3D PRINTED WAVEGUIDES: A REVOLUTION IN LOW VOLUME MANUFACTURING FOR THE 21ST CENTURY

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3D printing is a disruptive technology, offering the inherent capabilities for creating truly arbitrary 3D structures, with low manufacturing costs associated with low volume production runs. This paper provides an overview of the current progress in 3D printing of metal-pipe rectangular waveguide (MPRWG) components, from 10 GHz to 1 THz, at Imperial College London. First, measurements performed at the UK National Physical Laboratory demonstrate that 3D printed MPRWG performance is comparable to standard commercial waveguides at X-band and W-band. Then, a fully 3D printed X-band dielectric flap tuneable phase shifter and W-band 6th-order inductive iris bandpass filter are demonstrated experimentally. Finally, an optically-controlled 500 GHz IQ vector modulator will also be presented; packaged laser diodes and high resistivity silicon implants are integrated within a hybrid 3D printed split-block module, representing a paradigm shift in additive manufacturing for realizing tuneable THz applications.

Introduction

The 3-D printer was first invented back in 1980 [1]. It is only in the past decade that a dramatic interest has been seen in additive manufacturing using the 3-D printer for rapid prototyping and manufacturing of high geometrical complexity components. Furthermore, this highly disruptive technology offers the possibility of replacing components onsite, which may be critical in remote or hard to access locations and/or when the lead time is a limiting factor. Traditionally, radio frequency (RF) waveguides are made using subtractive manufacturing techniques (e.g. the machining of metal or electroforming a machined mandrel). Recent advances in 3-D printing technology have led to their use in creating high performance and low weight RF components; only appearing since *ca.* 2012 [2].

In this paper we give an overview of the research, led by Imperial College London, into 3-D printing of metal-pipe rectangular waveguide (MPRWG) components. The initial research into the 3-D printing of MPRWGs was for X-band (8-12 GHz) [3]. The success of this work gave us confidence to move up to W-Band (75-110 GHz), where the small dimensions require a tighter manufacturing tolerance [3]. The experimental measurements at both frequency bands showed performances commensurate with comparable off-the-shelf commercial waveguides. This high level of performance was also demonstrated at W-band with a 6th-order Chebyshev filter [3], being notoriously sensitive to manufacturing tolerances. The next challenge was demonstrating tuneable components. This was achieved with a fully 3-D printed X-band dielectric-flap phase shifter [4]. The most recent work has pushed the mechanical limits for any commercial 3-D printing process for breaking the frequency limit with 3-D printed MPRWGs. This was achieved with an I-Q vector modulator operating up to 500 GHz. Moreover, integrating a pair of silicon implants and laser diodes, we demonstrated the first hybrid solution that combines high performance semiconductor devices with low-cost passive 3-D printed structures [5].

Fused Deposition Modelling (FDM)

FDM printing heats a material above its glass transition temperature and then selectively deposits it through a nozzle to build an object, layer by layer; representing the entry-level in low-cost 3-D printing. FDM provides the lowest spatial resolution 3-D printing method, with build layer heights from 50 to 500 μm, but resolution is limited by nozzle aperture diameter.

By metalizing the surfaces of the printed plastic part, it is possible to manufacture metal-pipe rectangular waveguide components using 3-D printing. Our team has shown that it is possible to 3-D print 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 comparable waveguides, as shown in Fig. 1.

