

# DESIGN AND CONSTRUCTION OF WAVEGUIDE BANDPASS FILTERS

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## ABSTRACT

This paper describes the computer program WGFIL that synthesizes a wide range of post and aperture (iris) coupled waveguide bandpass filters. A construction technique for these filters that does not require machine shop facilities is described. Three and five section filters for 10 GHz and a 3 section 24 GHz filter built using WGFIL are included as examples.

## INTRODUCTION

For operation at 10 GHz and above, waveguide filters become an attractive alternative to microstrip or interdigitated filters. Unfortunately there are a limited number of published waveguide filter designs [1][2]. Much surplus gear uses WR-75 and WR-137, and there is a need for WR-42 designs for 24 GHz. LO filters are needed for frequencies removed from the amateur band. The techniques for the design of post and aperture coupled waveguide filters are available in the professional literature [3] but they are too involved to undertake conveniently with a pocket calculator.

## WGFIL: WAVEGUIDE FILTER PROGRAM

WGFIL was written to overcome these difficulties. The program will design either a post or aperture coupled filter with one of three different responses: Butterworth, Chebyshev, or Equal Element given the desired center frequency, bandwidth, and waveguide broadwall dimension. Bandwidths for the Butterworth and Equal Element filters are specified at the 3 dB down points. Bandwidth for the Chebyshev is specified between equal ripple points. This means the 3 dB bandwidth is greater than the specified ripple bandwidth. The relationship between the two can be calculated:

$$3 \text{ dB BW} = (\text{Ripple BW})(\cosh[(1/n)\operatorname{arccosh}(1/e)])$$

Where  $n$  is the number of filter elements and  $e$  is the Chebyshev passband ripple as a ratio (not dB).

The Equal Element filter may be unfamiliar to amateurs. An Equal Element passband response looks like Butterworth with a “nose” on it. Its stopband response approaches that of a Butterworth filter. It is possible to estimate the number of filter sections for

Equal Element filters by looking at the Butterworth filter curves [4]. Equal Element filters have the least loss for a given number of sections, although small ripple Chebyshev is close [5], and all the sections are the same. They require only two different size posts for the entire filter where the Chebyshev requires a different post for each pair of resonators.

The filters that WGFIL generates consist of series lengths of transmission line, in this case waveguide, with shunt inductive reactances placed between each transmission line section. The shunt reactances are either inductive posts placed across the broad wall of the guide or inductive apertures as shown in Figure 1.

WGFIL calculates the electrical length of the transmission line sections and the shunt reactances for the desired filter response. If inductive apertures are used, they are assumed to be of zero thickness. This is a reasonable assumption if the aperture thickness is less than a few percent of the distance between apertures. The posts have a finite "thickness" so the program must compensate the electrical length of the transmission line to correct for this. WGFIL then calculates the physical distances between the inductive obstacles and the physical dimensions of the obstacles. The approximations for the obstacle dimensions are taken from Marcuvitz [6].

If you build aperture-coupled filters, generally the apertures will be made the specified width. With post-coupled filters, it may be desirable to use a post diameter somewhat different than that calculated by the program. Posts can be made of standard sized hobby brass tubing, which comes in 1/32-inch steps, and even if the posts are turned from rod stock, one is limited by standard fractional or number sized drills.

WGFIL will calculate the post size and then request a post size. If anything other than the calculated size is desired, WGFIL will go back and correct the distance between posts to accommodate the new post size. Use this feature with prudence since the post size affects the passband as well as the center frequency of the filter. WGFIL corrects only the center frequency. Experience gained from test filters seems to indicate that a 10% change in post diameter can be tolerated. It is often possible to select the center frequency and the filter bandwidth to get the posts to come out close to a standard drill or tubing size.

If thin apertures are used, their center-to-center separation can be the dimension given by WGFIL. The result will be cavities that are short by an aperture thickness. The center frequency will be high. Metal screws placed in the broadwall of the waveguide halfway between each aperture will tune the filter down in frequency.

Tuning screws can also be placed half way between each post. Metal screws will tune the filter down in frequency and good results have been obtained by choosing the center frequency 1-2% higher than desired. The best screws were silver plated screws with rounded ends that were salvaged from old microwave gear. Plating is not necessary, but keep screw penetration to a minimum to keep losses low. Screw sizes are not critical: 8-32 screws were used in WR-90, 6-32's in WR-75, and 4-40's in the WR-42 waveguide.

