Article:

Chudpooti, N, Savvides, G orcid.org/0000-0002-4189-6144, Duangrit, N et al. (3 more authors) (2022) Harmonized Rapid Prototyping of Millimeter-Wave Components using Additive and Subtractive Manufacturing. IEEE Transactions on Components, Packaging and Manufacturing Technology, 12 (7). pp. 1241-1248. ISSN 2156-3950

https://doi.org/10.1109/TCPMT.2022.3181886

IEEE Transactions on Components, Packaging, and Manufacturing Technology

Harmonized Rapid Prototyping of Millimeter-Wave Components using Additive and Subtractive Manufacturing

Journal:	*Transactions on Components, Packaging and Manufacturing Technology*
Manuscript ID	TCPMT-2022-041
Manuscript topic:	ELECTRONICS MANUFACTURING
Date Submitted by the Author:	28-Jan-2022
Complete List of Authors:	Chudpooti, Nonchanutt; King Mongkut's University of Technology North Bangkok, Faculty of Applied Science Savvides, Giorgos; University of Leeds, School of Electronic and Electrical Engineering Duangrit, Nattapong; Rajamangala University of Technology Lanna, Faculty of Engineering; Akkaraekthalin, Prayoot; King Mongkut's University of Technology North Bangkok, Electrical and Computer Engineering; Robertson, Ian; University of Leeds, School of Electronic and Electrical Engineering Somjit, Nutapong; University of Leeds, Institute of Microwaves and Photonics
Keywords:	Millimeter-wave technology, substrate integrated waveguide, additive and subtractive manufacturing

Harmonized Rapid Prototyping of Millimeter-Wave Components using Additive and Subtractive Manufacturing

Nonchanutt Chudpooti, *Member, IEEE,* Giorgos Savvides, *Non Member, IEEE,* Nattapong Duangrit, *Member, IEEE,* Prayoot Akkaraekthalin, *Member, IEEE,* Ian D. Robertson, *Fellow*, *IEEE*, and Nutapong Somjit*, Senior Member*

Abstract— **In this paper, a harmonized fabrication and assembly process combining additive and subtractive manufacturing is introduced for the rapid manufacture of millimeter-wave components, especially those using hollow substrate integrated waveguide (HSIW). HSIW has been shown to have some significant advantages for millimeter-wave communications, radar and sensing systems, but its fabrication can be challenging. To pattern the metallic layers that form the top and bottom HSIW walls, as well as other structures such as microstrip lines and landing pads for integrated circuits and passive components, a subtractive fabrication process using a water-jet laser cutter was employed. To fabricate the dielectric substrate using low-cost Acrylonitrile Butadiene Styrene (ABS), with cavities for the waveguides, a Stratasys PolyJet 3D printer (Objet1000) was used. The HSIW components were then assembled using commercially-available through-substrate copper transitions, completely eliminating the process of through-substrate via-hole formation and metallization. The manufacturing techniques conventionally used for these vias are generally expensive and intricate at millimeter-wave frequencies. Therefore, the proposed fabrication and assembly process in this paper decreases the overall fabrication cost and complexity, and it is shown that this is achieved without compromising the performance of the millimeter-wave HSIW components. The measurement results show that a propagation loss of 13.55 dB/m (0.01355 dB/mm) is achieved for the first HSIW prototype, which is believed to be among the lowest propagation losses ever reported at these frequencies. The proposed harmonized fabrication and assembly technique has also a strong potential, by combining the advantages of additive and subtractive manufacturing techniques, to realize a new class of millimeter-wave components with the possibility of manufacturing conformal and flexible component shapes, based on the materials used.**

Index Terms— **Millimeter wave technology, substrate integrated waveguide, additive manufacturing, subtractive manufacturing.**

This work was supported in part by the King Mongkut's University of Technology North Bangkok under contract KMUTNB-64-KNOW-44, and in part by the Engineering and Physical Science Research Council under Grant EP/S016813/1 and Grant EP/N010523/1.

N. Chudpooti is with Research Center of Innovation Digital and Electromagnetic Technology (iDEMT), Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Thailand. (e-mail: nonchanutt.c@sci.kmutnb.ac.th)

G. Savvides, I. D. Robertson and N. Somjit are with School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, U.K. (e-mail: el13gs@leeds.ac.uk, i.d.robertson@leeds.ac.uk, and n.somjit@leeds.ac.uk)

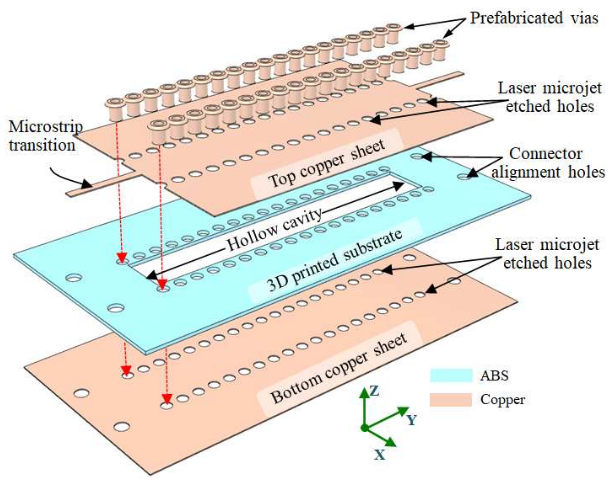
N. Duangrit is Faculty of Engineering, Rajamangala University of Technology Lanna, Chiang Mai 50300, Thailand. (e-mail: nattapong.du@rmutl.ac.th)

P. Akkaraekthalin is with Department of Electrical and Computer Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand. (e-mail: prayoot.a@eng.kmutnb.ac.th)