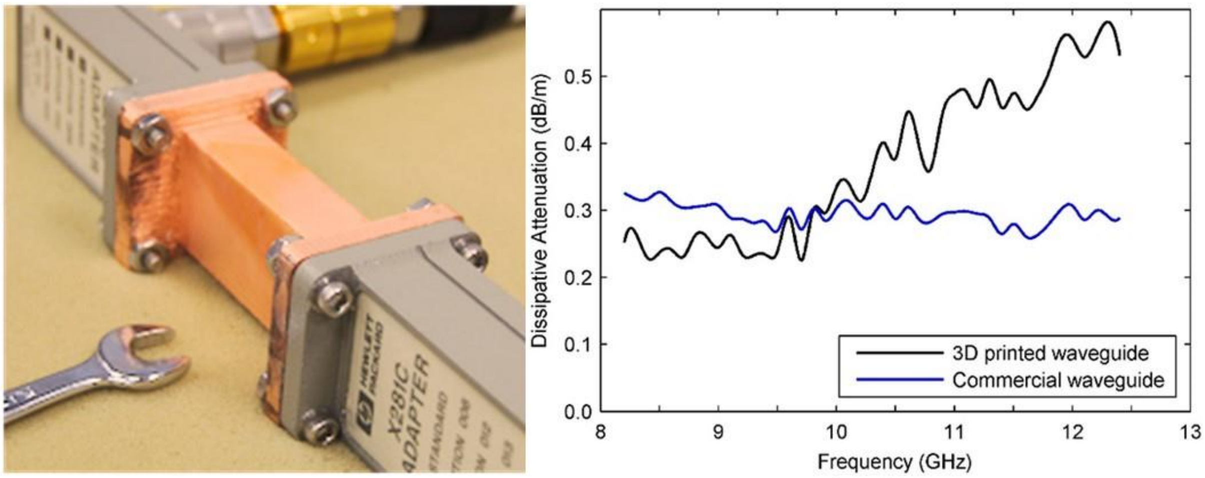

Figure 1: (left) Experimental measurement setup for the FDM WR-90 thru line and (right) measured dissipative attenuation for the 60-mm length FDM printed waveguide and 127-mm length commercial machined WR-90 waveguide. Copyright IEEE [3].

With the advantages that 3-D printing has to offer and comparable performance, we investigated proof-of-principle tuneable front-end components under mechanical control. This led to the first fully 3-D-printed variable phase shifter to be demonstrated [3]. With this X-band exemplar, an FDM-printed dielectric-flap MPRWG phase shifter exhibited 142° of relative phase shift at 10 GHz with minimal PM-AM conversion, as shown in Fig. 2.