WGFIL uses several approximations that limit the range over which it will give valid results. Fractional bandwidth in terms of guide wavelength should be less than 20%. WGFIL calculates and reports this as "Guide BW." It is difficult to make post filters much wider than 5% because the posts become too small, and bandwidths much less than 1% will probably not give good results since the program does not account for filter losses. One approximation requires that post diameter,  $D$ , divided by the waveguide broadwall inside dimension,  $a$ , be less than 0.25. WGFIL will report a caution when  $D/a$  is greater than 0.25. Several of the test filters exceed this limitation but good results were still obtained. In general, the approximations fail gracefully so usable results may be obtained beyond these stated limits.

## USING WGFIL

Filter 3 shows a typical run of WGFIL. The example is the 3 section 24 GHz filter described later in this paper. The first screen contains the sign-on message and a series of prompts requesting various filter parameters. The second screen contains the calculated post diameters and a request for the desired post diameter. If the calculated post size is acceptable, pressing <Enter> will accept the post size and WGFIL will display the next post size. If a different sized post is desired, it may be entered at the prompt followed by <Enter>. The third screen displays the completed design. Note the  $D/a$  caution message. If a new design is requested, the program will prompt you for a new center frequency and bandwidth. It will then do a new calculation and return you to the second screen.

## BUILDING WAVEGUIDE FILTERS

The test filters were constructed with standard waveguide and flanges. Waveguide can often be found at hamfests or guide and flanges can be purchased new at a fairly reasonable cost [7].

The most elegant way to build these filters is with a milling machine. Several test filters were built this way, however such equipment is not available to most amateurs. A hand technique came from a retired machinist friend. It requires a set of vernier or dial calipers, a drill press, scriber, machinist's square, and some C-clamps. The calipers cost \$25-150 and are available from machinist's supply or by mail-order [8]. They are a good investment if you plan to do much microwave work.

First, cut a convenient length of guide for the filter. Use the machinist's square and a flat file and file the ends of the guide reasonable square. You can check your work by holding the piece up to the square and then holding them both up to the light. If the end is perfectly square, you will not see any light between the end of the piece and the blade of the square.

Scribe a line down the center of the filter piece and then mount the scriber tip in the drill press. Place the filter piece next to a long straight section of metal. A piece of the filter

waveguide is ideal. Place the long section on the drill press table so that the scribe tip will come down on the centerline of the filter piece. Use C-clamps to hold the long section in place on the table. Study Figure 4 for a typical setup. The centerline of the drill press should pass through the line scribed down the center of the filter piece as it is moved along the straight section.

Clamp a piece of metal perpendicular to the straight section at some location removed from the filter section. Measure between this reference block and the end of the filter section as shown in Figure 4. Adjust the filter section so the first hole is in a convenient location, clamp the filter piece to the straight section, and measure the distance between the end of the filter and the reference block. For example, if this distance is 4.426" and the next hole must be 0.332" down the guide, after drilling the first hole, unclamp the filter section and move it 0.332" toward the reference block. The distance between the block and the end of the filter section should now be 4.094". Reclamp the filter section and drill the next hole.

Check your measurement after clamping. "Measure twice and drill once!" With a little practice and care you should get within 0.001" or two. Practice on some scrap pieces first. When you drill, first drill a starter hole with a center drill and then drill the desired size. Drill the starter hole and the final size without moving the filter section. For holes 1/8" or less, use a #1 center drill, otherwise a #2 drill is fine. A center drill is a stubby stiff drill used for starting holes. They only cost \$1-2 and they can be obtained from any machinist's supply house. Drill only one side of the guide for a tuning screw and both sides of the guide for a post. When you set things up, you may wish to position the drill press table so that you will drill over a table hole so as not to drill into the table itself.

You can check your work by pressing the posts into the holes and measuring the distance between the outside of the posts with calipers. Now subtract half the diameter of each post from the measurement and you will have the center to center dimension of the posts. In general, it is better to have the posts a bit too close than to have them too far apart since metal tuning screws will lower the center frequency of the filter.

