Understanding the OE9PMJ Microwave Filter
For 24, 47, and 78 GHz

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As we move to successively higher microwave bands, we usually start out with a barefoot mixer, which does not discriminate between sidebands – signals on both sides of the Local Oscillator are transmitted and received, as well as LO leakage. As the equipment is improved, filtering the LO and image signals from the mixer is desirable. We don't want to waste transmitter amplifier power on these signals, and removing the image from the receiver removes half of the noise, lowering the Noise Figure.

For the common 144 MHz IF frequency, filtering becomes harder with each higher band. A bandpass filter must be less than perhaps 100 MHz wide, which is a bandwidth of 0.4% at 24 GHz, 0.2% at 47 GHz, and 0.13% at 78 GHz. A low-loss filter with a bandwidth of less than 1% is considered difficult.

The only amateur filter I know of that can meet this requirement is one attributed to Peter Riml, OE9PMJ (SK). Other filters are described in the professional literature, but practical details are few. Most commercial filters are made by small companies with closely guarded secrets, and most products are broadband filters rather than narrow ones.

Even for the OE9PMJ filter, very little has been published[1,2,3,4], at least in English. A few sketches like Figure 1 may be found on the web[1,2], but no explanation of how or why this filter works. I only found one similar filter[5] in professional literature, and rather than tuning screws, it has tuning disks with posts for unwanted mode rejection.

Before I retired, I had access to the Ansoft **HFSS** Electromagnetic simulator[6] and was able to run interesting projects at off hours. I simulated the OE9PMJ filter to try and understand it, and to see if it was possible to make filters with amateur facilities, or whether fancy machinery would be required.

Filters

The OE9PMJ filter is basically two coupled resonant cavities. A cavity resonator is just a tuned circuit, so the filter is just a double-tuned ciruit. The coupling is what determines the shape of the bandpass response, shown in the example in Figure 2. If there is not enough coupling between the resonators, the undercoupled response is very narrow and lossy, while if there is too much coupling, the overcoupled response has two peaks with a dip between them. The input Return Loss also has two peaks, which are not necessarily at the same frequency as the bandpass peaks. If the coupling is just right, called critical coupling, the response is maximally flat and the Return Loss is pretty good across the bandpass.

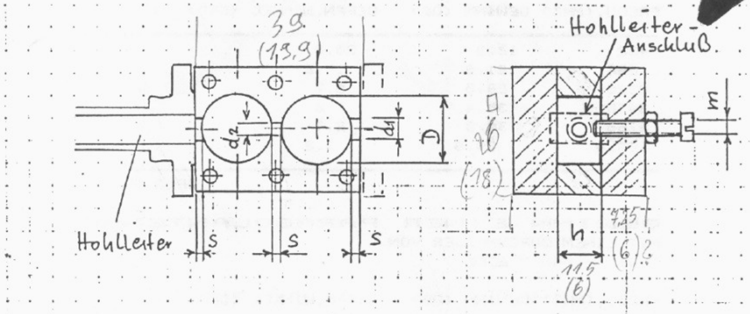
Hubert Krause

micro – mechanik

mechanische komponenten für mikrowellen – funkanlagen und messtechnik

Darmstädter Straße 79 b D-64839 MÜNSTER

High-Q-Filter für mm-Bänder OE9PMJ



fo (GHz)	D	h	d_1	d_2	s	m
24.192	18,00	11,50	4,30	3,50	1	M 4 26□ x 39
47.088	9,20	6,00	2,20	1,80	0,5	M 3 18□ x 19,9
75.500	5,75	3,70	1,40	1,15	0,3	M 2 (M2,5)
78.384	5,55	3,60	1,35	1,10	0,3	M 2 (M2,5)

Auf die Lage (90°) der Hohlleiteranschlüsse achten!

Beim Eindrehen der Abstimmschrauben erhöht sich fo!

Bei etwa fo/2 kommt es zum Übersprechen durch die E01 – Resonanz, diese wird jedoch durch den Hohlleiter-Cutoff eliminiert.

Juni 1989

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St.-Nr. 00883830995

Figure 1 – Sketch of OE9PMJ Filter (thanks to K0CQ)

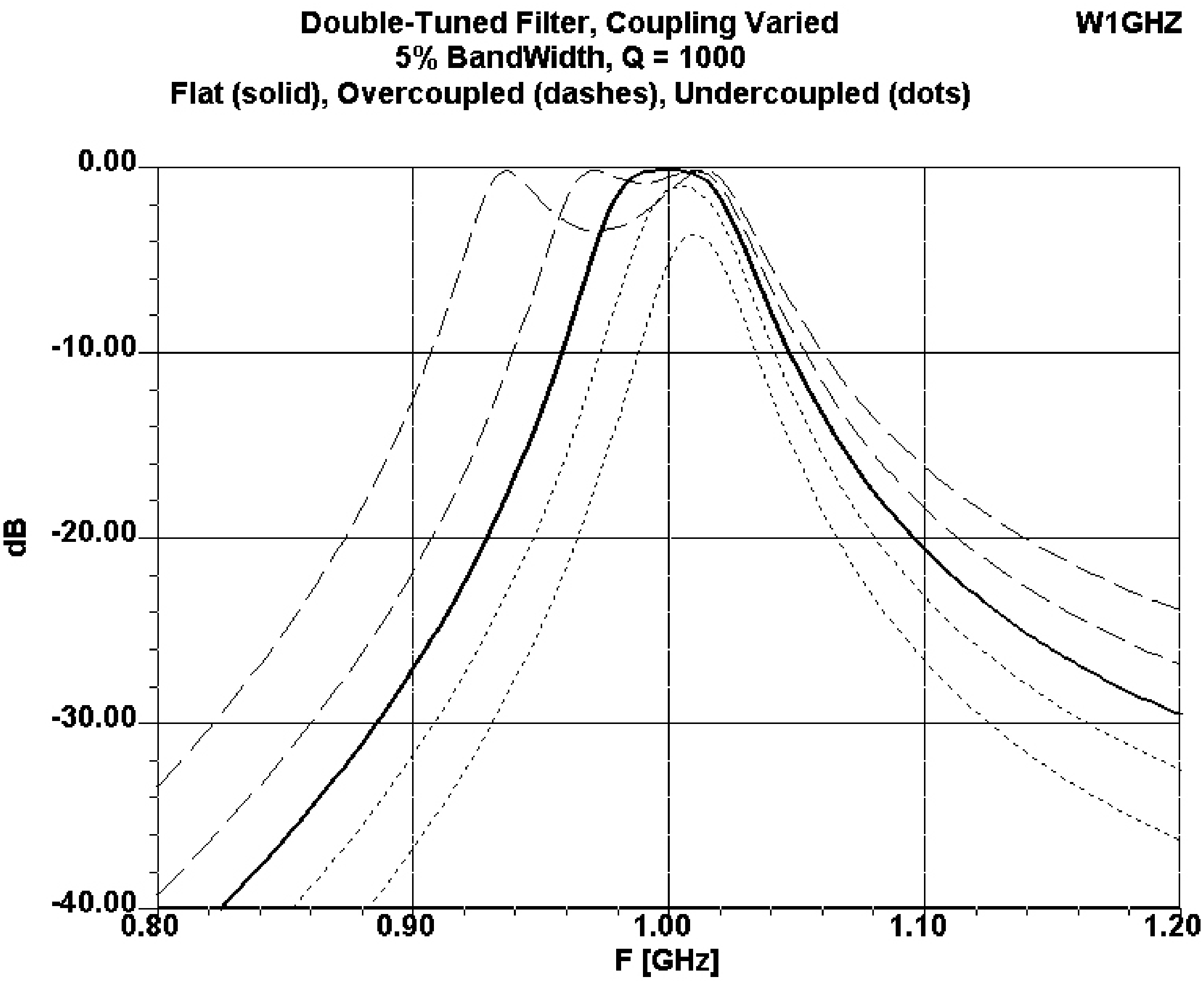

Figure 2 - Coupling response for double-tuned circuit

To make a very narrow filter, a very small amount of coupling is required and the loading from the input and output must be very light, so that the circuits have high loaded Q_L. The required Q_L is

$$Q_L = \frac{Frequency}{BW_{3dB}}$$

or about 500 for 0.2% bandwidth. To keep the loss low, the unloaded Q_U, the inherent Q of the cavity, must be much higher – roughly ten times as high for loss under 1 dB. The Q_U required at 24 GHz is about 2500 for a filter with 100 MHz bandwidth, or about 5000 at 47 GHz.

I have made good waveguide post filters[7] for frequencies up to 24 GHz that are narrow enough for a 144 MHz IF and have reasonably low loss. The estimated Q of these waveguide cavities is about 4000, so this type of filter would not be good enough for 47 GHz and up, even if you could make one – dimensions would be very tiny and critical.

One way to make higher Q cavities is to use right cylindrical cavity modes rather than waveguide transmission modes – this is what is happening in the OE9PMJ filter. Microwave reference books[8] have mode charts that show very high Q for some modes. They also show that there can be several modes with little frequency separation – that is why we prefer the lowest order waveguide mode for transmission whenever possible. What they don't show is how to couple energy in and out of the cavity in a desired mode, so a working example like the OE9PMJ filter is a great place to start.

One problem with simulating a very narrow filter is that there are no software tuning screws to adjust. Dimensions must be very close and simulation must be in small frequency steps to find the narrow response – this takes a lot of compute time. Then each change takes another long run (get the results the next morning). Since Reference 1 had changes penciled in, I varied all the dimensions to be sure that the original 24 GHz cavity dimensions are correct: 18mm in diameter and 11.5 mm deep.

24 GHz Filter

For 24 GHz, there are some results on the web[4] for comparison. What we find, in both measurement and simulation, is that there are multiple responses, as shown in Figure 3. In addition to a desired passband at 24 GHz, there are two others, at ~20 GHz and ~25.2 GHz. The one at 20 GHz is far enough away to ignore.

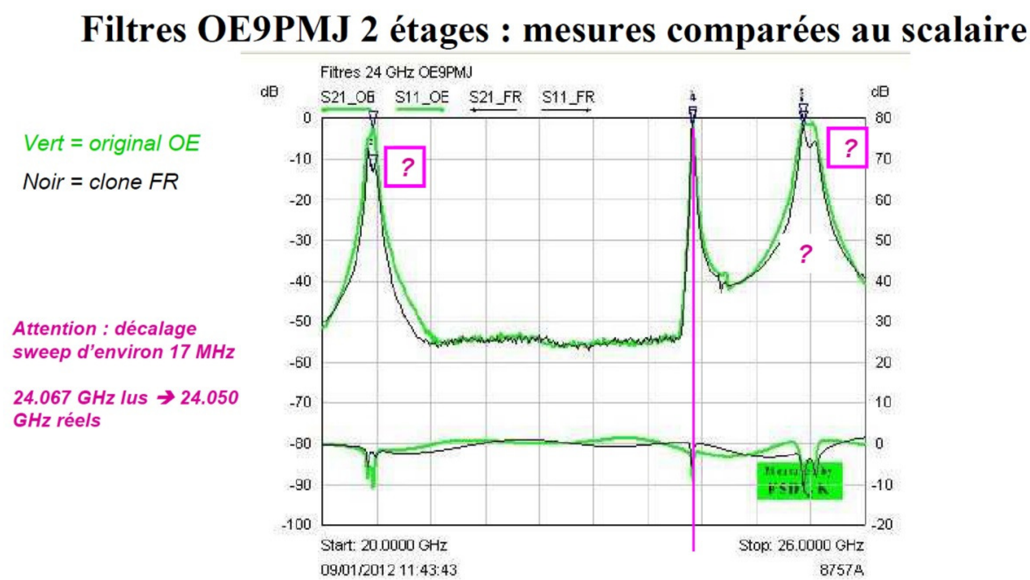

Figure 3 – Wideband response of 24 GHz OE9PMJ filter from F5DQK

Some trials with tuning screw depth in Figure 4 show that the tuning screw moves the 24 GHz bandpass *upward* in frequency as the screw is inserted – it is reducing the effective height of the cavity rather than adding capacitance. Yet the tuning screw has no effect on the 25.2 GHz response – it is only changed by changing the full cavity height.