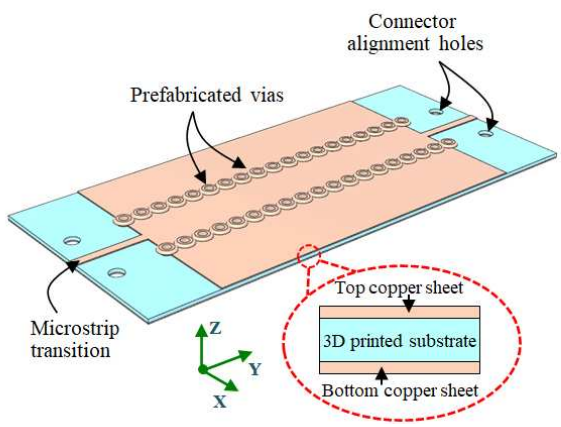
I. Introduction

THE 3D printing technology, also known as additive manufacturing (AM), is defined as the development of an arbitrary 3D shape, by building layer upon layer [1]. Specifically, material jetting [2]-[3] offers the best printing accuracy and resolutions when compared with fused deposition modelling (FDM). This technique uses a nozzle head to drop the liquid photopolymer onto a plate. The photopolymer materials are cured by UV light to create 3D parts from CAD models with a fully automated process. Advancements in 3D printing technology have offered the benefit to develop fast and low-cost prototypes. It has replaced the time consuming and costly methods of production and manufacturing, like the computer numerical control (CNC), molding or casting. In the case of rapid prototyping and medium volume production, the 3D printing technology is an excellent alternative [4]. According to [5], it is a printing process widely used to produce mechanical and electronic devices, even for high-frequency electronics ranging from a few MHz to optical regimes [6]-[10]. More specifically, it is being used in many sectors like medical, personal healthcare, dentistry, consumer goods and wireless communications [11], [13]-[16]. AM processes have been extensively used recently in the development of microwave, millimeter-wave, and even terahertz devices. Some examples include the design and prototyping of antennas, waveguides, filters and many other functional RF devices [6]-[8], [11], [17]-[22]. The authors in [17] have designed and fabricated a microwave rectangular waveguide (RWG), operating in the Ku-band, by using a FDM 3D printing process with Polylactic Acid (PLA) filament. The internal part of the waveguide is metal liquid filled. The authors achieved an attenuation constant better than 1.29 dB/m and demonstrated a low cost and high performance RWG. The authors in [16], fabricated a 3D printed dielectric lens for a slot antenna, that enhances the total radiated power. In [23], a 3D printed flexible antenna is demonstrated that combines Acrylonitrile Butadiene Styrene (ABS) and PLA filaments and is compact in size and light weight. The 3D printing process gave the added benefit of building flexible devices since many different materials can be mixed and used by 3D printing machines.

In contrast to additive manufacturing, subtractive manufacturing (SM) is the process of cutting material away, using methods of grinding, cutting, or drilling, to form a 3D



(a)



(b)

Fig. 1. 3D geometry of HSIW : (a) before assembly and (b) after assembly.

shape. The process could be performed manually or by computer numerical control (CNC). In an automated CNC process, the machine can perform fabrication based on data from CAD, with minimal human assistance, or in many cases without user interaction. The user may need to consider the feeding rate and the cutting speed of the material to set the fabrication settings on the machine before starting the process. In general, SM process are used typically in prototyping where traditional manufacturing methods like molding and casting are not able to provide the required precision and fabrication tolerance. Newer methods of laser and water laser cutting methods are more efficient and able to process harder materials. The SM manufacturing processes have been also widely used in manufacturing many high-frequency components from RF to even some millimeter-wave devices [12], [24]-[29]. The authors in [26], [29] have built microwave sensors by using subtractive manufacturing with a LPKF ProtoLaser machine. The designed microwave sensors achieved high accuracy and can be integrated to industrial and biomedical systems. In [29], instead of building an SIW by using traditional PCB methods, the authors used milling and drilling to cut smooth and precise copper sheets to form an empty SIW, eliminating all dielectric losses. In general, the subtractive manufacturing methods used in these devices, have provided a precise and accurate cutting that enhance the performance of millimeter-wave and THz devices.

These previous research works are generally based on only either additive or subtractive manufacturing. In this paper, a harmonized fabrication technique combining both AM and SM to fabricate high performance microwave and millimeter-wave components is introduced. To demonstrate the coordinated fabrication process, a HSIW transmission line operating from 21-31 GHz was fabricated and characterized, with a primary interest in signal transmission losses. The proposed harmonized fabrication technique combines the advantages from both additive and subtractive manufacturing, i.e., rapid device prototyping and ease of fabrication with fully automated processes. The harmonized fabrication also completely removes the need for the chemical processes generally required for conventional material etching and metallization, such as photolithography and electroplating, which require toxic chemicals and experienced users to operate the process. Moreover, the commercially-available vertical through-substrate copper transitions were used during the assembly process as electrical connections of the patterned metallic layers on top and bottom of the 3D-printed substrate. This process completely eliminates the traditional through-substrate etching and via hole metallization processes, introducing superior cost effectiveness, ease of fabrication and fabrication reliability.

II. Design and Geometry

The geometrical structure of the HSIW consist of four parts. These are, a top and a bottom copper sheet, a dielectric substrate and prefabricated copper rivets, all shown in Fig. 1. The top and bottom copper sheets represent the waveguide horizontal walls. The copper sheets have a height of 0.15 mm and are supplied by Goodfellow [30]. Between the copper sheets, there is a dielectric ABS substrate, that is hollow in the middle; the hollow dielectric substrate minimizes the dielectric losses and so contributes to a lower propagation loss. Some commercially available copper rivets from Fortex [31], are used to attach the aforementioned layers together and these represent the vertical metallic walls of the waveguide. The prefabricated copper rivets are pressed with a mechanical PCB through hole plating (THP) method also supplied by Fortex [31], in order to bind the three layers (copper sheets and dielectric) together.