Clean the burrs from the guide with a small file before soldering the posts in. The posts should just press into the holes. If they are too tight, solder will not flow around them, too loose and the dimensional accuracy suffers. A ding with a center punch on an end edge of a loose post will hold it in place while soldering. A small torch and plenty of flux is recommended. After soldering, clean the filter with flux remover.

If you have access to a lathe, you can make some holders for the tuning screws. The holder shown in Figure 2 was used for the 10 GHz test filters. Brass rod stock for holders or posts can be obtained by mail-order [9]. These holders give the finished result a professional look and make for smooth tuning. The little bit of plastic under the setscrew permits continuous friction on the tuning screw. It came from a milk jug but most any soft plastic will do. Instead of the holders, you can tap the waveguide for the screw and solder a nut on the guide to give greater strength. Hold this nut in place with a stainless

steel screw while soldering. Solder won't stick to the stainless and you can remove the screw after soldering. You can then use a plastic nut as a lock nut and this will apply a smooth tension to the screw while tuning.

## TUNING WAVEGUIDE FILTERS

Filter adjustment can be a problem. A simple signal source and a detector will probably work for two or three section filters as their stopbands are not very strong and you can blast through a badly mistuned filter. Care in construction will produce a filter that is close to the desired tuning. A more sophisticated tuning technique is described in [10] or in Chapter 11 of [3]. This is the so-called "peak-dip" of Dishal, but it requires a slotted line.

The accuracy of the center frequency appears to be limited more by the construction technique than by the approximations in WGFIL. With care on a milling machine, it is possible to build filters that require little or no tuning. Very narrowband filters are more susceptible to construction errors. The author has constructed 29 GHz 2% BW filters in WR28 that required no tuning. The milling machine used by the author tends to be on the short side so the filters come out slightly high in frequency. A ding with a center punch in the broadwall of the waveguide between two posts will bring the resonator frequency down.

## TEST RESULTS

A number of test post filters were constructed. No aperture filters were built since the apertures were too difficult for the author to fabricate. However, WGFIL will accurately reproduce the aperture-coupled example in [3]. Table 1 tabulates the test filters constructed.

Table 1: Test Filters

WG	Type	Sections	Center Frequency	Design 3 dB BW	Measured 3 dB BW	Loss
WR-90	0.1 dB Chev	3	10.368 GHz	138.8 MHz	111.4 MHz	0.67 dB
WR-90	0.1 dB Chev	5	10.368 GHz	130.5 MHz	140.8 MHz	1.64 dB
WR-75	Equal Elem	5	10.368 GHz	102.4 MHz	118 MHz	1.10 dB
WR-42	0.1 dB Chev	3	24.125 GHz	448.5 MHz	441 MHz	1.32 dB

Figure 5 is a photo of several of the test filters. Figure 6 shows the response of the 5 section WR-90 filters. This filter has a waveguide port at one end and a co-axial port at the other. The waveguide to co-ax transition is very similar to the one described in [1].

Figure 7 is the response of the WR-42 filter. Two of these filters were constructed. One was made on the milling machine and the other using the technique described above. The filter built with the mill was measured without the tuning screws. It had a properly

formed passband centered about 0.5% higher than the design frequency. No tune for 24 GHz anyone?! The two different WR-42 filters are shown in the Figure 5 photo.

## CONCLUSION

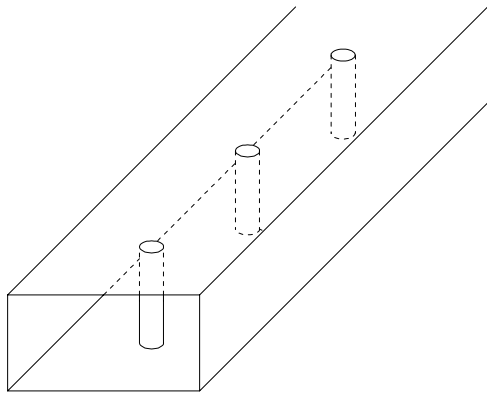
WGFIL should be a useful tool for anyone desiring to build transverters and use waveguide. WGFIL is available for non-commercial amateur use for the price of a computer disk and postage if necessary. It can be supplied either on 5.25" or 3.5" MS-DOS formatted media and it should run on PC type computer.

