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Waveguide Filters You Can Build—*and* Tune Part 2 Waveguide Post Filters

In this second of his three part series, the author introduces us to a handy technique for waveguide filter design and construction.

In all but the simplest microwave systems, filtering is needed, to eliminate both undesired radiation and unwanted interference. For most amateurs, this means copying some published filter. Simple filters often have inadequate performance, while more complex ones can be difficult — in understanding, fabrication or tuning. Simple waveguide filters can be designed to provide excellent performance, using available software and fabricated in a modestly equipped amateur workshop.

Waveguides have very low loss because the energy is contained inside the guide, in air, rather than traveling in a conductor. A resonant length of waveguide, with very low loss, thus forms a high-*Q* resonator; for X-band waveguide, the theoretical *Q* approaches 10,000.[1] This high unloaded *Q* enables the design of very sharp filters with low loss. Since only metal and air are involved, and the waveguide dimensions are tightly controlled, results are quite predictable.

If you need a review of filter terminology and design basics, please see Part 1 of this series, "Filter Tour," in the Nov/Dec 2009 issue of *QEX* for a brief filter overview with minimal mathematics.

The waveguide filters to be described here are direct-coupled resonator filters.[2] The *WGFIL* program by Dennis Sweeney, WA4LPR, does an excellent job of designing either *iris* or *post* filters.[3] An iris filter is more intuitive — each waveguide iris is a perpendicular wall across the guide, so that two irises create a resonant cavity in a section of waveguide. A small hole in each iris provides coupling out of the cavity, with coupling controlled by the size of the hole. Fabrication involves cutting very thin slots across the waveguide and soldering an iris in each slot.

Waveguide post filters are much easier to

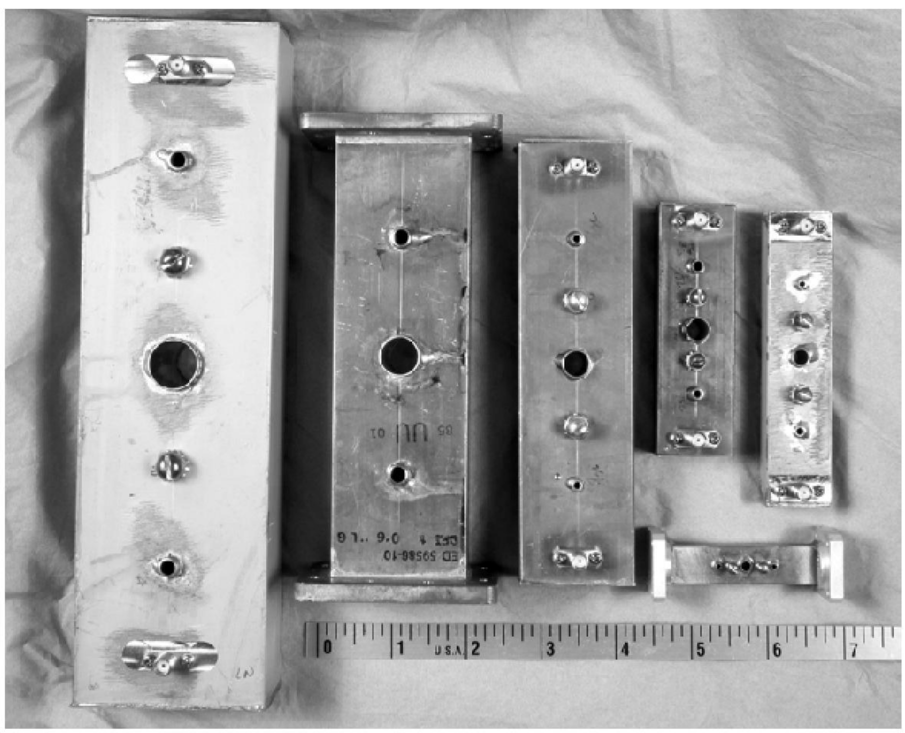

Figure 1 — This photo shows waveguide post filters in many sizes of waveguide.

[1]Notes appear on page 25.

build — just drill a hole through the center of the wide dimension, insert a post all the way through, and solder both ends. Design is a bit more complicated: a post is a shunt inductance in the waveguide, which acts both as a cavity wall and as an impedance inverter, coupling the adjacent cavities. A larger post blocks more of the waveguide, so coupling is reduced by larger posts. The most difficult calculation is the distance between posts for a desired resonant frequency, since the diameter of the post also affects the resonance. The *WGFIL* program does an excellent job here, and I have made several filters that perform exactly as expected; a few of them are shown in Figure 1. All my successful filters are tabulated in Table 1 for those who prefer to duplicate a proven design.

