WR-1.5 (500–750 GHz) waveguide bandpass filter fabricated using high precision computer numerically controlled machining

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WR-1.5 (500-750GHz) waveguide bandpass filter fabricated using high precision CNC machining

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***Abstract*- In this paper, a WR-1.5 band (500-750 GHz) 3rd order waveguide bandpass filter has been designed and fabricated using high precision computer numerically controlled (CNC) metal micromachining. The filter has been measured with a 7.29% (48.7 GHz) bandwidth at the centre frequency of 667.5 GHz. The minimum passband insertion loss is measured to be 0.87 dB and the measured return loss is better than 10 dB across the whole passband. A yield percentage is analysed and estimated based on the fabrication tolerance.**

I. INTRODUCTION

In recent years, the fabrication of high precision components working at terahertz frequencies has received considerable attention due to their emerging applications in security scanning, astronomy, medical and other imaging as well as communication and radar. High precision is needed in the fabrication process. For example, a WR-1.5 rectangular waveguide is only 0.381 × 0.1905 mm in cross section. Many different micromachining technologies have been employed to achieve this small size with high precision. In [1–4], silicon deep reactive ion etching (DRIE) was employed with waveguide filters up to 1.033 THz. However, high-accuracy fixtures are required to make the connection with other standard waveguides, which causes additional loss and mismatch. The process also requires a clean room environment with expensive etching facilities. The SU-8 photoresist technology [5-7] has been used to fabricate components up to terahertz frequencies. In [7], a 3rd order filter at 671 GHz with 0.65 dB insertion loss and an 8% bandwidth was demonstrated. SU8 exhibits advantages of excellent low insertion losses and high fabrication accuracy. However, the multiple-layer process is subject to assembly errors at higher frequencies [7].

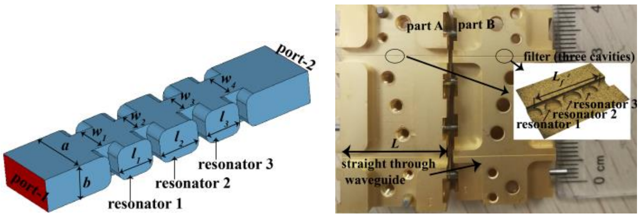
Computer numerical controlled (CNC) milling is a traditional machining technology for metal waveguide structures. Some components fabricated by CNC milling with excellent performance have been reported in [8-15]. A pseudo-elliptic waveguide bandpass filter at 357 GHz with 0.7dB insertion loss and a 9.9 % bandwidth was presented in [8]. A backward wave oscillator working from 405 to 423 GHz was presented in [12] showing a 4 dB insertion loss. In [13], a high pass filter at 385-500 GHz was used in ALMA telescope. In [14], a series of milled filters working at 675- 700 GHz were fabricated for NASA's Aerosol, Cloud and Ecosystems mission. As reported by Jet Propulsion Laboratory in [15], the CNC technique has been further developed and applied to terahertz waveguide circuits up to 1.5 THz, with a very high dimension accuracy (typically within 2-3 µm of the designed values). However, most of these are by very specialized machining processes. In this paper we use a MAKINO CNC machine from a commercial workshop and consider the yield from an example filter. The novelty here lies in the fact we are using standard commercial CNC at terahertz frequencies where very few filters have been made at all. We also provide a yield analysis.

Fabricating CNC waveguide filters at terahertz frequencies is limited by the tool sizes and the cutting depth to tool diameter ratios. Currently the minimum tool sizes are around 50 µm in radius, which limits the depth to around 150 µm. In this work, a 3rd order filter using standard WR-1.5 waveguide (0.381 × 0.1905 mm) is fabricated by CNC machining to demonstrate the high-end milling techniques in producing terahertz waveguide components. The filter was designed at a centre frequency of 660 GHz with 5% bandwidth. Good results are obtained showing commercial high-precision CNC is a viable technology even for frequencies approaching 1 THz.

II. DESIGN AND FABRICATION

A diagram of the filter is shown in Fig. 1*a*. Three TE_{101} resonators are coupled together via inductive irises. The filter is electroplated in gold with a nominal conductivity of 4.56×10^7 S/m used in the simulation. It is designed using the coupling matrix approach [16] to have a Chebyshev response with a centre frequency of 660 GHz, a bandwidth of 5 %, and a return loss of 20 dB.

The external quality factor, Q_e and coupling coefficients are calculated to be $Q_{e1} = Q_{e3} = 17.03$, and $k_{12} = k_{23} = 0.0516$. They are controlled by the irises.



