Waveguide Interdigital Filters

Build sturdy, predictable microwave filters from waveguide. Here are designs for three bands: 1296, 2304 and 3456 MHz.

By Paul Wade, W1GHZ (N1BWT)

Most microwave transverters, especially the "no-tune" variety, need some additional filtering to operate in locations with "RF pollution"—accessible mountaintops are notoriously bad environments. Waveguide post filters provide superior performance at 10 GHz[1] and 5760 MHz,[2] but become large and heavy at lower frequencies. Interdigital filters are excellent performers at the lower microwave frequencies,[3] but the usual construction techniques require some machining, mostly tedious tapping of threads in many holes. One of the beauties of waveguide filters is that the basic structure is accurately defined by the waveguide, so construction requires only drilling and soldering. Since surplus waveguide is reasonably plentiful, I wondered if it could be used to build interdigital filters for the lower microwave bands. As we shall see, my experiments were quite successful.

[1]Notes appear on page 8.

161 Center Rd
Shirley, MA 01414
wade@tiac.net

Interdigital Filters

The basic structure of an interdigital filter, shown in Fig 1, is a group of coupled resonators in a metal housing. Each resonator is an electrical λ/4 long, but physically shortened by capacitance at the open end. The resonators are *interdigitated*, with the position of the open ends of the resonators alternating as depicted in Fig 1. (A similar filter with all resonators aligned in the same direction is called a comb-line filter.) The coupling between resonators is controlled by their separation. Several methods are commonly used to make input and output connections, but a simple one is to use taps on the input and output resonators.

The starting dimension for an interdigital filter is the width of the housing, which should be λ/4 at the operating frequency. All of the other dimensions are interrelated—a change in one affects others—so that empirical design of a filter would be difficult and frustrating. Fortunately, computer programs are available to design interdigital filters. A BASIC program,[4] by N6JH, appears in *ham radio* magazine. I translated this into PASCAL and compiled it. My version, *INTFIL.EXE*, is available for downloading at **http://www.qsl.net/~n1bwt/intfil.zip**. One 1296 MHz filter that I built using this program was carefully measured using an automatic network analyzer and found to match the predicted performance almost perfectly with no tuning. This gave me confidence in the accuracy of the program.

Filter Design

The first part of filter design is the same for all types of filters—calculation of coupling coefficients and other parameters to achieve the desired performance. These are tabulated in *The ARRL Handbook*[5] and other reference books[6] for the most common types of filters: the Butterworth (maximally-flat) and the Chebyshev response, which trades some passband ripple (amplitude variation) for somewhat steeper skirts at the passband edges. The tabulated parameters, g_{mn}, are for a normalized prototype filter, so that further calculations are required to find actual component values for a desired frequency and impedance.

The second part of filter design is to convert the normalized parameters into component values or physical dimensions. The calculations are quite tedious, so graphical solutions were often published[7] before computers were commonly available. Now these calculations are easily performed on a PC, allowing us to evaluate multiple filter designs before choosing one to build.

Design of an interdigital filter begins with the choice of a required bandwidth. Simple filter programs such as ***INTFIL*** are only reliable for bandwidths between about 1% and 10% of the center frequency, and very-narrow-bandwidth filters are lossy and require tight tolerances in construction. Therefore, a 3% to 5% bandwidth is recommended as a good starting point. The next step is to decide how steeply the skirts roll off at the passband edges. For example, steeper skirts are required to reject an image

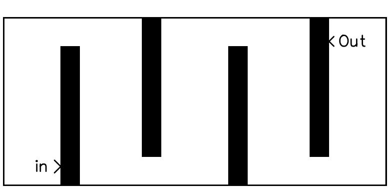

Fig 1—Interdigital filter cross-section sketch.

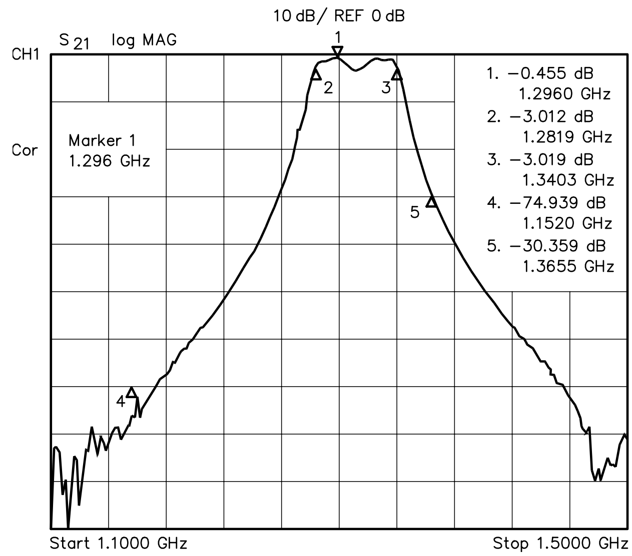

Fig 2—Performance of 1296-MHz filter—WR-229 waveguide.