Since a waveguide filter is not hard to build, and results are predictable, there is a temptation to design a really high performance filter, with multiple sections. The filter may be easy to build, but it is really difficult to tune — we must allow for some tuning to compensate for construction tolerances. A multi-section filter has extremely good stop-band rejection, and a mistuned filter has *no* passband — if nothing detectable gets through, then it is nearly impossible to do any tuning. I have a nice six-section filter that I built for 24 GHz that looks great on the computer, but I've never been able to tune it properly, even with a fancy Vector Network Analyzer (VNA).

Some very good waveguide post filter designs have been published — I can recommend filters by N6GN for 10 GHz and 5.76 GHz.[4, 5] These are three section (four-post) filters with good performance that can be built and tuned by a reasonably well-equipped microwaver. Figure 2 shows the performance of two 10 GHz filters built and tuned in my basement — all the data shown is measured with a nice Rohde & Schwarz *ZVA* VNA (**www.rohde-schwarz.com**) set up by Greg Bonaguide, WA1VUG, at the Eastern VHF/UHF Conference in 2008.

The easy-to-build waveguide post filters use surplus waveguide and posts of brass or copper hobby tubing, available at some hardware stores and hobby shops, or online from **www.smallparts.com**. The hobby tubing comes in increments of 1⁄32 inch diameters, so only a few of the smallest sizes are suitable for the higher microwave bands, particularly 10 GHz and 24 GHz. Using stock sizes severely limits filter design to a very few bandwidths, particularly for multiple-section filters that require several different post diameters.

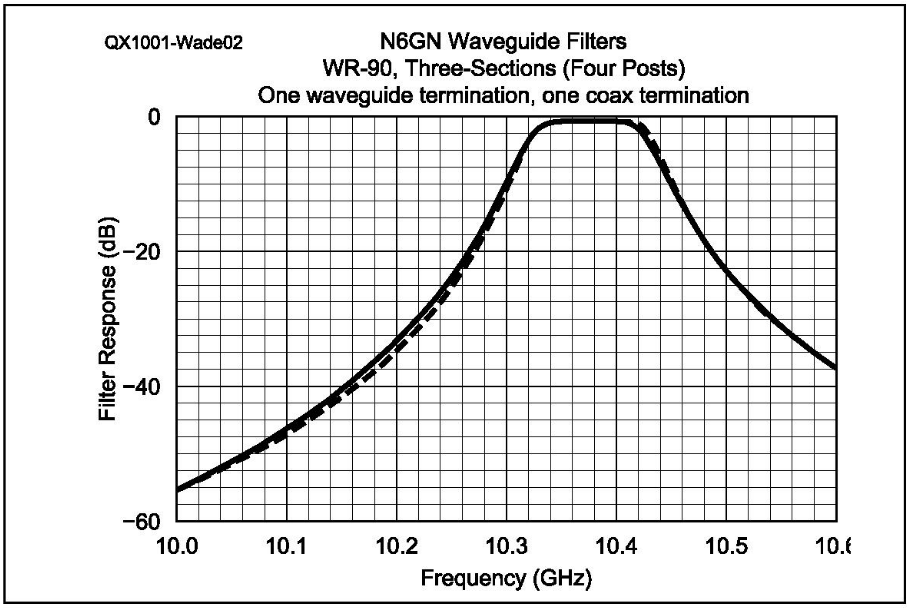

Figure 2 — A graph of the performance of N6GN 10 GHz waveguide filters.

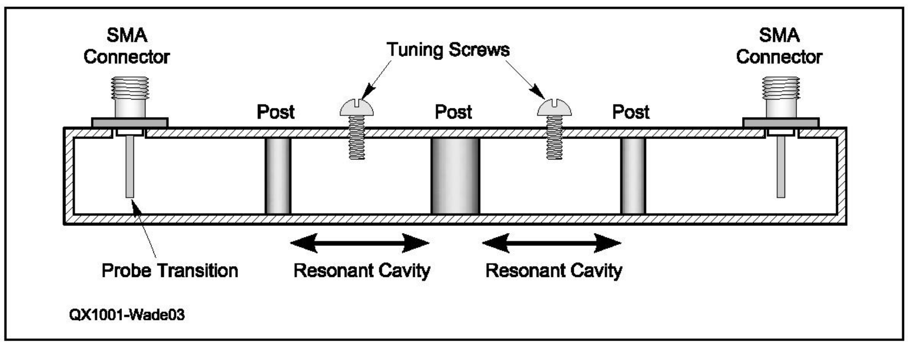

Figure 3 — This sketch represents a three-post (two-section) waveguide filter.

