SHEN, JUNYU. Additive Manufacturing of Millimeter-Wave Waveguide Components. (Under the direction of David S. Ricketts.)

Millimeter-wave (mm-Wave) waveguide components are principle pieces for mm-Wave radio communication and radar systems. Additive manufactured mm-wave waveguides are a relative new research area that provides a potential solution for lower cost, lower weight, and complex geometry units. This dissertation presents a methodology for realizing complex, high-performance mm-Wave components using digital-light-processing (DLP) 3D printing. The approach addresses numerous challenges of successful component realization, including: metalization of acrylate-based polymers, defect reduction in printing, increased precision through off-axis printing of waveguide channels and re-design of precision internal structures for self-supporting in the build process. The demonstrated components are competitive with commercial, high-performance machined microwave components.

The first thrust of this research focuses on addressing the metallization challenge for additive manufactured plastic mm-Wave waveguides. As a pioneer work, a silver electroless plating system is adopted for the metallization on plastic 3D-printed waveguides which can provide good metal adhesion. Based on the work, a comprehensive plating method incorporating silver and copper plating is developed to enhance the metal deposition to over 5 times skin depths at W-band, resulting in a reduction on waveguide loss. The fabricated waveguide section has a measured loss at 0.16 dB/inch, averaged from 75 to 110 GHz.

The second thrust of the PhD work focuses on increasing the precision and reducing the defect printing through using proposed modelling strategies. Analysis on the model
orientation effect to the 3D-print W-band waveguide dimension indicates the suitability of using an off-axis 45°-print strategy for building waveguide structures that possess orthogonal waveguide channels. Besides, the modification to include curved corners and rounded edges brings two benefits: to eliminate the plating cracks and allow a continuous coverage of metal; to have self-support during the print. The proposed method is demonstrated through the realization of two W-band waveguide components. One is a high-performance, single composite, broadband magic tee, which includes several functional additive structures made possible by 3D printing. The other one is a turnstile junction orthomode transducer incorporating the proposed "swan neck" twists forming a compact volume.
Additive Manufacturing of Millimeter-Wave Waveguide Components

by
Junyu Shen

A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

Electrical Engineering

Raleigh, North Carolina
2019

APPROVED BY:

Jacob J. Adams  Michael D. Dickey

Michael Steer  David S. Ricketts
Chair of Advisory Committee
DEDICATION

Dedicated to my parents, YuanTong Shen and Yanyun Zhang.
BIOGRAPHY

Junyu Shen was born in Wuhan, Hubei Province, China in 1989. He received his Bachelors in Engineering degree in Electrical Information and Engineering from Wuhan University of Technology at Wuhan, China in 2011 and his Master of Science degree in Electronic Science and Technology from Beijing University of Posts and Telecommunications at Beijing, China in 2014. From 2014 to 2019, he pursued his doctoral degree in Electrical Engineering at North Carolina State University, Raleigh, NC, USA, and worked as a research assistant at Dr. David S. Ricketts Lab. His topics of interests include waveguides, 3D printing, millimeter-wave and antennas.
ACKNOWLEDGEMENTS

Five years past since I first entered North Carolina State University as a fresh graduate student. It comes to the time I am going to finish my study and research here and start a professional career.

First, I would like to express my gratitude to my advisor, Dr. David D. Ricketts for being a mentor that guide me through all challenges and hardships through my PhD life. I was introduced to new concepts and got insights on working the research, and I was trusted to work as an independent researcher to generate thoughts, conduct experiments, and verify ideas. I would also like to thank Dr. Michael D. Dickey for providing me an interactive working environment in which I completed my chemical experiments. Without his support, this dissertation would not have been possible. I also want to thank my other committee numbers, Dr. Jacob J. Adams, Dr. Michael B. Steer, for their professional suggestions and helpful discussions.

Along with strong support from professors, I have also been fortunate enough to have excellent lab collaborators. Michael Aiken helped me on all my early experiments of 3D printing, Deeksha Lal often encouraged me and provided me advice, in addition, Carter Hiarris, Juncheng Zhou, Vivek Bharambe, Dishit Parekh, Collin Ladd, Binbin Yang, Fenglan Yang, Viswanath Padmanabhan Ramesh, Kirti Bhanushali, Munirah Boufarsan, all gave me supports to my research. A special thanks to my friends who I shared happiness and sorrows, including but not limited to, Weihu Wang, Meng Wang, Xiao Xiang, Haotao Ke, Bowen Li, Jian Zhang, Yi-Shin Yeh, Yuan Chang, Tiantong Ren, Zhangjie Hong.

Lastly but most importantly, I would like to thank my mother, Yanyun Zhang and my father Yuantong Shen, whom I owe to most and love me most. Also, special thanks to my girl friend, Yang Shi, who lights up my sky.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................ viii

LIST OF FIGURES .................................................................................................... ix

Chapter 1  Introduction ......................................................................................... 1
  1.1 Printing Methods and Performance ............................................................ 2
  1.2 Challenges in 3D printing ................................................................. 5
    1.2.1 Challenge I - Anisotropic Printing Accuracy .................................... 5
    1.2.2 Challenge II - Printing Material Plasticity and Supporting Issues ...... 5
    1.2.3 Challenge III - Metallization of 3D-Printed Parts ......................... 7
  1.3 Focus of the Work ..................................................................................... 10
    1.3.1 Simple Electroless Plating Solution for 3D Printed Mm-Wave Components ................................................................. 11
    1.3.2 3D Printing Low-Loss Components ................................................ 11
    1.3.3 3D Printing Broadband Magic-Tees at W-Band ............................. 13
    1.3.4 3D Printing Compact Orthomode Transducer and Dual-polarized Antenna at W-band ......................................................... 13
  1.4 Contributions ......................................................................................... 14
  1.5 Dissertation Organization ...................................................................... 15

Chapter 2  Simple Electroless Plating Solution for 3D-Printed Mm-Wave Components ........................................................................................................... 16
  2.1 Fabrication ............................................................................................ 17
    2.1.1 Modeling ....................................................................................... 17
    2.1.2 Printing ....................................................................................... 18
    2.1.3 Metallization .............................................................................. 19
    2.1.4 Final Assembly .......................................................................... 22
  2.2 Measurement ......................................................................................... 24
  2.3 Summary .............................................................................................. 26

Chapter 3  3D Printing of Low Loss Microwave Components ......................... 27
  3.1 3D Printing Low-Loss Mm-Wave Waveguides ........................................ 28
    3.1.1 Mechanical and Mating Considerations ....................................... 28
    3.1.2 Metallization ............................................................................. 29
    3.1.3 Measurement ........................................................................... 31
    3.1.4 Summary .................................................................................. 35
  3.2 3D-Printed Coaxial Line Using Low Loss Dielectric and Liquid Metal Conductor ........................................................................................................... 36
    3.2.1 Design ....................................................................................... 36
    3.2.2 Fabrication ............................................................................... 38
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1</td>
<td>Comparison of the attenuation from W-band waveguides built by different AM technologies.</td>
<td>3</td>
</tr>
<tr>
<td>Table 1.2</td>
<td>3D-Print time comparison between DLP and SLA technologies on building waveguides.</td>
<td>4</td>
</tr>
<tr>
<td>Table 1.3</td>
<td>Comparison of waveguide bands, components types, metallization processes, number of assembly pieces, and side wall opening conditions of reported metallized polymer-based waveguide Components.</td>
<td>8</td>
</tr>
<tr>
<td>Table 2.1</td>
<td>Comparisons of assembly methods and attenuation, of published W-band waveguides from different technologies.</td>
<td>25</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Performance comparison of 3D-printed waveguides and metal commercial waveguides.</td>
<td>35</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Comparison of Coaxial Transmission Line.</td>
<td>41</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Comparison of 3D Printed Dimension Accuracy of WR-10 Channels (2.54 mm × 1.27 mm) in Different Orientations.</td>
<td>56</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Design Dimensions of W-Band Broadband Magic Tee.</td>
<td>70</td>
</tr>
<tr>
<td>Table 4.3</td>
<td>Summary of Measurement Performance of Four Types of Magic Tees: DLP 3D Printed Broadband Magic Tee (in bold), CNC-machined Magic Tee, DLP 3D Printed Traditional Magic Tee (in bold), and Machined Traditional Magic tee.</td>
<td>76</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>Comparison of this proposed OMT to other published W-band OMT in the simulation results.</td>
<td>83</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Comparison of this proposed OMT to other published W-band OMT in the simulation and measurement results.</td>
<td>89</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>(a) I. DLP printing: an image is shown on a thin layer of liquid polymer to cure the desired solid structure. (a) II. and III. The build table is move vertically (z direction) as the part is printed. (b) profilometer scan of an y-z slice of a waveguide wall. Note significant, periodic variation in the z direction due to table movement.</td>
<td>6</td>
</tr>
<tr>
<td>1.2</td>
<td>The focus and outline of the work.</td>
<td>10</td>
</tr>
<tr>
<td>2.1</td>
<td>3D-printed WR-10 waveguide designs at each stage of the design and fabrication process: (a) Contour drawing of initial modifications to a standard waveguide design, (b) CAD rendering, with radial fin structures (blue) and a cylindrical shell (transparent) added around waveguides’ central core (c) Photograph of UV cured printed parts, (d) Photograph of after silver plating.</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Waveguide metallization process outline.</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>S-parameter measurements, comparing 3D-printed WR-10 waveguides to a traditionally fabricated (EDM) WR-10 waveguide, including: (a) reflection coefficients, (b) insertion coefficients, and (c) loss per meter.</td>
<td>23</td>
</tr>
<tr>
<td>3.1</td>
<td>Photograph of 3D-printed 1-inch D-band (front) and W-band (rear) waveguides presented in this paper.</td>
<td>30</td>
</tr>
<tr>
<td>3.2</td>
<td>Photographs show the metal plating thickness using two methods (a) silver electroless plating [33] (b) the copper electroless plating on top of the plated silver.</td>
<td>32</td>
</tr>
<tr>
<td>3.3</td>
<td>Photographs of 3D-printed W-band (a) and D-band (b) waveguide testbenches.</td>
<td>32</td>
</tr>
<tr>
<td>3.4</td>
<td>S-parameter comparison of 1-inch W-band waveguides by presented method, silver electroless plated method (in Chapter 2), and commercial machining: (a) reflection coefficient, (b) insertion coefficient.</td>
<td>34</td>
</tr>
<tr>
<td>3.5</td>
<td>Transducer loss comparison of 1-inch D-band waveguides by presented method and commercial machining.</td>
<td>34</td>
</tr>
<tr>
<td>3.6</td>
<td>Calculated coaxial lines loss per centimeter against the conductor metal conductivity in the parameter of the dielectric loss factor at 10 GHz, assuming $a = 1.35 m m$, $b = 5.7 m m$, and $\varepsilon_r = 3$.</td>
<td>37</td>
</tr>
<tr>
<td>3.7</td>
<td>3D-printed coaxial line fabrication process. (a) The 3D printing of the coaxial line dielectric; (b) The filling of the coaxial line inner channel with the liquid metal EGAln; (c) The deposition of the silver seeding layer on the dielectric surface; (d) The coating of EGAln on the top of the silver layer.</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 3.8  Equipment setting for EGaIn filling ........................................... 39
Figure 3.9  Measurement results for 2-inch 3D-printed coaxial lines, one using cyanate ester dielectric and the other VisiJet Crystal M3 dielectric. (a) $S_{11}$, (b) $S_{21}$ ................................. 40
Figure 3.10  2ns 3D-printed coaxial delay line fabrication process. (a) The modeling of the delay line; (b) The EGaIn filling into the delay line; (c) The metalization of the delay line using the silver seeding and the EGaIn coating ....................................................... 42
Figure 3.11  Measured result for 2ns 3D-printed coaxial delay line. (a) $S_{11}$, (b) $S_{21}$, (c) group delay ................................................................. 43
Figure 3.12  Design platform of AntSyn shows the input of electrical specifications and geometry constrains .............................................. 46
Figure 3.13  3D-mesh antenna synthesis result in AntSyn software. Top figures (from left to right): 3D model, return loss, and max gain; bottom figures (from left to right): 3D pattern, H-plane pattern, E-plane pattern 47
Figure 3.14  EM simulated result for the synthesized antenna. Top figures (from left to right): 3D model, return loss, and max gain; bottom figures (from left to right): 3D pattern, H-plane pattern, E-plane pattern 48
Figure 3.15  3D-mesh antenna prototyping with dimension 5 cm×5 cm×3 cm: (a) CAD model, (b) 3D printed antenna, (c) silver-coated antenna, (d) plated antenna under test .......................................... 50
Figure 3.16  Comparison of measurement and Analyst EM simulation result of the 3D-mesh antenna: return loss, gain, H-plane pattern at 5 GHz, and E-plane pattern at 5 GHz ........................................ 51
Figure 4.1  Definition of WR-10 sections (2.54 mm × 1.27 mm) in multiple orientations ................................................................. 53
Figure 4.2  Experiment on 3D printing dimension accuracy of WR-10 sections in multiple orientations, as defined in Fig. 4.1. (a) The diagram and numbering of WR-10 sections in multiple orientations. (b) The photograph of the 3D printed sections. (c) The diagram of dimensional characterization of the section's cross-section. (d) The cross-section measurement (optical) to characterize the 3D printed WR-10 section's dimensions .......................................................... 54
Figure 4.3  Recipe developed for the metallization of complex mm-Wave waveguide structures .................. 57
Figure 4.4 Experiment on the effect of the curved corner design on the waveguide. (a) The plated 3D printing waveguide showed cracks on the channel corners. (b) The equivalent cracked corner waveguide design was modeled. (c) The modified waveguide in curved corners was fully plated. (d) The equivalent curved corner waveguide design was modeled. (e) A comparison of the simulated insertion loss between the ideal model (solid line), the curved corner model (dash line), and the crack corner model (dotted line).

Figure 4.5 Fabrication of the 3D printed W-band traditional magic tee following the criteria in Sec. (a) The traditional W-band magic tee model was optimized for 3D printing, with the curved corner design. (b) The model was orientated such that the four arms were in 45° angle to the build table plane (x-y plane). (c) The magic tee was metallized by the proposed process.

Figure 4.6 Photograph of the setup for the characterization of the W-band 3D printed traditional magic tee.

Figure 4.7 Measurement and EM simulation results for the 3D printed W-band traditional magic tees compared with measurement results of a machined traditional magic tee in terms of (a) matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$), (b) isolation from Port 2 to Port 1 ($S_{12}$), and Port 4 to Port 3 ($S_{24}$), (c) insertion loss characterized from Port 3 to Port 1 ($-S_{13} - 3$ dB) and Port 3 to Port 2 ($-S_{23} - 3$ dB), (d) magnitude imbalance between Port 1 and Port 2 ($|S_{13} - S_{23}|$).

Figure 4.8 Characterization of the surface profile on 3D printed W-band traditional magic tee. (a) 3D surface profile. (b) Primary profile. (c) Roughness profile.

Figure 4.9 Conventional model and proposed broadband W-band magic tee model in front view, left view and top view. (a) The conventional cylinder posts, difficult for self-supporting in 3D printing, were replaced by round-tip cones. (b) The conventional central sharp-tipped cone, difficult for 3D printing accurately, was replaced by a round-tipped cone. (c) All five cylinder posts were replaced by round-tip cones. (d) The cross-section view of the proposed 3D printing model and the zoomed in view of the central complex structure, which enables broad-matching.

Figure 4.10 Comparison of EM simulation results of the traditional magic tee model and the broadband magic tee model in terms of (a) the matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$), (b) the isolation from Port 2 to Port 1 ($S_{12}$), and Port 4 to Port 3 ($S_{34}$).
Figure 4.11 Fabrication for the W-band 3D printed broadband magic tee. (a) The magic tee model was 3D printed by the DLP 3D printer at an angle of 45° between waveguide channels and the build table. (b) The central matching element was printed in good quality. (c) The magic tee was metallized by the proposed process.

Figure 4.12 Measurement and EM simulation results for the 3D printed W-band matched magic tee compared with measurement results of a CNC-machined magic tee in terms of (a) matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$), (b) isolation from Port 2 to Port 1 ($S_{12}$), and Port 4 to Port 3 ($S_{34}$), (c) insertion loss characterized from Port 3 to Port 1 ($-S_{13} - 3$ dB) and Port 3 to Port 2 ($-S_{23} - 3$ dB), (d) magnitude imbalance between Port 1 and Port 2 ($|S_{13} - S_{23}|$).

Figure 5.1 The proposed W-band turnstile junction OMT design and its sub-circuits. (a) Turnstile junction; (b) "Swan neck" twist; (c) E-plane Y-junction; (d) Simulated input port matching of (a), (b) and (c); (e) Complete OMT model with two polarizations (V-pol and H-pol) labeled.

Figure 5.2 Simulated RL of the optimized turnstile junction with rounded edges on superimposed cylinders.

Figure 5.3 The proposed 3D-printing adjusted turnstile junction OMT design.

Figure 5.4 Simulated results of the proposed OMT design on RL of H-port (solid line) and V-port (dotted line), IL of H-port (plus sign) and V-port (circle), and isolation between H-port and V-port (dash-dotted line).

Figure 5.5 Photos of (a) 3D printed plastic OMT prototype and (b) metallized turnstile junction OMT.

Figure 5.6 Ports response measurement setting for OMT.

Figure 5.7 Measured and simulated RL of H- and V-port of the proposed OMT.

Figure 5.8 Measured and simulated IL of H- and V-port of the proposed OMT.

