Low-Cost Method for Waveguide Device Components Fabrication at 220 – 325 GHz

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***Abstract*—This work explores a rapid design and manufacturing approach to realize complex 3D pillar type filter and transmission line structures for applications in the $220 - 325$ GHz range and which cannot be economically reproduced by conventional machining processes or present rapid prototyping methods. The significance of this investigation is that at sub-millimetre-wave or THz frequencies, where the waveguide features are less than $100\mu m$ and the skin depths are less than $200nm$, the exact conductor shape and surface roughness have a significant electrical effect and any variations result in an important disagreement between the modelled and measured characteristics. This is a proof of concept validation of the rapid manufacturing approach and is aimed at paving the way to a range of THz passive waveguide components, where the availability and cost of such components is typically prohibitive and where the surface roughness is minimized and highly reproducible. Using this approach the fabrication times can be as rapid as a few days and can yield many hundreds of highly reproducible millimetre scale components.**

I. Introduction

Multiple commercial and scientific applications in the millimetre-wave and THz frequency ranges require powerful oscillators in the form of Backward Wave Oscillators (BWOs) [1], and as the use of this portion of the spectrum is expanded, the need for frequency filtration would increase.

Currently, most circuits and components are implemented in rectangular waveguide form, thus necessitating the design and fabrication of low loss components and devices in this technology.

Conventional fabrication techniques, such as CNC milling, may be prohibitively expensive, as feature size tends to be on the order of $100\mu m$. Furthermore, as is the case with the Slow Waveguide Structure (SWS) part of a BWO, the shapes of the structures may not be rectangular, further complicating their fabrication [2].

In this paper, a method and approach is presented for the fabrication of structures, which can be used both as part of a BWO, and as a standalone waffle-iron waveguide filter. In particular, the waveguide block shown in Fig. 1 is used as a housing enclosure for filter structures. The pocket in the bottom half allows the quick evaluation of multiple structures.

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(a) (b)

Fig. 1. Waveguide block enclosure, individual halves (a), and fully assembled (b).

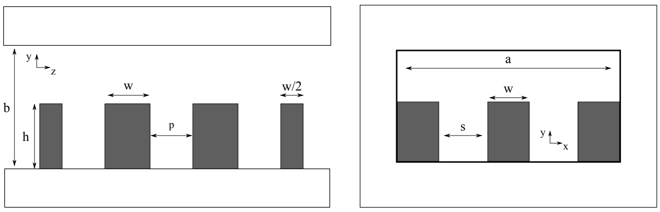
The fabrication method itself uses thick layers of SU8 to implement the rows of pillars, which can act either as a SWS or as a low-pass waveguide filter.

II. Waveguide Filter Design

A. Initial Design

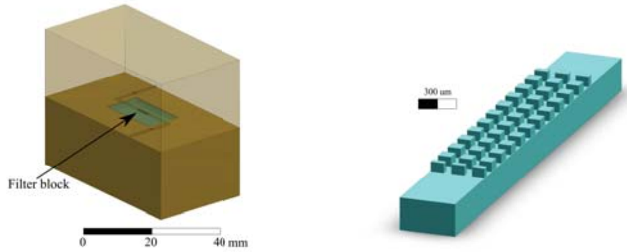
The waffle-iron filter used to validate the presented methodology was originally invented by S. B. Cohn in the 1950s [3], and since then has been developed and used as a high-power, low-pass filter in systems operating in the RF and microwave range [4], [5]. Traditionally, such a filter has corrugations along both the bottom and top wall of a rectangular waveguide [4]. However, due to the enclosure setup used (Fig. 1), the filter structures reported here only have pillars along the bottom wall. It would still be possible to incorporate both top and bottom wall pillars using a variation of the approach described here. Furthermore, it is possible, using this micro-fabrication method to form microstructures where the shape and spacing cannot be realized using conventional milling techniques and the electrical effects of these more complex shapes are investigated herein. The frequency range chosen for the study was simply driven by equipment availability in terms of the intended follow-up measurements and the difficulty in conventional milling and repeatable flange alignment of the measurement test fixtures, which becomes problematic for the 750 1100 GHz band [6].

