GA–A27871

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This is a preprint of a paper to be presented at the Thirty-Ninth International Conference on Infrared, Millimeter and Terahertz Waves, September 14–19, 2014 in Tucson, Arizona.

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Work supported by
the General Atomics IR&D Funding
and MIT Lincoln Laboratory's Technology Office

GENERAL ATOMICS PROJECT 49009
JULY 2014

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Fabrication of a 35 GHz Folded Waveguide TWT Circuit Using Rapid Prototype Techniques

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***Abstract*—Microfabrication techniques are commonly used to build circuits for millimeter-wave and THz vacuum electron devices. A cost effective solution is becoming available, at least for building prototype circuits intended for cold-testing. Rapid prototyping machines such as 3D printers have advanced to the point that their resolution is below the wavelength of many microwave circuits. This paper reviews the application of this quickly-advancing technology towards waveguide components of vacuum electron devices. The authors use a rapid prototype technique called Direct Metal Laser Sintering (DMLS) to "print" sample 35 GHz circuits in metal. Circuits in two different materials (aluminum and chromium cobalt) are printed and cold-tested. The test data shows good agreement with simulation.**

I. INTRODUCTION AND BACKGROUND

MOST vacuum electron devices require a slow waveguide structure to propagate electromagnetic waves interacting with an electron beam. Since these circuits scale with wavelength the dimensions become very small and thus the device becomes challenging to build in the millimeter-wave and THz regimes. A number of advanced techniques have been used to microfabricate such components, including electron discharge machining (EDM), photolithography, laser ablation, and deep reactive ion etching (DRIE) in silicon [1]. Such processes are effective, but time-intensive and costly.

Many recent advances have been made with rapid prototyping machines, which fabricate prototype parts directly from three-dimensional computer aided design (CAD) packages. High-resolution 3D printers have been effective in constructing small parts with fine features. Originally considered useful as plastic models and toys, such parts are now commonly found in commercial products, advanced science applications, health devices, and even rocket engines.

Rapid prototyping machines may be useful for constructing microwave circuits intended for vacuum electron devices. This technology is investigated for a 35 GHz millimeter wave TWT amplifier.

II. RESULTS

A 3D printing process called Direct Metal Laser Sintering (DMLS) was used to build several circuits. DMLS builds the part layer by layer, fusing metal powder into a solid by melting it locally using a focused laser beam. It uses a CAD model as input, similar to plastic 3D printers.

The waveguide geometry was based on a 35 GHz TWT folded-waveguide structure that was originally made using a lithography process known as LIGA [2]. Four circuits were printed, two units in two different materials, aluminum (Al7075) and chromium cobalt (CrCo, Fig. 1). To simplify the process, only 9 periods of the 30-period original interaction section were printed. For this particular experiment, the circuits were printed in upper- and lower-halves and pinned together. (It should be noted that it may be possible for the DMLS process to produce a fully enclosed circuit instead of two halves. Doing so would avoid alignment and leakage issues.) An electron beam tunnel was included in the circuit. A quarter-wave transition section was designed to interface the serpentine section with WR-28 rectangular waveguide for testing. Each unit cost less than $500 to fabricate.

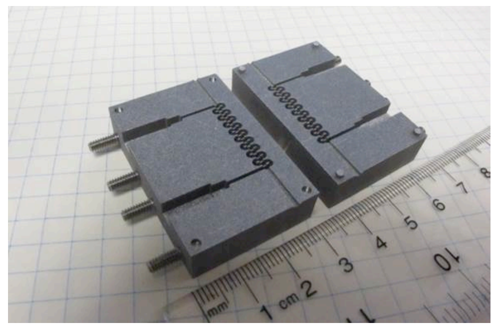

Fig. 1. Two halves of a prototype folded waveguide TWT circuit. The circuit was made in layers of chromium cobalt using an inexpensive rapid prototyping process called DMLS.

The circuits were tested "as is," without any surface finishing or polishing treatments. A network analyzer was used to measure their electrical response from 30-40 GHz (Fig. 2). The results were compared with simulations using Ansoft's High Frequency Structure Simulator (HFSS). The measured insertion loss and reflections agree well with the predicted result for the Aluminum circuits. It should be noted that the simulations use a boundary conductivity of 2.0e7 S/m. This is an assumed value; in reality there is a large range of conductivities based on the purity of the metal, which is unknown in this case.

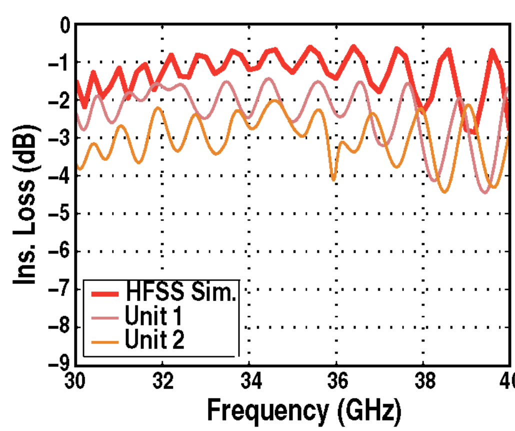

Fig. 2. The insertion loss for two aluminum circuits made using DMLS, compared with the same circuit geometry modeled in HFSS.