Figure 5.9 Measured and simulated isolation between H- and V-port of the proposed OMT.

Figure 5.10 The CT-scanned 3D photo for the built OMT.

Figure 5.11 The CT-scanned 2D photos on orthogonal planes that cut along the central superimposed cylinders, for the built OMT.

Figure 5.12 The simulated isolation of the proposed OMT using an asymmetric junction imitating its realistic shape.

Figure 5.13 The corrugated horn design and the dimension.

Figure 5.14 Model of the dual-polarized antenna integrated with the turnstile junction OMT and the corrugated horn designs.

Figure 5.15 Photos of (a) 3D printed dual-pol antenna prototype, and (b) metallized dual-pol antenna.
Figure 5.16  Simulated results for the matching at H- and V-port, and the isolation between those two ports of the dual-pol antenna. ........................................ 92
Figure 5.17  Block diagram of the experiment setup for the measurement of co-polar and X-polar radiation patterns. ......................................................... 93
Figure 5.18  Ratio of H-port Co-polar to V-port X-polar across the frequencies. . 93
Figure 5.19  Measured boresight gain for the dual-pol antenna over W-band frequency. ................................................................. 94
Figure 5.20  Measured E-plane radiation patterns for the dual-pol antenna at 85 and 100 GHz........................................... 94
Figure 5.21  Measured H-plane radiation patterns for the dual-pol antenna at 85 and 100 GHz........................................... 94

Figure 6.1  Component build process: modeling, parallel 3D printing of multiple parts, mechanical preparation, metalization and post assembly. . . . . . . 98
Figure 6.2  (a) single layer of Ag metalization. (b) dual layers of Ag metalization. (c) electroless copper on Ag layer. (d) sharp corner causes defects and discontinuities in metallic layer. (e) curved corners eliminate defects. 99
Figure 6.3  (a) waveguide channel printed parallel to x-y plane (Note printing error – red dashed is desired shape – at top and bottom.), z-axis, and at 45 degree angle to both. (b) impedance matching structure from [61]. (c) rotated impedance matching structure. Note the cylinder (seen from side as a rectangle) cannot be printed at 45 degree angle as there is no support as the part is printed in the z-direction. (d) structure modified to use a cone shape so that as the feature is printed it will self-support. (e) 3D model of magic tee with impedance matching structure. (f) magic tee printed at 45 degree angle to minimize error of the orthogonal waveguide channels. (g) zoomed in photo of printed structure [shown at 45 degree angle for comparison to (d)]. . 104
CHAPTER 1

INTRODUCTION

High frequency millimeter wave (mm-Wave) spectrum (30-300GHz) is enabling the global development of 5G wireless communications, with research being actively conducted in both industry [1] and academia [2]. Frequencies of 5G mm-Wave radio systems move to a higher operating frequency band, compared to 4G or other previous technologies. However, at such frequencies attenuation from atmospheric absorption and free-space path loss increase [3]. Thus, it becomes crucial to minimize the loss when the signals propagate in guided modes, within either in a transmitter or receiver. Therefore, waveguides that feature minimal energy loss are commonplace in high performance antenna feeding networks and in mm-Wave system front-ends packaging [4, 5].

Commercial waveguide components are implemented by using typical subtractive manufacturing technologies, such as computerized numerically controlled (CNC) machining [6] or electronic discharge machining (EDM) [7]. These machining methods are capable of
producing waveguides with high precision and low surface roughness, both critical for achieving a low-loss transmission. However, only a limited selection of geometries can be machined with these techniques. As a result, sub-components are often necessarily mated through labor-intensive processes that involve precision alignment and fastening.

Additive manufacturing (AM) is an alternative to subtractive manufacturing. AM, notably including 3D printing, is an emerging technology suitable for both rapid prototyping (RP) and industrial-scale manufacturing of mechanical parts [8]. AM often presents several benefits over traditional subtractive manufacturing technologies, such as the possibility of fabricating parts with arbitrary geometries, modifying material properties within a part, and consolidating several sub-assemblies into a single part, thus eliminating several mechanical interfaces. Furthermore, AM processes can offer significant reductions in lead time, expenses, and material waste compared to subtractive processes. As such, 3D printing is an attractive option for rapid-prototyping mm-Wave passive components, such as waveguides and associated derivatives.

1.1 Printing Methods and Performance

Based on printing material properties, the AM of mm-Wave components can be divided into two approaches: metal deposition and plastic deposition.

For metal deposition, metallic objects are directly printed from the laser sintering/melting or electron beam melting metallic powders. Technologies used for metal printing are selective laser sintering (SLM), selective laser sintering (SLS) and electron beam melting (EBM) [9]. Resulting 3D prints do not require metallization because of their metallic composite. However, additional metallization of the structures can be used to improve surface roughness or conductivity. [10].
Table 1.1 Comparison of the attenuation from W-band waveguides built by different AM technologies.

<table>
<thead>
<tr>
<th>AM Technology</th>
<th>Conductive Material</th>
<th>Att. (dB/m)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal deposition</td>
<td>EBM</td>
<td>Cu</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>Inconnel 625 (Ni)</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GRCop-84 (Cu)</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AlSi10Mg</td>
<td>(10,23)</td>
</tr>
<tr>
<td>Plastic deposition</td>
<td>Polyjet</td>
<td>Plated Cu</td>
<td>&gt;30</td>
</tr>
<tr>
<td></td>
<td>DLP (this work)</td>
<td>Plated Cu and Ag</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>SLA</td>
<td>Plated Cu</td>
<td>4.2</td>
</tr>
</tbody>
</table>

For plastic deposition, the object is printed in its plastic form by the polymerization process to expose the liquid resins using ultraviolet (UV) light. Plastic printing may be done using stereolithography (SLA), digital light processing (DLP), or Polyjet [9]. These techniques differ in the deposition and exposure method of the resin. SLA uses a UV laser for writing and solidifying the resin. The laser scans the horizontal surface and cures in a serial process, drawing on the plane pixel by pixel. DLP uses a UV projector to simultaneously expose any selected portion of the entire horizontal workspace in a parallel process thereby building the part layer by layer. In contrast, the Polyjet process outputs the resin from multiple printing heads in a serial or quasi-parallel (multiple heads) process and solidifies the resin by using the UV lamp. The plastic prints from any of these methods must undergo a post-metallization process to function as mm-Wave components.

Generally, plastic 3D prints from DLP and SLA technologies have smoother surfaces compared to Polyjet 3D prints and metallic 3D prints [11], leading to lower loss due to the decreased surface roughness. Table 1.1 shows a comparison of the attenuation from W-band waveguides, as built by different AM technologies of DLP [12], SLA [13], Polyjet [14], SLS [15] and EBM [16].
Table 1.2 3D-Print time comparison between DLP and SLA technologies on building waveguides.

<table>
<thead>
<tr>
<th>Model</th>
<th>Printing time for DLP</th>
<th>Printing time for SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single one-inch WG-10 waveguide</td>
<td>2.1 hr</td>
<td>2.3 hr</td>
</tr>
<tr>
<td>Six one-inch WG-10 waveguides</td>
<td>2.2 hr</td>
<td>3.7 hr</td>
</tr>
</tbody>
</table>

Although both DLP and SLA technologies benefit from similarly smooth surfaces, DLP 3D prints are generally built faster than SLA 3D prints when the printing model’s horizontal area is larger than its vertical dimension. As described before, SLA uses a UV laser for writing on the horizontal plane pixel by pixel, while DLP uses a UV projector to simultaneously expose any selected portion of the entire. The latter is more time efficient when building multiple pieces. Table 1.2 compares the printing times for DLP and SLA 3D printers building one-inch WR-10 waveguides. The estimated times were calculated for printing a single piece as well as printing six pieces. While the printing time for the DLP 3D printer remains generally the same for the two tasks, the SLA printing time greatly increases from printing one to six waveguides (see Table 1.2). For those reasons of better printing accuracy and less batch printing time, the dissertation focus on DLP printing and the corresponding challenges in building millimeter-wave waveguide components.
1.2 Challenges in 3D printing

1.2.1 Challenge I - Anisotropic Printing Accuracy

Fig. 1.1(a) shows DLP printing on a waveguide structure. A 2-D image of ultraviolet (UV) light of the desired printed plane is shown on a liquid polymer layer on a UV-transparent substrate. The pattern causes portions of the plane to be solidified, and thus remain part of the final structure. Non-illuminated portions simply flow away. The substrate is then stepped by a small amount (50\(\mu\)m) and the next plane imaged. The process allows batch fabrication of each plane. The resolution and alignment of each plane relative to the other, however, is quite different. The resolution of the projector determines the resolution of the printed form in the \(x\)-\(y\) plane. The mechanical movement of the substrate between each plane determines the resolution in the vertical, or \(z\)-plane and also any movement in the substrate while the structure is vertically stepped, will introduce alignment error.

Fig. 1.1(b) shows a profilometer scan of a section of the printed waveguide channel. The variation in layers in the \(z\) direction can be clearly seen, as well as the roughness in the \(yz\)-plane. The surface was characterized in showing surface profile variation in the \(x\)-direction as \(\pm 10\mu\)m.

1.2.2 Challenge II - Printing Material Plasticity and Supporting Issues

Ideal waveguide structures have sharp edges, transitions, and points that can be difficult to print precisely using 3D printing technologies, which generally have print resolutions larger than 50\(\mu\)m. Moreover, sharp printed features are prone to poor metal adhesion, which can cause the plated metal to crack along the corner. This in turn affects the insertion loss of the component, as will be discussed in this work.
Figure 1.1 (a) I. DLP printing: an image is shown on a thin layer of liquid polymer to cure the desired solid structure. (a) II. and III. The build table is move vertically (z direction) as the part is printed. (b) profilometer scan of an y-z slice of a waveguide wall. Note significant, periodic variation in the z direction due to table movement.
For prints built incrementally from the base to the top, floating or overhanging areas require external supports which should be included as a part of the designed model. The supports of the model don't carry any electrical function and can be immediately removed after the printing process, however they are necessary to guarantee the model's accuracy. Most software provides options for manually adding supports on the model surfaces or automatically generating supports using a built-in algorithm. Unfortunately, adding supports may cause one or more of the following problems:

- The supports are susceptible to bending and distorting during the 3D printing process. Also, they may be designed improperly if the designer lacks mechanical design experience and, as a result, not function well.

- In some designs, the automatically generated supports may be densely distributed, which increases the cost of building the model. Moreover, the dense supports do not always guarantee a successful print, especially to models that have a flat face.

- Many components integrate small structures to better impedance match and/or shape propagation modes into the channels or junctions. Any supports added to those feature will impact to the electrical performance. However, there is no means to build those structures without supports.

1.2.3 Challenge III - Metallization of 3D-Printed Parts

The metallization of polymer components is one of the key processes in fabricating 3D-printed waveguides. Challenges to this process include surface adhesion, chemical compatibility, as well as waveguide-specific challenges, like the metallization of fine geometries and long narrow cavities, such as the W-band waveguide channels. Table 1.3 compares metallized polymer-based waveguide components.
Table 1.3 Comparison of waveguide bands, components types, metallization processes, number of assembly pieces, and side wall opening conditions of reported metallized polymer-based waveguide Components.

<table>
<thead>
<tr>
<th>Waveguide bands</th>
<th>Compo. types</th>
<th>Metallization processes</th>
<th>Assy. pieces</th>
<th>Openings</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR-90</td>
<td>Bandpass Filter</td>
<td>Conductive painted Ag $\sim 20 \mu m$ + ElectroPlate Cu $20 \mu m$</td>
<td>2</td>
<td>N</td>
<td>[18]</td>
</tr>
<tr>
<td></td>
<td>Slotted array</td>
<td>Electroless Ni + Electroplated Cu</td>
<td>1</td>
<td>Y</td>
<td>[19]</td>
</tr>
<tr>
<td>WR-62</td>
<td>Waveguide</td>
<td>Electroless Cu $\sim 5 \mu m$</td>
<td>1</td>
<td>N</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>Horn antenna</td>
<td>Conductive painted Ag</td>
<td>2</td>
<td>N</td>
<td>[21]</td>
</tr>
<tr>
<td>WR-42</td>
<td>Waveguide</td>
<td>Electroless Cu + Electroplated Cu</td>
<td>2</td>
<td>N</td>
<td>[22]</td>
</tr>
<tr>
<td></td>
<td>Bandpass filter</td>
<td>Chemical coated Pd + Electrolated Cu</td>
<td>1</td>
<td>N</td>
<td>[10]</td>
</tr>
<tr>
<td>WR-28</td>
<td>Bandpass filter</td>
<td>Electroplated Cu $10 \mu m$ + Electroless Ag $1 \mu m$</td>
<td>1</td>
<td>Y</td>
<td>[23]</td>
</tr>
<tr>
<td></td>
<td>Waveguide</td>
<td>Electroless Ni $3 \mu m$ + Electroplating Cu</td>
<td>2</td>
<td>N</td>
<td>[24]</td>
</tr>
<tr>
<td>WR-10</td>
<td>Bandpass filter</td>
<td>Proprietary plated Cu</td>
<td>1</td>
<td>Y</td>
<td>[25]</td>
</tr>
<tr>
<td></td>
<td>Coupler</td>
<td>Proprietary plated Cu</td>
<td>1</td>
<td>N</td>
<td>[17]</td>
</tr>
<tr>
<td></td>
<td>Slotted array</td>
<td>Jet Metal sprayed Ag $1 \mu m$</td>
<td>1</td>
<td>Y</td>
<td>[26]</td>
</tr>
<tr>
<td>WR-5</td>
<td>Waveguide</td>
<td>Electroless Ni + Electroplate Cu</td>
<td>2</td>
<td>N</td>
<td>[27]</td>
</tr>
<tr>
<td>WR-3</td>
<td>Waveguide</td>
<td>Proprietary plated Cu</td>
<td>1</td>
<td>N</td>
<td>[28]</td>
</tr>
<tr>
<td>WR-1</td>
<td>Waveguide</td>
<td>Electroless Ni $1 \mu m$ + Electroless Au $30 \text{ nm}$ + Electroplated Au $1 \mu m$</td>
<td>1</td>
<td>N</td>
<td>[29]</td>
</tr>
</tbody>
</table>
Electroless plating is a commonly used metallization method developed for the exterior surfaces and vias found on printed circuits boards (PCBs). Metal is deposited directly onto the surface through a chemical or ionic bond with the plastic \([30]\). The chemistry of the plating process depends on the specific polymer and chemical procedures. Standard electroless plating kits do not perform well on many 3D printing designs due to poor surface wetting and non-optimized chemical processes for the specific designs.

Often, electroless plating is followed by electrolytic plating (also referred to electrolytic plating), which uses an electrolytic and current to deposit metallic ions on the surface. Electrolytic plating can form very thick layers of metal, however it requires the initial electroless plating to establish the current flow. The electrolytic plating process can be particularly challenging in narrow waveguide channels, such as W-band waveguides, as both the electrolyte and current must flow to all parts of the channel. Owing to the small size of these channels, current flow may not be uniform, resulting in areas of low or no plating.

For W-band or above frequency waveguide components, the required waveguide metallic wall thickness, related to five times of skin depth, is approximately 1 \(\mu\)m \([31]\). The reported metalization approaches in Table 1.3 include using a split multi-part model \([24, 27]\), introducing sidewall openings \([25, 26]\), or using a proprietary plating service for a specific material \([13, 28]\). These techniques are not without limitations. The split model approach sacrifices the advantage of building a composite part using 3D printing technologies, creating a problem with alignment. Introducing sidewall openings to improve channel plating reduces the waveguide's mechanical strength and makes the component susceptible to collecting moisture. While effective, proprietary metallization processes limit the material choices available to researchers, potentially inhibiting the adoption of the practice. These limitations indicate the need for a robust plating process that can be used on multiple materials and is suitable for the fine geometries and long narrow channels.
found in millimeter wave structures.

1.3 Focus of the Work

While working on the modeling and post-metallization challenges discussed above, it is realized the necessity of developing a systematic methodology for the fabrication of 3D printing mm-Wave components. This methodology should contain the guidelines and principles for modeling, 3D printing, and metallization during the design and fabrication processes, as well as accounting for the key factors that impact the electrical performance of the fabricated components.

The focus of this work is outlined in a logical sequence that includes investigating the fabrication method, exploring of the simple component performance enhancement, demonstrating the method of building complex structure components, and finally, successfully implementing the method on a compact sub-system application, as depicted in Fig
1.3.1 Simple Electroless Plating Solution for 3D Printed Mm-Wave Components

This section demonstrates a simple silver electroless plating system, which successfully metallizes the exterior and high-aspect-ratio channel of a 1-inch WR-10 acrylate-based polymer 3D-printed test waveguide section. My process is based on the commonly known Tollens’ Test (or silver-mirroring test), used to determine the presence of aldehyde, indicated by the precipitation of silver, often producing a characteristic "silver mirror" on the inner surface of the reaction vessel \[32\]. Advantages over other methods, such as electroless copper deposition, are that this process can be carried out at room temperature and without the need for surface etching, catalyst deposition pretreatment steps or extraneous PH buffering additives. No further plating through additional electroplating was necessary to achieve a sufficient thickness for W-Band signal transmission, which is advantageous when metallizing occluded geometries such as waveguide interiors.

Measurement results of plated WR-10 one-inch waveguide sections show reflection coefficients of less than -21dB and an insertion loss of less than 0.53dB, which are comparable to similar studies using specialized plating and split-block designs. Furthermore, this approach shows great potential in providing an affordable passive microwave component rapid prototyping solution for research applications.

