**Journal Article**

# WR-3 Waveguide Bandpass Filters Fabricated Using High Precision CNC Machining and SU-8 Photoresist Technology

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# WR-3 Waveguide Bandpass Filters Fabricated Using High Precision CNC Machining and SU-8 Photoresist Technology

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*Abstract*— **This paper presents two WR-3 band (220-325 GHz) filters, one fabricated in metal using high precision computer numerically controlled milling and the other made with metallized SU-8 photoresist technology. Both are based on three coupled resonators, and are designed for a 287.3 GHz to 295.9 GHz passband, and a 30 dB rejection between 317.7 GHz and 325.9 GHz. The first filter is an extracted pole filter coupled by irises, and is precision milled using the split-block approach. The second filter is composed of three silver-coated SU-8 layers, each 432 $\mu$m thick. The filter structures are specially chosen to take advantage of the fabrication processes. When fabrication tolerances are accounted for, very good agreement between measurements and simulations are obtained, with median passband insertion losses of 0.41 dB and 0.45 dB for the metal and SU-8 devices respectively. These two filters are potential replacements of frequency selective surface (FSS) filters used in heterodyne radiometers for unwanted sideband rejection.**

*Index Terms*—**Micromachining, SU-8, Waveguide Filter, Terahertz components**

## I. INTRODUCTION

**M**ULTICHANNEL air and spaceborne sounders are employed for spectroscopic characterization of the Earth's atmosphere [1]. These instruments perform molecular spectroscopy at millimeter and submillimeter wavelengths in relatively narrow frequency channels. Within the instrument, linearly polarized signals are frequency de-multiplexed by a quasi-optical feed chain using frequency selective surfaces (FSSs). FSSs are also used to prevent the signals in the

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unwanted sideband from reaching the double sideband heterodyne mixers [2]. As the atmospheric signals are weak, the sideband rejecting FSS needs to have a very low insertion loss and a high isolation between two adjacent channels which are close to each other in frequency [3]. For instance, the FSS reported in [3] transmits 316.5–325.5 GHz radiation with a maximum insertion loss of 0.6 dB and achieves greater than 30 dB rejection from 349.5–358.5 GHz. To achieve this specification a transmission zero is required and we believe this paper describes the first filter to achieve this at these high frequencies.

Waveguide technology is potentially an attractive alternative to FSS for sideband selection, due to its low loss and the possibility to construct lower volume filters. For waveguide components in general, device dimensions decrease as frequency increases. This means a reduction in size and mass of components, but also a tighter dimensional tolerance is required during fabrication. Different micromachining techniques such as computer numerically controlled (CNC) milling [4-6], Si deep reactive ion etching (DRIE) [7-9], lithographic micromachining technique (LIGA) [10] and SU-8 photoresist technology [11-13], have been developed and employed to achieve high-dimensional accuracy in the fabrication of high frequency waveguide filters. Laser micromachining [14] and 3-D printing [14] have also been utilized for high frequency filters by the authors using different designs at about 100 GHz. This paper is complementary showing how alternative technologies cope, at higher frequencies, for a filter with demanding specifications.

