus of the coupled active meshed patch, over-coupled active meshed patch, and stacked meshed patch antenna.

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \quad 4.1$$

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-1/2} \quad 4.2$$

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{reff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{reff} - 0.258) \left(\frac{W}{h} \right) + 0.8} \quad 4.3$$

$$L_{eff} = L + 2\Delta L \quad 4.4$$

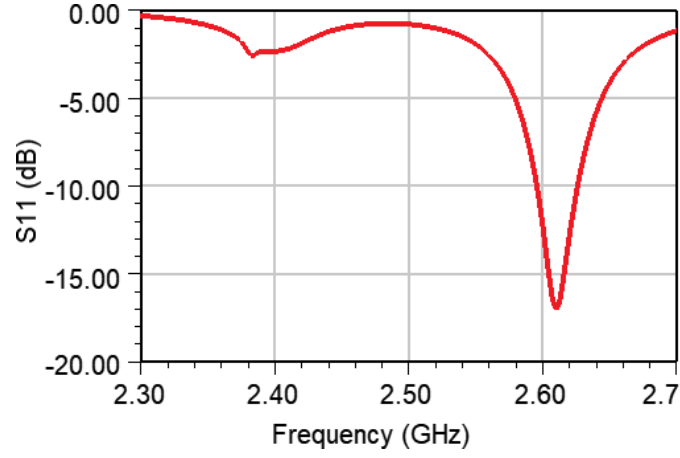
$$L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L \quad 4.5$$

The purple dash circle in Fig. 4.2b is the impedance locus of the coupled active meshed patch. The probe location (X_f) is moved from 3.4 mm to 7.4 mm to create the over-coupled active patch (blue line). To design the second layer, the initial parasitic meshed patch dimension is selected to be the same as the lower patch and the thickness of the second substrate layer is increased in 0.5 mm steps until the S11 gets lower than -10 dB. The following steps summarized the design procedure for this stacked antenna. The findings of this section have been published in [57].

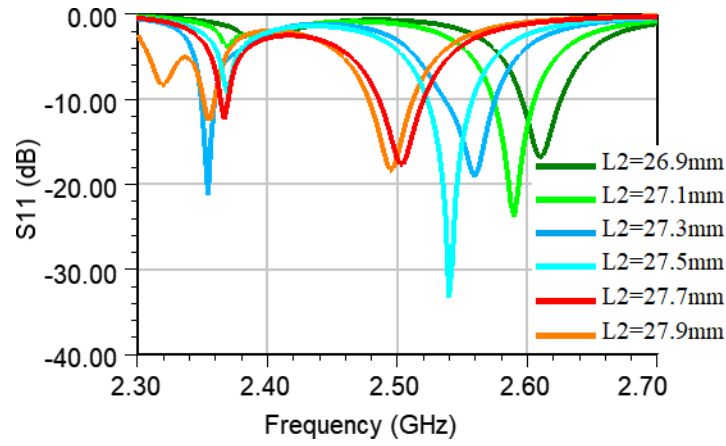
- Design the active patch for a slightly higher frequency.
- Move the probe location towards the edge, on the central line to have an over-coupled patch. To find a start point for feed location, the over-coupled antenna input impedance must have these conditions; 1) Impedance locus outside the VSWR circle of 2.5:1. 2) Input impedance of approximately 250 Ohm [54].
- Add the parasitic patch with the same length and width ($L_1 = L_2 = W_1 = W_2$).
- Increase the height of the upper substrate layer to find the best bandwidth. There is a maximum height at which the bandwidth starts degrading beyond that.

- Tune patch dimension and feed location to place the resonance loop at the center of the Smith chart and have the widest bandwidth.
- Change the height of the lower substrate and repeat all the steps to find the optimum value for H_1 and H_2 and as a result optimum field coupling between the layers.
- After finding the proper heights again, the lengths of the patches can be tuned to move the S11 to the desired frequency band.

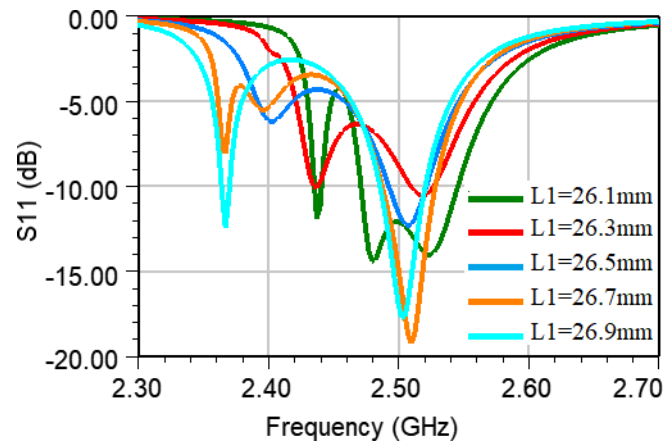
Fig. 4.3 shows the iterations that led us to the final design. The design procedure started with $H_1 = 1$ mm (lower substrate height). A single-layer square meshed patch antenna was designed to resonate at 2.52 GHz. The antenna's bandwidth was 18 MHz, the meshed patch length was 26.9 mm, and the probe was located 3.4 mm away from the patch center on the x-axis. After designing the active coupled meshed patch, the probe was moved toward the edge of the patch to have an over-coupled meshed patch. The new feed location was 7.1 mm from the center, and the input impedance at this point was 225Ω . The next step is adding the second meshed patch antenna with the same dimension and thickness as the parasitic meshed patch. Fig. 4.3a shows that the two resonance frequencies are 212 MHz apart. The higher resonance (f_H) is related to the upper patch, and the lower resonance (f_L) is related to the lower patch. Then, the two resonance frequencies are designed to be closer by increasing the upper patch length and decreasing the lower patch length. The result for the L_2 sweep is shown in Fig. 4.3b, for $L_2 = 27.9$ mm the higher resonance frequency is at the higher end of the frequency range. Then this length is selected for sweeping L_1 . L_1 was decreased to increase f_r . The result is illustrated in Fig. 4.3c.



(a)



(b)



(c)

Fig. 4.3: Stacked meshed patch antenna design procedure. a) $H_1 = 1$ mm, $H_2 = 1$ mm, $L_1 = 26.9$ mm, $L_2 = 26.9$ mm, $X_f = 7.1$ mm. b) $H_1 = 1$ mm, $H_2 = 1$ mm, $L_1 = 26.9$ mm, $X_f = 7.1$ mm. c) $H_1 = 1$ mm, $H_2 = 1$ mm, $L_2 = 27.9$ mm, $X_f = 7.1$ mm.

Reducing L_1 to beyond 26.3 mm did not cause f_L and f_H to become closer. Then L_1 was set to be 26.3 mm. With these initial values of L_1 and L_2 and changing the feed location, we can find a couple of designs in which the stacked antenna's input reflection coefficient is better than -10 dB. Fig. 4.4 illustrates the input reflection coefficient of these designs, and the dimensions are summarized in Table 4.1. Case 1 from Fig. 4.4 has the largest bandwidth (65 MHz) but investigating the radiation pattern showed that the cross-polarization is -9.4 dBc at 2.518 GHz which is high for the antenna. Therefore, considering the radiation properties of the antenna, case 4 has the best performance with 53.5 MHz bandwidth which is 3 times better than the single layer meshed patch on a 1-mm thick fused silica, 6.2 dBi gain, -17 dBc cross-polarization level, and 1.6 dBi gain flatness in its -10 dB bandwidth.

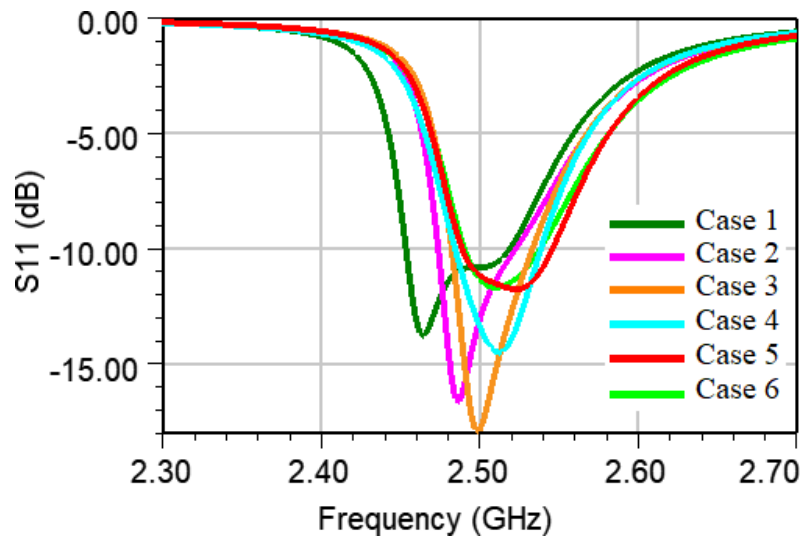


Fig. 4.4: 2-mm thick stacked meshed patch antenna results for S11 lower than -10 dB. Case 6: $H_1 = 1$ mm, $H_2 = 1$ mm, $L_1 = 27.9$ mm, $L_2 = 26.2$ mm, $X_f = 9.5$ mm.

Table 4.1: Summary of Case 1 to Case 6 dimensions.

	H_1 (mm)	H_2 (mm)	L_1 (mm)	L_2 (mm)	X_f (mm)
Case 1	1	1	26.2	27.9	8.4
Case 2	1	1	26.25	27.9	8.4
Case 3	1	1	26.2	28	8.4
Case 4	1	1	26.3	28	8.6
Case 5	1	1	26.25	27.85	8.4
Case 6	1	1	27.9	26.2	9.5

Fig. 4.5 demonstrates sensitivity analysis for case 4. In this study, the upper meshed patch length was swept by 0.05 mm steps from 27.9 mm to 28.1 mm. We can see that a small change in L_2 can change the S11 significantly.

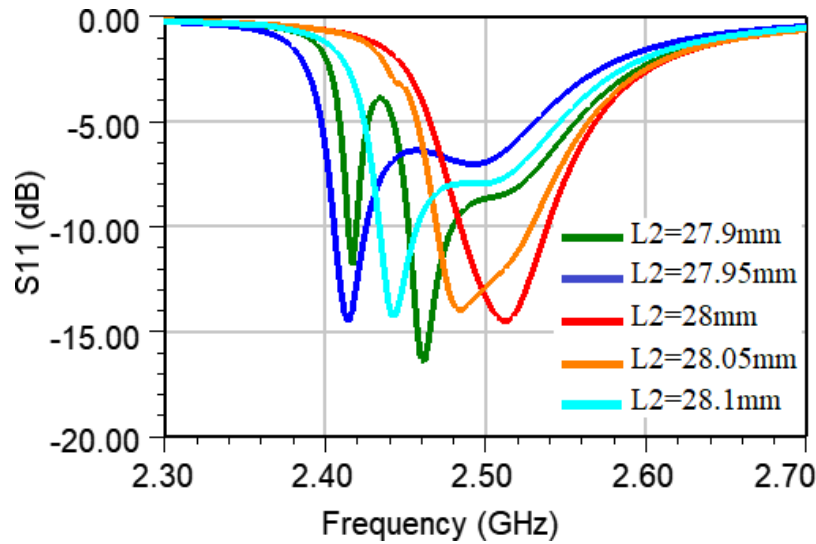


Fig. 4.5: Sensitivity analysis of case 4 to L_2 .

The HFSS simulations were performed with fast sweep analysis. Changing the sweep type to discrete gives more accurate results. Fig. 4.6 shows the S11 of case 1 to case 6 with the discrete sweep. It is seen that there is a second resonance around 2.45 GHz for all cases except case 2, which has 49 MHz bandwidth, 6.1 dBi peak gain, 2 dBi gain variation and cross-polarization level better than -20 dBc.

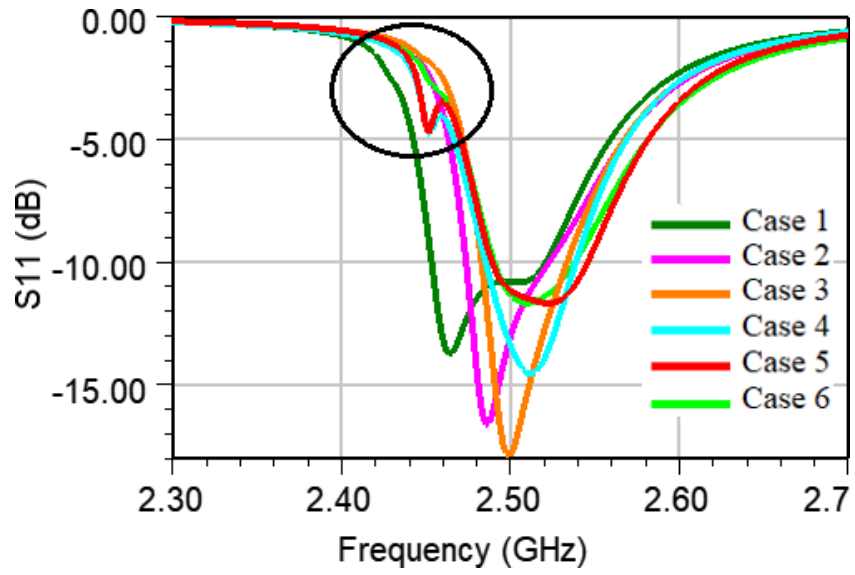


Fig. 4.6: S_{11} of case 1 to case 6 with discrete sweep analysis.

The Smith chart representation of Case 2 input impedance is illustrated in Fig. 4.7.

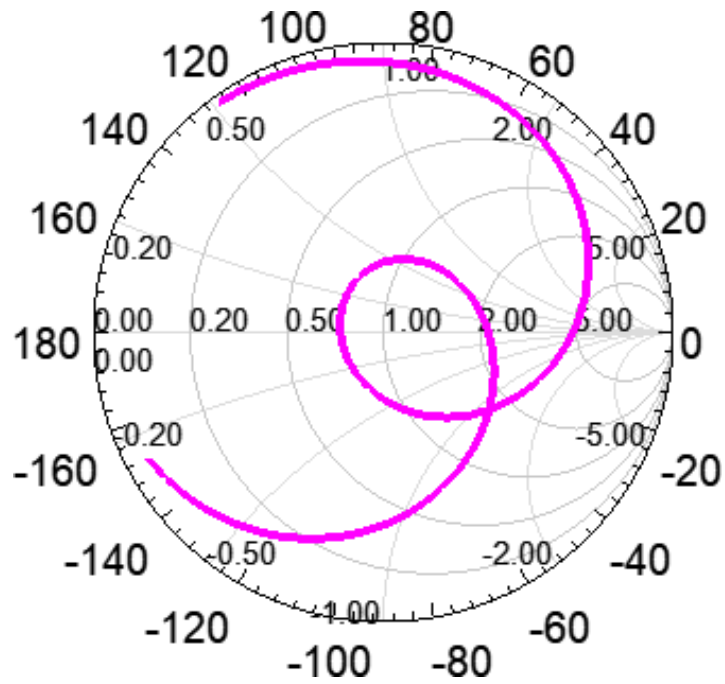
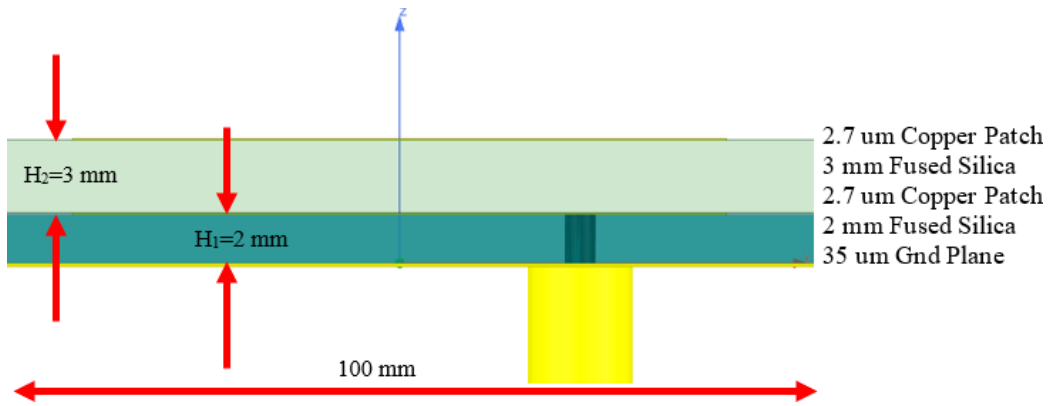


Fig. 4.7: Impedance locus of case 4 on Smith chart.

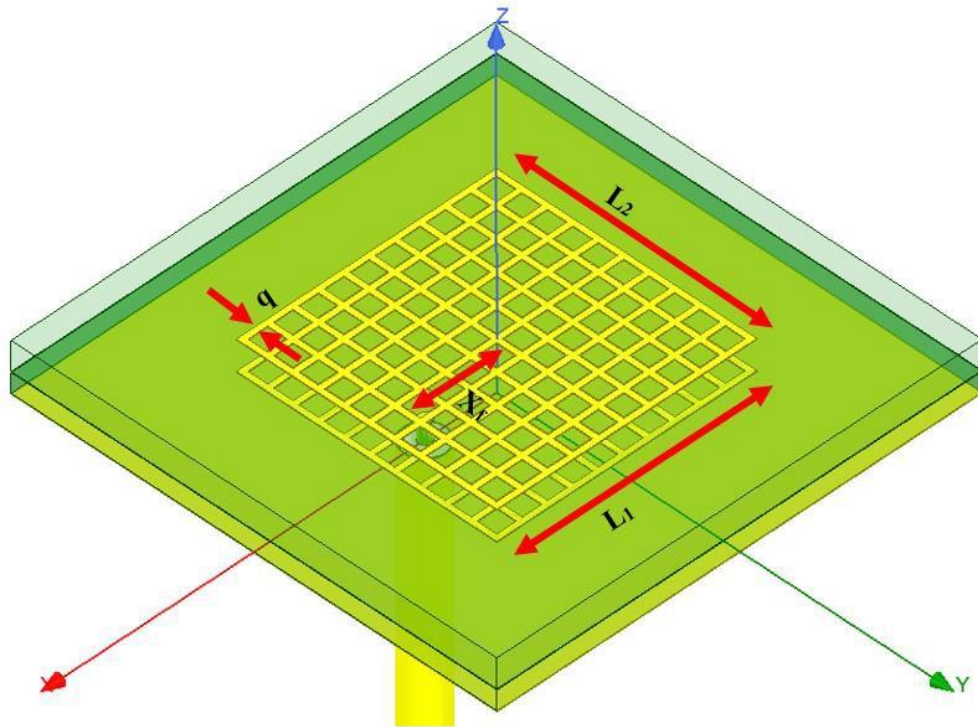
4.3 Characterization of Probe-fed Stacked TMPAs

The design procedure was repeated until an overall thickness of 5 mm was reached to have a wider bandwidth and reduce the antenna sensitivity to the design parameters. In this section, the performance of a probe-fed stacked TMPA with $H_1 = 2$ mm and $H_2 = 3$ mm is discussed further, and the parametric study is presented.

Fig. 4.8 shows the proposed stacked TMPA. The patch conductor is 2.7 μm thick copper (imposed by fabrication limitation), then an air gap of 2.7 μm is considered between the two layers when modelled in ANSYS HFSS. The lower substrate height is 2 mm ($0.0258\lambda_c$), and the upper layer is 3 mm ($0.0387\lambda_c$) thick. Fig. 4.9 illustrates the antenna's S11 and resonance loop on the Smith chart. The proposed antenna has a bandwidth of 6.3%, from 2413 MHz to 2571 MHz, which is 5.5 times better than the single-layer antenna. The two frequency resonances arise due to the coupling interactions between the two patches. Although the two patches have nearly identical physical dimensions, their effective electrical lengths differ due to different dielectric layer thicknesses and the coupling effects.

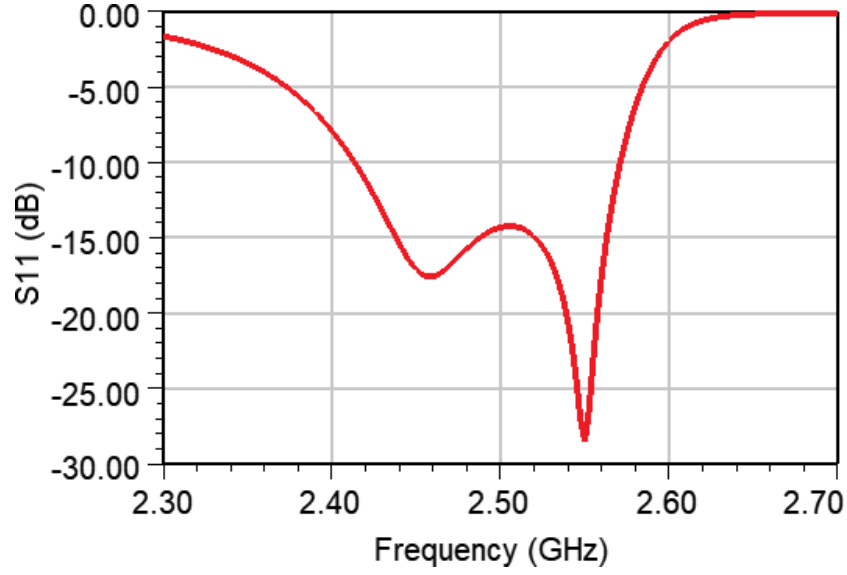


(a)

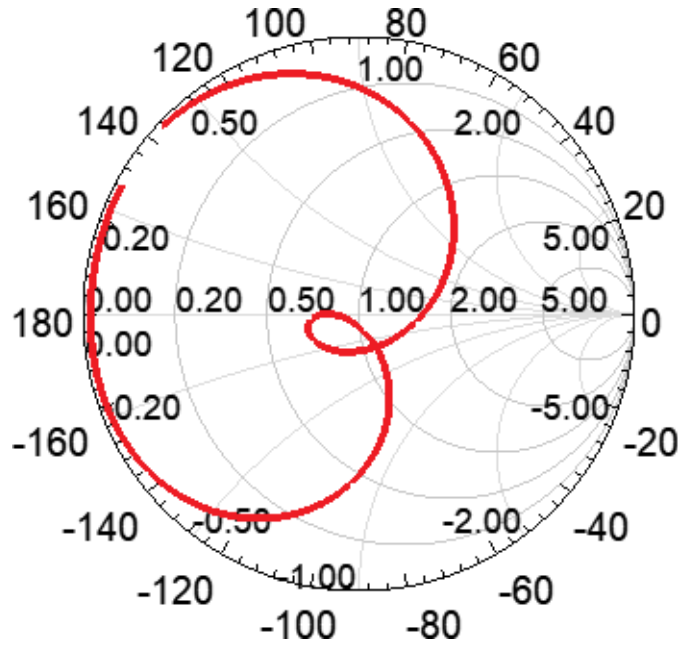


(b)

Fig. 4.8: Stacked transparent meshed antenna's geometry. a) Side view. b) 3D view.



(a)



(b)

Fig. 4.9: Impedance matching of the stacked TMPA. a) S_{11} . b) Impedance locus ($H_1 = 2$ mm, $H_2 = 3$ mm, $L_1 = 26.4$ mm, $L_2 = 26$ mm, $X_f = 6.9$ mm).

The other advantage of using the stacking technique is that the antenna's radiation pattern remains symmetrical in the entire bandwidth [44]. Fig. 4.10 shows the E-plane and H-plane

radiation patterns at 2.42 GHz, 2.5 GHz, and 2.57 GHz. The maximum radiation pattern direction points broadside at all frequencies, the cross-polarization is better than -20 dBc, and the half-power beam width is 80 degrees. High cross-polarization levels can lead to unwanted signal components interfering with the main signal, reducing the overall efficiency of the communication link.