Figure 4 also shows a glitch between the two responses – this appears to be due to the tuning screw. The glitch becomes larger as the screw depth increases. I also found that a larger tuning screw diameter made the glitch larger.

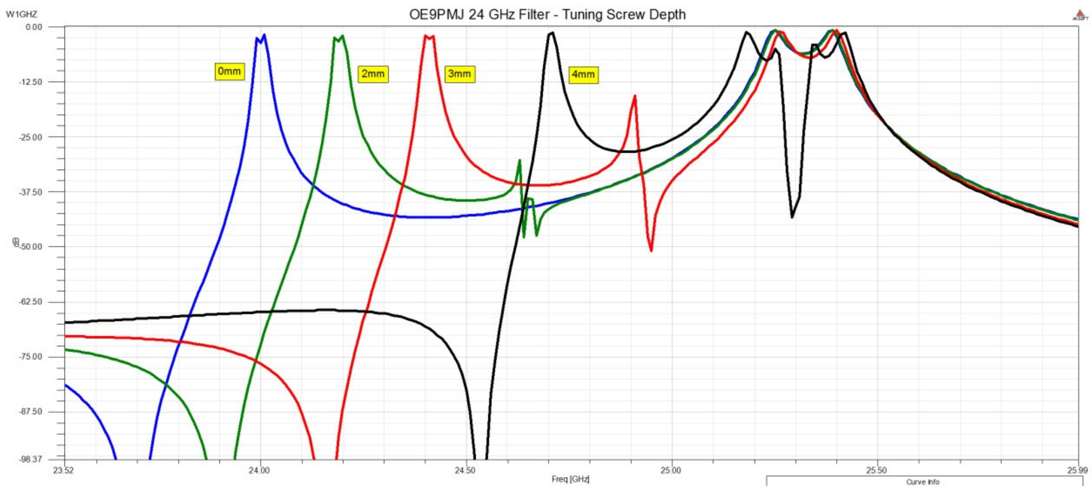

Figure 4 – Tuning screw insertion *increases* frequency

With the simulator, we can look at fields and see that the 24 GHz (Figure 5) and 25.2 GHz (Figure 6) responses are different modes. In Volume 11 of the RADLAB books[9], there is an explanation of mode numbering in circular cavities, along with the mode chart that has become the standard in all reference books[10]. The mode chart confirms that Figure 5 is the TE_{011} mode – the E-field does not contact any of the walls, so loss is low and Q is high. The 25.2 MHz resonance in Figure 6 is at the right frequency for the TE_{311} mode. The resonance around 20 GHz is at the right frequency for the TE_{211} mode.

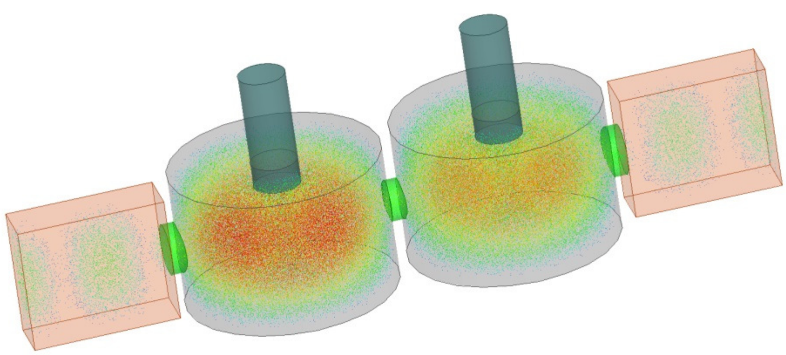

Figure 5 – E-field at 24.2 GHz

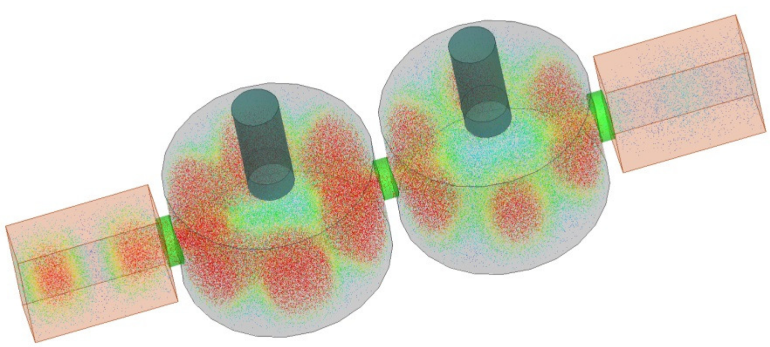

Figure 6 – E-field at 25.2 GHz

Looking more closely at the 24 GHz bandpass in Figure 4, it appears overcoupled, both in simulation and in published results, with a dip in the middle of the bandpass. Overcoupling makes the skirts slightly steeper, but it also makes tuning more difficult – there are two peaks, and it is hard to peak the filter and have good VSWR simultaneously. Even if the bandpass appears flat, the input Return Loss will have two peaks, making it hard to center the bandpass. Note that the skirt is very steep on the low side with excellent rejection, but poor on the high side, so this filter is only really good for low-side LO injection.

There are three coupling holes – one input and one output at the ends, which should be identical, and a central hole which is the coupling between the two cavities. The holes are coupling the H-field oriented in the z-direction[5], parallel to the cavity centerline. I tried various combinations of hole diameters, and found that increasing the central hole diameter increases the coupling between the two cavities, and the bandwidth is proportional to the coupling.

Loading is trickier. For a given coupling hole, increasing the end hole diameter increases the loading, which reduces the effective coupling, so that increasing the end hole diameter changes the response from overcoupled to critical (maximally flat) to undercoupled (Figure 2).

For a low-loss filter, we would like to make the bandwidth as large as possible and still have adequate image and LO rejection, then make the loading for critical response for smooth tuning, with a single broad peak and single best VWSR at the same frequency.

For the OE9PMJ filter, increasing the center coupling hole increases the bandwidth. Then the end hole diameters can be increased for critical coupling and maximum flatness. As the bandwidth increases, loss decreases and tuning becomes easier. Several combinations are simulated in Figure 7.

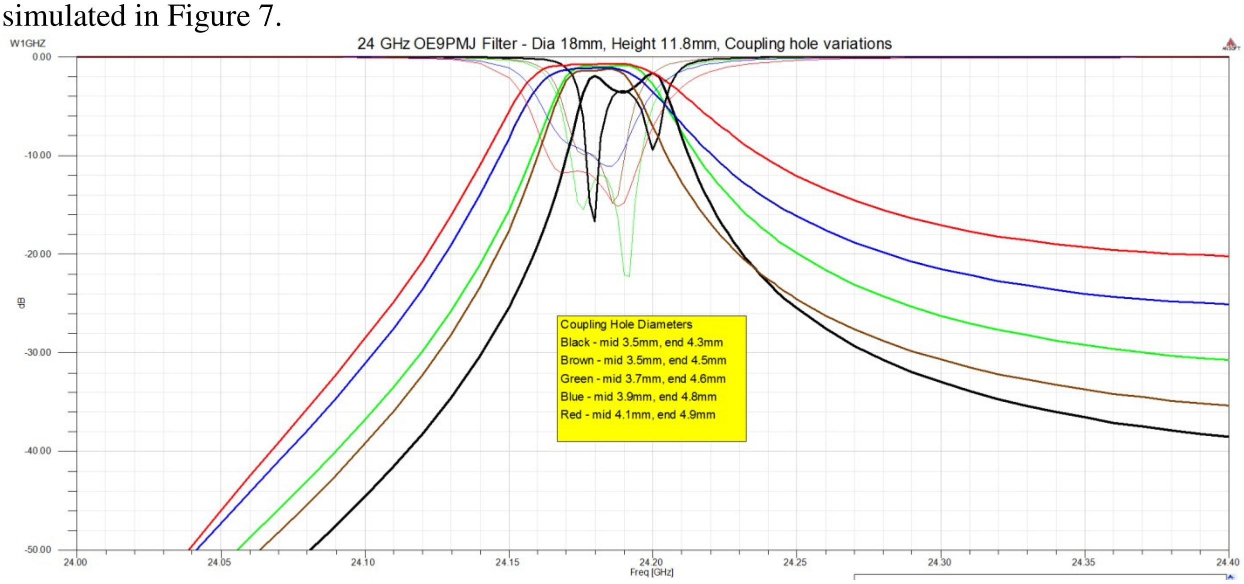

Figure 7 – OE9PMJ Filter Coupling Hole Variations

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However, as the bandwidth is increased, the high-side rejection between the 24 GHz response and the undesired 25.2 GHz response gets worse. If anything in this range matters, then the wider bandwidth may not be a good choice.

Measured results

In the past year, I have become part of a local Makerspace with a good machine shop. This has provided access to CNC (Computer Numerically Controlled) machinery and expertise so that I have been able to learn how to use it. Now I have the facilities to accurately and reproducibly machine OE9PMJ filters and other microwave gizmos. The completed filter in Figure 8 shows the construction, with the cavities machined into one block and the tuning screws in the cover. An alternate construction, if CNC machinery is not available, is to make the filter in three pieces, with a center piece the exact height of the cavities and two cover pieces.