CNC milling is a traditional way of fabricating metal waveguide components, especially at lower frequencies. Waveguide components fabricated by CNC milling with excellent performance have been reported. References [4] and [5] describe fourth order W-band filters. In [4], the filter is measured to have 0.5 dB insertion loss and a 4.53% (4.20 GHz) bandwidth, and in [5], the filter is measured to have 0.6 dB insertion loss and a 10% (10 GHz) bandwidth. For the 220 to 325 GHz WR-3 band, waveguide features and tolerances decrease by a factor of around three. Fabricating waveguide filters at such a frequency requires an expensive, high precision CNC mill. Filter design flexibility is also limited by tool sizes and depth to diameter aspect ratios [5]. However, the limits of conventional CNC milling are still being pushed: examples of WR-3 band CNC milled filter can be found in [6], where two fourth order bandpass filters are presented, one with measured 0.7 dB insertion loss and 8.77% (22.6 GHz) bandwidth and another with measured 0.5 dB insertion loss and
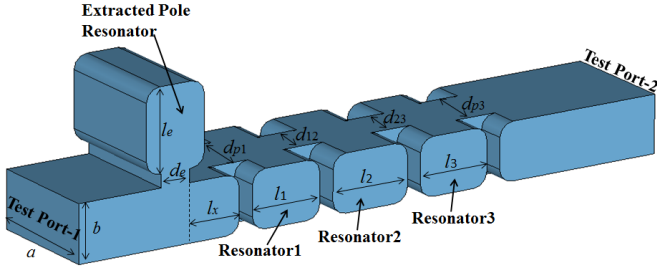
Fig. 1. Diagram of extracted pole filter structure. $a = 864$, $b = 432$, $l_1 = l_3 = 510$, $l_2 = 517$, $l_e = 619$, $l_x = 383$, $d_e = 205$, $d_{p1} = d_{p3} = 432$, $d_{12} = d_{23} = 309$. (Unit: $\mu$m)
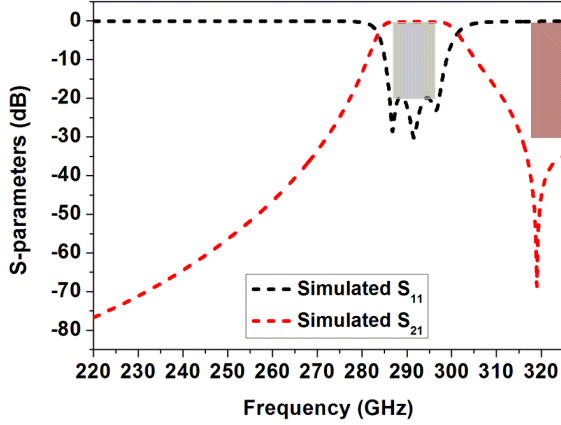


Fig. 2. Simulated $S$-parameters for the CNC milled extracted pole filter. Passband and stopband specifications are shown in gray and red respectively.

9.83%(25.2 GHz) bandwidth. In this paper, we present a WR-3 band CNC milled extracted pole filter with an improved performance, which is designed specifically for sideband rejection.

SU-8 photoresist is a promising technology for manufacturing millimeter and submillimeter waveguide components, and is used for the second filter discussed in this paper. SU-8 is a photolithographically patterned, epoxy-based, resin that is resistant to organic solvents once cured, and can have a thickness ranging from 0.5 $\mu$m to 1 mm [15]. There are several advantages of using SU-8 micromachining over CNC machining. For example, SU-8 can achieve a similar high dimensional accuracy with potentially lower cost. It may also allow sharper internal corners and higher corner radius to depth ratios. Meanwhile, SU-8 process is a batch fabrication which allows repeatability between devices as well as production of several devices in a single fabrication run [15]. Compared with DRIE, standard photolithography processes are used with SU-8 with better surface roughness on the sidewalls of waveguide structures [15]. SU-8 photoresist technology has been employed to demonstrate filters in the WR-10 [11], WR-3 [12], and WR-1.5 bands [13]. In this paper, a new WR-3 band waveguide filter is designed for the SU-8 process to meet a specification similar to the FSS filter described above.

For both the CNC and the SU-8 filters presented and compared below, the specifications in [3] were adjusted to cope with the available measurement capability. Both filters have transmission zeros with the CNC filter having a conventional design, however the SU8 filter is a completely new design
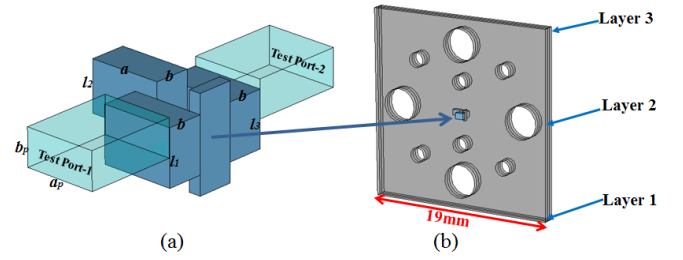