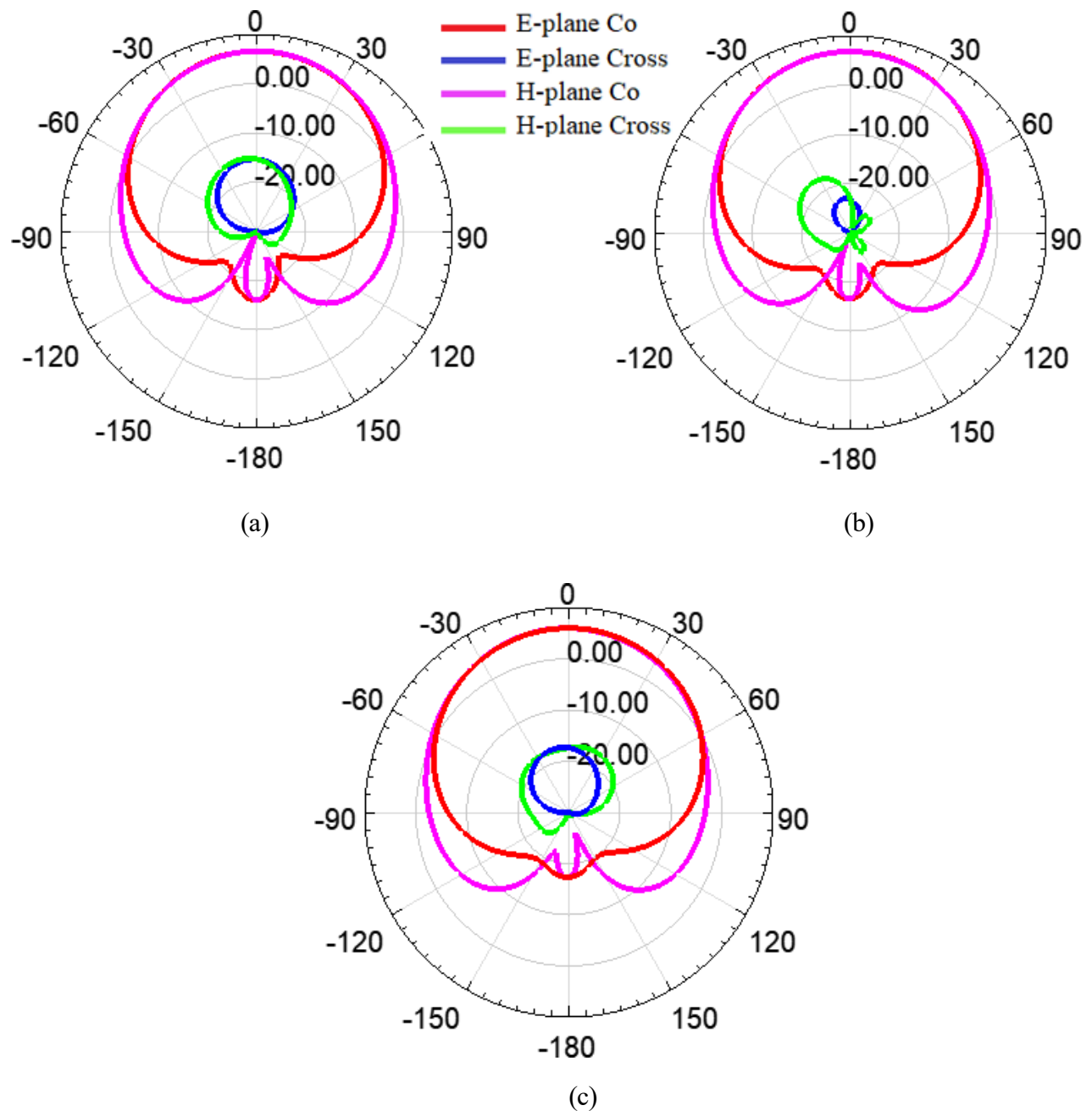


Fig. 4.10: The antenna E-plane and H-plane radiation pattern. a) 2.42 GHz. b) 2.5 GHz. c) 2.57 GHz.

The antenna gain was simulated in the entire bandwidth and is plotted versus frequency in Fig. 4.11. The maximum realized gain is 6.9 dBi, and the gain variation is less than 1 dBi in the -10 dB impedance bandwidth. Gain fluctuations across the bandwidth can significantly impact the communication link by causing variations in signal strength. This results in a lower Signal-to-Noise Ratio (SNR) at certain frequencies, increasing the Bit Error Rate (BER) and potentially causing data loss or retransmissions. Additionally, fluctuations in antenna gain affect the Effective Isotropic Radiated Power (EIRP), directly impacting the link budget and communication range [58].

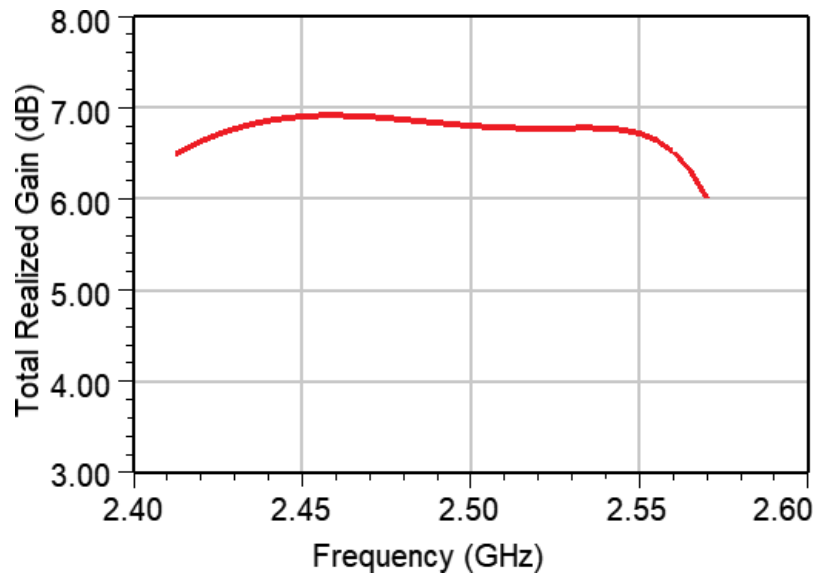


Fig. 4.11: Stacked TMPA's gain in -10 dB impedance bandwidth.

4.3.1 Surface Current

The electric current on the meshed patches at the lower and higher end of the frequency range was studied, and the results are shown in Fig. 4.12. It is seen that, at higher frequencies, the electric current on two meshed patches is out of phase and causes performance degradation, as stated in [44] for stacked solid patches. Also, it shows that the electric current vectors are

approximately uniformly distributed on the lower patch mesh lines at both frequencies. However, on the upper meshed patch, the current is concentrated on the edge lines at low frequencies and is uniformly distributed at high frequencies.

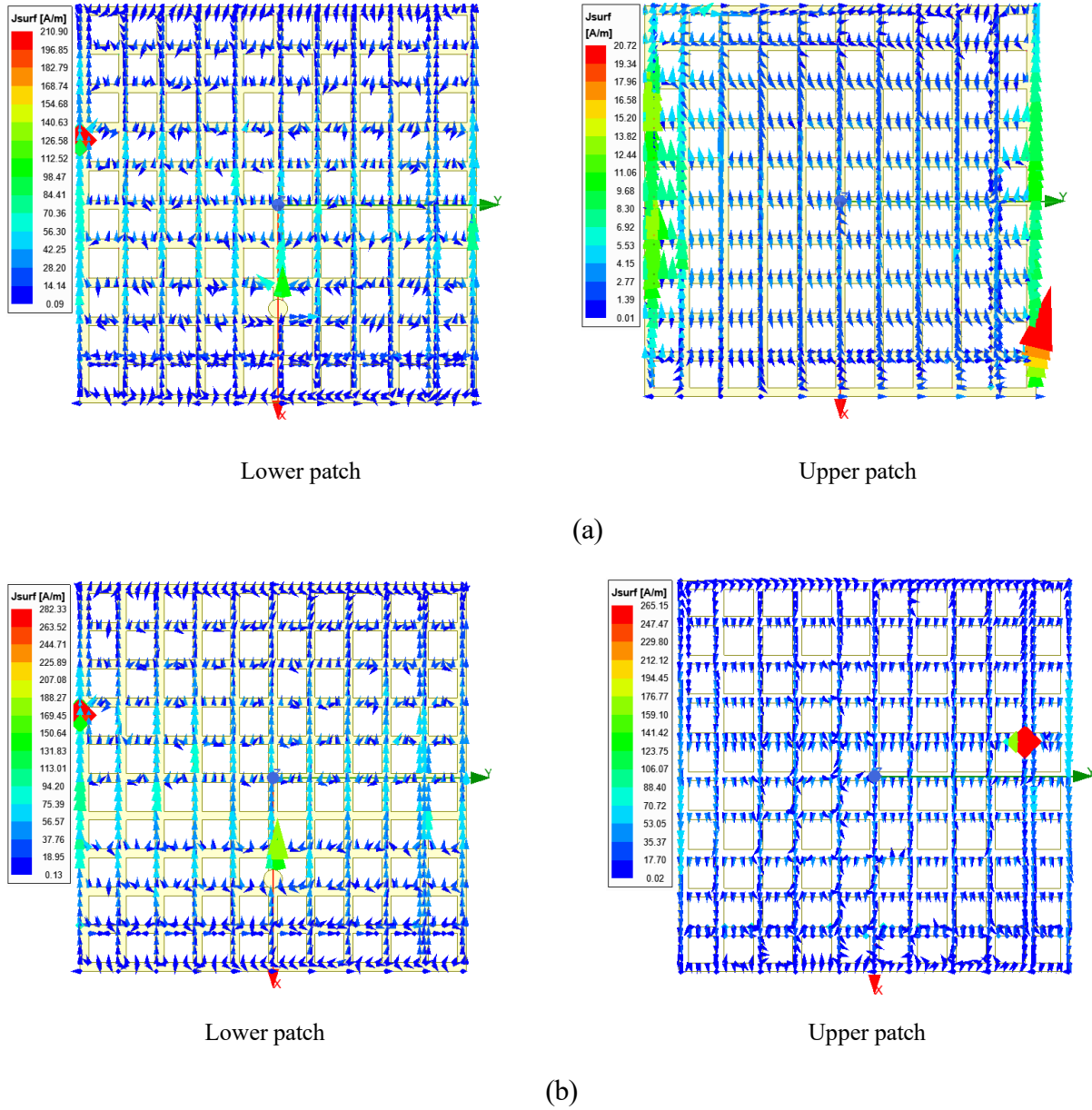


Fig. 4.12: Electric surface current distribution on lower and upper meshed patches. a) 2.42 GHz. b) 2.57 GHz.

The S11 of a single-layer meshed patch and a solid patch on the 2 mm thick fused silica is compared with the proposed stacked TMPA in Fig. 4.13.

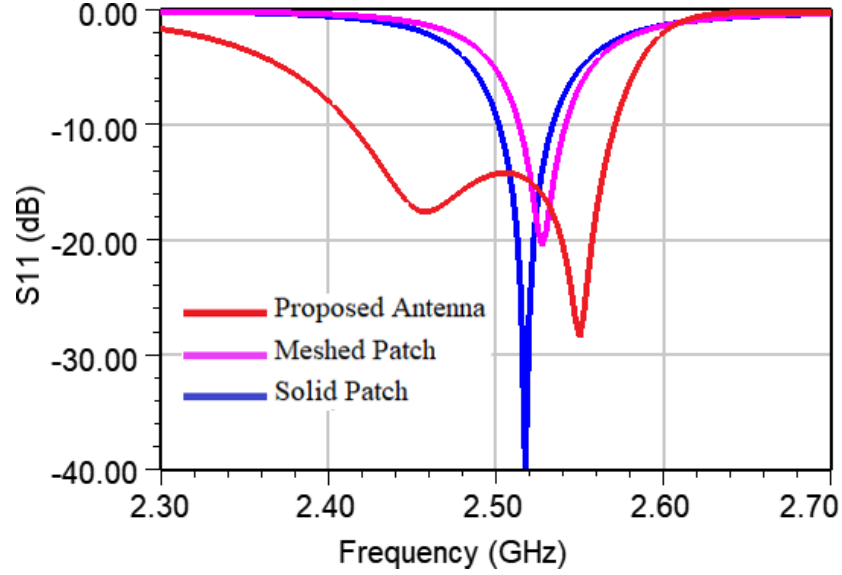


Fig. 4.13: Comparing S11 of a single layer meshed patch antenna ($L = 27.05$ mm, $X_f = 2.85$ mm) and a solid patch ($L = 27.45$ mm, $X_f = 3$ mm) on 2-mm thick fused silica substrate with the proposed stacked TMPA.

The total transparency of the proposed antenna in normal incidence is calculated from Equation (4.6). The calculated value is 96.9%, which is high enough to minimize the effect of the antenna on the solar cell's efficiency. The total transparency here represents the percentage of the $10 \text{ cm} \times 10 \text{ cm}$ antenna area that is not occupied by the metal mesh. The equation accounts for the area occupied by the horizontal and vertical mesh lines on top surfaces, providing the overall optical transparency of the complete meshed antenna. The ground effect on transparency is not considered here as it depends on the method of integration which will be later discussed in section 6.6.

$$1 - \frac{(N_v + N_h) \times d \times L_1 - N_v \times N_h \times d^2}{100 \times 100} \quad (4.6)$$

4.3.2 Effect of Substrate Size

Three cases were considered for fused silica substrate dimension. Case-1 is the proposed antenna in the previous section with a 10 cm by 10 cm square ground plane to be compatible with 1U CubeSats. In Case-2 the substrate size was reduced to 7.07 cm to present cutting a square

substrate out of a standard 100 mm diameter wafer. The substrate size was increased to 15.48 cm $\times$ 15.48 cm in Case-3, two times the substrate medium's wavelength (λ_c). Fig. 4.14 compares the S11 for these three cases. All the dimensions are the same as in Case-1, and only the substrate size was changed.

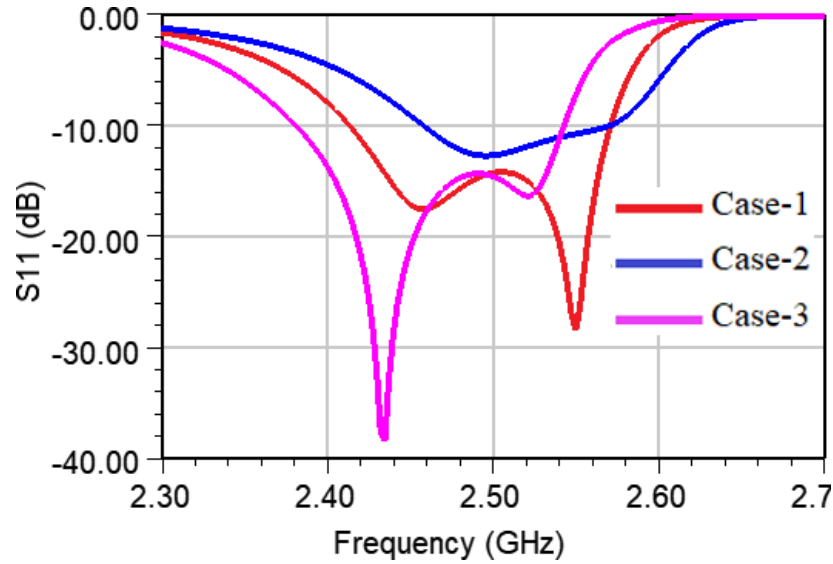


Fig. 4.14: Comparing S11 of three stacked TMPAs with different substrate sizes (Case-1: $L_g = 10$ cm, Case-2: $L_g = 7.07$ cm, Case-3: $L_g = 15.48$ cm).

Increasing the substrate size to $2\lambda_c$ moved the S11 to lower frequencies, but the bandwidth remained the same. Reducing substrate size to 7.07 cm, which is approximately equal to λ_c , caused a reduction in the antenna's bandwidth. However, it can be compensated by adjusting the patch dimensions and feed location. Fig. 4.15 illustrates the Case-2 S11 after optimization. The new Case-2 antenna has a bandwidth of 5.9%, maximum gain of 6.9 dBi, a gain uniformity of 1 dBi, and cross-polarization better than -20 dBc.

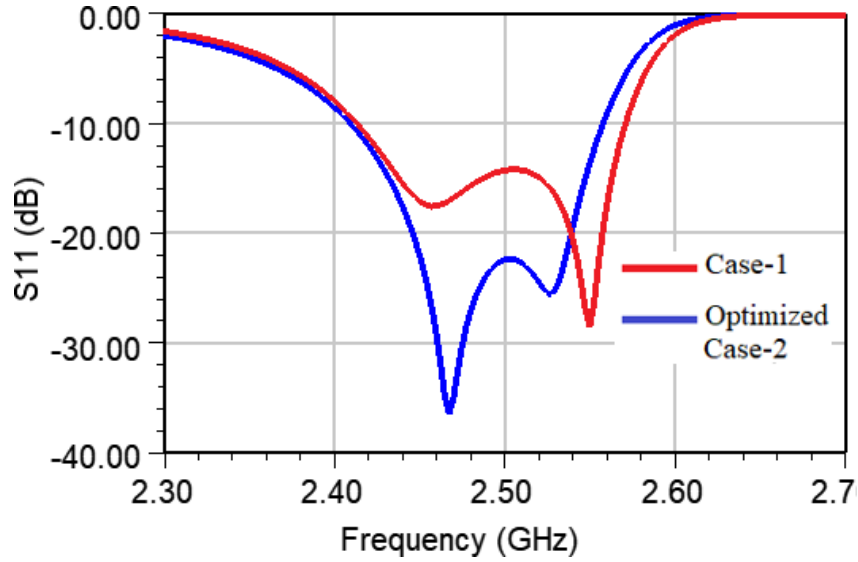


Fig. 4.15: Comparing S11 of Case-1 with optimized Case-2 ($L_1 = 26$ mm, $L_2 = 26.2$ mm, $X_f = 6.5$ mm).

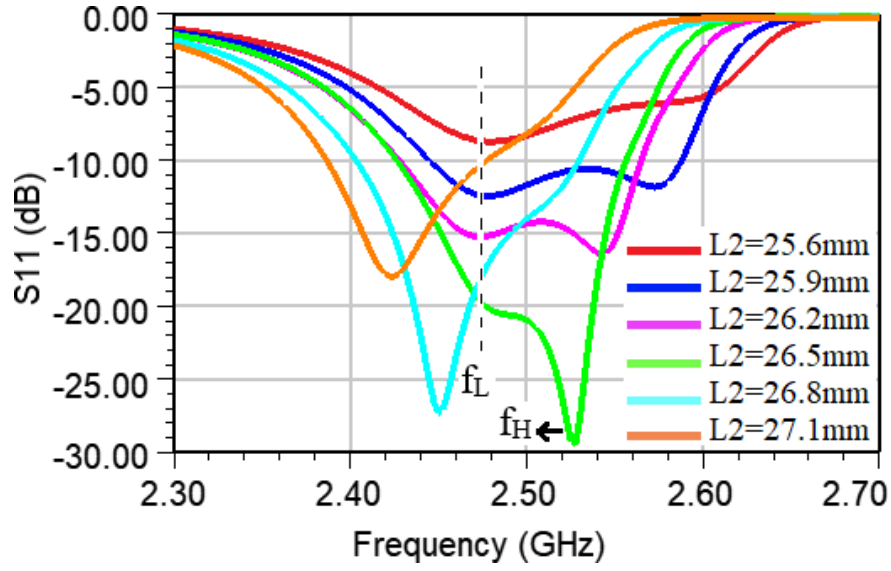
4.4 Parametric Study

Various parameters define the performance of a stacked antenna. In this section, the effect of changing the dielectric heights and meshed patch lengths on the antenna's S11 is discussed.

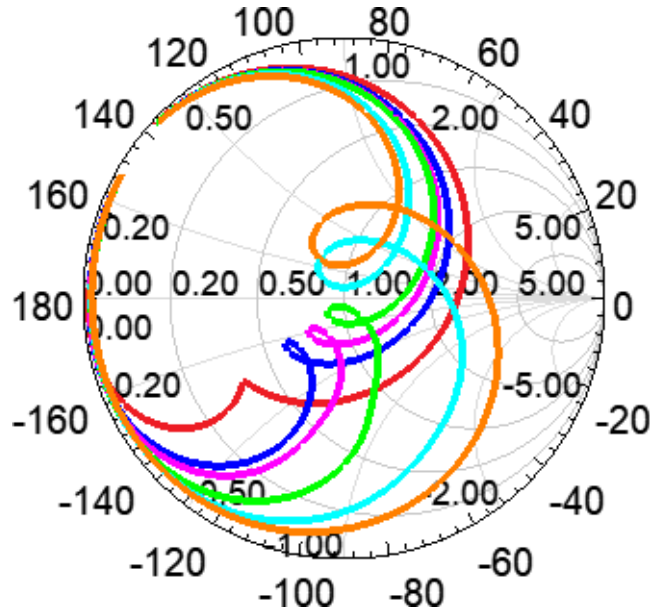
4.4.1 Meshed Patches Lengths

The effect of changing the length of the upper and lower meshed patches on the stacked TMPA performance is presented here. Fig. 4.16 shows the results for changing the upper meshed patch length when L_2 was swept between 25.6 mm to 27.1 mm with 0.3 mm steps, and other parameters were kept constant.

In this structure, the upper patch length defines the upper resonance frequency. Then as the length of the upper patch increased, the second resonance frequency moved towards the lower frequencies, and the resonance loop in the Smith chart moved from the capacitive region toward the centre. When the upper patch length was made larger than the lower one, the resonance loop moved to the inductive region and the resonance frequency moved to the lower range.



(a)

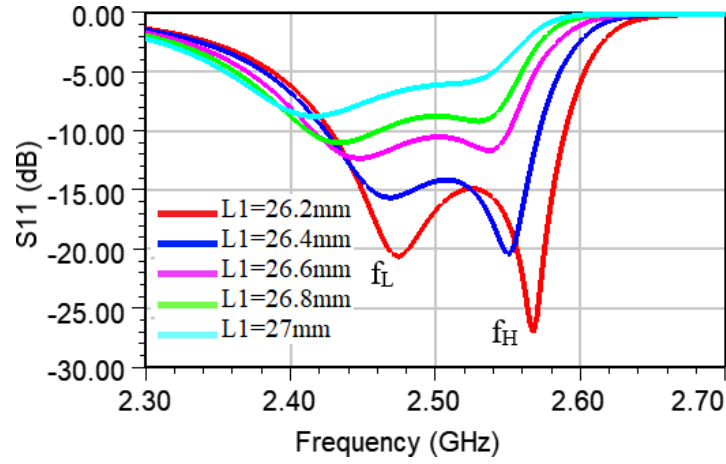


(b)

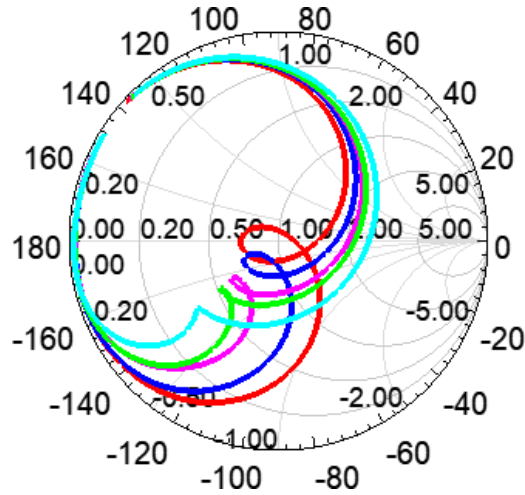
Fig. 4.16: Simulated S_{11} of the stacked TMPA when L_2 is swept. a) S_{11} . b) Smith chart. ($H_1 = 2$ mm, $H_2 = 3$ mm, $L_1 = 26.4$ mm, $X_f = 6.9$ mm)

The lower patch length was swept from 26.2 mm to 27 mm in 0.2 mm steps. Fig. 4.17 demonstrates the results. Increasing L_I caused the frequency response to move to the lower frequencies. The Smith charts can be used to place the resonance loop at the center. When L_I was

made larger than L_2 , the resonance loop moved to the capacitive region. It entered the inductive region when L_2 increased. In both studies, changing L_1 and L_2 means changing the size of the outer meshes. Therefore, the mesh spacing remained the same in all cases.



