3-D Printed Circuits for RF and Microwave Applications

Xiaobang Shang, Cheng Guo, and Michael J. Lancaster

Department of Electronic, Electrical and Systems Engineering, University of Birmingham, B15 2TT, UK E-mail: shangxiaobang@gmail.com, c.guo.1@bham.ac.uk, m.j.lancaster@bham.ac.uk

Abstract

3-D printing is a promising technique to produce RF and microwave passive circuits. Compared with conventional machining techniques, 3-D printing enables the manufacture of complex structures with great geometrical complexity and/or printing the devices into a standalone part without the need of further assembly. Another great advantage of 3-D printing is the significant weight reduction, when the device is printed from polymer and metal coated.

This paper presents a range of 3-D printed passive circuits investigated at the University of Birmingham. These circuits cover a wide frequency range, from 0.5GHz to 100GHz, and include a 0.5 GHz helical resonator filter [1], a 3 GHz combline filter [2], two 10 GHz waveguide filters based on spherical resonators [3]-[5], a 15 GHz filtering Butler matrix [6], a 30 GHz OMT [7], and two 90 GHz waveguide filters [8]. Among them, the 90 GHz filters represent the highest frequency 3-D printed filters reported in open literature to date. These devices will be discussed in detail in the sections below.

Most of the devices are based on lightweight polymers, which are capable of handling high temperature when ceramic filled resin is used. 3-D metal printing is also utilised to produce several designs including a W-band filter. All of the circuits are optimised for 3-D printing, so that enhanced microwave performance and/or considerable weight reduction can be achieved. This cluster of work demonstrates the great potential of using 3-D printing for microwave applications.

0.5GHz Helical Resonator Filter [1]

A filter working at a centre frequency of 0.5 GHz and a 4% fractional bandwidth (FBW) formed of four coupled helical resonators is designed and fabricated for potential applications in communication systems operating in the VHF and UHF ranges. The filter design as well as the fabricated device is shown in Figure 1. For each resonator the helix is fixed at both ends so that the resonator is less prone to vibration. The helix is designed to have variable width and this yields enhanced performance in terms of a higher unloaded quality factor and a spurious resonance at higher frequencies. Such a helix is ideally suited to 3-D printing which allows easy production of complex structures. Coupling into and out of the filter is realized through coaxial connectors.

The filter is printed from a resin (Somos) using a stereolithography (SLA) printer, and is subsequently coated with around 25 μ m thick copper. The filter is made in two pieces (the helical structures and a separate lid), in order to facilitate the metal plating process which requires access to inner surfaces. After metallization, these two pieces are assembled using bolts through holes 3-D printed through the whole side of the structure. The simulated and measured filter responses are shown in Figure 2. The measured return loss is better than 16.5 dB across the whole passband. The measured average passband loss is around 0.4 dB, which is around 0.1 dB higher than the expected value from simulations using conductivity of copper. Overall, there is a good agreement between measurement and prediction from CST simulation.



Figure 1. (a) Configuration of the helical resonator filter together with a pair of SMA connectors. (b) Photograph of the 3-D printed filter before metal coating. (c) Photograph of the filter (without the lid) after metal coating. The filter is made by 3-D Parts Ltd (UK).



Figure 2. Measured (solid lines) and simulated (dashed lines) *S*-parameters responses of the helical resonator filter. There has been no tuning of the filter.

3GHz Combline Filter [2]

A fourth-order 3-D printed combline filter with a Chebyshev response, operating at central frequency 3 GHz and having a 3% fractional bandwidth, is the second filter. The filter design is shown in Figure 3. Traditionally, such filter is made using CNC machining in individual parts, due to the great complexity of the filter structure. High current points (e.g. between the base and the quarter wavelength resonators) need to be fully connected, in order to minimize insertion loss owing to tiny gaps. 3-D printing is capable of producing such complex structures quickly and easily, and enabling continuous metallization in high current areas which are of importance to the insertion loss.

The manufacturing process used to fabricate the filter is stereolithography (SLA) printing, producing a polymer model which is then plated with copper. In order to ease the plating process, the filter is printed into two parts (main structure and lid) which are assembled together using nuts and long threaded rod. The structure is extremely lightweight and compact for such a high Q device. The weight of the filter (without connectors and screws for the lid) is 57 g which is only 13% of the weight of an equivalent copper filter. Test performance of the filter can be found in Figure 4, which shows an excellent agreement between simulation and measurement. The measured insertion loss is about 0.31 dB, which is only 0.08 dB higher than simulation using copper. The measured responses have a small (0.4%) frequency shift, and this is attributed to the dimensional inaccuracies which are on the order of 100 μ m.