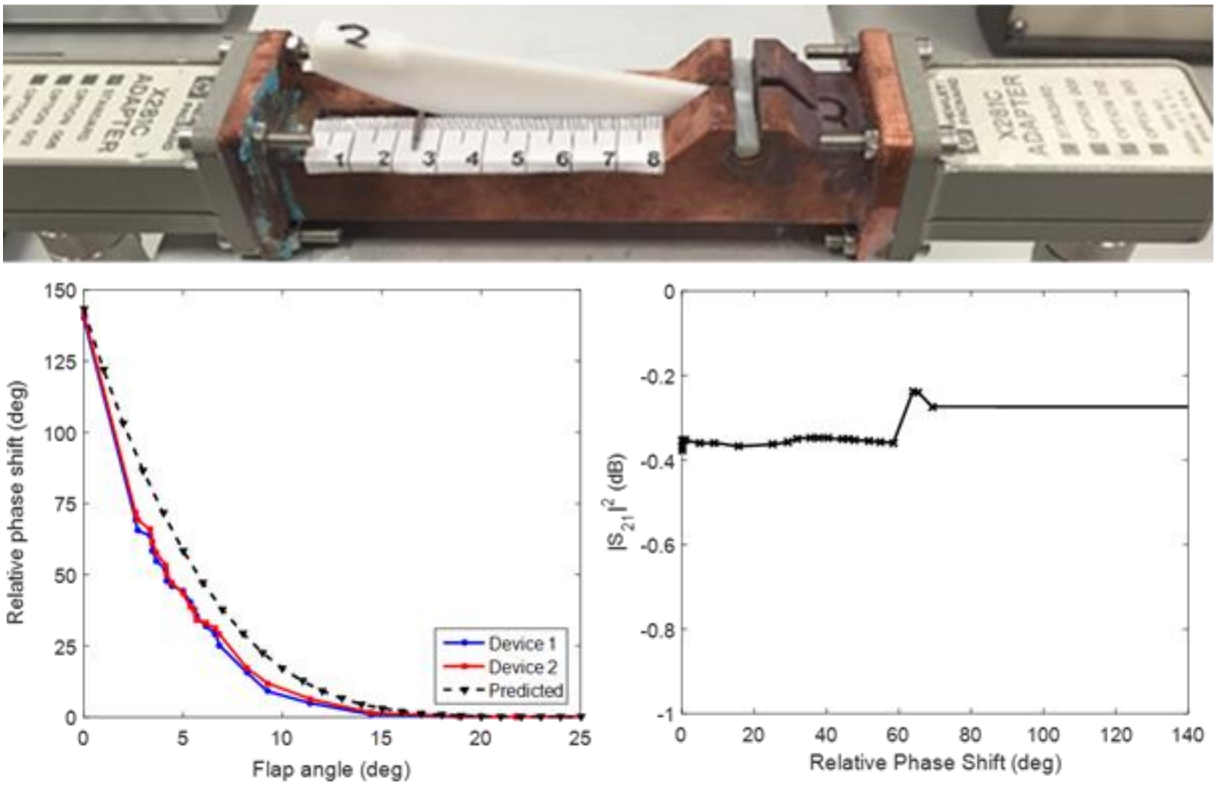

Figure 2: (top) Experimental measurement setup for the variable phase shifter, (bottom left) predicted and measured relative phase shift at 10 GHz against dielectric flap angle and (bottom right) measured transmission for different relative phase shifts at 10 GHz indicating a worst-case PM-AM conversion of ±0.1 dB across the whole tuning range. Copyright IEEE [4].

Stereolithographic Apparatus (SLA)

SLA printers use an ultraviolet (UV) curable resin that is exposed with a specific pattern for each print layer, defined either by a laser beam above or a projected image below the build plane. This process can achieve much greater resolution, when compared to FDM, as SLA is limited by the small spot size of the laser or spatial resolution of the projector. It is expected that with future development, micron level accuracy can be achieved similar to micromachining and microelectromechanical system (MEMS) technologies [6].

SLA has been used to demonstrate several components. When compared to FDM, 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 [3]. These split-block W-Band MPRWGs demonstrate a worst-case return loss of 19 dB and an insertion loss of 11 dB/m at 110 GHz; this is comparable to a conventional machined copper MPRWG having an insertion loss of 10 dB/m at 110 GHz [3], as seen in Fig. 3.

Furthermore, to demonstrate the advantage of SLA printing, a W-band 6th-order Chebyshev inductive iris bandpass filter was implemented, being notoriously sensitive to manufacturing tolerances. The measured insertion loss of the complete structure (filter, feed sections and flanges) was only 0.95 dB at the centre frequency of 107.2 GHz and a 6.8 GHz bandwidth, giving an unloaded quality factor of 152, as seen in Fig. 4 [3].

