Design, Simulation and Fabrication of Terahertz Antenna Using Two-Photon Polymerization Technology

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ABSTRACT

As part of this project, a complex terahertz (THz) antenna was fabricated using two-photon polymerization (2PP), a highly precise additive manufacturing method. The design and rigorous simulation testing were conducted using Ansys HFSS, with a focus on achieving minimal losses. Special emphasis was placed on impedance matching, confirmed by the S11 parameter showing minimal power reflection over a large part of the THz band. The antenna was fabricated using OrmoComp, a hybrid polymer. A significant portion of the thesis is dedicated to fine-tuning the intricate fabrication steps necessary for producing complex designs, demonstrating the capability to also fabricate simpler structures. The most significant outcomes of this work on the highly directional THz antenna are the optimized process parameters such as slicing direction, way of printing, power and speed settings of laser for 2PP and finally development time of post processing, which enabled the production of the complex structure. The fidelity of the final fabricated design was verified using electron and light microscopy.

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Chapter 1

Introduction

Due to the rapid development of telecommunication technologies in recent years, more sophisticated and efficient antenna systems have emerged. Terahertz antennas have become one of them and have gained significant popularity due to their feasible application in high-speed wireless communications, imaging, and sensor systems. This thesis presents the report on the design and realization of a THz antenna using innovative simulative and manufacturing techniques[1][2]. THz antennas, which generally operate in the THz range from 0.1 to 10 THz, have unique challenges and potentials. Firstly, since the frequency is high, the antenna can cover a wide bandwidth and be able to sustain data rates in the order of tens of gigabits per second necessary for the future wireless communication systems[3]. Antennas operation at these frequencies necessitates careful engineering and design to deal systematically with material selection, signal loss, and accurate fabrication requirements[4][5].

To address these limitations, this research employs the use of the Ansys High Frequency Structure Simulator. Ansys HFSS is an extremely sophisticated software that is specifically tailored for the electromagnetic wave simulation with a physical structure[6]. Ansys HFSS gives an optimal platform to model, simulate, and examine the performance of the THz antenna prior to its real manufacturing. It is a rough simulation stage while designing the THz specification antenna[7].

Fabrication of the THz antenna using two Photon Polymerization technology is an innovative method enabled. It is a kind of additive manufacturing, which is popularly known as 3D printing[8][9]. Such a technology permits the development of extremely precise and complex microstructures[10]. The usage of the 2PP technology is particularly appropriate and necessary for the fabrication of a THz antenna because it can structure the features at a sub-micrometer level[9]. Therefore, the fabrication technology should be capable of processing the small THz signal's wavelengths[11].

A new challenge in THz antenna development, the integration of Ansys HFSS design, and 2PP technology fabrication sets this procedure apart from the conventional framework. This thesis covers the fundamentals of the theory of THz antenna work's research, an accurate representation process by HFSS, and the manufacturing process of 2PP stacking. The purpose of the project is to create a successfully developed and produced THz antenna that passes the operational test, opening the way for subsequent developments in THz technology accomplishments.

This study's value does not only lay in the impact it would produce in the telecommunications sector, but in the other areas it could transform or improve, such as security scanning and medical imaging. Thus, by attempting to expand on the capabilities of THz antenna technology and capabilities, the study seeks to impact the wider electromagnetic field and use.

Thesis Objectives:

Conclusively, the objective of this thesis is to advance the terahertz antenna by a systematic approach incorporating designs and physical implementations. The following goals are outlined:

1) **To create and simulate the terahertz antenna:** design and model a terahertz antenna using ANSYS HFSS. The purpose is to calculate and predict its performance features such as S11 parameter and radiation patterns.
2) **Investigate design factors:** analyze several designs' factors on and compare their performance in order to analyze them systematically and find the best configuration for an improved bandwidth and performance.
3) **Create and develop the antenna using 2PP:** the two-photon polymerization is used to achieve the required intricate structures at terahertz frequencies.

4) **Investigate the printing factors:** analyze which printing factors affect the manufacture process to optimize and magnify the antenna's quality.
5) **Compare the simulated and manufactured antenna:** compare the performance of the manufactured antenna from simulation, focusing on vital metrics to validate the simulation methods and highlight areas for future development.

It is hoped that such a comprehensive approach will narrow the gap between designs and their implementations in an effort to advance performance terahertz antennas.

Structure of This Thesis:

This thesis is divided into five chapters, each outlining an integral part of the current research on design, simulation, and the 2PP technology employed in the additive manufacture of terahertz antennas. Summarily, the thesis is as follows:

a) As said in Chapter 1: Introduction, fabricating terahertz antennas with additive manufacturing technologies—specifically, the 2PP technique—is a fresh and pertinent way to introduce the subject.
b) Chapter 2: Background Study provided a foundation that prepares the reader to understand the research by presenting critical background information on the terahertz

antenna technology that includes materials, equipment, design, simulation software, and other relevant information.

c) Chapter 3: Methodology included descriptions of steps taken during the design, simulation, and building of the terahertz antenna from the idea to the final product.
d) Chapter 4: Results and Discussion: the research findings were extensively evaluated, the simulation results presented and compared to the fabrication results.
e) Chapter 5: Conclusion and Future Work: the main conclusions, implications, and findings of the study are outlined, thus ending the thesis, and possible research directions for further study on terahertz antenna manufacturing utilizing additive manufacturing are revealed.

Such a framework guides the reader through the research process and findings in the simplest possible manner.

Chapter 2

Background Study

The present chapter includes the following topics constituting the background necessary for this research: the general understanding of terahertz technology, the explanation of additive manufacturing as a process and two-photon polymerization as one of the techniques, the definition of necessary tools and materials, such as Ansys HFSS, nTopology, and Micro Resist's photoresists, the physical equipment description – the KEYENCE Microscope, some of the most crucial aspects of fundamental antenna theory, including the reflection coefficient and radiation pattern, the term of electrical measurements with the definition of vector network analyzers. The following chapter will represent the ideas obtained from this study.

2.1 Fundamental of Terahertz Technology:

According to Xiaojian Fu and Yujie Liu, "the electromagnetic spectrum, which is between microwave and infrared regions, or more precisely in the frequency range of 0.1 to 10 terahertz is the basis of what is known as terahertz technology"[12]. This spectrum is interesting for multiple uses because of its exclusive properties and capabilities[13]. In this context, the following paper explores the foundation and possible applications of terahertz technology to demonstrate its capability and potential.

2.1.1 Properties of Wave in Terahertz:

I. **Penetrative capability:** They are actively used for non-destructive testing and security screening systems. The waves can pass through almost all non-conducting materials such as paper, plastic, or most types of clothes. This property allows for internal examination of hidden objects without destroying their protective barriers[14].

II. **Low photon energy:** These waves are good for biological investigations and testing in medical imaging systems. Their photon energy is much lower than UV or X-radiation; thus, these waves are less biologically harmful[15].

III. **The Spectral Analysis signatures:** Due to the various compounds' absorption characteristics at the THz region, these waves are an appropriate spectroscopic tool. Several THz absorptions 'fingerprints' have been used for this purpose to be applied in drug and explosive detectors[16].

2.1.2 Creation and Recognition:

Due to the frequent failures of traditional electrical and photonic technologies in the "terahertz gap," both generation and detection of THz have hitherto been difficult.

However, recent technological developments have enabled a variety of different approaches:

I. **Photoconductive Antennas:** Using ultrafast laser pulses, these antennas are capable of generating and sensing THz waves[17].

II. **Terahertz Time-Domain Spectroscopy (THz-TDS):** this is now a popular way of generating and sensing THz waves; it provides data on phase as well as intensity[18].

III. **Quantum Cascade Lasers:** when coherent sources are required, quantum cascade lasers are quite useful since they create THz waves with frequencies[19].

2.1.3 Applications of Terahertz Technology

a) Security screening: THz imaging may thus be used for security screenings of people, revealing knives or hazardous materials hidden under their clothes without the use of X-rays[20].

b) **Non-destructive evaluation:** When THz waves detect a structural flaw in the analyzed item, they enable the assessment of parts for their damage, defects, and artwork without causing damage[21].

c) **Medical imaging:** Because THz waves detect variations in tissue types, they might aid in less traumatizing diagnostic procedures, imaging tumors during a cancer examination[22].

d) **Wireless communications:** THz waves might have rates that are sufficiently fast to enable advancement in the domains of mobile telecommunication[23].

e) **Spectroscopy and identification:** Since it recognizes different materials by their THz spectra, security, clinical, and atmospheric tracking all need identification[12].

2.1.4 Obstacles:

Terahertz (THz) technology has significant challenges in terms of development and implementations that limit its application in high-speed communications, medical imaging, and sensor systems. These limitations largely arise from materials and manufacturing. THz frequencies—from 0.1 to 10 THz—correspond to wavelengths that are orders of magnitude shorter than those used in traditional RF communications. This requires antennas with very small and precise designs, which adds complexity to the design and manufacturing. Whereas conventional materials provide copper (with antennas operating at lower frequencies) shown increased ohmic loss because the skin depth is lower and have restricted effectiveness of the antenna. Even FR-4, the industry-standard board material, exhibits extremely high losses at THz frequencies, impairing antenna performance and forcing engineers to consider expensive and complex manufacturing techniques for novel materials, such as graphene and carbon nanotubes[24][25].Another significant obstacle is that the small size and extremely high operating frequency of THz components demand especially tight tolerances in their manufacture. Existing manufacturing techniques are too imprecise or too expensive to be adopted at scale. While techniques such as micromachining, electroforming, and focused ion beam (FIB) technology can offer some solutions, they are often complicated, costly or require specific expertise. Further complicating the matter is the fact THz antennas are sensitive to environmental influences and must be accurately aligned and packaged into current system. Creating and utilizing THz components is challenging because standard electronics are designed for lower frequencies, not the extremely high THz frequencies. The process of creating, assembling, and integrating these high-frequency components with traditional electronics is made more difficult by this disparity. [24][25].Furthermore, many challenges in designing THz systems are driven by the operating environment. For example, the high absorption of water vapor in the atmosphere strongly limits the range at which THz signals can be used in outdoor scenarios, especially in case of activities in motion [13]. Moreover, suitable THz antennas are nowadays fabricated with very expensive materials and manufacturing processes, limiting their broader usage and availability for technological developments [26][27].

Even though the THz range is promising, it is still a relatively unexplored frequency band compared with other ranges. This requires a lot of research in terms of signal generation as well as various technical challenges due to the fact everything is working in the Terahertz, so we need faster, more power-efficient systems and beamforming. In the year and decade to come, the commercial THz technology market will proliferate, but only in synergistic connection to research opportunities resulting in yet more efficient and cheaper THz sources, detectors, and systems. Solving these problems would pave the way to the numerous applications expected of THz technologies and would be critical for the future research-and-development goals. Tackling these hurdles would enable THz technology in addition to the promise of permeating several sectors from security through telecommunications [13][26][27]

2.2 Additive Manufacturing:

Additive manufacturing (AM), widely known as 3D printing, is a transformative technology for producing lightweight and strong parts and systems by adding materials in a series of layers. AM is fundamentally distinct from conventional subtractive manufacturing or similar ultra-high vacuum fabrication methods [28][29][30]; it entirely revolutionizes the practice of design, development, and production in several industries, like consumer, healthcare, automotive, and aerospace. AM significantly reduces the material waste and energy consumption involved with the production of high-quality and customized items from digital designs, which is not the case when intentionally growing the filaments [31][32][33][34][35][36][37][38], [39] or other laser-based fabrication methods [40][41][42][43] Simultaneously, it allows the use of a broad range of materials, from polymers and metals to ceramics [44]. As a result of its versatility, the technology is adaptable to specific needs: product customization, efficient small-batch manufacture, and quick prototyping. This opens up novel business prospects specifically for areas requiring customization, such as healthcare. Personalized products include medical implants and prosthetics [45]. Moreover, as a result of the use of materials, AM aids in the optimization of supply resources and the reintroduction of intermediate localization and production, which have been established to be significant factors in improving sustainable manufacturing by a decrease of the whole carbon dioxide emitted as a result of all linked logistics and product operations [46].

