3D Printed Patch Antennas with Varying Infill Densities

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***Abstract*—This paper presents fully 3D printed patch antennas with varying infill densities. Both the substrate, as well as the metallic layer of these antennas, were manufactured using additive methods. We have used the linear approximation method derived from our previous study to estimate the effective relative permittivity values for lower infill densities for these antenna substrates and tested the validity of that approximation with these 3D printed antennas. Additionally, we demonstrated a parameter optimization technique to accommodate the changing infill densities, ensuring that antennas with lower infill density substrates can still function within the desired frequency range. The measured results were compared to the simulated data, and the influence of solid layers on the substrate was investigated. The study validates the linear approximation method and highlights the potential of 3D printing in antenna design, offering researchers greater flexibility and control over custom antenna development for specific applications.**

***Index Terms*—3D printing, printed antenna, patch antenna, infill density, substrate characterization, PETG**

I. Introduction

The use of 3D printing technology has gained significant attention in the field of electromagnetics. Several research studies have explored the application of additive manufacturing methods in antenna design as reviewed in [1]. This is primarily due to the ease of 3D printing in the design and fabrication process. Advanced electromagnetic simulation tools, such as CST Microwave Studio, allow users to simulate an antenna model as well as export the designs to 3D printers, making the manufacturing process more convenient and efficient. In this paper, we present a case study of fully 3D printed patch antennas, where the substrates are manufactured with different infill densities. Our objective in this research is to build upon the findings of a previous study [2] on the relationship between effective relative permittivity and infill density and provide insights into the application of infill density in the manufacturing process of 3D printed antennas.

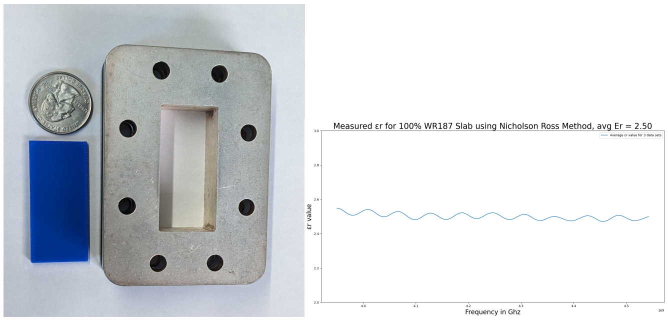
In a lot of previous studies, 3D printing has been generally used as a support structure over which a metallic layer is printed, but this permanent support structure lowers the best operating frequency of an antenna [3]. Several of these studies include a 2018 paper where additive manufacturing has been used to design a circularly polarized antenna with four inverted-F monopoles with 3-D-printed supporting structures [4]. A dipole antenna was designed in a 2016 paper where the conducting layer of the dipole was embedded into the substrate of the antenna fabricated using Acrylonitrile butadiene styrene (ABS) material. [5]. In some cases including a 2016 paper, an epoxy has been used to bind the metallic layer of an antenna with a 3D printed substrate [6]. Depending upon the epoxy material, there might be some effect on the operating frequency of the antenna due to these extraneous layers as well as there is a chance of depletion of these layers when subjected to environmental conditions. That is why fully 3D printed antennas might be more efficient and reliable, and as a result, more interest has been growing in them. Some of the studies on fully 3D printed working antennas include **9229736** where prototypes of 3D printed dipole antennas for passive UHF RFID tags are presented. They have used a conductive copper-based thermoplastic filament as the printed material in the Fused Deposition Modeling method for 3D printing.

One of the parameters that can be readily adjusted in the 3D printing process is the infill density. The effective relative permittivity of a 3D printed substrate decreases as the infill density is lowered [2], [7]. A 2021 paper has studied a method to compensate for the reducing infill density which changes the resonance frequency of the different Dielectric resonator antenna (DRA) implementations, by using a 3D printed metallic cap and varying its dimensions [8].

We believe that one of the other techniques to mitigate the change in infill density comes from the study of the relationship between infill density and the effective relative permittivity which was found to be linear, especially for the higher infill densities [2]. This result can be interpolated to determine the effective relative permittivity when a substrate with lower infill density is desired. The effective relative permittivity is the permittivity at the lower infill density and by gaining an idea of it, we can design our antenna accordingly and sometimes a small parameter adjustment might be enough to compensate for the lower infill as shown in this study. This study was conceived with this idea where three different patch antennas are designed with Fused Deposition Modeling (FDM) method which is an additive manufacturing method to realize a fully 3D printed antenna whose dielectric substrate has infill density lower than 100%.