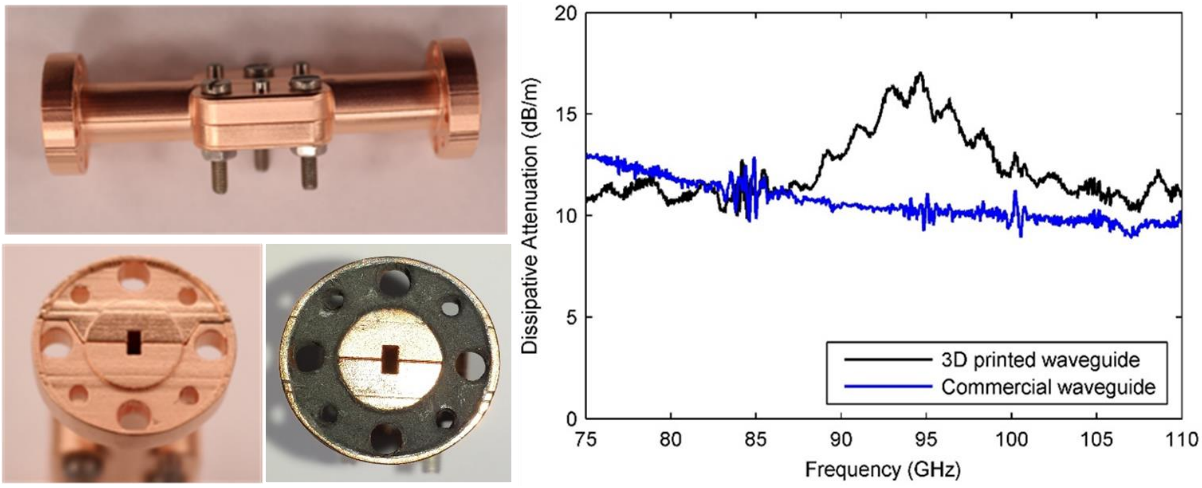

Figure 3: (left) SLA split block WR-10 thru line with detail showing the self-aligned flange and (right) measured dissipative attenuation for the 60-mm length SLA printed waveguide and 50-mm length commercial machined waveguide. Copyright IEEE [3].

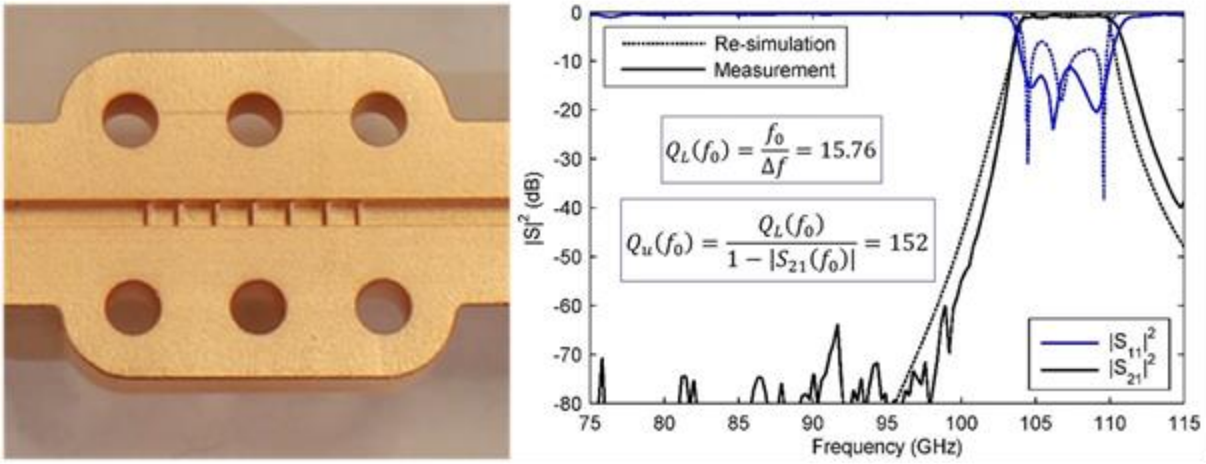

Figure 4: (left) Photograph of a single manufactured split-block of the W-Band 6th-order filter showing the inductive irises and (right) measured and simulated performance of the filter. Copyright IEEE [3].

Polymer Jetting (Polyjet)

Currently, Polyjet printing provides state-of-the-art resolution for commercially available 3-D printers using plastics. UV curable photopolymers are jetted from multiple nozzles to form each layer of the print. The photopolymer is immediately UV cured by the print head. Pushing this technology to its limits of special resolution, we developed an optically tuneable I-Q vector modulator at 500 GHz [5].

The design of this hybrid structure was again a split block, so that a pair of silicon implants can be integrated within the 3-D-printed MPRWGs, as shown in Fig. 5. The complex geometrical design offered by 3-D printing also allows us to print the mounts for the packaged laser diodes directly within the 3-D-printed module, in order to achieve optical self-alignment. The preliminary measurements, shown in Fig. 5, demonstrate that at-carrier 4-QAM digital communications is feasible at 500 GHz with this proof-of-principle I-Q vector modulator.

