WM380 (675-700GHz) Band-Pass Filters in Milled, Split-Block Construction

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***Abstract*—Filters play an invaluable role in RF analysis and communications hardware, blocking unwanted signals, limiting bandwidth, attenuating harmonic components, etc. In waveguide construction for mm-wave frequencies, where the powers are generally low, the iris-coupled-resonator band-pass filter has proven to be very practical and amenable to easy machining. Described here is a WM380 (WR1.5) filter for the 500-750 GHz waveguide band having a pass-band of 675-700 GHz.**

Measured results of a batch of filters are shown and compared to simulations to illustrate just how well these filters can be made. Furthermore, the filters can be tuned by simple mechanical means and data are presented to illustrate how easily the filters can be adjusted. Additional modifications to the filter topology to simplify machining, and allow other construction techniques to be utilized are also demonstrated. Ultimately it should be possible to push the split block technology to manufacture iris coupled resonator filters for use at frequencies of well over 1 THz.

I. Introduction

The specific motivation for the work described here was the development of a 640 GHz integrated-block heterodyne polarimeter, intended to serve as a proof-of-concept for future instruments in which many complex mm-wave components are integrated into a single machined part[1]. As shown in the block diagram in Figure 1 below, a pair of identical filters is required to pass only the upper sideband of an input signal, from 675-692 GHz. The two filters must be closely matched, and more importantly need to meet a tight, and absolute frequency specification as determined by the science for which the instrument is designed.

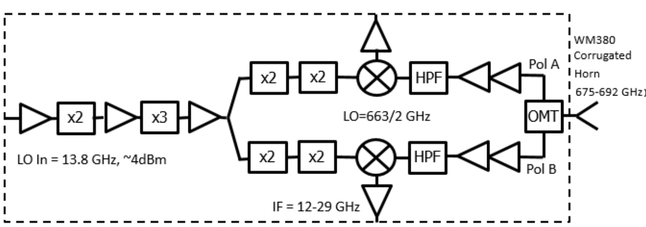

Figure 1 Block diagram of an Integrated 640 GHz Heterodyne Polarimeter

The filters chosen for the project are of the iris-coupled resonator design, adapted to a split-block construction, which lends itself readily to CNC machining[2]. In such a device, thin inductive irises milled into the block divide the waveguide into a series of coupled resonators. A typical resonator length for the WM380 band in question is on the order of 250 microns, yet state-of-the-art CNC milling allows a machining tolerance of +/-2.5 microns. In a worst-case scenario, the errors can be independent, yielding a length variation of the resonators of +/-2%. The corresponding variation in frequency for a 675 GHz filter is approximately +/-14 GHz, which is more than half of the target pass-band and will clearly not work for the instrument pictured above. A possible solution is to design the filters to operate at frequencies nominally higher than the desired pass band and to tune them down mechanically to the desired values. Several techniques for doing so are described below.

II. Filter Design I

A filter, hereafter referred to as X1, was designed with a 3-dB pass-band of 670-710 GHz to allow for some initial compensation for machining tolerances. X1 is of a "conventional" design in which machined irises, each 1/10 the waveguide width in thickness, stand out from the waveguide sides. The irises are of different heights. Construction is of the split-block design in which half of the structure is located in part of a metal block with the other half in an identically machined block, and the structure is split down the middle along the E-symmetry plane of the waveguide. By pushing state-of-the-art milling machines to their limits, five blocks were delivered with mechanical tolerances better than +/-2.5 microns in all dimensions. A micrograph of one of the filters is shown in Figure 2.