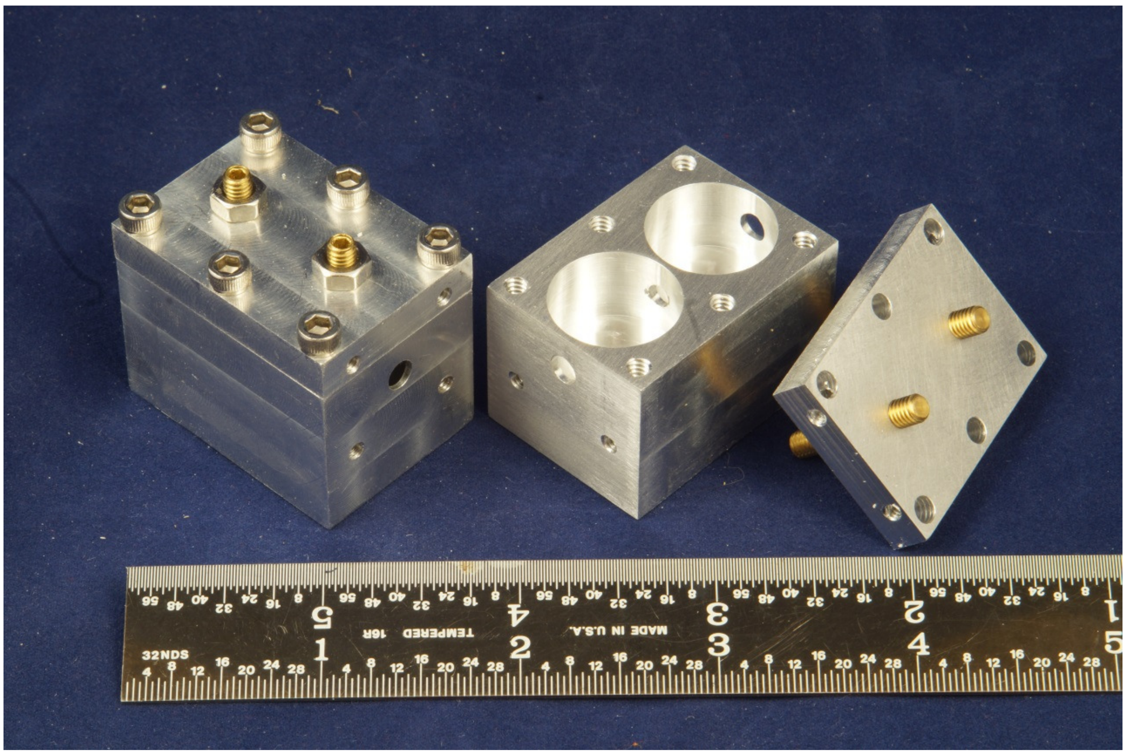


Figure 8 – 24 GHz OE9PMJ Filters showing construction

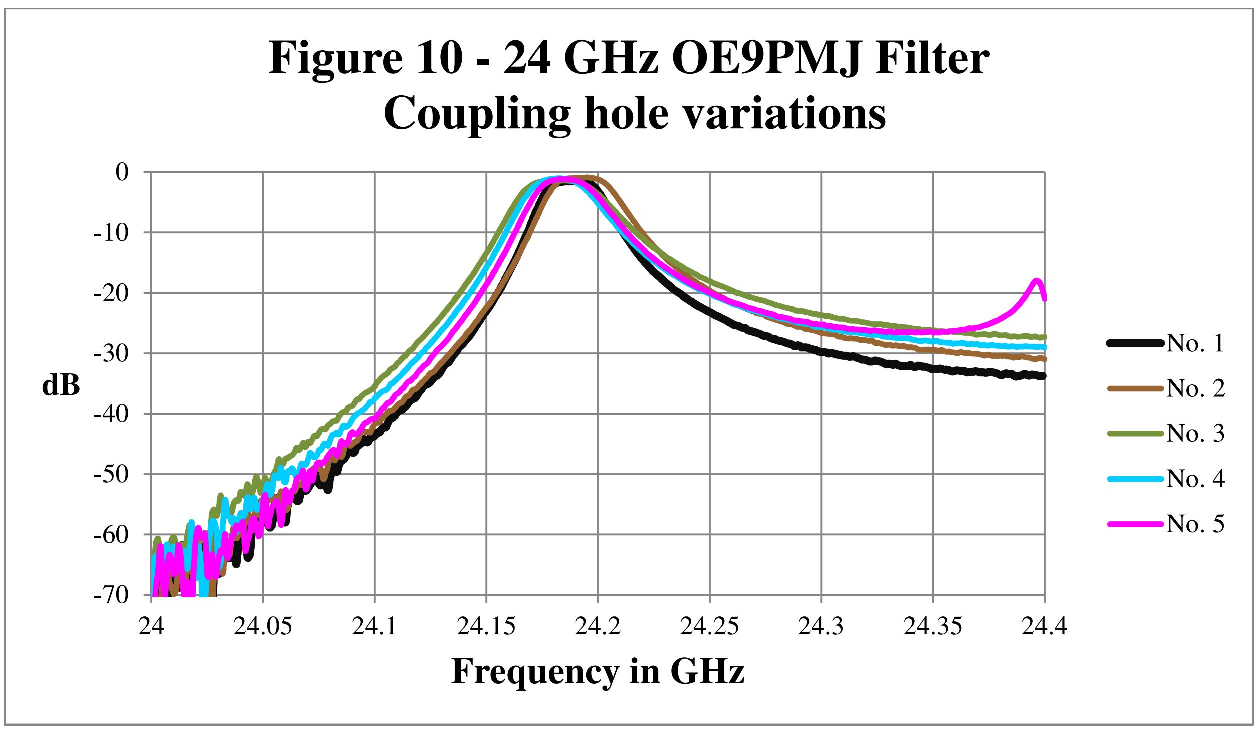
Figure 9 – OE9PMJ Filters for 24 GHz – note Waveguide orientation

I started out to machine three 24 GHz filters to compare to Figure 7 and validate the simulation results. Since I was just learning, I screwed up 2 of the 3 and had to start more. I figured that if I started 5 more, I might end up with 2 good ones, but all in this batch were successful, resulting in 6 good filters, shown in Figure 9, including one with larger diameter tuning screws. I attempted to make the range of coupling holes similar to the simulated values in Figure 7 – actual diameters are shown in Table 1:

24 GHz OE9PMJ
Filter
CouplingHoleDimensions

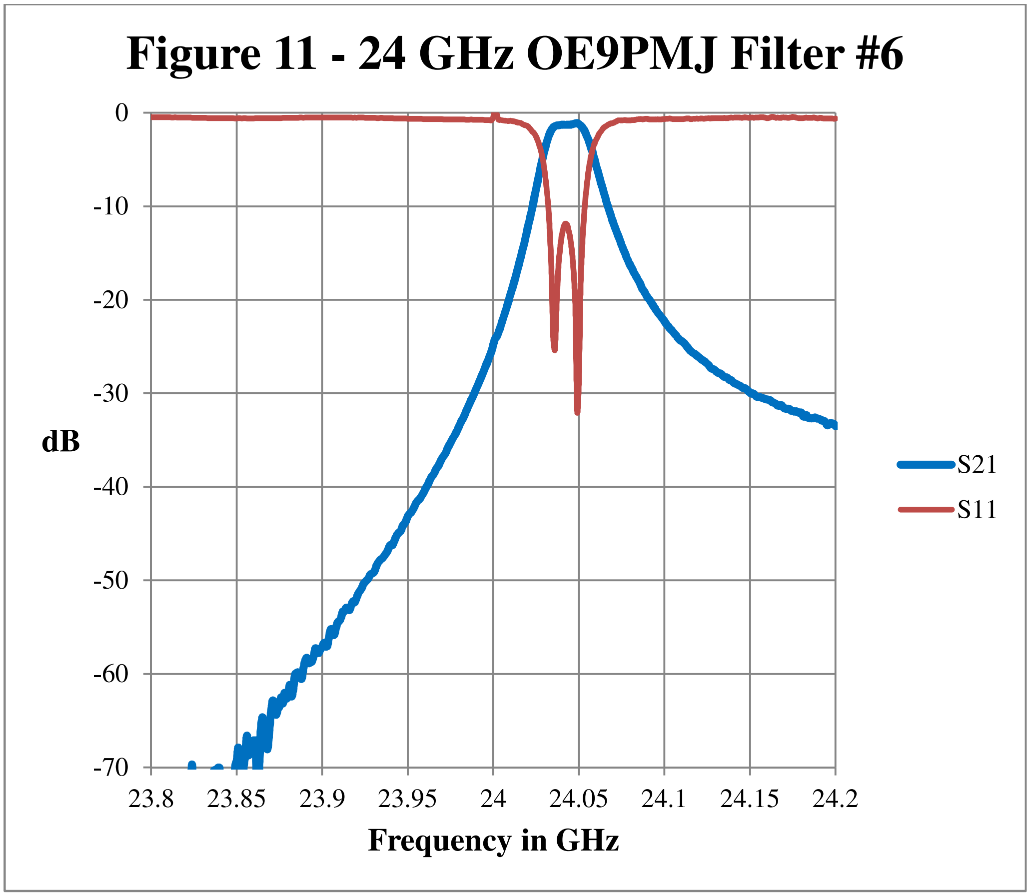
Filter #	Mid hole		Endholes	
1	3.43	mm	4.34	mm
2	3.49	mm	4.46	mm
3	3.68	mm	4.57	mm
4	3.53	mm	4.55	mm
5	3.28	mm	4.32	mm
6	3.4	mm	4.34	mm
Published	3.5	mm	4.3	mm

The measured results with a VNA, in Figure 10, are quite close to the simulated results, so the simulations are valid. Even the widest one only has a bandwidth of 38 MHz, much sharper than needed, with LO rejection roughly 50 dB down. Loss is about 1 dB for all.



Another result validated in measurement concerns tuning screw size. All the filters except one are tuned with M4 tuning screws from some cellphone surplus, and show a small glitch in the response somewhere between the 24 GHz bandpass and the 25.2 GHz unwanted response. One filter, #5, is tuned with larger M6 screws, and it has a larger glitch visible in Figure 10, demonstrating that the glitch is due to the tuning screws and a smaller tuning screw is preferable. This is an important result for higher frequencies.

The sixth filter was tuned to 24.048 MHz, the European calling frequency, also used for EME. The measurements are shown in Figure 11. This filter is slightly overcoupled – the bandpass is nearly flat, but the return loss has two peaks.



We can estimate the unloaded Q_U of the cavity resonators from the bandwidth and loss. For all these filters, the unloaded cavity Q_U is roughly 8000, which is pretty spectacular, even though the theoretical Q_U much higher. This measured Q_U for these cavities is higher than the textbook number for the lowest mode rectangular waveguide resonator used in post and iris filters. These cavities are just bare aluminum – I don't have a convenient way to get good electronic-grade silver plating, and most other plating is just cosmetic, with additives to make it shiny without increasing conductivity.

Tuning and Fine Tuning

I tuned up the 24 GHz filters without a fancy network analyzer. I have an X-band signal generator, a frequency doubler, and power meters to measure transmitted and reflected power, with an isolator before the filter so that the input power stays reasonably constant. Note the waveguide orientation in Figures 9 and 12 – the tuning screws are parallel to the large sides of the waveguide.

I start with the tuning screws all the way out, and tune the signal generator to find the resonant frequency – since the CNC machining is precise, the two cavities should be very close to the same frequency. This starting frequency is just below 24 GHz. Then I adjust the signal generator frequency higher until the output power drops perhaps 8 or 10 dB, and repeak with the two tuning screws at the new frequency. Repeat until the desired frequency, 24.048 or 24.192 GHz, is reached.

Then I manually tune the signal generator and record the power output to plot the response. If it is undercoupled or too narrow, the center coupling hole may be enlarged slightly to increase the coupling. On the other hand, if it is overcoupled, the end holes may be enlarged slightly to increase the loading. Slightly is perhaps 0.1 mm, or one size of US numbered drills.

If you don't have a tunable signal generator, just adjust both tuning screws together slowly until you find some output, then tune for maximum smoke.