(a)



(b)

Fig. 4.17: The simulated S11 loss of the stacked TMPA when L_2 is swept. a) S11. b) Smith chart. ($H_1 = 2$ mm, $H_2 = 3$ mm, $L_1 = 26.4$ mm, $X_f = 6.9$ mm)

4.4.2 Dielectric Heights

The effect of changing H_2 on the antenna's S11 is plotted in Fig. 4.18. The dielectric height was swept between 2.75 mm and 4.25 mm while other parameters were kept constant. For heights

smaller than 2.75 mm, and larger than 4.25 mm the S11 is above the -10 dB limit. Therefore, there is a minimum and maximum for selecting the upper dielectric height, which depends on the lower substrate thickness. The widest bandwidth with S11 lower than -10 dB happened at $H_2 = 3.75$ mm. As the second dielectric layer got thicker, the coupling between the two patches became too weak to excite the parasitic patch.

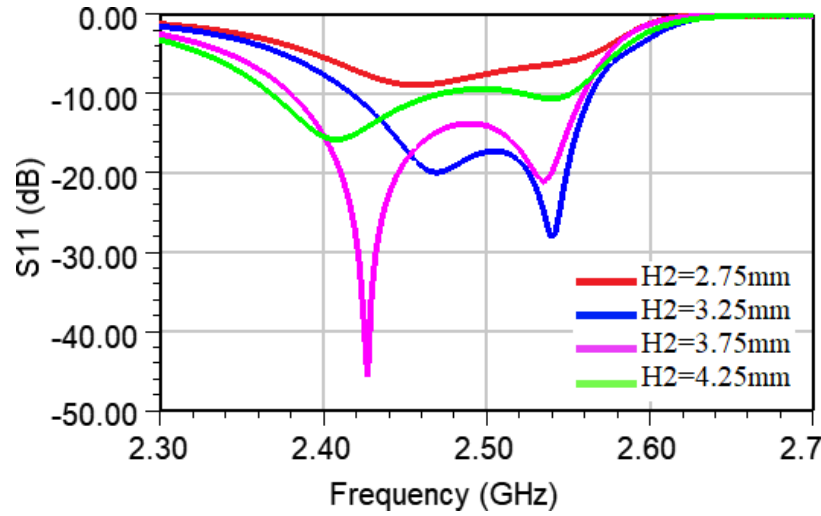


Fig. 4.18: Simulated S11 of the stacked TMPA for H_2 sweep ($H_1 = 2$ mm, $L_1 = 26.4$ mm, $L_2 = 26$ mm, $X_f = 6.9$ mm).

The lower layer dielectric height was swept from 1.5 mm to 3.5 mm. The simulated result of the stacked TMPA's S11 is in Fig. 4.19. The graph shows that H_1 's value plays an important role in defining the antenna's bandwidth. Increasing the thickness of the lower layer improved the impedance bandwidth. However, the amount of S11 increased. It can be reduced by increasing the upper layer thickness, but the impedance bandwidth will be limited.

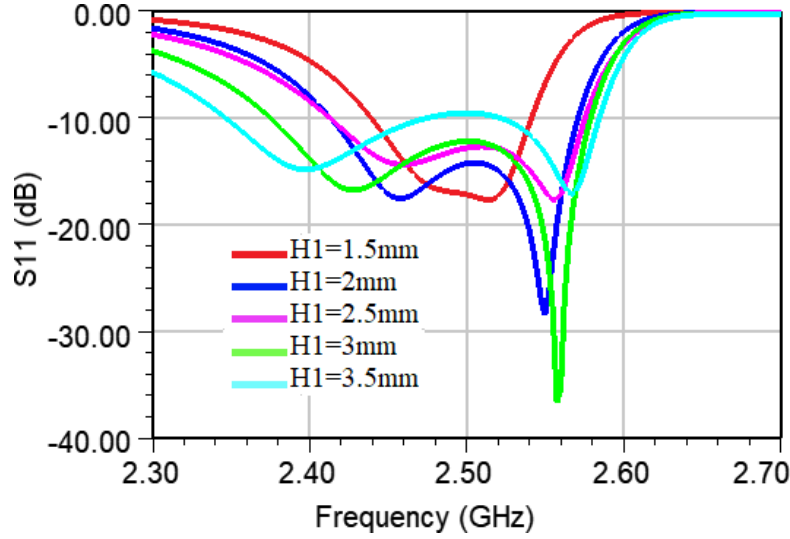


Fig. 4.19: Simulated S11 of the stacked TMPA for H_1 sweeps. ($H_2 = 3$ mm, $L_1 = 26.4$ mm, $L_2 = 26$ mm, $X_f = 6.9$ mm).

4.5 Conclusion

This chapter explored the challenges and advancements in designing meshed patch antennas for CubeSat applications, focusing on overcoming the bandwidth limitations. Various techniques, including coplanar elements, multimoding, and stacking, were reviewed for their efficacy in bandwidth enhancement while maintaining transparency and integration compatibility with solar cells.

The stacked TMPA design presented in this chapter demonstrates a significant improvement over single-layer meshed patches, achieving a 6.3% bandwidth, 5.5 times wider than conventional designs, while maintaining high transparency (96.9%) and compactness suitable for 1U CubeSats. Using fused silica glass as the substrate balances transparency and robustness, enabling integration with solar cells and the CubeSat structure.

Key contributions include an optimized design process for stacked TMPAs, a detailed parametric study of substrate heights and patch lengths, and the characterization of the designed

antenna's radiation pattern and S_{11} . The design achieved a consistent gain across the bandwidth, symmetric radiation patterns, and minimized sensitivity to variations in design parameters.

Chapter 5

Glass/SU-8 Stacked Transparent Meshed Patch Antennas

5.1 Introduction

In the previous chapter, to make the stacked antenna compatible with solar cells' integration, and deliver the required transparency for space applications, both substrate layers were suggested to be glass. In [57] bandwidth of 1.5% was achieved for a 2 mm thick antenna. One way to increase the bandwidth is to thicken both substrates relatively. As was done in Chapter 4, 6.3% relative bandwidth was achieved for an overall thickness of 5 mm. However, it imposes additional weight and could be a problem especially when an array of the stacked element is needed for multiunit CubeSats. In this chapter, three stacked antenna designs with a combination of glass, SU-8 photoresist, and air are designed to address the problem and achieve low-mass antennas. Finally, their performance is compared with a full glass antenna and a suspended patch. These are candidate final designs that are being explored for possible fabrication.

5.2 SU-8 Material

SU-8 is a negative epoxy-based photoresist designed by MicroChem Corporation and has been widely used in Micro-Electro-Mechanical Systems (MEMS) applications. Its unique features, such as optical transparency, ability to form different thicknesses from a few microns to

millimeters, good adhesion, chemical robustness, good thermal stability after hard-bake, and low loss, make it a good choice for fabricating microwave devices [59]. Some studies have investigated the use of SU-8 in antenna fabrication. However, in only a few of them, the SU-8 was used as part of the radiator, and its properties directly affected the antenna performance and its radiation properties. In [60], a flexible SU-8/PDMS-based microstrip patch antenna was developed. Polydimethylsiloxane polymer (PDMS) is a transparent polymer with a low dielectric constant and the ability to attach to other materials. They demonstrated the applicability of the SU-8 in wearable devices and achieved a bandwidth of 3% from 6.2 to 6.4 GHz with a maximum gain of 2.17 dBi. In [61], SU-8 was utilized as a resonating material to fabricate a rectangular resonator antenna, and in [62] a bandwidth-enhanced, inkjet-printed stacked patch antenna was developed using SU-8 as a spacer and Kapton polyimide as the substrate, achieving a gain of 4.5 dBi and -10 dB impedance bandwidth of 5.3% at 4.9 GHz.

We investigated the feasibility of using SU-8 as the main dielectric substrate for the microstrip patch antennas used in CubeSats in [63]. A 1 mm thick SU-8 layer was deposited on a hybrid composite panel and aluminum pieces by several spin coatings. However, the difference in the thermal coefficient of the layers and the maximum allowable temperature of the composite panel imposed fabrication difficulties on the design. To solve those issues, we deposited SU-8 on the glass layer, which offers a robust design, good adhesion, and high integration with solar cells. The other advantage of using SU-8 is its lower density. SU-8 2075 density is 1.236 g/cm^3 compared with 2.13 g/cm^3 for fused silica, which offers 42% lower weight in similar substrate height. Besides that, the SU-8 photoresist can be removed partially. This feature can further reduce the antenna's weight, which is an important factor for antenna installation on CubeSats and array antennas.

For the SU-8, the dielectric constant and loss factor are highly dependent on the fabrication process and temperature [64], the type and age of the SU-8 [65], and being fully or partially cross-

linked [66]. Different material measurement techniques have been used to characterize the SU-8 microwave properties. In [66], the permittivity of a fully and partially cross-linked SU-8 is measured with a THz-TDS system. Based on their study the values of 3.25 and 0.015 were obtained for the dielectric constant and loss tangent of a fully cross-linked SU-8 at 2.5 GHz. S-parameter measurements on microstrip lines were used in [67] to determine SU-8 material properties. Their finding suggested a dielectric constant of 2.9 and a loss tangent of 0.045. In [68], a microstrip ring resonator was used. Their study suggested a dielectric constant of 3.25, but a numerical value for the loss factor was not presented. In this thesis, a dielectric constant of 3.25 and a loss tangent of 0.015 based on the proposed formula in [66] were considered in the simulations to model the SU-8 substrate.

5.3 Antenna Design and Simulation

This chapter proposes three stacked meshed patch antennas using SU-8 as the second dielectric layer, aiming to reduce the antenna's weight. The performance of these antennas is compared with that of a directly stacked antenna with two layers of glass and a suspended meshed patch antenna using air as the upper dielectric layer. All the designs employed solid ground plane.

5.3.1 Ant-1: Glass/Glass Stacked Antenna

Ant-1 in this study is the reference antenna with two layers of fused silica glasses, designed and discussed in Chapter 4. The antenna's height and weight are 5 mm and 110 g. As explained before, it has a total transparency of 96%, a gain of 6.9 dBi, and bandwidth of 6.3%.

5.3.2 Ant-2: Glass/SU-8 Stacked Antenna

The structure of Ant-2 shown in Fig. 5.1 is similar to Ant_1 except for the upper dielectric

material which was substituted with a thick layer of SU-8. The bottom layer is a 1.5 mm thick fused silica glass and the SU-8 layer on top is 3.5 mm thick. The goal was to reduce the antenna's weight while maintaining the same performance. Total height was kept constant (5 mm) for comparison purposes. Ant-2 showed a bandwidth of 8.2% and weighs 75 g which is 30% lower than Ant-1.

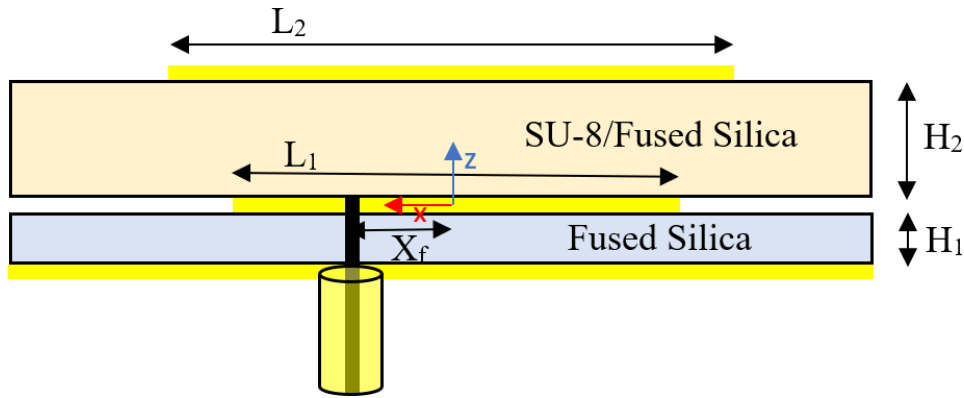


Fig. 5.1: Ant-1 and Ant-2 side view (Ant-1: $H_1 = 2$ mm, $H_2 = 3$ mm, $L_1 = 26.4$ mm, $L_2 = 26$ mm, $X_f = 6.9$ mm. Ant-2: $H_1 = 1.5$ mm, $H_2 = 3.5$ mm, $L_1 = 26.8$ mm, $L_2 = 27.9$ mm, $X_f = 9$ mm).

5.3.3 Ant-3: Glass/Cubic SU-8 Stacked Antenna

Ant-3 was designed to further reduce the stacked antenna mass by partially removing the SU-8 substrate. In this design, the SU-8 dielectric only exists below the upper meshed patch, which has a length of 32.4 mm and 13 equally spaced vertical and horizontal lines. To reduce the shadowing effect in all antennas, both upper and lower grids have the same filling factor ($d/(d+p)$) except for the outer meshes of the upper patch, which were adjusted to get two close resonance frequencies. The antenna weight was reduced to 36.5 g, which is 66.8% lighter than Ant-1, while its bandwidth and gain are still comparable to both Ant-1 and Ant-2. Fig. 5.2 demonstrates the antenna structure. The fused silica glass layer and SU-8 are 1.5 mm and 3.5 mm thick, respectively.

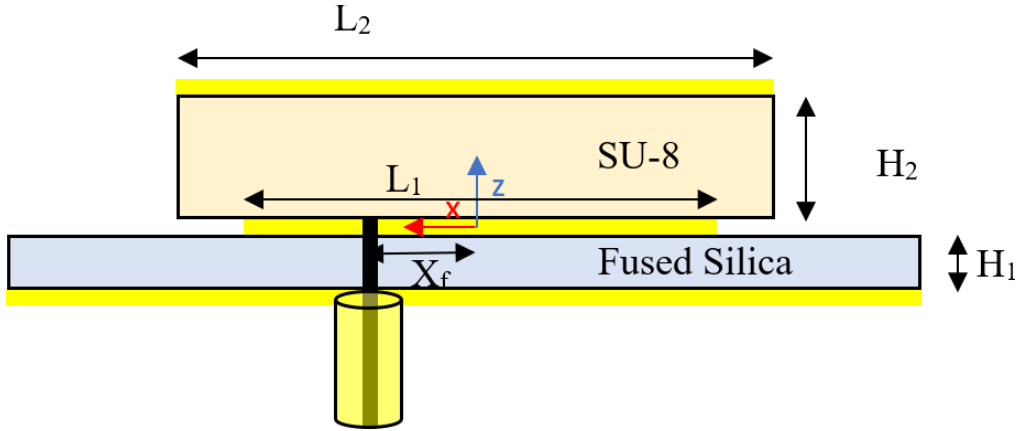


Fig. 5.2: Ant-3 side view (Ant-3: $H_1 = 1.5$ mm, $H_2 = 3.5$ mm, $L_1 = 26.9$ mm, $L_2 = 32.4$ mm, $X_f = 8$ mm).

5.3.4 Ant-4: Glass/Perforated SU-8 Stacked Antenna

The fourth antenna is a perforated stacked meshed patch structure. In this configuration a glass layer is used as the lower substrate and the upper dielectric layer only exists below the upper meshed patch. Fig. 5.3 depicts the antenna structure. The perforated substrate was modelled as SU-8 in the simulations. Other transparent materials such as PDMS and plexiglass are also good choices for this antenna as the effect of the material properties on the antenna's performance is less critical in this design. The perforation reduced the average dielectric constant of the upper substrate and shifted the resonance frequency to a higher one. By thickening the second substrate and increasing the size of the upper patch the resonance frequency was brought back to the desired one. Therefore, the overall weight remained the same as Ant-2 but the bandwidth and gain would improve significantly. The antenna weighs 36.9 g, close to Ant-3's weight and has a total thickness of 8.3 mm. To improve the transparency of Ant-4 and reduce its effect on the cell's performance, the number of horizontal lines can be reduced while maintaining the same performance [33].

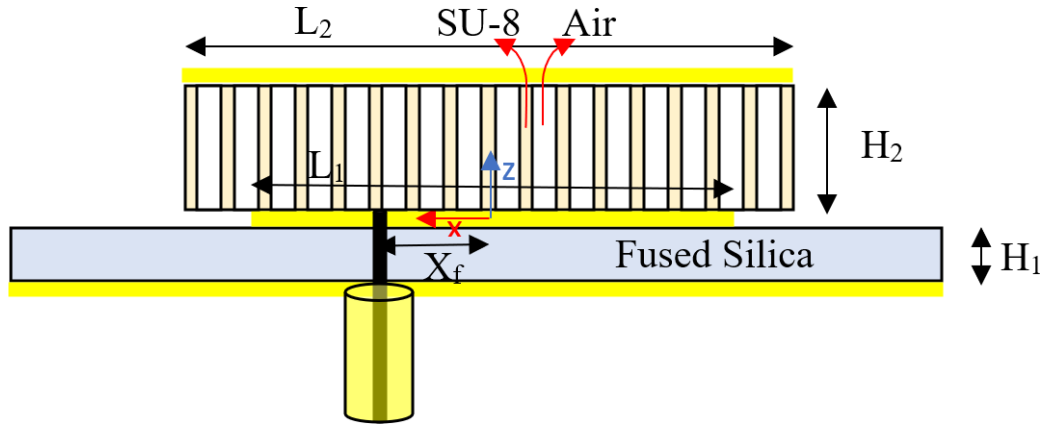


Fig. 5.3: Ant-4 side view (Ant-4: $H_1 = 1.5$ mm, $H_2 = 6.8$ mm, $L_1 = 28.4$ mm, $L_2 = 37.2$ mm, $X_f = 13.2$ mm).

5.3.5 Ant-5: Suspended Meshed Patch Antenna

The final design considered in this chapter is a suspended meshed patch antenna. The antenna structure is depicted in Fig. 5.4. The first dielectric layer is a 1.5 mm thick fused silica glass substrate, and the second substrate is air with a dielectric constant of 1 and thickness of 8 mm. The second meshed conductor is deposited on a 0.3 mm thick fused silica glass layer and is held by four PTFE (Polytetrafluoroethylene) posts located at the corners of the structure, with one post positioned at each corner of the upper substrate with height of 8 mm. The posts act as spacers that maintain the air gap between the lower and upper dielectric layers while providing the mechanical support required for the suspended configuration. PTFE was selected due to its low dielectric constant and low loss tangent, which minimize its impact on the electromagnetic performance of the antenna. Furthermore, the posts are positioned away from regions of maximum surface current density, reducing their influence on the antenna impedance matching, radiation characteristics, and efficiency.

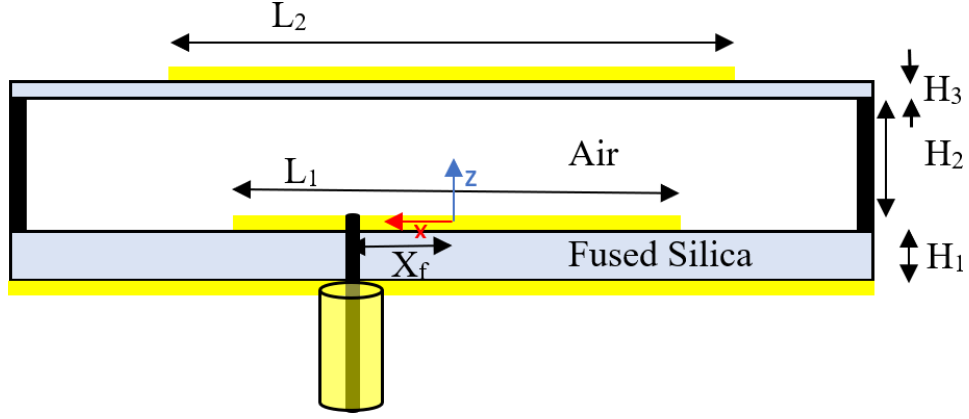


Fig. 5.4: Ant-5 side view ($H_1 = 1.5$ mm, $H_2 = 8$ mm, $H_3 = 0.3$ mm, $L_1 = 29.4$ mm, $L_2 = 41.6$ mm, $X_f = 14.2$ mm).

5.4 Results and Discussion

The S_{11} and gain of the designed antennas are plotted in Fig. 5.5 and Fig. 5.6. Ant-1, Ant-2, and Ant-3 have the same overall thickness of 5 mm. Changing the upper dielectric layer from glass (Ant-1) to SU-8 (Ant-2) increased the bandwidth from 6.3% to 8.2%. The bandwidth improvement is partly because of the loss associated with the SU-8 dielectric. The loss also reduces the antenna gain. Ant-1 has a peak gain of 6.9 dBi and a gain variation of less than 1 dBi in the -10 dB impedance bandwidth, while Ant-2's maximum gain is 6.4 dBi with a gain flatness of 2.2 dBi. Further removing the SU-8 in Ant-3 compensated for the gain reduction however, the bandwidth was reduced to 5.7%.

Meshing the upper substrate decreased the average dielectric constant of the material below the patch. As the dielectric constant of the upper layer decreased in Ant-4 and Ant-5, the antennas' performance improved. The suspended patch has the highest gain of 9.2 dBi and the widest bandwidth of 15%.

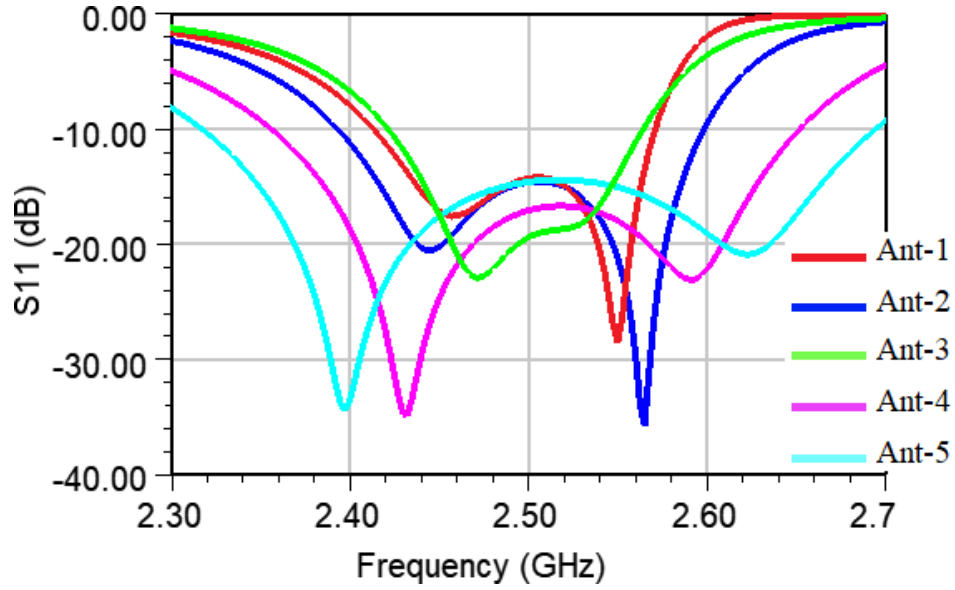


Fig. 5.5: S11 of the designed antennas.