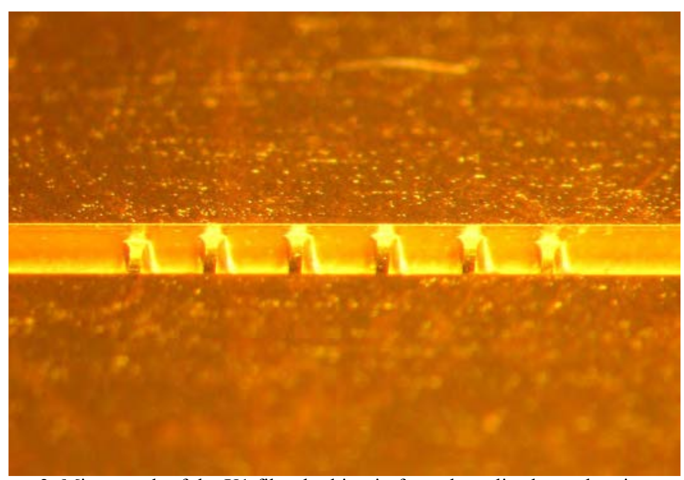

Figure 2 Micrograph of the X1 filter looking in from the split-plane, showing the thin irises.

RF performance of all five filters was measured on a Keysight Vector Network Analyzer with a pair of Virginia

Diodes WM380 frequency extension heads, using an SOLT calibration. Results for all five units are shown in Figure 3 below. Note that two of the filters (#1-01 and #1-05) are shifted down in frequency relative to the others, presumably due to tolerance variation. Otherwise, the filters are very tightly grouped, indicating good control over the machining.

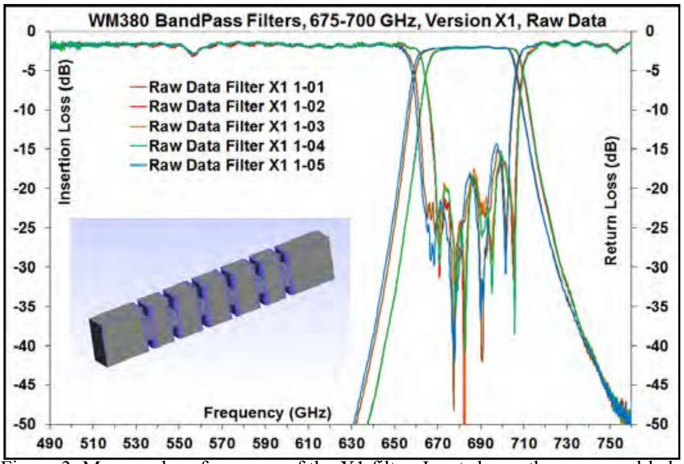

Figure 3 Measured performance of the X1 filter. Inset shows the as-assembled filter geometry.

The expected behaviour of the X1 filter upon intentionally introducing various gaps between the block halves was simulated in HFSS and the results are shown in Figure 4. The lower edge of the pass band shifts linearly at the rate of -1.9 GHz per micron of introduced gap. The upper band edge shifts slightly less, at a rate of -0.9 GHz per micron so the overall pass-band of the filter increases as the filter response is shifted down. The return loss of the filter also worsens as the gap is increased, but the decay is well behaved. The simulations hint at an elegant way to "tune" the filter by introducing a gap between the block halves in a controlled manner. Because the filter is E-plane split, RF leakage from the gap is small and does not appreciably deteriorate the insertion loss of the device.

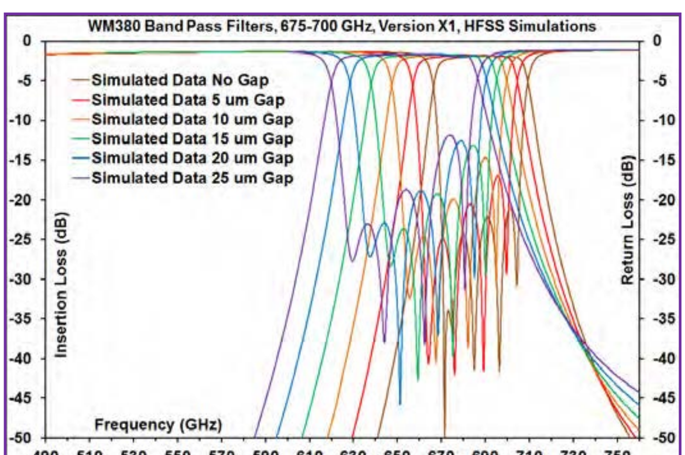

Figure 4 HFSS simulations of X1 filter, "tuned" by separating the halves at the split-plane.