## ACKNOWLEDGMENTS

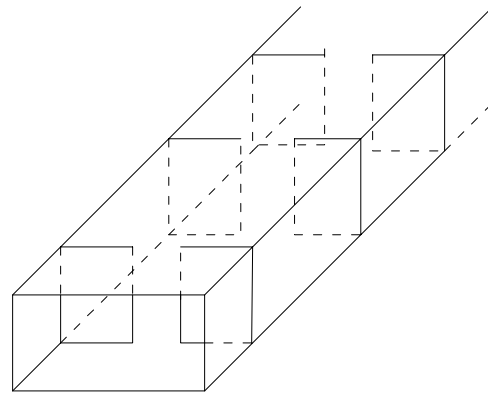
I would like to thank Ken Backer KC4LOL for doing the HP8510 network analyzer plots, Mike Barts, N4GU for the photos and helpful suggestions, and Joe Hurley for the drilling technique. Also thanks to AL Ward WB5LUA who encouraged me to search for a simple construction technique.

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3. Matthaei, G., L. Young, and E.M.T. Jones, *Microwave Filters Impedance-Matching Networks, and Coupling Structures*, Artech House, 1980, section 8.06.
4. Taub, Jesse J., "Design of Minimum Loss Band-Pass Filters," *Microwave Journal*, September 1963, pp. 67-76.
5. Blinchikoff, Herman J. and Antatol I. Zverev, *Filtering in the Time and Frequency Domain*, John Wiley, New York, 1975, pp. 281-286.
6. Marcuvitz, N., *Waveguide Handbook*, Peter Peregrinus Ltd, London, 1986, Ch 6.
7. Lectronic Research Labs, Inc., 665 Winks, Bensalem, PA 19020, 800-358-8378. LRL accepts credit cards. Waveguide must be ordered in 5-foot minimum lengths. The author's last purchase of WR-90 was \$3.90/ft.
8. Rutland Tool & Supply, 2225 Workman Mill Rd., Whittier CA 90601-1437. 800-289-4787, website: [www.rutlandtool.com](http://www.rutlandtool.com). Rutland accepts credit cards.
9. Small Parts Inc., 13980 NW 58th Court, PO Box 4650, Miami Lakes, FL 33014-0650, 800-220-4242, website: [www.smallparts.com](http://www.smallparts.com). Small Parts accepts credit cards.
10. Dishal, M., "Alignment and Adjustment of Synchronously Tuned Multiple-Resonator-Circuit Filters," *Proceedings of the IRE*, No. 39, November 1951, pp. 1448-1455.