1.3.2 3D Printing Low-Loss Components

This section presents a printing and plating method to fabricate low-loss mm-Wave hollow waveguides. Two DLP 3D printed waveguide designs at different millimeter-wave bands,
W-band (WR-10, 75 to 110 GHz) and D-band (WR-6, 110 to 170 GHz) are demonstrated for this study. The measured W-band 3D printed waveguide exhibits a mean insertion loss of 0.16 dB/in. Measurements for the D-band 3D printed waveguide show a mean transducer loss of 0.65 dB/in, comparable to the performance of a machined and gold-plated metal waveguide.

Then, an innovative method is introduced for building a coaxial transmission line using a low-loss 3D-printed dielectric and a liquid metal conductor. The dielectric part is 3D printed from a low loss factor resin, cyanate ester (\(\tan\delta = 0.0046\)). The inner conductor is formed by pumping eutectic gallium indium (EGaIn) through the empty channel of the dielectric part, and the outer conductor is electrolessly plated with silver and then coated with EGaIn. An implemented two-inch straight coaxial line shows a measured insertion loss of 0.26 dB/cm at 10 GHz, 70% less than the loss of a coaxial line that uses a common 3D printing substrate, like VisiJet Crystal M3. Additionally, a 2-ns 3D printed coaxial delay line was fabricated with a similar approach. It has a low dispersion at the measured group delay of 2ns ± 88ps, as 4.4% variation from 0 to 10 GHz.

Besides, the fabrication method of a complex 3D-mesh antenna is investigated. This antenna consists of small sections of cylinders connected within a confining volume of 5 cm cube. The 3D-mesh antenna, due to its highly complex structure, can be costly and difficult to build using the traditional machining method, however, it can be easily realized with 3D printing. A 45-degree orientation of the model was chosen, minimizing the number of external support structures. The 3D printed antenna part was metallized by silver electroless plating, and copper electroplating for the increase the metal thickness to 30\(\mu\)m. The measured patterns at E- and H-plane are consistent with the simulation result at 5 GHz.
1.3.3 3D Printing Broadband Magic-Tees at W-Band

This part proposes a method for building complex-structured mm-Wave waveguides using a strategy that combines Digital Light Processing (DLP) 3D printing technology, a curved corner design, an off-axis print angle of 45°, and a robust post-metalization process. To demonstrate the capability of this combined-strategy method, a traditional magic tee prototype and an adapted inherently-matched magic tee prototype are fabricated for use in the W-band. The measured performance of the fabricated inherently-matched magic tee demonstrates return loss better than 13.5 dB, isolation coefficients higher than 15.7 dB, insertion losses smaller than 1.3 dB, and a magnitude imbalance of less than 1.3 dB across 80 to 105 GHz. The 3D printed magic tee has a comparable performance to a W-band CNC-machined magic tee, but weighs 77.5% less than the metallic one.

1.3.4 3D Printing Compact Orthomode Transducer and Dual-polarized Antenna at W-band

The section presents a compact W-band OMT using a "swan neck" twist for the connection between a turnstile junction and a E-plane Y-junction, for minimizing the overall OMT structure. The core volume for the proposed OMT is 9× less than the previously reported stacked layer OMT. The compact W-band OMT was built by DLP 3D printing technology and was post-metalized by silver electroless plating. The return loss of the vertical-polarized port (V-port) and the horizontal-polarized port (H-port) is characterized, as averagely 17 dB and 15 dB. The measured isolation between V-port and H-port is averagely 28 dB. Furthermore, the turnstile junction asymmetry along central axis was revealed in CT scanned images. The simulation shows a negative effect of the asymmetric structure to the OMT isolation. Additionally, the dual-polarized (dual-pol) antenna combining such OMT and a corrugated
horn was realized in a compact size. The cross-polarization level of the OMT, characterized in a far field test of this dual-pol antenna, is averagely -18 dB at W-band.

1.4 Contributions

While addressing the challenges on additive manufacturing of mm-Wave and microwave components, this research work has done several pioneer work listed as below.

- 1st in applying DLP 3D-printing for microwave components fabrication.
- Innovatively selected Tollen’s silver plating as a plastic 3D prints metalization method.
- 1st introduced Tollen’s silver and copper electroless plating for W-band waveguides.
- Pioneered in using cyanate ester as low-loss microwave dielectric material.
- Innovatively realized mechanical coating on silver using Eutectic Gallium Indium.
- 1st realized meandered coaxial structure delay-line in 3D printing.
- Proposed 45° print orientation for better print precision on orthogonal channels.
- 1st designed a self-support 3D printing model for broad-band magic-tees
- Pioneered in roughness characterization on DLP microwave 3D prints.
- 1st proposed "swan neck" twists for minimizing orthomode transducer volume.
- Pioneered in using CT scanning for characterizing 3D-printed orthomode transducer.

These PhD work have been published on [33], [12], [34], [35], and [36].
1.5 Dissertation Organization

The organization of the dissertation is as follows.

In Chapter 2, the fabrication method for 3D-printed mm-Wave components is explained in four steps: modeling, printing, metallization, and final assembly.

In the first part of Chapter 3, the mechanical and mating considerations is discussed, in addition to the improved metallization method that has been used for building low-loss 3D-printed waveguides in W- and D-bands. In the second part of Chapter 3, an innovative method to fabricate coaxial transmission lines is presented. A 3D-printed 2-inch coaxial line and a 2-ns delay line are illustrated. In the third part, the simulation and fabrication of a complex 3D-mesh antenna is demonstrated.

In Chapter 4, a method is proposed for building complex-structured millimeter-wave waveguides using a technique that combines Digital Light Processing (DLP) 3D printing technology, a curved corner design, an off-axis print angle of 45°, and a robust post-metallization process. To demonstrate the capability of this combined-strategy method, a traditional magic tee prototype and an adapted inherently-matched magic tee prototype are fabricated for use in the W-band.

In Chapter 5, a compact OMT core design and its 3D-printing-compatible design are introduced. The electrical and mechanical characterization results are discussed. Additionally, the dual-polarized antenna, which integrates the proposed OMT and a corrugated horn, is implemented by 3D printing technology.

Chapter 6 summarizes the main contributions of this work and suggests the research scope for future work.
CHAPTER 2

SIMPLE ELECTROLESS PLATING SOLUTION FOR 3D-PRINTED MM-WAVE COMPONENTS

Consumer-grade DLP 3D printers are the best choice for printing mm-Wave components in the research environment because they print with high native printing resolution (on the order of $30\mu m \times 30\mu m \times 20\mu m$ per voxel), relatively low surface roughness, and at relatively low cost (sub- $5,000$ USD for the printer and ~$200$ USD/L of printing resin). However, one of the greatest challenges in adapting the acrylate-based polymers used in DLP 3D printing for producing conductive microwave components, such as waveguides, lies in the metallization process.

The work in this chapter pioneers on adopting a silver electroless plating system on the
metallization of plastic 3D-printed mm-Wave waveguides. The chapter also presents the modelling and the printing strategies prior to metallization.

2.1 Fabrication

2.1.1 Modeling

As in many other engineering disciplines, existing off-the-shelf product designs are often unsuitable for direct 3D printing without incorporating one or more process-specific modifications. Current metallic waveguide design standards generally prove too fragile to withstand extensive handling when printed in polymers, even when employing high-strength resin blends.

In the design presented here, several modifications were made, in order to maximize overall mechanical performance and minimize macroscopic part geometry variances. In addition, such a test standard needed to show acceptable geometric repeatability when printing on a consumer-grade DLP 3D printer (B9 Creator v1.2, B9 Creations, LLC). Two primary modelling challenges relevant to printing waveguides on a DLP printer are: (1) the induced stresses caused by shrinkage, which accrue during the layer-by-layer polymerization process; and (2) the lower strength and stiffness of polymer-based substrates versus their metal counterparts.

In this proposed design, radial fin structures enclosed by a cylindrical shell were added around an 8mm diameter central core, as shown in Fig. 2.1 (b). This type of structure accomplishes several goals. First, it acts as an integral printing support structure, allowing the part to be printed vertically, directly bonded to the build plate, without an angled orientation or through using external supports. Secondly, the structure reduces waveguide
channel geometry errors between adjacent layers at major transitions in the part's diameter, due to polymerization shrinkage effects. Finally, it adds a degree of geometric stiffness to the overall structure.

Flanges, as in Fig. 2.1 (a), were based on a design made popular by Agilent/HP, an anti-cocking version of the UG-387 type flange [37]. For the current project, overall flange thickness was increased to 4.5mm, and the center-boss's chamfer and locating pin holes were removed. In addition, holes were dimensioned 100μm undersized, with countersinking, to facilitate post-print machining.

2.1.2 Printing

As previously mentioned, a DLP 3D printer was chosen for its high native resolution and overall affordability. Parts presented were printed at x-y- and z-axis resolution settings of...
50µm to balance resulting waveguide channel surface roughness and printing speed. The waveguide model was printed without supports, with one flange face directly attached to the build table. By orienting the waveguide channel orthogonally to the build table surface in this manner, aperture size can be maintained with the greatest amount of precision along the majority of its length.

Parts were printed [as shown in Fig.1 (c)] using a quick-curing acrylate-based resin (B9R-2 Black, B9 Creations, LLC), chosen for the polymer’s relatively high mechanical strength. The printed waveguides were then doubly-rinsed in a 75% isopropyl alcohol/ 25% distilled water solution to thoroughly remove uncured resin from the surface of the print. Post-printing curing was performed on both the top and bottom flange sides for 2 minutes each, using a 600 W UV source (IntelliRay 600, UVITRON Intl.).

2.1.3 Metallization

It is found that commercial electroless plating processes did not work well for the UV sensitive acrylate-based polymers. The principle problem was in the adhesion on the plastic and also coverage - it was difficult for the electroless plating to cover long, narrow channels, such as in simple waveguide. The poor metal adhesion and cracks were often observed on waveguide corners and on valleys of wavy printed channels. This dissertation pioneers in the work of metallizing waveguides using the Tollens' reaction (silver mirror reaction) [32]. This method provides good adhesion of a metallic surface to a wide variety of polymers and was able to cover complex internal channels.

The process flow is outlined in Fig. 2.2, and consists of surface preparation, Tollens’ reagent preparation, and reducing agent mixing steps. To complete this process, the steps are as follows:
**Figure 2.2** Waveguide metallization process outline.
1. Begin with a thorough ultrasonic cleaning of the plating sample: first in acetone, then methanol, and finally isopropanol (i.e. the AMI method) [38]. This method ensures surface cleanliness, which is critical to plating quality and waveguide losses, as dust and organic contaminants can affect coverage, or trap undesired obstacles inside of the waveguide channel.

2. Prepare solutions using a volumetric ratio of 5:1 of Tollens’ reagent to reducing agent solution, respectively. Prepare the reducing agent solution by dissolving 0.4g of dextrose ($\text{C}_6\text{H}_{12}\text{O}_6$) in 10mL of water. Next, Tollens’ reagent is prepared by first dissolving 0.5g of silver nitrate ($\text{AgNO}_3$) in 25 mL of water. Then, slowly add 28% ammonium hydroxide ($\text{NH}_4\text{OH}$), dropwise, until a brown precipitate forms. Continue to add drops of $\text{NH}_4\text{OH}$ until the solution becomes clear. These two steps are conveniently referred to as the "color test" in Fig. 2.2. Then, add a solution of 0.35g of sodium hydroxide ($\text{NaOH}$) dissolved in 25mL of water. Again, a brown precipitate will form. Perform the “color test” again on the new precipitate, adding $\text{NH}_4\text{OH}$ dropwise until the solution becomes clear.

3. Begin the plating process by immersing the sample into the Tollens’ reagent. To ensure consistent plating, remove any air bubbles from the waveguide channel or other features using strong agitation. With moderate agitation, pour all of the dextrose solution into the Tollens’ reagent. A black to light brown precipitate will form and silver will begin to plate all surfaces exposed to the solution. The silver deposition reaction takes place for approximately 1 to 5 minutes. The plated part should then be removed and thoroughly rinsed with water to remove loosely attached particles. Promptly dispose of all unreacted and reacted Tollens’ reagent.

All experiments are performed under a suitable chemical fume hood. Tollens’ reagent is
suggested to be prepared prior to use and properly disposed of after. The Tollens’ reagent solution has the potential to form an explosive precipitate when allowed to stand for extended periods and must be handled appropriately [39].

2.1.4 Final Assembly

After plating, hand reaming is used to bring all holes to their final sizes. Pin bores are dimensioned to 0.0605 in. and 0.0645 in. for mounting and receiving, respectively. Threaded hole bores are dimensioned to 0.0890 in. Since flange locating holes are critical alignment features, for the current experiment a jig was built on an optical breadboard to keep all tools within about 3° of perpendicularly with the flange faces. A #4-40 starting taper hand tap was then used to cut threads directly into the polymer. Threads proved to be adequate for limited use in testing, without noticeable deformation. Standard spherical end dowel pins are then carefully mounted into the pin retaining holes, completing the waveguide assembly. Fit quality is checked against a commercially manufactured WR-10 waveguide flange.

In total, the fabrication process takes approximately 10 hours for modelling, printing and plating a new waveguide design from start to finish (assuming 5 hours of design work for the new waveguide, and a 2-hour average printing time). For existing (previously adapted) designs and with further optimization of the printing and plating process flow, the entire process could theoretically be completed in approximately 4.5 hours of work and in approximately 3.5 hours with multiple people expediting the process.
Figure 2.3 S-parameter measurements, comparing 3D-printed WR-10 waveguides to a traditionally fabricated (EDM) WR-10 waveguide, including: (a) reflection coefficients, (b) insertion coefficients, and (c) loss per meter.
2.2 Measurement

S-parameter measurements of plated prints and off-the-shelf traditionally manufactured one-inch WR-10 waveguide sections were performed by a Vector network analyzer (VNA) using W-band frequency extenders (results in Fig. 2.3). Measured return loss, shown in Fig. 2.3 (a), was on average 21 dB. Average insertion loss, as shown in Fig. 2.3 (b), were 0.37 dB for the printed part, about 0.27 dB larger than the 0.10 dB from the off-the-shelf waveguide. The measured dissipative attenuation ignoring port mismatching [24], as shown in Fig. 2.3 (c), ranges between 10 dB/m (0.036 dB/λg) and 20 dB/m (0.13 dB/λg), with an average of 14 dB/m (0.063 dB/λg). This is also approximately two times higher than the dissipative attenuation of the commercial waveguide, at 4 dB/m (0.017 dB/λg).

These results are comparable to [24], which used a commercial plating house and a split block design, thus requiring good alignment and also increasing development time and cost. However, higher comparative measured losses in the printed part versus the off-the-shelf waveguide could be caused by any number of variables in both the printing and plating processes.

Foremost, insufficient plating thickness, uniformity, or conductivity could explain the relatively high contribution of dissipative losses in the printed waveguide’s measurement results. All three characteristics have yet to be fully characterized in the course of this project and could present a future course of action to follow in post-analysis work. Tomographic data could be generated by destructive testing methods, such as sample slicing and subsequent measurement via SEM to characterize plating thickness variations along the length of the waveguide channel and flange circumference. A comparatively high channel wall surface roughness, initially estimated to be around 15µm RMS through contact probe measurements, could also contribute to the high observed losses. Furthermore, smaller
Table 2.1 Comparisons of assembly methods and attenuation, of published W-band waveguides from different technologies.

<table>
<thead>
<tr>
<th>Manufacturing Technology</th>
<th>Frequency (GHz)</th>
<th># Assy Pcs</th>
<th>Att. dB/m</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtractive Manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNC</td>
<td>75-110</td>
<td>2</td>
<td>~4</td>
<td>[6]</td>
</tr>
<tr>
<td>EDM</td>
<td>75-110</td>
<td>1</td>
<td>~6*</td>
<td>[7]</td>
</tr>
<tr>
<td>Micromaching</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Micromachining</td>
<td>100</td>
<td>2†</td>
<td>14*</td>
<td>[40]</td>
</tr>
<tr>
<td>Surface Micromachining</td>
<td>100</td>
<td>2†</td>
<td>130*</td>
<td>[41]</td>
</tr>
<tr>
<td>Moulding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micromoulding</td>
<td>92.5</td>
<td>4</td>
<td>28</td>
<td>[42]</td>
</tr>
<tr>
<td>Additive Manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLA 3D printing</td>
<td>75-110</td>
<td>2</td>
<td>13*</td>
<td>[24]</td>
</tr>
<tr>
<td>DLP 3D printing</td>
<td>75-110</td>
<td>1</td>
<td>14</td>
<td>This work</td>
</tr>
</tbody>
</table>

* from the figure data
† additional metal blocks required

Loss contributions caused by flange mating misalignments and macroscopic geometry errors could explain some of the observed loss. However these are more difficult to quantify without further geometric analyses.

From a larger process-comparison perspective (see Table 2.1), this 3D-printed waveguides exhibit lower attenuation than W-band waveguide examples made from non-RP techniques such as surface micromachining and micro molding technologies [41, 42]. Attenuation was comparable to examples prepared via traditional SLA 3D printing techniques and bulk micromachining [40]. However, there is still a performance gap between the waveguides presented here and those made using traditional mass-production technologies like precision CNC and EDM machining processes [6, 7]. Aside from considering the performance comparisons, there are additional merits to using the process presented...
here, including the time and effort saved in accurately aligning split block designs, low total system cost, and perhaps most importantly, the extremely rapid turn-around time.