It should be noted that this assembly step can be performed using a lamination technique, such as those used for large area multilayer PCBs in the mass production of consumer products. Frequencies in the 26-40 GHz range are already widely used in 5G systems, employing quite conventional transmission-line components fabricated on these traditional laminate materials. For 6G systems, it is likely that so-called Terahertz frequencies will be used (over 100 GHz) and then the dielectric losses become much more of a problem and the HSIW can offer significant advantages. The designed HSIW has been simulated in the commercially available Electromagnetic (EM) solver CST Studio [32]. For measurement purposes, the HSIW is matched to 50-Ω microstrip feed lines, as shown by the geometry in Fig. 1.

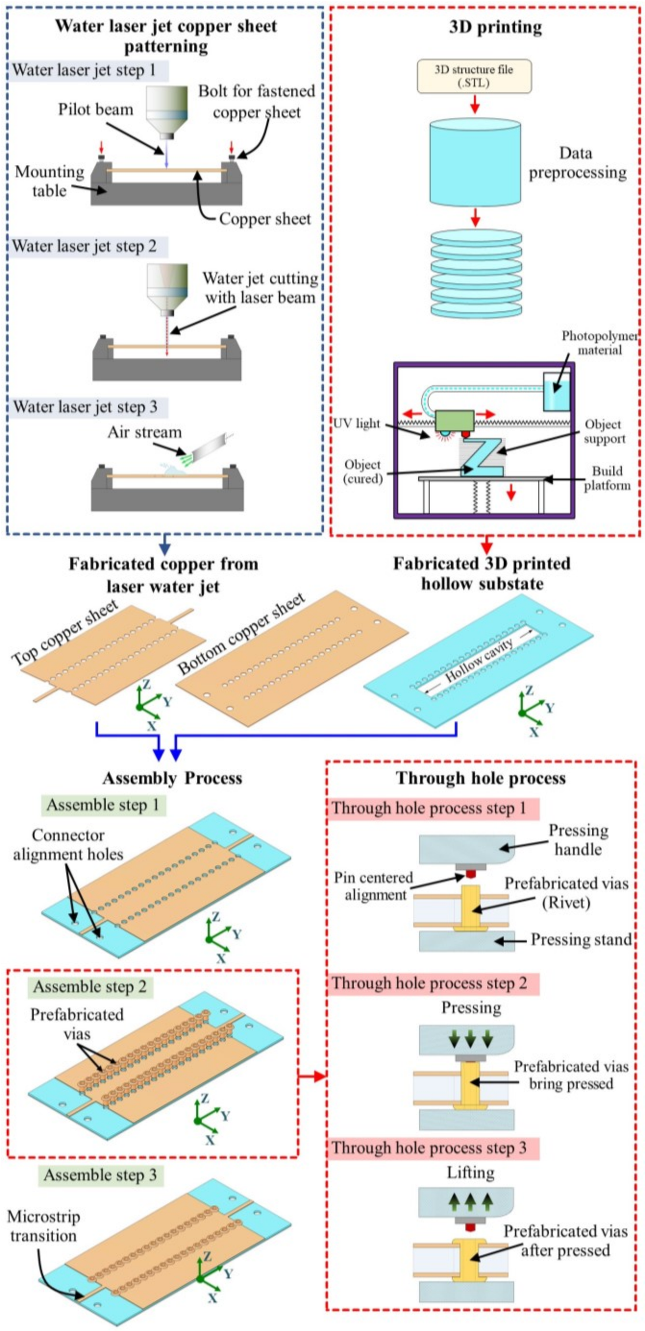


Fig. 2. Process flow for 3D printed substrate, top and bottom copper sheet patterning and HSIW integration process.

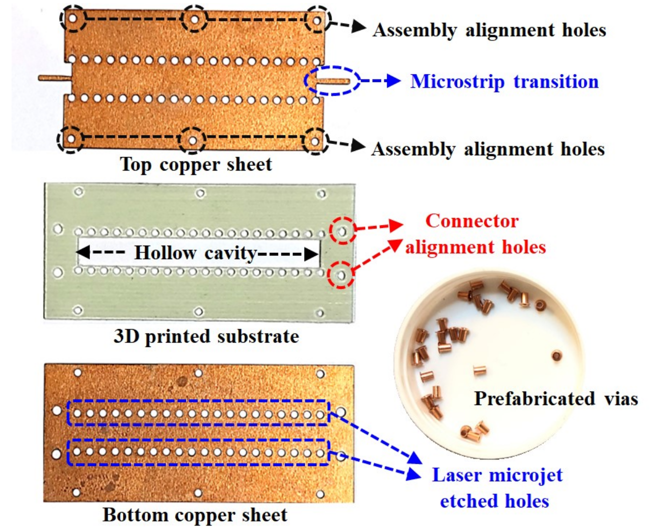


Fig. 3. Fabricated HSIW prototype before assembly, which consists of the top copper sheet, 3D printed substrate, the bottom copper sheet and prefabricated vias.

III. Fabrication and Assembly

All the HSIW parts were fabricated in-house at the University of Leeds National Facility for Innovative Robotics, using a Synova MCS 300 Laser MicroJet® Cutter [33] and a Stratasys Objet 1000 PolyJet 3D printer. The processing of the copper sheets and dielectric substrate fabrication are now described.

A. Copper Sheet Fabrication

The copper sheets, supplied by Goodfellow [30], were patterned using the laser cutter. The Synova MCS 300 has an emitted power up to 100 W and water pressure up to 500 bar and is powerful enough to process metals like super alloys, aluminum, copper, stainless steel, nickel, titanium, etc. It also provides high precision cutting, with a beam diameter up to 30 µm. The accuracy of the machine is ± 1 micron with repeatability ± 1 micron. The laser cutter operates by using a jet of deionized and filtered water to guide the laser beam via total internal reflection, helping to cool the sample and remove debris. With the laser beam having minimum losses, it is possible to keep the material sample further from the emitted laser beam. According to Synova [33], the beam can be placed at up to 10 cm range, as opposed to a conventional laser beam cutter that has a limited working distance.