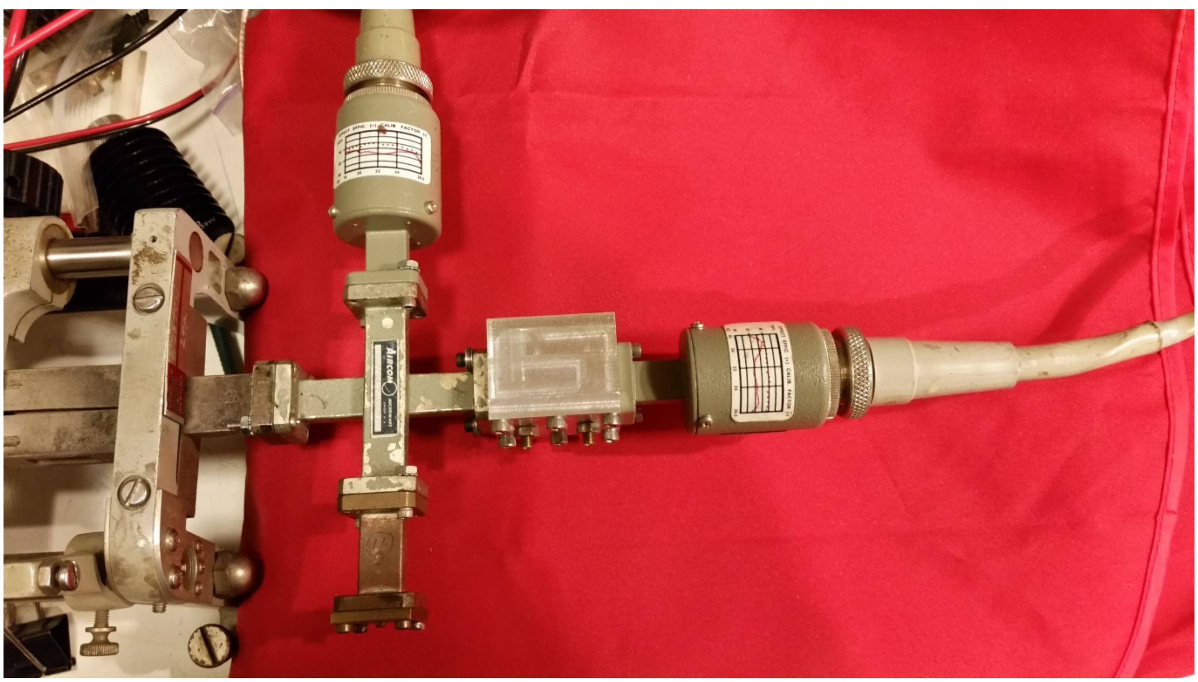


Figure 12 – Test setup for tuning filters

Single Cavity Resonator

One published source also shows a single resonator, which isn't as good a filter but is sometimes easier to make – probably not for these filters. However, it does make it easier to understand the loading of the input and output holes. Since I had two filters with one good cavity and a broken drill in the other, it was simply a matter of milling off a bad half to make a single cavity resonator.

I started out with very small input and output holes and made measurements with increasing hole diameters, always equal. The resulting bandwidths and losses at 24.192 GHz are shown in Table 2. Numbers are approximate since these were measured manually. For the largest hole size and widest bandwidth, the LO rejection at 24.048 GHz is about 25 dB, about half as much as a two-resonator filter.

Single Resonator

Hole		Bandwidth		Loss	
3.3	mm	5	MHz	12	dB
3.5	mm	7	MHz	4.5	dB
4.04	mm	16.5	MHz	1.5	dB
4.47	mm	34	MHz	0.5	dB

Table 2

From these numbers, we can again estimate the unloaded cavity Q_U at around 8000.

Summary – 24 GHz

The OE9PMJ filter is quite sharp with a steep skirt on the lower side good for low-side LO injection. For 24 GHz, it is sharper than necessary – a waveguide post filter is adequate and is much easier to build. However, for high-side LO injection, the rejection is much poorer – for a 24 GHz system with 432 MHz IF and high-side LO, there might be almost no image rejection.

Higher bands

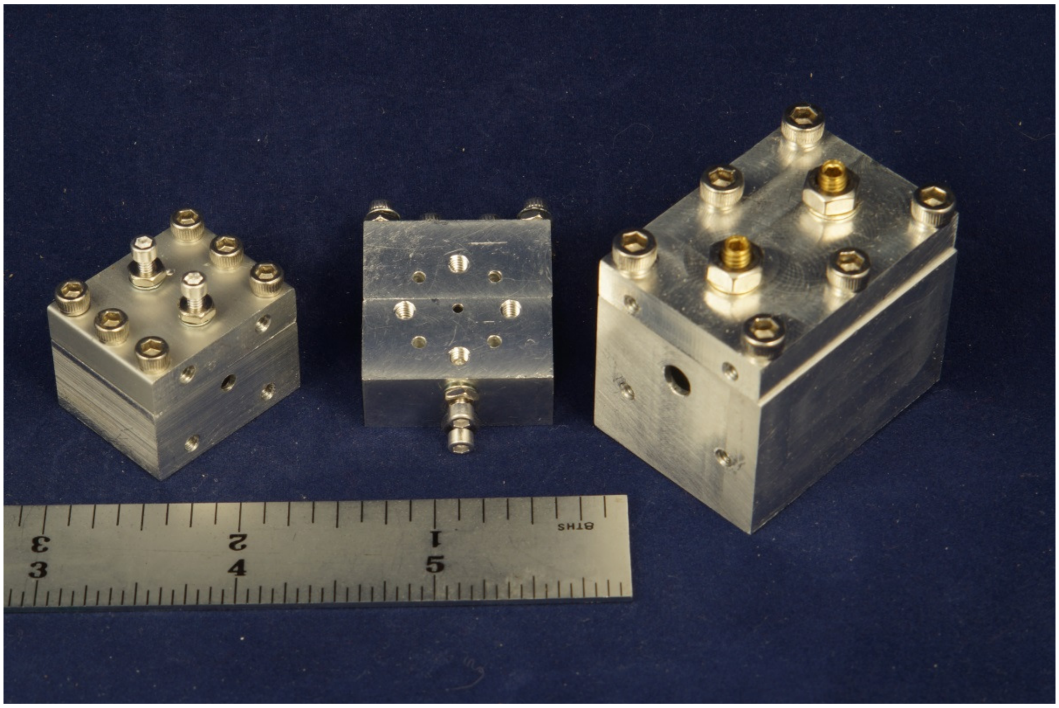


Figure 13 – OE9PMJ Filters for 47, 78, and 24 GHz

I had also simulated filters for 47 and 78 GHz when I had access to the **HFSS** software. Once the 24 GHz results were validated, I also machined filters for 47 GHz and 78 GHz. Figure 13 shows the filters for all three bands. Like the 24 GHz filters, the 47 GHz version has the cavities milled into the aluminum block and the tuning screws threaded into the cover plate. Figure 14 is an inside view.

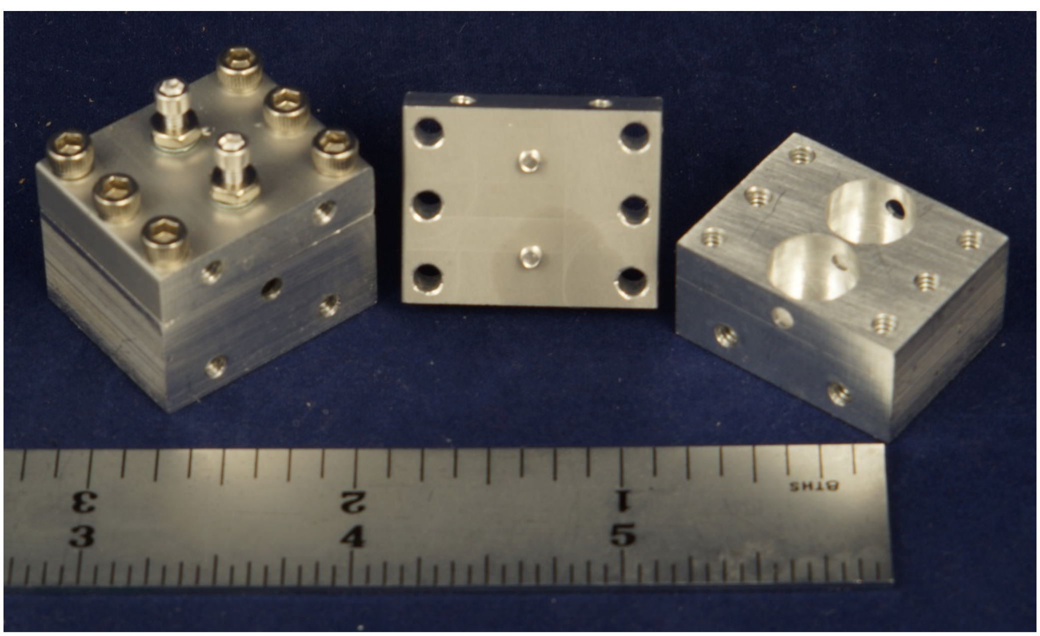


Figure 14 – 47 GHz OE9PMJ Filters showing construction

A simulation of the published filter dimensions for 47 GHz shows a response, in Figure 15, show in response similar to the 24 GHz filters in Figures 3 and 4. There is a very sharp response at the desired frequency for the TE_{011} mode, a broad response at a higher frequency for the TE_{311} mode, and probably the TE_{211} response at a much lower frequency, out of the simulation range.

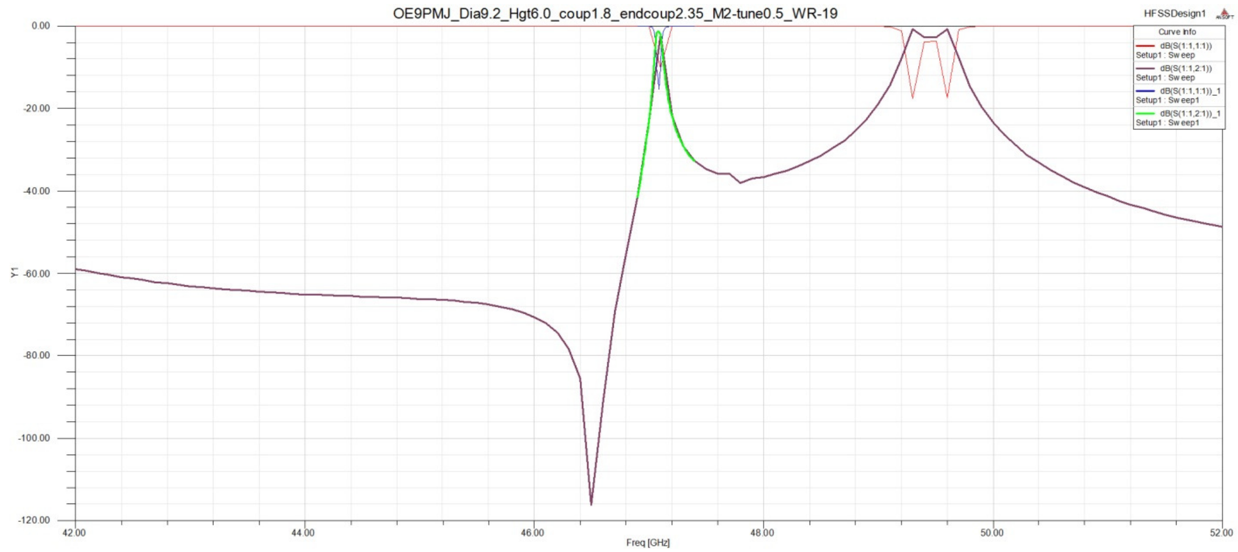


Figure 15 – Simulated response of OE9PMJ filter for 47 GHz

The published dimensions for these bands appear to be scaled up from the 24 GHz dimensions. A consequence is that the wall thickness between the cavities and at the ends becomes very thin, since it is only 1mm at 24 GHz. A perennial frustration for microwave engineers is that formulas and charts in the books always specify "for a thin wall," leaving the reader to guess how thin or thick is acceptable. Using the **HFSS** simulator, I tried slightly thicker walls and found that increasing the hole diameters slightly would compensate without any obvious ill effects. I made some 47 and 78 GHz filters with thicker walls to validate this as well.