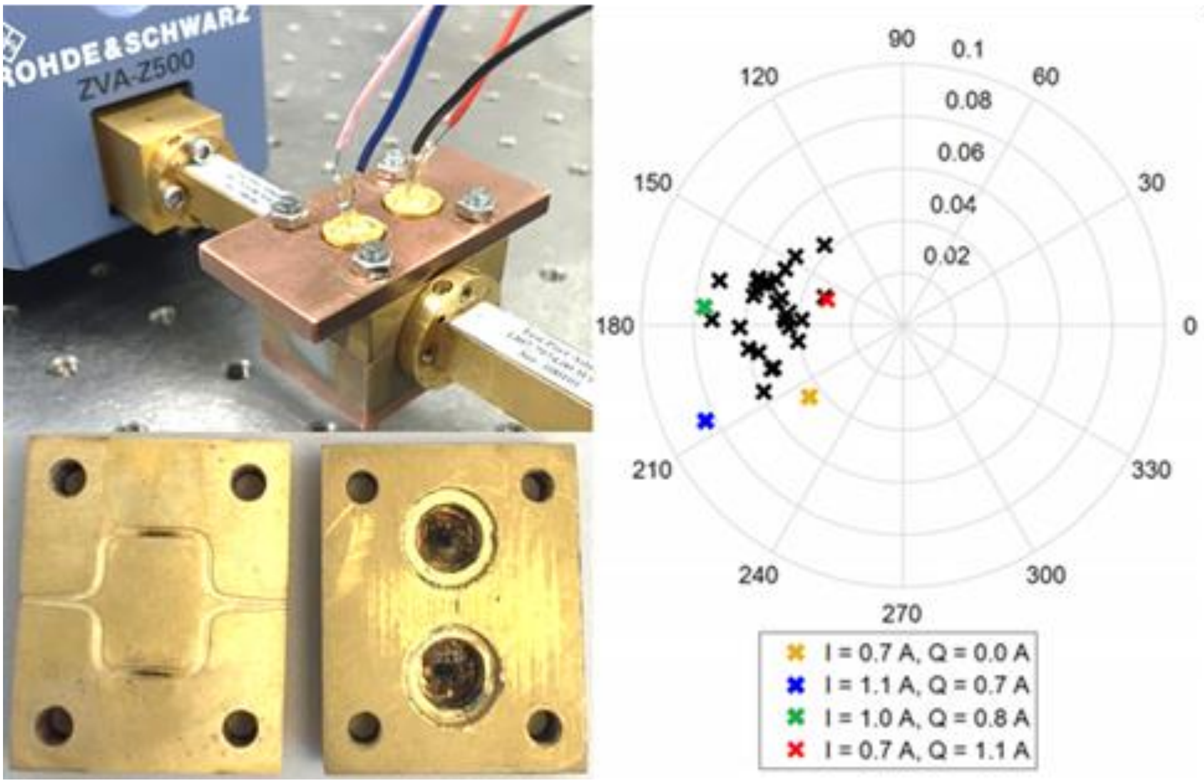

Figure 5: (left top) Measurement setup for the fully assembled hybrid 3-D-printed THz IQ vector modulator module, (left bottom) split block parts showing the pair of silicon implants and laser holders and (right) Preliminary S-parameter measurements of the experimental proof-of-principle THz vector modulator at 500 GHz. The raw static constellation has 25 unique vectors. A 4-QAM constellation is created by selecting the four vectors having coloured markers (with associated laser bias currents given in the key). Copyright IEEE [5].

The Future

This paper has shown that the past couple of years has seen intense activity in the development of 3-D printed waveguides from 10 GHz to 1.1 THz, led by Imperial College London. Current research includes pushing the frequency limit up to and beyond 1.1 THz [7], as well as the development of minimal-part subsystems that can break conventional design rules by exploiting the multiple degrees of freedom offered by 3-D printing. In addition, we are looking beyond MPRWGS. This includes a new project on quasi-optical components for next generation satellite payloads, funded by the UK Space Agency.

The authors expect that within a decade, ultra-high resolution low-cost 3-D printing will be ubiquitous. It will become the norm to replace parts by downloading CAD files, printing and spray coating metal onsite. This is particularly important for remote and inaccessible locations. Moreover, a printer offering multiple materials, perhaps even having exotic properties, will be available that will be capable of printing whole subsystems; the only limit being our imaginations.

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