Design and Fabrication of a Terahertz Antenna Using Two-Photon Polymerization

Azizul Islam, Daniel Adu-Gyamfi, Srikanth Itapu, Frank X. Li, Pedro Cortes and Vamsi Borra

Abstract— **The recent prospective field of application for terahertz (THz) technology includes imaging, sensor systems, and high-speed wireless communication. The design and fabrication, as stated, of terahertz antennas, put the design engineers in various challenges, such as material selection, signal attenuation, and fabrication with highest accuracy of the smallest features. This paper presents the design, simulation, and fabrication of a compact monopole terahertz antenna with physical dimensions of 0.25mm x 0.25mm x 0.44mm. The antenna is developed through Ansys High-Frequency Structure Simulator, and the fabrication process utilizes Two-Photon Polymerization (2PP). The designed antenna was properly simulated in order to achieve good features of the reflection coefficient (S11) and the radiation patterns. This antenna was fabricated with high microscale accuracy by 2PP technology to demonstrate the ability to build complex THz structures at any required resolution. The simulation results showed a good impedance match along a wide bandwidth operating in the THz range with low levels of S11 and good power transmission. For the inspection of the high-resolution features of the fabricated antenna, light and electron microscopes were used, which validated the integrity of the structure.**

Keywords - Additive Manufacturing, Ansys HFSS, Two-Photon Polymerization, Terahertz Monopole Antenna.

I. Introduction

Newer, more sophisticated, and more effective antenna systems have been made possible by the recent, quick developments in telecommunications technology. Terahertz antennas is one of the first and gained popularity because to its potential uses in imaging, sensor systems, and high-speed wireless communications. Using cutting-edge manufacturing and simulation techniques, the design and implementation of a THz antenna are reported in the recent research[1]. Different problems and potential benefits are presented by THz antennas, which typically operate in the THz range of 0.1 to 10 THz. First, as it can be seen, the high frequency of operation can be used for wide bandwidth coverage, and able to support data rates of tens of gigabits per second, which will be necessary for future wireless communication systems. Second, antennas at THz frequencies require careful and sophisticated engineering and design to address material selection, signal attenuation, and precise manufacturing properly[2]. In other words, micrometer-sized antennas operating in the THz range will have to face various technological challenges including unique material properties, manufacturing, and designing requirements[3][4].

For these challenges, the current research uses Ansys High Frequency Structure Simulator (HFSS). Developed by Ansys, HFSS is a tool to an extent that is highly advanced in nature, and it is used to simulate electromagnetic waves while they pass through physical structures[5]. Before a THz antenna is ever manufactured, it serves as an excellent resource for modeling, simulating, and analyzing its performance. It forms the primary phase of the simulation in the designing of antennas that are tailor-made to THz specifications[6].

Conventional fabrication techniques of monopole antennas, such as PCB etching, machining, or wire antennas, are all sorts of drawbacks that include material limitations, high production costs, environmental concerns, inflexibility in design, and more[7]. Processes are complex; basically, most of them involve some poisonous chemicals. Besides, machining is expensive and wasteful, and sometimes wire antennas are not durable or precise[8]. These procedures frequently struggle to strike a balance between performance and cost, particularly when it comes to quick prototyping and custom design. Additive manufacturing emerges as a potent solution.

The significance of additive manufacturing, popularly known as 3D printing, has taken a huge role within manufacturing industries due to its fast-prototyping features and low cost for manufacturing. It has been given the liberty to use a very large variety of conductive and dielectric materials suitable for this purpose of 3D printing. Additive manufacturing has a larger role, and fused deposition modeling (FDM), digital light processing (DLP), and polymer jetting (PolyJet) form the three most practiced techniques in manufacturing components for millimeter wave and THz technologies, particularly comprising antennas, waveguides, and sensors [9][10][11][12][13][14][15]. At the same time, a new approach in Additive Manufacturing, which is currently under an extensive exploration process, is the Two-Photon Polymerization (2PP) technology[16]. This becomes very well suited for the fabrication of THz antennas because it is capable of fabricating complex microstructures very accurately[17]. This technique can capture and provide features on the sub-micrometer scale, and this is a practically necessary feature in the case of THz signals, the wavelengths of which are on the order of micrometers, taking 3D printing

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to a whole new level with such advanced technology [16][18].