2.3 Summary

Measurement results show comparable performance characteristics to other W-band waveguides, manufactured with other rapid prototyping techniques. Moreover, any potential performance tradeoff could be easily justified by the ability to produce inexpensive, customized waveguide assemblies at a moment’s notice.
Chapter 2 showed that electroless silver plating would provide a robust initial metallization layer on acylate-based polymers. The insertion loss of those parts, however, was still higher than that of commercial waveguides. This chapter presents a novel plating method by applying electroless copper plating on the electroless plated silver, enhancing the metal deposition on plastic waveguide to over 5 times skin depths at W-band, thus reducing the waveguide attenuation.

This chapter further explores the performance limit on another commonly used transmission line, the coaxial transmission line, when it is fabricated using 3D printing technology. The dielectric part of the line was 3D-printed from a low-loss factor resin, cyanate ester ($\tan \delta = 0.0046$). The inner conductor was formed by pumping eutectic gallium indium
(EGaIn) through the empty channel of the dielectric part, and the outer conductor was electrolessly plated with silver and then coated with EGaIn.

3.1 3D Printing Low-Loss Mm-Wave Waveguides

3.1.1 Mechanical and Mating Considerations

Generally, standard metallic waveguide designs [43] are not suitable for printing using the DLP process. Thus, some design modifications needed to be made, both to address design for manufacturability concerns and to achieve suitable mechanical performance. As discussed in Chapter 1, some geometric deformations is due to orientation-dependent accuracy during printing. After several experiments, it was decided to orient the primary axis of the waveguide parallel to the Z axis of the printer (i.e. orthogonal to the build plate), with one of flanges directly attached to the build table. Radius-dependent shrinkage of the interior channel, as well as localized layer delaminations and deformations, were reduced by using conical flange reinforcements (similar to [44]). Additionally, to compensate for the difference in material stiffness between metals and polymers, the minimum wall thickness was increased to 2 mm, increasing the structural stiffness and overall toughness of the part when combined with the conical reinforcements.

Poor mating and alignment at the flanges can cause both impedance and polarization mismatch. The additional stiffness added by the conical reinforcements helps to minimize both flange and body strain during use. Cylindrical cutouts in the conical features allow standard #4-40 captive screws to be used from two directions. In order to remove typical printing defects, such as blooming, from the first few layers of the parts, flange faces were sanded to 1200 grit, removing enough material to ensure the rectangular hollow aperture is
defect-free. Undersized flange hole features were designed into the printed part model and then enlarged using manual machining with hand tools, as described in Chapter 2. Hand-machined screw threads and pinholes were used to improve the assembly quality, which are tapped by specific size taps and reamers. Finally, standard dowel pins were mounted to the pin holes, completing the waveguide assembly.

3.1.2 Metallization

Insertion loss in a hollow rectangular waveguide is due to the ohmic loss associated with conducting walls. In a simple model, ohmic loss constant can be expressed by Equation 3.1

\[
\alpha = \frac{R_s}{\eta b} \sqrt{\frac{2 b \omega^2 c \omega^2_{c}}{\omega^2 - \omega^2_{c}}}.
\]

where \( \omega \) is the operating frequency, \( \omega_c \) is the cutoff frequency, \( a \) and \( b \) are waveguide dimensions, \( \eta \) is the characteristic impedance of the waveguide, and \( R_s \) is sheet resistance of the conductor walls. \( R_s \) is given by Equation 3.2

\[
R_s = \frac{1}{\sigma \delta}, \quad \delta = \frac{2}{w \mu \sigma}.
\]

where \( \sigma \) is the metal conductivity, \( \delta \) is the skin depth, and \( \mu \) is the permeability.

From Equation 3.1 and Equation 3.2, the ohmic loss is determined by the sheet resistance. For commercial metal waveguides, the resistance is mainly affected by the surface roughness of metal walls, decreasing of the effective metal conductivity. Polymer-based 3D-printed waveguides however, experience a more complex situation. Due to the difficulty in metallization of high aspect ratio holes [24], thickness of the deposited metal on the inter-
Figure 3.1 Photograph of 3D-printed 1-inch D-band (front) and W-band (rear) waveguides presented in this paper.

The internal surfaces of the 3D-printed waveguide may be comparable to or thinner than one skin depth. As an example, the skin depth for copper at 100 GHz is 207 nm, and a W-band plastic waveguide should have a minimum metallized layer thickness of 1 µm. Although this may be possible by following the electroless plating process with standard electroplating [14], the experimental results showed inferior metallization quality on the internal surfaces. This could be attributed to non-optimized plating techniques for working on acrylate-based photopolymers with high aspect ratio features, but nonetheless leads to higher insertion loss. Therefore, this work seeks an effective metallization method specifically for low-loss mm-Wave waveguides without the need for electroplating.

Metallization begins with a commercial electroless copper plating process [46], then incorporates three significant changes. First, the initial glucose sensitization and silver activation steps was replaced with a silver electroless plating process. The silver plating process, modified from Tollens' test, can easily plate waveguides’ inner holes and flanges with a conformal silver layer [33]. The plated silver acts as a seeding layer to facilitate the subsequent copper electroless plating process. Second, because 3D-printed polymers have a low melting point, the working temperatures and reaction times were adjusted to lower
values, with the degreasing step at 40°C, the etching step at 40°C for 20 minutes, and the neutralization step at 30°C. Third, the copper electroless plating solution was prepared in a specific order with mild air agitation to maintain the solution's stability [47]. Parts were rinsed twice between each step to reduce cross-contamination. Oxidation of the plated copper may affect performance as time passes, when exposed to typical indoor atmospheric conditions, so plated parts were placed in a desiccated cabinet to reduce the oxidation effect before testing. The completed waveguide prototypes are shown in Fig. 3.1.

The electroless metallization technique as explained above, can completely cover the waveguides’ internal surfaces, while depositing sufficient metallization thickness for the tested frequencies. Parts can therefore be printed as one solid body.

### 3.1.3 Measurement

The plated metal thickness was characterized on the fabricated W-band waveguides in two ways: one used the copper plating process described above, the other used silver electroless plating solution as in [33]. The measured metal thickness is shown in Fig. 3.2. The metal thickness obtained by silver plating is 0.3 µm, approximately 1 skin depth. The thickness is enhanced to 2 µm by applying the proposed copper plating method, greater than 5 skin depths. With increased metal thickness, the 3D-printed waveguide loss performance was expected to approach that of the commercial waveguides.

The 3D-printed W- and D-band waveguides were tested using different measurement techniques. At W-band, full two-port S-parameters of the presented 3D-printed one-inch waveguide, as well as a commercial waveguide, were measured using a VNA with external frequency extenders. The measurement testbench is configured as in Fig. 3.3 (a). Standard TRL calibration was performed to remove systematic errors and move the reference planes.
Figure 3.2 Photographs show the metal plating thickness using two methods (a) silver electroless plating \[33\] (b) the copper electroless plating on top of the plated silver.

Figure 3.3 Photographs of 3D-printed W-band (a) and D-band (b) waveguide testbenches.
Fig. 3.4 shows the measured performance of the one-inch 3D-printed W-band waveguide. As can be seen in Fig. 3.4(a), the $|S_{11}|$ is lower than -16.5 dB over the entire band. The measured data for a 3D-printed waveguide with only silver electroless plating and a commercial metal waveguide are added for comparison. The metal waveguide exhibits a lower return loss compared to 3D-printed waveguides, which is believed caused by imprecise printed aperture sizes and forms of the inner walls. Shown in Fig. 3.4 (b), the measured 1-inch 3D-printed waveguide insertion loss is between 0.12 dB to 0.25 dB with a mean value of 0.16 dB. This value is slightly higher than the measured commercial waveguide, which ranges between 0.05 dB to 0.10 dB. Insertion loss is reduced to half of the silver-plated 3D-printed waveguide, because of an adequate metallic layer added by the copper electroless plating process proposed in this paper.

Due to limited lab equipment, the D-band waveguide was characterized by its transducer loss, which captures both impedance mismatch and insertion loss. The transducer loss is the difference between measured total power, with and without the waveguides inserted between the source and power meter. The measurement testbench is shown in Fig. 3.3 (b). In Fig. 3.5, the transducer loss for the 1-inch D-band 3D-printed waveguide is between 0.26 dB to 1.01 dB from 120 to 170 GHz with a mean value of 0.65 dB. The loss is slightly higher than the commercial gold plated waveguide, which measured between 0.13 dB to 0.75 dB. The data from 110 to 120 GHz is omitted because the loss was measured as a negative value for both waveguides at multiple times.

The performance comparison between 3D-printed waveguides and metal commercial waveguides is summarized in Table 3.1, in which return loss is defined as the maximum return loss over the band, and mean attenuation is defined as the mean loss over the band. From Table 3.1, this 3D-printed W-band waveguide exhibits low loss, 6.34 dB/m, which is much closer to the metallic commercial waveguide than other reported 3D-printed
Figure 3.4 S-parameter comparison of 1-inch W-band waveguides by presented method, silver electroless plated method (in Chapter 2), and commercial machining: (a) reflection coefficient, (b) insertion coefficient.

Figure 3.5 Transducer loss comparison of 1-inch D-band waveguides by presented method and commercial machining.
### Table 3.1 Performance comparison of 3D-printed waveguides and metal commercial waveguides.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Technology</th>
<th>Length</th>
<th>Return Loss (dB)</th>
<th>Mean Att. (dB/m)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>75-110</td>
<td>SLA</td>
<td>2-inch</td>
<td>-19</td>
<td>12.4*</td>
<td>[24]</td>
</tr>
<tr>
<td>75-110</td>
<td>SLA</td>
<td>2-inch</td>
<td>-</td>
<td>7.16</td>
<td>[44]</td>
</tr>
<tr>
<td>75-110</td>
<td>Polyjet</td>
<td>10mm</td>
<td>-22</td>
<td>&gt;30</td>
<td>[14]</td>
</tr>
<tr>
<td>75-110</td>
<td>DMLS</td>
<td>10mm</td>
<td>-</td>
<td>&gt;20</td>
<td>[14]</td>
</tr>
<tr>
<td>75-110</td>
<td>DLP</td>
<td>1-inch</td>
<td>-19</td>
<td>14.0</td>
<td>[33]</td>
</tr>
<tr>
<td>75-110</td>
<td>Metal</td>
<td>1-inch</td>
<td>-22</td>
<td>3.15</td>
<td>Commercial</td>
</tr>
<tr>
<td>75-110</td>
<td>DLP</td>
<td>1-inch</td>
<td>-17</td>
<td>6.34</td>
<td>This work</td>
</tr>
<tr>
<td>110-170</td>
<td>SLM</td>
<td>2-inch</td>
<td>-19</td>
<td>19.0</td>
<td>[15]</td>
</tr>
<tr>
<td>120-170</td>
<td>Metal</td>
<td>1-inch</td>
<td>-</td>
<td>15.3</td>
<td>Commercial</td>
</tr>
<tr>
<td><strong>120-170</strong></td>
<td><strong>DLP</strong></td>
<td><strong>1-inch</strong></td>
<td>-</td>
<td><strong>25.6</strong></td>
<td><strong>This work</strong></td>
</tr>
<tr>
<td>220-330</td>
<td>SLA</td>
<td>1-inch</td>
<td>-</td>
<td>13.9*</td>
<td>[28]</td>
</tr>
</tbody>
</table>

* estimated from the figure data

counterparts.

Few D-band waveguides have been previously reported in the literature. This D-band waveguide has an attenuation of 25.6 dB/m, which is 6.6 dB/m higher than [15]. While [15] does show a lower loss, it is a direct metal fabricated part, rather than a metallized polymer SLA part, as proposed here. Loss of both 3D-printed D-band waveguides is still higher than that of commercial metal waveguides.

### 3.1.4 Summary

This section presents a complete manufacturing method of 3D-printed mm-Wave waveguides featuring relatively low loss. With controls on printing, metallization, and assembly quality, the 3D-printed waveguides' performance approaches that of traditional metal-machined counterparts, but with additional advantages including rapid turn-around time and low manufacturing costs.
3.2 3D-Printed Coaxial Line Using Low Loss Dielectric and Liquid Metal Conductor

3.2.1 Design

Loss is the main specification for the coaxial line characterization. From Equation 3.3, the coaxial line loss consists of the dielectric loss and the conductive loss

\[ \alpha = \alpha_c + \alpha_d = \frac{R_s \varepsilon_r}{2 \eta_0} \left( \frac{1}{a} + \frac{1}{b} \right) + \frac{\omega \varepsilon_r}{2 \varepsilon_0} \tan \delta. \]  

(3.3)

where \( a \) is the diameter of the inner conductor, \( b \) is the diameter of the dielectric, and the sheet resistance \( R_s \) is given by Equation 3.4

\[ R_s = \sqrt{\frac{\omega \mu_0}{2 \sigma}} \]  

(3.4)

For the simplification of the analysis, the dielectric relative permittivity \( \varepsilon_r \) is assumed to be 3, a common permittivity value of materials used for 3D printing. The ratio of the dielectric diameter to the inner conductor diameter \( b/a \) is assumed to be 4.2, which is specified by the characteristic impedance of 50 Ohm. Moreover, the inner conductor diameter \( a \) is selected to be 1.35 mm to be compatible with the SMA extruded pin size. As a result, the dielectric diameter \( b \) is 5.7 mm.

Fig. 3.6 shows the calculated loss of the coaxial line at 10 GHz with regards to the metal conductivity and the dielectric loss factor. Three dielectric materials, VisiJet Crystal M3 at a loss factor of 0.045, cyanate ester at a loss factor of 0.0046, and polyethylene (abbreviated as PE) at a loss factor 0.0007, are chosen. Respectively, these represent
Figure 3.6 Calculated coaxial lines loss per centimeter against the conductor metal conductivity in the parameter of the dielectric loss factor at 10 GHz, assuming $a = 1.35\, mm$, $b = 5.7\, mm$, and $\varepsilon_r = 3$.

The commonly used materials for 3D printing, the low loss factor materials for 3D printing, and the commonly used cable dielectric. The curves show that, for a fixed conductor metal conductivity, the decrease observed in the loss is about 0.6 dB/cm when the dielectric loss factor changes from 0.045 to 0.0046 and 0.1 dB/cm when the dielectric loss factor changes from 0.0046 to 0.0007. In comparison, for any of three dielectrics (VisiJet Crystal, Cyanate Ester, and Polyethylene) the decrease of the loss is about 0.1 dB/cm when the metal conductivity of the conductor changes from $10^5 \, S/m$ to $5.8 \times 10^7 \, S/m$. The conclusion can be drawn that, for a 3D-printed coaxial line, an easy and effective way to decrease the loss is to use the lowest dielectric loss factor available. The effect of the metal conductivity to the loss is negligible when the dielectric loss factor is relatively high.

This experiment used cyanate ester ($\varepsilon_r = 3.12$, $\tan \delta = 0.0046$) as the dielectric material of the coaxial line. To author’s knowledge, cyanate ester has the lowest loss factor among commercially available materials for 3D printing. Since cyanate ester has the relative permittivity slightly higher than 3, the dielectric diameter was modified to 5.9 mm, while the inner conductor diameter remains as 1.35 mm to maintain the same characteristic impedance.
Figure 3.7 3D-printed coaxial line fabrication process. (a) The 3D printing of the coaxial line dielectric; (b) The filling of the coaxial line inner channel with the liquid metal EGaIn; (c) The deposition of the silver seeding layer on the dielectric surface; (d) The coating of EGaIn on the top of the silver layer.

For the central conductor of the coaxial line, EGaIn ($\sigma = 3.4 \times 10^6 \text{S/m}$) was used because it can form conductive channels of an arbitrary shape in a small size (greater than 100 $\mu$m) [51][52]. Although the inner conductor diameter was chosen as 1.35 mm for the proof of concept, the diameter size can be altered according to the operating frequency and the total size requirement.

### 3.2.2 Fabrication

Fig. 3.7 shows the fabrication process for a 3D-printed coaxial line. The cyanate ester coaxial line 3D print was created by continuous liquid interface production (CLIP) 3D Printer (Carbon 3D M1 through). The layer thickness resolution was set to 100 $\mu$m, with the $XY$ plane tolerance of $\pm 0.1 \text{ mm}$ and the $Z$ direction tolerance of $\pm 0.4 \text{ mm}$. Then, the finished 3D print in Fig. 3.7(a) was polished by hand. As the cyanate ester dielectric is translucent, the empty channel can be clearly seen in Fig. 3.7(a).

The inner part of the 3D-printed dielectric was filled by the liquid metal EGaIn. The filling process was conducted using a peristaltic pump to convey EGaIn through tubes to
the inlet of the dielectric as shown in Fig. 3.8. The 3D-printed adapter was used for the connection between the tube and the coaxial line dielectric. Two SMA connectors were mounted on two ends of the dielectric section and sealed with Norland Optical Adhesive 63 (NOA 63), as shown in Fig. 3.7(b).

After that, the deposition of a silver seeding layer on the dielectric exterior surface was performed by electroless silver plating [33]. The purpose for applying a silver seed layer is to provide a high conductive surface, as well as to facilitate the next coating step. The avoidance of the plating on connectors was realized by masking connectors with caps, as shown in Fig. 3.7(c). However, the junction between the dielectric and the SMA covered by NOA 63 was difficult to metalize.