Fig. 3. Diagram of WR-3 band filter formed of three SU-8 layers with same thickness of 432 $\mu$m. (a) Diagram of the filter structure. Dimensions of the test ports are: $a_p = 864$ $\mu$m, $b_p = 432$ $\mu$m. Dimensions of the resonators are: $a = 876$ $\mu$m, $b = 432$ $\mu$m, $l_1 = l_3 = 647$ $\mu$m, $l_2 = 589$ $\mu$m. (b) Illustration of the whole filter device including dowel holes and screw clearance holes designed to match the UG-387 waveguide flange. (c) A perspective front-view of the filter structure. The blue rectangle represents the input/output of test port. The black rectangle represents the first (or third) resonator, whereas the cavities in the second layer are represented by red rectangles. $d = 327$ $\mu$m, $h = 578$ $\mu$m, $l_c = 1100$ $\mu$m, $h_c = 143$ $\mu$m.
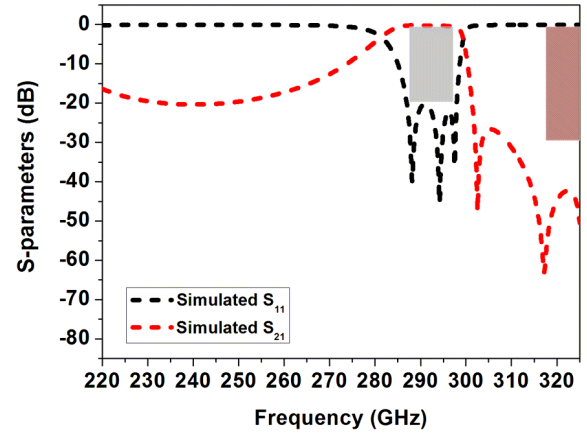


Fig. 4. Simulated $S$-parameters for the SU-8 micromachined filter. Passband and stopband specifications are shown in gray and red respectively.

topology to produce the transmission zero. Frequencies have been scaled down by a factor of 1.1, so that the new passband is 287.3-295.9 GHz and the stopband attenuation specification becomes 30 dB between 317.7 GHz and 325.9 GHz.

Structural details and design methods of the two filters are presented in Sections II and III, which is followed by a description of fabrication process in Section IV. Measurements and discussions are presented in Section V, and conclusions are given in Section VI.

## II. DESIGN OF CNC MILLED EXTRACTED POLE FILTER

The CNC filter design is shown in Fig. 1. It is based on three coupled resonators operating at $TE_{101}$ mode and an extracted pole resonator [16]. The material conductivity is assumed to be
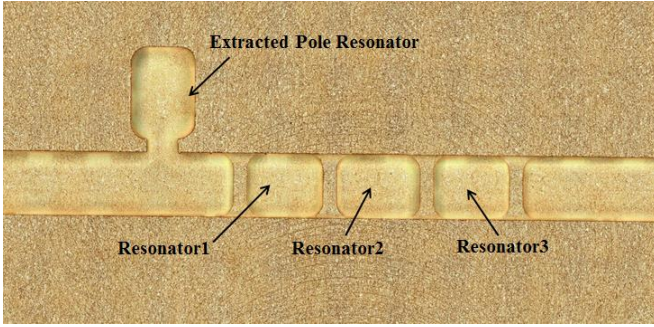
Fig. 5. Photograph of the internal cavities of the fabricated CNC milled extracted pole filter.



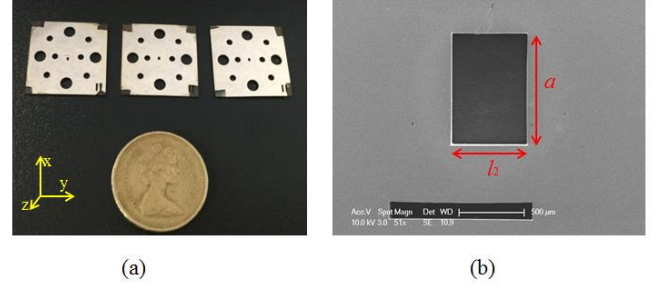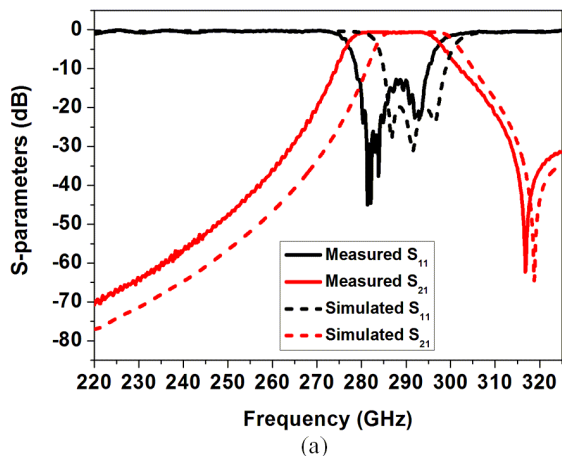(a)                                    (b)