The copper fabrication process starts by placing and fastening the copper sheet sample on the mounting table as shown in Fig. 2, step I. A pilot beam is emitted by the laser cutter to analyze the material and its dimensions. In step II, the water-jet laser cutter starts emitting the water laser beam that is cutting the copper sheet to the required shape, and finally, in step III, the air steam is activated to remove the remaining water on the surface of the copper sheet. The water-jet laser cutter has offered a very precise cut to the thin copper sheets. The fabricated copper sheets can be seen in Fig. 3(a) and these forms the enclosing top and bottom walls of the HSIW structure.

B. Dielectric Substrate Fabrication

Stratasys's Digital ABS Plus material [34] was chosen for the design and fabrication of the 3D printed substate, which forms the core of the HSIW. This ABS material provides high flexural strength of 65-75 MPa and tensile strength of 55-60 MPa that these offer a new degree of design freedom for applications benefitting from the use of conformal and flexible structures in the future. The ABS material has a dielectric constant of $\varepsilon_r = 2.75$ and a loss tangent of tan $\delta = 0.025$ [1], [35]-[37]. The dielectric component was fabricated using the Objet 1000 3D printer [38], which uses poly-jet printing technology. The lateral dimensional accuracy of the machine is up to 600 microns and the smallest

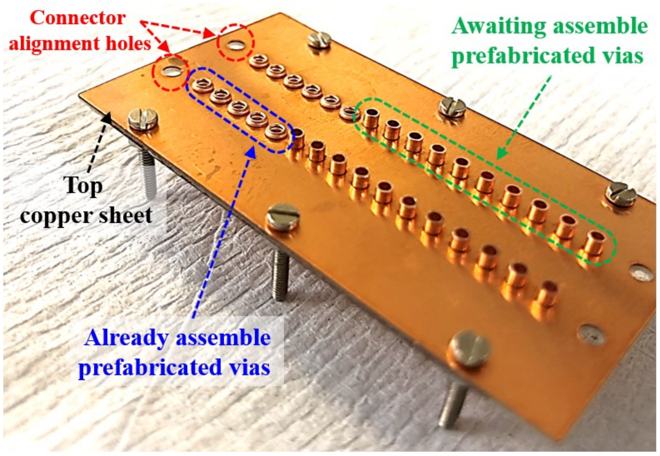


Fig. 4. Fabricated HSIW with prefabricated vias inserted through the via holes.

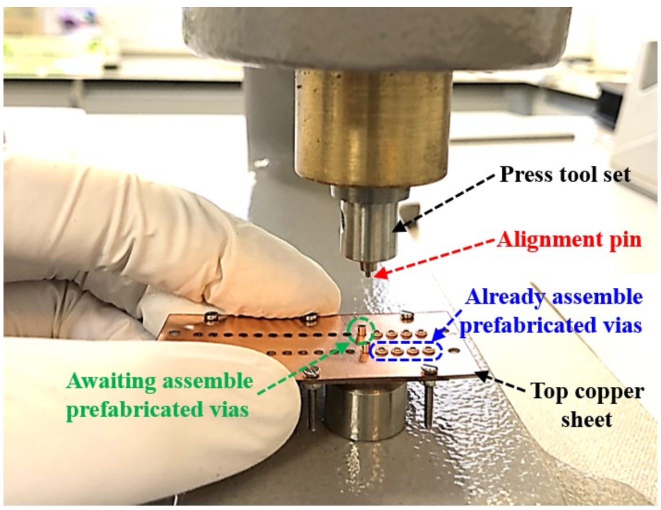


Fig 5. Assembly process of the proposed HSIW, by using the Mechanical Through Hole Plating method.

thickness in each deposited layer is 16 microns. The geometry of the HSIW, after being designed and analyzed in the electromagnetic solver CST Studio [32], is exported in Stereolithographic (STL) format for the Objet Studio software which comes with the Objet 1000 Plus 3D printer. In this software, the user assigns materials to the assembly's components and the build file are sent to the printer. The model material container of the 3D printer is filled with the photo-polymer resin, that is ABS material for this work, and the support material container is filled with water soluble polymer. The print heads can then start jetting the model and the support materials onto the build tray. The machine carries on jetting droplets until it builds the complete 3D layer and the UV light on top of the platform is emitted to cure the layer into a solid and strong material. The process is repeated until all the layers overlap to form the final 3D structure. At the end, the water-soluble material is washed away, leaving behind the 3D printed part. The fabricated dielectric substrate of the HSIW is shown in Fig. 3.

C. Assembly

To construct the HSIW, the fabricated structures of the dielectric ABS and copper sheets are integrated. The three

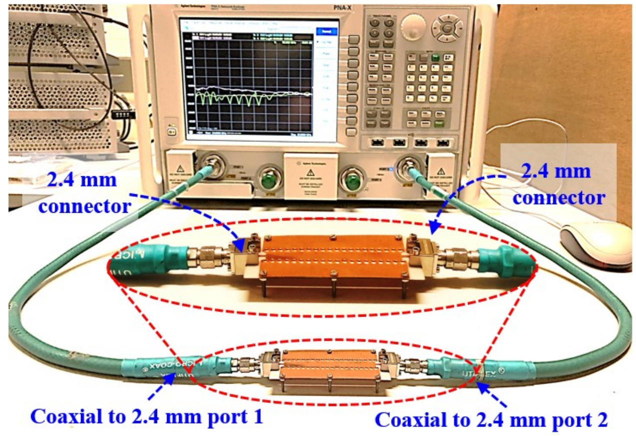


Fig. 6. Measurement of Scattering parameters on Agilent E8361A PNA.