Figure 3. (a) Configuration of the fourth-order combline filter. (b) Photograph of the 3-D printed filter (after metal coating) together with a pair of SMA connectors. (c) Photograph of the assembled filter. The filter is made by Swissto12 (Switzerland).



Figure 4. Measurement (solid lines) and simulation (dashed lines) results of the 3-D printed combline filter. (a) S_{21} responses – the inserts show a good wide stopband as well as a low passband insertion loss. (b) S_{11} responses. There has been no tuning of the filter.

10GHz Spherical Resonator Filter [3]

A fifth order X-band waveguide filter, formed of coupled spherical resonators operating at TM_{101} mode, is designed and fabricated by stereolighography (SLA) based 3-D printing. The design of the filter is shown in Figure 5. The topology is specially chosen to reduce the impact of higher order modes in the resonator and ultimately to obtain a good out-of-band rejection. Compared to the standard rectangular TE_{101} resonator with the same resonant frequency of 10 GHz, the spherical resonator has a much higher unloaded Q (14450 vs 7957). This enables the filter with ultra-low insertion loss. However, the fabrication of such spherical shape resonators is difficult for the conventional CNC machining process. 3-D printing allows easy fabrication of such shapes and structures with even greater complexity. The filter is designed to have a centre frequency of 10 GHz and a fractional bandwidth of 5%.

The structure of the filter is printed on a SLA printer, and then plated with 25 μ m thick copper all around. To facilitate the plating process, the filter is made into three pieces which are assembled together after metallization. Figure 6 shows the measurement and simulation results of the filter, which are in excellent agreement with simulations. The measured passband insertion loss is about 0.107 dB on average, whereas the simulated value is 0.072 dB. The weight of the filter is 0.28 kg which is only 14% of that made from copper.



Figure 5. Configurations of the 5th-order spherical resonator filter. The filter is made by 3-D Parts Ltd (UK).



Figure 6. Measurement and simulation results of the 5th-order spherical resonator filter. The inserts show the measured responses over the whole X-band as well as the expanded view of S_{21} responses across the passband. There has been no tuning of the filter.

10GHz spherical dual-mode resonator filter [4]-[5]

Spherical dual-mode resonators are utilized to construct a fourth-order X-band filter with small size and good out-of-band rejection response. The filter is designed to have a centre frequency of 10 GHz and a fractional bandwidth of 3%. As shown in Figure 7, the filter is formed of two coupled spherical cavity resonators using the degenerate TM_{101} mode (i.e. each cavity supports two orthogonally polarized TM_{101} resonances). This yields a filter with minimized size and a pair of transmission zeros in the S_{21} response. Additionally, the spherical dual-mode resonator filter is superior over its counterparts based on conventional square or cylindrical dual-mode resonators, in terms of offering a higher rejection over stopband and an improved spurious-free region, as shown in Figure 8 (a).

The filter is printed from a ceramic filled resin (Smos PerForm) using SLA process, and then coated with 10 μ m thick copper. This ceramic filled resin is able to extend the filter's operating temperature from about 60°C (e.g. Accura Xtreme) to 140°C. Figure 8 (b) and (c) show the measurement results of the filter at different temperatures. The filter's responses generally remain the same with raising temperatures, except for the centre frequency which shifts downwards linearly with temperature. Noteworthy, the ceramic filled resin has a density of 1.61 g/cm³, which is still significantly lower than that of aluminum (2.7 g/cm³) and copper (8.96 g/cm³).

The filter has rectangular holes through the waveguide and the spherical cavity walls to further reduce the filter weight. These holes also facilitate the electroplating process, allowing the plating solution flow into the cavities without the need of splitting the cavities into two halves. The sizes and positions of these holes are specially designed to avoid any radiation loss.



Figure 7. (a) Photograph of the 4th order X-band spherical dual-mode filter. (b) Coupling topology of the filter together with a longitudinal section view of the filter showing the internal coupling and tuning structures.



Figure 8. Measurement and simulation results of the 3D printed X-band spherical dual-mode filter. (a) Simulation responses of the spherical dual-mode filter, in comparison with filters based on square and cylindrical dual-mode resonators. It can be observed that the spherical filter has the best out-of-band rejection. (b) Measured S_{21} of the dual-mode filter at different temperatures. (c) Measured S_{11} at different temperatures. The filter is made by 3-D Parts Ltd (UK).