I completed six filters for 47 GHz, with the dimensions shown in Table 3. Filters # 1 and 2 have 0.5mm thick walls between the cavities and at the ends, like the published dimensions. The rest have 0.75mm thick walls, with larger holes to compensate. The hole sizes were chosen to match good simulation results. All the filters have silver tuning screws with 2-56 threads except for #5 which has 2-56 brass screws.

47 GHz OE9PMJ Filter CouplingHoleDimensions

Filter #	Mid hole		Endholes	
1	1.8	mm	2.3	mm
2	2.03	mm	2.49	mm
3	1.98	mm	2.46	mm
4	2.03	mm	2.54	mm
5	2.16	mm	2.56	mm
6	2.03	mm	2.54	mm
Published	1.8	mm	2.2	mm

Table 3

The simulations suggested that the published dimensions produce an overcoupled response, with two peaks and about a 2dB dip between the peaks. Increasing the end hole dimension to 2.3mm flattened the passband as shown in Figure 16, and the measurement confirms this, with excellent correlation.

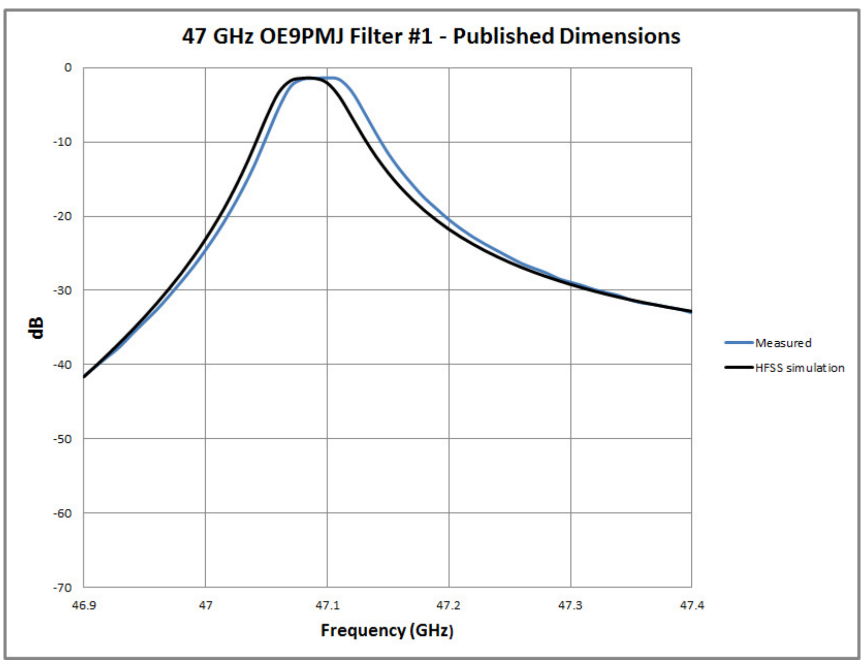


Figure 16 - 47 GHz Filter #1, simulation and measurement

I don't have any 47 GHz measurement capability, but I was able to use a Rohde and Schwarz ZVA67 VNA provided by Greg Bonaguide, WA1VUG, at the 2017 Eastern VHF/UHF Conference. The VNA only has 1mm coax connectors in and out, so I made WR-19 waveguide to coax transitions with small-pin SMA connectors – I couldn't find a source for K connectors. The VNA was only calibrated to the 1mm connectors, so measurements were made with two uncalibrated adapters at each end: 1mm coax to 3.5mm coax, and SMA to WR-19. A plot of the two waveguide adapters connected together is shown in Figure 17. Return Loss S11 is OK, and the insertion loss S21 is 2 dB or so total for the all the adapters.

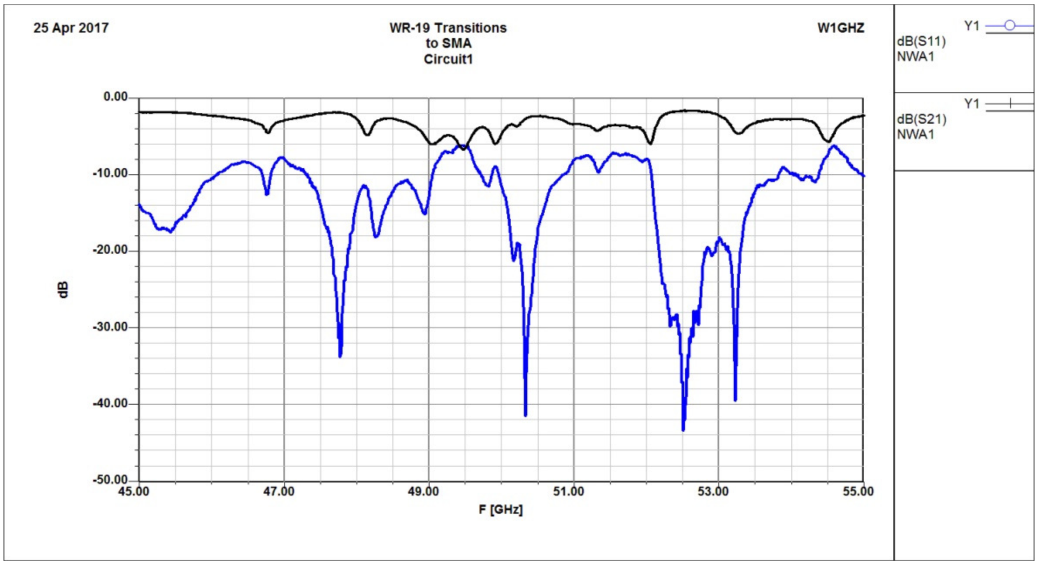


Figure 17 – Plot of the uncalibrated coax and waveguide adapters connected together

The measured insertion loss in Figure 16 and subsequent figures has the insertion loss in Figure 17 subtracted algebraically from the raw measurement – Figure 18 is an example. The difference is about 2.7 dB at 47.1 GHz. I did not attempt to correct the S11 plot. You may estimate for yourself the uncertainty in these measurements.

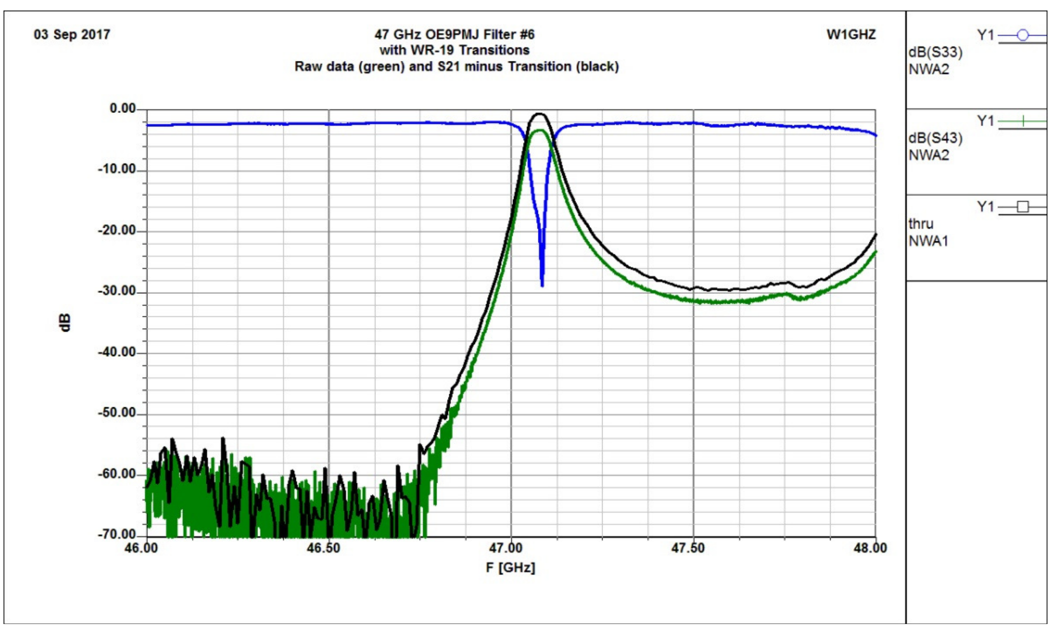


Figure 18 – 47 GHz filter raw data and insertion loss after subtracting transitions

All the 47 GHz filters are plotted together in Figure 19. Except for #4, all have excellent filter characteristics with low loss and good LO rejection for a 144 MHz IF. Filter #5, with the brass screws, has no more loss than the others, so the expense for the silver screws was unnecessary. As for filter #4, I don't remember whether it had a problem or whether I was did not tune it properly – I had very limited time with the VNA to tune and measure the filters.

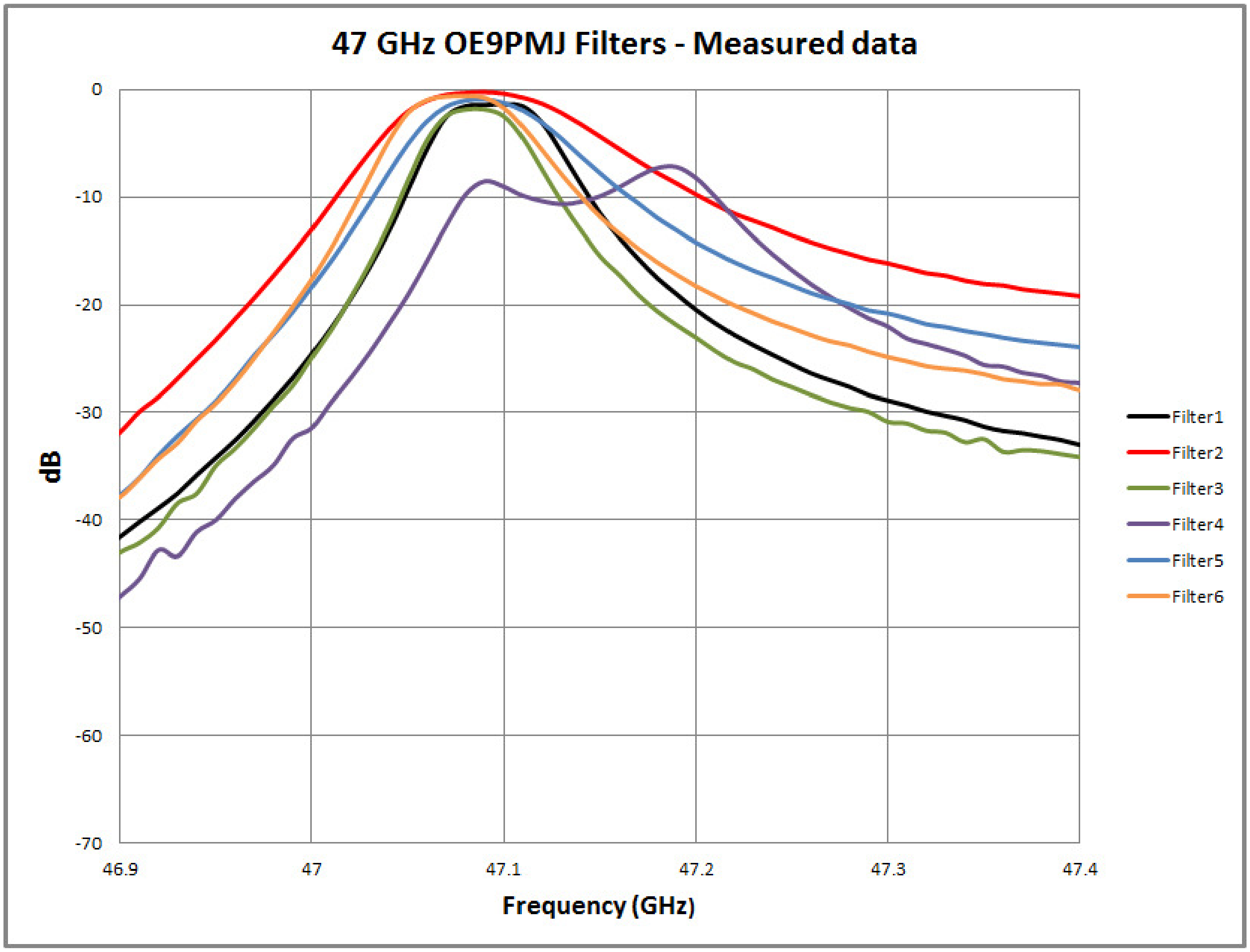


Figure 19 – Measured response of six filters for 47 GHz

A wider-band response for the six filters in Figure 18 shows results similar to the 24 GHz filters. All the filters have a steep, deep cutoff on the low-frequency side, but less rejection on the high side. The filters with larger holes have a wider passband but even less high-side rejection.