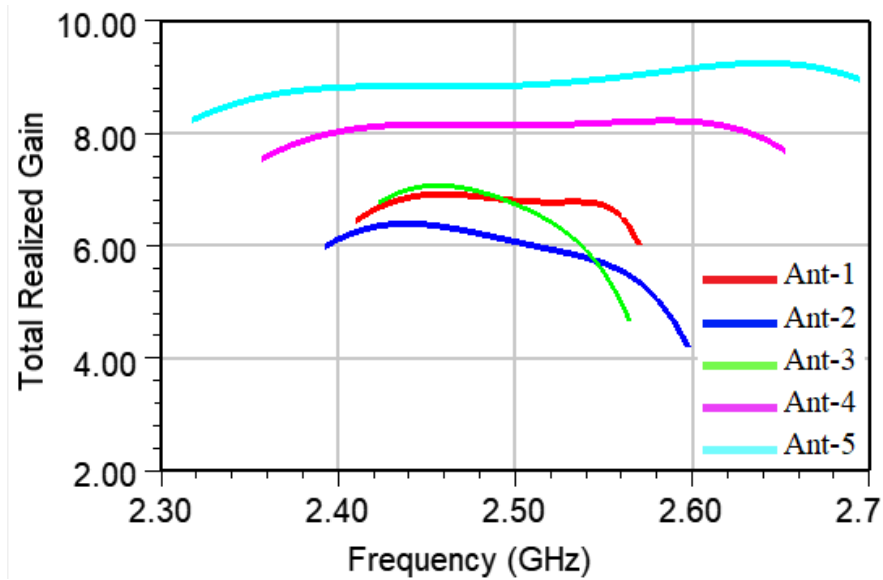


Fig. 5.6: Total realized gain of the designed antennas.

Table 5.1 summarizes the performance of the designed antennas. As shown in the table, Ant-1, which is the reference antenna with a full glass structure, provides a bandwidth of 6.3% and a peak gain of 6.9 dBi. It is relatively heavy at 110 g, and its transparency is the highest among the designs, with a normal transparency of 96%. Ant-2, which replaces the upper dielectric glass layer with a thick SU-8 layer, achieves a bandwidth of 8.2% and a slightly reduced peak gain of 6.4 dBi,

but it significantly reduces the mass by 30% (75 g). Ant-3 further reduces mass by removing part of the SU-8 substrate, achieving a very light weight of 36.5 g while maintaining comparable performance, though its bandwidth decreases to 5.7%. Ant-4, a perforated design, increases the bandwidth to 11.8% and enhances the gain to 8.2 dBi, while maintaining a similar weight to Ant-3 at 36.9 g. The suspended meshed patch antenna (Ant-5) achieves the best overall performance with the highest peak gain of 9.2 dBi and the widest bandwidth of 15%. However, its transparency is slightly lower at 93%, and the overall structure is thicker than the previous designs. Increasing the height of the upper dielectric layer decreases the transparency at oblique incidence. This can be compensated by removing the horizontal lines of the upper patch. As discussed in [29], reducing the number of horizontal lines to a certain degree will not affect the meshed antenna's performance because the electric current mostly passes through the vertical lines.

Table 5.1: Summarizing the performance and physical specs of the five designed TMPAs.

	Ant-1	Ant-2	Ant-3	Ant-4	Ant-5
Frequency (GHz)	2.5	2.5	2.5	2.5	2.5
Bandwidth (%)	6.3	8.2	5.7	11.8	15
Peak Gain (dBi)	6.9	6.4	7	8.2	9.2
Gain Uniformity (dB)	0.9	2.2	2.4	0.6	1
Normal Transparency (%)	96	96	95	94	93
Efficiency (%)	98-88	86-56	86-51	94-85	99
Cross-Pol (dBc)	< -21	< -23	< -20	< -22	< -35
Mass (g)	110	75	36.5	36.9	38.3
Thickness (h/λ_0)	0.041	0.041	0.041	0.069	0.081
H1 (mm)	2	1.5	1.5	1.5	1.5
$d/(d+p)$	0.232	0.229	0.228	0.215	0.208
Lower/Upper ϵ_r	3.8/3.8	3.8/3.25	3.8/-	3.8/~1	3.8/1/3.8
$N_v \times N_h$					
Lower patch	11×11	11×11	11×11	11×11	11×11
Upper patch	11×11	11×11	13×13	15×15	15×15

5.5 Conclusion

The study in this chapter demonstrated that using SU-8 as the upper dielectric layer can reduce the antenna mass while maintaining acceptable bandwidth and gain. The results also showed that modifying the geometry of the upper dielectric layer provides an effective approach for improving the trade-off between antenna performance and weight.

Improved electromagnetic performance must be balanced against fabrication complexity and mechanical robustness. Ant-1 and Ant-2 employ continuous dielectric layers and therefore provide mechanically stable structures that are relatively straightforward to fabricate and assemble. Ant-3 and Ant-4 significantly reduce antenna mass through partial removal of the dielectric material while maintaining acceptable performance, making them attractive candidates for CubeSat applications with strict mass constraints.

The perforated antenna design (Ant-4) offers the best overall compromise between weight reduction and antenna performance. By reducing the effective dielectric constant of the upper region, this structure achieves a substantial improvement in bandwidth and gain while maintaining a mass comparable to Ant-3. The suspended meshed patch antenna (Ant-5) further improves the antenna performance by replacing the upper dielectric layer with an air-filled region. Although Ant-5 achieved the highest simulated gain and widest impedance bandwidth, the suspended structure requires additional supporting elements and precise control of the air gap between the two meshed patches. These requirements increase fabrication complexity and may introduce additional assembly tolerances compared to the substrate-supported designs.

Although fused silica and SU-8 were used in this chapter to develop and evaluate the proposed antenna architectures, the presented design methodology is not restricted to these materials. The performance of the stacked meshed patch antennas is primarily governed by the dielectric properties of the substrate layers and the resulting electromagnetic coupling between

the patches. Therefore, the proposed design framework can be extended to other transparent dielectric materials, including alternative glass and polymer substrates, through appropriate adjustment of the antenna dimensions and design parameters.

Overall, the results demonstrate that the proposed transparent stacked antenna architectures can be tailored to satisfy different mission requirements. Glass-based structures provide simplicity and robustness, polymer-based structures enable substantial mass reduction, and suspended structures maximize electromagnetic performance. The discussions in this chapter have been published in [69] and [70].

Chapter 6

Fabrication and Measurement of Stacked Transparent Meshed Patch Antennas

6.1 Introduction

This chapter presents the fabrication and experimental validation of the stacked transparent meshed patch antennas designed and modeled in chapter five. To demonstrate the feasibility of the proposed designs, Ant-1 (the glass/glass stacked TMPA) and Ant-3 (the glass/cubic SU-8 stacked TMPA), designed in chapter five, were fabricated and tested. The fabrication process is detailed in the following sections.

To evaluate the performance of the fabricated antennas, key parameters such as the S_{11} , 2D radiation patterns, and gain were measured. Impedance characterization was performed using a Keysight E5063A vector network analyzer (VNA), while radiation pattern measurements were conducted in the Compact Antenna Test Range at the University of Manitoba's Antenna Laboratory. The results were then compared with simulated data to identify discrepancies and assess the impact of fabrication tolerances on the antennas' performance.

The objective of this chapter is to validate the feasibility of the stacked transparent meshed patch antennas for CubeSat applications by analyzing the measured data, identifying potential design challenges and fabrication constraints, and providing insights for future optimization and practical implementations.

6.2 Ant-1: Glass/Glass Stacked Antenna Fabrication and Measurement

The performance of Ant-1 was analyzed in Chapters Four and Five, where a 50-ohm probe was used for modeling and simulation. However, a proximity-coupled feeding method was selected for fabrication to avoid drilling into the glass substrate. The overall concept and design approach of the stacked antenna remained unchanged. The antenna geometry with the proximity-coupled feeding structure is illustrated in Fig. 6.1. For a direct comparison with the measured results, all simulations were repeated using the proximity-coupled feeding configuration and the same antenna dimensions as the fabricated prototype.

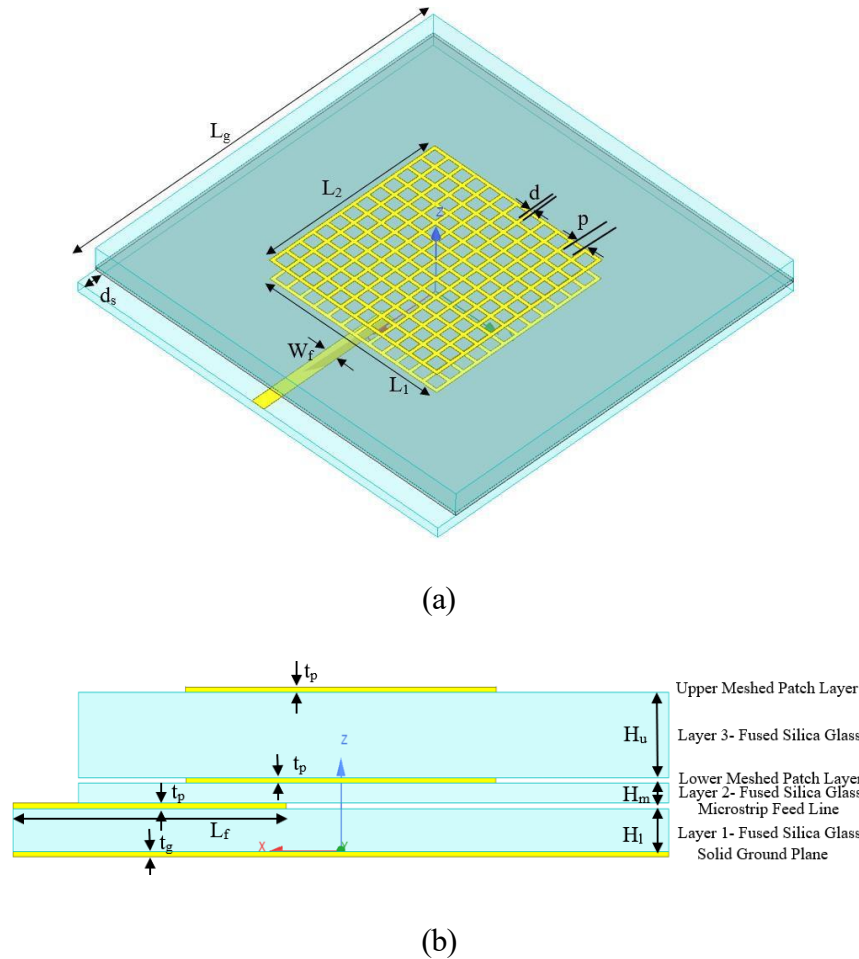


Fig. 6.1: ANT-1: glass/glass stacked antenna's geometry. a) 3D view. b) Side view.

Ant-1 consists of three stacked substrate layers. The bottom layer is a 1.5 mm thick fused silica glass substrate that supports the 50-ohm microstrip feed line with width (W_f) 3.25 mm and length (L_f) of 41.9 mm and is backed by a solid ground layer. The middle layer, which is 0.5 mm thick, holds the lower meshed patch with a dimension of $L_1 = 27.8$ mm, while the top layer is 3 mm thick and supports the upper meshed patch with a size of $L_2 = 27.9$ mm. Then, the two frequency resonances arise due to the coupling interactions between the two meshed patches and the feed structure. Although the two patches have nearly identical physical dimensions, their effective electrical lengths differ due to different dielectric layer thicknesses and the coupling effects. Each meshed patch consists of 13 vertical and horizontal metal strips, each 0.5 mm wide. The patch dimensions were slightly adjusted from the original design with coaxial probe fed to optimize the field coupling between the feed line and the patches and achieve the same impedance bandwidth.

All substrate layers have a lateral dimension of 10 cm $\times$ 10 cm to fit within the CubeSat structure. However, to accommodate the feed connection, the middle and upper layers were slightly trimmed to 9.7 cm $\times$ 10 cm, providing space for mounting the connector. A PCB edge-mount SMA connector was soldered to the microstrip feed line to enable RF signal transmission, and the layers were stacked using double-sided adhesive tape.

The purchased fused silica glass substrates did not have a pre-existing conductive layer to etch. Therefore, the copper had to be deposited on the glass substrates to form the meshed patches and the feed line.

Two different fabrication methods were employed to deposit the copper layer. In the prototype (Ant-1a), 0.5 mm wide copper strips were manually cut from a 35 μ m-thick copper foil and placed onto the glass substrate. In the second prototype (Ant-1b), a 3 μ m-thick copper layer was deposited onto the glass using a sputtering technique. The following sections provide further

details on the fabrication process and measurement results of Ant-1a and Ant-1b.

6.2.1 Ant-1a: Copper Foil

Fig. 6.2a to Fig. 6.2c illustrates the individual antenna layers, and Fig. 6.2d shows the fully assembled structure.

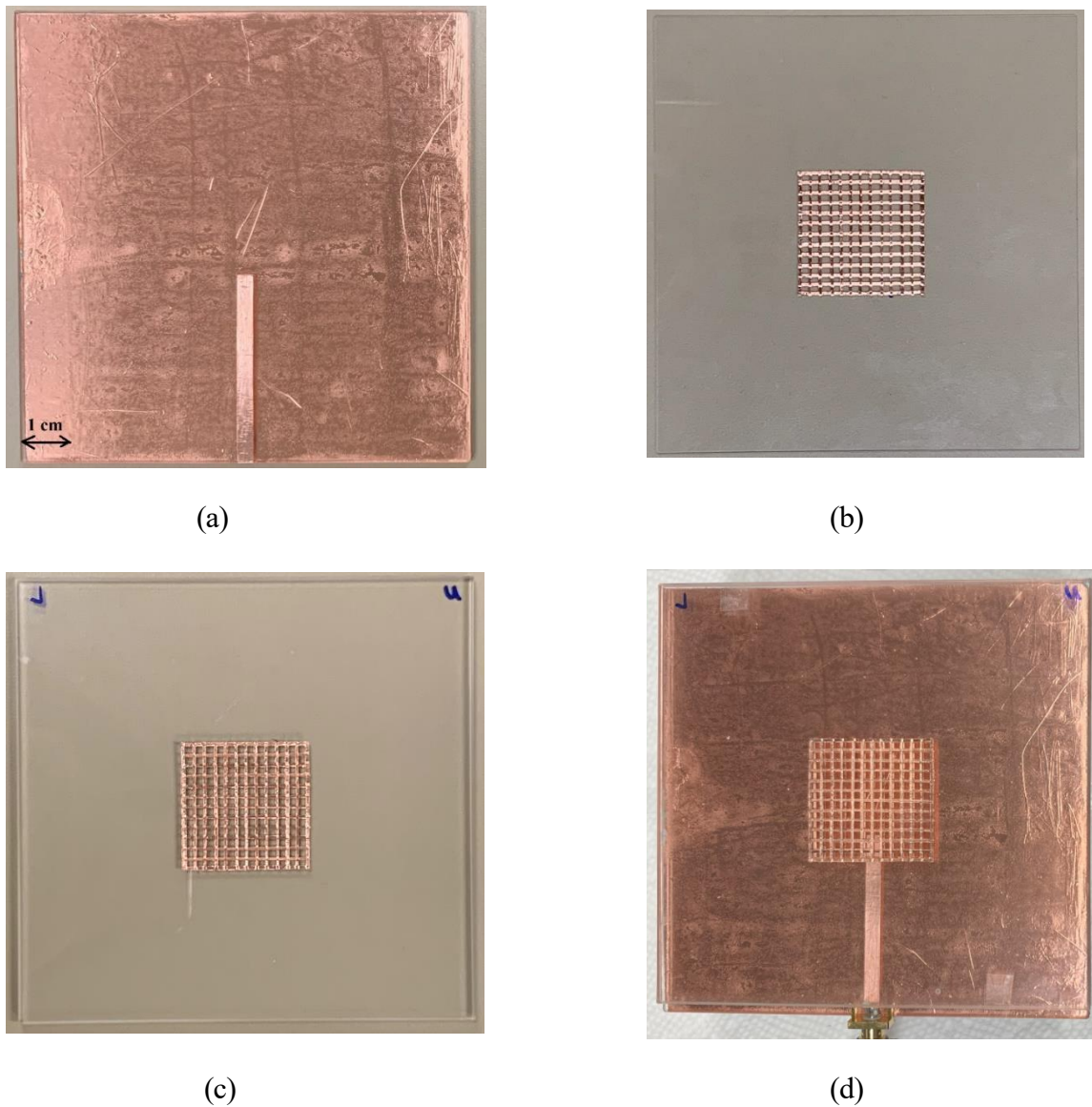


Fig. 6.2: Ant-1a prototypes. a) Layer one, feed line backed by the ground plane. b) Layer two, lower meshed patch. c) Layer three, upper meshed patch. d) Assembled stacked antenna with foil copper (the dimensions of the substrates are $10\text{ cm} \times 10\text{ cm}$).

The S11 was measured and compared with the simulation results to validate the design. Fig.

6.3 shows the S11 for a single-layer meshed patch antenna on a 2 mm thick fused silica glass substrate and simulated and measured data of the glass/glass stacked antenna with copper foil. Simulations showed that the final designed antenna had a bandwidth of 150 MHz (6.2%) from 2.34 GHz to 2.49 GHz, which is a significant improvement over 28 MHz for the single-layer meshed antenna. The measured data showed a 160 MHz impedance bandwidth from 2.43 GHz to 2.59 GHz. This is approximately a 100 MHz shift of the 10 dB impedance bandwidth to the higher frequencies.

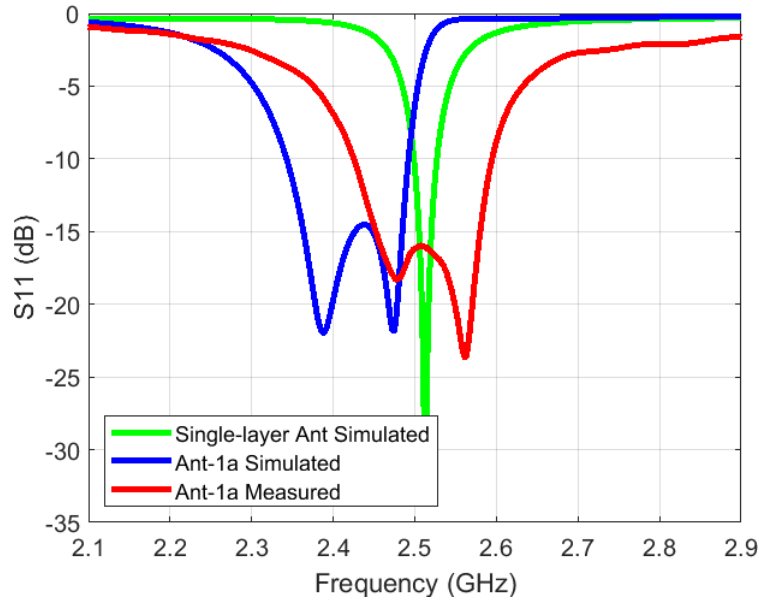


Fig. 6.3: Comparison of simulated and measured S11 of the Ant-1a with a single-layer meshed patch. (Ant-1a dimensions: $L_1 = 27.8$ mm, $L_2 = 27.9$ mm, $d = 0.5$ mm, $W_f = 3.25$ mm, $L_f = 41.9$ mm, $p = 1.775$ mm, $d_s = 3$ mm, $t_p = 35$ μ m, $H_l = 1.5$ mm, $H_m = 0.5$ mm, $H_u = 3$ mm. Single-layer meshed antenna dimensions: $L = 28.9$ mm, $p = 1.866$ mm, $d = 0.5$ mm, $H = 2$ mm, inset feed length = 12.6 mm, inset feed width = 6.6 mm, $W_f = 4.2$ mm, $L_f = 48.15$ mm.)

To investigate the cause, the material properties of the purchased fused silica glass substrate were measured in the lab using the transmission line method. The measurement procedure is explained in Appendix 1. The results demonstrated a dielectric constant of 3.5 and a loss tangent of 0.0055 compared to the 3.8 and 0.00002 obtained from the datasheet. Substituting the new material properties in the simulation model led to a good agreement between the simulation and

measurement. Fig. 6.4 illustrates the updated simulated results with new material properties and compares them with the measurement data. The slight shift in the resonance frequencies between the simulation and measurement is the result of the change in the lower or upper microstrip meshed antenna length due to fabrication tolerances.

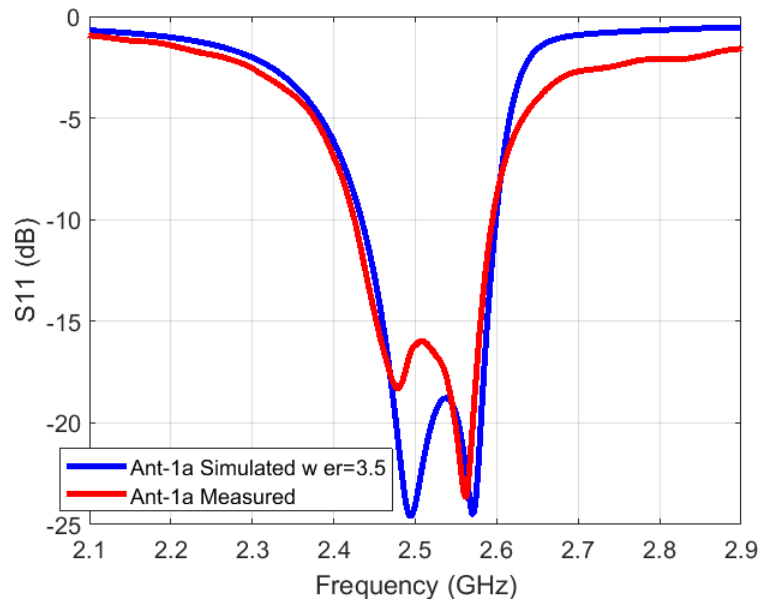


Fig. 6.4: Comparison of the measurement results with the simulated ones with updated material properties ($\epsilon_r = 3.5$, $\tan\delta = 0.0055$) obtained from material characterisation using the transmission line method.

The radiation patterns in the E-plane and H-plane were simulated using HFSS and measured in the University of Manitoba compact range anechoic chamber. The measurement setup involved a standard horn antenna as the reference, with proper calibration to ensure accurate gain and pattern measurements. The antenna under the test was mounted on a rotator to capture patterns at different angles. Fig. 6.5 shows the mounted antenna.