Lastly, the seeded silver layer was manually coated by EGaIn by simply rubbing it on top, which completed an outer conductor of the coaxial line. The 2-inch fabricated 50 Ohm coaxial line is shown in Fig. 3.7(d). Another 3D-printed coaxial line made from Visijet Crystal
Figure 3.9 Measurement results for 2-inch 3D-printed coaxial lines, one using cyanate ester dielectric and the other VisiJet Crystal M3 dielectric. (a) $S_{11}$, (b) $S_{21}$.

M3 is fabricated using a similar process. The goal of this experiment is to evaluate the effect of the dielectric material on the coaxial line loss.

3.2.3 Measurement and Comparison

Fig. 3.9 shows the measurement results of S-parameters of the two 3D-printed 2-inch coaxial lines, one using cyanate ester dielectric denoted by the solid line, and the other using VisiJet Crystal M3 dielectric denoted by the dashed line. Fig. 3.9(a) shows that the cyanate ester line has a low reflection loss ($|S_{11}| < -20$ dB) up to 7.5 GHz, and an acceptable reflection loss ($|S_{11}| < -14$ dB) up to 11 GHz. The figure also shows a similar reflection loss
Table 3.2 Comparison of Coaxial Transmission Line

<table>
<thead>
<tr>
<th>Type</th>
<th>Dielectric</th>
<th>Conductor</th>
<th>IL@10G dB/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG-142 [53]</td>
<td>PTFE</td>
<td>SCCS</td>
<td>0.03</td>
</tr>
<tr>
<td>This Work</td>
<td>VeroWhitePlus</td>
<td>Cu</td>
<td>0.31 (0.16)</td>
</tr>
<tr>
<td>This Work</td>
<td>Visijet Crystal</td>
<td>EGaIn</td>
<td>0.79</td>
</tr>
<tr>
<td>This Work</td>
<td>Cyanate Ester</td>
<td>EGaIn&amp;Ag</td>
<td>0.26</td>
</tr>
</tbody>
</table>

on a visijet crystal M3 line. The increase of the reflection loss at the higher frequency is caused by the propagation of $T E_{11}$ mode with the cut off frequency of 8.5 GHz. The effect of the 3D-printed dielectric type seems insignificant on the reflection loss. From Fig. 3.9(b), at 10 GHz, the measured 2-inch cyanate ester line insertion loss is 1.3 dB, and the Visijet Crystal M3 one line is 4 dB. The insertion loss of the cyanate ester coaxial line is one third of the Visijet Crystal coaxial line loss. This result indicates the importance of using a low loss factor dielectric material, such as cyanate ester, for a high performance 3D-printed coaxial line.

Table 3.2 compares the coaxial line presented here to [53] and a commercial coaxial cable in terms of the dielectric, conductor types, and loss performance. For [53] there are two values, a measured one and another de-embedded one marked in parentheses. This coaxial line using cyanate ester and EgAln conductor exhibits the lowest loss among three 3D-printed coaxial lines. From the table, the loss of the 3D-printed coaxial line is rather high compared to the commercial coaxial cables. As a lower loss tangent 3D printing material is available or a primarily air-dielectric design [53] is used this gap in performance could be closed. The effect of surface roughness, though not discussed here, could be a concern as the losses get lower.
3.2.4 2ns Coaxial Delay Line

Time delay lines are common for a microwave system. In order to reduce the overall area, they often need to be meandered making their shapes more complex and difficult to make. To further illustrate the benefit of my approach, I constructed a serpentine 2-ns coaxial delay line. Fig. 3.10(a) shows the CAD model for the 2-ns coaxial delay line. The coaxial line of the delay line has the same cross-section dimension as the designed 2-inch coaxial line. The length and shape of the delay line was optimized based on the delay time, the mechanical strength, and the fabrication capability. The space between the adjacent lines, was set as 10 mm from center to center. The diameter of 180° bend was designed as 10 mm. The straight line length between bends was designed as 52.2 mm. On each end of the delay line, an extra line with a length of 7.95 mm was added for the feasibility of the connector assembly. Small round posts were added between lines to improve the strength of the structure. The total effective length of the coaxial line is 340 mm, while the total dimension is 68.1 mm × 45.9 mm × 5.9 mm. The fabrication of the 2-ns coaxial line follows the previous description in Section III. Fig. 3.10(b) and (c) shows the EGaIn filled coaxial delay line and
Figure 3.11 Measured result for 2ns 3D-printed coaxial delay line. (a) $S_{11}$, (b) $S_{21}$, (c) group delay.
the coated delay line.

Fig. 3.11 shows the measured S-parameters and the group delay for the fabricated delay line. From Fig. 3.11(a), \(|S_{11}|\) is less than -14 dB up to 10GHz, and \(|S_{21}|\) at 10 GHz is 8.1 dB. The unit loss for the delay line is 0.24 dB/cm, which is consistent with that in Table 3.2. From Fig. 3.11(b), the measured result for the fabricated 2-ns delay line has the variation of ±88ps up to 10 GHz, indicating the low dispersion.

### 3.2.5 Summary

This section proposed an innovative method for the fabrication of coaxial lines, using 3D printing technology. The coaxial line used liquid metal EGaIn as the conductor, and the 3D-printed cyanate ester as the dielectric. Experimental results demonstrate that using a low-loss factor dielectric material, low-loss performance can be achieved. Moreover, the use of EGaIn provides a high level of freedom in designing the coaxial line structure. In future work, reconfigurable coaxial designs could be considered to leverage the benefit of EGaIn.

### 3.3 3D Printing Synthesized 3D-Mesh Antenna

New technologies in cloud computing, advanced Electromagnetic (EM) simulation, and additive manufacturing are enabling new microwave components across the spectrum of applications and frequencies. The availability of cloud computing has removed the barrier to novel EM designs, in particular genetic algorithms for complex, three-dimensional (3D) antenna design. Moreover, the advent of additive manufacturing enables engineers to easily realize designs whose complexity would have been extremely difficult and expensive using traditional manufacturing methods.
3.3.1 Antenna Synthesis

To demonstrate the power of these emerging technologies, a 3D-mesh antenna, was designed using antenna synthesis software AntSyn, which utilizes genetic algorithms and simulates on Amazon’s computing cloud. The 3D-mesh antenna is in the class of evolved antennas, consisting of the rod-shaped conductor (in straight or 90-degree bending), intersected in a way that was synthesized by AntSyn. For this design, the frequency was set for operation between 5.0 and 5.1 GHz. The synthesis goals include three electrical specifications and one geometry constrain: the required return loss was set greater than 10 dB, gain on the boresight was set greater than 5 dBi, gain at 45° off the boresight was set greater than 3 dBi, and the overall geometry of the antenna was constrained to a 6 cm cube. The design platform of the software is shown in the Fig. 3.12.

The synthesis will result in a number of candidate antenna designs, each with an assigned quality rating that reflects how well the design met the antenna requirements. Fig. 3.13 shows the synthesis result of the 3D-mesh antenna including the rating of the synthesized design (top-left corner). The simulated return loss is greater than 18 dB on the designed frequency band. The simulated gain of the antenna at the boresight is 5 dBi. The pattern tapers smoothly from the boresight to 90° off the boresight. The total model size is within 6 cm×6 cm×3 cm including the build-in ground. All specifications met the design requirements.

The results form the synthesis was then exported to HFSS, for further analysis as shown in Fig. 3.14. Several modifications were made to the model to fit for 3D printing fabrication and SMA port assembly. The ground was trimmed to an area of 5 cm×5 cm from its original size. Also, a ring-shape cut was made around the feeding rod. From the result, the simulated return loss is greater than 20 dB, consistent with the synthesis result. The simulated gain,
Figure 3.12 Design platform of AntSyn shows the input of electrical specifications and geometry constrains.
Figure 3.13 3D-mesh antenna synthesis result in AntSyn software. Top figures (from left to right): 3D model, return loss, and max gain; bottom figures (from left to right): 3D pattern, H-plane pattern, E-plane pattern.
Figure 3.14 EM simulated result for the synthesized antenna. Top figures (from left to right): 3D model, return loss, and max gain; bottom figures (from left to right): 3D pattern, H-plane pattern, E-plane pattern.
around 4 dB, is slightly lower than the synthesized gain (5 dB). The H-plane pattern at 5 GHz has an approximating symmetric pattern, but E-plane pattern is not symmetric.

### 3.3.2 Fabrication

The 3D-mesh antenna, due to its highly complex structure, can be costly and difficult to build using the traditional machining method, however, it can be easily realized with 3D printing. The fabrication process for the 3D-mesh antenna is shown in Fig. 3.15. The EM simulated model in Fig. 3.15 (a) with minor modifications on the feeding port can be directly used for 3D printing. The model was 3D printed using a digital light processing (DLP) 3D printer and acrylate-based resin material. A 45° orientation of the model was chosen, as shown in Fig. 3.15 (b), allowing the number of external support structures to be minimized. The 3D printed antenna part was metalized [Fig. 3.15 (c)] by using a method developed in Chapter 2, which is an electroless plating process adapted for 3D printing material coating the surface with 200 nm thickness of silver. The metal layer thickness was increased to 30 µm by using electrolytic copper plating. The total dimension of the fabricated antenna is within 5 cm×5 cm×3 cm.

### 3.3.3 Test

The fabricated antenna was then mounted on a rotary station in the anechoic chamber for the pattern testing, Fig. 3.15 (d). The S-parameters, gain, and radiation pattern of the 3D-mesh antenna were measured and compared to the EM simulation result, as shown in Fig. 3.16. The measured return loss shows the wideband matching from 5.0-5.1 GHz. The measured gain is around 4 dBi near 5 GHz. The measured patterns at E- and H-plane are consistent with the simulation result at 5 GHz. The discrepancy between the simulation
and measurement could be raised by the dimension errors during the 3D printing process or the effect of coaxial feeding, which was not included in the simulation.

### 3.3.4 Summary

This work demonstrated the simulation and fabrication of a complex 3D-mesh antenna. The design was enabled by the genetic algorithm based design used in AntSyn combined with fast (cloud-based) electromagnetic analysis. 3D printing as a fabrication method can be used for building antenna structures that were too-difficult to prototype using traditional methods. The combination of advanced synthesis, cloud based computing and 3D printing are likely to enable a new paradigm for antenna design.
Figure 3.16 Comparison of measurement and Analyst EM simulation result of the 3D-mesh antenna: return loss, gain, H-plane pattern at 5 GHz, and E-plane pattern at 5 GHz.
This chapter contributes a pioneer approach of combining the use of the curved edges design and off-asis 45°-print for a better printing accuracy and the capability of printing complex internal structure in waveguide components. The proposed method is demonstrated through the realization of a high-performance, single composite, broadband magic tee, which includes several functional additive structures made possible by 3D printing.

4.1 3D Printing for Accurate Dimensions and Metallization

As mentioned previously, SLA and DLP are very similar processes, but DLP benefits from faster print times due to its parallel processing of the $x$-$y$ plane in a single exposure. It is for this reason I focus on DLP printing and the challenges that present themselves in achieving
4.1.1 45° Orientation 3D Printing Set

3D printers typically treat the $x$-$y$ dimensions and the $z$ dimension differently. The difference in printing processes for the $x$-$y$ plane and the $z$ axis can create discrepancies in printing accuracy between the two directions. This presents a challenge for complex parts who have structures in multiple directions, such as magic tees or orthomode transducers. This research found that optimizing the orientation of the printed model can alleviate the problem of differing $x$-$y$ and $z$ behaviors.

Fig. 4.1 defines WR-10 sections (2.54 mm $\times$ 1.27 mm) in multiple orientations. Fig. 4.2 illustrates an experiment where the dimensional accuracy was examined for 3D printed WR-10 sections using Fig. 4.1 definition during the DLP printing process. A batch of eleven

![Diagram](image-url)

<table>
<thead>
<tr>
<th>Group</th>
<th>#</th>
<th>WG parallel direction</th>
<th>WG vertical direction</th>
<th>Channel direction angle to x-y plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>$x$</td>
<td>$z$</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$x$</td>
<td>$y$</td>
<td>90°</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>$y$</td>
<td>$z$</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>$y$</td>
<td>$x$</td>
<td>90°</td>
</tr>
<tr>
<td>II</td>
<td>5</td>
<td>$x$</td>
<td>$y$</td>
<td>90°</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>$x$</td>
<td>$y$</td>
<td>90°</td>
</tr>
<tr>
<td>III</td>
<td>7</td>
<td>$x$</td>
<td>$-y,z$</td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>$x$</td>
<td>$-y,z$</td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>$-y,z$</td>
<td>$x,y,z$</td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>$-y,z$</td>
<td>$x,y,z$</td>
<td>45°</td>
</tr>
<tr>
<td>IV</td>
<td>11</td>
<td>$-x,z$</td>
<td>$x,z$</td>
<td>0°</td>
</tr>
</tbody>
</table>
Figure 4.2 Experiment on 3D printing dimension accuracy of WR-10 sections in multiple orientations, as defined in Fig. 4.1. (a) The diagram and numbering of WR-10 sections in multiple orientations. (b) The photograph of the 3D printed sections. (c) The diagram of dimensional characterization of the section's cross-section. (d) The cross-section measurement (optical) to characterize the 3D printed WR-10 section's dimensions.
pieces of WR-10 section models in four orientation groups were 3D printed, as shown in Fig. 4.2(a)-(b).

After fabrication, a cross-section cut was made to characterize the 3D printed channel's dimensions, as shown in Fig. 4.2(c)-(d). The expected dimensions of a standard WR-10 channel is shown as a red rectangle superimposed on the samples' photographs. Fig. 4.2(d) shows high printing accuracy of the WR-10 channel when the aperture is rotated by 90° (Group II) or 45° (Group III) from the x-y plane.

Prints that feature the waveguide channel direction at an angle of 0° (Group I, IV) to the x-y plane exhibited poor dimensional accuracy, specifically in the z-axis. In this orientation, the length of the waveguide was parallel to the printer's build table. The printed layer was elevated incrementally in the z-dimension between each corresponding x-y plane's UV exposure. The bottom part of the waveguide was printed first, and the build table drew up and away from the liquid resin pool. Subsequently, the side walls were exposed and printed, during which the waveguide hollow area without the exposure was filled with liquid resin. Then, the top part was printed and the area originally filled with resin was under exposure again. However, from the observation, the sudden transition to a large unsupported layer caused the over-sized wall.

Table 4.1 compares the accuracy of the 3D printed waveguides' cross-sectional dimensions in different orientations. From the table, the least accurate dimensions occur in Group I, when the channel direction is oriented 0° from the x-y plane, with a tolerance of 0.6 mm. An improved tolerance of 0.1 mm can be obtained by orienting the waveguide aperture at 45° or 90° from the x-y plane, as in Groups II and III.

As previously mentioned, more complex waveguide models like magic tees require precise dimensions for two orthogonal waveguide channels. The results of this experiment suggest that a print orientation of 45° is optimal for such models.
Table 4.1 Comparison of 3D Printed Dimension Accuracy of WR-10 Channels (2.54 mm × 1.27 mm) in Different Orientations.

<table>
<thead>
<tr>
<th>Group</th>
<th>Hole Orientation</th>
<th>Length Error (mm)</th>
<th>Width Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0°</td>
<td>±0.60</td>
<td>±0.06</td>
</tr>
<tr>
<td>II</td>
<td>90°</td>
<td>±0.08</td>
<td>±0.05</td>
</tr>
<tr>
<td>III</td>
<td>45°</td>
<td>±0.10</td>
<td>±0.08</td>
</tr>
</tbody>
</table>

4.1.2 Metallization

The success of printed waveguide components is intrinsically tied to a robust metallization process that is effective when applied to materials used in the 3D printing system. Fig. 4.3 presents the recipe that is developed for the metallization of complex mm-Wave waveguide structures. The metallization process consisted of four steps. First, the print was prepared for metal adhesion by increasing its wettability. Second, the prepared print was seeded by silver that coated the entire print with a thin metal layer (~200 nm). In the third step, a thick copper layer (~2 µm) was deposited on the silver-seeded part through electroless plating. Finally, the part was passivated by silver to prevent the part from oxidizing [54]. An electrolytic plating was not used due to the aforementioned complexity; additionally, the resulting structures performed very well in mm-Wave measurements, indicating an electrolytic process is unnecessary.

4.1.2.1 Wetting

Each 3D printed waveguide was ultrasonically cleaned for 15 minutes in a degreasing solution that consists of 100 mL of DI water, 4 g of sodium hydroxide, and 5.3 g of sodium carbohydrate, held at a temperature of 40°C. The cleaned print was then immersed in an etching solution consisting of 100 mL of DI water, 3.2g of potassium permanganate, and 2.5 mL of 98% sulfuric acid at a temperature of 50°C for 20 minutes. After being etched, the
Figure 4.3 Recipe developed for the metallization of complex mm-Wave waveguide structures.
print was immersed in a neutralizing solution consisting of 100 mL of DI water, and 4.5 g of oxalic acid at a temperature of 40°C for 10 minutes.

The effectiveness of surface wetting was evaluated by examining the water contact angle, measured by a goniometer, before and after the wetting step. A lower water contact angle indicated a higher wettability of the surface, which indicated a coating is more likely to have good adhesion[55]. A comparison of the measured water contact before and after wetting is shown on the top left side in Fig. 4.3. The decreasing of the water contacted angle from 82° to 63°, after wetting, confirms that the step is effective to prepare the 3D print for metallization.