Block Diagram of Additive Manufacturing Process:

In additive manufacturing, the material layer by layer addition eventually changes a computer model into a real object. The process involves several steps. A block diagram can be used to represent the process at scale which is commonly described as follows:

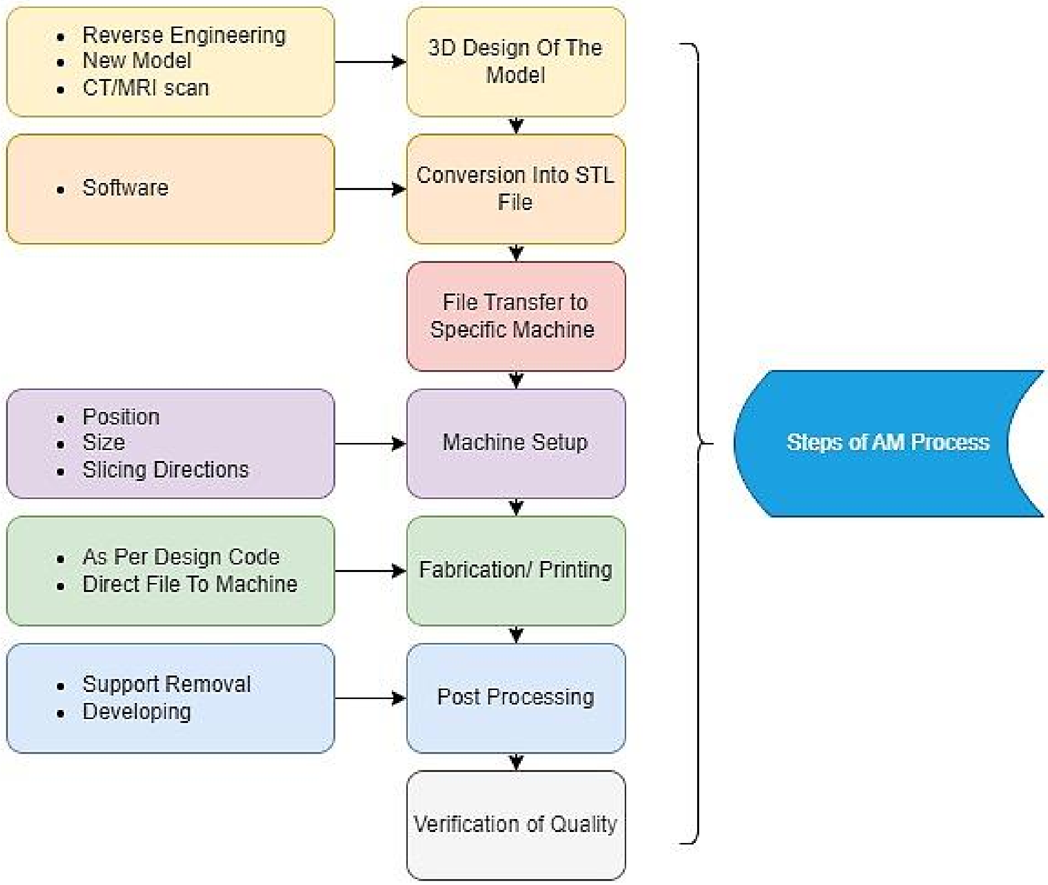


Figure 2. 1: Different steps of AM process.

Firstly, **Design:** This refers to generating a three-dimensional electronic computer-aided design model which is a virtual blueprint of the initially thought physical object, then **Conversion to STL:** the next stage includes breaking up the CAD model's geometry into small triangular facets named according to Standard Tessellation Language or in other words: the triangles only slightly illustrate the object's surface, hence making up its complex geometry more approachable for processing, **Slicing:** this is a stage when specialized software takes and convert an STL file of the object model to be processed into hundreds of thin flat horizontal layers and results in a series of cross-sectional plans. Then the printer receives instruction layer by layer on how to produce the object, **Printing:** these instructions are read by an AM machine who prints each layer one after the other. The substance is laid, melted, or cured, depending on the model item being done, **post-processing:** additional steps such as removing supports form, gives a shiny surface polish—heat treatment to acquire the exact characteristic needed. Last **verification of Quality:** this last stage verifies the product to check it meets the correct attributes of the printed object in terms of material used and accuracy [44].

2.3 Two Photon Polymerization Technology:

The Two-Photon Polymerization (2PP or TPP) technology is a revolutionary invention in the sphere of 3D printing that allows constructing micro and nano structures of complex forms and outstanding accuracy. In contrast to the traditional 3D printing where the single photon was combined to make materials that will be solid, the two-photon polymerization used its optical uniqueness – two-photon absorption. The use of an optical phenomenon to prove my points, convince, and respond to your questions will be preceded by a detailed explanation based on the principles of science and the results of research [47].

2.3.1 How TPP Functions:

The TPP is a technique that uses an ultrafast laser to emit a concentric stream of photons into a photosensitive resin, or what is known as a photopolymer, ultimately causing the process of a photochemical reaction. More specifically, a targeted focus level of this flow's simultaneous absorption of a pair of two infrared light's photons enables the secure adequate energy input for polysensitization to commence. As a consequence, the resin is solidified in which the laser's emphasis is placed. By directing this emphasis through the matter, it is feasible to create objects in three dimensions. The distinct feature of TPP lies in its ability to carry out selective polymerization, which allows the addition process to be as accurate as necessary. The figure below illustrates a normal setup of TPP system.

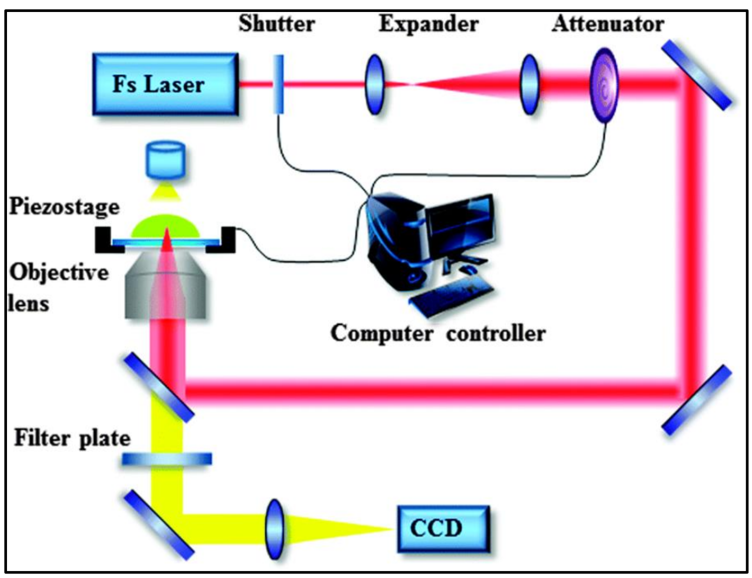


Figure 2. 2: A typical experimental setup of TPP[48]

2.3.2 Contrasted with Traditional 3D Printing:

TPP stands out against traditional methods of 3D printing, such as Fused Deposition Modeling and Stereolithography, for relying on a fundamentally different mechanism. The resolution of single-photon absorption methods is defined by the wavelength of the light and how inter-layers have to be placed, making them far inferior to TPP in the sub-micrometer range. Using non-linear optical effects and the fact that focus can be adjusted with a nearly one-nanometer precision, TPP is particularly well suited for projects that require detailed manipulations at a nano-level [9].

2.3.3 Main Applications of TPP in Industry

In industry, TPP has the following major applications. First, it is used to develop complex pathways or frameworks for managing very small quantities of fluids; this is mainly in microfluidics. Second, to produce tissue scaffolds, miniature surgical devices, and prosthetics in biomedical engineering devices. The third one is crystal development and the manufacture of light conduits for the nano-level light manipulation, i.e., photonics. Other areas include the development of small-sized sensors, actuators, and other micro-scale mechanical devices under the newly emerging micro-electro-mechanical systems [49].

2.3.4 Recent Advancements in TPP Technology:

The most recent achievements in TPP technology concern material improvement, speed increase, and resolution lift. These will be represented by the new photopolymerizable substances gentling the final products, making them more durable or more convenient for biological tissues. It is also beneficial to continue increasing the speed of printing while not losing the details, which can be achieved through improved scanning and the use of stronger and faster laser systems [50].

2.3.5 Scalability and Adoption Issues:

The main challenges of the TPP technology are scalability and broader acceptance. Since its process is more detailed and precise, the TPP is slower and more expensive than other 3D printing methodologies, meaning that it is used in the areas requiring maximum precision. A higher level of expertise and specific equipment is another barrier to its broad implementation. Efforts are being made to address the problems in developing and existing laser systems, optimizing the characteristics of resins utilized in the process, and developing more accessible software [9].

2.3.6 Effects of Industry and Academic Collaboration:

It is vital for the TPP technology's development to rely on cooperation between academic institutions and the industrial sector. The former is responsible for the fundamental research in the area of materials science, optics, process optimization, while the latter is charged with the creation of working solutions, scalability, and commercialization. Cooperation between the two is necessary to turn research-based solutions into viable technologies that can be effectively used across industries[49].

2.4 MICROFAB-3D:

Taking the position of advanced 3D printing technology is Microlight3D's MICROFAB-3D shown the figure 2.3, which not only achieves versatility with advanced two-photon polymerization but also leads precision. MICROFAB-3D raises 2PP to perfection, enabling the printing of microstructures with vertical and horizontal features as thin as 0.2 microns. Precision in creating structures of utmost minuteness broadens the technology's scope, expanding to microfluidics, micro-optics, and cellular biology [51].

Figure 2. 3: MICROFAB-3D printer by Microlight3D [52]

2.4.1 Operational Principles:

The entire MICROFAB-3D concept is centered on the two-photon polymerization process from which the technology derives its name. In this process, there is a certain unique property of the photo-reactive material that retains transparency when interacting with the laser light but at the focal point. This is where the absorption of two photons takes place and results in a chemical change that converts the liquid monomer into a solid polymer in a very small volume sometimes referred to as a "voxel". Considering that this is done on a voxel basis, there is no need for additional materials or post-processing and the printer can be used to make complex and fine 3D structures that were previously not possible [53].

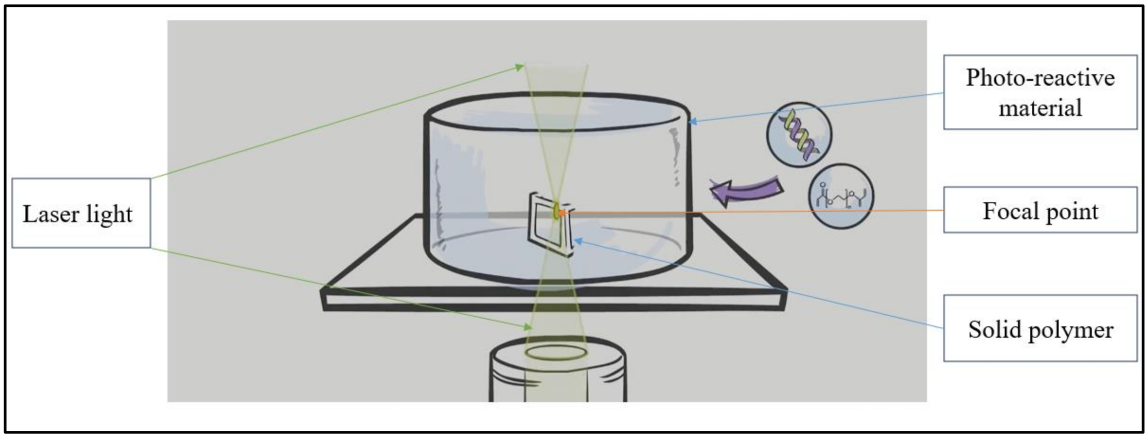


Figure 2. 4: Two photon polymerization technique [54]

2.4.2 Specifications and Capabilities:

I. **Resolution:** The high transmission variability means features can be printed as thin as 0.2 microns. Thus, MICROFAB-3D is one of the most accurate and detailed 2PP systems on the market.

II. **Material Compatibility:** The company produces its own proprietary photoresists specifically developed for use with 2PP technology. This allows for a much wider range of research applications and industrial uses.

III. **Adaptability:** Because the machine's design is highly flexible, the resolution can be changed on-the-fly to achieve a balance between fabrication speed and intricacy. The system can also print on otherwise impossible environments, such as the reflective surface of an optical fiber tip.

IV. **Software Integration:** The manufacturers developed their own processing software, Luminis. This program reduces the entire processing pipeline to a single step, dramatically improving efficiency. Luminis should significantly reduce overall turnaround time at the manufacturing stage[55].

V. **Utilization Scope:** The MICROFAB-3D technology has become an invaluable tool in a wide range of sectors where it is applied for the intricate assembly of microfluidic networks, manufacturing micro-optical tools, and more achievements. In addition, with the implications offered by this 3D printing advancement, it is easier to consider the new possibilities for microscale manufacturing and overall application developments. The MICROFAB-3D technology developed by Microlight3D is an important innovation leap in comparison to the previous generations of 3D printers. It is characterized by an exceptionally high level of detail, a great choice of materials, and advanced software application streamlining and acceleration [51][53]. Table 1 demonstrates the specifications of MicroFAB-3D printer.