III. Filter Design II

A second series of filters was also designed and built. The X2 structure is intended to be more amenable to scaling to higher frequencies, where a two-level electroforming technique might provide higher dimensional accuracy. All the irises are of the same height, but the widths vary. The design was carried out by optimizing in FEST-3D but forcing the iris heights to be constant, while maintaining the same target performance as the X1 design[3]. A micrograph of half of an X2 filter is shown in Figure 5.

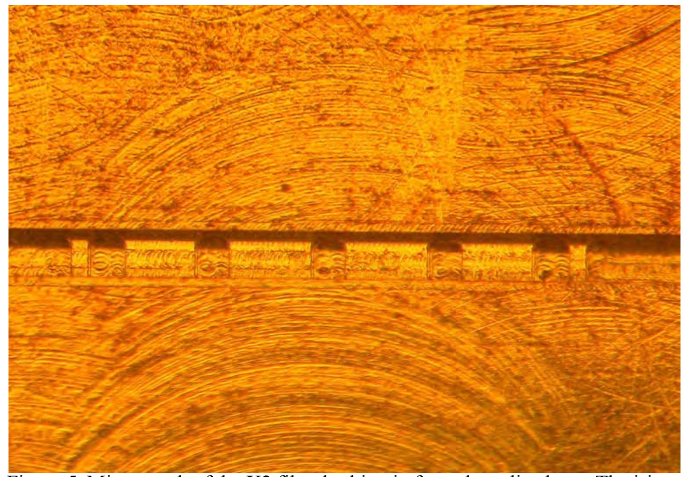

Figure 5 Micrograph of the X2 filter looking in from the split-plane. The irises are all the same height, but the "widths" vary.

All five units were measured on a VNA and the results are presented in Figure 6, which also includes an image of the unusual filter structure in the inset. Note that all five filter responses are relatively closely matched, and as with the X1 design, there is a net shift down in frequency from the design target.

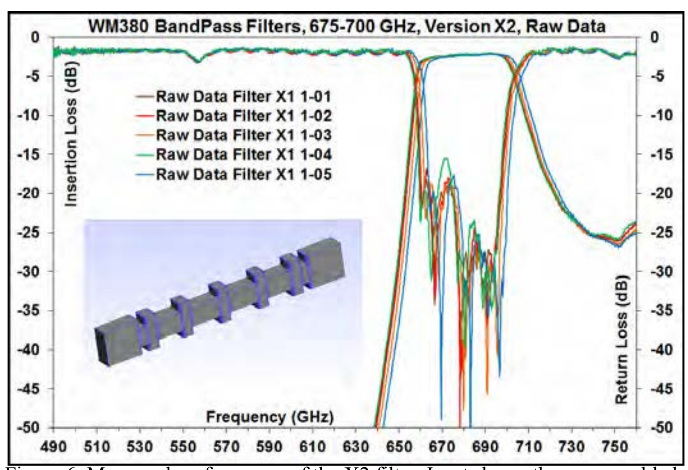

Figure 6 Measured performance of the X2 filter. Inset shows the as-assembled filter geometry.

The simulated effect of tuning the filter by introducing a gap between the block halves is again explored in Figure 7 and some notable differences are evident. The lower and upper edges of the band shift downward at the rate of 2.6 and 2 GHz per micron respectively, a rate much greater than that of the X1 design. In addition the bandwidth increases by only 0.6 GHz per micron, vs. 0.95 GHz per micron for the X1 design. Overall, the X2 design is much more sensitive to tuning by introduction of a gap between the block halves and the bandwidth changes more slowly.

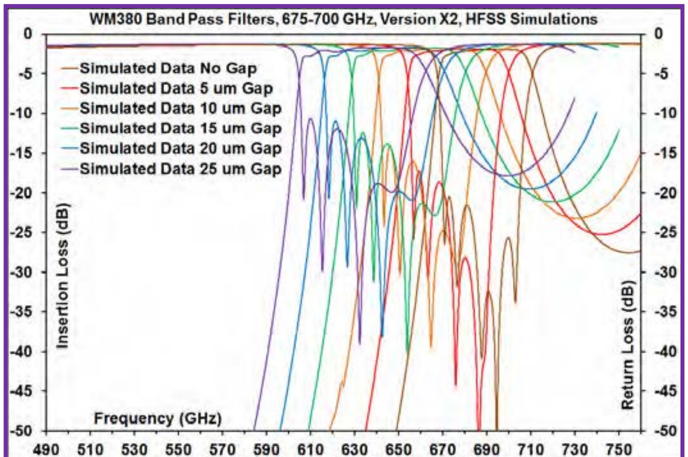

Figure 7 HFSS simulations of X2 filter, "tuned" by separating the halves at the split-plane.