II. Substrate Characterization and Simulations

We have used a commercially available 3D printing filament called polyethylene terephthalate glycol (PETG) manufactured



(a) WR 187 slab with sampleholder (b) ε_r measurement result

Fig. 1. Measured ε_r of the WR187 slab manufactured using PETG filament

by 3DXTECH that is promised to have an improved chemical resistance compared to PLA (Polylactic Acid) or ABS [9]. As the permittivity of this filament was not listed on the technical data sheet, it was important to first characterize the electrical properties such as dielectric permittivity and loss tangent of the material. The dielectric characteristics of the printed substrate mostly depend on the printing material used, the infill pattern as well as the layer height, and it was also important to note that the same material can exhibit slightly different properties when printed with different settings [6]. The printed substrate was required to exhibit a tangible dielectric constant as well as low loss [10]. A rectangular slab of around 2 mm thickness was printed for the WR187 waveguide to obtain the required information. The thickness was kept at 2 mm because the antenna substrates were designed to be 2 mm and this particular waveguide was selected because its operating frequency includes the resonating frequency of the patch antennas that were designed for this study. The permittivity of the slab which was printed at 100% infill was measured using the waveguide method, as described in [2]. The printed WR187 slab as well as the result of the permittivity measurement is shown in Fig. 1.

The permittivity and loss tangent of the printed WR187 slab was measured using the Nicholson Ross method that was later adapted to automatic network analyzers by Weir [11], [12]. The waveguide method provided multiple permittivity values for several frequencies on the operating range of the waveguide. We computed an average relative permittivity value for the slab which was 2.50. The slab was expected to be non-magnetic, and the relative permeability value of the slab across the waveguide frequency range was close to that of air (average of 0.922), which confirmed our belief. The electric loss tangent for the WR187 slab varied in the range of 0.00089 - 0.0297 and its average value across the waveguide band was 0.0137 confirming it as a relatively low-loss material suitable to be used as an antenna substrate. Using the linearity approximation as described in [2], [7], we interpolated the permittivity values for 25%, 50%, and 67% infill density, which were 1.25, 1.75, and 2 respectively. These permittivity values were then used to design three different patch antennas each resonating at 5GHz. We used CST Microwave Studio software to design three simulated patch antennas whose substrates had the above mentioned interpolated permittivity values. Simple patch antennas were chosen because they are widely studied which makes them easy to design and fabricate. Also, we needed an antenna with single resonance as the purpose of this research was to facilitate comparison between antennas with varying infill densities to test the measurement results obtained in [2] for practical applications.

We attempted to maintain most of the parameters constant for these three simulated antennas but we had to adjust some parameters to account for the changing infill density of the antenna substrate. To keep the number of varied parameters minimal, we only varied the length of the patch (L_p) and hence the length of the substrate (L_s) between these three patch antennas. The other parameters such as the width of the patch antenna (W_p), the width of the dielectric substrate (W_s), the width (W_m), and the length (L_m) of the microstrip feed line were all kept constant. The modeled antenna in CST Microwave Studio is presented in Fig. 2 and the dimensions of the patches have been presented in Table I. The width (W_m) and length (L_m) of the microstrip feed line were set to be 2.1 mm and 10 mm respectively. The thickness of the substrates for all patches was set to be 2 mm and all of these patches had a full ground plane made with a copper tape on the opposite side of the substrate. Moreover, we ensured that the substrate layer was 1 mm larger on the sides of the radiating patch to allow for some tolerance during the ink printing process. The antenna substrates were printed with two solid layers on each of the top and bottom surfaces of the slab so that the exterior surface of the substrate has a smooth surface for accommodating the metallic ink layer.

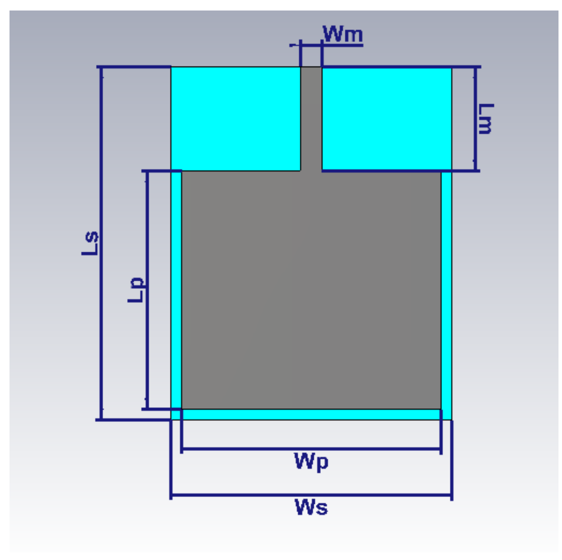


Fig. 2. Antenna model Simulated in CST Microwave Studio

III. Printed Patch Antennas

To fabricate the fully 3D patch antennas, we used a commercially available 3D printer made by nScrypt. This printer has two separate micro dispensing nozzles each with