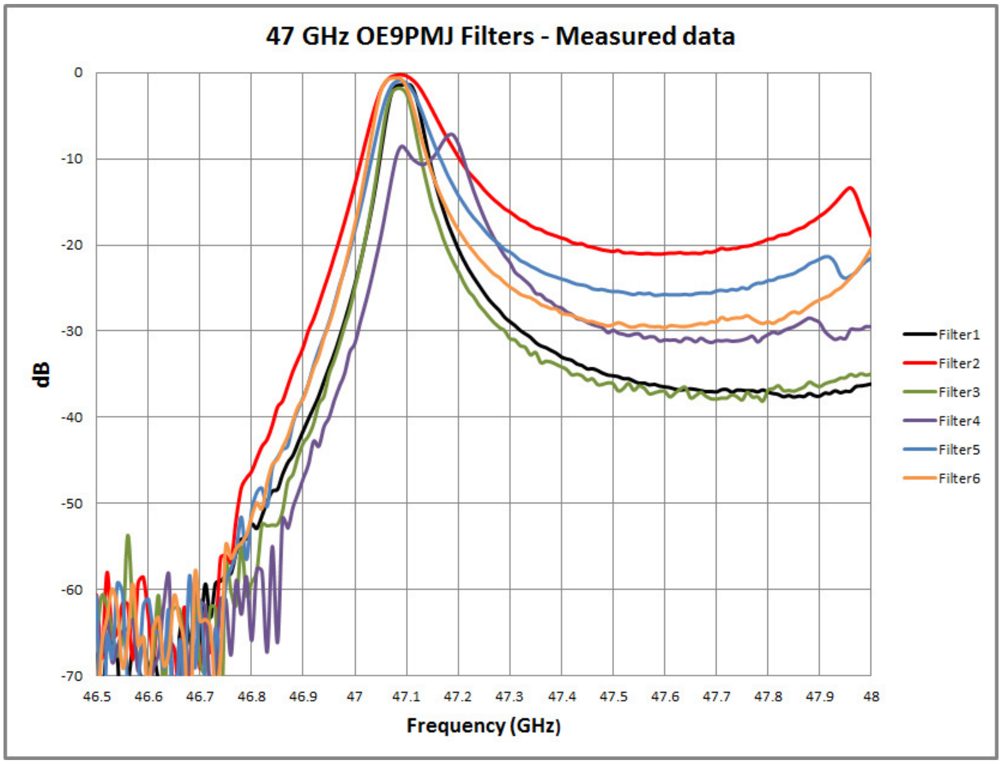


Figure 20 – Wideband Measured response of six filters for 47 GHz

An even wider band plot of one of the filters in Figure 21 shows a response comparable to the simulated response in Figure 15, with the narrow desired passband and the wider one at higher frequency. There is also a glitch between the two passbands like the one attributed to a tuning screw at 24 GHz.

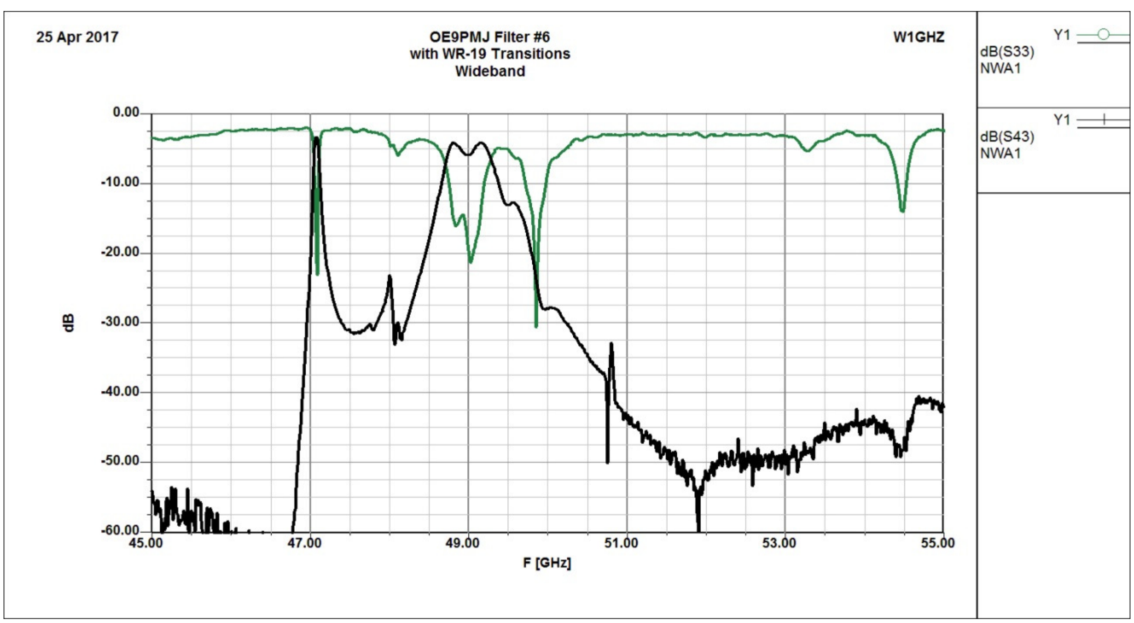


Figure 21 – Wideband raw data plot for 47 GHz OE9PMJ Filter

Thicker walls

Several of the filters were made with thicker walls, since I wasn't sure how thin a wall can be milled, especially the very thin ones for 78 GHz. At 47 GHz, the thick walls are 0.75mm vs 0.5mm for the published dimensions.

The first experiment is Filter #3, which has holes larger than the holes in Filter #1 by slightly less than the wall thickness. A comparison of the two filters is shown in Figure 22. Filter #3 is slightly undercoupled – it might be improved by making the center coupling hole slightly larger, to at least the wall thickness.

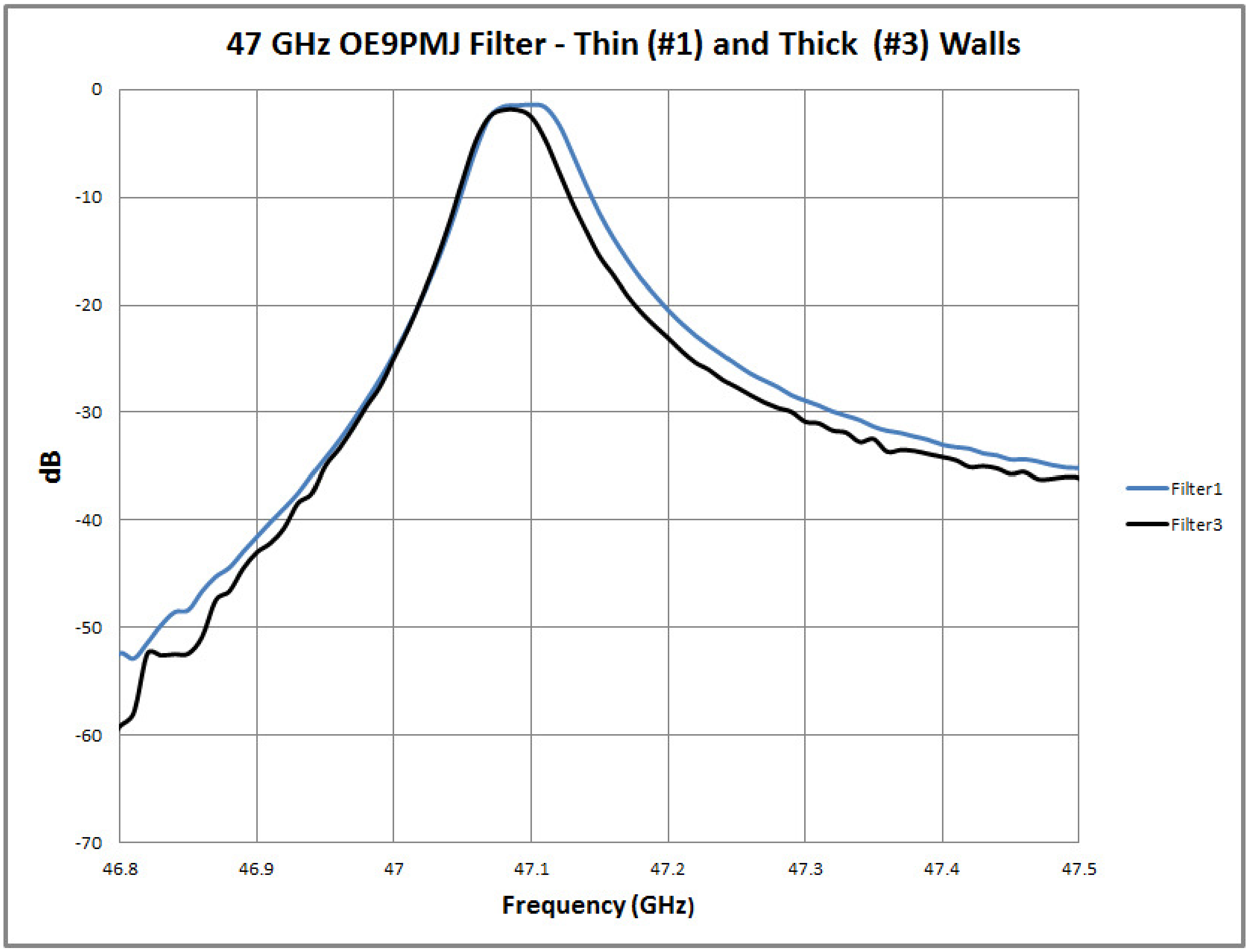


Figure 22 – Comparison of 47 GHz Filters with thick and thin coupling hole walls

Filter #3 shows good correlation between simulation and measurement in Figure 23, as does Filter #6 in Figure 25. This confirms that simulation is able to predict the performance with both thick and thin walls, and that the wall thickness may be increased a modest amount without hurting performance. It appears that the hole size should be increased by roughly the same distance as the increase in wall thickness, at least as a starting point.