The structures presented were designed using the approach reported in [3], with an added existing constraint on the rectangular waveguide dimensions a and b. Drawings illustrating the parameters of a waffle-iron filter structure, which need



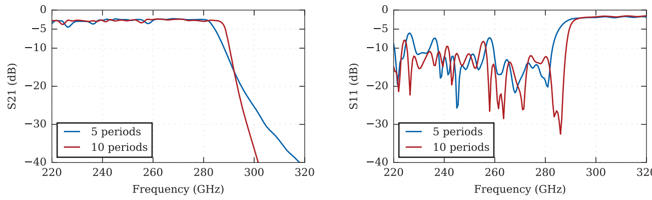
(a) (b)

Fig. 2. Waffle-iron filter dimensions (not to scale), along the waveguide (a), and across the waveguide (b).



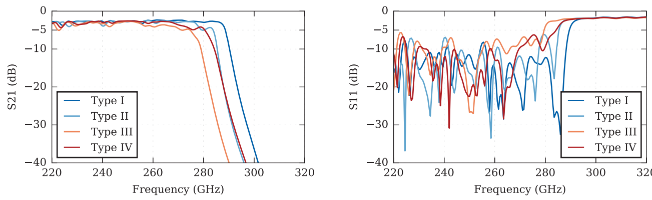
(a) (b)

Fig. 4. Full model used for 3D EM evaluation (a), and individual filter block (b).



(a) (b)

Fig. 5. Effect of N on filter transmission (a) and reflection (b).



(a) (b)

Fig. 6. Effect of pillar shape on filter transmission (a) and reflection (b).

to be initially determined, are shown in Fig. 2. The number of pillars, N, along the waveguide can also be varied, and its effect on the frequency response of the filter structures is presented in the next Section. The half-width corrugations at either end of the filter serve as impedance transitions.

The dimensions a and b are fixed by the waveguide enclosure available (Fig. 1), at $864\mu m$ and $230\mu m$, respectively. Targeting a cut-off frequency $F_c = 290$ GHz, the initial values of the rest of the parameters were determined to be $h = 150\mu m$, $w = 200\mu m$, $p = 180\mu m$, and $s = 132\mu m$. Structures with both $N = 5$ and $N = 10$ were then investigated.

B. FE EM Simulations

Once the initial values for the waffle-iron filter elements were found, model structures with four different pillar profiles were created using SolidWorks and imported into Ansys HFSS for full-wave 3D EM simulation. The shapes of these profiles are summarized in Fig. 3, while the simulation model of the whole assembly, along with one of an entire filter block, and are presented in Fig. 4. HFSS was used to optimize the

Fig. 3. Pillar profiles investigated. Dimension w kept constant.

dimensions h and p, in order to obtain a filter with a sharp roll-off and F_c between 280 GHz and 290 GHz. The final values obtained were $h = 120\mu m$ and $p = 200\mu m$.

C. Simulation Results

The influence of pillar shape, together with number of pillars along the waveguide, were investigated. Simulation results for S_{21} and S_{11} for both comparisons are shown in Fig. 5 and Fig. 6. The results suggest that an increase in the number of periods, N, leads to a slight increase in the cut-off frequency, while at the same time "sharpening" the roll-off of the filter, as might be expected, resulting in a more abrupt transition between the passband and the stopband. The effect on the reflection is similar, with higher attenuation at some of the resonances observed. Overall, the return loss is close to 10 dB over the passband, while transmission losses are around 3 dB.

The shape of the pillars appears to mainly affect the cut-off frequency, as evident by Fig. 6a, with performance in passband and roll-off steepness largely the same. Similarly, reflection behaviour is approximately the same for all pillar shapes, with the main difference lying in the transition region between stopband and passband.

These filter structures are adequate for the purpose of evaluating the rapid prototyping fabrication technique, discussed in the next Section and to expose the shortfalls between the simulation and the subsequent measured results. Further optimization could be performed to obtain better performance in the passband and stopband, however this is outside the scope of this work.