Fig. 6. (a) Photograph of the 3 silver-coated SU-8 layers, 20 × 20 mm for each layer with a thickness of 0.432 mm. (b) Scanning electron microscope image of the cavity structure for the second SU-8 layer.

that of gold (i.e., $4.10 \times 10^7$ S/m). A third order waveguide cavity filter which has a Chebyshev response was designed first, using the synthesis technique described in [17], to have a center frequency of 291.6 GHz, a bandwidth of 3% (8.6 GHz) and a return loss in the passband of $\geq$ 20 dB. For this structure, an iris between the test ports and the first/last resonators controls the external coupling ($Q_e$), the iris between resonator 1 and 2 (or resonator 2 and 3) controls the coupling coefficient $k_{12}$ (or $k_{23}$). To meet this specification, the external $Q$ and coupling coefficients are calculated to be $Q_{e1} = Q_{e3} = 28.87$, $k_{12} = k_{23} = 0.030$. To meet the upper stopband specification, a steep roll-off is needed on the high frequency side of the passband. It has been shown [16] that the selectivity of a conventional waveguide filter can be improved by using inductively coupled stopband cavities connected to the broad wall of the waveguide [18]. In [19], the advantages of this extracted pole technique have been demonstrated. A single extracted pole resonator, added to the third order waveguide filter using the method of reference [20] and [21], provides a transmission zero in the rejection band and achieves a very high cut-off rate into the upper sideband.

In order to be compatible with CNC milling process, the corners of the resonators have a radius of 0.10 mm (see Fig. 1) to permit fabrication with a 0.20 mm end mill. Meanwhile, the minimum dimension in the E-plane must also be larger than 0.20 mm. After initial design of the structure using the coupling matrix approach [17], full-wave simulation and optimization for this filter are carried out by CST Microwave Studio (version 2016) using the Trust Region Framework algorithm. The cavity dimensions achieved after optimization are shown in Fig. 1. To give an idea of scale, the total length of the filter structure is 4 mm.

In order to test the filter, a CNC machined block which contains the filter is designed. The input and output waveguides have both been extended by 8 mm in order to accommodate standard waveguide flanges and screws. A 20 mm length of straight WR-3 waveguide is included as a measurement reference in the same block as the waveguide filter. Standard UG-387 waveguide flanges were machined in the block. By utilizing an E-plane split-block technique, the transmission loss is minimized as no surface current flows across the contact plane. The simulation results after optimization for S-parameters are shown in Fig. 2. The predicted passband insertion loss for the extracted pole filter (4 mm filter structure) is below 0.4 dB and the rejection in the unwanted sideband is above 30 dB. Passband reflectivity, $S_{11}$, is below -20 dB.
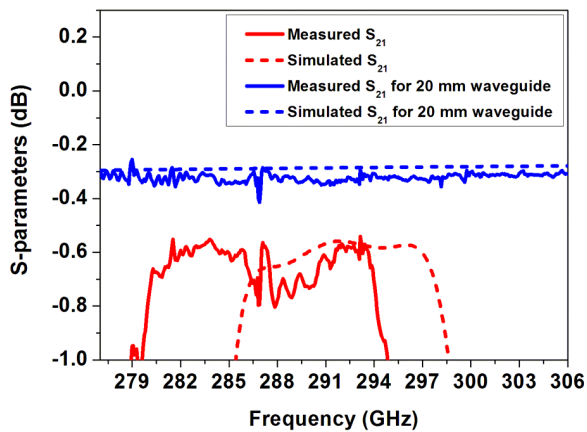
## III. DESIGN OF SU-8 MICROMACHINED FILTER