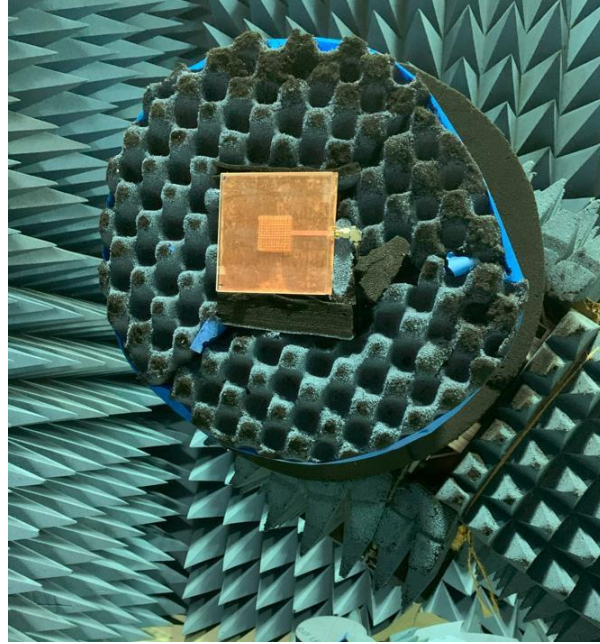
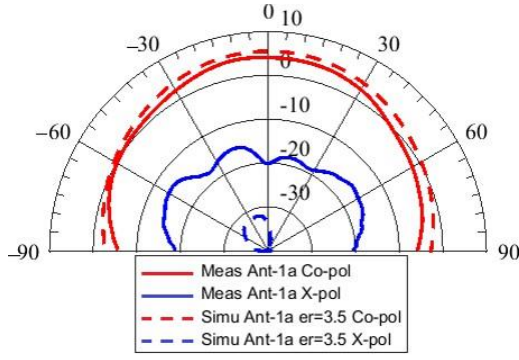


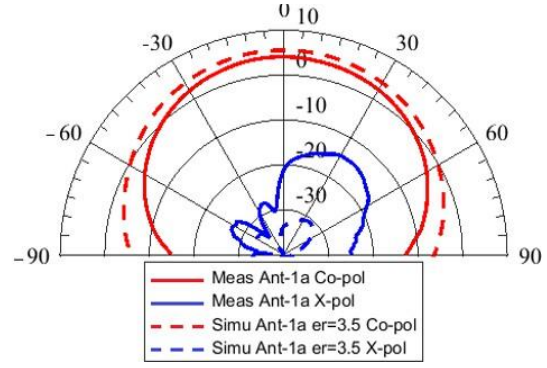
Fig. 6.5: Radiation pattern test setup for Ant-1a.

Fig. 6.6 shows the results for Ant-1a at three frequencies: 2.43 GHz, 2.52 GHz, and 2.59 GHz. The simulation results were obtained using updated material properties ($\epsilon_r = 3.5$ and $\tan\delta = 0.0055$), derived from measurements. It can be observed that the radiation pattern remains consistent across the frequency range, with the maximum radiation directed broadside. The simulated antenna gain at the center frequency was 5.9 dBi, closely matching the measured value of 5.4 dBi. However, the discrepancy between simulated and measured gains increased at the lower and upper ends of the frequency range, likely due to fabrication tolerances such as misalignment between antenna layers, air gaps, and variations in material properties.

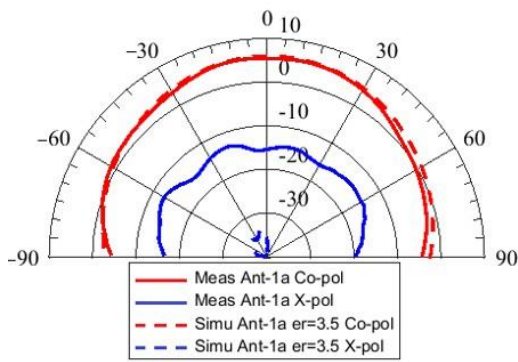
The antenna's cross-polarization level remained better than -20 dBc across all measured frequencies. Differences between the simulated and measured cross-polarization levels can be attributed to factors such as changes in feed length and location, as well as misalignment during the fabrication and assembly processes.



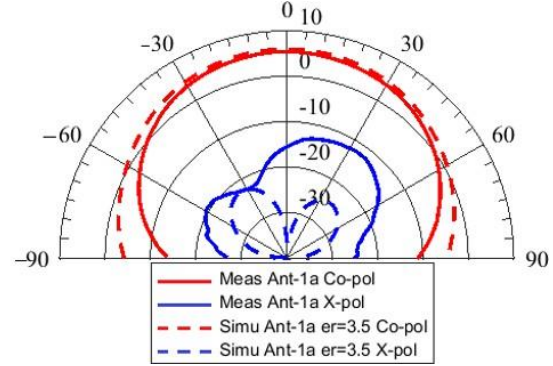
(a)



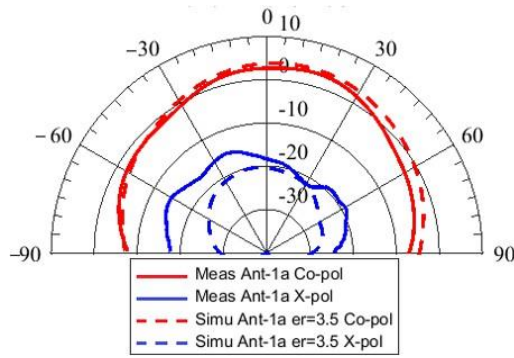
(b)



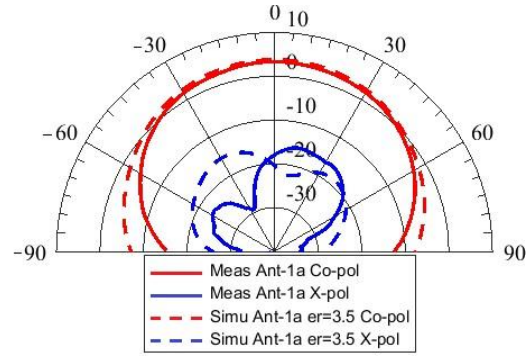
(c)



(d)



(e)



(f)

Fig. 6.6: Compared simulated and measured radiation pattern of Ant-1a in E-plane and H-plane. a) E-plane at 2.43 GHz. b) H-plane at 2.43 GHz. c) E-plane at 2.52 GHz. d) H-plane at 2.52 GHz. e) E-plane at 2.59 GHz. f) H-plane at 2.59 GHz.

The realized gain versus frequency is plotted in Fig. 6.7 in order to further assess the antenna's performance. This graph compares simulation results using the original material

properties ($\epsilon_r = 3.8$ and $\tan\delta = 0.00002$) with the measured results and simulations using the updated material properties ($\epsilon_r = 3.5$ and $\tan\delta = 0.0055$). The original design exhibited better gain flatness, with variations of less than 1 dB over its 10 dB impedance bandwidth, compared to simulations with adjusted material properties. Therefore, improved performance may be achieved by re-optimizing the antenna design to account for the updated material properties.

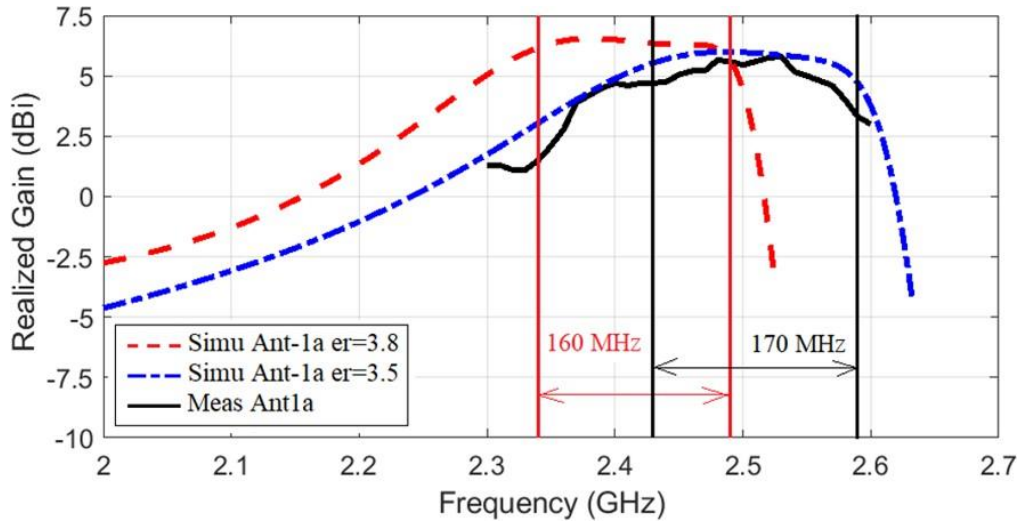


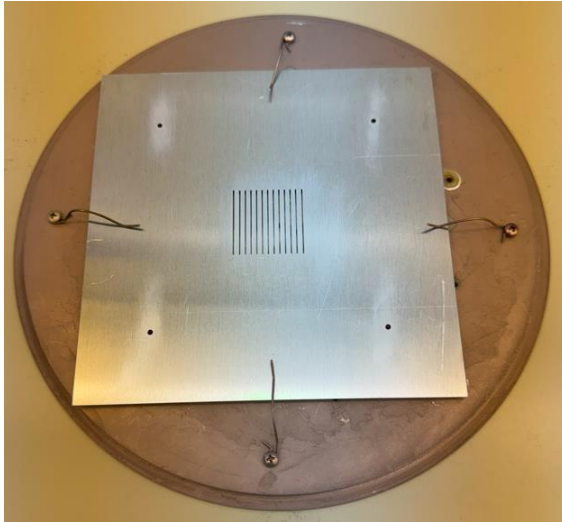
Fig. 6.7: Comparison of simulated and measured realized gain of Ant-1a versus frequency.

6.2.2 Ant-1b: Sputtered Copper

For the fabrication of the second prototype (Ant-1b), a 3 μm thick copper layer was deposited onto a glass substrate using the DC magnetron sputtering technique. The deposition process was carried out with a DC power of 150 watts, utilizing a high-purity (99.999%) copper target. Before deposition, the sputtering chamber was evacuated to a base pressure of 2×10^{-6} Torr. The copper layer was deposited for 95 minutes.

Aluminum stencils were placed on top of the glass substrate during the deposition process to define the microstrip feed line and mesh patterns. Fig. 6.8a shows the stencil for the mesh

vertical lines and Fig. 6.8b demonstrates the antenna in the sputtering chamber. After the deposition process was complete, the stencil was rotated to deposit the horizontal lines.



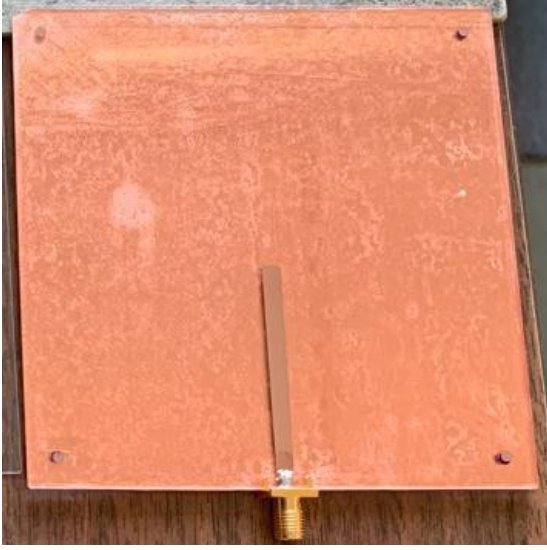
(a)



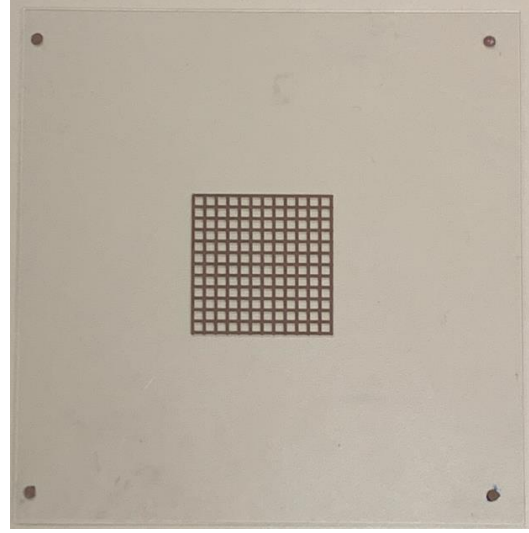
(b)

Fig. 6.8: Copper deposition. a) Aluminum stencil placed on top of the glass substrate. b) Sample placed inside the sputtering chamber.

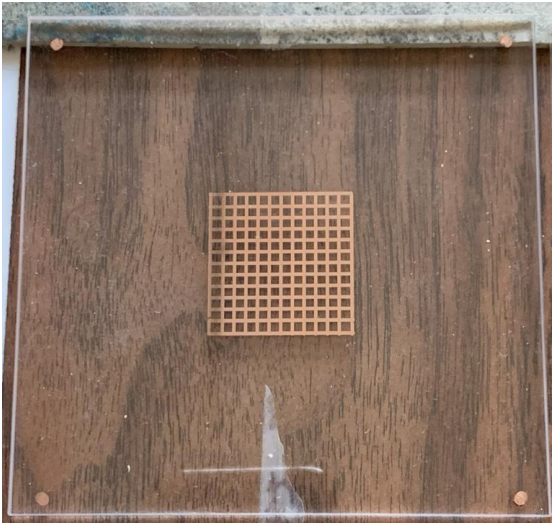
After deposition, the copper thickness was measured using an Alpha-Step D500 stylus profiler from KLA Instruments. To ensure Ant-1b exhibited the same response as Ant-1a, slight dimensional adjustments were made. For lab measurements, a solid ground plane was placed beneath the microstrip feed line, though in practical CubeSat applications, the satellite body can function as the ground plane. The different layers of the Ant-1b prototype and the assembled stacked antenna are illustrated in Fig. 6.9.



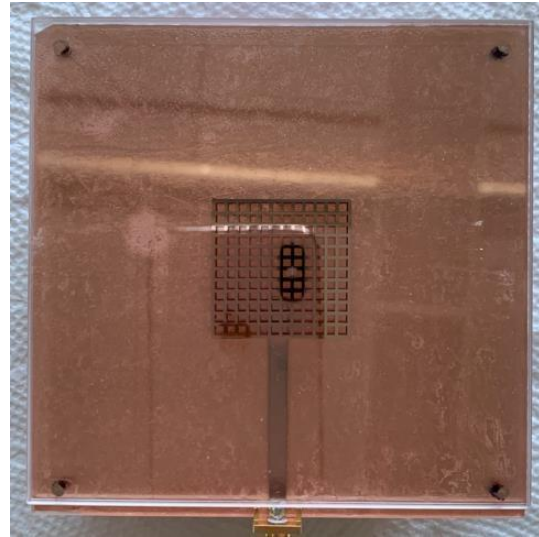
(a)



(b)



(c)



(d)

Fig. 6.9: Ant-1b prototypes. a) Layer one, feed line backed by the ground plane. b) Layer two, lower meshed patch. c) Layer three, upper meshed patch. d) Assembled stacked antenna with sputtered copper (the dimensions of the substrates are $10\text{ cm} \times 10\text{ cm}$).

The S11 parameter was measured and compared with the simulation results to validate the design. Fig. 6.10 compares the measured data of the glass/glass stacked antenna with sputtered copper and the simulated results, considering both the original material properties of the glass substrate and the measured values. A good agreement was observed between the measured S11 of

Ant-1b and the simulation when the measured material properties are considered. The measured bandwidth is 170 MHz, ranging from 2.42 GHz to 2.59 GHz.

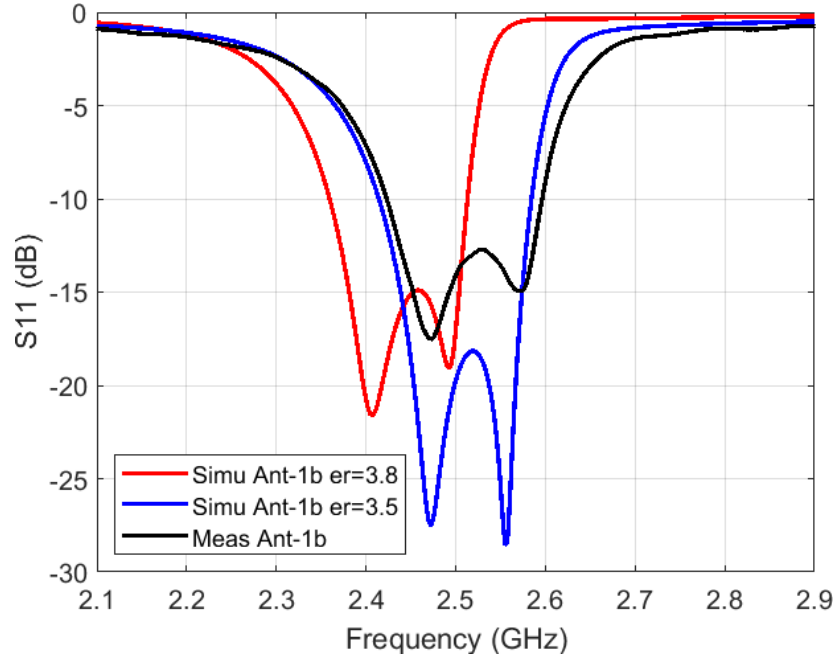


Fig. 6.10: Comparison of the measured S11 of the glass/glass stacked antenna with sputtered copper and the simulated results using the original and measured material properties of the glass substrate.

6.3 Ant-3: Glass/Cube SU-8 Stacked Antenna Fabrication and Measurement

As stated before, Ant-3 was designed to further reduce the mass of the stacked antenna by removing portions of the SU-8 substrate. In this design, the SU-8 dielectric is retained only beneath the upper meshed patch. In Chapter Five, the antenna was designed and fed using a 50-ohm coaxial probe; however, for prototyping, a proximity-coupled feed was chosen. The 3D and side views of the antenna are illustrated in Fig. 6.11. Fused silica glass was used for both the feed layer and the middle layer, with thicknesses of 1.1 mm (H_l) and 0.4 mm (H_m), respectively. The transmission line is 2.25 mm wide and 44 mm long. The lower patch consists of 13 evenly spaced horizontal

and vertical lines, while the upper patch has 15 horizontal and vertical lines. The upper and lower meshed patches have the same pitch, except for the outer meshes of the upper antenna. The 0.5 mm wide mesh lines were cut from a copper foil sheet.

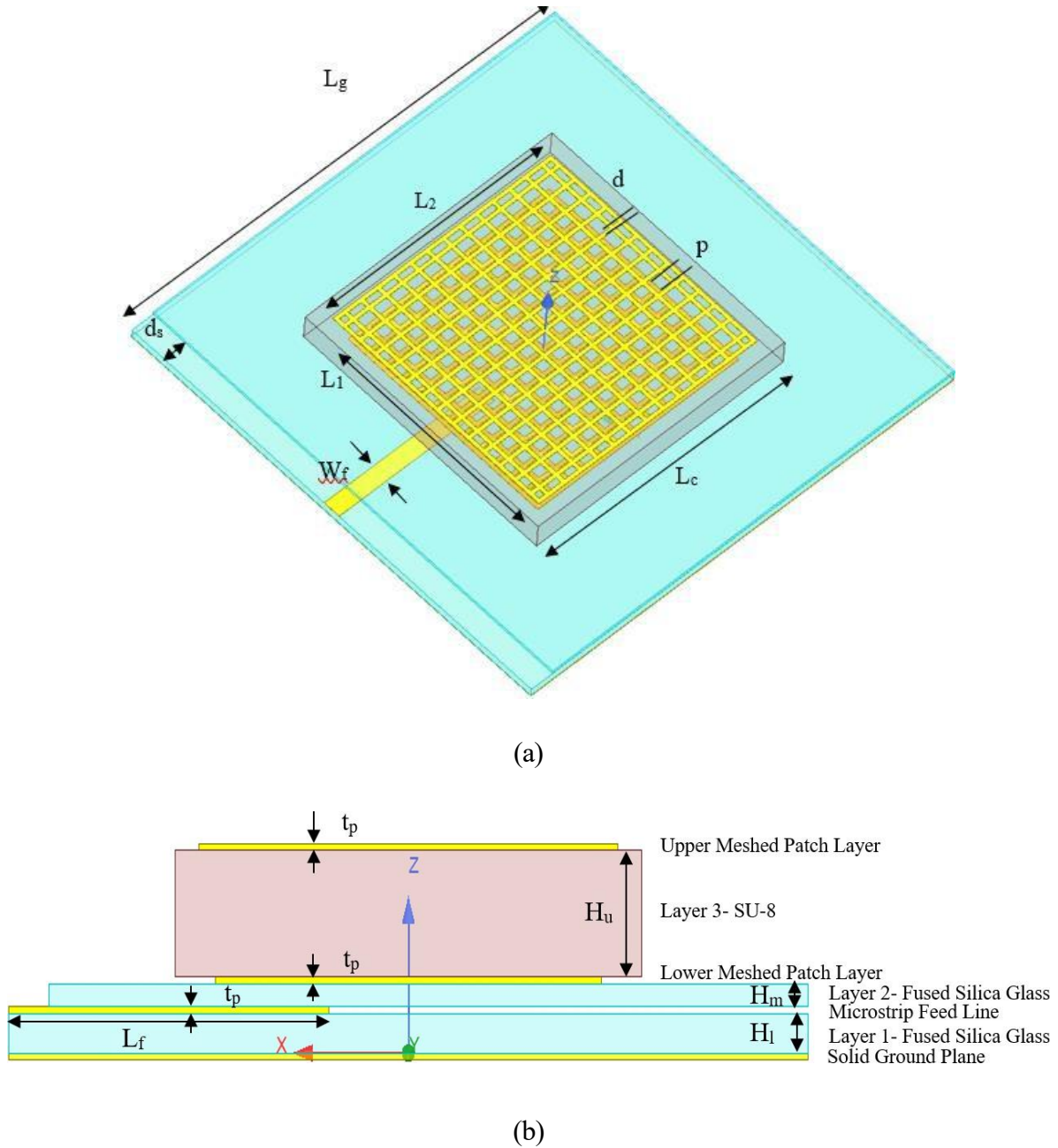


Fig. 6.11: Ant-3: Glass/Cube SU-8 stacked antenna's geometry. a) 3D view. b) Side view.

Fig. 6.12 demonstrates each layer of Ant-3. To fabricate the SU-8 cube, a polydimethylsiloxane (PDMS) mold, measuring $35\text{ mm} \times 35\text{ mm} \times 3.5\text{ mm}$, was used. PDMS, a transparent polymer with a low dielectric constant, was selected due to its flexibility and ease of demolding. The Fabrication process of the PDMS mold is explained in Appendix 2. The mold was filled with liquid SU-8 2075, a negative epoxy-based photoresist commonly used for microfabrication, which then underwent a multi-step thermal and ultraviolet (UV) processing sequence to achieve the desired mechanical and electrical properties.

First, SU-8 was subjected to a two-step soft bake process to remove solvents and enhance adhesion. In the initial stage, the sample was heated at $65\text{ }^{\circ}\text{C}$ for 5 hours. The temperature then increased to $95\text{ }^{\circ}\text{C}$, and the sample was left to bake overnight (approximately 18 hours) to ensure uniform solvent evaporation and minimize internal stress.

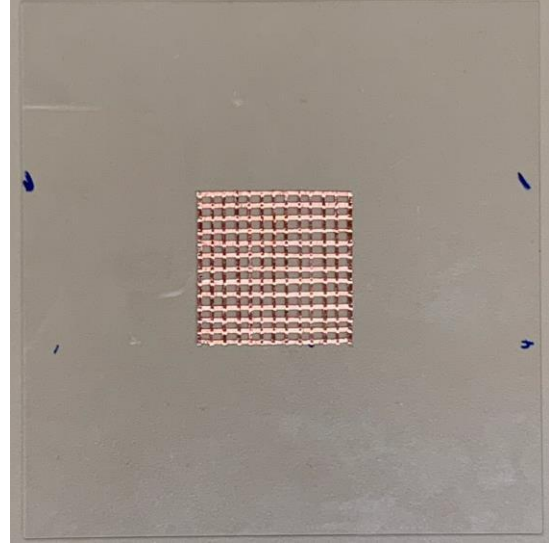
Next, the SU-8 was exposed to UV light for a total of 240 seconds to initiate cross-linking. To prevent excessive hardening of the top surface, exposure was performed in 12 cycles of 20 seconds each, with 15-second intervals between exposures [64]. This step ensured uniform light penetration.