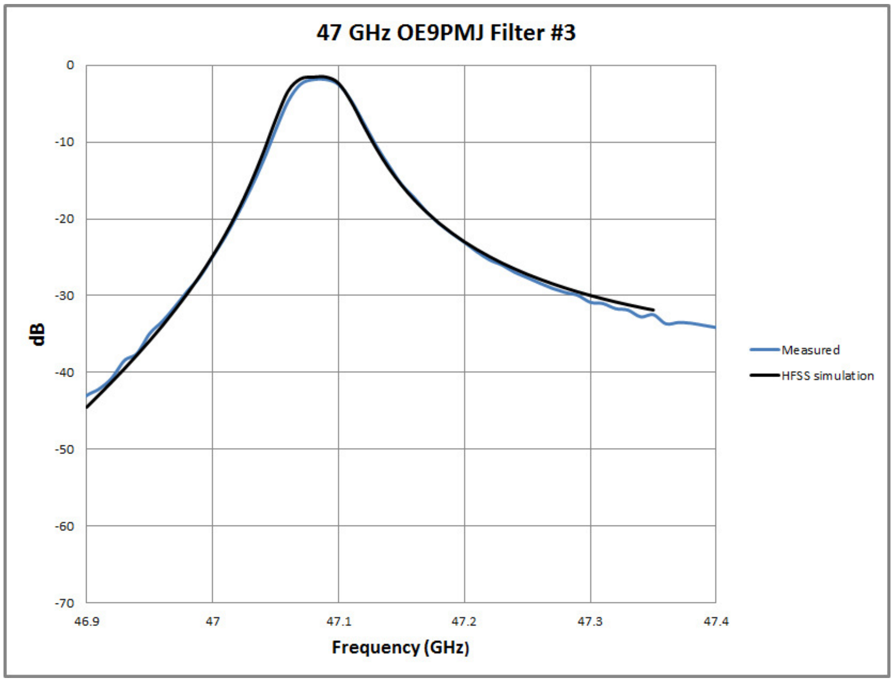


Figure 23 - 47 GHz Filter #3, simulation and measurement

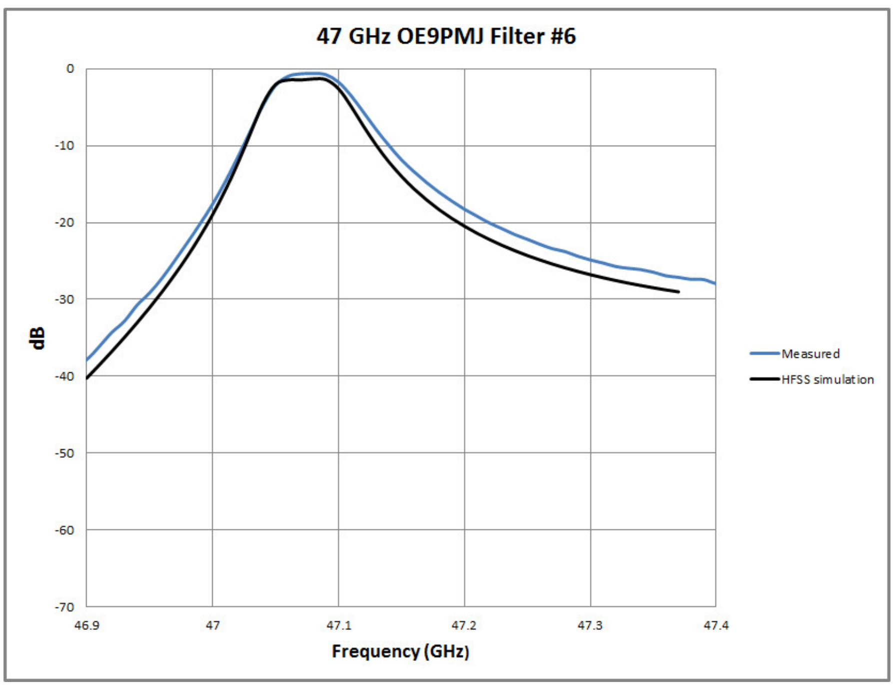


Figure 24 - 47 GHz Filter #6, simulation and measurement

However, when the hole sizes are increased further, to widen the bandwidth, correlation between simulation and measurement is not quite as good, but still reasonable. This is the case for both thin walls, for Filter #2 in Figure 25, and thick walls, for Filter #5 in Figure 26. The advantage of the wider bandwidth is that these filters have lower loss, as can be seen in Figure 19.

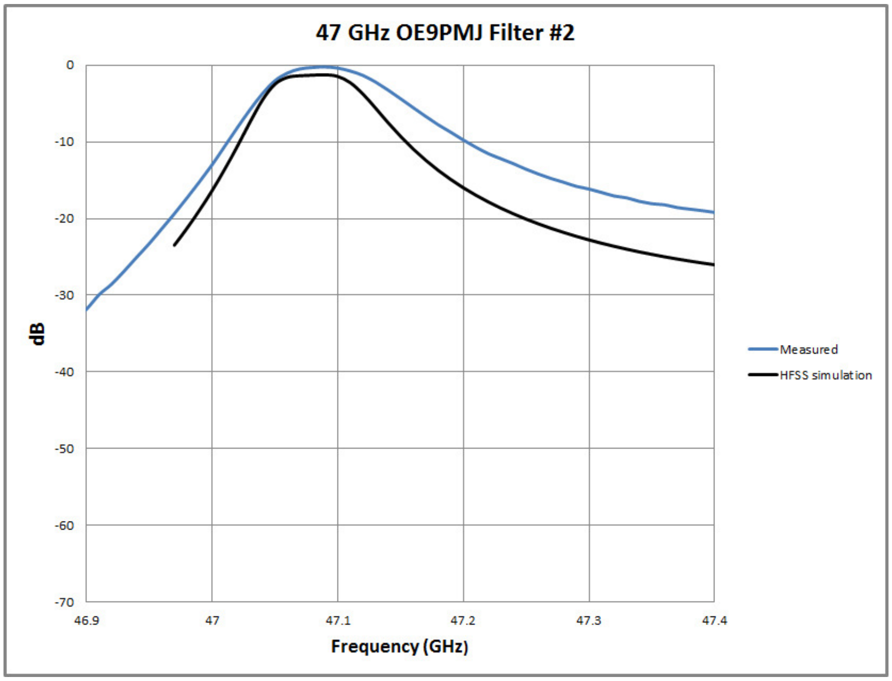


Figure 25 - 47 GHz Filter #1, simulation and measurement

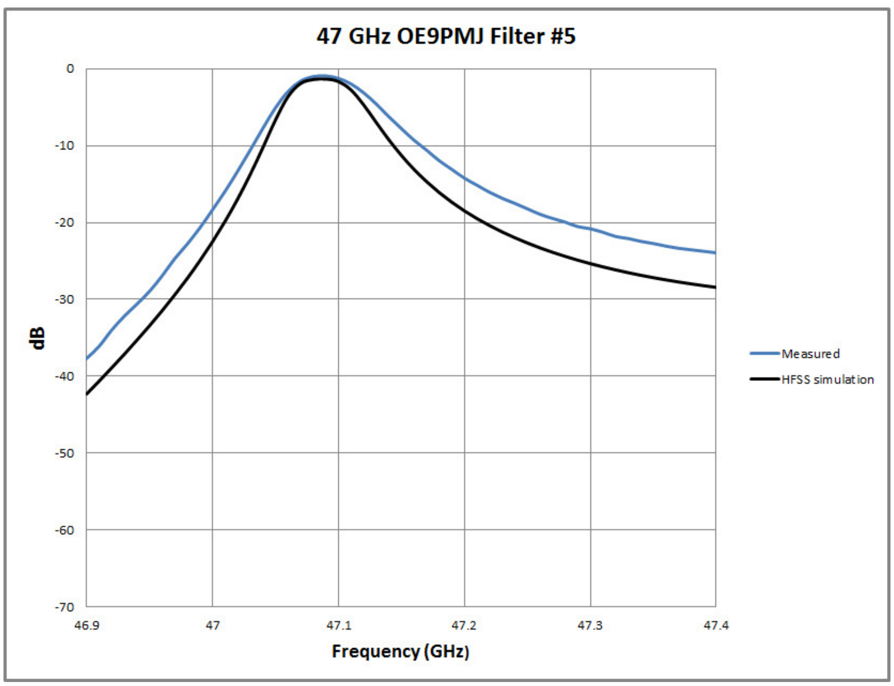


Figure 26 - 47 GHz Filter #5 (thick wall), simulation and measurement

Summary – 47 GHz

The OE9PMJ filters for is quite sharp with a steep skirt on the lower side good for low-side LO injection. I know of no other filter configuration capable of being made narrow enough for a 144 MHz IF at 47 GHz.

78 GHz

The previous results verify that it is possible to build OE9PMJ filters that match simulated results and work well at 24 and 47 GHz, so I was confident that 78 GHz filters would work also. I machined six filters for 78 GHz – Figure 27 shows the construction. These are very small, and there is very little meat left for screw threads, particularly the waveguide screws.

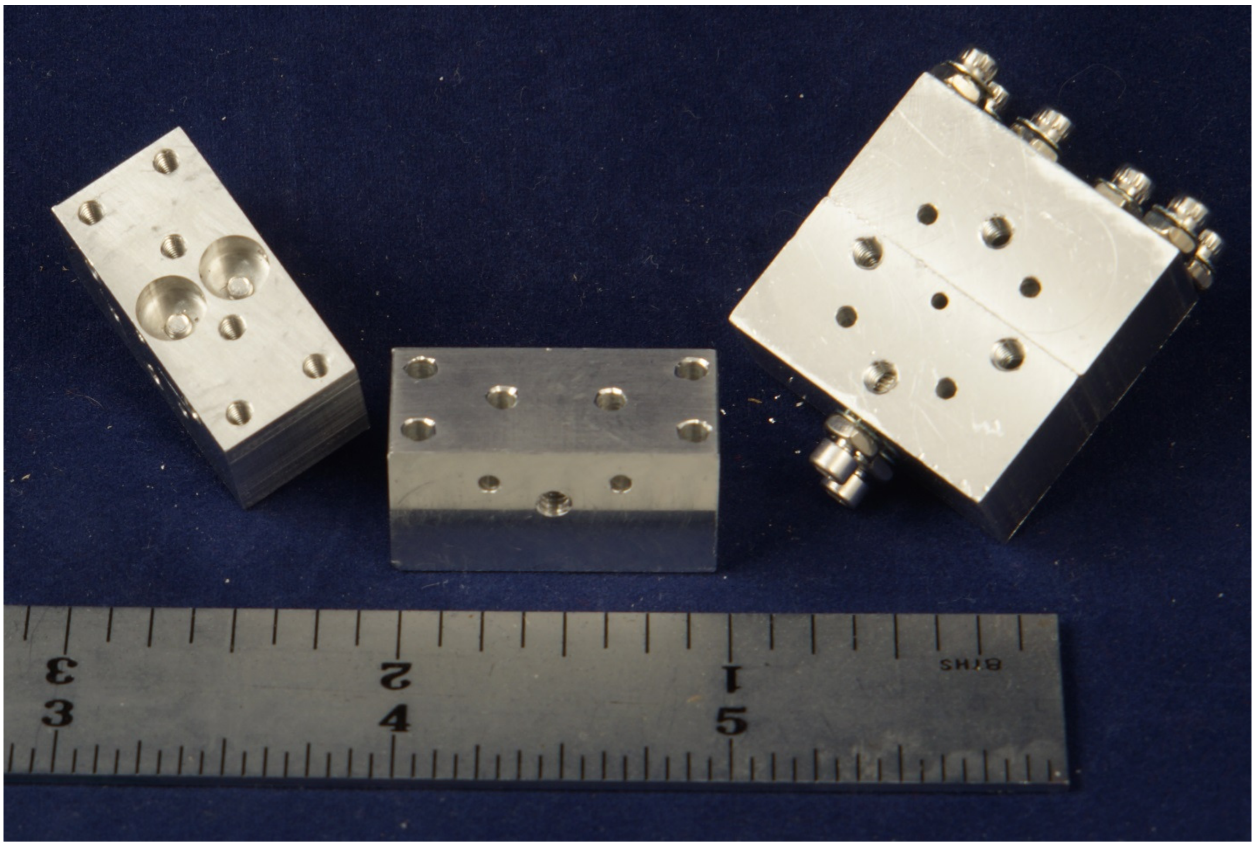


Figure 27 – OE9PMJ filter for 78 GHz showing construction

Testing at 78 GHz is another problem. Tom Williams, WA1MBA, has a scalar network analyzer with waveguide ports covering this range, so I sent him the first prototype to test. He had difficulty tuning it, so I arranged to visit and spend a day tuning all the filters. I had also acquired a set of miniature pin gages to accurately measure the small hole diameters.