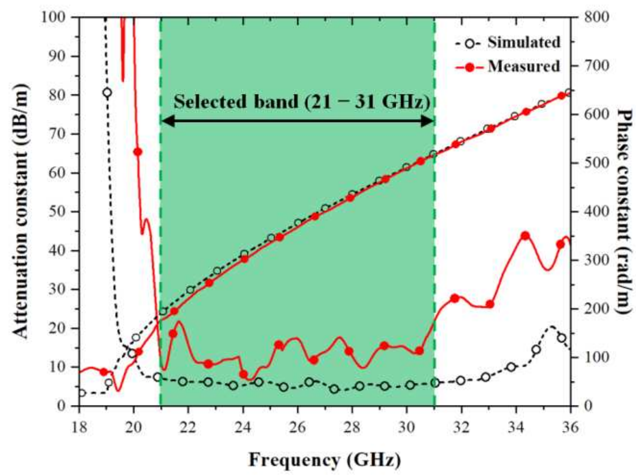
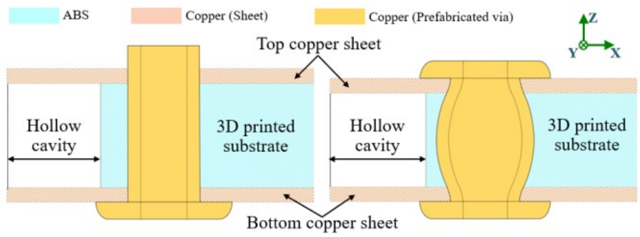


Fig. 7. Simulated and measured propagation loss.

layers with sequence of top copper sheet, 3D printed substrate and bottom copper sheet, are attached using the Fortex Mechanical PCB THP machine and copper rivets [31]. First, the copper rivets, which are the outer diameter of 1.6 mm, are inserted through the via holes of the three layers as shown in Fig. 2. This is done for all via holes as shown in Fig. 4. After that, the THP is pressing the copper rivets until they shrink to permanently fix the three surfaces together as shown in steps at Fig. 2. The assembly process as performed in the University of Leeds laboratory can be seen in Fig. 5. After all the copper rivets are pressed and fixed, at each end of the structure a SOUTHWEST 2.4 mm connector is attached for connection to the measurement system.

IV. Results

An Agilent (now Keysight) Technologies E8361A PNA 67 GHz vector network analyzer was used to measure the samples, as shown in the set-up in Fig. 6. By following the multi-line calibration method as described in [39], it is possible to extract the propagation constant by manipulating the scattering parameters of two HSIW devices of different lengths. A two-port coaxial Short-Open-Load-Through (SOLT) calibration was used to set the reference planes at the ends of the cables and remove as many errors as possible. The frequency range of 15- 40 GHz was



(a) (b)

Fig. 8. Cross section drawing *XZ* plane (a) before assembly and (b) after assembly.

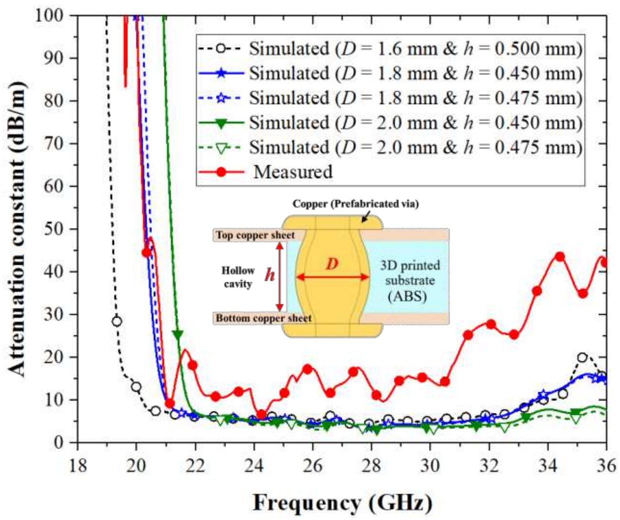


Fig. 9. Simulated results of the bending effect by varying the diameter of the vias, *D*, and height of the hollow substrate, *h*.

chosen, with 3200 points, for the *S*-parameter measurements. The measured propagation losses were calculated from the two *S*-parameter files and are plotted in Fig. 7, along with the results from the CST Studio simulation. There is some deviation of the measurement against the simulated attenuation constant. This difference is caused by the fabrication tolerances like surface roughness of the dielectric. Also, the assembly process caused some variations since the process was implemented manually; the use of PCB mechanical through-hole-press method has meant the manual force was variable and the three layers were not attached precisely. The deviation can be up to ~9 dB/m for some frequencies. Beyond 31 GHz, there is a significant increase in the attenuation constant and so the HSIW is presented as have an operating range of 21-31 GHz. Overall, the designed HSIW achieves for the selected band of operation with an exceptionally low propagation loss of 13.55 dB/m (0.01355 dB/mm), which is one of the lowest values reported among other state-of-the-art designs, as summarized in reference [11].

V. Discussion

Figure 8(a) shows the cross-sectional drawing in the *XZ* plane before assembly. After pressing the prefabricated vias to fix the three surfaces, Fig. 8(b) shows the cross-sectional drawing in the *XZ* plane after assembly, including the bending effect from over pressing force of THP machine. Figure 9 shows the attenuation constant versus frequency when varying the diameter of the vias, *D*, from 1.6 mm to 2.0 mm in step of 0.2 mm and height of the hollow substrate, *h*, from 0.50 mm to 0.45 mm in step of 0.025 mm. The results show that the diameter of via does affect the cut-off frequency. The bigger diameter gives a higher cut-off frequency, which is to be expected. On the other hand, the variation in hollow substate height has only a small effect on propagation loss.

For SIW design, the frequency limit is dictated by design limitations and fabrication limitations. The main design limitation relates to the diameter of the vias and the distance between them [40]. In the practical case, the selected diameter of prefabricated vias depends on available diameter sizes that are available in the market [41]. In this paper, the HSIW is designed and fabricated for operating at 21 – 31 GHz. We choose the via diameter of 1.6 mm which satisfactory for use in this band. However, at higher frequencies the required diameter of vias is very small. We can change the technique for creating the via as reported in [42].