Table 1: Specifications of MicroFAB-3D[53]

System	microFAB-3D. Advanced
Lateral writing resolution (X, Y)	Adjustable from <0.2µm to 3µm
Vertical writing resolution (Z)	Adjustable from <0.6µm to 10µm
XYZ high resolution writing range (without stitching)	300µm
Minimal surface roughness (with anti-vibration bench)	20nanometers
Printing speed	100µm/s at high resolution (0.2µm), 1mm/s at lower resolution (2µm)
Stitching and replication (X, Y)	Automated. Precision: down to 0.7µm
Stitching and replication area (X, Y)	100×75 mm²
Maximum object height (Z)	0.45 mm
Stitching (Z)	No
Auto-focalization	Yes
Alignment Mode	Yes – Precision: 1 µm
Laser Wavelength	532nm

2.5 Luminis:

Developed by Microlight3D, Luminis is a proprietary Computer-Aided Manufacturing application designed specifically for the microFAB-3D environment. The software represents a revolution in the micro-scale 3D printing process – in essence, the software unites two separate process stages of micro-3D printing, pre- and post-process, into one single procedure enacted through a single interface. This unification results in an unprecedented level of effectiveness, making the process of micro-scale 3D printing accessible and user-friendly, providing relatively novice users with a more solid platform from which to undertake highly precise and detailed projects [55]. Luminis is the synthesis of two essential facets of the 3D microprinting process:

a) **Preparing a 3D Model:** The only tasks that are eliminated are the manipulation of different software tools. Users needed to manipulate the model in CAD software and then use various tools to convert the file into a printable format then to modify it for a printable quality that matches the intended use case. Luminis prevents the first step and offers control options. The second step is simplifying due to Luminis`3D design toolkit. There is a full toolkit that allows the modeling of 3D models and prepares this model to the printing process shall be done in Luminis. Additionally, the control of the print process is part of the process [56].

b) **Printing Process Control:** While producing, constant control of the process is important; while dealing with micro-scales and the movement of substances and precision, the user must control the printer. In the instance of Luminis, the process not only involves the user, but they possess control over the microFAB-3D apparatus. The user the printer to the movement of the substrate, controlling the laser intensity which adjusts the quantities of the tessellated square, the movement modulus of the substrate, the printing speed, substrate resolution [57].

2.6 Ansys HFSS:

Ansys HFSS is one of the most prominent 3D electromagnetic simulation software, widely used in designing and analysis high-frequency and high-speed electronic devices at present. Standing for high-frequency structure simulator, since it is a part of extensive Ansys engineering simulation suite, it specially provides the tools to precisely model the electromagnetic fields and waves. Thus, it becomes an irreplaceable tool in developing antennas, microwave components, high-speed interconnects, and many other items, where the behavior of electromagnetic waves is important [58].

2.6.1 How Ansys HFSS Operates

Ansys HFSS utilizes the Finite Element Method to solve Maxwell's equations, allowing highly accurate electromagnetic phenomenon simulation in discretized space. This allows for elaborate representations of device components and materials under varying conditions, in five main stages[59]. These include:

a) **Geometry Creation and Import:** Input the physical geometry of the device, feature, or component, using either internal drawing tools, or importing existing Computer-Aided Design software (CAD) geometry [60].
b) **Material Assignment:** Assigning materials to selected sections of the defined geometry is done using a material library with electromagnetic properties that can be entered, such as permittivity, permeability, or conductivity.

c) **Boundary Conditions and Excitations:** To simulate the real environment as precisely as possible, it is necessary to define boundary conditions to detail how EM waves will interact with the boundary, and excitation sources to mimic variations within the space. This might include voltage sources and current sources that will produce the EM fields.

d) **Meshing:** This is the process of generating a grid system that will be laid over the geometry, breaking it down into small and simple elements, with the fineness of this mesh, dictating the computational demands, and accuracy of the simulation.

e) **Solving:** With the above aspects put in place, HFSS uses the FEM to numerically solve Maxwell's equations, which are used to calculate EM field distributions, and certain other quantifies such as S-parameters, impedance, and radiation patterns as dictated by simulation goals [61].

2.6.2 Applications of Ansys HFSS:

Ansys HFSS has multiple areas of application across numerous industries, including antenna design and placement, where it is used to design antennas and place them optimally on structures such as vehicles and buildings to meet specifications and microwave and RF components, which are components like filters, couplers, and amplifiers that require accurate modeling of EM behavior. It is also used in analyzing signal integrity, as high-speed digital designs need it to design digital circuits subjected to signal degradation across interconnects. EMC/EMI also utilizes it as EMC/EMI prediction and optimization are achieved by it on EMC and interference matters. The use of Ansys HFSS Tool provides simulation capabilities for EM-sensitive areas to engineers and designers to simulate performance characteristics and enhance them prior to the physical prototype stage [62].

2.7 nTopology:

nTopology is a sophisticated engineering design software that is pushing boundaries by moving beyond the constraints of conventional CAD tools through advanced computational approaches. Strengths of the software are creation and processing of demanding geometries and performance-tuning of designs via cutting-edge technologies such as Implicit Modeling, Field-Driven Design, and Design Process Automation. These optimizations allow nTopology to handle real-world data, physics, and logic to quickly optimize designs in ways that were not possible before [63].

2.7.1 Features and Performance Enhancements in nTopology 3.0:

Much faster than the previous version, nTopology 3.0 accelerates the design of parts and products. Released more improved latticing workflows, better topology optimization tools, expanded engineering simulation, and refined design automation will help speed the path from engineering problem to engineering design fix. Most notably, thanks to the innovation of GPU acceleration even more, the workstation will now instantly regenerate the complex geometry PDF and come to life [64].

2.7.2 File Compatibility and Workflow Integration:

In addition, another feature that makes nTopology stand out is its comprehensive support of files of various types, enabling users to freely import and extract what they need to and from other aspects of their engineering work. These include CAD file formats such as STEP, Parasolid, CATIA, mesh file types including STL, OBJ or CAE files that can be saved in Abaqus or ANSYS format. Therefore, this makes product use more convenient and more easily adaptable to other engineering implementation [63].

2.8 Photoresists:

A key role in photolithography is assigned to photoresists, necessary to create structures at the micro- and nanometer scale. They are sought to be made sensitive to light of certain lengths, upon exposure of which the solubility of the material changes and it can be removed in the selected area of the substrate. This method allows us to create drawing patterns on the surface of the substrate, the formation of which is intended for the production of semiconductors, MEMS, and any other nanotechnology.

2.8.1 Use of Photoresists in microFAB-3D:

Microfabrication in three dimensions (microFAB-3D) is a godsend due to its dependence on photoresists, for one can create very complex 3D objects with high precision, layer-by-layer. Photoresists allow making detailed 3D microstructures thanks to advanced photolithography methods, such as stereolithography or two-photon polymerization. Modern manufacturing processes show evidence of how useful and crucial photoresists are by using these technologies in multiple fields, including biomedical engineering, microfluidics, and optoelectronics.

2.8.2 Photoresist type used in microFAB-3D:

The selection of photoresists for microFAB-3D application is undertaken or comparatively depends on unique requirements such as sensitivity, solution, mechanical properties, and biocompatibility. Photoresists mentioned are specialized examples having a wide variety for various fabrication requirements:

OrmoGreen is a prototype meant for high-resolution direct laser writing with green laser and its ideal for two-photon polymerization meant for precise 3D structuring. **Ormocomp** is a hybrid photoresist with unique optical qualities, mechanical stability, and biocompatibility; also, it can be used to produce micro-optical elements meant for biomedical devices**.** **Rigid-A** is meant for application scenarios needing high mechanical strength and stability such as MEMS fabrications. **Green-A** is fine-tuned for a green laser and, therefore, it enables fabrication of finely detailed structure with a significant aspect ratio. This is **Green-Gel** with similar functionality as **Green-A** but it is specifically designed for gel-like applications and process flexibility. **Ormobio** is a bio-friendly type of photoresist giving high resolution for bio-compatible microstructure. The **Green-A-Bio**

is bio-friendly than before and is meant for biomedical applications requiring a bio-friendly microstructure with precise 3D structuring with a green laser. **Rigid-E** features higher rigidity than the earlier photoresists hence suited for sustainable microstructures. **UV-Gel** is UV sensitive and has a gel-type of photoresist optimized for UV lithography application needing flexible material qualities. The **Ormored** is known for its durability and clarity, and it is meant for the most challenging microstructure and microfabrication applications technologies. **Flex-A** is flexible and hence suited for microstructures that need integrated bending capabilities. The list of photoresists presented in the overview on the most suitable and diverse range for microFAB-3D. Keynote solutions [53][51].

2.9 OrmoComp:

OrmoComp is a "hybrid" polymer; it cures under UV light and becomes a material comparable to glass. This affordability makes OrmoComp perfect for the microfabrication of inorganic optical elements and microsystems because it is more transparent near UV and visible light with a wavelength area of 350 nm or more. It is characterized by large thermal and mechanical stability; OrmoComp can be subjected to 270°C for a short period of time. In addition, it is feasible to make structures less than 100 nm from this, which makes this polymer excellent for the most intricate microfabrication duties. Research conducted by Ju et al. indicated that the syntheses of OrmoComp and PDMS could be applied optimally both. Plasma processing greatly enhances the connection between OrmoComp and PDMS; the degree of surface PDMS hydrophilicity increases, which means these materials will be able to attach better to each other. The end product does not disintegrate under conditions of severe bending and compression, still diligently attached to the PDMS base [65]. The properties of the OrmoComp photoresist shown in the Table 2.

Table 2: Properties of OrmoComp [66].

Parameters	**OrmoComp**
Solvent-free	Yes
Viscosity [Pa·s]	2 ± 1
Spectral sensitivity [nm]	300 – 410
Volume shrinkage during UV curing [%]	5 – 7
Film thickness upon spin coating [µm] 3000 rpm 6000 – 1000 rpm	20 10 - 60
RI @ 589 nm, 25 °C, cured	1.520
dn/dT (589 nm) [10-4/K]	-2.0

2.10 OrmoDev:

OrmoDev is a developer used in the hybrid polymer sector. Its most crucial function is the eradication of uncured hybrid polymer substances as part of a process like mask lithography [67]. The uses of the substance include long-range substrate conformal imprint lithography; two-photon laser lithography used for active microcavity formation; and bio-inspired microneedle creation for drug/vaccine application improvement [68][69][70].

OrmoDev is solvent compatible, including isopropanol and methyl isobutyl ketone used during dye mixing and extrapolation with OrmoComp polymer. The functionality allows the making of tailored macroporous solutions [69]. OrmoDev, yet again, finds its way in laser manufacture, used to align the focal spots on the opaque substrate aiding in the structure-applying process [71].

2.11 FR-4:

The most common dielectric material for printed circuit boards is FR-4. “FR” stands for flame retardant, and “4” stands for woven glass-reinforced epoxy resin. To be more precise, the FR-4 dielectric constant can range from 3.8 to 4.8 simply based on the glass weave type, thickness, and the resin content. It is used in most electronic devices, ranging from small consumer electronics to the largest industrial systems. Even if the exact properties of FR-4 will vary from manufacturer to manufacturer, the main advantages of using FR-4 is that the material is low cost, the dielectric strength is over 300 volts per mil, the material is mechanically tough, and is able to carry loads while wet and has a value of higher moisture resistance and a glass transition temperature over 290 degrees Celsius, and the state of decomposition at 560 degrees Celsius [72].

2.12 KEYENCE Microscope:

The KEYENCE microscopes, designed for precise imaging and versatile measurements, are used for various industries, including electronics, semiconductors, and biotechnology. In the research, the Keyence Microscope VHX-S750E has been utilized to take pictures of all the specimens under high magnification. The sample should only be placed on the stage after which all the other consecutive steps, such as alignment and focusing adjustment, magnifying the image, and other processes, are executed automatically. This allows individuals even with little experience to carry out an in-depth observation of one's selective desired area easily. Other measurements can be performed or obtained directly on the screen using a simple hand mouse method. It includes measurements of two-point distances, angles, diameters, parallelization, and areas. In addition, it has a high-speed image stitching capacity that accumulates six times greater data than existing technologies. Lenses such as VHX-E20, VHX-E100, and VHX-E500 likewise helped in detailed study and photography [73].

Figure 2. 5: Shows a setup of Keyence Microscope 7000 series.

2.13 S11 Parameters of Antenna:

S-parameters are important for assessing and improving the performance of RF circuits, such as antennas. It defines the relationship between incoming and outgoing signals through different ports in a circuit. S11 reveals the reflection coefficient, which is the proportion of the power reflected backward mostly by the antenna. Thus, S11 is always important in the assessment of the antenna with respect to reflection, impedance matching as well as radiation. For this reason, S11 helps to establish whether the antennas can efficiently radiate the electromagnetic wave or absorb the same. The S11 values that are small correspond to the best matching and efficiencies. It is important to note that S11 is a function of frequency, and it is described using complex numbers associating magnitude and phase. The engineers utilize vector network analyzers to optimize the antenna design to increase radiation capability and improve impedance matching condition, and this is achieved by striving for the optimal criterion for radiation pattern and impedance matching. Indeed, one of the optimization targets in antenna development is to optimize S11. Possible means of achieving this can be through changes in physical structure, selection of material, or matching network to shift the impedance of the antenna to the optimized limit. Usually, the ideal S11 in this case should lie below -10dB; hence the array should only reflect 10% of the power and lower.

Chapter 3

Methodology of THz Antenna Design, Simulation and Fabrication

The chapter talks about the creation of a THz antenna, which is vital for more revolutionary high-speed wireless communication in the future. This chapter will explain software simulating and designing the creation, materials needed and finally the entire process of its creation.