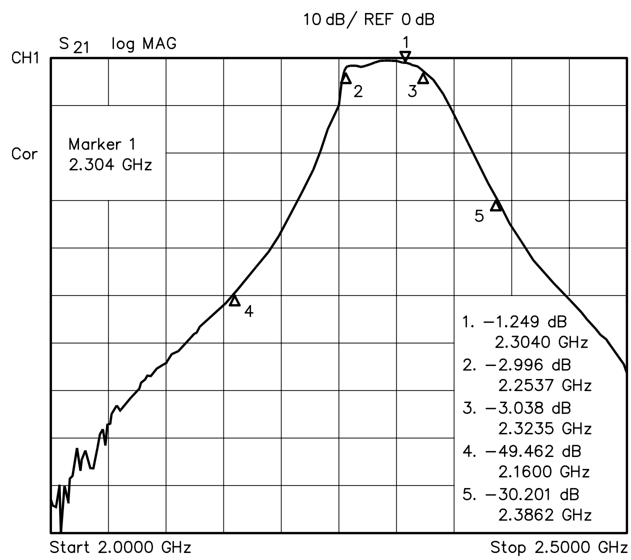

Fig 3—Performance of 2304-MHz filter—WR-137 waveguide.

Table 1: Waveguide Dimensions for Interdigital Filters

Waveguide	*Wide Dimension*	*Frequency (λ/4, MHz)*
WR-340	3.4″	868
WR-284	2.84″	1039
WR-229	2.29″	1289
WR-187	1.872″	1577
WR-159	1.59″	1857
WR-137	1.372″	2152
WR-112	1.12″	2636
WR-90	0.90″	3280
WR-75	0.75″	3937
WR-62	0.622″	4747
WR-50	0.51″	5789

close to the operating frequency. Generally, filters with steeper skirts require more resonators and have more loss, so a compromise may be in order. It is possible to calculate the number of resonators required, but a few trial designs on the computer should yield the same result and provide some insight as well.

Waveguide Interdigital Filters

Now let's design a filter in an available waveguide. As mentioned above, we should start with the width of the enclosure at $\lambda/4$ at the center frequency. This would be the large inside dimension of a waveguide used as the enclosure. Table 1 lists the inside dimensions for some commonly available waveguides and the frequencies for which the wide dimensions are $\lambda/4$. The large dimension for WR-229 is $\lambda/4$ at 1289 MHz, so it is a logical material for a 1296 MHz filter. Simply designing a filter for the 1289 MHz center frequency with enough bandwidth to include 1296 MHz does the trick. I chose a 50 MHz bandwidth and used ***INTFIL*** to calculate the rest of the dimensions for a resonator diameter of $^{3}/_{8}$ inch. Since WR-229 is being scrapped as 4 GHz telephone microwave links are decommissioned, I was able to find all I could carry at a flea market for $5.

Once the filter was assembled, I found that the bandpass was slightly above 1296 MHz, a little higher than the design. This was easy to fix, however: I drilled and tapped holes for tuning screws opposite the open ends of the resonators and inserted screws to add capacitance and lower the frequency. On the other hand if the frequency ended up a bit low, then it would be necessary to shorten the resonators slightly.

I first adjusted the screws for minimum insertion loss at 1296 MHz, then readjusted them for minimum SWR at both ends. The second adjustment is a bit more involved since each adjustment affects both ends and a few reversals were needed. The final passband, shown in Fig 2, is about 58 MHz wide with an insertion loss less than 0.5 dB at 1296 MHz.

Tuning is straightforward for these filters, with moderate bandwidth and a reasonable number of resonators. However, filters with very narrow or wide bandwidths, or with many resonators, require a more complex tuning procedure. Dishal's procedure[8, 9] allows the tuning of one resonator at a time.

For other bands, no waveguide exactly matches $\lambda/4$, but there are some good candidates that fall within about 10% of the desired frequency. The ubiquitous X-band waveguide, WR-90, is close to $\lambda/4$ at 3456 MHz, while WR-137 (used in 6-GHz microwave links) is close to 2304 MHz. For these two, simply making a wide filter is not good enough. The bandpass would include the commonly used LO frequencies for a 144-MHz IF. Thus, we need a design procedure that can move the center frequency slightly.

The design procedure that I use makes two similar designs, one at the desired frequency and one at the $\lambda/4$ frequency waveguide, using the same percentage bandwidth (bandwidth÷center frequency) for both designs. Using the same percentage bandwidth results in two designs differing only in the resonator lengths and tap positions, and the difference is small because the frequencies are close together. Since the higher-frequency design also calls for the $\lambda/4$ distance to be shorter, making the resonators this short would result in less capacitance and an actual resonant frequency higher than desired. My compromise is to split the difference between the two design lengths and make the resonator lengths halfway between the two designs.