The SU-8 photoresist filter is designed [16] to meet the same specifications. It exploits the stacked metallized layer approach associated with SU-8 [22]. The filter has three coupled resonators and a cross-coupling between the first and third resonators and is shown in Fig. 3. With this topology and by setting the frequency of the transmission zero at 317.7 GHz, which is the lower boundary of the upper stopband, external $Q$ and coupling coefficients are calculated as: $Q_{e1} = Q_{e3} = 27.65$, $k_{12} = k_{23} = 0.031$, $k_{13} = 0.006$, $k_{11} = k_{33} = 0.002$, $k_{22} = -0.006$. Each of the silver-coated SU-8 layers has a thickness of 432 $\mu$m and contains one resonator. As shown in Fig. 3(a), the value of the SU-8 layer thickness determines the WR-3 waveguide resonator height, $b$. Since the central resonator couplings $k_{12}$ and $k_{23}$ are equal, layers 1 and 3 are identical and the whole structure is symmetrical. Rather than controlling the coupling through a conventional iris, the relative positions of the resonators are shifted to obtain the desired coupling coefficients. In other words, the horizontal displacement $h$, shown in Fig. 3(c), determinates $k_{12}$ and $k_{23}$, whereas the offset $d$ between the test port and first/third resonators controls the external coupling. The cross-coupling between first and third resonators is accomplished by a slot in the middle layer. The frequency of the resulting transmission zero is controlled by the width of this cross-coupling slot, $h_c$. The above geometric design parameters, shown in Fig. 3, are optimized by the SMEAFO method [23] using CST Microwave Studio (version 2016). Fig. 3 provides the detailed dimensions of this filter after optimization.

The filter is designed to be inserted between standard UG-387 waveguide flanges for measurement. As shown in Fig. 3(b), holes to accommodate the flange dowels, thereby accurately aligning the different SU-8 layers, are incorporated in the design. Larger clearance holes for the waveguide flange screws are also introduced.

The optimized S-parameter response of the filter is shown in Fig. 4. The predicted passband insertion loss is below 0.4 dB and the rejection in the unwanted sideband is better than 35 dB. Passband reflectivity, $S_{11}$, is below -20 dB. The simulations predict two unexpected transmission zeros, one located between passband and upper stopband at 302.5 GHz and another at 326.2 GHz, just above the waveguide band's upper edge. These zeros are caused by unwanted cancellation effect of the signals transmitted by different paths from the input to the output due to the special structure of the design. That is

Fig. 7. Comparison of the simulated and measured results of the filter produced by CNC milling. (a) Response over whole WR-3 band. (b) Expanded view of $S_{21}$ showing the passband. The simulations are performed assuming a material conductivity corresponding to that of bulk gold.
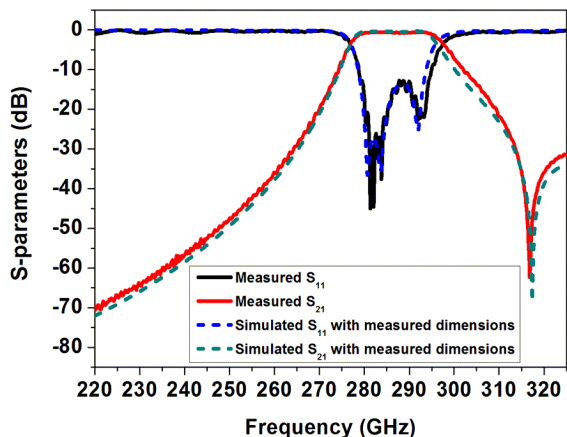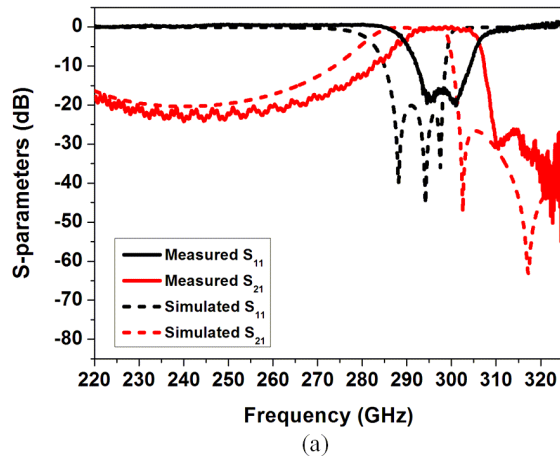


Fig. 8. Simulated response of the CNC milled extracted pole filter with measured dimensions shown in Table I.