VI. Future Work

The method of rapid prototyping HSIW-based millimeter-wave components using a combination of additive and subtractive manufacturing processes has proved effective. The proposed technique has advantages in the ease of design, low fabrication and material cost, requires no chemical processing, and can be used to realize a new class of microwave and millimeter-wave components with the possibility of conformal and flexible structures [43]. However, this method was necessary for fabricating the prototype components for testing the performance before considering mass production. This work has proved the concept, but further work is required to further automate the process to reduce the tolerance of the assembly processes. For example, controlling the pressed force of the mechanical head during assembly and using automatic stepping motors to align the center of the prefabricated vias before pressing. When comparing with a PCB process, fabrication of through substrate vias in the PCB process is very problematic since the via diameter is very small and thus the metallization process of filling or covering sidewall of the via with copper are very difficult, unreliable and very costly and require very sophisticated machines to achieve the task.

VII. Conclusion

In this paper, a new method for fabricating a HSIW waveguide at millimeter-wave frequencies has been demonstrated, using a combination of additive and subtractive manufacturing techniques. These methods provide fast development and assembly and low-cost fabrication, compared to other methods, which can be extremely costly and require specialist facilities. The methos obviates the need to use any chemical processing, which is particular advantageous as health, safety and environmental legislation rightly imposes ever greater requirements on laboratory management.

The additive manufacturing process provides enhanced flexibility in choosing the dielectric material to be used as the hollow substrate. It has advantages of stability, ease of design, low-cost, lightweight, and the possibility for mechanical flexibility. It offers a new degree of design freedom for applications benefitting from the use of conformal and flexible structures. Specifically, the material jetting 3D printing technology provides the opportunity to choose from hundreds of materials and they can be mixed to produce composite 3D materials for a number of important new millimeter-wave components.

Finally, the propagation constant results show an average 12.5% difference between simulations and measurements over the operating frequency range. A very low attenuation constant of 13.55 dB/m (0.01355 dB/mm) is achieved for the whole operating frequency range of 21-31 GHz.

References

[1] N. Duangrit, B. Hong, A. D. Burnett, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "Terahertz Dielectric Property Characterization of Photopolymers for Additive Manufacturing," in *IEEE Access*, vol. 7, pp. 12339-12347, 2019

[2] J. D. Kechagias and S. Maropoulos, "An investigation of sloped surface roughness of direct Poly-Jet 3D printing," in *Proc. Int. Conf. Recent Adv. Mech., Mechatronics Civil, Chem. Ind. Eng. J.*, 2015, pp. 150-153.

[3] A. Kampker, K. Kreisköther, and C. Reinders, ''Material and parameter analysis of the PolyJet process for mold making using design of experiments,'' *Int. J. Chem., Mol., Nucl., Mater. Metall. Eng.*, vol. 11, no. 3, pp. 242–249, 2017.

[4] V. W. Sahana and G. T. Thampi, "3D printing technology in industry," in *2018 2nd International Conference on Inventive Systems and Control (ICISC)*, 2018.

[5] J. Li, Y. Wang, J. He, H. Liu and G. Xiang, "Rapid Production of Customised Electronic Systems Via Multifunctional Additive Manufacturing Technology," in *2018 IEEE 3rd International Conference on Integrated Circuits and Microsystems (ICICM)*, 2018.

[6] N. Chudpooti, N. Duangrit, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "220-320 GHz Hemispherical Lens Antennas Using Digital Light Processed Photopolymers," *IEEE Access,* vol. 7, pp. 12283-12290, 2019.

[7] B. Hong, M. Swithenbank, N. Greenall, R. G. Clarke, N. Chudpooti, P. Akkaraekthalin, N. Somjit, J. E. Cunningham and I. D. Robertson, "Low-Loss Asymptotically Single-Mode THz Bragg Fiber Fabricated by Digital Light Processing Rapid Prototyping," *IEEE Transactions on Terahertz Science and Technology,* vol. 8, no. 1, pp. 90-99, 2018.

[8] B. Hong, M. Swithenbank, N. Somjit, J. Cunningham and I. Robertson, "Asymptotically single-mode small-core terahertz Bragg fibre with low loss and low dispersion," *Journal of Physics D,* vol. 50, no. 4, p. 45104, 2017.

[9] Z. Wu, M. Liang, W.-R. Ng, M. Gehm and H. Xin, "Terahertz Horn Antenna Based on Hollow-Core Electromagnetic Crystal (EMXT) Structure," *IEEE Transactions on Antennas and Propagation,* vol. 60, no. 12, pp. 5557-5563, 2012.

[10] X. Yu, H. Zhang, S. Jia, T. Morioka, X. Zhang, P. U. Jepsen and L. K. Oxenlowe, "Exploring THz band for high speed wireless communications," in *2016 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, 2016.

[11] G. Savvides, N. Duangrit, N. Chudpooti, P. Akkaraekthalin, U. Imberg, I. D. Robertson and N. Somjit, "3D Rapid-Prototyped 21-31-GHz Hollow SIWs for Low-Cost 5G IoT and Robotic Applications," *IEEE Access,* vol. 9, pp. 11750-11760, 2021.

[12] N. Chudpooti, N. Duangrit, P. Sangpet, P. Akkaraekthalin, B. U. Imberg, I. D. Robertson and N. Somjit, "In-Situ Self-Aligned NaCl-Solution Fluidic-Integrated Microwave Sensors for Industrial and Biomedical Applications," IEEE Access, vol. 8, pp. 188897-188907, 2020.

[13] B. T. Malik, V. Doychinov, S. A. R. Zaidi, I. D. Robertson and N. Somjit, "Antenna Gain Enhancement by Using Low-Infill 3D-Printed Dielectric Lens Antennas," IEEE Access, vol. 7, pp. 102467-102476, 2019.

[14] N. Chudpooti, N. Duangrit, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "Electronics-Based Free-Space Terahertz Measurement Using Hemispherical Lens Antennas," IEEE Access, vol. 7, pp. 95536-95546, 2019.

[15] B. Andres-Garcia, E. Garcia-Munoz, S. Bauerschmidt, S. Preu, S. Malzer, G. H. Dohler, L. Wang and D. Segovia-Vargas, "Gain Enhancement by Dielectric Horns in the Terahertz Band," IEEE Transactions on Antennas and Propagation, vol. 59, no. 9, pp. 3164-3170, 2011.