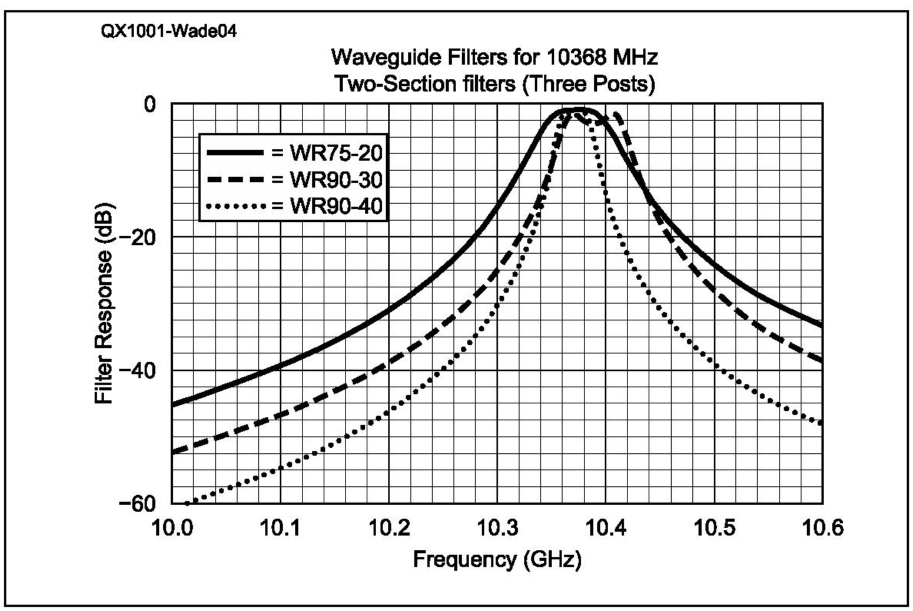

Figure 4 — The performance of two-section (three-post) waveguide filters for 10 GHz are shown in this graph.

Simple Double-Tuned Filters

While I was playing with *WGFIL* trying to find a better filter using stock tubing diameters, it occurred to me that hams don't need multiple-section filters with steep skirts. Our main requirement is to reject LO leakage and mixer images. The most popular intermediate frequency is 144 MHz, so a usable filter needs perhaps 30 dB of rejection at a frequency 144 MHz away from the operating frequency, like the ones shown in Figure 2. A balanced mixer provides some additional rejection, and the image frequency, twice as far removed, will be further down.

This requirement doesn't seem too difficult. Perhaps something as simple as a double-tuned filter would be adequate. It could be a narrow, high-Q filter, because waveguide has low loss and a double-tuned filter has only two tuning adjustments, and they should be identical. Some trial runs with *WGFIL* for a two-section (three post) filter suggested that several possibilities existed using the available hobby brass. Figure 3 is a sketch showing the simplicity of these filters. This sketch includes integral waveguide-to-coax transitions.

I did a bit of simulation using the Ansoft *HFSS* electromagnetic software, then built a couple of filters for 5760 and 10,368 MHz.[6] These worked so well that I tried some other waveguide sizes and frequencies. Measured results are shown in Figure 4 for 10,368 MHz, with filters in both WR-90 and WR-75 waveguide, with different bandwidths. All provide adequate LO rejection for a 144 MHz IF at 10,368 MHz, with about 0.7 dB of loss at the operating frequency. The narrower two, WR75-20, with 20 MHz bandwidth, and WR90-30, with 30 MHz bandwidth, appear over-coupled. The latter one is tuned to one of the peaks, the one providing best rejection, rather than centered. We shall see later how to adjust a filter design for coupling that yields a flatter response.

Figure 5 plots three filters for 5760 MHz, in two different waveguides, WR-137 and WR-159, with different bandwidths. All of these provide at least 35 dB of LO rejection for a 144 MHz IF, at 5760 MHz, with about 0.5 dB of loss at the operating frequency. The version in WR-159 waveguide is slightly overcoupled, and tuned to one of the peaks, rather than centered.

Waveguide filters for 3456 MHz are relatively large, but provide excellent performance, as shown in Figure 6. Loss of these filters is less than ¼ dB, with a flat response, and LO rejection for a 144 MHz IF is more than 30 dB.