3.1 Design principles of THz Antenna:

Antennas for the terahertz range, from 0.1 to 10 THz, a frequency range, due to the high frequency of interactions and small wavelength, have their specific design principles and require consideration. At the same time, the need for the development of such antennas for a variety of applications, including spectroscopy, imaging, and ultrafast wireless communications. Thus, we will introduce some basic principles of antenna structure, along with explanations and equations.

I. **Size and scaling:** In general, the physical size of an antenna is inversely proportional to the operational frequency, and at THz frequencies, wavelengths are so middling that the antenna dimensions must also be mart.

The equation for wavelength is,

$$\lambda = \frac{f}{C} \quad \dots \dots \dots \dots \dots \dots \dots (i)$$

where, c is the speed of light (≈3×10^8 m/s), and f is the frequency. This means THz frequencies will yield λ ≈ 0.3mm to 3mm for f ranging from 0.1 THz to 1 THz.

II. **Materials selection:** Scales and frequencies small enough to make THz antennas practical demand materials with high conductivity and low dispersion. Although metals like gold or copper are common at these scales, photonic materials and graphene are other materials used for specialized reasons.

III. **Bandwidth.** One of the primary reasons for the higher bandwidth of THz antennas as compared with ones of lower frequency is their small physical size. A possible reason is that the relative bandwidth is relatively higher at higher frequencies, given the equation is being,

$$Bandwidth = F_1 - F_2 \quad \dots \dots \dots \dots \dots \dots \dots (ii)$$

Where, F1 and F2 are the lower and upper frequency limits of the antenna, respectively.

IV. **Radiation Pattern:** As THz frequencies propagate through free space with high losses, a THz antenna's radiation pattern should be designed cautiously to focus and scatter the energy most resourcefully. The utilization of beam steering and focusing is a conventional application in THz antenna arrays.

V. **Efficiency and Gain:** Because of the high propagation losses at high frequencies, efficiency and gain are also essential for THz antennas. The usual design approaches include shaping the antenna or structuring it to enhance its gain or directivity.

***Formula**: Antenna Gain G,*

$$G = 10\log\left(4\pi * \frac{Radiated\ Power}{Input\ Power}\right) \quad \dots\dots\dots\dots\dots\dots\dots (iii)$$

The following formula shows a gain in dB which is the ability of the antenna to convert the input power to RF energy directed in a given path.

VI. **Integration and Fabrication:**

Integration with other components such as sources, i.e., THz generators, and detectors is more important at THz frequencies because of the smaller antenna size and greater system sensitivity. This Process fabrication is usually based on microfabrication.

VII. **Impedance matching:**

Finally, it is important to ensure that the antenna and the transmission line have the greatest possible impedance matching. With THz frequencies, even small mismatches will lead to significant losses.

Equation: *Reflection Coefficient Γ*,

$$\Gamma = \left(\frac{z_A - z_L}{z_A + z_L}\right) \quad \dots \dots \dots \dots \dots \dots \dots (iv)$$

Where, ZA is the antenna impedance and ZL is the load or line impedance.

3.2 The main Design Criteria of Monopole Antenna:

In this regard, the design of a monopole antenna – a single rod or conductor placed over a ground plane – involves design criteria to ensure its optimal performance in the camouflage – based applications. The criteria include:

1. **Antenna length:** This is about one quarter of the wavelength (λ/4) of the target destructive frequency. This length makes the antenna resonate at that frequency thus, making it radiate optimally.
2. **Ground Plane:** A sufficient ground plane is also important. It acts as a reflector, enabling radiated signals from the antenna. Although the practical size and shape

depend, the ground plane should extend at least λ/4 in all directions from the base of the antenna. A larger, more conductive ground plane is generally better.

3. **Impedance Matching:** The impedance of a monopole antenna is generally about 50 ohms, which is well-matched with typical transmission line and equipment standards. Impedance matching is very imperative in satisfying signal reflections and in the adept of maximum power transfer from the transmission line to the antenna.
4. **Material:** Materials affect the efficiency of the antenna and also longevity. Some of the materials comprise copper, aluminum, and stainless steel. The commonly found attribute in all three materials is a high rate of conductivity. The frame has to be strong enough to avoid environmental challenges.
5. **Height above ground:** The amount of the antenna which is above the ground determines the radiation pattern and other characteristics. The height above ground can be manipulated to ensure that the radiation pattern is ideal for a given kind of application. In casting and broadcasting, the height above the ground can also be varied to change the angle of the radiation for optimal coverage.
6. **Bandwidth:** Concerning bandwidth, monopole antennas usually have narrow bandwidth. However, the bandwidth can be increased by different methods, including thicker elements or additional loading coils or capacitive hats. These items allow the antenna to be efficient at a bigger frequency range.

7. **Radiation Pattern:** The radiation pattern of a monopole antenna is 360 degrees in the horizontal plane and has a null in the vertical plane, along the vertical axis of the antenna. Regarding this plane pattern, a monopole is omnidirectional, is proper for applications requiring vertical coverage reaches the sky or decays toward the ground due to radiation inefficiency, while in the horizontal field, the coverage is constant because no energy is wasted in the vertical plane.
8. **Stability and durability:** the design must withstand the physical stress brought on by natural factors, including wind, fluctuation of acreage, and precipitation. Structural stability and weatherproofing are required to ensure that the consequences remain regular over time.
9. **Mounting and Installation:** The design of the antenna should be such that it is easy to install and maintain. It should have a mounting mechanism that ensures the antenna is securely mounted in place and also adjusts the position of the antenna with ease whenever adjustments are necessary.

3.3 Process Steps of the Study

In this thesis, a thorough investigation of the design, simulation, fabrication, and characterization processes of a terahertz (THz) antenna is presented, with specific attention to the manufacture of its sub-wavelength microstructure. The beginning of the journey starts with conceptual design using Ansys HFSS — an advanced simulation tool enabling prediction of electromagnetic behaviors necessary for optimization of performance parameters of the antenna. This simulation was conducted to show that the design meets the strict accuracies that are required for THz applications.

After the simulation is complete, the design is taken into nTopology software, where it is redesigned and prepared for fabrication. It is one of the most important conversions as it keeps the design integrity straight and represents accurately the simulated expectations within the physical system model.

The fabrication of the antenna is based on two-photon polymerization, an advanced technique best suited for creating the well-defined microstructures needed in the THz range. After fabrication, Ormodev performs post-processing on the antenna to fine-tune its features for optimal performance. Using a SEM Coating Unit, the last stage involves applying a special coating to get it ready for more thorough analytical investigations.

Finally, the thesis presents a detailed study of the 3D-printed antenna using microscopes to capture the exquisite details of the print and evaluate the print against the simulated design. Such a detailed methodology not only showcases the possibility of utilizing 2PP for THz antennas but also provides a reference for future work in the field. The process model below (Figure 3.1), represented in the accompanying diagram, details each step in the workflow, from conceptual design to empirical validation.

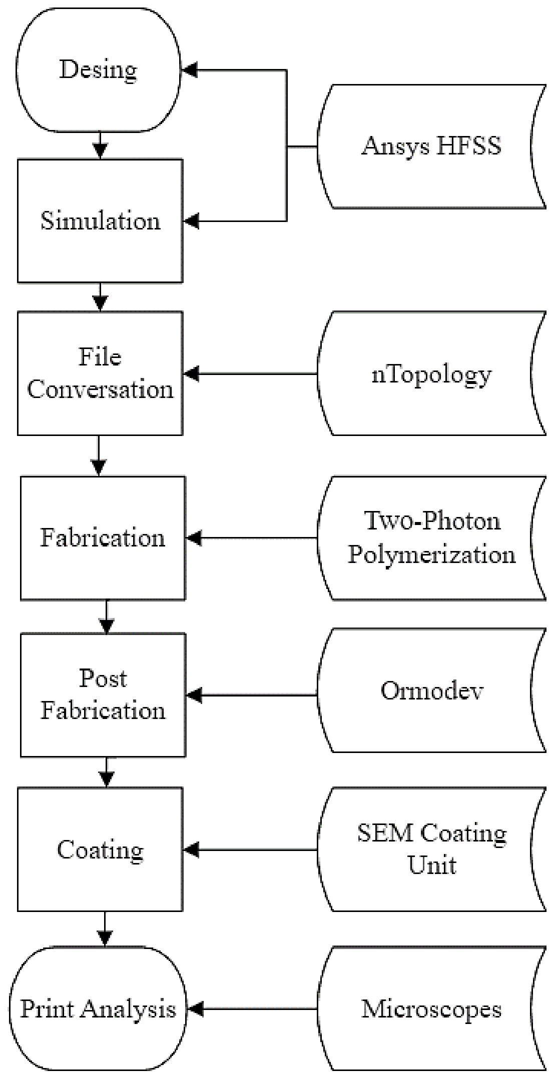


Figure 3. 1: The process model of the work

3.4 Design and Simulation Specifications for THz Monopole Antenna in HFSS:

Throughout the study, the THz monopole antenna was designed through the software called Ansys HFSS in terms of some specific dimensions and material parameters. The designed whole structure in terms of width and depth is 0.25mm and the height is 0.440mm. The whole designed structure includes the ground plane, the substrate, the feed line, a vertical stick comprising a chain of tori as the main rod of monopole and a top rod. The ground plane is a mirror size of the whole antenna while the substrate size is 0.25mm by 0.25mm by 0.01mm, made of FR4 epoxy. The copper feed line is fabricated upon the substrate and its size is 0.02mm by 0.145mm by 0.0025mm. The biggest difference in the design is the vertical stick which is 15 long copper tori where seven tori are designed in x-direction while eight in Y-direction as shown in Figure-3.2. The torus is made of copper with a minor radius of 0.006mm and a major radius of 0.015mm. The last top rod is also of copper material whose size is 0.02mm by 0.05mm by 0.01mm. Figure 3.2 demonstrates the whole graphical design in the HFSS software and the various parts of the antenna.

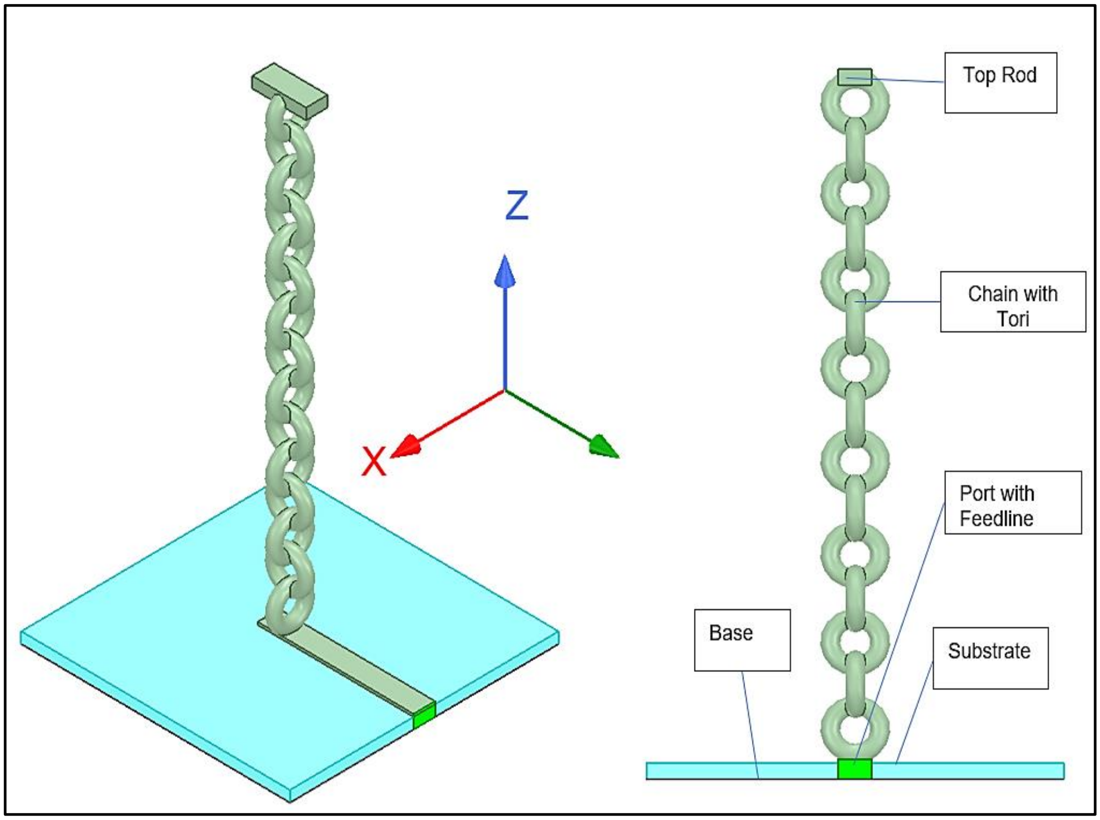


Figure 3. 2: Graphical representation (Left) and different components (Right) of THz monopole antenna from HFSS.

The electromagnetic simulation is set up with the help of a lumped port interface placed arbitrarily close to the edge of the ground plane and the spot to which the feed line is connected to it, in such a way to retain its input port's impedance to 50 Ohm across the spectrum. The antenna is simulated via a sweep running from 50 GHz to 4 THz with interpolating sweeps applied to streamline the anticipatory optimization. Such parameters of functionality are sufficient to carry out an in-depth investigation of the subject and objectively analyze its active domain, which is why they are balanced for parametrization in a more extended frequency spectrum so that they can be honed and adjusted for a sharper performance within the THz domain.