[16] E. Lacombe, F. Gianesello, A. Bisognin, C. Luxey, D. Titz, H. Gulan, T. Zwick, J. Costa and C. A. Fernandes, "Low-cost 3D-printed 240 GHz plastic lens fed by integrated antenna in organic substrate targeting sub-THz high data rate wireless links," in 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2017.

[17] K. Y. Chan, R. Ramer and R. Sorrentino, "Low-Cost Ku-Band Waveguide Devices Using 3-D Printing and Liquid Metal Filling," *IEEE Transactions on Microwave Theory and Techniques,* vol. 66, no. 9, pp. 3993-4001, 2018.

[18] G. Mitchell, T. Anthony, Z. Larimore and P. Parsons, "Antenna Comparison for Additive Manufacturing versus Traditional Manufacturing Methods," 2021 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), 2021, pp. 3-4, doi: 10.23919/USNC-URSINRSM51531.2021.9336492.

[19] G. Mitchell, Z. Larimore and P. Parsons, "Additive Manufacturing of a Dual Band, Hybrid Substrate, and Dual Polarization Antenna," 2020 International Applied Computational Electromagnetics Society Symposium (ACES), 2020, pp. 1-2, doi: 10.23919/ACES49320.2020.9196147.

[20] V. Gjokaj, J. Papapolymerou, J. D. Albrecht and P. Chahal, "Design and Fabrication of Additively Manufactured Hybrid Rigid-Flex RF Components," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 9, no. 4, pp. 779-785, April 2019, doi: 10.1109/TCPMT.2019.2900210.

[21] X. Yu et al., "3-D Printed Parts for a Multilayer Phased Array Antenna System," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 11, pp. 2150-2154, Nov. 2018, doi: 10.1109/LAWP.2018.2873116.

[22] J. Bito, R. Bahr, J. G. Hester, S. A. Nauroze, A. Georgiadis and M. M. Tentzeris, "A Novel Solar and Electromagnetic Energy Harvesting System With a 3-D Printed Package for Energy Efficient Internet-of-Things Wireless Sensors," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 5, pp. 1831-1842, May 2017, doi: 10.1109/TMTT.2017.2660487.

[23] M. Mirzaee, S. Noghanian, L. Wiest and I. Chang, "Developing flexible 3D printed antenna using conductive ABS materials," in *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2015.

[24] N. Chudpooti, E. Silavwe, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "Nano-Fluidic Millimeter-Wave Lab-on-a-Waveguide Sensor for Liquid-Mixture Characterization," *IEEE Sensors Journal,* vol. 18, no. 1, pp. 157-164, 2018.

[25] E. Silavwe, N. Somjit and I. D. Robertson, "A Microfluidic-Integrated SIW Lab-on-Substrate Sensor for Microliter Liquid Characterization," *IEEE Sensors Journal,* vol. 16, no. 21, pp. 7628-7635, 2016.

[26] I. E. Obuh, V. Doychinov, D. P. Steenson, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "Low-Cost Microfabrication for MEMS Switches and Varactors," *IEEE Transactions on Components, Packaging and Manufacturing Technology,* vol. 8, no. 9, pp. 1702-1710, 2018.

[27] N. Chudpooti, V. Doychinov, P. Akkaraekthalin, I. D. Robertson and N. Somjit, "Non-Invasive Millimeter-Wave Profiler for Surface Height Measurement of Photoresist Films," in *IEEE Sensors Journal*, vol. 18, no. 8, pp. 3174-3182, 15 April15, 2018, doi: 10.1109/JSEN.2018.2806185.

[28] B. Hong, N. Feng, J. Chen, G. P. Wang, V. Doychinov, R. Clarke, J. Cunningham, I. Robertson and N. Somjit, "Substrate integrated Bragg waveguide: an octave-bandwidth single-mode hybrid transmission line for millimeter-wave applications.," *Optics Express,* vol. 28, no. 19, pp. 27903-27918, 2020.

[29] N. B. M. Najib, N. Somjit and I. Hunter, "Design and characterisation of dual-mode suspended-substrate stripline filter," *IET Microwaves Antennas & Propagation,* vol. 12, no. 9, pp. 1526-1531, 2018.

[30] "GoodFellow," [Online]. Available: http://www.goodfellow.com/. [Accessed 6 January 2021].

[31] "Fortex PTH400," [Online]. Available: http://www.fortex.co.uk/download/pth400-mechanical-through-hole-press/. [Accessed 6 January 2021].

[32] "CST Studio Suite," Dassault Systèmes, [Online]. Available: https://www.3ds.com/products-services/simulia/products/cst-studio-suite/. [Accessed 6 January 2021].

[33] "Synova laser microjet®: Water jet guided laser technology," [Online]. Available: https://www.synova.ch/technology/laser-microjet.html. [Accessed 18th May 2021]

[34] "Digital ABS plus," [Online]. Available: https://www.stratasys.com/materials/search/digital-abs-plus. [Accessed 6 January 2021].

[35] C.-K. Lee, J. McGhee, C. Tsipogiannis, S. Zhang, D. Cadman, A. Goulas, T. Whittaker, R. Gheisari, D. Engstrom, J. Vardaxoglou, and W. Whittow, ‘‘Evaluation of microwave characterization methods for additively manufactured materials,’’ Designs, vol. 3, no. 4, p. 47, Sep. 2019.

[36] J. Pourahmadazar and T. A. Denidni, ‘‘Towards millimeter-wavelength: Transmission-mode fresnel-zone plate lens antennas using plastic material porosity control in homogeneous medium,’’ *Sci.Rep.*, vol. 8, no. 1, Dec. 2018, Art. no. 5300.

[37] H. Xin and M. Liang, ‘‘3-D-printed microwave and THz devices using polymer jetting techniques,’’ Proc. IEEE, vol. 105, no. 4, pp. 737–755, Apr. 2017

[38] “OBJET1000 PLUS,” [Online]. Available: https://www.stratasys.com/3d-printers/objet1000-plus. [Accessed 6 January 2021].