All of these two-section filters were easily tuned using basement test equipment, since there are only two tuning screws, and the screws should have identical settings. Also, the dimensions were chosen for ease of tuning, so that tuning would only require a small penetration by the tuning screws.

Over-Coupled Filters

The response of most of these filters has a nice flat top, with reasonably steep skirt — an ideal Maximally-flat, or Butterworth,

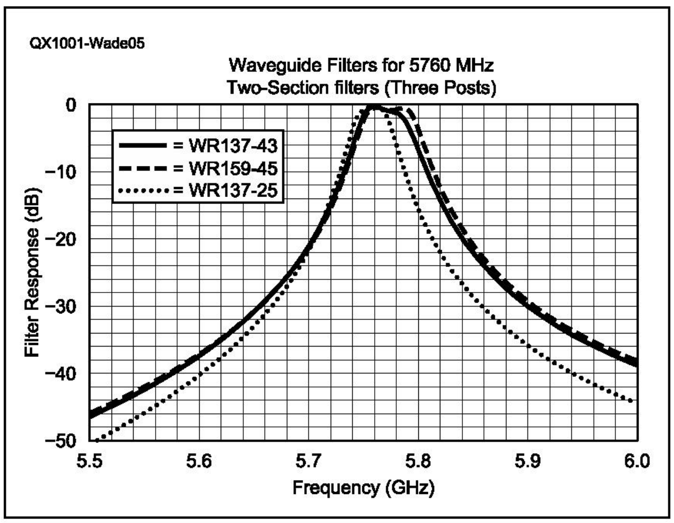

Figure 5 — This graph shows the performance of two-section (three-post) waveguide filters for 5760 MHz.

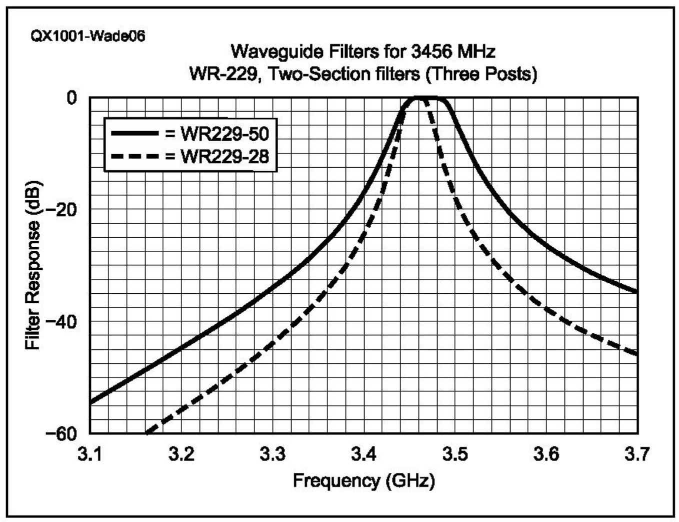

Figure 6 — The performance of two-section (three-post) waveguide filters for 3456 MHz are shown in this graph.

Table 1

Three-Post Waveguide Filters W1GHZ 2008

Waveguide	*Frequency (MHz)*	*Bandwidth (MHz)*	*End Post Diam (Inches)*	*Mid Post Diam (Inches)*	*Spacing (Inches)*	*Data*	*F - 144 (dB)*
WR-75	10368	20	0.125	0.250	0.950	WR75-3-20	–42
WR-90	10368	30	0.188	0.313	0.860	WR90-3-30	–34
WR-90	10368	40	0.156	0.313	0.830	WR90-3-40	–28
WR-137	5760	25	0.188	0.406	1.620	WR137-3-25	–41
WR-137	5760	43	0.156	0.375	1.600	WR137-3-43	–34
WR-159	5760	45	0.250	0.500	1.480	WR159-3-45	–33
WR-187	3456	7	0.250	0.438	3.000	(not built)	–50
WR-229	3456	50	0.188	0.500	2.500	WR229-3-50	–33
WR-229	3456	28	0.250	0.625	2.540	WR229-3-28	–41
WR-42	24192	140	0.094	0.156	0.360	WR42-3-140	–15
With Coupling Screw							
WR-75	10368	20	0.125	0.281	0.970	WR75-3c-20	–45
WR-75	10368	42	0.094	0.250	0.940	WR75-3c-42	
WR-42c	24192	70	0.094	0.188	0.375	WR42-3c-70c	–20