TABLE I
DIMENSIONS OF THE PATCH ANTENNAS (IN MM)

Patch name	For Patch		For Substrate	
	L_p	W_p	L_s	W_s
25% infill	22.90	25	33.90	27
50% infill	20.18	25	31.18	27
67% infill	18.85	25	29.85	27

different characteristics. The first nozzle called "nFD" is fed the appropriate dielectric filament material where a heater ring attached to the nozzle melts the filament at a high temperature (around 245-250°C for PETG) and extrudes it through a narrow ceramic tip to deposit a thin stream of the filament material layer by layer, manufacturing the required substrate material [13]. The speed used for the feed of the filament to the print head was $0.18\, mm/s$ for our process. The other nozzle called "smartpump" enables a user to micro dispense semisolid material with the use of air pressure [14]. The conductor ink stored in a syringe is dispensed by air pressure to extrude it through a ceramic tip to manufacture a metallic layer of an antenna. We used an air pressure of around 20 psi to extrude the conductor ink during our printing process. The two micro dispensing nozzles of the printer are shown in Fig. 3. More crucial parameters used for the 3D printing process are listed in Table II. In our workflow, we first manufactured the substrates with the appropriate infill density (25%, 50%, and 67%) and printed the conductive ink layer on their top surfaces [15]. More detailed guidelines for the printing process can be found in Keathley's thesis [16]. The printed patch antennas are shown in Fig. 4.

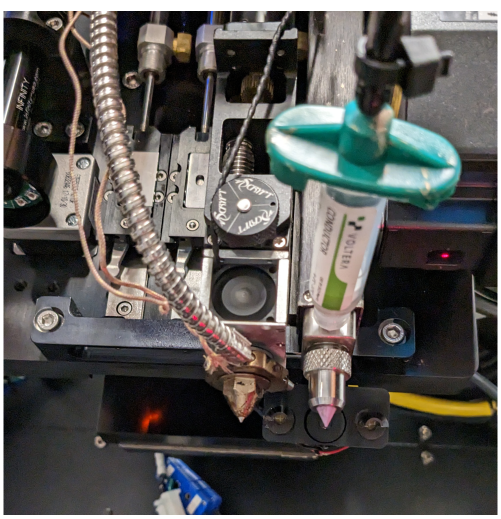


Fig. 3. Printing tips of the 3D printer, The left is for printing dielectric filament while the right one (pink colored) is for silver ink printing

IV. RESULTS AND DISCUSSION

An SMA connector was soldered to each of the fabricated antennas. To evaluate antenna performance, we employed an Agilent PNA X which was calibrated with an 85052D

TABLE II
3D PRINTING PARAMETERS

Parameter	For Substrate	For Ink Layer
Layer height	0.180 mm	0.10 mm
Travel speed	80 mm/s	20 mm/s
Infill speed	50 mm/s	10 mm/s
Fill pattern	rectilinear	rectilinear
Extrusion width	0.4 mm	0.150 mm
Extruder temperature	250 °C	ambient
Printing bed temperature	70 °C	ambient
Number of layers printed	11	1

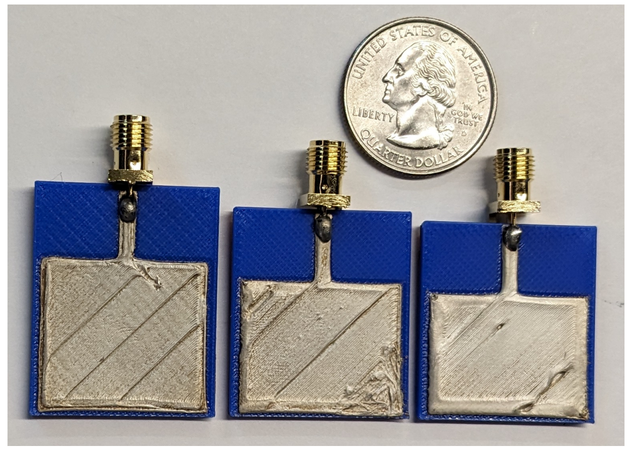


Fig. 4. Fully 3D Printed Patch Antennas with 25%, 50%, and 67% infill substrates (left to right)

calibration kit. This calibration standard uses a short, open, and broadband load (SOL) to calibrate the port used for the antenna measurements [17]. The results obtained from the return loss measurements of the patch antennas are presented in Figs. 5, 6, and 7 for patches with 67%, 50%, and 25% infill density substrate respectively. Each figure depicts the simulated data generated in CST Microwave Studio by the solid blue line with a cross, while the dashed orange line with dots represents the measurement results. The simulated antennas were designed to resonate at 5 GHz and hence exhibit a perfect match at the desired frequency. However, some deviations are observed in the measured results, the 67%, 50%, and 25% patches each resonate at 4.86, 4.90, and 4.75 GHz respectively.