Post Filter



Aperture Filter

Figure 1: Waveguide bandpass filters using either posts of inductive apertures

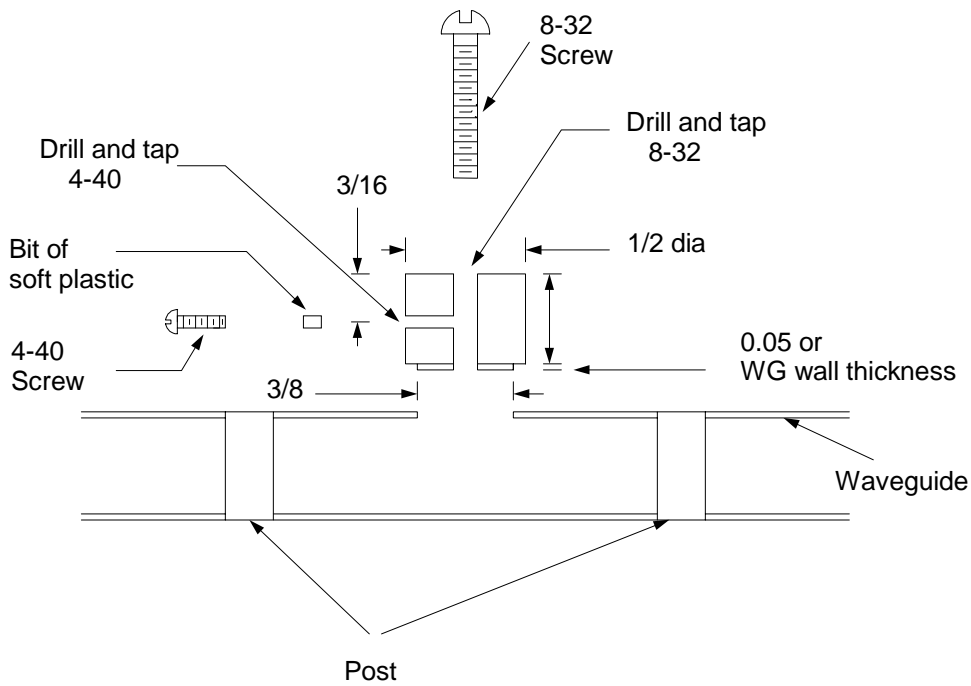


Figure 2: Tuning Screw Holder

Waveguide Filter Synthesis Program  
 written by Dennis Sweeney WA4LPR  
 Version 1.1

Filter type:            Butterworth     : 1  
                          Chebyshev         : 2  
                          Equal Element    : 3  
                          Enter # of desired type    : 2  
                          Enter passband ripple in dB : 0.1

Filter structure :        Post        : 1  
    Iris        : 2  
    Enter # of desired type: 1

Enter waveguide width (inches)    0.42

Enter # of elements : 3

Center frequency in MHz = 24362

Bandwidth in MHz = 325

**WGFIL screen 1**

Post Coupled Filter

Calculated Post dia	Desired post dia
Post[0] = 0.0624	0.0625
Post[1] = 0.1251	0.1250
Post[2] = 0.1251	0.1250
Post[3] = 0.0624	0.0625

**WGFIL screen 2**

Post Coupled Filter

Center : 24361.458 MHz BW: 325.000 MHz  
 Fractional BW    1.33 %        Guide BW    2.00 %  
 Chebychev response, ripple:    0.10 DB

Post diameter	Cavity length
0.0625"	0.3316"
0.1250	0.3735"
0.1250	0.3316"
0.0625	

Caution: D/a > 0.25  
 Caution: D/a > 0.25

Do you wish another design (y/n)? y

Center frequency in MHz = 24300

Bandwidth in MHz = 300

**WGFIL screen 3**

Figure 3: Typical run of WGFIL. The example is the 24 GHz filter in Figures 5 and 7.



Figure 4: Drill press set up for accurately drilling waveguide filters. The dark object in the center is the filter to be drilled. The reference block is in the foreground to the right.

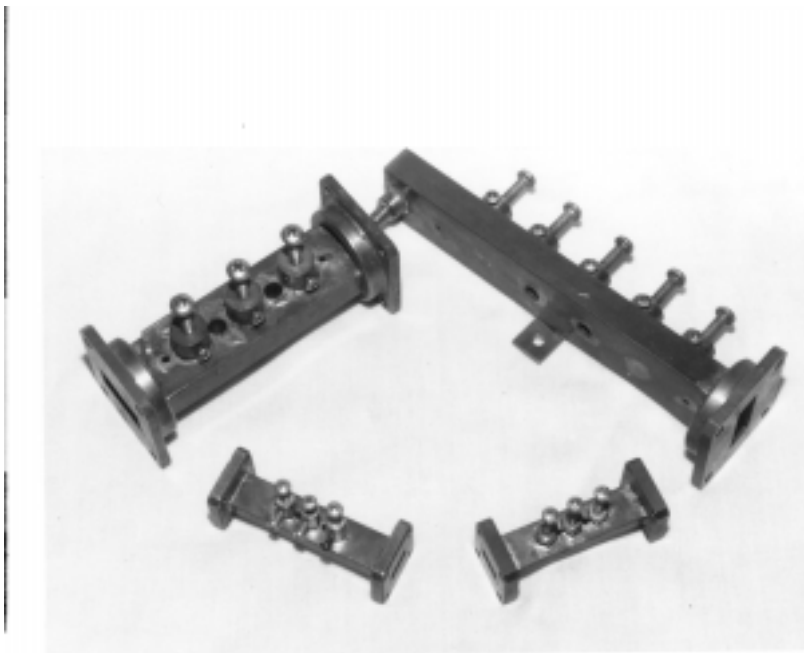


Figure 5: Test filters. In the upper left is a 3 section 10 GHz WR-90 filter. In the upper right is a 5 section 10 GHz WR-90 filter with a co-ax input. A 3 section WR-42 24 GHz filter made on the milling machine is in the lower left and the same filter built with the described technique is in the lower right.