[39] R. Marks, “A multiline method of network analyzer calibration,” *IEEE Transactions on Microwave Theory and Techniques,* vol. 39, no. 7, pp. 1205-1215, 1991.

[40] Feng Xu and Ke Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 1, pp. 66-73, Jan. 2005.

[41] “Fortex PTH400,” [Online]. Available: http://www.fortex.co.uk/product/favorit-through-hole-mechanical-plating/. [Accessed 31 July 2021].

[42] S. J. Bleiker et al., "High-Aspect-Ratio Through Silicon Vias for High-Frequency Application Fabricated by Magnetic Assembly of Gold-Coated Nickel Wires," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 5, no. 1, pp. 21-27, Jan. 2015.

[43] A. C. Fischer et al., “High aspect ratio TSVs fabricated by magnetic self-assembly of gold-coated nickel wires,” *2012 IEEE 62nd Electronic Components and Technology Conference*, 2012, pp. 541-547, doi: 10.1109/ECTC.2012.6248882.

NONCHANUTT CHUDPOOTI (Member, IEEE) received the B.Sc. degree (Hons.) in industrial physics and medical instrumentation and the Ph.D. degree in electrical engineering from the King Mongkut's University of Technology North Bangkok, in 2012 and 2018, respectively, where he was appointed as a Lecturer at the Department of Industrial Physics and Medical Instrumentation, Faculty of Applied Science, in 2018. His main research interests include the application of microwave microfluidic sensors, millimeter-wave substrate integrated circuit applications, and substrate integrated waveguide applications. He was a recipient of the Best Presentation Award from the Thailand-Japan Microwave, in 2015 and 2018, and the Young Researcher Encouragement Award, in 2016.

GIORGOS SAVVIDES was born in Nicosia, Cyprus, in 1993. He received the M.Eng. degree (Hons.) in electronics engineering from the University of Leeds, Leeds, U.K., in 2018, where he is currently pursuing the Ph.D. degree, supported by EPSRC DTP Scholarship. His current research interest includes millimetre-wave circuits and devices.

NATTAPONG DUANGRIT (Member, IEEE) received the B.Eng. degree in electronics and telecommunication engineering from the Rajamangala University of Technology Thanyaburi (RMUTT), in 2014, and the Ph.D. degree from the King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand, in 2019. His Ph.D. was supported by the Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program. His current research interests include the application of 3D printing technology for millimeter-wave and THz devices, and substrate integrated waveguide applications.

PRAYOOT AKKARAEKTHALIN (Member, IEEE) received the B.Eng. and M.Eng. degrees in electrical engineering from the King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand, in 1986 and 1990, respectively, and the Ph.D. degree from the University of Delaware, Newark, DE, USA, in 1998. From 1986 to 1988, he was a Research and Development Engineer with Microtek Products Co., Ltd., Thailand. In 1988, he joined the Department of Electrical Engineering, KMUTNB. He was the Head of the Senior Research Scholar Project which is supported by the Thailand Research Fund, from 2015 to 2017. He has authored or co-authored more than 40 international journals, more than 200 conference papers, and four books/book chapters. His current research interests include RF/microwave circuits, wideband and multiband antennas, telecommunication, and sensor systems. He is a member of IEICE, Japan, ECTI, and the EEAAT Association, Thailand. He was the Chairman of the IEEE MTT/AP/ED Thailand Joint Chapter, from 2007 to 2010, and the Vice President and the President of the ECTI Association, Thailand, from 2012 to 2013 and from 2014 to 2015, respectively. He was the Editor-in-Chief of the ECTI Transactions, from 2011 to 2013.

IAN D. ROBERTSON (Fellow, IEEE) received the B.Sc. (Eng.) and Ph.D. degrees from King's College London, London, U.K., in 1984 and 1990, respectively. From 1984 to 1986, he was with the GaAs MMIC Research Group, Plessey Research, Caswell, U.K. Then, he returned to King's College, initially as a Research Assistant working on the T-SAT project and, then, as a Lecturer leading the MMIC Research Team, where he became a Reader, in 1994. In 1998, he became a Professor of microwave subsystems engineering with the University of Surrey, where he established the Microwave Systems Research Group and was a Founding Member of the Advanced Technology Institute. In 2004, he was appointed to the Centenary Chair in Microwave and Millimetre-Wave Circuits, University of Leeds. He was the Director of learning and teaching, from 2006 to 2011, and the Head of the school, from 2011 to 2016.

Dr. Robertson was the General Technical Programme Committee Chair of the European Microwave Week, in 2011 and 2016.

NUTAPONG SOMJIT (Senior Member, IEEE) received the Dipl.-Ing. (M.Sc.) degree from the Dresden University of Technology, in 2005, and the Ph.D. degree from the KTH Royal Institute of Technology, in 2012. In 2012, he returned to the Dresden University of Technology to lead a research team in micro-sensors and MEMS ICs for the Chair for Circuit Design and Network Theory. In 2013, he was appointed as a Lecturer (Assistant Professor) with the School of Electronic and Electrical Engineering, University of Leeds. His current research interests include integrated smart high-frequency components, heterogeneous integration, and low-cost microfabrication processes.

Dr. Somjit has been a member of the International Editorial Board of the International Journal of Applied Science and Technology, since 2013. He was appointed as a member of the Engineering, Physical and Space Science Research Panel of the British Council, in 2014. He was a recipient of the Best Paper Award (EuMIC prize) from the European Microwave Week, in 2009. He received a Graduate Fellowship from the IEEE Microwave Theory and Techniques Society, in 2010 and 2011, and the IEEE Doctoral Research Award from the IEEE Antennas and Propagation Society, in 2012. In 2016, he was the Chair of the Student Design Competition for the European Microwave Week. In 2018, he was appointed as an Associate Editor of Electronics Letters (IET).