The main goal of the research, a extension of our previous work [19], [20], [21], is to design and simulate a monopole terahertz (THz) antenna to achieve the best reflection coefficient (S11) possible within the THz frequency range using Ansys HFSS (High-frequency Structure Simulator)[22]. Towards this effort, optimization has been carried out to achieve the reflection coefficient (S11) as the best in the THz frequency range, and for the antenna radiation pattern to be finer. This work will also delve into the possibility of developing complex microstructures on THz antennas, using the 2PP technique. This synergy of enhancement in performance with precision and complexity at par with 2PP-based manufacturing will promise enhancement in the efficiency of THz antennas and minimize the gap between the design of a complex microstructure and complex shape fabrication for its use in THz technology, which might finally lead to substantial progress in practical application and effectiveness of THz antenna technology.

II. METHODOLOGY

A. Design and Simulation

In this report, we have modeled a THz monopole antenna very carefully in Ansys HFSS, keeping in consideration some tight dimensions and the material properties. The whole antenna structure shown in the Fig. 1 consists of a ground plane, an FR4 epoxy substrate, a feed line made of copper material, a vertical chain of copper tori, and a copper top rod. The whole construct holds 0.25mm x 0.25mm x 0.44mm. The ground plane and the substrate have the identical size - 0.25mm x 0.25mm; though, the substrate has a thickness of 0.01mm. Above the substrate, there is located the copper feedline, with the dimensions of 0.02mm in width, 0.145mm in length, and 0.0025mm in thickness, and its placement ensures optimal performance of the antenna.

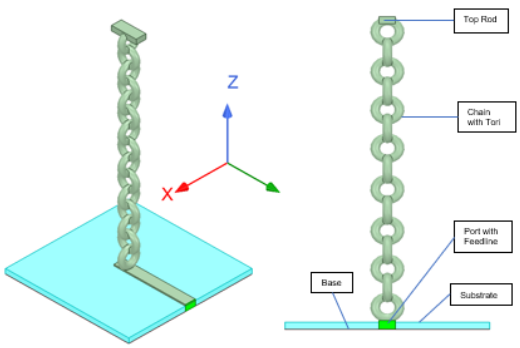

Figure 1: Structural Design of Terahertz Monopole Antenna (Right), Different Component of Terahertz Monopole Antenna (Left)

Above the feedline, the vertical chain, acting as a typical rod of monopole antenna, consists of a series of fifteen tori, arranged seven tori in the x-direction and eight in the y-direction, see Fig. 1. Each torus has a minor radius of 0.006mm and a major radius of 0.015mm. Finally, the top rod forms the last part of the structure with the dimensions 0.02mm x 0.05mm x 0.01mm. Fig. 1 also illustrate breakdown of different component of the designed THz antenna using HFSS.

This antenna configuration extends a lumped port interface for electromagnetic simulation all the way to the edge of the ground plane, but it is close to the feed line connection point. As a result, the input port was maintained at 50 Ohms impedance with all frequency levels. A frequency sweep of 50 GHz to 4 THz was used for simulation with interpolated sweeps to make target optimizations. These parameters are used to perform exhaustive parameterization, which is an analysis of an improvement of the performance of the antenna in the THz range to realize a design suited for a high-resolution THz spectrum application.