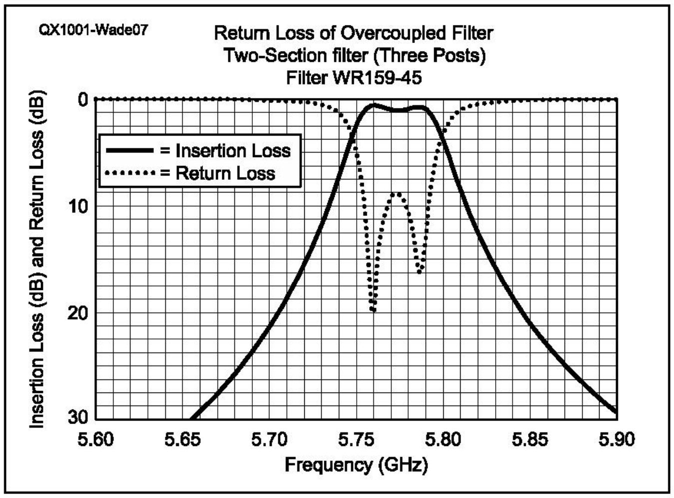

Figure 7 —This graph illustrates the double-humped response of an overcoupled waveguide filter.

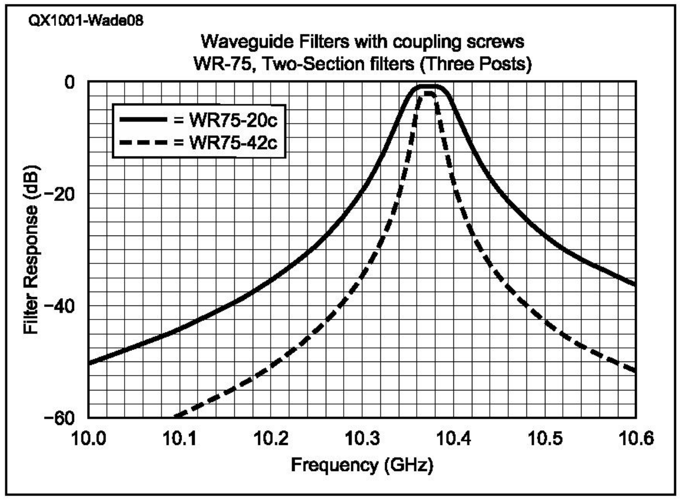

Figure 8 —The performance of waveguide post filters with coupling screws, adjusted for a flat response are shown in this graph.

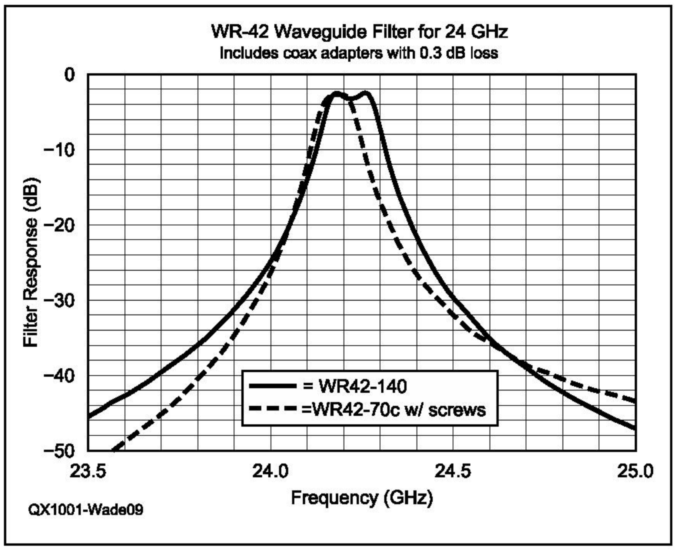

Figure 9 —This graph shows the performance of two-section (three-post) waveguide filters for 24 GHz, with and without a coupling screw.