### 4.1.2.2 Silver Seeding

The seeding step started from the preparation of Tollens' reagent: first 28% ammonium hydroxide was added dropwise to the silver nitrate solution, consisting of 0.51 g of silver nitrate and 30 mL of DI water forming a brown precipitate. Ammonium hydroxide was added dropwise until the precipitate disappeared. Another brown precipitate formed after adding a sodium hydroxide solution, consisting of 0.96 g of sodium hydroxide and 30 mL of DI water. Once again, ammonium hydroxide was added until the solution was clear. The wetted print was then placed in the Tollens' reagent before the addition of a reducing agent, consisting of 0.11 g of glucose, and 2.5 mL of water. After 2 minutes, the silver seeding process was complete.

This silver seeding process was demonstrated on a W-band waveguide print in Chapter 2. The strategy was proven to coat the entire print including the interior channel with a silver layer 200 nm or less in thickness. The seeded waveguide presented the average loss of 0.36 dB/inch.

I note that silver nitrate is found to be a very robust deposition of metal for a wide range
of polymers. Additionally, the absence of current and thin deposition thickness, make it ideal for very small features and channels.

4.1.2.3 Copper Plating

The copper plating step required a stable plating bath, consisting of two solutions and a stabilizer. The first solution was composed of 1.68 g of copper sulfate, 0.12 g of nickel sulfate, 2.23 mL of 37% formaldehyde, and 75 mL of DI water. A second solution, composed of 2.4 g of sodium hydroxide, 8.46 g of potassium sodium tartrate, and 75 mL of DI water, was added to the first solution. Afterwards, 4.68 mg of 2,2'-Bipyridine was added as a stabilizer. The silver-seeded print was immersed in the copper plating bath for one hour at a room temperature with air agitation.

The deposited copper on silver reached \( \sim 2.5 \mu m \) thickness, more than 5 times the skin depth of copper at 90 GHz. The tested W-band waveguide achieved the average loss of 0.16 dB/inch (see Chapter 3).

4.1.2.4 Silver Passivation

The purpose of silver passivation is to protect the plated surface from oxidation. The bath consists of 0.4 g of silver nitrate, 10 g of ammonium sulfate, 180 mL of DI water, 20 mL 28% ammonium hydroxide, 0.25 g of hydrazine sulfate, and 0.2 mL of Triton X-114. The plated print was immersed in the passivation bath for 2 minutes at a room temperature, thus completing the print process.

A plated strip with the surface area of 1 mm \( \times \) 29.5 mm was prepared for the DC bulk conductivity analysis. Measurement of the resistance between probes at different distances along the sample was made. The average resistance on a length of 7.34 mm line was measured as 0.1 \( \Omega \). The plated metal layer thickness of 5 \( \mu m \) was estimated using an optical
scale bar on microscope image. Based on the above information, the DC bulk conductivity was estimated at $1.5 \times 10^7$ S/m.

### 4.1.3 Curved Corner Model Design

Ideal waveguide structures have sharp edges, transitions, and points that can be difficult to print precisely using 3D printing technologies, which generally have print resolutions larger than $50 \mu m$. Moreover, sharp printed features are prone to poor metal adhesion, which can cause the plated metal to crack along the corner. This in turn affects the insertion loss of the component, as will be discussed below. Both problems can be mitigated by modifying designs to include curved surfaces in place of sharp edges and other fine geometric features. Although the rounded corner has been reported in the filter design to enhance the power handling [56], its effect on metal plated polymer-based waveguides has not been reported to the best of my knowledge.

Fig. 4.4(a) shows a plated 3D printing waveguide that cracked along its inside corner. The crack was a result of poor metal adhesion, likely related to the limited contact area between the plating solution and the plastic on a sharp edge. Fig. 4.4(b) shows a simulated model used to evaluate the cracking effect in HFSS. The model used was a one-inch WR-10 waveguide with $2 \mu m$ width slits on the corners, surrounded by 1 mm thick polymer. The waveguide wall's boundary condition was assigned as silver conductor. As a reference, an ideal model with no slits was built as well. Fig. 4.4(e) shows a comparison of the simulated insertion loss between the cracked corner model (dotted line) and the ideal model (solid line). The simulation result shows ~1 dB more attenuation solely from the crack. The plated waveguide, in Fig. 4.4(a), was measured and showed a greater than 1 dB attenuation, as the problem was magnified by the factor of surface roughness of the waveguide walls.
Figure 4.4 Experiment on the effect of the curved corner design on the waveguide. (a) The plated 3D printing waveguide showed cracks on the channel corners. (b) The equivalent cracked corner waveguide design was modeled. (c) The modified waveguide in curved corners was fully plated. (d) The equivalent curved corner waveguide design was modeled. (e) A comparison of the simulated insertion loss between the ideal model (solid line), the curved corner model (dash line), and the crack corner model (dotted line).
A curved corner design was proposed for the replacement of the straight corner design, as shown in Fig. 4.4(d). The curved corner has a shape of an arc in an angle of \( \pi/2 \) and a radius of 0.2 times longer width of the waveguide. The curved corner model was 3D printed and metallized, following the same step as the straight corner model. Fig. 4.4(c) shows the channel was fully metallized and no cracks on the corner. The effect of the modification was also evaluated by the simulation. The simulated insertion loss of the curved corner model, added in Fig. 4.4(e) (dashed line), shows negligible difference compared to the ideal model. This suggests that the use of curved corners on a waveguide model facilitates total coverage in the metallization process without compromising the RF performance. This could be the critical modification to maintain a low attenuation.

### 4.2 3D Printed W-band Magic Tee - Example I

In this section, I describe the fabrication of a traditional magic tee to illustrate how my approach can overcome the problems of printing and metallization of orthogonal waveguide channels. The magic tee provides an excellent example of a multi-channel device with orthogonal orientation, as well as demanding requirements for matching, isolation, and power distribution. Operating at W-band demonstrates its applicability to high-performance and emerging systems.

#### 4.2.1 Model and Fabrication

A magic tee is a four-port hybrid waveguide component devised to divide incident power evenly across two output ports; the output signals are either in-phase or out-of-phase depending on which of two input ports are used. The traditional magic tee model, developed by Bell Labs, has two co-linear ports and two cross-polarized ports joined at the junction
Figure 4.5 Fabrication of the 3D printed W-band traditional magic tee following the criteria in Sec.  
(a) The traditional W-band magic tee model was optimized for 3D printing, with the curved corner design. (b) The model was orientated such that the four arms were in 45° angle to the build table plane (x-y plane). (c) The magic tee was metallized by the proposed process.
Fig. 4.5 (a) shows a traditional W-band magic tee model optimized for 3D printing. (The term "traditional" introduced here is to differentiate the design to a modified design in Section 4.3.) This design used curved corner features to facilitate the metallization process, whose benefit was explained in Section 4.1.3. Fig. 4.5 (b) shows the model was orientated such that the four arms were in 45° angle to the build table plane (x-y plane). As discussed in Section 4.1.1, the 3D printing accuracy will be within 100 μm when the channel’s direction is 45° to the x-y plane. The traditional magic tee was built in a DLP 3D printer (B9 Creator v1.2) with the acrylate-based resin (B9R-2 Black). The magic tee print was then rinsed in a Trimethyl ether solution and a 75% isopropyl alcohol solution to remove uncured resin. Post-curing was performed for 4 minutes, using a 600 W UV source (IntelliRay 600). Finally, the prepared magic tee was metallized following the steps of wetting, seeding, plating, and passivating in Section 4.1.2, Fig. 4.5(c) shows the photo of the metallized magic tee created using the roadmap outlined in Section 4.1. The port numbering is added for reference.

4.2.2 Simulation and Measurement

The magic tee is characterized by four groups of parameters: port matching, port isolation, insertion loss, and magnitude imbalance. A two-port measurement of the 3D printed magic tee was performed using a PNA (Agilent E8361C) and W-band extenders (Agilent N5260A), with the two remaining ports connected to waveguide terminators, as shown in Fig. 4.6.

Measurement and EM simulation results for the 3D printed W-band traditional magic tee were compared with measurement results of a machined traditional magic tee, as shown in Fig. 4.7. The measured results of the 3D printed magic tee, the machined magic tee, and the EM simulation are represented by the solid line, the dashed line, and the dotted line, respectively.
**Figure 4.6** Photograph of the setup for the characterization of the W-band 3D printed traditional magic tee.

**Figure 4.7** Measurement and EM simulation results for the 3D printed W-band traditional magic tees compared with measurement results of a machined traditional magic tee in terms of (a) matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$), (b) isolation from Port 2 to Port 1 ($S_{12}$), and Port 4 to Port 3 ($S_{34}$), (c) insertion loss characterized from Port 3 to Port 1 ($-S_{13} - 3$ dB) and Port 3 to Port 2 ($-S_{23} - 3$ dB), (d) magnitude imbalance between Port 1 and Port 2 ($|S_{13} - S_{23}|$).
Fig. 4.7(a) shows the matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$). From the figure, the maximum magnitude of $S_{33}$ and $S_{44}$ for the 3D printed magic tee was -4.8 dB and -3.7 dB across 80 to 105 GHz. When compared to the machined magic tee, $S_{44}$ for both magic tees are approximately the same, and $S_{33}$ of the 3D printed magic tee was slightly better. Fig. 4.7(b) shows the isolation from Port 2 to Port 1 ($S_{12}$) and Port 4 to Port 3 ($S_{34}$). From the figure, the maximum magnitude of $S_{12}$ and $S_{34}$ for the 3D printed magic tee was -3.5 dB and -29.5 dB across 80 to 105 GHz. The result is similar to that of the machined magic tee, though the machined one was slightly better $S_{34}$. Fig. 4.7(c) shows the insertion loss characterized by subtracting the nominal power division of 3 dB from Port 3 to Port 1 ($-S_{13} - 3$ dB) and Port 3 to Port 2 ($-S_{23} - 3$ dB). From the figure, the maximum insertion loss to Port 1 and Port 2 was -5.5 dB and -4.2 dB across 80 to 105 GHz, comparable to the machined magic tee. A resonance appears at the end of the band for both magic tees, as verified by the simulation result. Fig. 4.7(d) shows the magnitude imbalance between Port 1 and Port 2 ($|S_{13} - S_{23}|$). From the figure, the maximum imbalance of the 3D printed magic tee was 1.3 dB across 80 to 105 GHz, twice that of the machined magic tee.

The 3D printed magic tee results are comparable to the machined magic tee in terms of matching, isolation, and insertion loss, although the 3D printed magic tee has a relative higher magnitude imbalance because the symmetric design is difficult to fabricate in 3D printing. The results demonstrates that my approach for 3D printed multi-axis and multi-channel components can produce results comparable to commercial components. In particular the issues of metallization and channel deformation during printing contiguous channels (cracks) were overcome.
4.2.3 Surface Roughness Characterization

One arm of the 3D printed W-band traditional magic tee was purposely split from the main body to characterize the surface profile on the waveguide’s inner wall. Fig. 4.8(a) shows the profile measured by a profile-analyzing laser microscope (Keyence VK-X1000) with the objective lens with the magnification factor 10×. The wavy surface feature is the accumulated result of 3D printing and plating. The profile shows a tilt angle because the part was printed in the 45° orientation.

Further analysis was carried out on the captured photo [Fig. 4.8(a)] in the software MultiFileAnalyzer to study the line surface roughness. The cutoff value ($\lambda_c$), the wavelength that is the branch point between roughness component and waviness component, was set to 25 $\mu$m. This value was selected as it is close to the DLP 3D printing $z$ direction layer thickness. The purpose of setting a cutoff value was to correctly separate waviness from roughness [58]. Fig. 4.8(b) and (c) demonstrates the primary profile, with waviness and roughness contained, as well as the roughness profile along a line with the length of 800 $\mu$m in the transversal direction. Therein, ripples in periods of $\sim$50 $\mu$m are visible because the $z$ axis increment in 3D printing was 50 $\mu$m. The absolute surface variation in the primary profile [Fig. 4.8(b)] is ±18 $\mu$m. With the waviness removed, the absolute surface variation in the roughness profile [Fig. 4.8(c)] is ±2 $\mu$m. The obtained surface roughness parameters are $R_a = 430$ nm and $R_q = 540$ nm.

4.3 3D Printed W-band Broadband Magic Tee - Example II

In this section I investigated the use of 3D printing to enable complex shapes that significantly increase the performance of complex waveguide components. Specifically, I
Figure 4.8 Characterization of the surface profile on 3D printed W-band traditional magic tee. (a) 3D surface profile. (b) Primary profile. (c) Roughness profile.
fabricated a single-composite magic tee with added small internal structures that provide broadband performance. These added fine structures significantly improved impedance matching and resulted in a 3D printed broadband magic tee (abbreviated as "matched 3DP magic tee" in figures and tables) comparable to high-performance machined magic tees. Moreover, they demonstrate the potential for single-piece, complex mm-Wave geometries using 3D printing.

4.3.1 Improved Design

To improve the performance of the magic tee, namely the device's matching and isolation, numerous modifications to the basic design have been proposed over the years. For example, a post or similar element inside the H-plane and an inductive iris or similar element inside the E-plane have been studied [59]. In another example, a double ridge waveguide magic tee [60] increased the magic tee's bandwidth. A more general solution for the broadband magic tee is to place a cone or a pin in the junction [61]. Since the internal matching networks are normally located close to or within the waveguide junction, it is difficult to directly machine those features, especially when the waveguide size becomes very small, as the frequency moves up to mm-Wave. Commercial solutions of broadband magic tees rely on multiple pieces, each precisely machined, and then assembled into a single component.

4.3.2 Model and Simulation

The left column of Fig. 4.9 shows a conventional approach to improve matching by placing a sharp cone at the center of the junction [61], with small cylinders prior to the junction in each waveguide branch. An initial attempt to replicate this design in 3D DLP printing proved unsuccessful, as the fine features were not reproducible. When a feature is not compatible
Table 4.2 Design Dimensions of W-Band Broadband Magic Tee.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Variable</th>
<th>Value</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.27 mm</td>
<td>d_4</td>
<td>0.1 mm</td>
<td>l_2</td>
<td>1.1 mm</td>
</tr>
<tr>
<td>b</td>
<td>2.56 mm</td>
<td>h_1</td>
<td>0.23 mm</td>
<td>l_3</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>d_1</td>
<td>0.55 mm</td>
<td>h_2</td>
<td>0.635 mm</td>
<td>s_1</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>d_2</td>
<td>3.5 mm</td>
<td>h_3</td>
<td>1.265 mm</td>
<td>s_2</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>d_3</td>
<td>0.55 mm</td>
<td>l_1</td>
<td>1.2 mm</td>
<td>γ</td>
<td>45°</td>
</tr>
</tbody>
</table>

with 3D printing capability, the resulting structure can have significant defects, rather than simply being a coarse approximation. These defects often lead to poor performance.

Here, three modifications were made to the original machining-oriented model. First, the conventional cylinder posts, difficult for self-supporting in 3D printing, were replaced by round-tip cones [Fig. 4.9(a)]. Second, the conventional central sharp-tipped cone, difficult to 3D print accurately, was replaced by a round-tipped cone [Fig. 4.9(b)]. Third, the wall edges were rounded, as in the traditional 3D-printed magic tee design, [Fig. 4.9(d)]. The dimensions of the broadband magic tee are shown in Table 4.2. The parameters were obtained by two steps: first, the parameters provided in [61] for M-band (10.0 to 15.0 GHz) were scaled down to the W-band size; second, the optimization was operated in HFSS to meet the desired specifications. The total dimension of the magic tee was 30.48 mm × 24.8 mm × 24.8 mm.

It should be noted that the added features are mostly sub-millimeter and multi-dimensional. This is one of the benefits of modern 3D printers – the ability to reproduce complex shapes in small dimensions. This is likely to be a key enabler for future microwave devices.

The EM simulation results of the traditional magic tee and broadband magic tee are shown in Fig. 4.10, represented by dotted lines and solid lines, respectively. From Fig. 4.10(a), the magnitude of $S_{33}$ and $S_{44}$ of the broadband magic tee is -16.2 dB and -17.1 dB across
Figure 4.9 Conventional model and proposed broadband W-band magic tee model in front view, left view and top view. (a) The conventional cylinder posts, difficult for self-supporting in 3D printing, were replaced by round-tip cones. (b) The conventional central sharp-tipped cone, difficult for 3D printing accurately, was replaced by a round-tipped cone. (c) All five cylinder posts were replaced by round-tip cones. (d) The cross-section view of the proposed 3D printing model and the zoomed in view of the central complex structure, which enables broad-matching.
Figure 4.10 Comparison of EM simulation results of the traditional magic tee model and the broadband magic tee model in terms of (a) the matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$), (b) the isolation from Port 2 to Port 1 ($S_{12}$), and Port 4 to Port 3 ($S_{34}$).

W-band, and the improvement from that of the traditional magic tee is at least 11.2 dB and 10.0 dB. From Fig. 4.10(b), the magnitude of $S_{12}$ and $S_{34}$ of the broadband magic tee is -18.1 dB and -49.0 dB, and the improvement from that of the traditional magic tee for $S_{12}$ is at least 12.1 dB, though there is a slight degeneration for $S_{34}$.

### 4.3.3 Fabrication and Measurement

Fig. 4.11 shows the fabrication for the 3D printed broadband magic tee. The magic tee model was 3D printed by the DLP 3D printer at an angle of 45° between waveguide channels.
Fabrication for the W-band 3D printed broadband magic tee. (a) The magic tee model was 3D printed by the DLP 3D printer at an angle of 45° between waveguide channels and the build table. (b) The central matching element was printed in good quality. (c) The magic tee was metallized by the proposed process.

and the build table, as shown in Fig. 4.11(a). The central matching element was printed in good quality, shown in Fig. 4.11(b). The previously described plating process was used to metalize the magic tee, and the final product is shown in Fig. 4.11(c). The test equipment setup was the same as before for the traditional magic tee.