IV. Fixed Tuning with Mylar and Aluminum Shims

For the initial series of experiments, small Mylar squares, each 5 microns thick, were placed *between* the clamp screws of filter X1 #1-02[4]. Because the spacers were not placed directly under the clamp screws, the block deformed when clamped and the desired gaps were less than expected. The blue curves in the shift summaries below were obtained.

In the next series of tests, larger sheets of Mylar were used that cover the full length of the block and the results for multiple filters with differing gaps are presented in Figure 8. Note that the filters were not identical so the resulting frequency shifts appear to be non-linear and curves for filters with the same gap are not coincident. When the frequency shifts relative to the un-gapped filter are determined, the response is indeed linear as will be further summarized below.

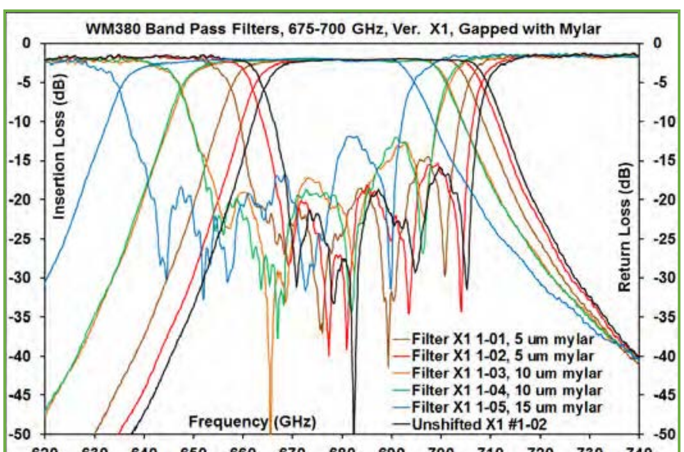

Figure 8 Multiple X1 filters tuned by adding pieces of Mylar between the block halves.

Finally, a 14 micron thick sheet of aluminum foil was used as shim material. One, and later two pieces of foil were laid down across the entire central section of the block straddling the position of the filter to ensure a uniform gap. The results are shown in Figure 9 along with the positioning of the foil as illustrated in the inset. The resulting filter tuning was linear and as predicted by the HFSS simulations.

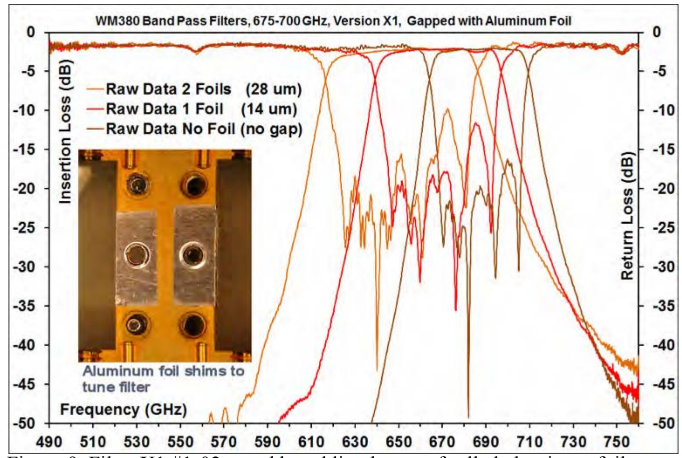

Figure 9 Filter X1 #1-02 tuned by adding layers of rolled aluminum foil.

V. Shift Summary

The performance of the shimmed X1 filters is summarized in Figures 10 and 11 below, with linear fits to the data for comparison. The non-linearity of the tuning with small Mylar squares is evident, and it also apparent that the larger Mylar sheets (not shown, but roughly the size and shape of the aluminum foil pieces shown above) are indeed effective.