(a) (b)

Fig. 1. Air model of the filter and the CNC machined prototype. (a) The air model inside the filter with optimised dimensions ($w_1 = w_4$= 205.1 µm, w_2= w_3= 151.9 µm, l_1= l_3= 213.1 µm, l_2= 241.4 µm). (b) Photograph and the view of cut plane (L= 20 mm, L_f= 0.96 mm)

The corners of the cavities are rounded as the radius of the cutter used is 50 µm. This is one of the smallest currently available commercially and is taken into consideration in the design. Full-wave simulation and optimization are carried out by CST Microwave Studio [17]. The optimized dimensions are given in Fig. 1*a*. The simulated response is shown together with the measured results later in Fig. 2.

The filter is split on the E plane into two halves (A and B) as shown in Fig. 1*b*. This is to minimize the effect of the cut on the insertion loss. The machined part is electroplated with 2 µm gold. The filter is only 0.96 mm in length. However, to accommodate the UG387 standard flanges, a waveguide section of 9.52 mm has to be added between the filter and the test ports, leading to additional losses. In order to estimate and then remove the effect of this extension from the measurement, a straight waveguide of 20 mm is also fabricated alongside the filter.

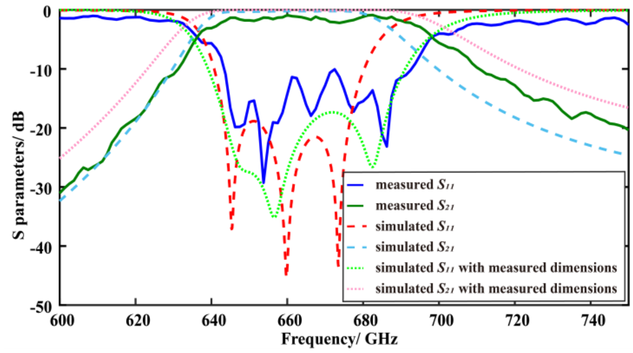


Fig. 2. Simulated and measured response of the filter.

III. MEASUREMENT AND DISCUSSION

The *S* parameter measurement was carried out using a Keysight network analyser with a pair of VDI (Virginia Diodes, Inc.) WR-1.5 waveguide heads. The comparison between the measured responses and the simulated is shown in Fig. 2 with reasonably good agreement. The measured filter has a 7.29 % (48.7 GHz) bandwidth at a centre frequency of 667.5 GHz. The measured minimum insertion loss is 0.87 dB and the return loss better than 10 dB across the passband. The centre frequency is shifted upwards by around 7.5 GHz and the bandwidth is slightly larger than designed. This discrepancy is mainly due to the smaller-than-designed dimensions of the resonators and larger irises between them. The small ripples seen in the S_{11} measurement are most probably caused by the non-perfect connection between the filter and waveguide ports.

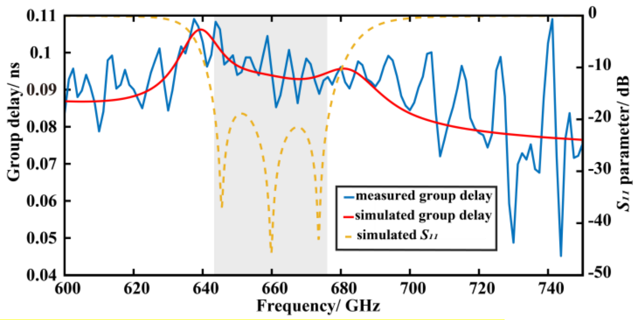


Fig. 3. Simulated and measured group delay of the filter.

The comparison between the simulated and measured group delay is shown in Fig. 3. The decreasing tendency is because of the long waveguide ~~ports~~ sections on ~~the~~ both sides of the filter. The group delay rises on the edges of the passband ~~is higher than the group delay in passband~~. ~~The measured group delay also shows the passband of the manufactured filter is wider than the simulated filter.~~ The large ripples in the measurements are mainly due to the imperfect connection between the filter and waveguide ports. The low sampling rate in measurement also leads to ~~the~~ un-smoothness of phase and affects the group delay further.

The dimensions for both halves (A and B) of the manufactured filter were measured using a confocal microscope (ZEISS Smart Proof 5), and the results are given in Table I. Note that all the lengths (l_1, l_2, l_3) are smaller than designed. When re-simulated using the measured dimensions, the performance agrees much better with the measurements as shown in Fig. 2.

Table II shows the comparison between waveguide filters reported in open literature and filter described here. These filters operate in the frequency range from WR-3 band to WR-1.5 band. All of the filters summarized in Table II are based on coupled rectangular resonant cavities, but fabricated using different micromachining techniques and have been described in the introduction.

Table I Comparison between the designed and measured dimensions.