The measurement and simulation results for the magic tee is shown in Fig. 4.12. Additionally, the test data for a commercially available W-band CNC-machined magic tee were added for comparison. Fig. 4.12(a) shows the maximum measured magnitude for $S_{33}$ and
$S_{44}$ is -14.3 dB and -13.5 dB across 80 to 105 GHz. The frequency response of the 3D printed magic tee across the band is flatter than the CNC-machined one that was optimized for a matching near the central frequency. Fig. 4.12(b) shows the maximum measured magnitude of $S_{12}$ and $S_{34}$ is -15.7 dB and -25.2 dB across 80 to 105 GHz. The measured isolation results for $S_{12}$, which is not as optimal as the commercial component, is consistent with the EM simulation result and is acceptable for most RF applications. Fig. 4.12(c) shows the maximum measured loss of 1.3 and 0.6 for the signal that traveled from Port 3 to Port 1 and Port 3 to Port 2, which is comparable to the CNC-machined counterpart. And Fig. 4.12(d) shows the maximum measured magnitude imbalance is 1.3 dB between Port 1 and Port 2, larger than that of the CNC-machined one.

The power handing capability of the magic tee was not considered in this initial work. The heat deflection temperature of the material is 149 °F at 0.45 MPa. More thermally stable polymers using similar fabrication techniques have been reported [62] and may yield higher temperature (power) operation of such devices.

### 4.3.4 Magic Tee Comparison

Table 4.3 summarizes the measurement performance of four types of magic tees: the 3D printed broadband magic tee, the CNC-machined magic tee, the 3D printed traditional magic tee, and the machined traditional magic tee. First, I can conclude the magic tees using internal matching model networks have better matching, higher isolation, and lower insertion loss when compared to the traditional magic tees. Second, when comparing between the 3D printed broadband magic tee and the CNC-machined one, both magic tees perform similarly even though the latter shows marginally better matching and isolation. However, the performance gap could be closed as the 3D printed broadband model is
Figure 4.12 Measurement and EM simulation results for the 3D printed W-band matched magic tee compared with measurement results of a CNC-machined magic tee in terms of (a) matching at Port 3 ($S_{33}$) and Port 4 ($S_{44}$), (b) isolation from Port 2 to Port 1 ($S_{12}$), and Port 4 to Port 3 ($S_{34}$), (c) insertion loss characterized from Port 3 to Port 1 ($-S_{13} - 3$ dB) and Port 3 to Port 2 ($-S_{23} - 3$ dB), (d) magnitude imbalance between Port 1 and Port 2 ($|S_{13} - S_{23}|$).
Table 4.3 Summary of Measurement Performance of Four Types of Magic Tees: DLP 3D Printed Broadband Magic Tee (in bold), CNC-machined Magic Tee, DLP 3D Printed Traditional Magic Tee (in bold), and Machined Traditional Magic tee.

<table>
<thead>
<tr>
<th>W-band (80 to 105 GHz)</th>
<th>This, 3D-DLP Broadband Magic Tee</th>
<th>CNC-Machined Magic Tee*</th>
<th>This, 3D-DLP Traditional Magic Tee</th>
<th>Machined Traditional Magic Tee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Matching ($-S_{33}$)</td>
<td>14.3</td>
<td>16.3</td>
<td>4.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Min Matching ($-S_{44}$)</td>
<td>13.5</td>
<td>13.9</td>
<td>3.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Min Isolation ($-S_{12}$)</td>
<td>15.7</td>
<td>23.6</td>
<td>3.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Min Isolation ($-S_{34}$)</td>
<td>25.2</td>
<td>25.3</td>
<td>29.5</td>
<td>34.6</td>
</tr>
<tr>
<td>Max IL ($-S_{13} - 3 \text{ dB}$)</td>
<td>1.3</td>
<td>0.8</td>
<td>5.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Max IL ($-S_{23} - 3 \text{ dB}$)</td>
<td>0.6</td>
<td>1.2</td>
<td>4.2</td>
<td>7</td>
</tr>
<tr>
<td>Max Imbalance ($</td>
<td>S_{13} - S_{23}</td>
<td>$)</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Weight</td>
<td>8.3 g</td>
<td>36.9 g</td>
<td>9.2 g</td>
<td>41.0 g</td>
</tr>
<tr>
<td>Assembly Block(s)</td>
<td>Single</td>
<td>Multiple</td>
<td>Single</td>
<td>Single</td>
</tr>
</tbody>
</table>

**Bold: This Work.** *Data Courtesy of SAGE Millimeter, Inc.*
further improved. Third, the magnitude imbalance of the 3D printed magic tees is higher than to the machined one, indicating a higher asymmetry level during the fabrication. The mechanical specifications are also included in Table 4.3. The 3D printed magic tee’s weight is only 22% of the machined metal one in both broadband and traditional cases. Moreover, the 3D printed magic tee was fabricated as a single block compared to the CNC-machined one that has multiple sub-components.

4.4 Summary

3D printing technology is experiencing an enhancement in printing accuracy and surface roughness. The quality of 3D prints are gradually approaching the quality available through precision machining, although there remains a performance gap between them in the case of a simple waveguide section. When it comes to complex waveguide structures, 3D printed parts can have competitive or better performance in some specifications when compared to machined parts, as shown by my results. These complex structures were traditionally machined in multiple blocks and mechanically fitted together, but now can be 3D printed as one single part, which can mitigate the shortcoming of the lower fabrication accuracy of 3D printing.
The AM benefits over traditional manufacturing technologies, such as the possibility of fabricating parts with arbitrary geometries, modifying material properties within a part, and consolidating several sub-assemblies into a single part, making it a good candidate for the fabrication of high complexity waveguide components, such as turnstile junction OMTs. The 3D printed groove gap waveguide Ka-band turnstile OMTs has been reported recently [63]. Besides, the V-band 3D printed OMT prototype is discussed in [64]. However, to the best of author's knowledge, there lacks studies or research on the 3D printed turnstile junction OMT above V-band.
The chapter proposes an orthomode transducer (OMT) design by substituting "swan neck" twists for the E- and H-plane bends in the W-band turnstile-based OMT, obtaining the volume reduction of 90% compared to the reported machining design in [65]. A method of using nano-CT scanning photosis was employed to characterize and analyze the symmetry of the matching stub in turnstile junction which turns out to be critical to OMT two polarizations isolation and cross-polarization.
5.1 OMT Core Design

This section presents first the model design for W-band turnstile junction OMT with a "swan neck" twist, then the modified design that is suitable for 3D printing.

5.1.1 Model Sub-Circuits Design

This OMT design [in Fig. 5.1(e)] contains three parts: a turnstile junction [in Fig. 5.1(a)], a "swan neck" twist [in Fig. 5.1(b)], and an E-plane Y-junction [(in Fig. 5.1(c))]. The OMT is a four-port device, though two of the ports share a common physical port. The common port, usually constructed in a circular or square waveguide structure, serves as the input port for two orthogonal polarized signals’ propagation [labeled as H-pol and V-pol in Fig. 5.1(e)]. The turnstile junction separates each of the two orthogonal polarizations, horizontal polarization (H-pol) and vertical polarization (V-pol), into two 180° out-of-phase signals. The signals from each polarization enters the twist that gradually shifts the polarization by 90° while making a 180° bend feature, the so-called "swan neck" twist. The signals, previously separated from H-pol or V-pol, leave the twists and combine with out-of-phase at the E-plane Y-junction. Finally, the rectangular waveguide ports (named as H-port and V-port in Fig. 5.1(e)) serves as the output port for the H-pol and V-pol signals.

The turnstile junction design [Fig. 5.1 (a)] uses two superimposed cylinders as the matching stub in the branching center. The turnstile dimension follows the design in [66], but at each of four branching outputs a smooth transition from its original output [66] to a standard WR-10 rectangular port is added.

The twist [in Fig. 5.1(b)] is designed by sweeping the waveguide cross section along a semicircle. The semicircle is located on the plane that is 45° to the plane containing the
waveguide cross section, starting from the center of the WR-10 cross section. Though, in theory, the diameter of the semicircle can be set to the minimum of 1.06 times the longer width of the waveguide cross section, limitations mainly from fabrication also affect the possible diameter. In this WR-10 twist design, the diameter of the semicircle was set as 4 mm.

The E-plane Y-junction [in Fig. 5.1(c)] was made up of a E-plane combiner, formed by two E-plane bends and a square-to-rectangular waveguide stepped impedance transition. In the E-plane bend, the circular bend with a diameter slightly larger than the shorter length of the WR-10 cross section was selected, similar to the bend structure for H-plane in [67]. The cusp was truncated (similar to [68]) as was required for fabrication. The three-section transformer from square-to-rectangular waveguide was designed with the procedure given in [69].

The simulation of the model was implemented in CST environment. Simulated return loss as a function of frequency at the twist port, at the input of turnstile junction, and the E-plane Y-junction are shown in Fig. 5.1(d). In all cases, the reflection is below -25 dB across the W-band.

5.1.2 3D Printing-Compatible OMT Design

As discussed in Chapter 4, sharp edges and transitions can be difficult to print precisely using 3D printing technologies and prone to poor metal adhesion if plating is necessary for post-processing. The OMT’s design was modified to include the curved surface in place of the sharp corner edges. For the same reason, two straight edges of the superimposed cylinders were rounded as well. Since the matching stub’s geometry is critical to the performance of an OMT, curved corners were added to the turnstile junction EM model. The height of the
two cylinders (in Fig. 5.2) were optimized for the minimum input reflection. The simulated return loss on the circular waveguide port of the optimized model are better than 28 dB over the full operating band.

The full OMT (see Fig. 5.3) EM simulation was implemented. An equivalent electrical conductivity of $1.5 \times 10^7$ S/m was used to account for the plating imperfection, fitting for the measurement result of the 3D-printed W-band component in Chapter 4. The simulated insertion loss, return loss, and isolation for the OMT are presented in Fig. 5.4. I obtained the insertion loss lower than 0.29 dB, return loss greater than 26 dB, and isolation greater than 65 dB over the frequency band of 75 to 110 GHz. Table 5.1 compares the simulated performance of this design compared to other published W-band turnstile junction OMT designs. The core OMT part excludes the flange area as the connection would be omitted in an integrated OMT design. Compared with other designs, this work is most efficiently designed spatially. The total volume is ten times less than the stack layer design [65] and fifty times smaller than Pisano’s design [66].

Figure 5.2 Simulated RL of the optimized turnstile junction with rounded edges on superimposed cylinders.
Figure 5.3 The proposed 3D-printing adjusted turnstile junction OMT design.

Figure 5.4 Simulated results of the proposed OMT design on RL of H-port (solid line) and V-port (dotted line), IL of H-port (plus sign) and V-port (circle), and isolation between H-port and V-port (dash-dotted line).

Table 5.1 Comparison of this proposed OMT to other published W-band OMT in the simulation results.

<table>
<thead>
<tr>
<th>Design</th>
<th>Frequency (GHz)</th>
<th>min. RL</th>
<th>min. Iso.</th>
<th>max. IL</th>
<th>OMT core design size</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>this work</td>
<td>75 - 110</td>
<td>26 / 26</td>
<td>65</td>
<td>0.29 / 0.29</td>
<td>5.7 × 5.7 × 8.2</td>
<td>0.27</td>
</tr>
<tr>
<td>[65]</td>
<td>75 - 110</td>
<td>27 / 27</td>
<td>-</td>
<td>0.28 / 0.28</td>
<td>18 × 28 × 47</td>
<td>15</td>
</tr>
<tr>
<td>[66]</td>
<td>80 - 108</td>
<td>25 / 25</td>
<td>60</td>
<td>0.29 / 0.29</td>
<td>25 × 25 × 4.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>
5.2 Experimental Verification of the OMT

5.2.1 OMT RL, IL, and Isolation Measurement

The OMT was built following the 3D-printing mm-Wave waveguide procedures in Chapter 3. Briefly, the OMT prints were built by the DLP 3D printer (B9 Creator v1.2) using acrylate-based resin (B8R-2 Black); the prepared OMT was metallized by Tollen’s silver electroless plating solution first, then was applied with $O_2$ plasma treatment, finally was treated by silver plating again. Fig. 5.5(a) and (b) show photos of the 3D-printed plastic OMT prototype, and metallized turnstile junction OMT.

Performance of the OMT was measured using a PNA (Agilent E8361C) and W-band extenders (Agilent N5260A). The measurement setting for OMT is shown in Fig. 5.6.

To measure the return loss (RL) of the two rectangular ports, a customized 3D printed antenna was used to terminate the circular port of the OMT. Normally, the circular port of the OMT should be terminated by a circular waveguide load. However, such a load was not available during the test because the port diameter ($d=3.031$ mm) was not a standard size. Instead, a low reflection horn at the same input diameter was used as the replacement. The
VNA was connected to one of the rectangular ports while the other one was terminated. The measured return losses are shown in Fig. 5.7. The average RL value $(-|S_{33}|, -|S_{44}|)$ across W-band is 17dB and 15dB for the H-port and V-port, respectively.

To measure the insertion loss (IL), the circular port was shorted. Each of the rectangular ports was alternately connected to the VNA, while terminating the other rectangular port, mimicking the approach in [66]. The derived IL values are shown in Fig. 5.8. The measured RL was assumed by approximating twice the IL of the OMT. The derived average IL $(-|S_{13}|, -|S_{24}|)$ across W-band are 1.0dB and 1.2dB.

To measure the isolation between two rectangular ports, the circular port of OMT was terminated by the above antenna, used in the RL measurement. Each of two rectangular ports connected to a twist and then to the W-band extender port. The measured isolation is shown in Fig. 5.9. The measured average isolation $(-|S_{34}|)$ across the band is -25 dB.
Figure 5.7 Measured and simulated RL of H- and V-port of the proposed OMT.

Figure 5.8 Measured and simulated IL of H- and V-port of the proposed OMT.

Figure 5.9 Measured and simulated isolation between H- and V-port of the proposed OMT.
5.2.2 Characterization and Result Analysis

The integrity of the 3D printed OMT channel was examined by a nano CT scanner (Zeiss Xradia Nano CT). Fig. 5.10 shows the scanned photo of the complete OMT. The hollow channel inside the OMT was highlighted at full opacity, while the surrounded polymer structure's opacity was switched to the minimum. The figure verifies the integrity of the whole OMT channel with no apparent collapse or crevice. The "swan neck" shape of the twist is clearly observed in the photo. The circular bend in E-plane combiner and the stepped feature in the impedance transformer are also visible. Besides, an abnormal transition can be observed between the turnstile junction's output and the twist, due to a model-combining function mistake in the CAD software.

Two 2D cross section views, orthogonal to each other, splitting across the superimposed cylinder at the center of the turnstile junction, are shown in Fig. 5.11. From the figure, a small extent of asymmetry along the central axis of the cylinders can be observed on both views. On one side, the edges have the curved shape consistent to the design; however,
Figure 5.11 The CT-scanned 2D photos on orthogonal planes that cut along the central superimposed cylinders, for the built OMT.

Figure 5.12 The simulated isolation of the proposed OMT using an asymmetric junction imitating its realistic shape.
Table 5.2 Comparison of this proposed OMT to other published W-band OMT in the simulation and measurement results.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Freq</th>
<th>Measurement</th>
<th>avg. RL</th>
<th>avg. Iso.</th>
<th>avg. IL</th>
<th>OMT total size</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(GHz)</td>
<td></td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(mm x mm x mm)</td>
<td>(mL)</td>
</tr>
<tr>
<td>this work</td>
<td>75 - 110</td>
<td></td>
<td>17 / 15</td>
<td>28</td>
<td>1.0 / 1.2</td>
<td>28 x 28 x 28</td>
<td>22</td>
</tr>
<tr>
<td>[65]</td>
<td>75 - 110</td>
<td></td>
<td>19 / 27</td>
<td>51</td>
<td>0.73 / 0.76</td>
<td>28 x 28 x 57</td>
<td>45</td>
</tr>
<tr>
<td>[66]</td>
<td>80 - 108</td>
<td></td>
<td>25 / 25</td>
<td>44</td>
<td>1.1/1.2</td>
<td>42 x 42 x 24</td>
<td>42</td>
</tr>
</tbody>
</table>

on the other side the edges have a chamfered feature probably due to the 3D printing fabrication error. The OMT including an asymmetric matching stub was simulated in CST for the analysis of the performance effect of the model's asymmetry. The comparison of the isolation between the symmetric and the asymmetric OMT designs is shown in Fig. 5.12. The simulated isolation between two rectangular ports dropped to 30 dB due to the asymmetric stub. Also, peak resonances appeared in on the frequency band. This explains the discrepancy of the isolation between the simulation and the measurement result of the OMT.

Table 5.2 compares the measured performance for the OMT compared to other published work. This work achieves a moderate RL, IL, and isolation but the total size including the flange is still compact. Future research should improve the symmetry of the 3D printing model, particularly the central stub, because the symmetry of the structure impacts the isolation of the OMT.

5.3 3D Printed Compact Dual-pol Antenna

In this section, I describe the fabrication of a compact dual-pol antenna that integrates a corrugated horn and a turnstile junction OMT structure, both operating at W-band. The
dual-pol antenna provides an excellent example of 3D printing capability on fabrication
the mm-Wave sub-assembly in a monolithic compact piece.