Fig. 9. Comparison of the simulated results and measured results of the filter based on SU-8 photoresist technology. (a) Response over whole WR-3 band. (b) Expanded view of $S_{21}$ over passband. The simulations are performed in CST assuming a material conductivity equal to that of silver.



Fig. 10. Simulated response of the SU-8 filter with measured dimensions in Table II.

apart from cross-coupling accomplished by the slot on the middle layer, there is an additional coupling path between resonators 1 and 3.

## IV. FABRICATION DETAILS

The extracted pole waveguide filter was fabricated at the Rutherford Appleton Laboratory using a high precision Kern milling machine and tungsten carbide cutters with diameters

down to 0.20 mm. The block material was copper alloy which was then coated with a thin film of gold (around 3 $\mu$m) by electroplating. As mentioned above, the internal corners of the filter had a radius of 0.2 mm. Fig. 5 shows a photograph of the split plane of the CNC machined block with its four resonators.

The fabricated layers of the SU-8 filter are shown in Fig. 6(a). The process details for the SU-8 filter can be found in references [13] and [24-25]. In summary, a single side polished,

TABLE I
COMPARISON BETWEEN DESIGNED AND MEASURED RESONATOR DIMENSIONS
FOR THE CNC MILLED EXTRACTED POLE FILTER

| Cavity # | Designed ($\mu$m) | Measured ($\mu$m) |
|---|---|---|
| | $a \times b \times l$ | $a \times b \times l$ |
| Resonator 1 | 864×432×510 | 874×438×521 |
| Resonator 2 | 864×432×567 | 874×438×574 |
| Resonator 3 | 864×432×510 | 874×438×519 |

TABLE II
COMPARISON BETWEEN DESIGNED AND MEASURED RESONATOR DIMENSIONS
FOR THE SU-8 FILTER

| Cavity # | Designed ($\mu$m) | Measured ($\mu$m) | |
|---|---|---|---|
| | | Side 1 | Side 2 |
| | $a \times l$ | $a \times l$ | $a \times l$ |
| Resonator 1 | 876×647 | 863×623 | 869×638 |
| Resonator 2 | 876×589 | 861×576 | 874×584 |
| Resonator 3 | 876×647 | 855×630 | 873×641 |

TABLE III
COMPARISON OF MEASUREMENTS BETWEEN CNC MILLED EXTRACTED POLE
FILTER AND SU-8 MICROMACHINED FILTER

| | CNC extracted pole filter | SU-8 filter |
|---|---|---|
| Passband Insertion loss | 0.41 dB | 0.45 dB |
| Passband Frequency Shift | -5 GHz | 7 GHz |
| Stopband Attenuation | >32 dB | >33 dB |
| Size of Filter Device | 20 mm × 20 mm × 4 mm | 19 mm × 19 mm × 0.432 mm (3 layers) |

100 mm diameter, 1 mm thick, silicon wafer was used as a base for forming the SU-8. OmniCoat from MicroChem was used as a 1.5 $\mu$m thick sacrificial layer between SU-8 and silicon. This thickness of OmniCoat was built up from five 300 nm thick layers. Each was formed from precursor spun at 350 rpm for 10 seconds and then at 700 rpm for 20 seconds. The coating was soft baked by placing the wafer on a hot plate at $200^{o}$C for 120 seconds. It was then cooled on a flat copper plate at room temperature for 300 seconds.