3.4 STL File Creation:

Once we designed and simulated the terahertz antenna, we saved the design files in an AEDT format. Before we can begin printing using the 2PP technology, we need to convert these files to an STL format, that is used with 3D printers. This conversion process was performed with the help of nTopology software, which not only imports those models but also further develops an optimized design. A mesh tolerance of 0.001 mm was used to fully capture all fine-level details of the antenna design, shown in Figure 3.3. This exacting precision is essential for the physical model to faithfully replicate the simulated behavior. The design: Once the design was successfully narrowed and the meshing completed, the next step was to generate an STL file. This serves as the last digital blueprint for the manufacturing stage. Now that we have an STL file, the next step towards bringing our simulated model into reality is via 2PP printing which allows us to fabricate the physical prototype of our designed antenna.

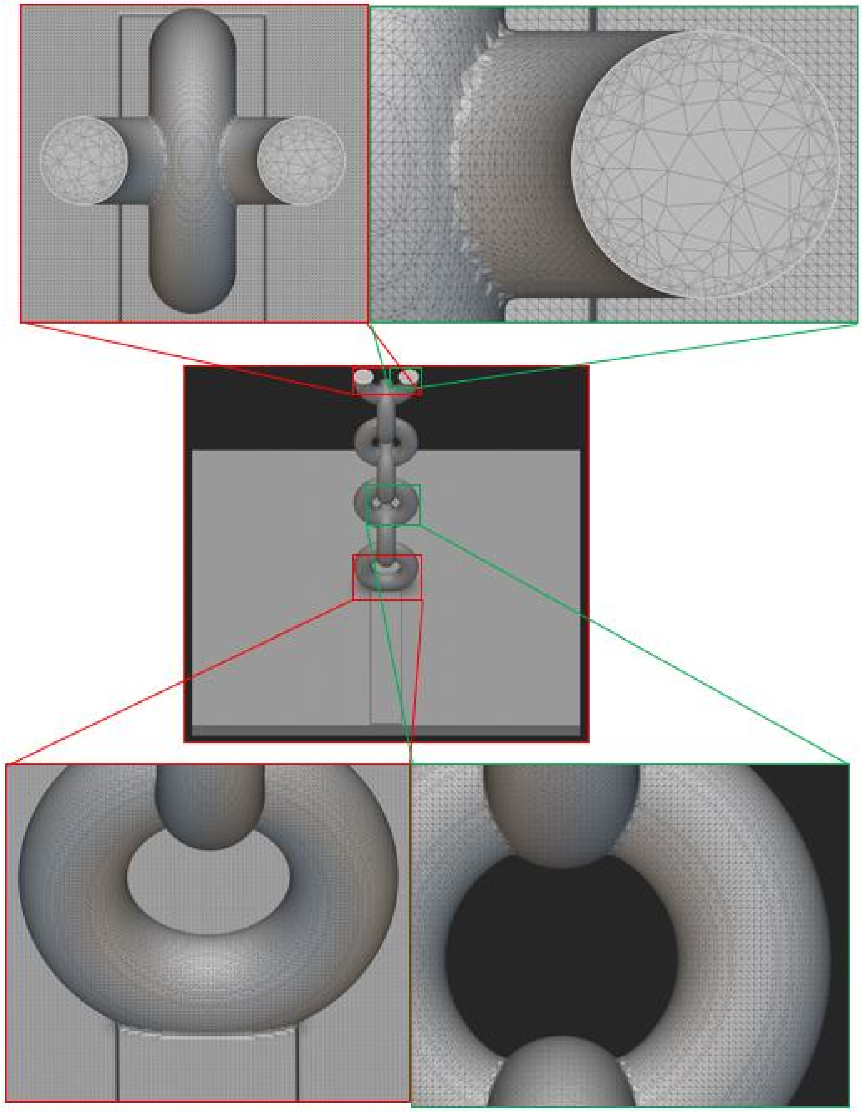


Figure 3. 3: Section cut view of the designed THz antenna in nTopology with inside and outside mesh

3.5 Fabrication of THz Antenna Using 2pp:

We used the MicroFab-3D (MicroLight 3D) machine in our work to print high-resolution three-dimensional structures using its proven two-photon polymerization method. Using a 20x objective lens and its green laser, the terahertz (THz) antenna was constructed, which able us to precisely fabricate the antenna structures with respect to 0.2 microns and also allowed us to retain tolerance for the design requirements [74][75]. Ormocomp was used as the photoresist material in this method because of its exceptional optical qualities and stability, which are essential for attaining the fine detail required for high-frequency antenna operation [76].

The fabrication of a terahertz antenna with two-photon polymerization involves three separate steps, which include: the setup of the 2PP system, the development of the printed antenna, and the application of the final coating. All the steps throughout the total fabrication process explained below:

1) Setup of 2PP System:

The 2PP setup is the most critical elements that determine the successful fabrication of THz antennas. The process has been divided into two parts:

a. **Sample Preparation:** Preparing the sample for 2PP involves several precise steps:

- **Sample Holder Setup:** Begin by securing the base coverslip, which measures 24x24 mm, onto the sample holder using two screws. This ensures the base coverslip remains stable during the printing process.

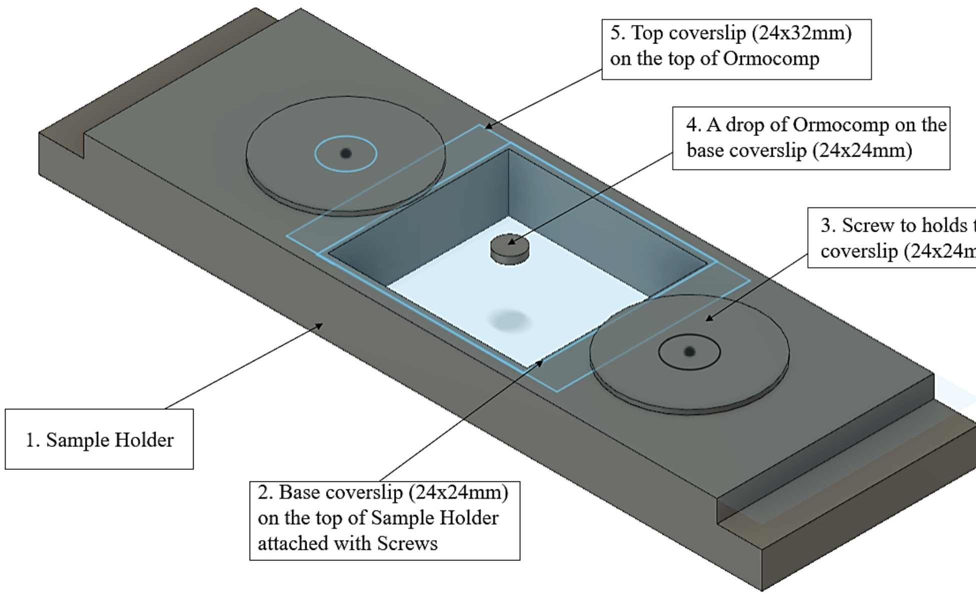
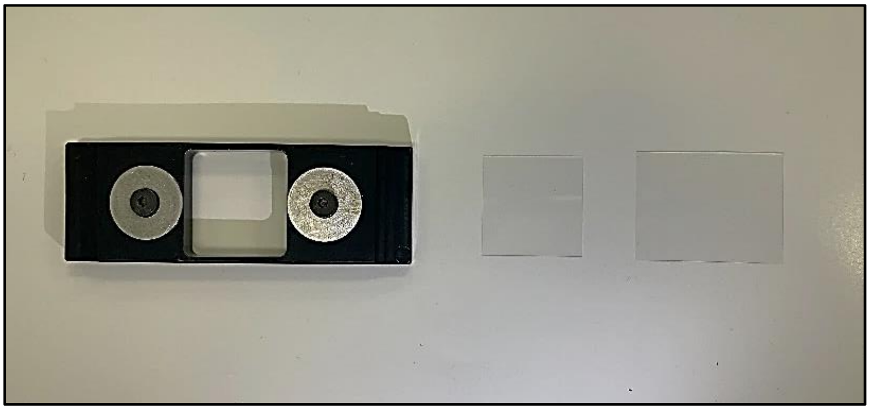


Figure 3. 4: Graphical representation of the complete setup of sample preparation

- **Photoresist Application:** Apply a drop of Ormocomp photoresist onto the base coverslip. Carefully place a top coverslip, sized 24x32 mm, over the drop to spread the photoresist evenly between the two coverslips. This arrangement prepares the sample for detailed antenna fabrication. Ensure that there are no air bubbles, and the photoresist layer is uniform. The complete setup of the sample preparation graphically shown in figure 3.4

and also the figure-3.5 in the below, shows the actual equipment (Sample holder, Base coverslip (24x24mm) and Top coverslip (24x32 mm)) need for sample preparation.



(a) **(b)** **(c)**

Figure 3. 5: (a) Sample holder, (b) Base coverslip (24x24mm), (c) Top coverslip (24x32 mm).

b. Software Configuration:

Software settings are a set of self-configurations that is installed to a specific program on the 2PP machine, namely the Luminis. The settings involve a few critical steps in ensuring that one optimizes the printing parameters.

I. **Settings of position and size:** after importing the antennae design the Luminous software, one must ensure that the design is positioned within the positive coordinates. However, size is to be fine-tuned according to the original designed specifications in nTopology to ensure that the scale is replicated accurately.

II. **Slicing direction:** The slicing direction determines the success of the given print. For the substrate, one selects an X slicing direction while the chain is Z. This is specifically chosen according to the specific requirement of the one taking into consideration them to confirm the structural analysis of play. After setting up the position and slicing the design the antenna structure shown in the figure 3.6 below.

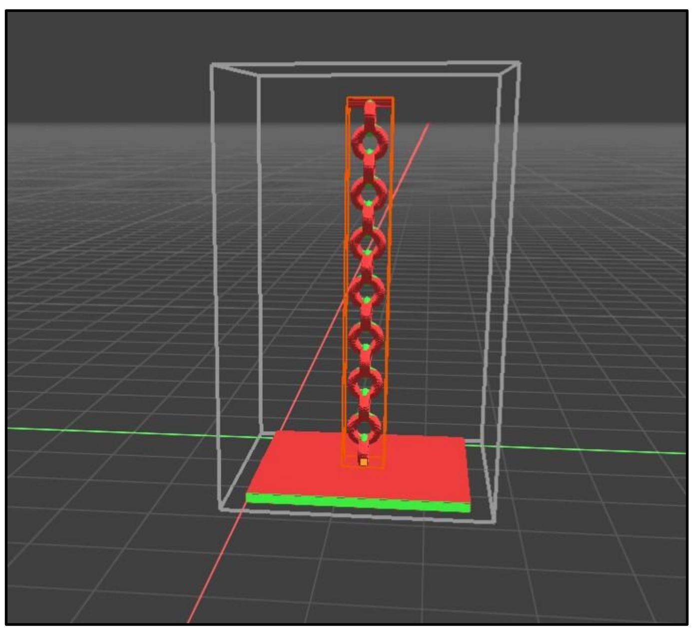


Figure 3. 6: Graphical representation of THz antenna after position setting and slicing in Luminis

III. **Power and speed of laser:** The laser power and speed are to be adjusted according to the slicing direction and the photoresist used in printing. The laser percentage is set to 16 while the speed is 85um/s, and for the chain, one set to 17% and 90um/s.

IV. **Ways of printing:** Due to the nature of the chain and complex structure of the design, selected the upside-down printing. The selected way plays a critical role in selecting the type of design that can be selected.

V. **Finding Focal Points:** Before starting the print, regulate the focal points – four critical points must be identified for proper printing, specifically when working through upside down – it is at the intersections of air to the top coverslip, top coverslip to photoresist, photoresist to base coverslip, and base coverslip to air. The third focal point, where photoresist meets the base coverslip, is crucial – that is where the print starts.

Figure 3. 7: Shows complete setup of the 2PP machine during fabrication in the Lab

2) Developing Printed Antenna: Next, once the THz antenna is successfully fabricated by 2PP, it is gently removed from the sample holder and moved to the development phase. The THz antenna is then placed in Ormodev, a development solution ideal for use with 1:1 Isopropyl alcohol and Methyl isobutyl ketone, thanks to efficient removal of the unexposed photoresist, thereby maintaining clear features of the exposed antenna. According to the experiment, the THz antenna is maintained in the solution for 12–15 minutes to remove all unexposed photoresist fully while maintaining all lines and curves of the antenna. Figure-3.8 illustrate the equipment and chemical needs during developing antenna.

(a) **(b)** **(c)**

Figure 3. 8: (a) OrmoDev (b) Petri dish (c) Plastic Forceps.