Following UV exposure, a post-exposure bake (PEB) was carried out to further the cross-linking process. The sample was first heated at $65\text{ }^{\circ}\text{C}$ for 30 minutes, followed by $95\text{ }^{\circ}\text{C}$ for 90 minutes. This gradual heating step prevented excessive stress buildup and potential cracking.

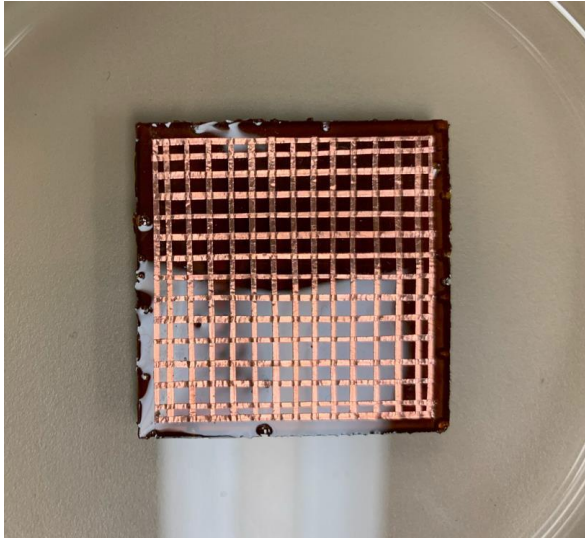
Finally, the structure underwent a hard bake at $150\text{ }^{\circ}\text{C}$ for 60 minutes to fully cure and stabilize the SU-8. This step enhanced the mechanical strength of the block, ensuring durability and robustness.



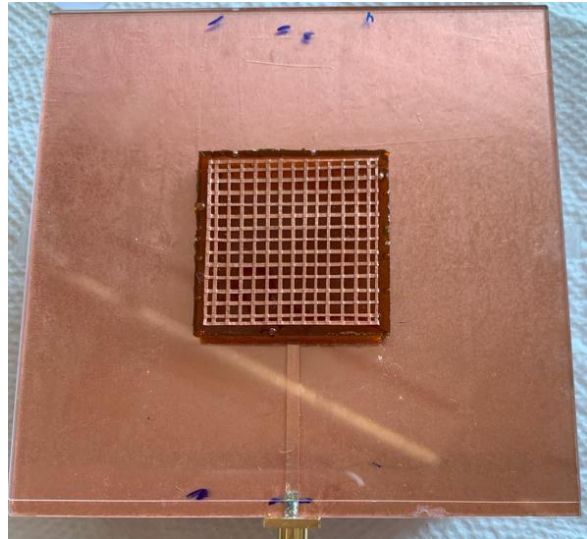
(a)



(b)



(c)



(d)

Fig. 6.12: Ant-3 prototype. a) First layer: 50-ohm feed line with a backing ground plane. b) Second layer: Lower meshed patch fabricated from copper foil. c) Third layer: Upper meshed patch positioned on an SU-8 cube. d) Fully assembled Ant-3 (all substrate layers measure $10\text{ cm} \times 10\text{ cm}$).

As discussed in the previous section, the glass substrate was initially modeled with $\epsilon_r = 3.8$ and $\tan\delta = 0.00002$. For SU-8, the dielectric constant and loss tangent are highly dependent on factors such as the fabrication process, the degree of cross-linking, and the type and aging of the material [65], [66]. According to the study in [66], a dielectric constant of 3.25 and a loss tangent

of 0.015 were reported for fully cross-linked SU-8 at 2.5 GHz, and these values were initially used for modeling and simulating Ant-3. However, when comparing the simulated and measured S11 of Ant-3, we found that the values reported in [67], a dielectric constant of 2.9 and a loss tangent of 0.045, better represented the material properties of the fabricated SU-8 in our study.

Fig. 6.13 compares the S11 of the simulated Ant-3 using both the original and adjusted material properties for glass and SU-8, alongside the measured results. A strong agreement was observed between the measured S11 and the simulation using the modified material properties. The initial simulation predicted a bandwidth of 150 MHz, ranging from 2.37 GHz to 2.52 GHz, while the measured bandwidth was 200 MHz, spanning 2.47 GHz to 2.67 GHz. This increase in bandwidth was primarily related to the reduction in SU-8's dielectric constant and increase in loss. The frequency shift between the simulated S11 (with adjusted material properties) and the measured data was less than 15 MHz, mainly due to fabrication tolerances, particularly variations in the dimensions of the lower and upper patches.

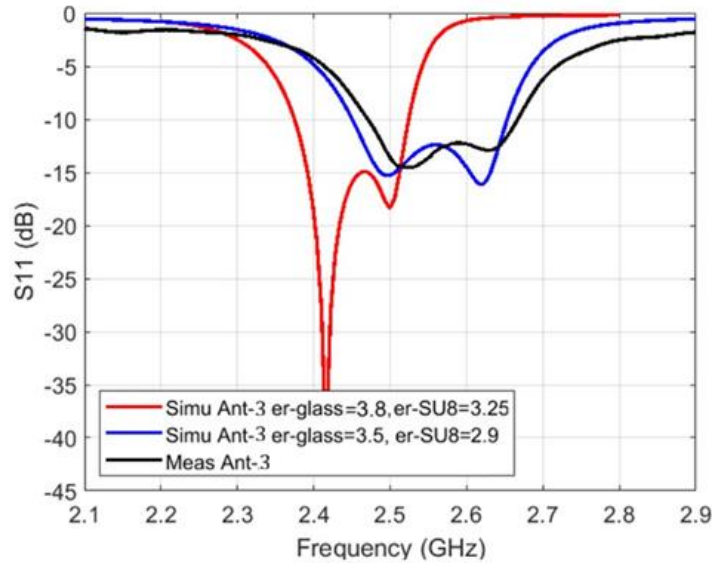
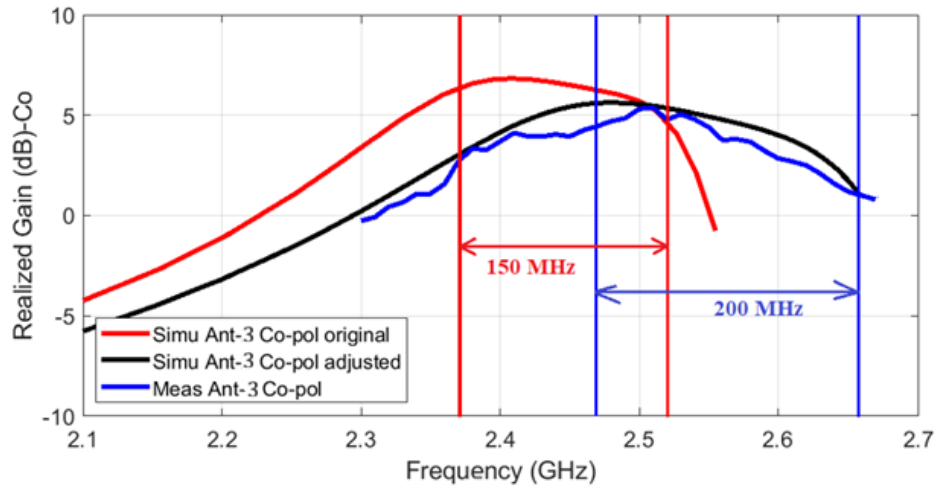
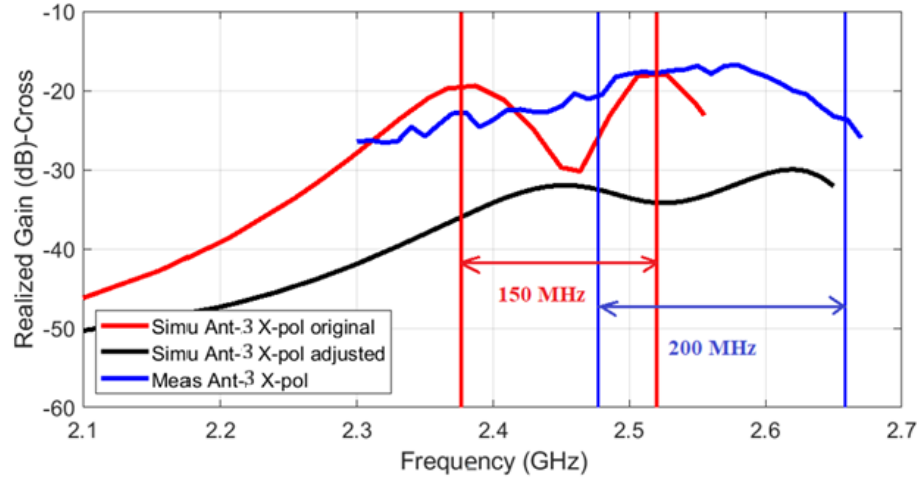


Fig. 6.13: Comparison of the S11 for Ant-3: simulated results using the original and adjusted material properties of glass and SU-8, alongside the measured data.

Fig. 6.14a and Fig. 6.14b compare the realized gain in the E-plane co-polarization and E-plane cross-polarization from both simulation and measurement to further evaluate the performance of Ant-3. For the optimized design using the original material properties, the maximum gain was 6.7 dBi, with a gain flatness of 2.5 dB across a 150 MHz impedance bandwidth. Compared to Ant-1, Ant-3 weighs 38 g, representing a 65% reduction in mass while maintaining a comparable bandwidth and gain.



(a)



(b)

Fig. 6.14: Comparison of the Ant-3 realized gain versus frequency from simulation and measurement. a) E-plane co-polarization. b) E-plane cross-polarization.

The fabricated prototype achieved a maximum gain of 5.1 dBi at 2.51 GHz and a minimum gain of 1.2 dBi at 2.65 GHz. The substrate's material properties significantly influence field coupling between the layers, playing a critical role in antenna performance [54]. Despite these variations, the measured and simulated results showed a good agreement when using adjusted material properties for both glass and SU-8 materials. Re-optimizing the antenna dimensions with updated material properties is necessary to improve performance further.

Fig. 6.15 illustrates the radiation pattern of Ant-3 in E-plane and H-plane at 2.52 GHz, showing that the antenna radiates broadside across the tested frequencies. Additionally, the cross-polarization level remained at least 20 dB below the co-polarized signal, ensuring minimal unwanted polarization effects.

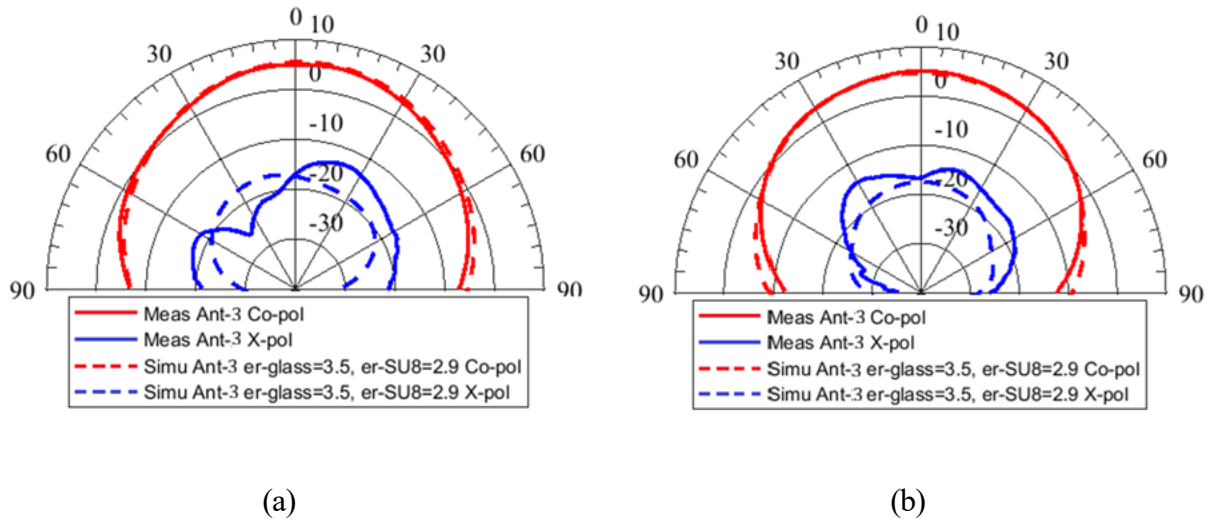


Fig. 6.15: Comparison of simulated and measured Ant-3 radiation pattern at 2.52 GHz. a) E-plane. b) H-plane.

6.4 Sensitivity Analysis and Fabrication Tolerances

This section conducts a sensitivity analysis to evaluate how variations in key design parameters affect the performance of the fabricated stacked TMPAs, Ant-1 and Ant-3. Fabrication tolerances, such as mesh width, layer misalignment, material property variations, and assembly

errors, can introduce deviations from the expected performance. This analysis aims to quantify these variations' impact on resonant frequency, impedance bandwidth, gain, and gain flatness.

6.4.1 Substrate Material Properties

The dielectric constant of the glass substrate plays a significant role in Ant-1 performance. A sensitivity analysis was conducted to evaluate the impact by simulating the antenna with different values of ϵ_r . Fig. 6.16 illustrates the simulated S11 for a nominal value of 3.8 and +/- 10% variation.

The results demonstrated that increasing the glass dielectric constant shifted the resonant frequency downward; while decreasing it shifted the frequency upward. This occurred because a higher dielectric constant increases the effective electrical length of the antenna, lowering its resonance. On the other hand, a lower dielectric constant reduces the electrical length, leading to a higher resonant frequency. Additionally, bandwidth variations were observed too. Dielectric constant of 3.42 provided the widest bandwidth, indicating reduced energy confinement within the substrate, and dielectric constant of 4.18 resulted in a narrower bandwidth.

Therefore, it is important to accurately characterize the glass substrate's dielectric properties during fabrication to ensure the antenna operates at the intended frequency with minimal tuning.

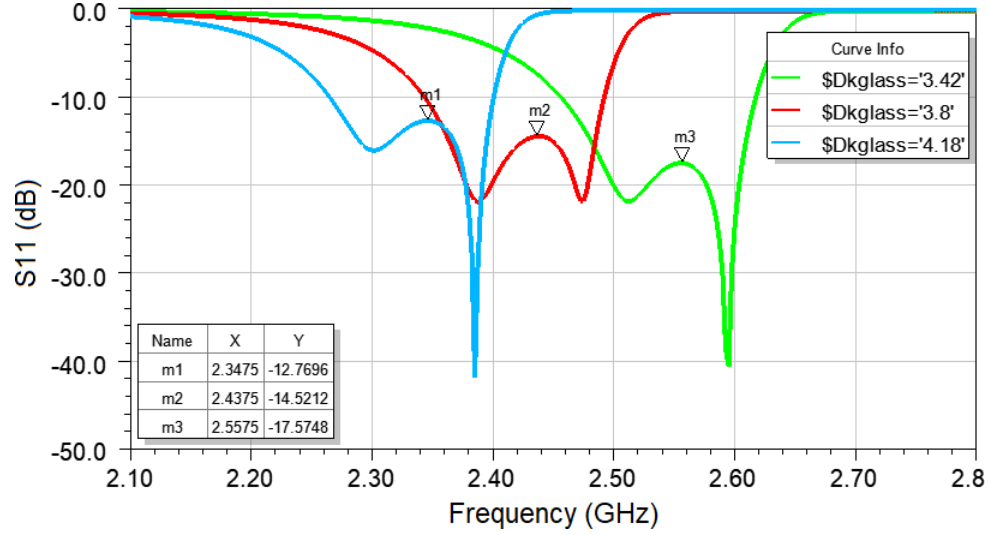


Fig. 6.16: Simulated S11 response of Ant-1 for different dielectric constants.

6.4.2 Feed Length

The sensitivity of Ant-1's cross polarization performance to microstrip feed line length variation was investigated. Simulations were carried out at the lowest, 2.34 GHz, and highest, 2.49 GHz, frequencies within the antenna's 10 dB bandwidth. The feed length varied around the nominal design value of 42 mm by small increments of ± 0.2 mm and large increments of ± 0.9 mm. The results showed that the antenna exhibits stable behavior at the lower frequency, with the X-pol level remaining below -20 dBc across all feed lengths. At the higher frequency, small changes in L_f also preserved a low X-pol level. However, larger variations resulted in degraded polarization purity, increasing the X-pol to approximately -15 dBc. The co-polarized gain showed only minor variations across all cases. Fig. 6.17 demonstrates the simulated E-plane cross-polarisation patterns of Ant-1a at 2.34 GHz and 2.49 GHz for different microstrip feed line lengths. The feed length affects the field coupling between the feed and the lower and upper patches. Investigation of S11 also showed a maximum shift of 20 MHz.

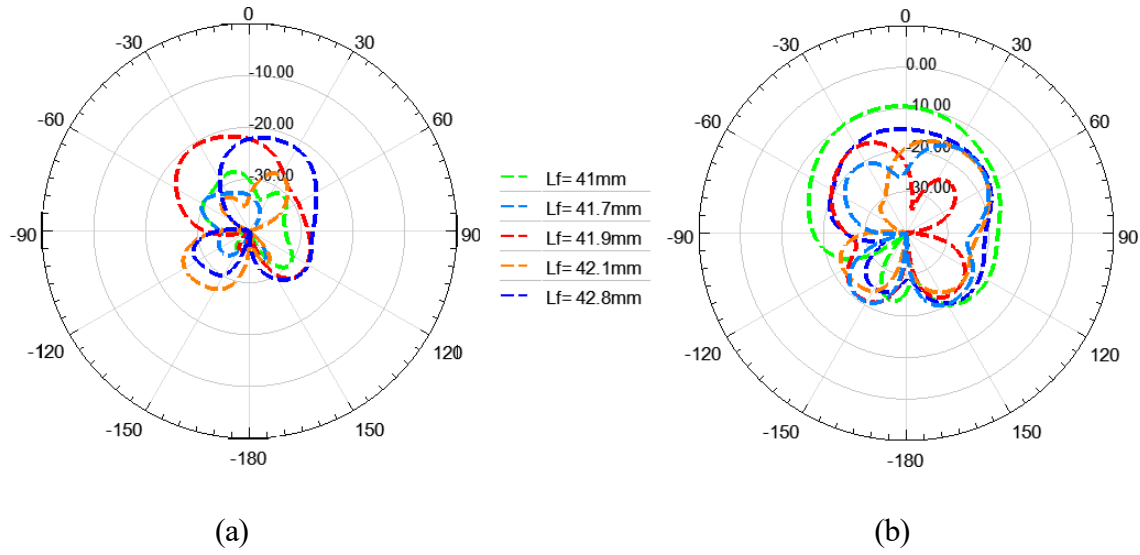


Fig. 6.17: Simulated E-plane X-pol of Ant-1a for different microstrip feed lengths. a) 2.34 GHz. b) 2.49 GHz.

6.4.3 Lower and Upper Mesh Patch Lengths

The lengths of both the lower and upper patch elements were swept by ± 0.5 mm around their nominal values, in order to investigate the effect of patch dimensions. The upper mesh patch length varied from 26.9 mm to 27.9 mm, with a nominal value of 27.4 mm. The resulting impedance loci of the antenna are presented in Fig. 6.18a. It can be observed that increasing the length of the upper patch shifted the antenna's frequency response toward lower frequencies, as expected due to the increased electrical length. Additionally, the size of the resonance loop in the Smith chart increased, which means higher mutual coupling between the two stacked patches.

Next, the length of the lower meshed patch was swept from 27.7 mm to 26.8 mm to examine its impact on the antenna's input impedance. The corresponding impedance loci on the Smith chart are shown in Fig. 6.18b. As the lower patch length decreased, the resonance shifted toward higher frequencies, and the size of the impedance loop increased, indicating stronger mutual coupling between the two patches. This behavior is opposite to the trend of varying the upper meshed patch length. Therefore, the relative size of the upper and lower meshed patches is critical in controlling

the coupling and overall input impedance characteristics. The effect is similar to the study performed in [55] for solid stacked patches.

Investigating the radiation pattern at 2.49 GHz showed a maximum gain variation of 0.5 dBi as a result of changes in L_2 by ± 0.5 mm.

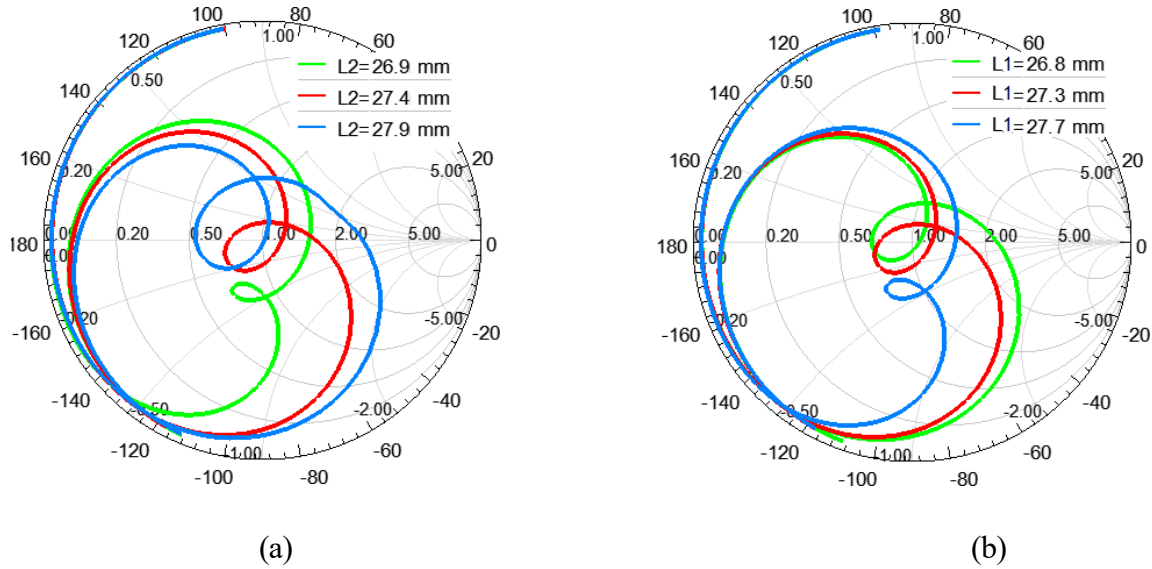


Fig. 6.18: Ant-1a Impedance versus length variation. a) Upper meshed patch swept. b) Lower meshed patch swept.

6.4.4 Mesh Line Width

The effect of mesh line width on the performance of the stacked antenna was investigated by conducting the simulations for three values: 0.4 mm, 0.5 mm (nominal), and 0.6 mm. These variations were applied to both the upper and lower mesh lines of Ant-1a. The impact on the bandwidth and highest resonant frequency is illustrated in Fig. 6.19. Additionally, Fig. 6.20 shows the variations in E-plane realized gain and X-pol levels at the center frequency, 2.42 GHz, and the upper resonance, 2.49 GHz.