In all cases, we observed a slightly lower resonance frequency in the printed antennas compared to the simulated results, indicating that the permittivity of the 3D printed substrates was slightly higher than what was calculated from the interpolation method. However, the 25% infill density showed more deviation compared to the patches with higher infill densities. This discrepancy may be attributed to the use of solid layers in manufacturing the substrate. This is because 4 out of the 11 total layers were solid layers since the substrate was relatively thin. This led to a notable increase in the relative permittivity, particularly for the 25% infill density, where the deviation was most pronounced between measured and simulated values. Notably, though, the patch antennas

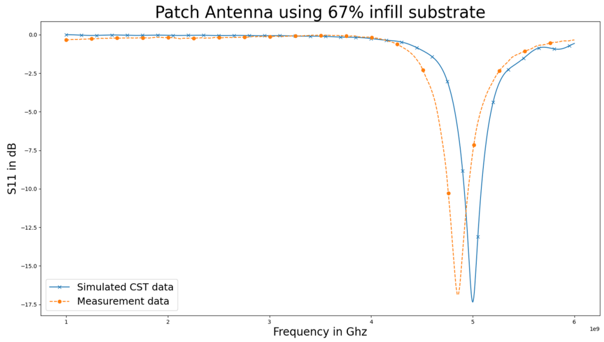


Fig. 5. Measurements result for Patch with 67% infill density substrate

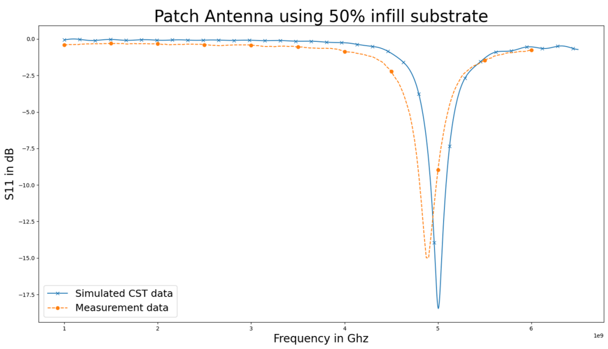


Fig. 6. Measurements result for Patch with 50% infill density substrate

exhibited a pattern, consistent with the findings of our earlier study [2] on various 3D printed waveguide slabs measurements as those slabs also had solid layers on the top and bottom surfaces.

Nevertheless, the difference between the simulated and measured results remained minimal for higher infill densities, and the linear approximation method proved to be a reliable means to estimate permittivity values for infill densities less than 100%. This knowledge of effective permittivity at lower infill densities can be leveraged to adjust antenna parameters, enabling antennas to operate in the desired frequency range. The promising results obtained for the two higher infill densities underscore the potential and significance of this research. As a result, the linear approximation method offers the possibility to design and fabricate antennas with customizable infill densities.

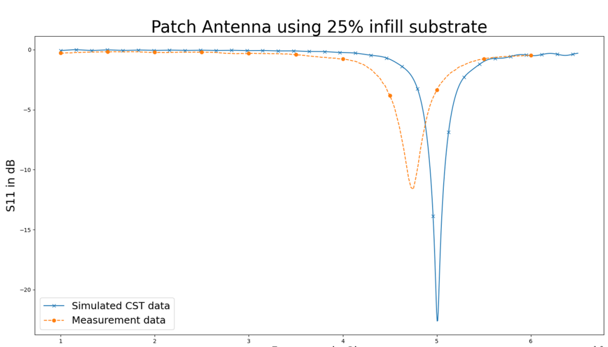


Fig. 7. Measurements result for Patch with 25% infill density substrate

V. Conclusion & Future Work

In conclusion, our study demonstrates the feasibility of using 3D printing for antenna design and fabrication with applications related to varying infill densities of an antenna substrate. The permittivity values calculated from our linear interpolation method were used to design and simulate three patch antennas, which were then fabricated using additive methods. The measured results were in close agreement with the simulated results, showing that with a few design changes, the antennas can still function effectively despite lowering the infill density. The main idea is that the infill density has to be considered for antenna design; particularly, adjusting some parameters of an antenna whenever a lower infill density is used. There are a lot of ways to compensate for a lower infill density but we think that the adjustment in a design parameter is one of the easiest effective techniques as presented in this study.

The advantages of 3D printing in antenna design were highlighted, including the ability to vary the thickness of the substrate as necessary and to modify the relative permittivity by using lower infill density. From our study and experience, these are the two distinct advantages of additive manufacturing. These advantages offer researchers greater flexibility and control over antenna design, enabling the development of custom antennas for specific applications. In future work, as insinuated we plan to design the substrate for the lower infill without any solid layers, building on the insights gained from this study.

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