15GHz Filtering Butler Matrix [6]

A WR-75 waveguide 4×4 Butler matrix is designed using solely coupled resonators and fabricated using 3-D metal printing. Figure 9 shows the structure of the Butler matrix as well as the photograph of the printed device. The Butler matrix is designed with a centre frequency of 12.5 GHz, a bandwidth of 0.5 GHz, and a return loss of 25 dB. It should be noted that all-resonator based Butler matrix is novel with the advantage of a significant size reduction. Volume of the resonator-based 4×4 Butler matrix (shown in Figure 9) is only around 70% of that of the conventional design formed of a transmission-line Butler matrix and four individual bandpass filters. More detailed discussions can be found in [6].

Figure 10 shows the measurement and simulation results of the Butler matrix. The measured responses have been shifted by 0.18 GHz in order to compare with the simulations better. The return loss is measured to be about 12 dB in the worst case. The worsening S_{11} and the frequency shift are in line with the tolerance of the 3-D metal printing process utilized in this work.



Figure 9. (a) Configuration of the 4×4 filtering Butler matrix. (b) Photograph of the 3-D printed Butler matrix.



Figure 10. Measurement results (solid lines) and simulation results (dashed lines) of the 4×4 filtering Butler matrix. Measured responses have been shifted by 0.18 GHz, in order to compare with simulations better.

30GHz Orthomode Transducer (OMT) [7]

A Ka-band waveguide orthomode transducer (OMT) is designed as a part of the TX/RX feed chain components of a satellite communication system. The design of the OMT is shown in Figure 11 (a) and (b). The OMT is designed to operate at two frequency bands, with each band passing an orthogonal polarization. The H-polarization operates in the band from 27 to 31 GHz and the V-polarization works in the band from 17 to 22 GHz. The OMT structure has waveguide steps only. This geometry is simple, compact in size and can be easily produced using 3-D printing. To achieve direct measurement of the OMT, two tapered waveguide transitions (see Figure 11 (c)) are designed and made using 3-D printing.

The OMT and the tapered waveguides are fabricated using stereolithography (SLA) printing and then coated with 5 μ m thick copper via electroplating. The OMT is split into two pieces to facilitate the plating process which needs access to the inner surface. Figure 12 shows the test performance of the OMT. The measured return loss is below -15 dB for V-polarization and is below -18 dB for H-polarization. The average measured insertion loss for the H-polarization is 0.2 dB, which is very close to the simulated value of around 0.1 dB. The measured loss for the V-polarization is much higher and it is around 2.5 dB. This is attributed to the way the OMT is split. For the lateral port (for V-polarization), the waveguide is split along the middle of narrow side wall. Current flows across the joints and air gaps at the interface lead to radiation loss. For the axial port (for H-polarization), the waveguide is split along the broad side wall. In this case, insertion loss is not sensitive to the quality of the joints as current does not flow across them.



Figure 11. Illustration diagram (a) and photograph (b) of the 3-D printed Ka-band waveguide OMT. (c) Tapered waveguides to convert the square waveguide to standard WR-42 and WR-28 waveguide, so that *S*-parameter measurements can be taken on the VNA. The OMT together with the tapered waveguide transitions is made by 3-D Parts Ltd (UK).



Figure 12. Measurement and simulation results of the 3-D printed Ka-band OMT. (a) Responses for the V-polarization. (b) Responses for the H-polarization.

100GHz Waveguide Filters [8]

In collaboration with Swissto12 Ltd, a W-band waveguide filter has been demonstrated, as shown in Figure 13. This is a fifth-order Chebyshev filter with a center frequency of 90 GHz and an equal ripple bandwidth of 10 GHz. The passband return loss is designed to be 20 dB. The filter is printed from photosensitive resin using stereolithography (SLA) process and is subsequently coated with 10 μ m thick copper all around. The filter is designed to have slots on both broadside and narrow side walls. This reduces the weight even further and facilitates the metal plating process allowing easy flowing of solution, while at the same time not having the penalty of degraded insertion loss. Measurement responses show visible frequency shift and this is attributed to fabrication inaccuracies. The modified filter model taking account of these inaccuracies is simulated in CST and the results agree well with measurements. The deviation in dimensions is due to enlargement in post-curing step of the printing process, and could be corrected by remaking the filter with modified dimensions.