Aluminum shims appear to be the most robust, and shift the frequency response of the filter by nearly the same amount as expected from the simulations. Corresponding plots for Filter X2 are provided in Figures 12 and 13.

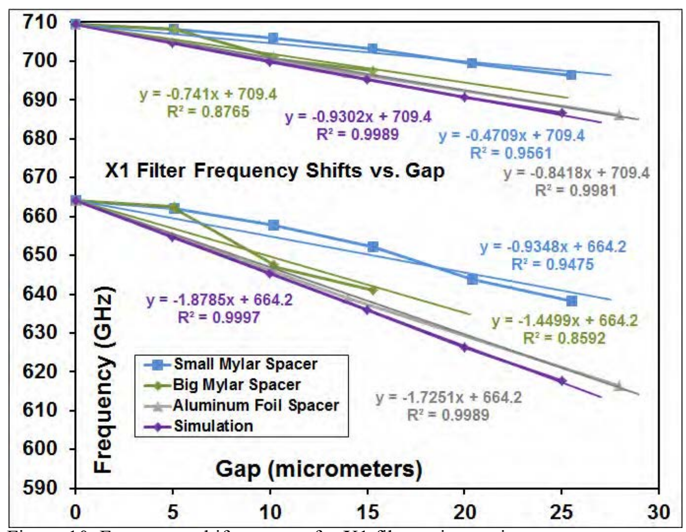

Figure 10 Frequency shifts vs. gap for X1 filter using various spacers.

Stability

Mylar is an established material for space-qualification, but stability of the filters remains a concern. Two X1 filters, each with 2 layers of 5 micron thick Mylar, were baked in an oven at 110C for 50 hours. Additionally two X2 filters, one with only one 5 micron layer, and one with 15 microns of Mylar, were similarly baked. There was no measurable change in the filter response of any of the filters.

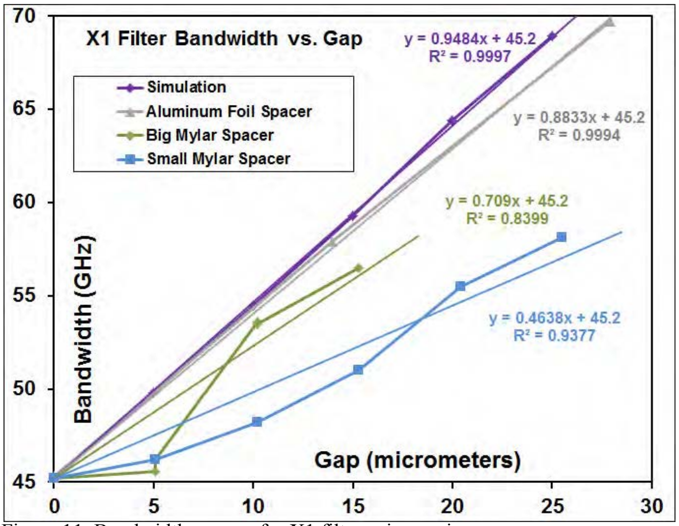

Figure 11 Bandwidth vs. gap for X1 filter using various spacers.

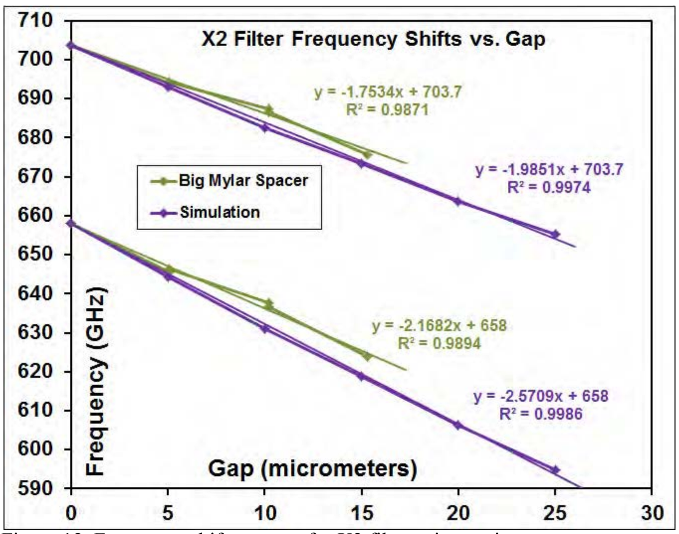

Figure 12 Frequency shifts vs. gap for X2 filter using various spacers.

