3-D Printing of Microwave Components for 21st Century Applications

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***Abstract*—Additive manufacturing using 3-D printing is an emerging technology for the production of high performance microwave and terahertz components. Traditionally, these components are made by (micro-)machining. However, recent advances in rapid prototyping technology have led to its use in creating high performance and low weight RF components. In this review paper ten state-of-the-art exemplars are described, covering a wide variety of applications (absorbers, waveguides, antennas and lenses) operating over a broad range of frequencies, from 8 to 330 GHz.**

***Index Terms* — Additive manufacture, 3-D printing, MPRWG, SLA, SLM, SLS, FDM, Polyjet, waveguide, absorber.**

I. Introduction

The 3-D printer was first invented back in 1980 [1]. However, the past decade has seen a dramatic interest in additive manufacturing using the 3-D printer for rapid prototyping and manufacturing of high geometrical complexity components. Traditionally, radio frequency (RF) waveguides are made by either the machining of metal or electroforming a machined mandrel. But, recent advances in 3-D printing technology have led to their use to create high performance and low weight RF components; only appearing since *ca.* 2012.

In this paper we give an overview of the five main methods of 3-D printing: fused deposition modelling (FDM), polyjet, stereolithographic apparatus (SLA), selective laser sintering (SLS) and selective laser melting (SLM), along with exemplars that demonstrate their application for RF components operating at microwave, millimeter-wave and terahertz frequencies..

II. Methods of 3-D Printing

A. Fused Deposition Modelling

FDM printing, representing the entry-level low-cost and low-resolution technology, is based on the selective deposition of extruded material (most commonly thermoplastics). The printer heats a material above its glass transition temperature and then deposits it through a nozzle, building an object layer by layer. The components that are printed can have micro air pockets and are not always uniform; a study of their dielectric properties was undertaken by Deffenbaugh *et al.* [2]. Further dielectric property characterization by Arbaoui *et al.* [3] showed that, while some of the materials are lossy, they can be used to create electromagnetic absorbers. The absorber they demonstrated has a VSWR of less than 1.025 across the whole of X-Band (8.5 to 12 GHz) and an ability to handle power levels up to 11.5 W.

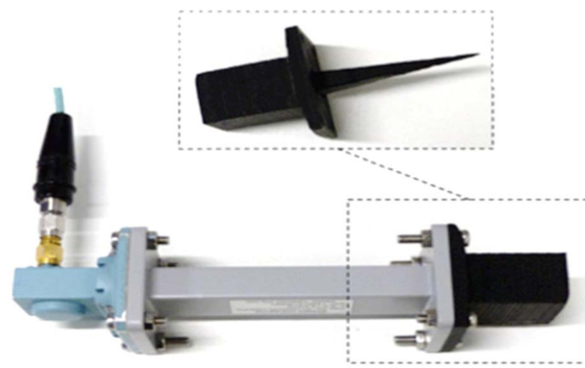

Fig. 1. X-band FDM absorbing termination [3].

The fill density of the 3-D print can be used to create a variety of components. Zhang *et al.* [4] have demonstrated that it is possible to 3-D print a wideband graded index flat lens using a polylactic acid (PLA) building material. This lens works at Ku-band (12 to 18 GHz) and at mid-band has a *H*-plane 3 dB beam width of 9° with a boresight gain of 8 dB.

Fig. 2. Ku-band FDM graded index flat lens [4].

By metalizing the surfaces of the plastic part that has been printed, it is possible to manufacture metal-pipe rectangular waveguide (MPRWG) components using 3-D printing. It has been shown by D'Auria *et al.* [5] that it is possible to 3-D print

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an X-Band MPRWG with excellent performance, when compared to a commercial copper alloy MPRWG, while being 480 mg/mm lighter in weight. The reported 3-D printed MPRWG has a worst-case return loss of -32 dB and insertion loss of only 0.33 dB/m at 10 GHz; the performance being commensurate with conventional machined waveguides.

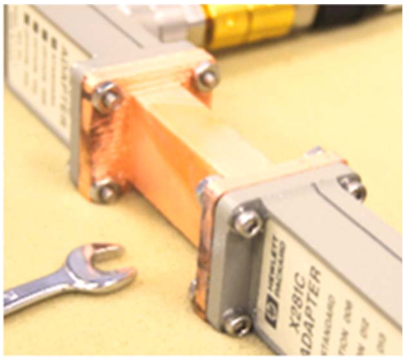

Fig. 3. X-Band FDM MPRWG [5].

In addition to conventional MPRWGs, it is possible to realize higher quality factor spherical cavity resonators, for use in filters, as demonstrated at X-Band by Guo *et al.* [6]. The 5th order 10 GHz band-pass filter has a measured average passband insertion loss of only 0.107 dB across its 0.5 GHz bandwidth.

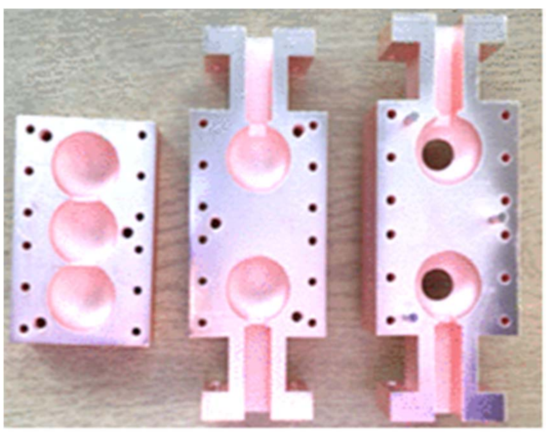

Fig. 4. X-Band FBM split block spherical cavity filter [6].

B. Polyjet Printing

Polyjet printing provides state-of-the-art resolution 3-D printing of plastics. It involves the jetting of a polymer from multiple print nozzles, which is then UV cured; layers are the built one on top of another.