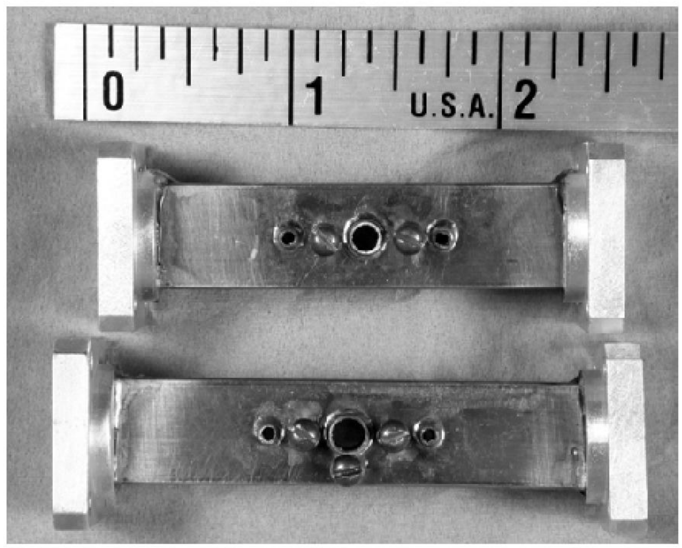

Figure 10 —This photo shows three-post waveguide filters for 24 GHz, in WR-42 waveguide.

filter. A couple of them show an overcoupled response, with a dip in the middle, however. These are a little harder to tune, since it requires picking the hump that gives the best LO rejection, and adjusting accordingly. The return loss is particularly sensitive to overcoupling; in Figure 7, the return loss is very good at the hump frequencies, but not as good in between. With ideal coupling, the return loss would be good over the whole passband. The *WGFIL* calculations are pretty good, but not perfect, especially for larger post diameters; that's why it gives a warning when the posts are bigger than ¼ of the waveguide width. As a result, we don't always get perfect coupling, especially when we round off the diameter to the nearest ⅓₂ of an inch.

I really wanted to make a reproducible 24 GHz filter, since I don't know of any that have been published. Trial runs with *WGFIL* weren't as promising, since only two or three sizes of hobby tubing are small enough, and I only found one promising combination. I considered using AWG wire sizes — copper wire is readily available — but the diameters weren't right. Some commercial filters use multiple small posts rather than a large one, but a bit of research didn't find any simple answers for designing them.

I recalled that some commercial filters have an extra screw next to each post, and I wondered if that varies the coupling. I went back to *HFSS* to find out. What I found was that the extra screw increases the coupling, in effect making the post *smaller*. This was the answer! I also found that the coupling screw must be inserted a long way, nearly half the waveguide height, to have a significant effect, so that small adjustments should be easy. I designed and built two more 10 GHz filters in WR-75 waveguide, with slightly oversize center posts, to try out the coupling screw. The coupling screw should decrease the effective size of the center post to adjust the coupling to the desired response. It worked perfectly, as shown in Figure 8. Both filters are adjusted for a flat response and centered on the operating frequency. The wider one, with 42 MHz bandwidth, has lower loss, about 0.75 dB. The narrow one, with 20 MHz bandwidth, has higher loss (about 2 dB) but is sharp enough to provide about 20 dB of LO rejection for a 30 MHz IF at 10,368 MHz. It is not surprising that the sharper filter has more loss, since a higher loaded *Q* is needed for the narrower bandwidth.

The coupling screw is next to the center post, halfway between the post and the side wall of the waveguide. While it would be possible to put a coupling screw next to the other posts and make them adjustable also, tuning would no longer be straightforward. For the simple three-post filters, it is unnecessary, and each screw adds a small additional loss.

Then I made two filters for 24 GHz, in WR-42 waveguide. One was the best combination of available post diameters I could find, while the other has an oversize center post and a coupling screw. The results are shown in Figure 9. Both filters are sharp enough to use for a 144 MHz IF at 24 GHz. The lower one, with the coupling screw, has a nice flat response; the other is slightly over-coupled and has a bandwidth slightly wider than expected as a result. Each has about 2.5 dB of loss. That's not bad for a sharp filter at 24 GHz. These filters were tuned up at a single frequency, 24.192 GHz, since I don't have a sweeper for 24 GHz. The plotted data was later measured with the VNA without any retuning. Figure 10 is a photo of the 24 GHz filters.

With the addition of the coupling screw, tuning these filters becomes very easy. Starting with all screws all the way out, the two tuning screws are slowly inserted simultaneously (turn one, then the other the same amount) until some output is found. Then peak the output. Since the response is under-coupled without the coupling screw inserted, there will only be a single peak. Next, insert the center coupling screw; the output will slowly increase, then start to decrease as the response becomes over-coupled with a dip in the middle. Backing the screw out to the peak yields the desired flat response. A final trim probably won't make much difference.