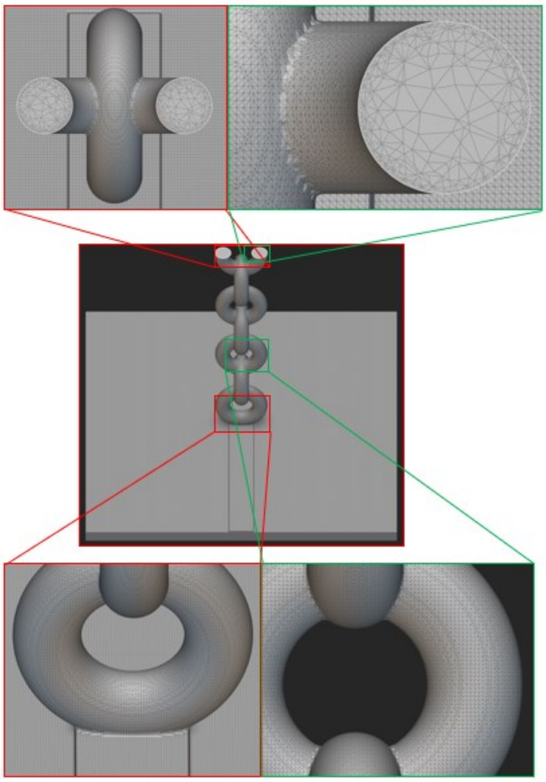

Figure 2: Section cut view of the designed THz antenna in nTopology

After the designing and simulation of the terahertz antenna, the design files were saved in AEDT format. For 2PP fabrication, the design file format is converted to STL file. For this, we import the design in nTopology software to reimplement to improve and fine-tune. In this way, the meshing process was carried out in nTopology by setting the mesh tolerance to be very fine at 0.001 mm in dimension. This fine level of tolerance was clearly important for catching fine details (shown in Fig. 2) of the antenna design so the physical structure will behave in the same way as was designed in our simulations. The successful reimplementation into nTopology would allow the generation of the required STL file. This file represents the final digital model that will be used in the fabrication process.

B. Fabrication Techniques

In our work, we employed the MicroFab-3D (MicroLight 3D) two-photon polymerization printer to fabricate antenna. A green laser in combination with a 20x objective lens was used. This configuration enabled us to exactly replicate the antenna structures with respect down to 0.2 microns - to maintained tolerance for the design requirements[23][24][25]. Photoresist material selected for this process was Ormocomp, chosen for its outstanding optical properties and stability, which are crucial for achieving the intricate detail necessary for optimal functionality of antennas at high frequencies[26].

The three-stage process for antenna fabricating is detailed below:

Stage 1: Setup of the 2PP System - The process starts with careful sample preparation. A 24 × 24 mm base coverslip is screwed in place to ensure that the sample holder is stable during the printing process. A drop of Ormocomp photoresist is dispensed over the base coverslip. A larger 24 × 32 mm top coverslip is placed over the base coverslip in such a way as to spread the photoresist evenly. This will ensure that there will be no air bubbles in the photoresist, and it is evenly distributed. This setup is very important to be able to fabricate the antenna with great precision.

Stage 2: Software Configuration and Printing - This is where the printing parameters are set on the Luminous software of the 2PP machine. The antenna design is set perfectly within the positive coordinates to dimensionally match the original design specification. After design analysis, we divided the whole structure in two parts: substate and feedline, chain and top rod. Great care is taken when selecting slicing directions. Suitable power and speed settings (which were selected by doing experiments) of the laser for the substrate and feedline, chain and top rod are carefully selected by considering the slicing direction, structure of the design, and photoresist properties. Selection of power and speed is crucial because excessive power can burn the antenna, while insufficient power can lead to loss of the antenna in post-processing. The antenna is printed in an upside-down print setting to incorporate complex structural detailing; for this particular upside-down setting, we had to find out the focal point where the photoresist meets the base coverslip to start the print.

Stage 3: Development - After printing, antenna was developed in an Ormodev solution. This 1:1 mixture which includes isopropyl alcohol and methyl isobutyl ketone abrogate the post-processing of structures aqueous solution derived from 2PP [27]. It is mainly used to develop or reveal the printed structures by dissolving unexposed photoresist. The printed antenna is then soaked in the Ormodev solution for an established period to completely dissolve all unexposed photoresist. An accurate timing is required to preserve its actual structure without any losses since too short will result in photoresist still remains and if time is too long, the antenna dissolve into Ormodev solution. After taking the sample out from the solution at the right time, it stays in the open air for not less than 30 minutes to allow the structure of the antenna to solidify before coating.

Verification: A few samples were tested for the integrity of the fabricated antennas, in this step, the antenna is verified by Keyence high-resolution microscope and Joel scanning electron microscope, the samples were coated with a gold–palladium to enable the additional in-depth investigation and quality assurance.

III. Result and Discussion

A. Simulation outcome

The THz monopole antenna, examined through ANSYS HFSS simulations, has demonstrated perfect impedance matching in the frequency range of 0 to 4 THz that is necessary for the purposes of power transfer with maximum efficiency in terahertz devices. All the S11 parameters show an extremely low level of reflected power, being below -10 dB in the vast majority of them, consequently indicating effective power transfer. In this regard, at 0.2080 THz, the antenna has registered an S11 of -25.0072 dB, hence showing almost perfect impedance matching when the power absorption or radiation is close to complete. At 0.5339 THz, the same reading is -10.3984 dB, meaning that the use of power will be close to 90.14% shown in the Fig. 3.