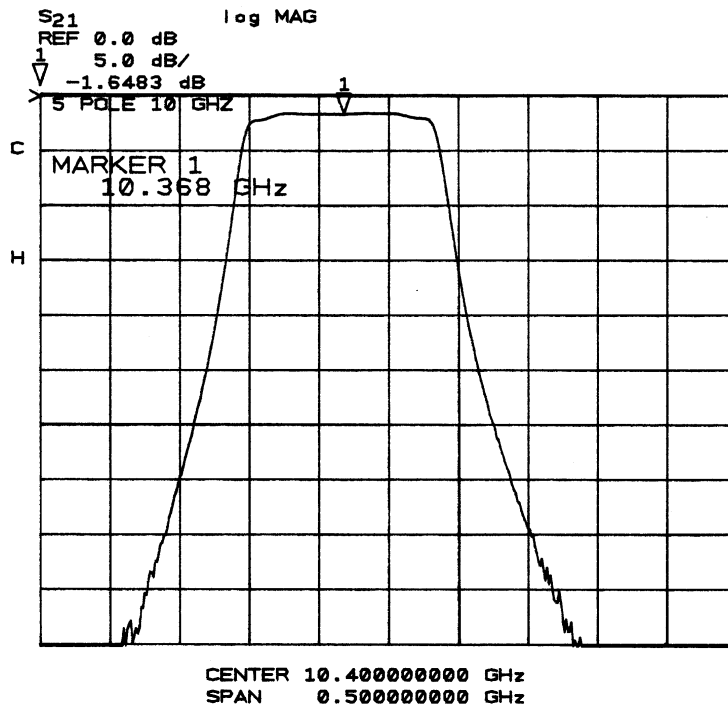


Figure 6: Frequency response plot of the 5 section 10 GHz filter. The x-axis is 50 MHz/div. centered at 10.4 GHz. The y-axis is 5 dB/div., top is 0 dB.

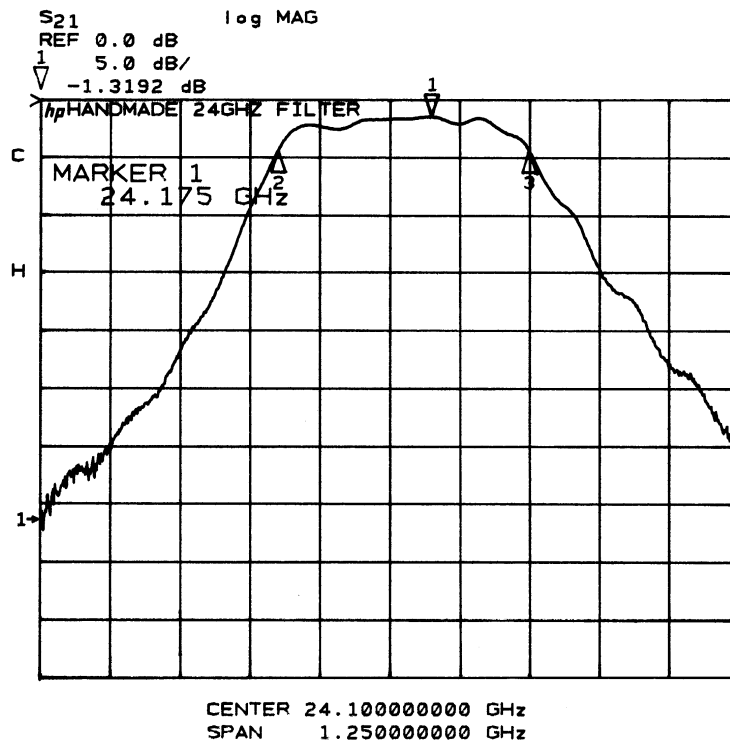


Figure 7: Frequency response plot of the handmade 3 section 24 GHz filter. The x-axis is 125 MHz/div. centered at 24.1 GHz. The y-axis is 5 dB/div, top is 0 dB. Markers 2 and 3 are the 3 dB points 441 MHz apart.