The tuning progression is illustrated in Figure 11, a simulation of the WR75-42c filter. The curve on the right shows the response before tuning, with no screws present. The filter is tuned to some higher frequency. The tuning screws alone move the response down to the desired frequency, yielding the curve labeled "No Coupling Screw." Then the coupling screw is inserted; at 0.100 inch deep, the response flattens and the loss is reduced. Inserting the screw farther produces an over-coupled response, first with a slight dip at the operating frequency, and then a huge dip if insertion is continued. Most of us would back up when the output started to dip.

Some of the filters in Figures 4 and 5, as well as one of the 24 GHz filters, show an over-coupled response. These designs could be improved by making the center post one size (1/32 inch) larger and adding a coupling screw next to the center post. Then they could be adjusted for a flat response.

End Termination

In a waveguide system, these filters only need waveguide flanges to connect. Most systems for 10 GHz and lower frequencies use semi-rigid coax for interconnections, however, so a coax-to-waveguide transition is needed. The most compact and convenient transitions are integral to the filters, one at each end. I use the transition dimensions that I published in *QEX*, spacing the transition probe at least one waveguide width from the end post.[7] A matching screw is neither needed nor desired. If the dimensions are correct, the return loss will be very good. Of course, a badly mismatched component following a filter can upset the filter response, but the place to correct this is not in the filter.

The filters with performance plotted in Figure 2 provide a good comparison. One has integral coax transitions, while the other has waveguide flanges and was tested with external transitions. Any slight difference in performance is probably due to construction tolerances and tuning difference.

Construction

These filters are physically simple to build. The posts, tuning screws and coax connectors are all on the centerline of the broad dimension of the waveguide. Important points are that the posts be accurately centered on the centerline and that the holes for the posts are snug, so that a minimal amount of solder is needed to make a good connection.

The highest frequency for each resonator is set by the distance between the posts. A tuning screw can only lower the frequency. The distances calculated by *WGFIL* are with no tuning screw, so they should be reduced slightly to raise the resonant frequency and allow a small amount of tuning. I estimate that I can locate a hole within 10 mils (0.25 mm), so I reduce the distance by 10 to 15 mils. Adjust the dimensions for your filters according to the tolerances you can achieve. With only a small reduction, a very few turns penetration of the tuning screw is needed. A larger reduction in spacing will require more penetration, increasing losses and making the tuning more critical.

I measure and mark the centerline and hole positions with a cheap caliper, either dial or digital, using the points as a scribe (this would be criminal abuse with a quality tool). Then the holes are marked with a center punch and started with a small center drill. A drill press is essential for drilling the holes. For accurate, round holes that fit the posts snugly, I find that DeWalt "Pilot Point" drill bits work well; Black & Decker "Bullet" drills are nearly as good. For larger holes, Unibit step drills work very well. A small pilot hole drilled through both sides of the waveguide will allow making the larger holes

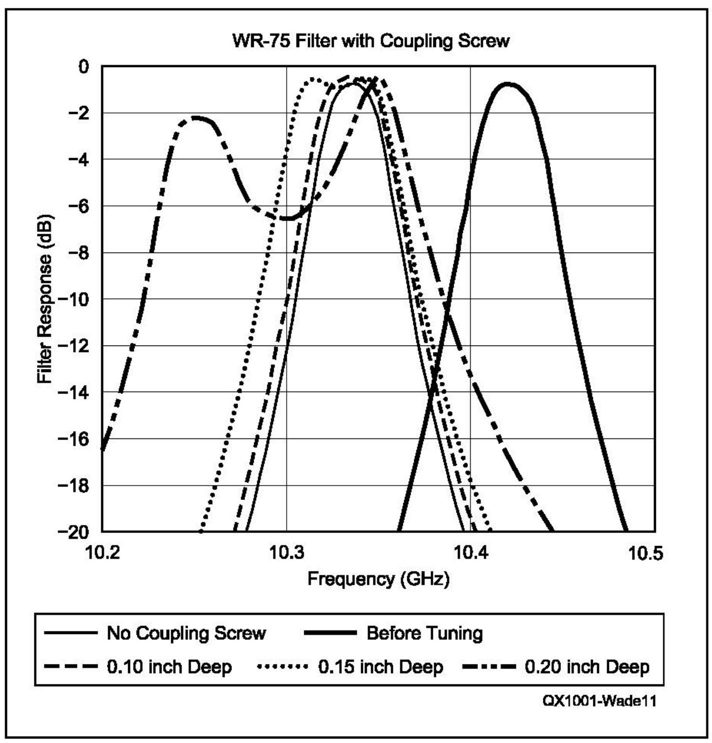

Figure 11 —This graph illustrates the tuning progression for a waveguide filter with a tuning screw.

from opposite sides.