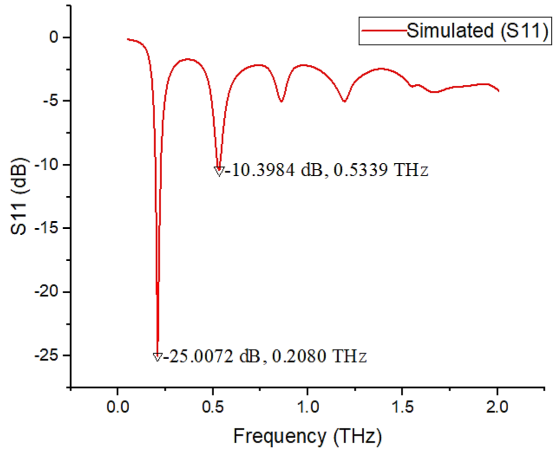

Figure 3: S11 Graph (0.0 – 2 THz)

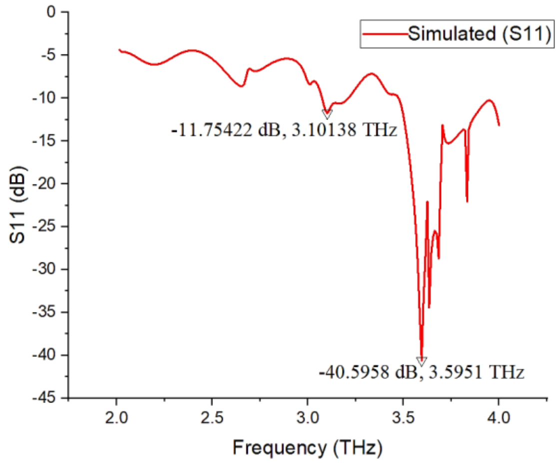

Figure 4: S11 Graph (2 – 4 THz)

Also, Fig. 4 illustrate the performance of the antenna was sustained in the higher frequency range of 2 to 4 THz. This is proven in that the antenna can retain performance at a higher frequency, given that an S11 measurement of -11.75422 dB at 3.10138 THz reflected that approximately 93.32% of power was effectively used. Therefore, the antenna distinctly remains at its higher frequency. An S11 of -40.5958 dB at 3.5951 THz represents great absorption of power, with low reflection, which supports that the impedance matching of the antenna is good and the operational efficiency is high across a broad extent of the terahertz spectrum.

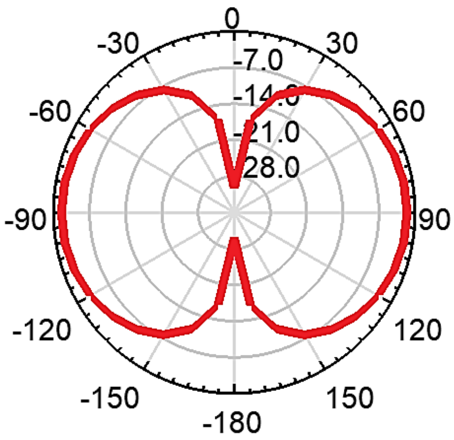

Figure 5: Radiation Pattern

Further, the performance efficiencies of the THz monopole antenna were brought to light in an analysis of radiation patterns. From Fig. 5 at a test frequency of 0.1117 THz, the antenna had a lot of radiation in the forward direction, with a peak gain at nearly 0°. This is an inherent characteristic of the monopole antenna, in that energy is directed to the source direction with high directivity. This sort of directionality is very important for applications that are related to directed energy transfer since the performance of the antenna is, therefore, enhanced and performance is elevated in practical scenarios.

The simulation results clearly suggest that the THz monopole antenna is extremely robust for a large fraction of the terahertz span and, hence, is highly recommended for applications that are state of the art and incorporate THz speed-of-light communications. The well-defined impedance at critical frequencies and the closely matching directional radiation patterns validate the design and operational efficacy of the antenna. Equipped with the high directivity and capable power-handling characteristics, the THz monopole antenna becomes capable enough to meet the challenges of stressful propagation in next-generation communication technologies and, hence, may be enabled for use in advanced THz applications.