	$D_{designed}$ (μm)	$D_{measured}^{A}$ (μm)	$D_{measured}^{B}$ (μm)	$D_{measured}^{A}$ - $D_{designed}$ (μm)	$D_{measured}^{B}$ -$D_{designed}$ (μm)
l_1	213.1	190.0	199.0	-23.1	-14.1
l_2	241.4	207.0	226.0	-34.4	-15.4
l_3	213.1	184.0	197.0	-29.1	-16.1
w_1	205.1	219.3	213.6	14.2	8.5
w_2	151.9	169.4	162.9	17.5	11
w_3	151.9	168.5	162.8	16.6	10.9
w_4	205.1	219.4	216.7	14.3	11.6

Table II Comparison of different waveguide bandpass filters operating in frequency range from WR-3 to WR-1.5 band.

f_0 (GHz)	FBW	Micromachining techniques	n	IL (dB)	RL (dB)	Reference
570	8.77%	DRIE (2 pieces)	3	0.9	>10	[1]
640	10%	DRIE (2 pieces)	5	1	>10	[2]
309	4.4%	SU-8 (5 layers)	3	0.4	>15	[6]
671	7.91%	SU-8 (3 layers)	3	0.65	>11	[7]
357	9.9%	CNC (2 pieces)	6	0.7	>14	[8]
687	6.55%	CNC (2 pieces)	5	2	>15	[14]
667.5	7.29%	CNC (2 pieces)	3	0.87	>10	This work

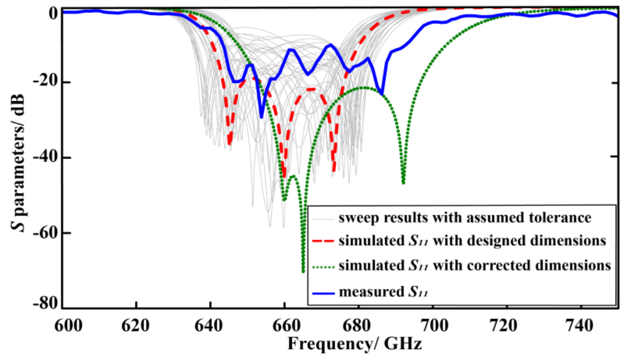


Fig. 4. The S_{11} parameter with the designed dimensions (red dashed curve) and the S_{11} parameter with corrected dimensions (green solid curve). The grey curves are the sweep results with assumed tolerance of 2.5 μm. The blue curve is the measured S_{11}.

IV. YIELD ANALYSIS

Fabrication tolerances lead to performance deviation from the specification. Therefore, a yield analysis is performed. Yield percentage is the ratio of the qualified over the total quantity. This can be estimated after a sensitivity analysis for each parameter in CST microwave studio [17]. Compared with traditional methods, this simplifies the analysis and reduces the calculation time dramatically. Assuming the selection criteria is that the return loss is higher than 10 dB over 643.5- 676.5 GHz, the yield of the filter would be 92.4 %, with assumed tolerance of 2.5 μm. An alternative way to depict this is shown in Fig. 4 where a set of sweep results with maximum dimensional variation of 2.5 μm are shown as grey curves. Note if the assumed tolerance rises to 10 μm then the yield reduced to 62.7%. The red dashed curve in Fig. 4 is the simulated S_{11} parameter with the designed dimensions.

The real dimensional difference between the as-fabricated device and the design is much larger than the assumed tolerance of 2.5μm in our case. As shown in Table I, the average difference in length is about -22 μm and 13 μm in width. Of course, this is for only two devices and not statistically significant. Nevertheless, it is not surprising to see that the yield percentage drops to 24.9 % using the same selection criterion. The low percentage is mainly due to the frequency shift upwards caused by the generally smaller-than-designed resonators.

If we repeat the simulation using the average measured dimensions (i.e. reducing the lengths by 22 μm and increasing the width by 13 μm), the passband of the filter will be shifted to 653.14 - 696.7 GHz. The S_{11} parameter with corrected dimensions is shown as green solid curve in Fig. 4. If we use this frequency range as the selection criteria, the yield percentage becomes 78.6% under the average machine tolerance.

V. CONCLUSION

A high precision CNC milled waveguide bandpass filter working in the WR-1.5 band has been designed and fabricated. The filter is centred at 667.5 GHz with a 7.29% bandwidth. Reasonably good agreement between the measurement and simulated results shows that the precision CNC milling is a viable technology for producing terahertz waveguide filters. However, machine tolerance would significantly reduce the yield of production. A high fabrication accuracy and tight tolerance control is needed for high yield in the fabrication of terahertz waveguide devices.

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