One way to formalize a dual-pol antenna is to feed the corrugated horn with a OMT
at the same frequency band, assuming the matching between the corrugated antenna's
input port and the OMT's common port. By adding of the corrugated antenna, the cross-
polarization between H-pol and V-pol of the antenna can be experimentally tested in its
far-field.

The W-band corrugated antenna was designed, starting with the procedure given in
[70]. The antenna model and dimension is presented in Fig. 5.13. A wide flare angle of 106°
was selected for the benefit of the compact size and the broad-band operation. The width
of corrugation teeth was set to 500 um to fit for the fabrication layer resolution in DLP 3D
printing. The fillet with a radius of 0.254mm was applied on the edges of the horn teeth.

5.3.1 Model and Fabrication

The model for the dual-pol antenna was shown in Fig. 5.14. Instead of being added sepa-
rately, the corrugated antenna was incorporated into a closed-box which contains both the
OMT and the flange. The total dimension of the design is $28 \text{ mm} \times 28 \text{ mm} \times 28 \text{ mm}$, is the
same as the dimension of the previous OMT design. Thus, the integration of the antenna

![Figure 5.13](image) The corrugated horn design and the dimension.
**Figure 5.14** Model of the dual-polarized antenna integrated with the turnstile junction OMT and the corrugated horn designs.

**Figure 5.15** Photos of (a) 3D printed dual-pol antenna prototype, and (b) metallized dual-pol antenna.
part doesn't add additional volume to the OMT.

In this type of flange, metal thread inserts were used. Fig. 5.15 shows photos of the 3D printed dual-pol antenna prototype and the metallized antenna.

5.3.2 Simulation and Measurement

The antenna was characterized by two groups of parameters: S-parameters and the far-field radiation. The S-parameter measurement was obtained using the setup described in Section 5.2.1. The port near the antenna aperture (in Fig. 6) is called horizontal port (H-port), because the input wave to the port is transmitted out horizontally. Similarly, the port located far from the antenna aperture is called vertical port (V-port). Fig. 5.16 shows the measured RL at H and V-ports, as well as isolation between the two ports. The average RL and isolation is 17/20 dB and 26 dB, as expected, close to the OMT measurement results, reported in Section 5.2.1.

Fig. 5.17 shows the experimental setup block diagram for measuring the radiation
Figure 5.17 Block diagram of the experiment setup for the measurement of co-polar and X-polar radiation patterns.

Figure 5.18 Ratio of H-port Co-polar to V-port X-polar across the frequencies.
Figure 5.19 Measured boresight gain for the dual-pol antenna over W-band frequency.

Figure 5.20 Measured E-plane radiation patterns for the dual-pol antenna at 85 and 100 GHz.

Figure 5.21 Measured H-plane radiation patterns for the dual-pol antenna at 85 and 100 GHz.
pattern. The configuration of H-port co-polarization (co-pol) pattern and V-port cross-polarization (cross-pol) pattern is illustrated in the diagram. Fig. 5.18 shows the cross-polarization across the frequency band. The average cross-polarization value across the W-band is -21dB. This value is lower than the measured isolation between H-port and V-port, because the corrugated horn, which is integrated in the dual-pol antenna, also affects the isolation between two polarisations.

Fig. 5.19 shows the measured gain of the dual-pol antenna over W-band, as compared to the simulated gain. The measured gain decreases 1.5 dB compared to the simulation results, likely due to the insertion loss in the OMT channel.

Fig. 5.20 shows the measured E-plane radiation patterns for the dual-pol antenna at 85 and 100 GHz. At 85 GHz, the antenna achieved a 3dB beamwidth of 34° and correlated well with simulation (36°). The measured cross-polarization levels are lower than -17 dB when Θ sweep from -60° to 60°. It was observed that at angles greater than 30 deg, the radiation pattern had a steep rise. This is attributed to the scattering effects around the antenna. At 100 GHz, the antenna achieved a 3dB beamwidth of 32°, smaller than the simulation (44°). The measured cross-polarization levels are lower than -18 dB when Θ sweep from -60° to 60°. The discrepancy between the simulation and the measurement is mainly attributed to the 3D printing error on the antenna corrugated teeth.

Fig. 5.21 shows the measured H-plane radiation patterns for the dual-pol antenna at 85 and 100 GHz. At 85 GHz the antenna achieved a 3 dB beamwidth of 42° and correlated well with simulation (48°). The measured cross-polarization levels are lower than -19 dB when Θ sweep from -60° to 60°. At 100 GHz, the antenna achieved a 3-dB beamwidth of 44° and correlated well with simulation (46°). The measured cross-polarization levels are lower than -18 dB when Θ sweep from -60° to 60°. However, the asymmetric co-pol pattern was also caused by 3D printing fabrication error.
5.4 Summary

In this work, by substituting "swan neck" twists for the E- and H-plane bends in the turnstile-based orthomode transducer (OMT), the novel OMT core design's volume is ten times smaller than [65] at W-band. A method of using nano-CT scanning photosis is employed to characterize and analyze the symmetry of the matching stub in turnstile junction which turns out to be critical to OMT two polarizations’ isolation and cross-polarization. Finally, the dual-pol antenna combining such OMT and a corrugated horn was realized in a compact size. The boresight cross-polarization level of the OMT, characterized in a far field test of this dual-pol antenna, is averagely -18 dB at W-band.
In this Chapter, I will give a summary of my research work and contributions in this dissertation, and then provide some recommendations for future work.

6.1 Summary of Dissertation

This dissertation reports on a complete fabrication process to realize complex, high-performance microwave components using digital-light-processing (DLP) 3D printing. This approach addresses numerous challenges of successful component realization, including: metalization of acrylate-based polymers, defect reduction in printing, increased precision through off-axis printing of waveguide channels and re-design of precision internal structures for self-supporting in the build process. The results of this approach have produced complex
Figure 6.1 Component build process: modeling, parallel 3D printing of multiple parts, mechanical preparation, metalization and post assembly.

microwave components with performance comparable to commercial, multi-part CNC machined components.

### 6.1.1 Printing Methodology

Figure 6.1 shows the overall approach of this process from CAD modeling through post assembly. It begins with 3D electromagnetic modeling of the component in HFSS or similar finite-element-modeling software. The design is then translated to a 3D modeling program, such as Solidworks, where mechanical supports and interfaces, such as waveguide flanges, are added. The print orientation is also modified to optimize print precision. The results is a 3D printer file that is printed using a Digital-Light-Processing (DLP) printer. After printing and removal of support structure, any mechanical surfaces, such as polishing or flattening waveguide flanges, are prepared. Finally, a robust metallization process is employed to allow several microns of metal thickness and complete component metallization.

### 6.1.2 Metalization

One of the key practical challenges for realizing microwave components from DLP and other 3D printing methods is the diversity of polymers used and the need for a robust
Figure 6.2 (a) single layer of Ag metalization. (b) dual layers of Ag metalization. (c) electroless copper on Ag layer. (d) sharp corner causes defects and discontinuities in metallic layer. (e) curved corners eliminate defects.
metalization process. In this work, it is found that commercial electroless plating processes did not work well for the UV sensitive acrylate-based polymers. The principle problem was in the adhesion on the plastic and also coverage - it was difficult for the electroless plating to cover long, narrow channels, such as in simple waveguide. The poor metal adhesion and cracks were often observed on waveguide corners and on valleys of wavy printed channels.

Chapter 2 reports on a robust method for plating silver (Ag) using the Tollen's reaction (silver mirror reaction). This method provides good adhesion of a metallic surface to a wide variety of polymers and was able to cover complex internal channels.

While solving the initial problem of plating, the thickness of the Ag was only a few hundred nanometers, Fig. 6.2(a). To increase the thickness, several successful techniques were adopted. The first was to simply repeat the Tollen's reaction a second time to add a second layer of Ag. This produced a thicker Ag layer overall, but still was thinner than desired, Fig. 6.2(b). Mentioned O₂ plasma treatment was required between the first and the repeated Ag plating steps. The second approach discussed in Chapter 3 was to follow the initial Ag with an electroless plating of copper (Cu) to increase the thickness to 2 µm, Fig. 6.2(c). It is found that the excellent coating of Ag was sufficient to allow good adhesion and coverage by standard electroless processes. The standard process was modified to be compatible with temperature limitations of the polymers used. The third approach was to perform an electrolytic copper plating after the electroless plating to achieve thicknesses of 10s of µm. Finally, due to the oxidation of copper, a final plating of Ag was helpful.

In addition to adhesion and thickness of the metallic layer, it is found stresses in the printed parts and variation in printing cause small cracks to sometimes form at sharp interior angles, Fig. 6.2(d). The cracks caused significant loss due to disruption of the conducting surface as presented in Chapter 4. As a solution, all designs were modified to include curved interior corners and beveled outer corners to eliminate the cracks and allow
a continuous coverage of metal.

6.1.3 Enabling Complex Geometries

In addition to the low-cost and rapid-fabrication of additive manufacturing, the ability to create arbitrary and complex shapes is a significant benefit. While almost any shape could be fabricated using standard fabrication techniques, the cost in time and materials can make exploring new geometries prohibitive.

Two geometries that are difficult to realize using traditional methods were explored. The first is a meandering coaxial delay-line. The difficulty in fabrication comes from the meandered shape. Those meandered shape brings the benefit of a compact size. Chapter 3 proposed an innovative method for the fabrication of these coaxial lines, using 3D printing technology. The coaxial line used liquid metal EGaIn as the conductor, and the 3D-printed cyanate ester as the dielectric. Cyanate ester has the lowest loss factor ($\varepsilon_r = 3.12, \tan \delta = 0.0046$) among commercially available materials for 3D printing. For the central conductor of the coaxial line, EGaIn ($\sigma = 3.4 \times 10^6 S/m$) is used since it can form conductive channels of an arbitrary shape in a small size [52]. In theory, the coaxial line can work up to mm-Wave frequency when the inner conductor diameter is small enough. However, the 3D printing fabrication method - Polyjet - limits the minimum inner channel size. In this work, as a proof of concept the single-mode operation range for the coaxial line is up to 8 GHz at the inner channel diameter of 1.35mm.

The second geometry is a non-traditional antenna that was designed using genetic algorithms, presented in Chapter 3. This antenna consists of small sections of cylinders connected within a confining volume of 5 cm cube. This shape was easily 3D printed, however would be extremely challenging to prototype using traditional methods. One
challenge was in the connection to the antenna as it required a coaxial connection (5 GHz operating frequency). This was accomplished by soldering the center pin of a pcb SMA connector to the input cylinder.

It should be noted that the two examples rely on a continuous coating of the part. Geometries that require metalization only on some portions of the structure are an open area of research.

6.1.4 Design and Printing for High-Performance Components

As described in Chapter 1, the DLP accuracy is asymmetric, with the $x$-$y$ plane having a different precision than the $z$-plane. In addition, due to the build sequence, each layer starts as a liquid polymer that is then hardened by UV light. The result is that the liquid and printed structures need to be properly supported as the component is made. In particular, in the interior of the component, there is no means to support structures as they are being built and therefore the component must be designed to self-support internal structures. This is critical to high-performance components, as they often integrate small structures to better impedance match and/or shape propagation modes into the channels or junctions. Examples include the addition of multi-tiered cylinders in the center of a turnstile junction and the addition of small geometries in the intersection of the magic tee and small stubs in the channels to better impedance match the ports.

In Chapter 4, the printing accuracy was systematically examined for channels that are aligned with the $x$-$y$ plane, the $z$-axis and at an angle to both. Fig. 6.3(a) shows the result of a channel printed parallel to the $x$-$y$ plane, the $z$-axis and at a 45 degree angle. When building parallel to the $x$-$y$ plane, the channel was well printed in plane, but had difficulty in printing the top (bottom defined in $z$-direction) as the liquid pooled at the bottom and
had to self-support on the top bridge. Channels built along the z-axis had high-accuracy as
the dimensions of the channel were well defined by high-accuracy of the x-y print plane.
Owing to the open end of the channel at either end, there were less issues with top/bottom
printing as in the x-y plane. These demonstrate that the axis of printing matters greatly.
The problem occurs, however, when one needs multiple channels, in particular if they are
orthogonal.

Figure 6.3(c) shows a solution. If the channel is printed at a 45 degree angle, there is
sufficient support during the print to support the upper (lower defined in the z axis) walls
for an accurate print. Owing to this, most components achieve the best accuracy when
printed at a 45 degree and this is the standard orientation for printing in this dissertation
work.

The need for self-support in channel printing is also important when printing internal
structures for improved performance. As an exemplar, the impedance matching features
proposed in [61] is used in Chapter 4. Fig. 6.3(b) shows the integration of two cones in
the center of a magic tee intersection and small cylinders in each channel. These have
been shown to significantly reduce reflections at each port [61]. The small structures failed
to print correctly, however, due to two problems. The first is that the sharp edges of the
small features were difficult to realize in the precision of the DLP used and also due to
the plasticity of the polymer during curing. The second, and more important, was that
the structures were not self-supported during the print. Fig. 6.3(c) shows the 45 degree
orientation. There was nothing to support the bottom corner of the referenced cylinders as
the part was built from the bottom up. To address both of these, this work re-designed the
internal structures to have round edges and also to have a shape that would self-support in
Chapter 4. In this instance a cone was chosen instead of a cylinder [See inset, Fig. 6.3(d)].

By modifying the component to be self-supporting the part was successfully fabricated.
Figure 6.3 (a) waveguide channel printed parallel to $x$-$y$ plane (Note printing error – red dashed is desired shape – at top and bottom.), $z$-axis, and at 45 degree angle to both. (b) impedance matching structure from [61]. (c) rotated impedance matching structure. Note the cylinder (seen from side as a rectangle) cannot be printed at 45 degree angle as there is no support as the part is printed in the $z$-direction. (d) structure modified to use a cone shape so that as the feature is printed it will self-support. (e) 3D model of magic tee with impedance matching structure. (f) magic tee printed at 45 degree angle to minimize error of the orthogonal waveguide channels. (g) zoomed in photo of printed structure [shown at 45 degree angle for comparison to (d)].
The performance was within 2dB of a commercially available high-performance magic tee, Fig. 6.3(h) and (i).

In Chapter 5, by substituting "swan neck" twists for the E- and H-plane bends in the turnstile-based orthomode transducer (OMT), the novel OMT core design's volume is ten times smaller than [65] at W-band. A method of using nano-CT scanning photosis was employed to characterize and analyze the symmetry of the matching stub in turnstile junction which turns out to be critical to OMT two polarizations' isolation and cross-polarization. Finally, the dual-pol antenna combining such OMT and a corrugated horn was realized in a compact size. The boresight cross-polarization level of the OMT, characterized in a far field test of this dual-pol antenna, is averagely -18 dB at W-band.

This PhD research presented a methodology for realizing complex, high-performance microwave components. By understanding printing limitations and methods for best print performance, components were created comparable to commercial available CNC machined parts. The methodology here can be used on many microwave components that use a complete metalized surface, which includes most major waveguide components.

6.2 Future Directions

Several future research directions could be pursued based on this dissertation work, as suggested in the below paragraphs:

- Metalization Recipe Customized for 3D Printing Waveguides

The success of printed waveguide components is intrinsically tied to a robust metalization process that is effective when applied to the materials used in the 3D printing system. The two methods proposed in Chapter 2 and Chapter 3 have their own limitations. The Tollen's reagent silver plating solution (in Chapter 2) could only deposit
a metal layer at a limited thickness, approximately 300nm. Although, the plating method can be improved by adding a copper electroless plating process to enhance the metallization thickness (in Chapter 3), the copper plating may have a poor quality, for example, the blistering, referring to the formation of subsurface cavities, can be observed on the plated metal surface. Moreover, the metallization thickness beyond a few µm often required by mm-Wave application at the lower frequency end cannot be obtained by the proposed method. Therefore, the metallization recipe customized for plastic waveguides prints which can achieve the good plating quality as well as the required metallization thickness would always be desirable.

• Low Reflection in 3D Printing Waveguides

The 3D printed straight waveguides in Chapter 2 and Chapter 3 can achieve the port reflection below than -20 dB. However, the waveguides that are usually used for the instrument calibration, machined by high-precision methods, can obtain a much lower reflection loss, such as -40 dB. The key factor for achieving a low reflection in waveguides is to fabricate the waveguide at a high accuracy and a rigid tolerance, such like ±0.2% [71]. For instance, the fabrication tolerance for W-band waveguide that can achieve -40 dB reflection is ±4µm. However, the 3D printer used for this work can only reach the tolerance of ±100µm. Thus, a 3D printer with the capability of high-precision fabrication is highly desirable for the AM of low reflection mm-Wave waveguide components.

• Compact Snap-Fit Waveguide Flange Suitable for 3D Printing Waveguides

The assembly of mm-Wave waveguide components are often realized by screws and fittings connected through the waveguide flange. The standard waveguide flange is designed for metal machined waveguides. However, at mm-Wave frequency, the
waveguide component’s volume may be increased by tens or even hundreds of times by adding the flange part, as describe in Chapter 5. One advantage brought by AM fabrication method is its enabling various of materials, including plastics, used for the waveguide base. As we know, the connection between plastics could be realized by a snap-fitting structure. A similar strategy could be used for the connection of 3D printed waveguides, where 3D printed waveguides can be assembled though snap-fits. The snap-fitting flange at the waveguide port can be designed in a more compact volume compared to the traditional standard flange, and moreover provides flexibility to switch between different waveguide components.
BIBLIOGRAPHY