SU-8 50 negative photoresist from MicroChem was then spin coated onto the OmniCoat. The thickness of the SU-8 layer is calculated by measuring the mass of the coating [13]. A mass of 5.20 g on a 100 mm diameter wafer corresponds to a thickness of 432 $\mu$m. The coated wafer is left on a leveled copper plate at room temperature for 1 hour for self-planarization. Then it was soft baked at 65 and $85^{o}$C for 40 and 240 minutes respectively. In order to reduce the thermal stresses during soft bake, the temperature was increased at $5^{0}$C/min from room temperature during heating. During cooling, the hotplate and wafer cooled naturally to room temperature after switching off the power. UV photolithography was carried out in Cannon PLA-510 mask aligner. The resist was exposed for 4 cycles of 40 s, with a 2 minutes interval between each cycle to allow the resist to stabilize. A PL 360 filter was placed over the chrome mask during UV exposure, which effectively blocked UV radiation with a wavelength below the 365 nm i-line [26]. The exposed wafers were baked at $70^{o}$C for 30 minutes, which helps the acid

assisted cross-linking of the exposed structures. After this bake, the SU-8/Si wafer was developed for 15 minutes in MicroChem EC at room temperature with constant magnetic stirring. The patterned SU-8 layers were released by dissolving the sacrificial layer in tetramethylammonium hydroxide based MFCD26 solution from MicroChem at room temperature for 5 hours. The released SU-8 pieces were cleaned with propan-2-ol and dried by nitrogen gas. Layers of 30 nm of chromium, and subsequently 1500 nm of silver, were deposited by sputtering and thermal evaporation respectively. This was done on both sides of the patterned SU-8 layers without breaking the vacuum. A purpose built sample tilted rotating rig allowed the metal to reach the inner walls of the waveguides and cavities.

## V. MEASUREMENT AND DISCUSSION

The *S*-parameter measurements for the CNC milled extracted pole filter were carried out using a Keysight PNA network analyzer with a pair of VDI (Virginia Diodes Inc.) WR-3.4 extension heads. For the measurement, the CNC machined block was fixed between the waveguide flanges of two frequency extension heads. The insertion loss for the 20 mm length of WR-3 waveguide in the same block was also measured. The results are shown in Fig. 7. The filter has an average passband insertion loss of around 0.65 dB and greater than 30 dB rejection in the upper stopband. As shown in Fig. 7(b), the insertion loss for 20 mm of waveguide is measured to be 0.3 dB, giving the waveguide a loss of 0.015 dB/mm. Allowing for a total of 16 mm of waveguide connecting the filter to the flanges, the loss of the 4 mm long filter structure is thus 0.41 dB.

The measurements are in very good agreement with simulations except that center frequency of the filter is shifted downwards by around 5 GHz. This frequency shift is mainly due to larger-than-designed dimensions of resonators, which have been measured with results shown in Table I. Generally dimensions are within a few microns of designed values, except for the width of the waveguide which is about 15 $\mu$m larger than assumed in the simulations. When the filter is re-simulated with CST using the measured dimensions excellent agreement with measurements is obtained as shown in Fig. 8.

For the SU-8 filter, the measurement is performed on an Agilent E8361A network analyzer using a short-open-load-thru calibration. The SU-8 filter is placed between two waveguide flanges of the network analyzer and the layers aligned by the high precision dowels on the waveguide flanges.

The measured results for the SU-8 filter are shown in Fig. 9. It can be observed from Fig. 9(b) that there are significant ripples in the measured $S_{21}$ response. A different network analyzer was used in these measurements to those of the CNC filter and the ripple is attributed to a poor match in the receiver head which has a transmit-only module at Port 2. This problem is discussed in detail in [27]. The measured insertion loss is around 0.45 dB in the passband and a larger than 30 dB rejection within the upper stopband. However the center frequency of this filter is shifted upward by around 7 GHz from the simulation. Because the layer thickness determines the resonator height $b$, simulations show that the center frequency of the filter does not strongly depend on the layer thickness. So the difference in center frequency of the filter between