III. Filter Block Fabrication

The filter blocks are fabricated in a cleanroom environment, using a combination of silicon wafers as a host substrate, SU8 for defining the pillars, and Au PVD coating followed by Au plating for metallisation. The method could easily be adopted to use a few clean workspaces in a less clean laboratory.

SU8, a negative tone epoxy photoresist [7], has previously been used to implement waveguide structures and waveguide components at millimetre-wave and THz frequencies [8]. Its properties are particularly suited for fabrication of the structures of interest, i.e. rows of pillars with different, often non-standard profiles, through photolithographic processing. The height of these profiles, an important parameter as evidenced by simulation results presented here and elsewhere [2], can be easily controlled by adjusting the speed at which the resist is spun. A diagram showing the individual steps of the core of the process used is shown in Fig. 7. Once the individual pillar structures have been defined in SU8 on a standard 2” Si wafer, the wafer is scribed into pieces with the same dimensions as that of the holding pocket of the waveguide enclosure (Fig. 1a). Reflected light microscope photographs of one of these filter structures is presented in Fig. 8. A thin seed layer of Au is subsequently sputtered onto the pillars, before Au plating a thickness of at least five skin depths. As was mentioned earlier, the surface roughness of the resulting metal coating can drastically affect performance.

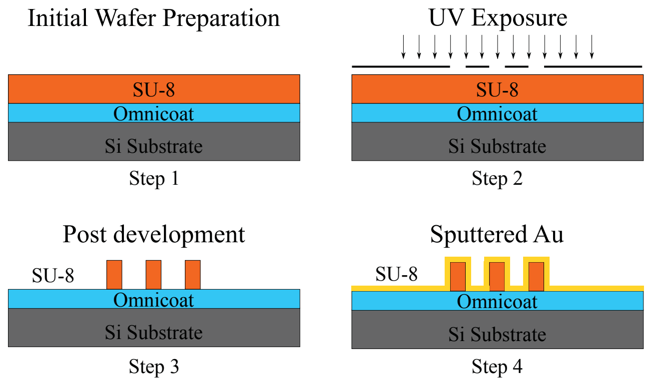


Fig. 7. SU8 Fabrication steps.

Fig. 8. Microscope photograph showing filter with rhomboidal pillars.

Test samples were fabricated and plated with different J_{avg}, ranging from $0.8mA/cm^2$ to $2.1mA/cm^2$. After measuring the surface roughness using a surface profiler, it was found that the sample plated at the lowest J_{avg} had an $R_a = 6.21nm$ and $R_q = 7.47$, as opposed to $R_a = 5.10nm$ and $R_q = 6.15nm$ for sputtered layers.

Better surface roughness can be achieved using even lower plating J_{avg}, however the plating time would need to be increased. Even then, using Au sputtering to deposit $1\mu m$ of Au can be much more expensive and time consuming.

The full process can take no more than two days of fabrication work in a cleanroom environment, generally yielding between 3 and 5 structures per 2” wafer. These are ready to be swapped in and out of the test fixture in order to perform S-parameter measurements. Using larger diameter host substrate can allow for 10s, if not 100s structures to be manufactured in one processing pass.

This can result in the rapid prototyping and evaluation of numerous pillar structures, either as standalone waveguide filters, or as SWS in BWOs at THz frequencies. In the case of BWOs, it can further help reduce the overall cost, as regular replacement of the SWS is anticipated [1], [2].

IV. Conclusions and Future Work

A method for inexpensive and quick fabrication of millimetre-wave and THz structures using SU8 has been developed and presented here, and its applicability in waffle-iron filter design demonstrated. Rapid turnaround times achieved are especially valuable for THz research, where commercially available 3D EM simulators can struggle to accurately model all of the second order effects, and where validation of these models is required.

The outstanding work for the immediate future is to measure and report on the structures already fabricated and discussed in abstract. Similarly the use of SUEX, an analogue of SU8, available in dry sheet form of certain thicknesses [9] will be evaluated and reported on which would facilitate even more rapid and lower cost microfabrication.

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