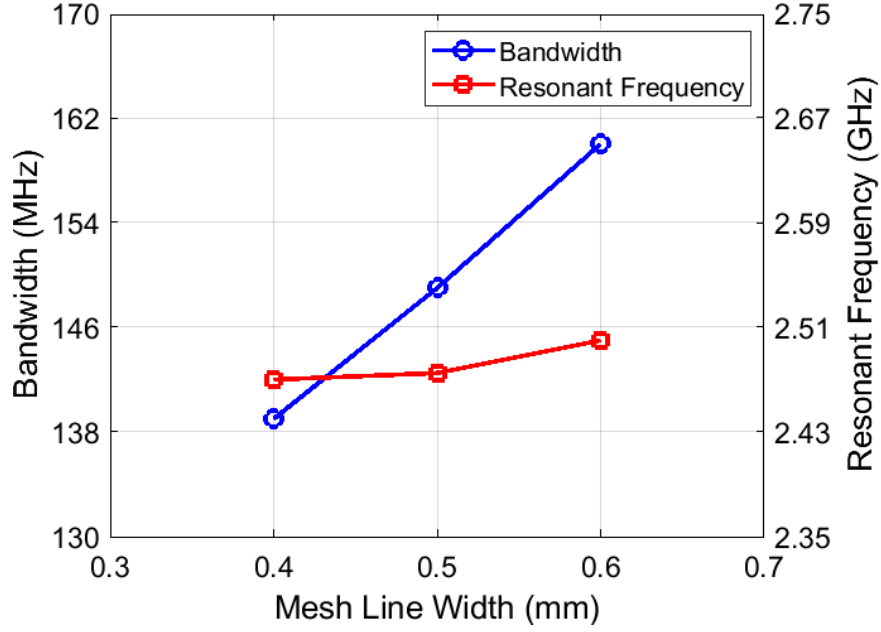


Fig. 6.19: Effect of mesh line width on the bandwidth and upper resonant frequency of the Ant1-a.

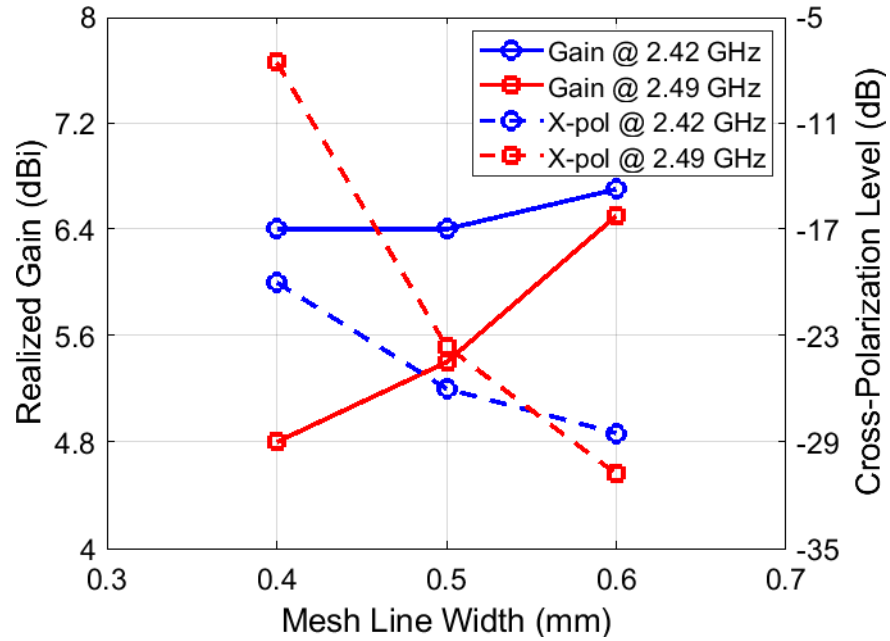


Fig. 6.20: Effect of mesh line width on realized gain and cross-polarization level of Ant-1a in E-plane at two frequencies: 2.42 GHz and 2.49 GHz.

It was observed that increasing the mesh line width led to a wider impedance bandwidth and a shift in the resonant frequency toward higher values. At 2.42 GHz, the realized gain improved

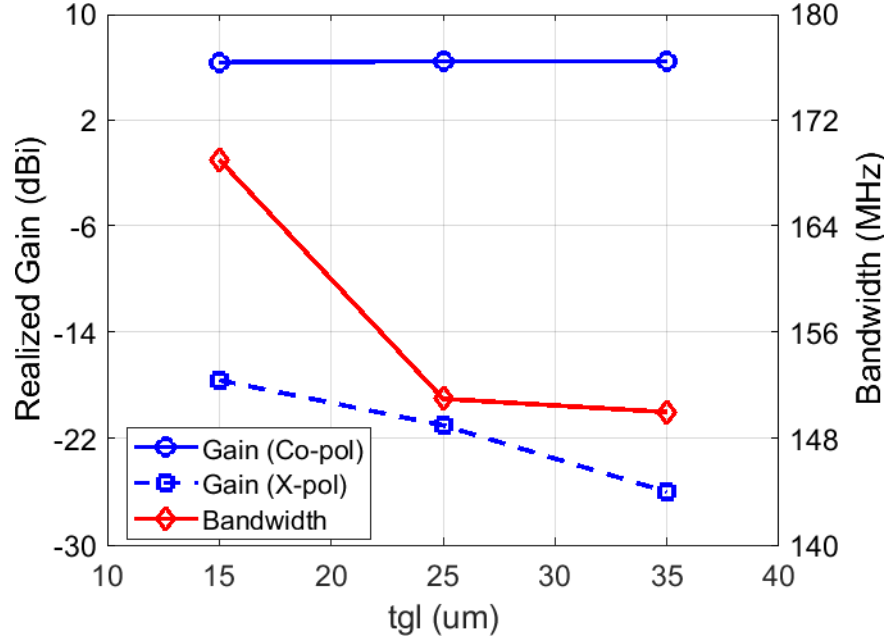
by approximately 0.3 dBi, while the cross-polarization level decreased by 2.4 dB. These effects were more pronounced at 2.49 GHz, where the gain increased by 1.1 dBi and the cross-polarization level was reduced by 7 dB.

Conversely, decreasing the mesh line width reduced the bandwidth due to the lower amount of conductive copper in the patch elements. At 2.49 GHz, this reduction in line width resulted in a 16 dB increase in the cross-polarization level and a 0.6 dBi drop in gain.

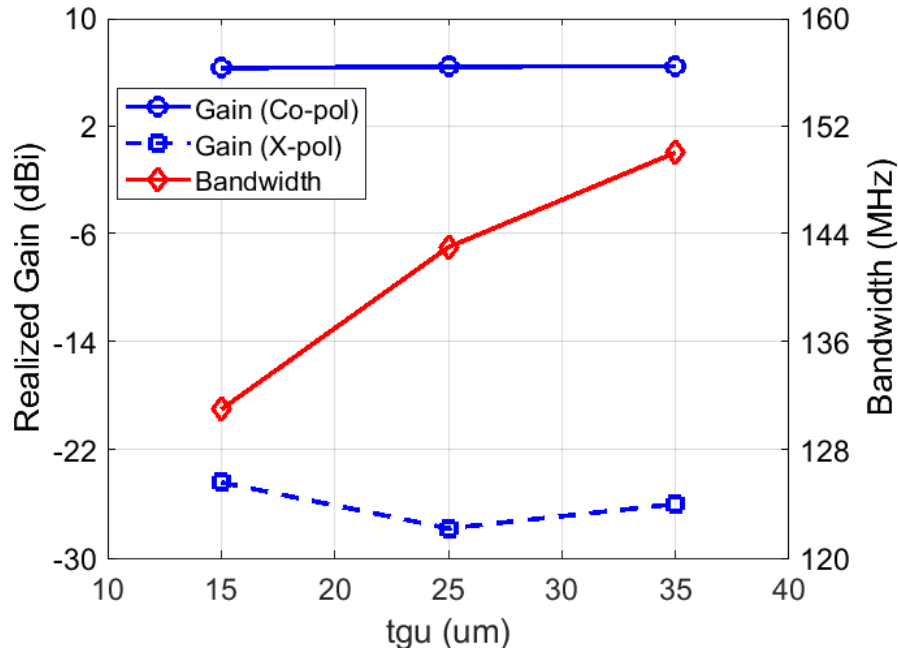
6.4.5 Air Gaps

The air gaps between the feed and middle substrates, as well as the middle and upper substrates, were varied in order to evaluate the impact of interlayer spacing on antenna performance. The original design had a nominal air gap of 35 μm , corresponding to the copper foil thickness. However, in practice, deviations are possible due to fabrication tolerances. In this study, the air gap between the feed and middle substrate (t_{gl}) was first varied to 35, 25, and 15 μm , while keeping the middle–upper substrate gap (t_{gu}) constant at 35 μm . The results for the 10 dB bandwidth and Co and Cross polarization realized gain in E-plane at 2.42 GHz are shown in Fig. 6.21a. Next, the middle–upper substrate gap was varied with the feed–middle gap fixed at its nominal value. Fig. 6.21b illustrates the results.

It can be seen that the antenna gain was not affected by the airgaps changes. However, its bandwidth can increase or decrease by 20 MHz.



(a)



(b)

Fig. 6.21: Effect of inter-substrate air gaps on the performance of Ant-1a at 2.42 GHz. a) The feed-middle substrates air gap. b) The middle-upper substrates.

6.4.6 Mesh Misalignment

The effect of misalignment between the upper and lower stacked mesh patches was investigated to evaluate the fabrication imperfections. In practice, slight shifts may occur during the alignment and assembly processes. Fig. 6.22 shows the misalignments that occurred while fabricating Ant-1a. Simulations were performed by shifting the upper and lower meshes in the horizontal (x-axis) and vertical (y-axis) directions. The displacement values were set to -0.2 mm, 0 mm, and +0.2 mm, where 0 mm represents perfect alignment between the meshes. The results indicate that mesh misalignment can lead to a frequency shift of up to 15 MHz in the antenna frequency response. The maximum variation in the E-plane co-polarized realized gain was 0.15 dBi at 2.42 GHz and 1 dBi at 2.49 GHz. Fig. 6.23 illustrates the simulated S11 when the upper patch is shifted by ± 0.2 mm in the y-direction. The E-plane cross-polarization level was also investigated. Depending on the direction of misalignment, it decreased by up to 12 dBi or increased by up to 8 dBi. However, in all cases, the cross-polarization level remained below -20 dBc.

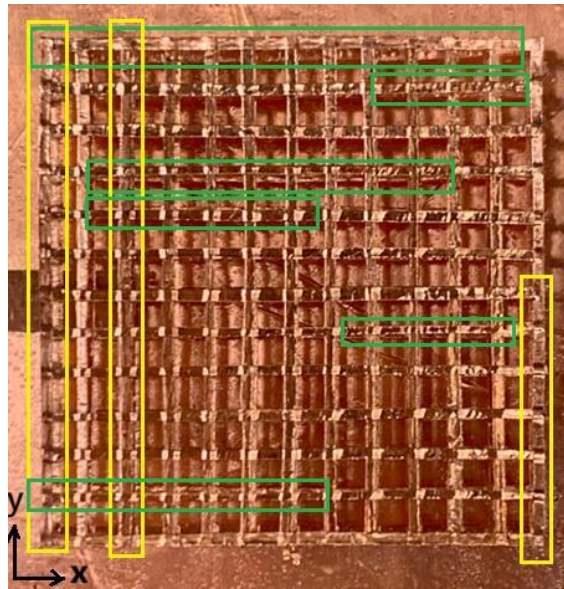


Fig. 6.22: Image of the fabricated stacked antenna (Ant-1a) showing misalignment between the upper and lower mesh layers. The yellow and green boxes highlight mesh lines from the top and bottom layers, with horizontal and vertical offsets due to fabrication tolerances.

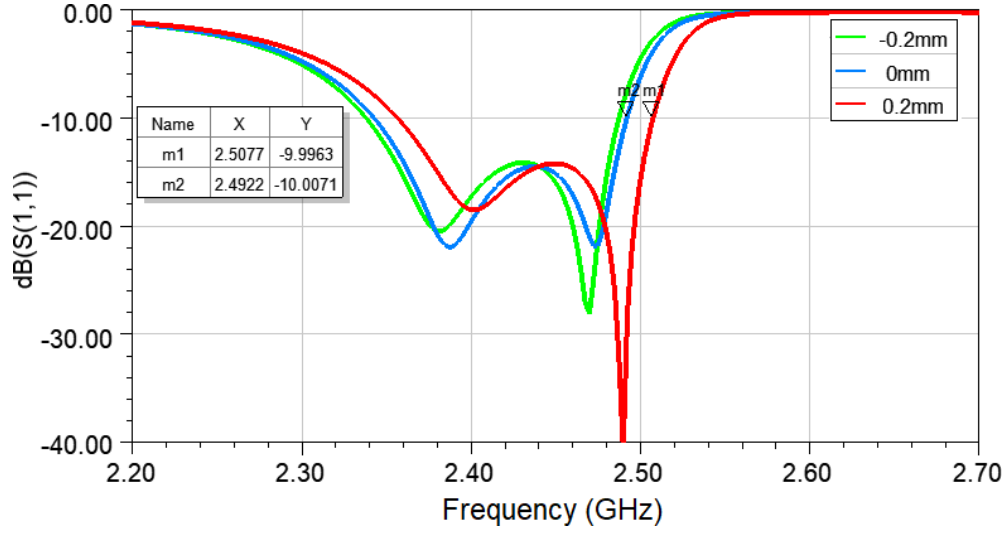


Fig. 6.23: Simulated S_{11} of the stacked antenna under mesh misalignment in the y-direction.

6.5 Effect of Satellite Body

Simulation was performed to assess the influence of the CubeSat body on the performance of the Ant-1a. The antenna was placed directly on one face of a 1U CubeSat, and the CubeSat body was modeled as a 10 cm $\times$ 10 cm $\times$ 10 cm aluminum cube in HFSS. A 3D view of the simulation model is presented in Fig. 6.24, illustrating the Ant-1a mounted flush on one face of the CubeSat. The S_{11} and 2D radiation pattern of the antenna, considering the presence of the CubeSat body, were simulated. The results are presented in Fig. 6.25 and Fig. 6.26, respectively. A comparison of the S_{11} with the free-space antenna performance reveals a frequency shift caused by the proximity of the CubeSat body. The E-plane and H-plane radiation pattern at 2.42 GHz is presented in Fig. 6.26. The results indicate a gain of 6.6 dBi and a cross-polarization level of -22 dBc, which is comparable to the antenna's performance in free space. However, at higher frequencies, such as 2.50 GHz, the cross-polarization level increased to -9.3 dBc, suggesting that the stacked antenna is more sensitive at the upper end of the frequency band while exhibiting more robust performance across the middle and lower frequency ranges. The antenna back radiation was also impacted by the presence of the CubeSat body. Its

value decreased from -4 dBi to -10 dBi.

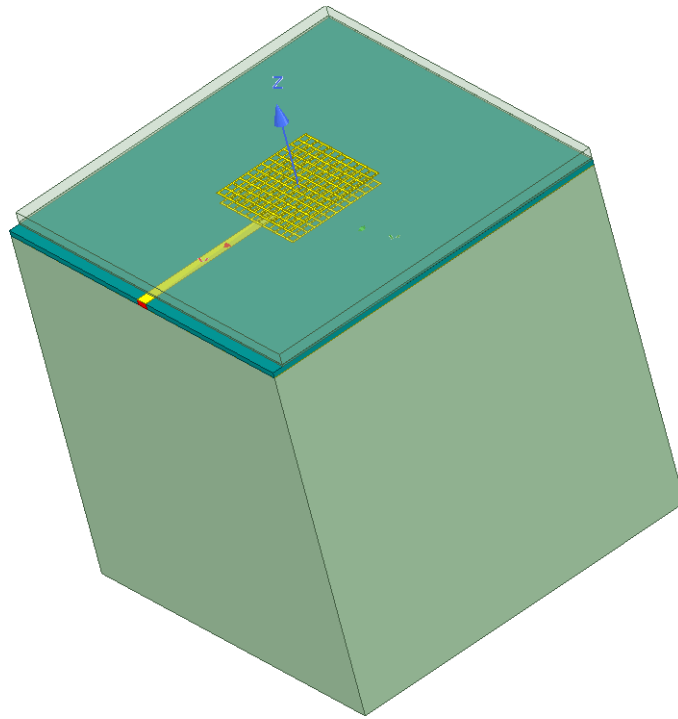


Fig. 6.24: Ant-1a mounted on one side of the 1U CubeSat body.

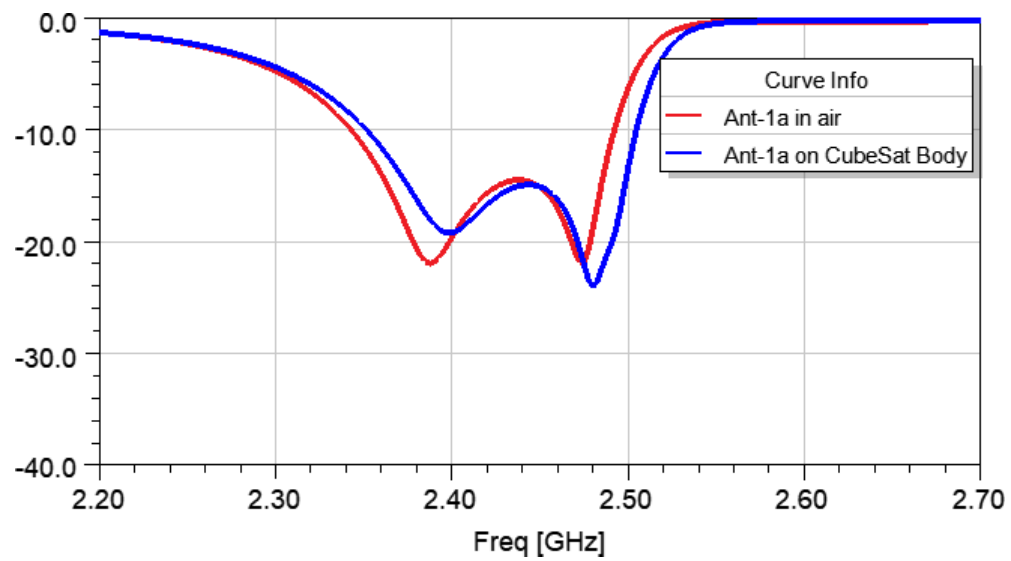


Fig. 6.25: Comparison of Ant-1a S11 while the antenna is in air versus mounted on CubeSat body.

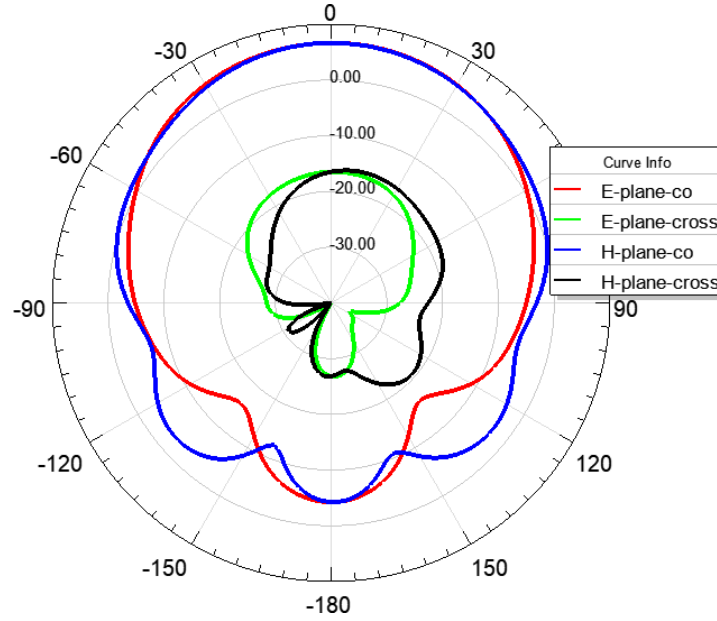
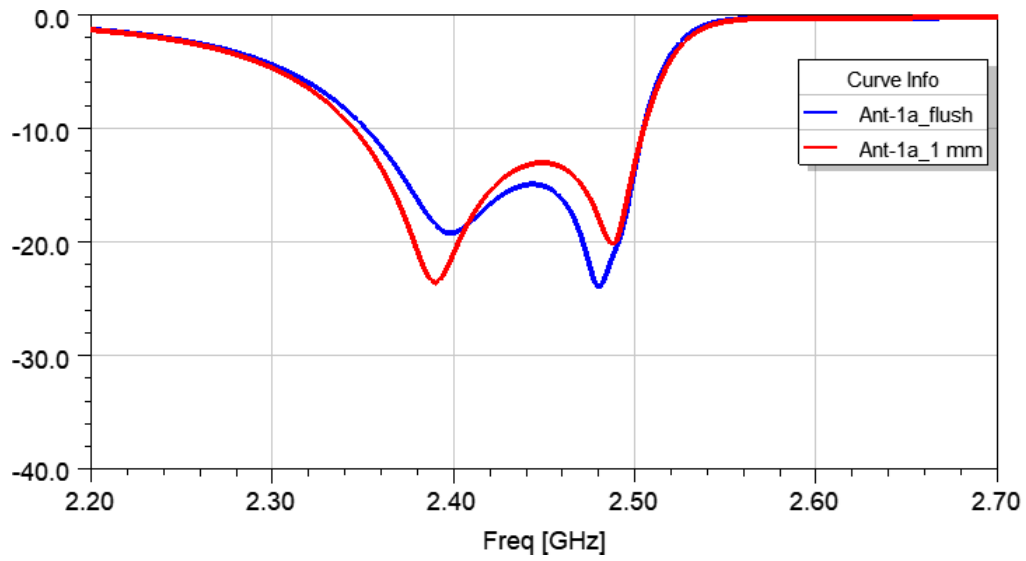
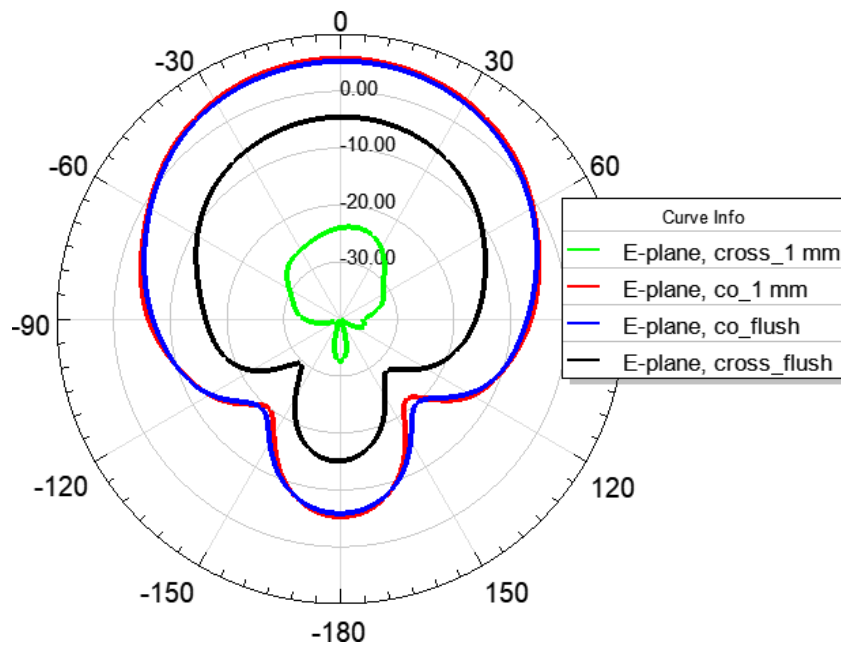


Fig. 6.26: E-plane and H-plane radiation pattern of the Ant-1a placed on one face of the CubeSat body at 2.42 GHz.