Although not shown here, network analyzer measurements were also made for the Chromium Cobalt units. The electrical performance of circuits in this material was not as successful.

Of primary concern regarding the DMLS fabrication process is the surface roughness of the waveguide walls (Fig. 3). Surface roughness should be as low as possible to minimize waveguide attenuation.

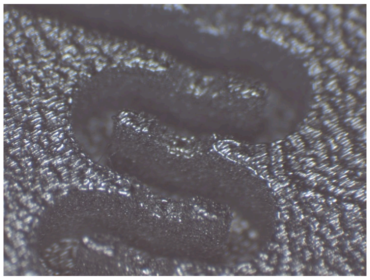

Fig. 3. A magnified view of the serpentine portion of the waveguide circuit.

Surface roughness measurements were taken of each of the circuits made with DMLS without any post-process surface treatment. In all cases, the surface roughnesses are much larger than the skin depth of the material at the design frequency. Generally, there is higher overall surface roughness for the aluminum units compared to the chromium cobalt circuits (Fig. 4). However, there is much more local variation of roughness in the chromium cobalt (Fig. 5).

		Al (δ ~ 23.7 μin)		CrCo (δ ~ 54.3 μin)	
		Unit 1	Unit 2	Unit 1	Unit 2
Roughness Ave.	Ra (μin)	405	433	321	369
RMS Roughness	Rq (μin)	514	516	388	468
Ave. Max. Height	Rz (μin)	2457	2660	1919	2495

Fig. 4. Surface roughness summary. The skin depth at 35 GHz is included for each material.

Although, there are empirical formulas for waveguide attenuation to account for surface roughness [3], the models are likely inaccurate here, since the surface roughness is larger than the skin depth. Some additional work is necessary to accurately calculate this effect.

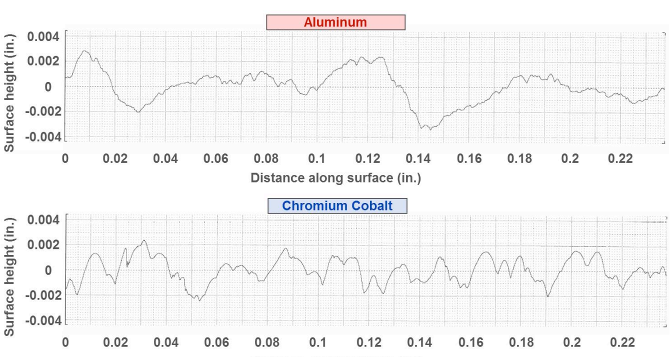

Fig. 5. Surface roughness measurements of both the aluminum and chromium cobalt versions of the circuit.

III. SUMMARY

The results show that the DMLS printed circuits based on a 35 GHz TWT design had large surface roughness, but still maintained good electrical performance. The losses measured for the Aluminum version were surprisingly close to what was predicted from simulation. The units were tested "as is," so it is likely that a smoothing process would improve the results further. This will be investigated in the next stages of testing.

Overall, the DMLS rapid prototype technique is effective for making mmW cold-test circuits for vacuum electron devices up to 35 GHz. The costs of printing such structures are much less than microfabrication techniques, enabling testing of many different geometries and design iterations. Such an approach would reduce the costs and time for the design and test stages of development.

Aside from vacuum electron devices, the technology has advanced to the point where it is useful for many other micro- and millimeter-wave devices, particularly those requiring complex structures. For example, an investigation is being made into printing mandrels used for the electroforming process of fabricating certain microwave components (Fig. 6). This will circumvent the need for machined metal mandrels and should reduce production costs considerably.

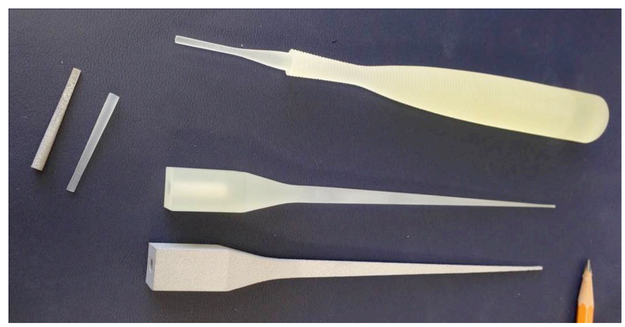

Fig. 6. Mandrels made via 3D printing techniques for electroforming millimeter wave components.

Finally, it is noted that 3D printing technology is advancing very rapidly. The resolution of the devices are becoming finer and finer, some reaching scales of 0.1 micron [4], less than the skin depth of the waveguide structures in this paper. Thus the approach will become even more effective in producing millimeter wave devices.

This work was supported by MIT Lincoln Laboratory's Technology Office and General Atomics Internal Funding.

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