An alternative to SLA printing is 3-D metal printing using selective laser sintering (SLS) process. SLS allows all metal devices to be printed and is of particular interest to devices demanding high thermal stability. In collaboration with 3DMicroPrint and University of Hong Kong, a W-band filter is printed

from steel powder, as shown in Figure 14. This filter is designed to have the same specifications as the plastic one shown in Figure 13. Measurement results of the metal filter agree well with simulations. The filter is being coated with copper, and will be tested again after plating.

There has been no tuning to either of the two filters. These two filters represent the highest frequency 3-D printed waveguide filters demonstrated to date. The manufacturing process will improve over time and we expect 3-D printed filters moving into the sub-terahertz region soon.



Figure 13. (a) Photograph of the 3-D printed W-band filter. (b) Measurement and simulation results of the filter. Passband insertion loss is measured as 0.4 dB, compared with simulated 0.15 dB. The filter is made by Swissto12 (Switzerland).



Figure 14. (a) Illustration diagram and photograph of the 3-D printed W-band steel filter. (b) Measurement and simulation results of the filter. Measured average passband insertion loss is around 2 dB, which is 1.5 dB higher than simulation. The filter is made by 3DMicroPrint (Germany), and the post-processing is done at University of Hong Kong.

Conclusions

A range of passive circuits covering the frequency range from 0.5GHz to 100GHz have been fabricated using 3-D printing technology. This cluster of work has demonstrated (i) the great flexibility in design enabled by 3-D printing and such flexibility would be beneficial to microwave designers who are in persistent pursuit of devices with improved performance and reduced size; and (ii) the state-of-the-art of 3-D printing technique with waveguide filters operating at frequencies as high as W-band produced successfully.

Additionally, three specific points demonstrated through the examples in this paper are:

- (i) In the case where the SLA printed devices need to electroplated, slots along current lines or at current null points facilitate the plating solution to flow into the inside of the device. This allows the device to be made in a single standalone part, without sacrificing performance. The slots also yield weight reduction, even to SLS printed all metal devices.
- (ii) SLA printing together with metal plating is capable of producing lightweight polymer-based devices, which are desirable for applications where weight is important (e.g. satellite applications). The resin utilised by Swissto12 has a service temperature of -65°C to 85°C. An extended temperature range can be achieved by using ceramic filled resins.
- (iii) Design for manufacture leads to easier printing and higher chance of having a working device. For instance, the 3-D metal printed W-band filter has replaced all the circular holes (for the flange) with hexagonal shaped holes which are easier and faster to print using SLS process.

References

[1] X. Shang, M. J. Lancaster, et al, "3-D printed filter based on helical resonators with variable width," in 2017 IEEE MTT-S International Microwave Symposium (IMS), Honolulu, Hawaii, USA, 4-9 June 2017

[2] L. S. Araujo, X. Shang, M. J. Lancaster, *et al*, "3-D printed band-pass combline filter," *Microwave and Optical Technology Letters*, vol. 59, no. 6, pp. 1388-1390, June 2017

[3] C. Guo, X. Shang, Michael Lancaster, *et al*, "A 3-D printed lightweight X-Band waveguide filter based on spherical resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 7, pp. 442-444, July 2015

[4] C. Guo, X. Shang, F. Zhang, *et al*, "A lightweight 3-D printed X-band bandpass filter based on spherical dual-mode resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 26, no. 8, pp. 568-570, Aug. 2016

[5] C. Guo, J. Li, D. Dinh, X. Shang, *et al*, "Ceramic filled resin based 3D printed X-band dual-mode bandpass filter with enhanced thermal handling capability," *Electron. Lett.*, vol. 52, no. 23, pp. 1929-1931, Nov. 2016

[6] V. T. Crestvolant, P. M. Lglesias, M. J. Lancaster, "Advanced Butler matrix with integrated bandpass filter functions," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 10, pp. 3433-3444, Oct. 2015

[7] X. Shang, P. Klasmann, M. J. Lancaster, "A compact Ka-band waveguide orthomode transducer fabricated by 3-D printing," in *46th European Microw. Conference*, London, UK, 4-6 Oct. 2016, pp.365-368

[8] X. Shang, P. Penchev, C. Guo, *et al*, "W-band waveguide filters fabricated by laser micromachining and 3-D printing," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 8, pp. 2572-2580, Aug. 2016