Finally, following the development duration, the antenna was withdrawn from the Ormodev solution and dried under standard air conditions for approximately 30 mins. Drying is vital as it facilitates the evaporation of the solvent, hence solidifying the structural implementation of the antenna, hence allowing it to be used and integrated into additional stages of fabrication. Careful implementation and processing are needed to guarantee this antenna produces the design criteria and achieves optimal performance in its intended functions.

3) **Coating:** Following the development phase of the THz antenna, a conductive coating was applied using a SEM coating unit, model E5100. Gold-palladium alloy was chosen for this process since it had significantly higher conductivity and also improved imaging characteristics. The antenna was then carefully situated inside the vacuum chamber of the E5100 unit so that a high vacuum is maintained to enable the sputter coating process. Gold-palladium targets were used, and plasma was created from argon gas to allow ion bombardment to detach atoms from the target surface. Specifically, these atoms were then sputtered onto the antenna surface in a uniform fashion to form a thin, conductive layer. The gold-palladium composite improved the electrical properties of the antenna and also its imaging under electron microscopy, which facilitated comprehensive analysis and quality check.

Chapter 4

Result and discussion

The chapter presents the results of the simulation of the monopole THz antenna in ANSYS HFSS and the fabrication results from the two-photon polymerization technique. The allowable metrics for the performance of the antenna as simulated and the practical results of its 2PP fabrication are necessary for verifying the design and future improvements.

4.1 Simulation Results:

The simulation of the monopole THz antenna was carried out in a detailed manner using ANSYS High Frequency Structure Simulator. As such, detailed genius on the parameters that are paramount for its optimal performance in THz-oriented applications was generated. It also provides the simulation of the frequency response, radiation patterns and polar plot supported with the graphical data generated during the simulation.

4.1.1 Frequency Response:

The THz monopole antenna exhibits high impedance matching from 0 to 2 THz band, which is critical in maximizing the power transfer for the terahertz applications as determined through ANSYS HFSS simulations. The low level of power reflection, indicated by the mostly negative S11 parameter values (often less than -10 dB), results in low power loss during transmission. For the frequency of 0.2080 THz, S11 is observed -25.0072 dB, suggesting almost ideal impedance matching, which means the power transmission and radiation are both largely completed. The S11 parameter is at -10.3984 dB at 0.5339 THz, which means that about 90.14% of the power being applied is utilized, see Figure 4.1.

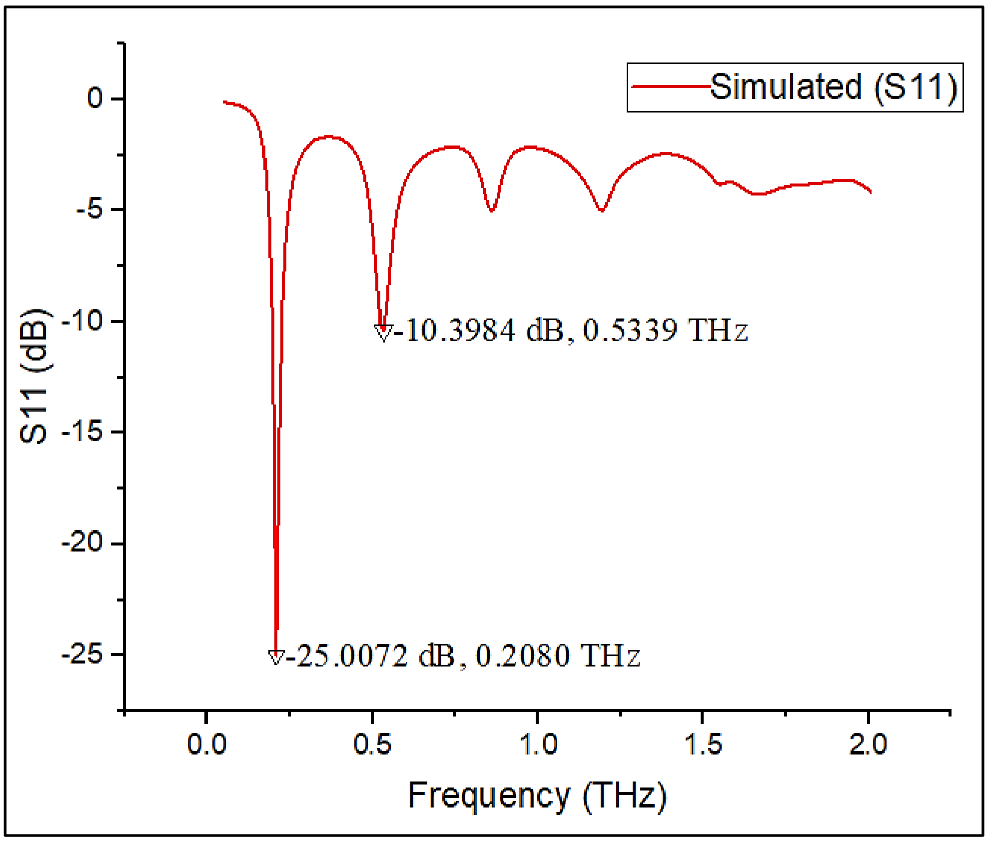


Figure 4. 1: S11 Graph (0.0 – 2 THz)

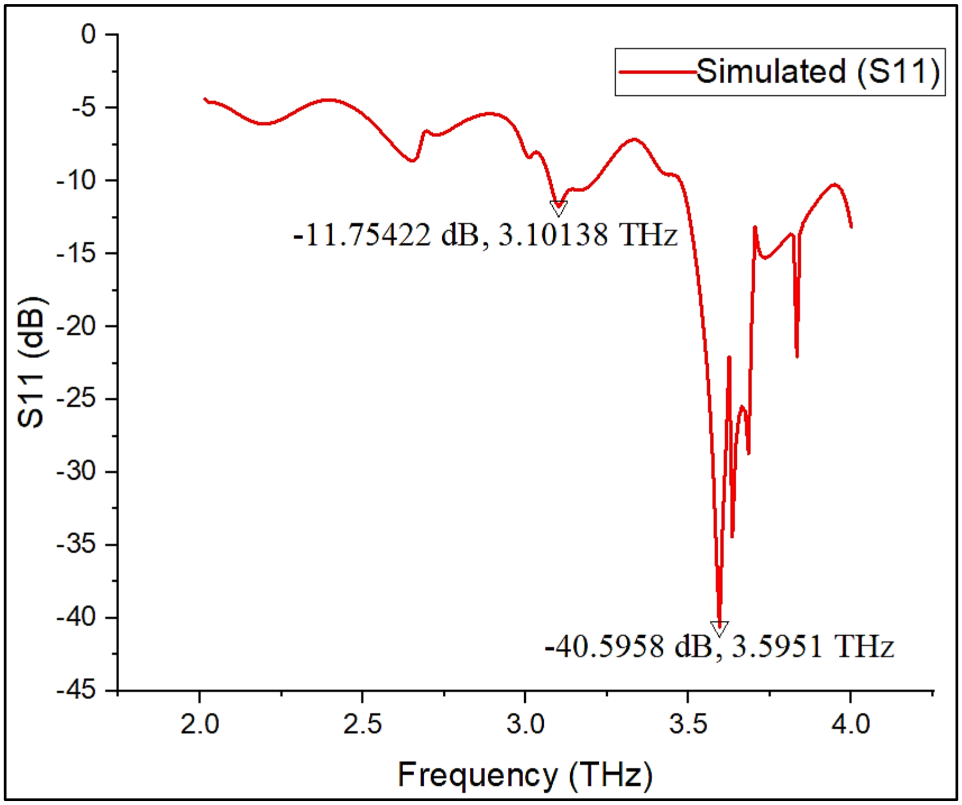


Figure 4. 2: S11 Graph (2 – 4 THz)

As it further reveals Figure 4.2, demonstrating that the antenna response remains high at 2 through 4 THz. Also in this frequency range, an S11 value of -11.75422 dB is obtained at 3.10138 THz demonstrating satisfactory performance at higher frequencies as well, in which about 93.32% is effectively used. That said, the efficiency of the antenna at higher frequencies remains apparent throughout. An S11 of -40.5958 dB at 3.5951 THz showcases strong power absorption with effectively zero power reflection, leading to great impedance matching and prolonged high efficiency throughout a significant fraction of the terahertz spectrum.

4.1.2 Radiation Pattern and Polar Plot:

The radiation pattern is another outcome of the analysis to present how the monopole antenna radiates energy in different directions, where this graph (in Figure 4.3) shows how the radiated pattern at 0.11171875 THz. The most notable feature in this pattern is the significant radiation in the forward direction indicated by the peak gain at nearly 0 degrees. Such high level of radiation in the direction of the source is a feature that characterizes the monopole antennas, since they generate the radiation with good directivity and high efficiency towards the source direction.

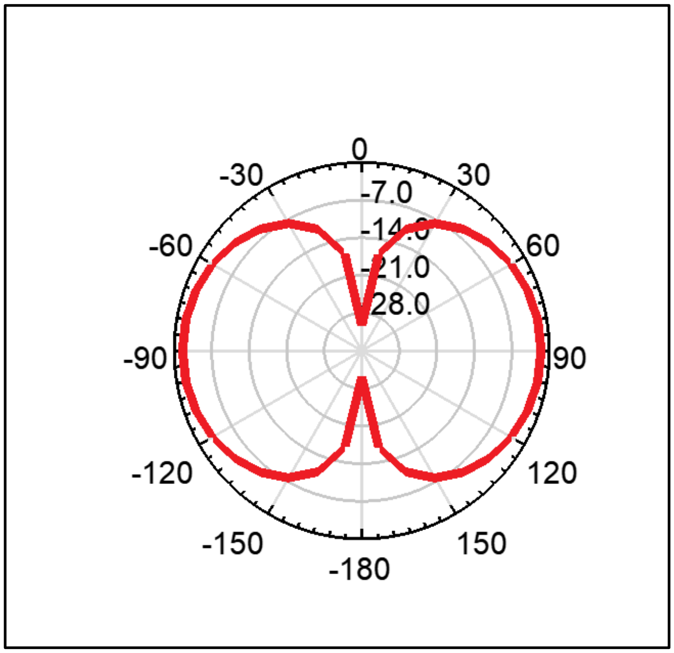


Figure 4. 3: Demonstrates the radiation pattern of the monopole THz antenna at 0.11THz.

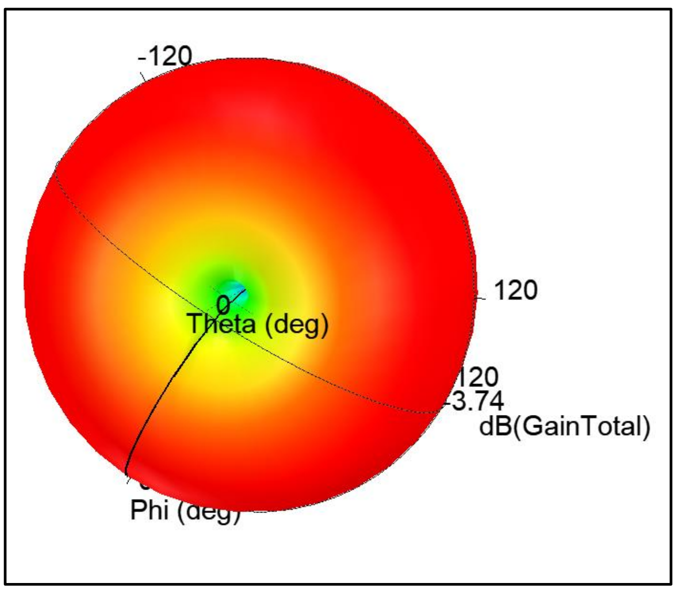


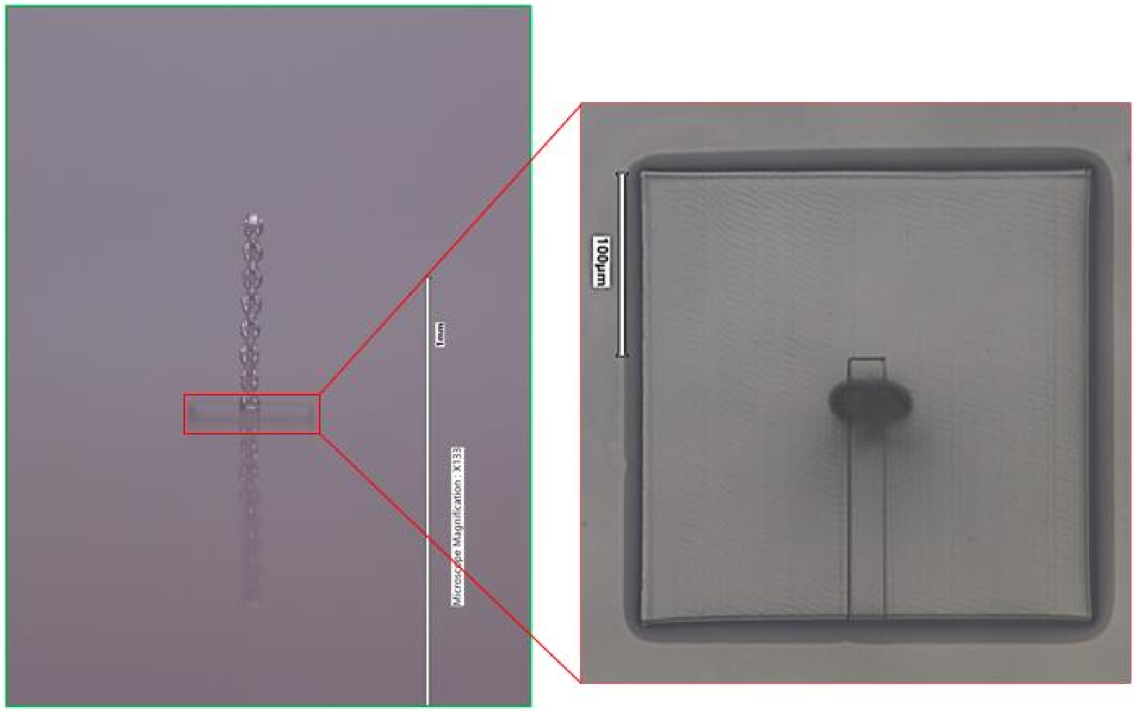
Figure 4. 4: Polar plot of THz antenna.