TABLE IV
COMPARISON OF RECENTLY PUBLISHED WAVEGUIDE BANDPASS FILTER OPERATING IN FREQUENCY RANGE FROM WR-3 TO WR-1.5 BAND

| Waveguide band | $f_0$ (GHz) | FBW | Micromachining techniques | Filter response | n | IL(dB) | RL(dB) | Reference (year) |
|---|---|---|---|---|---|---|---|---|
| WR-3 | 257.7 | 8.77% | CNC (H-plane split) | Quasi-elliptical, one TZ at lower stopband and one upper stopband | 4 | 0.7 | >14 | [6] (2017) |
| WR-3 | 256.3 | 9.83% | CNC (H-plane split) | Quasi-elliptical, one TZ at lower stopband and one upper stopband | 4 | 0.5 | >15 | [6] (2017) |
| WR-3 | 309.35 | 4.4% | SU-8 (three layers) | Chebyshev, one TZ at lower stopband | 3 | 0.4 | >15 | [12] (2013) |
| WR-3 | 286.6 | 5.58% | CNC (E-plane split) | Chebyshev, one TZ at upper stopband | 3 | 0.41 | >14 | This work |
| WR-3 | 298.6 | 5.36% | SU-8 (three layers) | Chebyshev, three TZs at upper stopband | 3 | 0.45 | >16 | This work |
| WR-1.5 | 570 | 8.77% | DRIE (two pieces) | Chebyshev, no TZ | 3 | 0.9 | >10 | [9] (2012) |
| WR-1.5 | 671 | 7.91% | SU-8 (three layers) | Chebyshev, one TZ at lower stopband | 3 | 0.65 | >11 | [13] (2013) |

*Note*: $f_0$: center frequency of the filter; *FBW*: fractional bandwidth; TZ: transmission zero; *n*: filter order; *IL*: passband insertion loss; *RL*: passband return loss.

measurement and simulation may be due to inaccurate dimensions in the layer plane. The dimensions of the SU-8 filter cavities were measured using a scanning electron microscope. The image in Fig. 6(b) shows the cavity within the second layer and Table II shows the measured resonator dimensions. Measured dimensions in the plane are around 1% smaller than designed values on one side of the SU-8 layer and 3% smaller on the other side, which means the frequency shift may be caused by both changed dimensions and non-vertical sidewalls. After inserting the measured dimensions in CST simulations, a much improved agreement with measurements is obtained, as shown in Fig. 10.

Table III is a comparison of measurements on the CNC extracted pole filer and the SU-8 micromachined filter. Both filters comfortably achieve the requirements of a lower than 0.6 dB passband insertion loss, with measured values of 0.41 dB and 0.45 dB for the metal and SU-8 devices respectively. The requirements for over 30 dB stopband attenuation are also achieved. The CNC milled extracted pole filter offers a better low frequency rejection, whereas the SU-8 device provides a steeper roll-off on this high frequency side of the passband and a smaller overall volume.

Table IV shows the comparison between waveguide filters reported in open literature and two filters described here. These filters operate in the frequency range from WR-3 band to WR-1.5 band. A comparison of some WR-10 band waveguide filters can be found in [14]. All of the filters summarized in Table IV are based on coupled rectangular resonant cavities but fabricated using different micromachining techniques. Care must be taken with the comparisons as the filters have different specifications.

## VI. CONCLUSION

A CNC milled extracted pole waveguide filter and a SU-8 micromachined filter working in WR-3 band have been designed to best exploit the characteristics of the fabrication processes. It is the first demonstration that a CNC milled filter with a steep rejection characteristic beyond 300 GHz and a SU-8 micromachined filter with novel cross-coupling topology working at WR-3 band. The measured performance of the filters is in very good agreement with the numerical predictions

once the latter have been corrected for the small errors in manufacturing. The two filters show no significant difference in performance despite the two alternative fabrication processes and designs. Both filters achieve an insertion loss of below 0.5 dB in a ~ 10 GHz wide passband and a rejection of more than 30 dB in the stopband. Either of these two micromachined waveguide filters can therefore be potential replacements of FSS filters used in spaceborne radiometers for unwanted sideband rejection.

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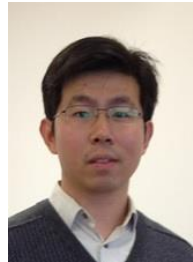
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