Optimizing the distance between the antenna and the CubeSat body can significantly enhance performance at higher frequencies. A parametric study was conducted by varying the mounting gap between the antenna and the CubeSat body from 0 mm (flush) to 5 mm, in 1 mm increments. The comparison of antenna gain indicates that even a small spacing between the antenna and the CubeSat body can enhance the performance significantly. Fig. 6.27 illustrates the S11 and realized gain for a 1 mm gap between the antenna and CubeSat body and compares it with flush-mounted condition. It can be observed that the 1 mm gap significantly improved the antenna's cross polarisation, and the performance is comparable to that of the antenna in free space in Fig. 6.26.



(a)



(b)

Fig. 6.27: E-plane radiation pattern of Ant-1a mounted on one face of the CubeSat body at 2.505 GHz, shown for both flush mounting and a 1 mm air gap.

6.6 Method of Integration

The proposed stacked transparent meshed patch antenna can be integrated with a solar cell using two different approaches. The first approach is to maintain the solar cell as a separate structure and place the antenna directly on top of the solar cell. In this configuration, the solar cell cover glass can be used as the first substrate layer of the stacked antenna and a meshed ground plane can be used, allowing incident sunlight to pass through the antenna while preserving the required RF performance. The solar cell therefore remains physically separate from the antenna, while the cover glass provides the supporting substrate. This approach allows the antenna maintain its performance but will reduce the transparency and efficiency of the solar cell [32].

The second approach is to incorporate the solar-cell structure itself as part of the antenna configuration. In this case, the solar-cell layers beneath the antenna are considered as part of the electromagnetic structure and can influence the antenna's impedance, resonant frequency, gain, and radiation characteristics. Previous studies have shown that the photovoltaic layer can introduce additional electromagnetic loss, while the electrode lattice can partially shield the antenna from the lossy semiconductor layer [72], [73]. Therefore, the antenna must be designed while considering the electrical properties and physical arrangement of the solar-cell layers. This approach preserves the transparency however the RF performance reduces.

The two integration approaches provide different design considerations. In the first approach, the antenna can be independently optimized before being placed on the solar-cell surface, whereas in the second approach, the solar-cell structure becomes an integral part of the antenna and must be included during the electromagnetic design and optimization process. In both cases, the optical transparency of the mesh is important for minimizing the impact of the antenna on solar-cell operation. Experimental investigations is needed to better evaluate the

performance of each integration method.

6.7 Conclusion

This chapter presented the fabrication process and measurement results for Ant-1 and Ant-3, followed by a detailed parametric study to evaluate the sensitivity of Ant-1a's performance to various design parameters and fabrication tolerances.

The measured results showed good agreement with simulations, especially around the center frequency of the operating band. Deviations were observed at higher frequencies which can be related to fabrication imperfections, such as mesh misalignment and width.

Sensitivity analysis showed that changes in the dielectric constant of the glass substrate significantly affect the resonant frequency and bandwidth, highlighting the importance of accurate material characterization. Feed line length variations had a greater effect on polarization performance at higher frequencies but minimal impact on gain. Modifying the dimensions of the stacked mesh patches shifted the impedance response and altered coupling behavior, with opposite trends observed for the upper and lower elements.

Mesh line width changes also had negligible effect on the antenna's performance at the center frequency but at higher end of the frequency range the performance was affected noticeably. Interlayer air gap variations introduced up to 20 MHz shifts in frequency response and small gain changes. Using transparent epoxies such as SU-8 can reduce the risk of air gap variations. The last parameter studied in this chapter was mesh misalignment between the lower and upper meshed patches. It can cause up to 15 MHz frequency shift and polarization degradation, though performance remained acceptable with cross-polarization levels staying below -20 dBc. The discussions in this chapter have been published in [71].

Chapter 7

Conclusion and Future Work

7.1 Summary

This thesis advanced the scientific understanding of transparent meshed patch antennas by conducting a comprehensive study of how the antenna's mesh geometry influences their electromagnetic behavior, leading to new insight into the antenna performance that are governed by mesh parameters, and demonstrating that how multilayer transparent structures can overcome the bandwidth limitation inherent to single layer meshed configurations. In addition, the research introduced new insight into the electromagnetic behavior of polymer-based transparent dielectrics, specifically SU-8, showing how their geometry and distribution affect coupling, loss, and effective permittivity in stacked antenna architectures. These contributions formed a foundation for the design of wideband, lightweight, and optically transparent antennas suitable for solar-integrated systems like CubeSats or other multifunctional platforms.

The research began with a comprehensive study of transparent antenna technologies. Among them, TMPAs were identified as the most promising due to their ability to achieve high efficiency and optical transparency simultaneously. Chapter 3 characterized the effects of mesh geometry, transparency level, conductor thickness, and substrate material on the performance of meshed patch antennas. The results established practical design guidelines for selecting mesh line widths and densities, demonstrating that fine and dense meshes yield performance approaching that of solid patch antennas.

Building upon these findings, Chapter 4 introduced the stacking technique as a method for bandwidth enhancement. By vertically coupling two meshed patches through low-loss transparent dielectric layers, the antenna bandwidth was expanded by nearly a factor of five compared to single-layer TMPAs, while maintaining high efficiency and above 90% optical transparency. The study also clarified how interlayer coupling, dielectric thicknesses, and material properties control the alignment of resonances in stacked transparent antennas.

Chapter 5 advanced this concept further by exploring lightweight designs through the introduction of polymer-based dielectrics. Three lightweight variations, full SU-8, partially removed SU-8, and perforated SU-8 were evaluated to understand how polymer distribution influence the mass and radiation properties. These designs achieved significant mass reduction, up to 68%, while maintaining satisfactory gain and efficiency. Among them, the perforated SU-8 structure demonstrated the best trade-off between weight, bandwidth, and efficiency, highlighting the potential of polymer-based substrates for multifunctional CubeSat structures.

Chapter 6 focused on fabrication and experimental validation. Two antennas were prototyped and tested:

- Ant-1 (glass/glass stacked TMPA): Measurements confirmed the effectiveness of stacking in bandwidth enhancement, yielding a 6.2% impedance bandwidth, a peak gain of 6.5 dBi, and efficiency greater than 90%.
- Ant-3 (glass/partially removed SU-8 TMPA): Measurements validated the feasibility of using polymer-based substrates, confirming acceptable gain, bandwidth, and radiation characteristics while achieving mass reduction.

Discrepancies between simulated and measured results were systematically analyzed through sensitivity studies of substrate permittivity, feed geometry, mesh alignment, and

fabrication tolerances. These analyses provided insights into design robustness and practical design tolerance considerations required for successful implementation of transparent antennas. Additionally, integration studies demonstrated that the proposed antennas can be mounted directly on CubeSat structures without significant performance degradation.

7.2 Concluding Remarks

The developed antennas demonstrated the following key achievements and unique contributions:

- Ant-1 (Glass/Glass Stacked TMPA): Achieved an impedance bandwidth of 6.2%, a peak realized gain of 6.5 dBi, and efficiency greater than 90%. These results confirm the effectiveness of stacking as a novel and practical solution for overcoming the inherent narrow bandwidth of transparent patch antennas.
- Ant-3 (Glass/Partially Removed SU-8 TMPA): Validated the use of lightweight polymer substrates for transparent antennas, achieving acceptable bandwidth and gain while realizing a significant reduction in antenna mass. This highlights the feasibility of polymer-based transparent dielectrics for nanosatellite applications.
- Ant-4 (Glass/Perforated SU-8 Stacked TMPA): Demonstrated the best trade-off between weight reduction and performance, achieving up to 68% mass reduction, a bandwidth of 11.8%, and a peak realized gain of 8.2 dBi. This design represents how material geometry can be engineered to simultaneously optimize mass, bandwidth, and efficiency.

Collectively, these results establish demonstrate that the scientific principles developed in this thesis regarding mesh geometry, stacked resonance coupling, and polymer dielectric engineering, enable transparent meshed patch antennas to simultaneously achieve wide bandwidth, high gain, high efficiency, lightweight construction, and optical transparency above 90%. Such

performance confirms their uniqueness and suitability as multifunctional CubeSat antennas, enabling seamless integration with solar panels while maintaining communication capability.

7.3 Future Work

Although this thesis has successfully demonstrated the feasibility of transparent meshed patch antennas for CubeSat applications, several opportunities remain for future investigation to advance their performance and integration. One important area for future work is the direct integration of the proposed antennas with solar cells. Experimental validation is required to evaluate the impact of photovoltaic layers on antenna impedance, radiation efficiency, and long-term stability under simultaneous optical and RF operation.

In addition, detailed optical transmission measurements should be performed on representative fabricated antenna stacks to quantify the actual light transmission through the complete structure, including the conductive meshes, dielectric layers, bonding layers, and supporting elements. Such studies would provide valuable insight into the practical realization of multifunctional CubeSat surfaces and establish the relationship between antenna transparency, radiation and solar-cell performance. Also, the thick SU-8 layer got darkened during fabrication, then other transparent polymer materials can be explored.

Another promising direction involves the development and analysis of transparent meshed patch antenna arrays. By investigating linear and planar configurations, mutual coupling effects, and surface integration on CubeSat structures, higher gain and beam-steering capabilities can be achieved, thereby extending the functionality of TMPAs beyond single-element designs.

Future research should also focus on advanced mesh optimization, where non-uniform grids, fractal geometries, and hexagonal or irregular meshes are systematically explored. Employing optimization techniques such as genetic algorithms or machine learning could enable simultaneous

enhancement of transparency, bandwidth, and efficiency.

In addition, the fabrication and experimental characterization of the perforated SU-8 antenna and the suspended meshed patch antenna (Ant-5) should be pursued. The perforated SU-8 design demonstrated the best trade-off between weight reduction and antenna performance, while Ant-5 achieved the highest simulated gain and widest impedance bandwidth among the investigated antennas. Experimental validation of these designs would confirm the simulated results and provide further understanding of the practical implementation challenges associated with perforated and suspended transparent antenna structures, including fabrication tolerances, structural stability, and air-gap control. Such studies would further evaluate the suitability of these lightweight transparent antenna architectures for CubeSat communication systems.

Appendix 1: Measurement of Fused Silica Substrate Dielectric Properties

A1.1 Introduction

A transmission line method was employed to accurately determine the dielectric constant and loss tangent of the fused silica glass substrate used in the antenna design. This technique involved fabricating two microstrip transmission lines of different lengths on a 1.5 mm thick fused silica glass substrate and measuring their S-parameters. The dielectric properties were extracted by comparing the measured results with simulated data in Keysight ADS.

A1.2 Theory and Methodology

The transmission line method relies on measuring the propagation constant (γ) of the microstrip line to find dielectric properties. The propagation constant is composed of attenuation (α) and phase (β) constants:

$$\gamma = \alpha + j\beta$$

The effective dielectric constant (ϵ_{eff}) is determined from the phase constant, which is related to the electrical length of the microstrip line at a given frequency. The loss tangent ($\tan\delta$) is obtained from the attenuation constant, which accounts for conductor, dielectric, and radiation losses.

By measuring two transmission lines of different lengths, the connector and mismatch effects are minimized through a de-embedding process. The difference in S21 (insertion loss) between the longer and shorter lines corresponds to the remainder length of the transmission line, making it possible to isolate substrate losses.

A1.3 Fabrication and Measurement Setup

Two microstrip transmission lines were designed with a width of 3.15 mm and lengths of 53.1 mm and 100 mm, respectively. Two PCB edge-mount SMA connectors were soldered to each transmission line and were connected to the vector network analyzer (VNA). The S-parameters (S_{11} and S_{21}) of each line were measured across the desired frequency range. Then, a de-embedding process was applied by subtracting the S_{21} measurements of the shorter line from those of the longer line to eliminate the effects of the SMA connectors and obtaining the S-parameters of a 46.9 mm long line. Fig. A1.1 shows the fabricated transmission lines.

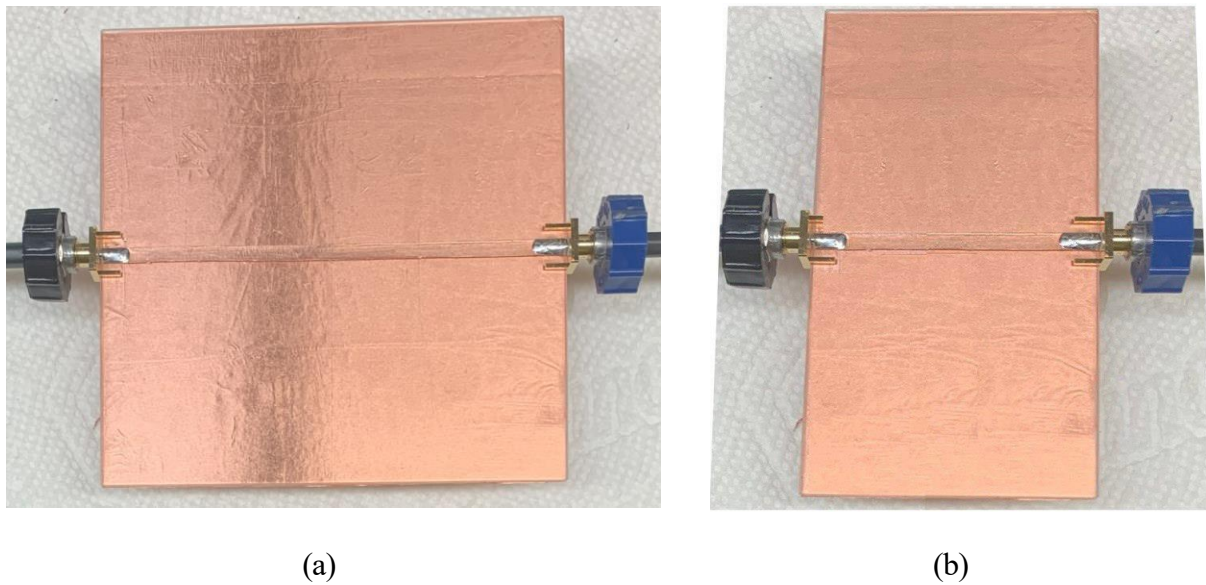
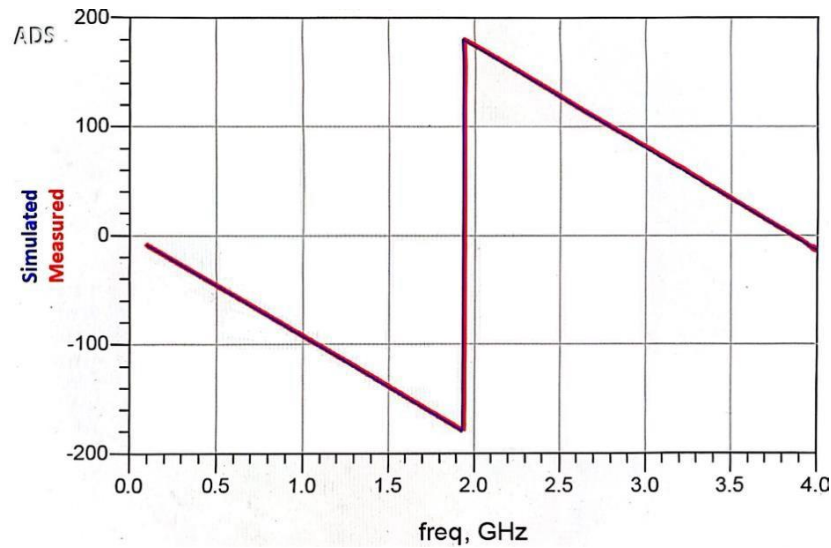


Fig. A1.1: Two microstrip transmission lines on 1.5 mm thick glass substrate. a) 100 mm long line. b) 53.1 mm long line.

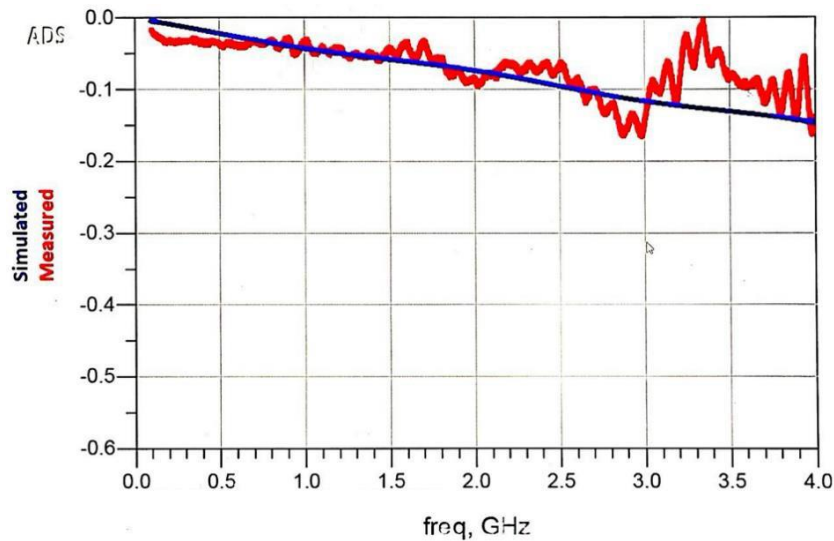
A1.4 Extraction of Dielectric Properties

The extracted S-parameters were compared with simulated results in ADS, where the dielectric constant and loss tangent of the substrate were tuned to achieve the best match between simulation and measurement. The simulation was performed by adjusting the substrate properties

until the simulated S11 and S21 parameters aligned closely with the measured results. The final values obtained were 3.5 for the dielectric constant and 0.0055 for loss tangent. Fig. A1.2 illustrates the comparison between the simulation result in ADS and measurements for S11 phase and S21 magnitude.



(a)



(b)

Fig. A1.2: Compared simulated and measured data of the de-embedded 46.85 mm long microstrip line. a) S11 phase. b) S21 magnitude.

Appendix 2: Fabrication Process of PDMS Mold

A two-component DMS from Dow Corning, Sylgard 184, was used to fabricate the PDMS mold for SU-8 substrate. The PDMS was prepared by mixing the base elastomer and curing agent in a 10:1 ratio by weight. Proper mixing was ensured to achieve a homogeneous solution, preventing inconsistencies in the final mold structure.

A 3.5 mm thick aluminum piece with dimensions of 35 mm $\times$ 35 mm was used as a template to define the mold. The prepared PDMS mixture was poured into a glass Petri dish, covering the aluminum piece to achieve a uniform mold surface. To remove air bubbles introduced during mixing, the Petri dish containing the PDMS was placed in a vacuum chamber for 30 to 45 minutes until visible bubbles disappeared. Then, the PDMS was cured by placing the Petri dish in an oven at 70 °C for 2 hours. After curing, the solidified PDMS mold was carefully separated from the Petri dish and aluminum piece. This mold was then used as a casting template for the SU-8 structure. Fig. A2.1 shows the fabricated PDMS mold.

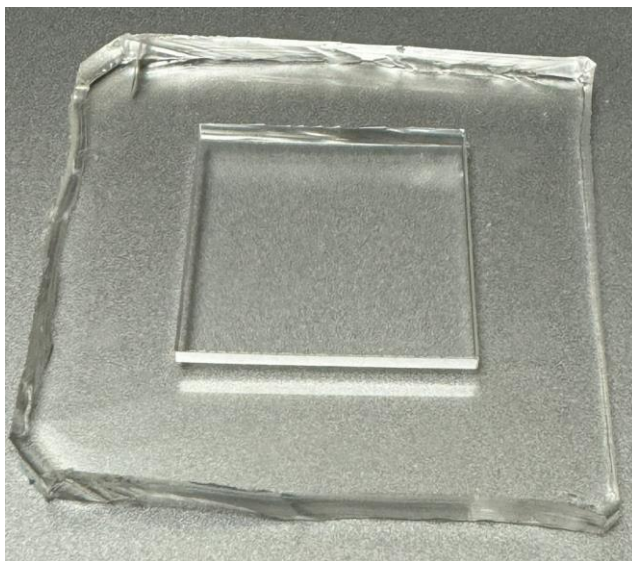
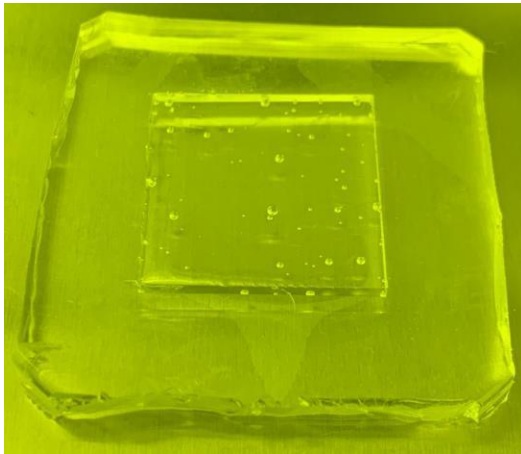
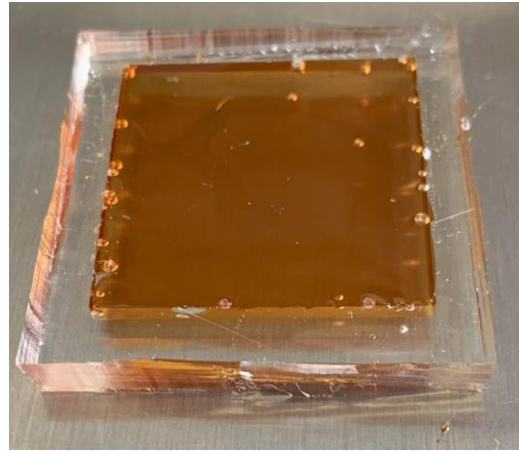


Fig. A2.1: Fabricated PDMS mold.

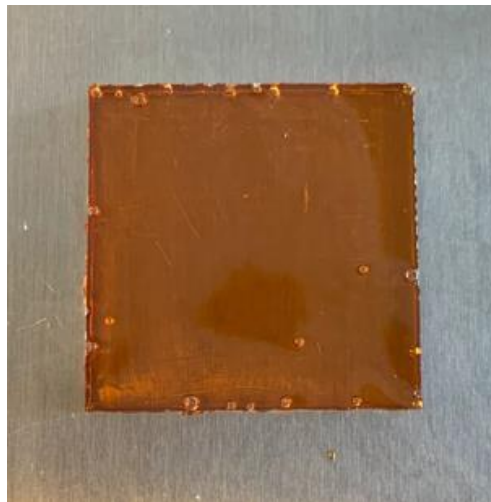
For SU-8 processing, liquid SU-8 2075 was poured into the PDMS mold and subjected to the required soft bake, UV exposure, post-exposure bake, and hard bake steps as detailed in Section 6.3. Fig. A2.2a illustrates the PDMS mold filled with SU-8. During the pouring process, air bubbles formed within the SU-8. However, after a soft bake at 65 °C for 5 hours, most of the bubbles dissipated. Fig. A2.2b shows the sample after the PEB. Following this step, the sample was carefully separated from the mold and subjected to a hard bake to finalize the curing process.



(a)



(b)



(c)

Fig. A2.2: Step-by-step process of SU-8 fabrication using a PDMS mold. a) SU-8 poured into the PDMS mold before the soft bake, showing air bubble formation. b) SU-8 sample after the post-exposure bake (PEB), with enhanced structural integrity. c) SU-8 sample after separation from the PDMS mold, before undergoing the hard bake.

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