This polar plot (in the figure 4.4) for the THz monopole antenna offers critical understanding of how the directional radiation of the monopole antenna is working and the efficiency at varying angles. The color with a transition from warm to cool colors ultimately allows visually encoding the gain of the antenna in the plot. In other words, the gain may be defined as the level of volume at which the antenna can work in terms of radiating the signals or also receiving the signals at varying angles. The plot is critical in demonstrating the possibility of focusing energy on certain directions using the antenna. Such ability is critical in applications that need a certain direction of radiation patterns to remain optimal. The application is also instrumental in ensuring minimal interference from the unwanted directions.

4.2 Fabrication Results

The primary printing parameters for fabricating the THz antenna using two-photon polymerization (2PP) technology were derived from experimental results. We effectively printed the substrate and feed line at a laser power of 16% and a speed of 85 μm/s in the X slicing direction, while the chain and top rod were printed with a laser power of 17% and a laser scanning velocity of 90 μm/s for Z-slicing, based on numerous experimental trials. For post-processing, the antenna was immersed in a 1:1 diluted solution of Ormodev in a mix of isopropyl alcohol and methyl isobutyl ketone to remove unexposed photoresist residues effectively. Our tests determined that the best duration for immersing the antenna to remove unexposed photoresist without harming its structure is between 12 and 15 minutes. It was noted that varying from this precise timing could result in damage or the loss of delicate structural features.

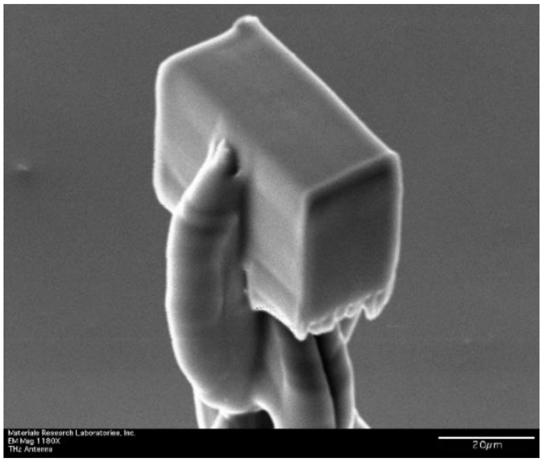
After the completion of the fabrication and development of the THz monopole antenna, we had to check its structure. For this reason, we used a Keyence Microscope 7000 series. Checking the antenna's structure is required to test its fabrication quality. The results of the check showed that all the structures of the antenna were correctly printed, as depicted in figure 4.5.



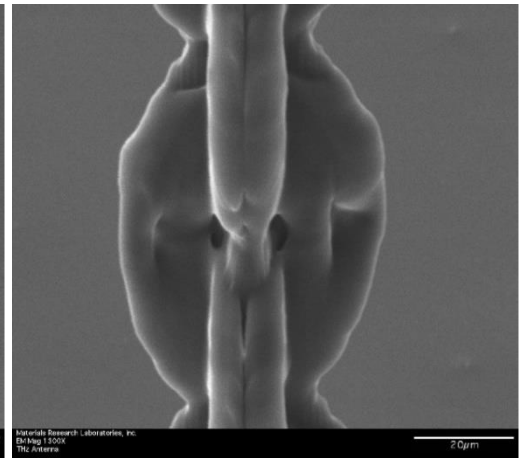
(a) **(b)**

Figure 4. 5: Picture of (a) Chain, (b) Substrate and feed line from Keyence Microscope.

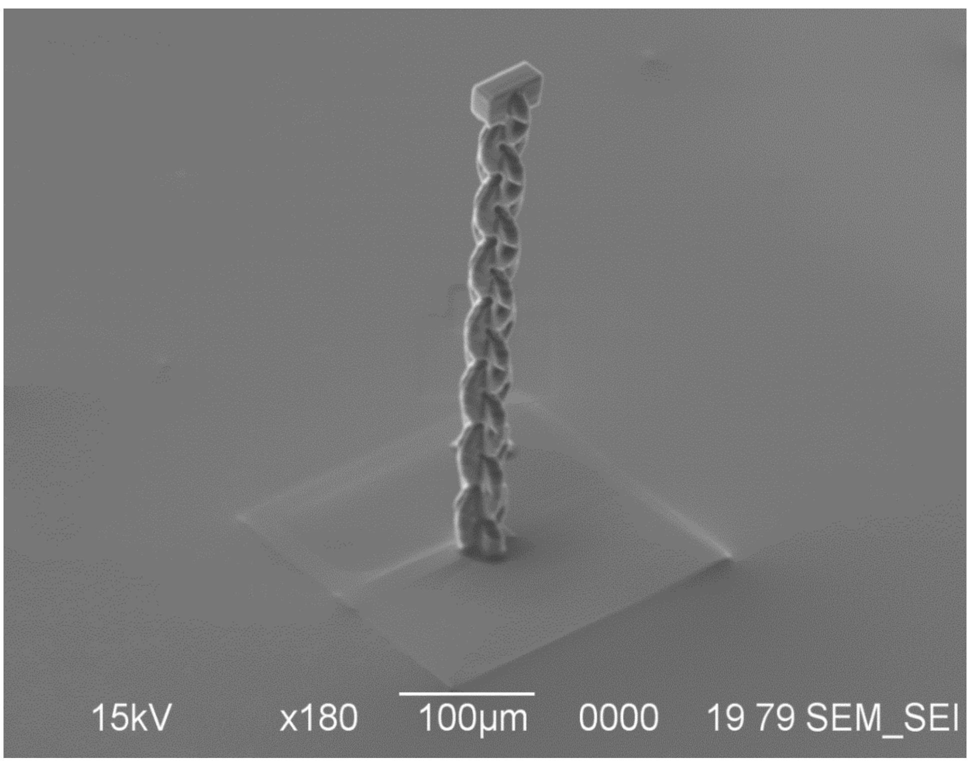
After the successful check of the structure, we applied a special coating to the antenna using the SEM coating unit, model E5100. This step was required to allow us to take pictures of the antenna's surface. After coating, we took detailed pictures of the antenna structure using the Keysight 8500 FE-SEM microscope. Figure 4.6 shows all the fine details and the finer Pictures of the whole antenna structure.



(a)



(b)



(c)

Figure 4. 6: Pictures of (a) Top rod, (b) Ring, (c) Whole Fabricated THz antenna structure from Keysight 8500 FE-SEM microscope.

Chapter 5

Conclusion and Future work

Conclusion:

Terahertz (THz) technology enables the future of communication, detailed imaging, and spectroscopy thanks to its ability to handle large amounts of data and penetrate various materials. However, there are obstacles like generating and detecting THz efficiently due to the signal loss during propagation, limitations in materials, complex integration processes, high costs and the lack of standard practices that potentially impede its progress. Overcoming these challenges calls for collaborative research efforts. Despite these hurdles the potential advantages such as using ionizing radiation and creating advanced communication systems highlight how THz technology could revolutionize future applications.

In this research we successfully developed and created a terahertz (THz) monopole antenna using design techniques and cutting-edge 3D printing method. The detailed design was carried out on Ansys HFSS, which involved creating a structure with measurements and material choices. The antenna setup included a ground plane, FR4 epoxy substrate, copper feed line, several copper rings and a copper rod on top all tailored for THz applications. The simulation outcomes displayed matching of impedance over a frequency range from 0 to 4 THz indicating efficient power transfer and high-performance levels. The simulated S11 parameters consistently showed reflection levels with values of -25.0072 dB, at 0.2080 THz and -40.5958 dB at 3.5951 THz confirming the antenna's reliable functionality.

The fabrication approach employs two-photon polymerization (2PP) technique for the required precision & resolution. High-resolution imaging methods validated the integrity of the antenna structure by fine-tuning printing parameters and applying special care during post-processing. This work demonstrates the preliminary insight into integrating simulation and 3D printing technologies to create high performing THz antennas in a rapid, scalable process. This work shows a novel approach to design and fabrication of complex THz devices which may be used for other types of innovative solutions beyond next-generation communication.

Future work

I. For this study, further improvement in the sensitivity and operability could be made for a fully functional THz monopole antenna. This can be potentially accomplished by reducing losses and improving THz response by enhances designs and use potentially use machine learning algorithms.

II. To be used more widely, the scalable and cost-effective fabrication processes demonstrated in this work need further development. Emerging additive manufacturing technologies that can give better precision in printing, with finer resolution and tighter control of crucial parameters will make it possible to develop more complicated, high-performance, and scalable structures.

III. In addition, one key study could be on how to fuse two different materials print simultaneously for a multi-material antenna.

REFERENCES

[1] V. Pacheco-Peña, "Terahertz technologies and its applications," *Electronics (Switzerland)*, vol. 10, no. 3. MDPI AG, pp. 1–2, Feb. 01, 2021. doi: 10.3390/electronics10030268.

[2] S. Lamsal, A. Uya, S. Itapu, F. X. Li, P. Cortes, and V. Borra, "Frequency selective asymmetric coupled-fed (ACS) antenna using additive manufacturing," *Memories-Materials, Devices, Circuits and Systems*, vol. 8, p. 100111, 2024.

[3] W. Shihzad, S. Ullah, A. Ahmad, N. A. Abbasi, and D. Y. Choi, "Design and Analysis of Dual-Band High-Gain THz Antenna Array for THz Space Applications," *Applied Sciences (Switzerland)*, vol. 12, no. 18, Sep. 2022, doi: 10.3390/app12189231.

[4] Y. F. S. M. H. Z. J. Z. A. G.-M. and M. N.-C. E. J. Y. Magaway, "Silica Nanoparticle-Based Photoresin for THz High-Resolution 3-D Microfabrication by Two-Photon Polymerization," *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 4, Jul. 2023.

[5] V. Borra *et al.*, "3D Printed Dual-Band Microwave Imaging Antenna," *ECS Trans*, vol. 107, no. 1, p. 8631, 2022.

[6] Z. H. Y. B. L. J. Q. L. X. F. Z. T. H. Q. H. Y. L. H. Z. Y. Li Xu, "High-Frequency Circuit Simulator: An Advanced Three-Dimensional Finite-Element Electromagnetic-Simulation Tool for Microwave Tubes," *IEEE Trans Electron Devices*, vol. 56, May 2009.

[7] J. A. Solano-Perez *et al.*, "On differential imaging using electromagnetic simulation for vehicular antenna signature analysis," *Sensors*, vol. 21, no. 11, Jun. 2021, doi: 10.3390/s21113796.

[8] A. E. Uya *et al.*, "Design and fabrication of terahertz (thz) antenna using aerosol jet printing," in *2023 IEEE 23rd International Conference on Nanotechnology (NANO)*, IEEE, 2023, pp. 157–161.

[9] A. Standaert, L. Brancato, B. Lips, F. Ceyssens, R. Puers, and P. Reynaert, "Three techniques for the fabrication of high precision, mm-sized metal components based on two-photon lithography, applied for manufacturing horn antennas for THz transceivers," *Journal of Micromechanics and Microengineering*, vol. 28, no. 3, Jan. 2018, doi: 10.1088/1361-6439/aaa74b.

[10] Z. Faraji Rad, P. D. Prewett, and G. J. Davies, "High-resolution two-photon polymerization: the most versatile technique for the fabrication of microneedle arrays," *Microsystems and Nanoengineering*, vol. 7, no. 1. Springer Nature, Dec. 01, 2021. doi: 10.1038/s41378-021-00298-3.