A good example of a polyjet demonstrator is the X-band cavity resonator and band-pass filter by Cai *et al.* [7]. These structures were created using a split-block structure and the two halves were d then sputter coated with a 5 µm copper layer. The measured loaded Q-factor of the cavity was 205 at 10.25 GHz and the filter had a 3.9 % fractional bandwidth and 2.1 dB insertion loss; compared to a simulated 5.1 % fractional bandwidth and 1.9 dB insertion loss.

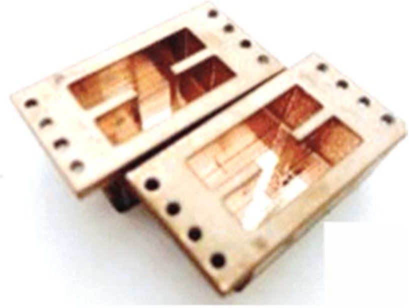

Figure 5: X-Band polyjet band-pass filter [7].

The second polyjet example is a millimeter-wave electromagnetic band gap (EBG) material electromagnetic crystal (EXMT) waveguide horn antenna [8], where the triangular lattice of air holes creates a bandgap and the defects in the lattice forms the antenna. The antenna is designed to operate at multiple pass bands and at 146 GHz shows a 10° 3 dB beam width, with first side lobe suppression of 20 dB.

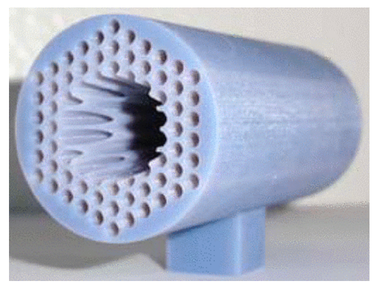

Fig. 7. 146 GHz polyjet EXMT waveguide horn [8].

C. Stereolithographic Apparatus

FDM and polyjet work on the principle of the mechanical movement of a print head to create the structure. SLA, SLM and SLS, however, are all based on using a laser spot that defines where the material is deposited. With SLA, a build plate sits in a bath of a photocurable resin. The laser traces a path in the resin to define each build layer.

SLA has been used to demonstrate several components. Although it is low cost, when compared to polyjet, it can achieve a low surface roughness of 0.93 µm along the length of a waveguide; compared to 4.02 µm for an FDM printed waveguide [5]. These split-block W-Band MPRWGs demonstrated a worst-case return loss of 19 dB and an insertion loss of 11 dB/m at 110 GHz, which is comparable to a conventional machined copper MPRWG having an insertion loss of 10 dB/m at 110 GHz [5].

A high-performance W-band 6th order inductive iris band-pass filter, having a center frequency of 107.2 GHz and a 6.8 GHz bandwidth, was also demonstrated [5]. The measured insertion loss of the complete structure (filter, feed sections and flanges) was only 0.95 dB at center frequency, giving an unloaded quality factor of 152—clearly demonstrating the potential of 3-D printed MPRWGs.

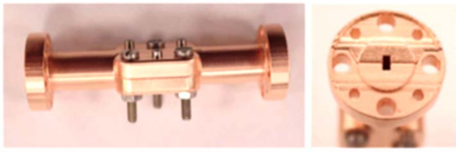

Fig. 8. W-Band SLA split-block MPRWG [5].

D. Selective Laser Sintering/Melting

Selective laser sintering and melting processes are similar to SLA, but print directly in metal. SLS systems sinters a metal powder together; whereas SLM melts the powder together. These are the only two methods currently in use to create parts directly in metal. However, they suffer from relatively poor surface roughness (~6 µm [9]); making them unsuitable for upper millimeter-wave applications without polishing.

Zhang *et al.* [9] demonstrated two SLM MPRWG filters, operating at E-band (60 to 90 GHz), made from a $CuSn_{15}$ alloy. They have pass bands from 73.5 to 77.5 GHz and 84 to 90 GHz, with an average insertion loss of 8 dB and 1.5 dB, respectively.

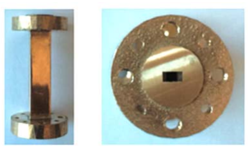

Fig. 9. E-Band SLM band pass filter [9].

III. Commercialization

Although the exemplars cited here have been researched within academia, this technology is already reaching the marketplace. Swissto12 is a world-leading commercial spin-out company from the Swiss Federal Institute of Technology in Lausanne (EPFL). In 2012, they reported the 3-D printing of passive structures for millimeter-wave and terahertz applications in their short note [10]. More recently, since 2014, Swissto12 have been advertising 3-D printed metal coated plastic (MCP) waveguides and diagonal pyramidal horn antennas [11, 12]. These air-filled MPRWGs operate in the WR-3.4 band (220 to 330 GHz) and, with copper metallization, have a reported minimum attenuation of 12 dB/m at *ca.* 280 GHz. In addition, WR-5.1 band (140 to 220 GHz) MCP waveguides are commercially available in both straight and with S-bend sections.

Fig. 10. Commercial WR3.4 band MPRWG (left) and diagonal horn antenna (right) [11, 12]

IV. Conclusion

This review paper introduces some of the highlights from a variety of RF components that have been fabricated using modern 3-D printing technologies. Apart from the commercial activities of Swissto12, these are all research-based exemplars. Rather than being an experimental technology of purely academic interest, 3-D printing of RF components offers important advantages. For example, MPRWG-based components may prove to be critical for future satellite payload applications. Here, in addition to cost reduction, weight is critical and so 3-D printed MPRWGs offers a clear advantage. Nevertheless, there still exists large gaps in our understanding; for example, outgassing of the materials in high vacuum environments, temperature stability, power handling and aging.

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