B. Fabrication Finding

Main printing parameters for THz antenna fabrication using 2PP were gained from the experimental result. We successfully printed the substrate and feed line using a laser power of 16% and a speed of 85 µm/s in the X slicing direction, as well as the chain and top rod with a laser power set to 17% and laser scanning velocity 90 µm/s for Z-slicing (among various other experimental trials). For post-processing, we dipped the fabricated antenna with a 1:1 diluted Ormodev solution in a mixture of isopropyl alcohol (IPA) and methyl isobutyl ketone (MIBK), which facilitates cleaning off photoresist residues not properly exposed. Through our experiments, we ascertained that to have unexposed photoresist removed while keeping the integrity of the antenna structure, 12-15 min was sufficient dwell time. This timing has to be precise; otherwise, the fine structural details of the antenna will either damage or can get lost.

After fabrication and the development of the THz monopole antenna, it is very necessary to inspect the integrity of the structure. We have done the structural examination with the Keyence Microscope 7000 series, very important to the quality of fabrication. As a result of the structural inspection, it came out that all the elements of the antenna were printed correctly, results documented in Fig. 6.

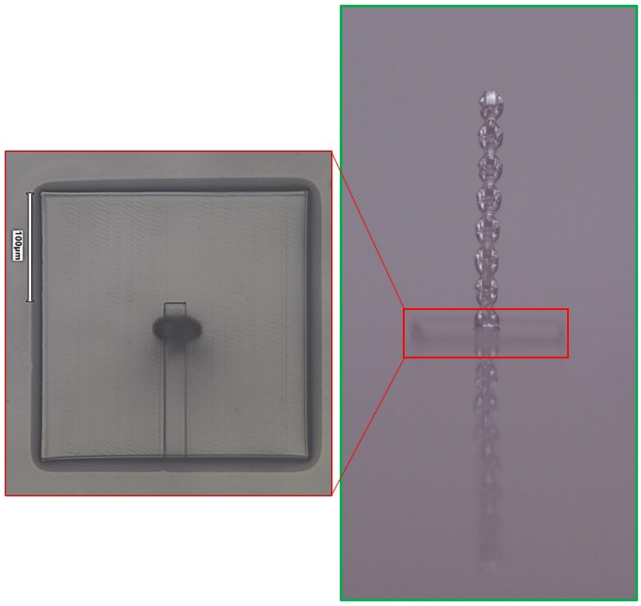

Figure 6: Picture of Substrate and Feedline (Left), Chain with Top Rod (Right), from Keyence Microscope.

High-resolution images of the surface structure of the antenna were captured using a Joel SEM microscope. We imaged and documented the imaging of the structure details of the antenna. The details are depicted in the figures shown in Fig. 7, which evidently shows the level of perfection in the fabrication of the antenna.

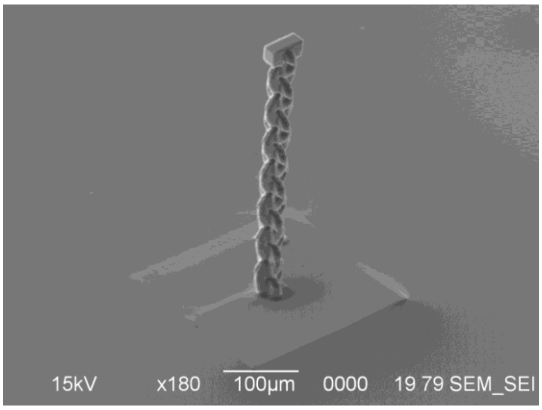

Figure 7: Picture of Fabricated THz antenna structure from Keysight 8500 FE-SEM microscope.

IV. CONCLUSION

Design and fabrication of a THz monopole antenna, using advanced ANSYS HFSS simulations and 2PP fabrication techniques, was realized. The X and Z slicing directions were optimized for laser powers of 16% and 17%, respectively, and for respective speeds of 85 µm/s and 90 µm/s. In order to preserve structural integrity and remove unexposed photoresist, post-processing included a 12–15-minute dip in a diluted Ormodev solution. The S11 parameters showed outstanding impedance matching over the THz spectrum with selected dimension of the design. Particularly noteworthy frequencies were 3.5951 THz and 0.2080 THz, both of which had remarkably low S11 values, indicating efficient antenna operation. The structural stability and meticulous construction of the were further confirmed by high-resolution FE-SEM imaging. Future studies aimed at testing the fabricated antenna might potentially utilize this research as a reference. With a view to addressing the remaining challenges, future studies will build over the present foundation to enhance the practical applicability and effectiveness of THz antenna technology, whereby a significant improvement in high-speed wireless communication and sensing capability could be realized.

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