[11] A. J. G. Otuka, N. B. Tomazio, K. T. Paula, and C. R. Mendonça, "Two-photon polymerization: Functionalized microstructures, micro-resonators, and bio-scaffolds," *Polymers (Basel)*, vol. 13, no. 12, Jun. 2021, doi: 10.3390/polym13121994.
[12] X. Fu, Y. Liu, Q. Chen, Y. Fu, and T. J. Cui, "Applications of Terahertz Spectroscopy in the Detection and Recognition of Substances," *Frontiers in Physics*, vol. 10. Frontiers Media SA, May 12, 2022. doi: 10.3389/fphy.2022.869537.
[13] P. H. Siegel, "Terahertz Technology," 2002.
[14] K. Kawase *et al.*, "Image detection systems; (120.4290) Nondestructive testing; (190.4410) Nonlinear optics, parametric processes; (300.6270) Spectroscopy, far infrared," 2002. [Online]. Available: http://www.riken.go.jp/lab-www/THz/index.html
[15] J. F. Federici *et al.*, "THz imaging and sensing for security applications - Explosives, weapons and drugs," *Semiconductor Science and Technology*, vol. 20, no. 7. Jul. 01, 2005. doi: 10.1088/0268-1242/20/7/018.
[16] M. Tonouchi, "Cutting-edge terahertz technology," *Nat Photonics*, vol. 1, no. 2, pp. 97–105, 2007, doi: 10.1038/nphoton.2007.3.
[17] D. Mittleman, *Springer Series in OPTIC L SCIENCES*, vol. 85. 1999.
[18] D. Grischkowsky, S. Keiding, M. Van Exter, and C. Fattinger, "Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors," 2006.
[19] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum Cascade Laser," *Science (1979)*, vol. 264, no. 5158, pp. 553–556, Apr. 1994, doi: 10.1126/science.264.5158.553.
[20] B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," 1995.
[21] C. Stoik, M. Bohn, and J. Blackshire, "Nondestructive evaluation of aircraft composites using reflective terahertz time domain spectroscopy," *NDT and E International*, vol. 43, no. 2, pp. 106–115, Mar. 2010, doi: 10.1016/j.ndteint.2009.09.005.
[22] A. Islam, S. E. A. Himu, N. B. Amin, M. S. Kaoser, F. Abrar and M. R. Islam, "Pulmonary Artery Pressure (PAP) Prediction Based On Three Physiological And Seven ECG Signal Features", 2022 IEEE 3rd Global Conference for Advancement in Technology (GCAT), pp. 1-5, 2022 , doi: 10.1109/GCAT55367.2022.9972058.
[23] H. -J. Song and T. Nagatsuma, "Present and Future of Terahertz Communications," *IEEE Transactions on Terahertz Science and Technology*, Sep. 2011.

[24] Y. He, Y. Chen, L. Zhang, S. W. Wong, and Z. N. Chen, "An overview of terahertz antennas," *China Communications*, vol. 17, no. 7, pp. 124–165, Jul. 2020, doi: 10.23919/J.CC.2020.07.011.
[25] M. A. Jamshed, A. Nauman, M. A. B. Abbasi, and S. W. Kim, "Antenna Selection and Designing for THz Applications: Suitability and Performance Evaluation: A Survey," *IEEE Access*, vol. 8. Institute of Electrical and Electronics Engineers Inc., pp. 113246–113261, 2020. doi: 10.1109/ACCESS.2020.3002989.
[26] V. P. Wallace *et al.*, "Terahertz pulsed imaging of basal cell carcinoma ex vivo and in vivo," *British Journal of Dermatology*, vol. 151, no. 2, pp. 424–432, Aug. 2004, doi: 10.1111/j.1365-2133.2004.06129.x.
[27] F. Sizov and A. Rogalski, "THz detectors," *Progress in Quantum Electronics*, vol. 34, no. 5. pp. 278–347, Sep. 2010. doi: 10.1016/j.pquantelec.2010.06.002.
[28] M. M. Islam, A. G. Ranga, V. Borra, and D. G. Georgiev, "Copper tantalum nitride (CuTaN2) thin films prepared by reactive radio-frequency magnetron sputtering," *Appl Phys A Mater Sci Process*, vol. 130, no. 6, Jun. 2024, doi: 10.1007/s00339-024-07537-0.
[29] S. Itapu, V. Borra, and S. Selvendran, "Microstructuring of cobalt (Co) thin films by UV laser irradiation," *Applied Physics A*, vol. 129, Nov. 2023, doi: 10.1007/s00339-023-07147-2.
[30] V. Borra, D. G. Georgiev, and C. R. Grice, "Fabrication of optically smooth Sn thin films," *Thin Solid Films*, vol. 616, pp. 311–315, 2016.
[31] V. Borra, D. G. Georgiev, and V. G. Karpov, "Cultivating metal whiskers by surface plasmon polariton excitation," *MRS Adv*, vol. 1, pp. 805–810, 2016.
[32] V. Borra, O. Oudat, D. G. Georgiev, V. G. Karpov, and D. Shvydka, "Metal whisker growth induced by localized, high-intensity DC electric fields," *MRS Adv*, vol. 3, no. 57–58, pp. 3367–3372, 2018.
[33] S. Devkota *et al.*, "Threshold Switching in CdTe Photovoltaics," *ECS Trans*, vol. 109, no. 1, p. 3, 2022.
[34] S. Devkota, B. M. Kuzior, V. G. Karpov, D. G. Georgiev, F. Li, and V. Borra, "Percolation Nature of Threshold Switching: an Experimental Verification," in *2023 IEEE 23rd International Conference on Nanotechnology (NANO)*, IEEE, 2023, pp. 1–5.
[35] V. Borra, S. Itapu, and D. G. Georgiev, "Sn whisker growth mitigation by using NiO sublayers," *J Phys D Appl Phys*, vol. 50, no. 47, p. 475309, 2017.
[36] M. Killefer *et al.*, "Whisker growth on Sn thin film accelerated under gamma-ray induced electric field," *J Phys D Appl Phys*, vol. 50, no. 40, p. 405302, 2017.
[37] V. Borra, D. G. Georgiev, V. G. Karpov, and D. Shvydka, "Microscopic structure of metal whiskers," *Phys Rev Appl*, vol. 9, no. 5, p. 054029, 2018.

[38] O. A. Oudat, V. Borra, D. G. Georgiev, and V. G. Karpov, “The statistics of tin whisker diameters versus the underlying film grains,” *J Phys D Appl Phys*, vol. 52, no. 16, p. 165305, 2019.
[39] V. S. V. Borra, “Whiskers: The Role of Electric Fields in the Formation Mechanism and Methods for Whisker Growth Mitigation,” 2017. [Online]. Available: http://rave.ohiolink.edu/etdc/view?acc_num=toledo1513381893591481
[40] S. Itapu, V. Borra, F. X. Li, P. Cortes, and M. H. Kumar, “Effect of laser irradiation on the tribological properties of RF-sputtered nickel oxide (NiO) thin films,” *Vacuum*, vol. 205, p. 111461, 2022.
[41] V. Borra, S. Itapu, V. G. Karpov, and D. G. Georgiev, “Modification of Tin (Sn) metal surfaces by surface plasmon polariton excitation,” *Scr Mater*, vol. 208, p. 114357, 2022.
[42] S. Itapu, V. Borra, and D. G. Georgiev, “Laser-based fabrication of microstructures on nickel thin films and its applications in on-chip thin film inductors,” *IEEE Trans Nanotechnol*, vol. 19, pp. 455–460, 2020.
[43] S. Itapu, B. S. R. I. PILLA, V. Borra, and F. Li, “Tuning the tribological properties of Ni/NiO thin films by Nd: YAG pulsed laser irradiation,” *SPAST Abstracts*, vol. 1, no. 01, 2021.
[44] I. , R. D. W. , & S. B. Gibson, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd ed. 2015 Edition. Springer, 2015.
[45] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O’Donoghue, and C. Charitidis, “Additive manufacturing: scientific and technological challenges, market uptake and opportunities,” *Materials Today*, vol. 21, no. 1. Elsevier B.V., pp. 22–37, Jan. 01, 2018. doi: 10.1016/j.mattod.2017.07.001.
[46] S. and D. M. Ford, “ Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges,” *Journal of Cleaner Production*, 2016.
[47] B. N. C. Andreas Ostendorf, “Two-Photon Polymerization: A New Approach to Micromachining,” *9*, 2006.
[48] J. F. Xing, M. L. Zheng, and X. M. Duan, “Two-photon polymerization microfabrication of hydrogels: an advanced 3D printing technology for tissue engineering and drug delivery,” *Chem Soc Rev*, vol. 44, no. 15, pp. 5031–5039, Aug. 2015, doi: 10.1039/c5cs00278h.
[49] X. Jing, H. Fu, B. Yu, M. Sun, and L. Wang, “Two-photon polymerization for 3D biomedical scaffolds: Overview and updates,” *Frontiers in Bioengineering and Biotechnology*, vol. 10. Frontiers Media S.A., Aug. 22, 2022. doi: 10.3389/fbioe.2022.994355.

[50] J. M. Kronenfeld, L. Rother, M. A. Saccone, M. T. Dulay, and J. M. DeSimone, "Roll-to-roll, high-resolution 3D printing of shape-specific particles," *Nature*, vol. 627, no. 8003, pp. 306–312, Mar. 2024, doi: 10.1038/s41586-024-07061-4.
[51] Microlight3d, "MICROFAB-3D."
[52] Microlight3d, "Microfab-3D by Microlight3d."
[53] Microlight3D, "MICROFAB-3D."
[54] LIQCREATE, "Two-Photon Polymerization (TPP) explained."
[55] "Microlight3D launches Luminis software, for faster, more user-friendly 3D microprinting," Nov. 07, 2023.
[56] GRENOBLE, "3D Microprinting Software," France, Nov. 24, 2023.
[57] Claire S, "The Best Micro 3D Printing Solutions On the Market," Jan. 20, 2023.
[58] I. J. Bahl, *Fundamentals of RF and microwave transistor amplifiers*. Wiley, 2009.
[59] J. L. ; C. A. K. L. C. Volakis, *Finite Element Method for Electromagnetics : Antennas, Microwave Circuits, and Scattering Applications*. Wiley-IEEE Press, 1998.
[60] I. B. R. G. A. I. P. Bhartia, *Microstrip Antenna Design Handbook (Artech House Antennas and Propagation Library)*. Artech House Publishers, 2000.
[61] Y. R.-S. Fan Yang, *Electromagnetic Band Gap Structures in Antenna Engineering (The Cambridge RF and Microwave Engineering Series)* , 1st ed. Cambridge University Press, 2008.
[62] David M. Pozar, *Microwave Engineering 4th Edition*. John Wiley & Sons Inc, 2011.
[63] © nTopology Inc, "Innovate. Iterate. Create."
[64] © nTopology Inc, "Introducing nTopology 3.0: Advanced engineering design faster than ever before."
[65] K. M. Huang *et al.*, "Selective metallic coating of 3D-printed microstructures on flexible substrates," *RSC Adv*, vol. 7, no. 81, pp. 51663–51669, 2017, doi: 10.1039/c7ra11171a.
[66] micro resist technokogy, "OrmoComp", Accessed: May 09, 2024. [Online]. Available: https://kayakuam.com/wp-content/uploads/2019/10/PI_OrmoCompClearFX.pdf
[67] Micro resist technology, "OrmoDev."
[68] M. Foerthner *et al.*, "Hybrid polymers processed by substrate conformal imprint lithography for the fabrication of planar Bragg gratings," *Appl Phys A Mater Sci Process*, vol. 122, no. 3, Mar. 2016, doi: 10.1007/s00339-016-9767-6.
[69] A. I. Maydykovskiy, E. A. Mamonov, N. V. Mitetelo, S. Soria, and T. V. Murzina, "Two-Photon Laser Lithography of Active Microcavity Structures," *JETP Lett*, vol. 115, no. 5, pp. 261–266, Mar. 2022, doi: 10.1134/S0021364022100150.

[70] C. Plamadeala *et al.*, “Bio-inspired microneedle design for efficient drug/vaccine coating,” *Biomed Microdevices*, vol. 22, no. 1, Mar. 2020, doi: 10.1007/s10544-019-0456-z.
[71] X. Jing, P. Zhao, F. Wang, M. Han, and J. Lin, “Precise Focal Spot Positioning on an Opaque Substrate Based on the Diffraction Phenomenon in Laser Microfabrication,” *Micromachines (Basel)*, vol. 14, no. 12, Dec. 2023, doi: 10.3390/mi14122256.
[72] QuikWeb Developer, “Standard & Custom Printed Circuit Boards.”
[73] “Digital Microscopes.”
[74] M. F. Imani *et al.*, “Review of Metasurface Antennas for Computational Microwave Imaging,” *IEEE Trans Antennas Propag*, vol. 68, no. 3, pp. 1860–1875, Mar. 2020, doi: 10.1109/TAP.2020.2968795.
[75] J. Hu, D. Mengu, D. C. Tzarouchis, B. Edwards, N. Engheta, and A. Ozcan, “Diffractive optical computing in free space,” *Nat Commun*, vol. 15, no. 1, Dec. 2024, doi: 10.1038/s41467-024-45982-w.
[76] V. Flauraud *et al.*, “In-Plane Plasmonic Antenna Arrays with Surface Nanogaps for Giant Fluorescence Enhancement,” *Nano Lett*, vol. 17, no. 3, pp. 1703–1710, Mar. 2017, doi: 10.1021/acs.nanolett.6b04978.