We adjusted the hole sizes in the first filter, cleaned it carefully, and adjusted the tuning, with the result shown in Figure 28. The loss is a bit high but still usable, and the filter response is pretty good.

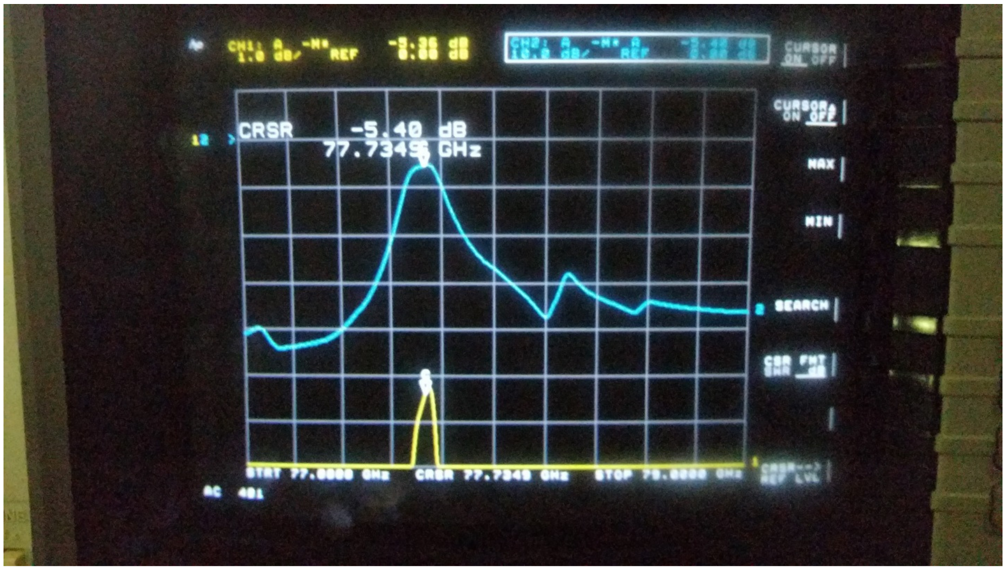


Figure 28 – Performance of 78 GHz OE9PMJ Filter #1

We then adjusted the hole sizes in the other five filters, cleaned and assembled them, and tested them. None of them could be tuned to frequency. Each one looked good before the tuning screws were inserted in the cavities, like Figure 29, but at a frequency below the band. Inserting the tuning screws raised the frequency, as expected, but also produced a notch in the response so the loss increased as tuning approached 78.2 GHz and the passband shape was distorted. My suspicion is that the tuning screw diameter is too large and produces a notch like the one produced by large screws at 24 GHz, only much worse, so that the bandpass is affected.

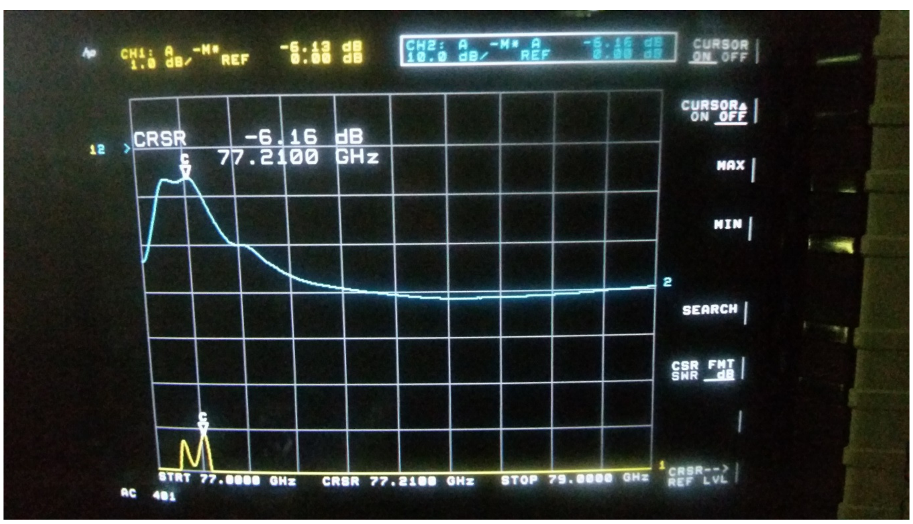


Figure 29 – Response of 78 GHz Filter #3 without tuning screws inserted in cavity

Since the tuning screws were not working, another way to raise the frequency is to reduce the size of the cavity. We sanded off perhaps 0.1mm with very fine sandpaper, then cleaned and reassembled. Now we were at least able to tune for a usable bandpass, but with high loss, shown in Figure 30. We considered sanding enough to move the passband up to 78.2 GHz, but that would take a lot of work and would make the coupling holes asymmetrical in the cavities.

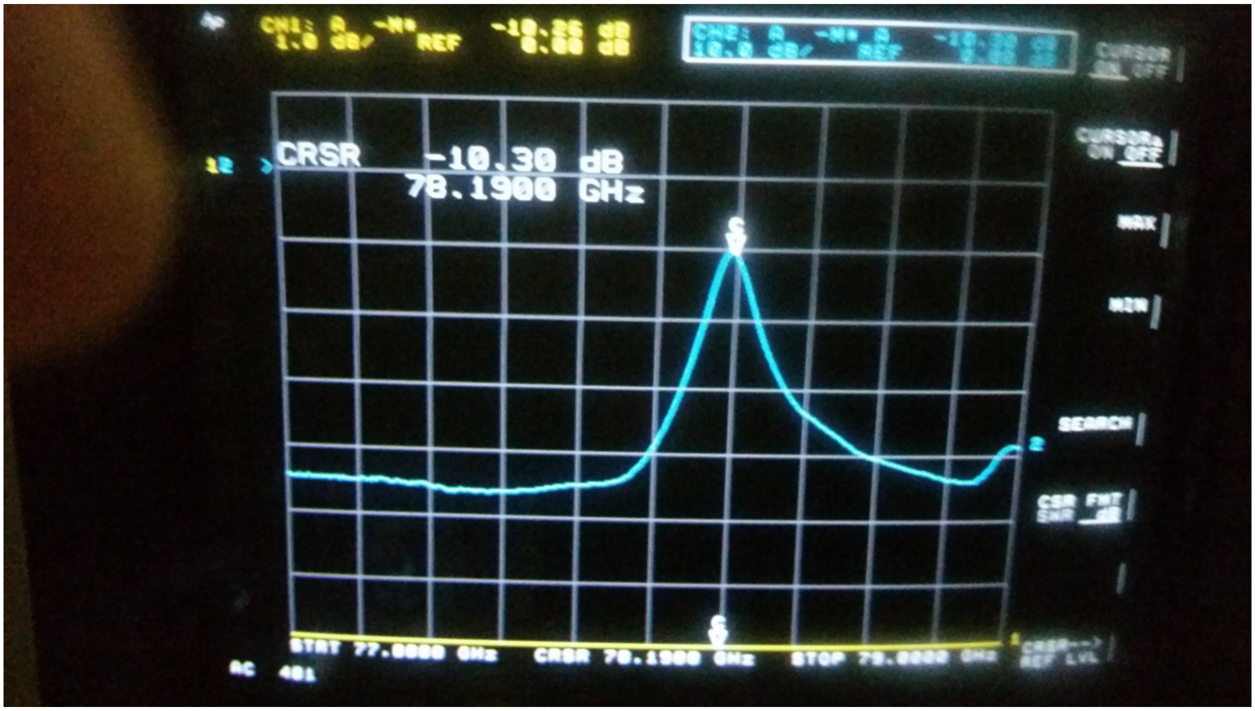


Figure 30 – 78 GHz Filter #2 after sanding and retuning

The filter in Figure 30 does have a use – our 78 GHz source for MDS testing previously had no filtering for image rejection. Several of the 78 GHz systems only have bare mixers, so they also have no image rejection, and would find two signals during testing, not necessarily at the same strength. Adding a filter to the MDS source will assure that the signal received is the correct sideband.

Photos I have seen of OE9PMJ filter for 78 GHz use commercial microwave tuning screws, with no thread inside the cavity. I didn't have any of these, and ordinary screws work well at the lower frequencies so I went ahead with silver screws. Obviously, we have found the limits for ordinary screws, so the next step is to acquire some microwave tuning screws and modify these filters or make new filters.

Summary – 78 GHz

The one successful filter demonstrates that it is possible to make an OE9PMG filter for 78 GHz, and this one is going in a system. More work is required to make them reproducible.

Conclusion

The OE9PMJ filter is quite sharp with a steep skirt on the lower side good for low-side LO injection and has low loss. For 24 GHz, it is sharper than necessary – a waveguide post filter is adequate and is much easier to build. For 47 GHz, it provides excellent performance where there are few viable alternatives. At 78 GHz, performance is also good, but construction details need work. However, for high-side LO injection, the rejection is much poorer – for a 24 GHz system with 432 MHz IF and high-side LO, there might be almost no image rejection.

The filters are difficult to build even with CNC machinery, requiring 16 tapped holes plus precision coupling holes. I see that DB6NT[11] now offers these filters for 24 and 47 GHz for a price at which I would not even consider making them. For 78 GHz, DL2AM[12] offers these filters at a higher price, but I can assure you that is also a bargain.

One lovely advantage of CNC machining is that all the screw holes line up exactly, with no filing required. I have never had that happen before.

Acknowledgements

I would like to thank Tom Bishop of *The Foundry* makerspace in Lyndonville, VT for all his help in showing me the basics of CNC machining.

I would also like to thank Greg Bonaguide, WA1VUG, of Rohde & Schwarz, for providing outstanding test equipment at many VHF conferences to enable accurate measurements at the higher microwave frequencies, and Tom Williams for encouragement and help with 78 GHz measurements.

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