Screw holes are tapped using the drill press to keep them square, turning by hand with the motor unplugged. Then the burrs inside the waveguide are cleaned up using a fine file.

The outside of the guide and the posts is cleaned using a Scotchbrite pad — the coarser brown variety may be needed for old, badly oxidized, waveguide.

If the posts fit snugly, they will need to have one end chamfered slightly so that they may be pressed in – if they are loose enough to fall out, the filter will probably still work but it may have higher loss. Then resin paste flux is applied around the ends of each post where they project from the waveguide. Finally, a single ring of thin solder is wrapped around each end of the posts and pressed into the flux to hold it in place. Tin-lead eutectic (63-37) solder is preferred — it will flow smoothly and at a slightly lower temperature than other solders.

Ends

If the filter includes an integral waveguide-to-coax transition, the ends must be closed with a short circuit. I use a plate of hobby brass a bit larger than the waveguide outside dimensions, so that the plate has a bit of overhang. I paint the ends of the guide, which have been filed square, with solder flux, then put the end plates on and clamp them in place. Scraps of firebrick or ceramic tile insulate the clamps from the end plates. Finally, I wind a ring of solder around the waveguide and press it into the flux to hold it in place.

Preparation for waveguide flanges is similar.

Soldering

For soldering with soft solder, I prefer a hot air gun to a torch. A hot air gun, the kind used for stripping paint, has no flame and doesn't get as hot, so the metal oxidizes less.

I've had good results preheating the filter assembly on a hot plate to near soldering temperature, and then applying the hot air gun to each area being soldered. A few seconds after the hot air is applied to a spot, the ring of solder around the joint will melt and flow into the joint. As soon as the solder flows around the whole ring, move on to the next joint. When all the joints have been flowed, use gloves or hot pads to gently move the assembly onto a firebrick or other heat-tolerant surface to cool slowly.

Summary

The filters described here are intended to provide good performance with minimum complexity, so that they are easy to design and to tune. These waveguide filters offer high performance but do require some metalworking. Some proven designs are tabulated and the *WGFIL* software is sufficient to design custom filters.

All the filters described here are designed for "good enough" performance at a particular microwave ham band. Good enough means that commonly used LO frequencies and mixer image frequencies are suppressed by at least 20 dB, and more than 30 dB in most cases. This should be adequate to radiate a clean signal and to suppress out-of-band interference.

Part 3 of this series will present "Evanescent Mode Waveguide Filters."

Notes

[1] G. F. Craven and C. K. Mok, "The Design of Evanescent Mode Waveguide Bandpass Filters for a Prescribed Insertion Loss Characteristic," *IEEE Transactions on Microwave Theory and Techniques*, March 1971, pp 295-308.

[2] Ralph Levy, "Theory of Direct-Coupled-Cavity Filters," *IEEE Transactions on Microwave Theory and Techniques*, June 1967, pp 340-348.

[3] Dennis G. Sweeney, WA4LPR, "Design and Construction of Waveguide Bandpass Filters," *Proceedings of Microwave Update '89*, ARRL, 1989, pp 124-132. The *WGFIL* program may be downloaded from **www.w1ghz.org/filter/WGFIL.COM**

[4] Glenn Elmore, N6GN, "A Simple and Effective Filter for the 10-GHz Band," *QEX*, July 1987, pp 3-5.

[5] Paul Wade, N1BWT, "A Dual Mixer for 5760 MHz with Filter and Amplifier," *QEX*, Aug 1995, pp 9-13. A PDF file of this article is available at **www.w1ghz.org/10g/QEX_articles.htm**.

[6] See the Ansoft Web site at **www.ansoft.com**

[7] Paul Wade, W1GHZ, "Rectangular Waveguide to Coax Transition Design," *QEX*, Nov/Dec 2006, pp 10-17. A PDF file of this article is available at **www.w1ghz.org/10g/QEX_articles.htm**.

QEX

Next Issue in *QEX*

ARRL President Joel Harrison, W5ZN, and Robert McGwier, N4HY, describe "The Design, Construction and Evaluation of the 8 Circle Array for Low Band." This 160 meter array was first designed by Tom Rauch, W8JI, and is described in the fourth edition of *ON4UN's Low Band DXing* by John Devoldere. Joel and Bob present a step by step guide to building, tuning and using this antenna array. This steerable receiving antenna system requires some significant real estate, but offers excellent performance for the effort to build it.