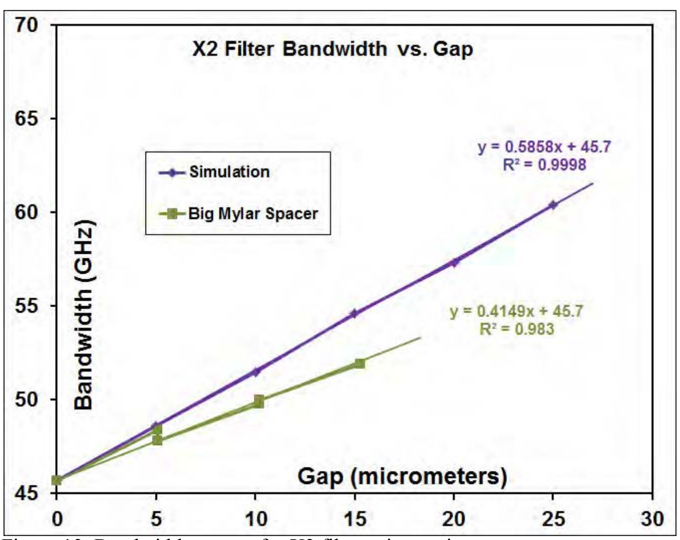

Figure 13 Bandwidth vs. gap for X2 filter using various spacers.

A more stringent test is the so-called "Bellcore" cycle, in which parts are subjected to a 70C bake followed by a -40C soak in a 1 hour period, for 1000 hours[5]. As before, two X1 filters, each with 10 micron Mylar spacers, and two X2 filters, one with a 5 micron spacer, the other with 15 microns, were put through Bellcore cycling. As before, no filter experienced any measurable change in performance, indicating that the Mylar and the clamping are stable under the tested conditions.

CONCLUSIONS

A WM380 675-700 GHz band-pass filter, with an inductive shunt, iris-coupled-resonator structure has been made in split-block construction. The filter design is "routine", well understood and has been in the literature for decades. What is unique is its frequency of operation. At 675 GHz, construction required pushing to the absolute limits of machining tolerances to make a repeatable filter capable of hitting absolute frequency targets. Despite the demonstrated reproducibility of the pass-band, the push towards even higher frequency, and smaller dimensions will require some sort of tuning of the filters. A predictable, stable means of shifting the pass band of the as-designed filter down by discrete steps with Mylar or aluminum shims has been demonstrated.

A second design, with a much simpler mechanical structure has been similarly proven. Rather than utilizing thin irises milled into the waveguide, the simplified design has features milled to only two depths. The intention is that the filter could be made more easily with CNC milling, but also by electroforming or etching techniques where an "etch to a depth" or "deposit to a height" fabrication method would benefit from having only two steps in the structure. While there is no theoretical design paradigm for developing the filter, a structure is easily obtained by optimizing a model, with constraints, using commercially available simulation software.

ACKNOWLEDGMENT

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REFERENCES

[1] Eric W. Bryerton, Jeffrey L. Hesler, Daniel Koller, Yiwei N. Duan, and Thomas W. Crowe, "A Compact Integrated 675-693 GHz Polarimeter", accepted for publication in the Proceedings of the 43st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), 2018.

[2] G. Matthaei, L. Young, and E.M.T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures,* New York: McGraw Hill, 1964, first ed.,pp. 450-464.

[3] FEST3D, www.fest3d.com, Aurora Software and Testing S.L.U. (CST/3DS).

[4] E.g. 5 micrometer thick clear Mylar, 7.0g /m^2, available from http://www.homefly.com/products.asp?id=31 [as of 12 June 2018].

[5] Bellcore (Bell Communications Research, Morristown, N.J.) Document TA-NWT-000765 and GR-765.