I followed the above design procedure for two more filters, one for 3456 MHz in WR-90 waveguide with 108 MHz bandwidth and the other for 2304 MHz in WR-137 waveguide with 75 MHz bandwidth. Each design uses four resonators with a Butterworth response. After fabrication, both filters had passbands that included the design frequency, as shown in Figs 3 and 4. Thus, they are usable with no further tuning. Any elective tuning would optimize the input and output SWR at the desired frequency.

To simplify testing, the effects of the end walls are minimized by locating them relatively far from the end resonators. The result is that leaving the end walls off during testing makes

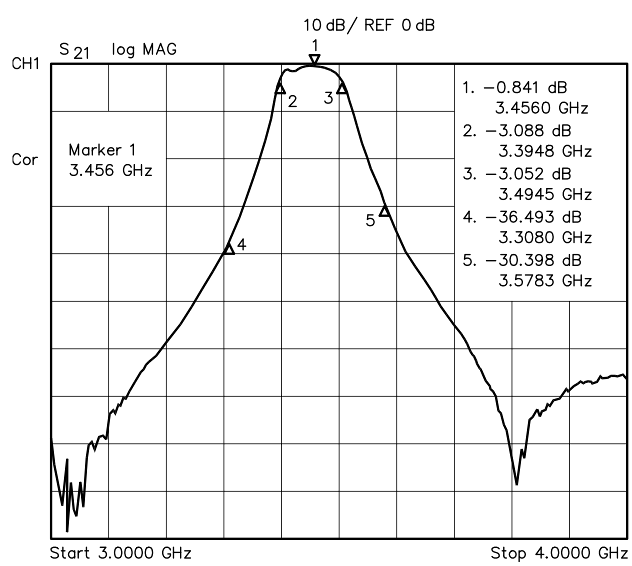

Fig 4—Performance of 3456-MHz filter—WR-90 waveguide.

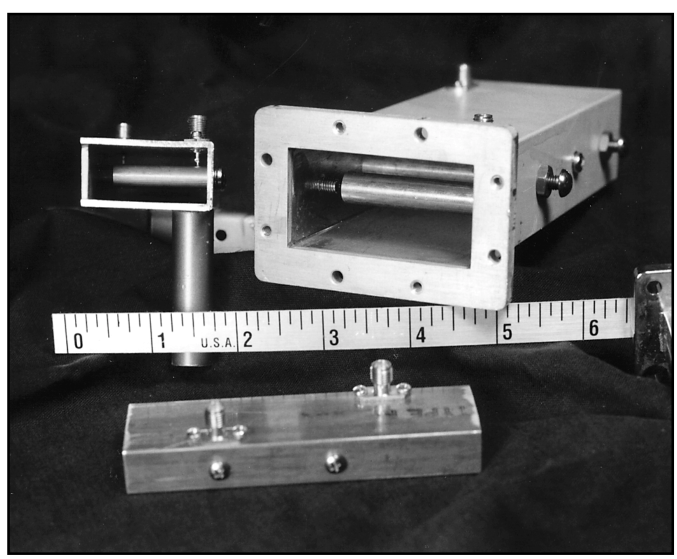

Fig 5—Waveguide interdigital filters for 1296, 2304 and 3456 MHz.

little difference in performance. I located the end walls one inch from the end resonators in the 1296 MHz filter, and could find only a slight performance difference with the end walls in place. There was no detectable difference for the higher frequency filters. Of course, the end walls should be installed for operation; stray leakage could otherwise negate the effect of the filter.

Construction

The three completed filters are shown in Fig 5. Each resonator is attached by a screw through a narrow wall of the waveguide and the coaxial connectors are mounted in a wide wall of the waveguide with short leads to the tap points on the end resonators.

Resonator lengths and spacings are fairly critical, so accurate measurement is needed. The holes are best made with a drill press (see the sidebar "Tools for Interdigital Filter Construction." Start with a center drill or small drill bit to spot the hole, then follow with a drill bit of the desired diameter. The mounting holes in the end of the resonators should be tapped and countersunk slightly, so contact is made around the resonator perimeter. For initial testing, I don't solder the input and output connections, but rather make them slightly long with a sharp point contacting the tap point on the resonators.

Using waveguide as the housing makes the filters easy to build, and results in a robust, stable filter, suitable for rover operations. Some of my previous experiments in filter construction using hobby brass and PC board were less successful due to mechanical instability: Vibrations or the weight of connecting coax cables affected their performance. One notably bad filter was so unstable that the frequency response would vary during measurement.

After building and testing the filters in Fig 5, I wondered if there was an even simpler way to make these filters. Since the resonator length for the 3456 MHz filter is just a hair's breadth over 3/4 inch, perhaps an ordinary 3/4-inch-long, 1/4-inch-diameter threaded standoff could be used as a resonator. The resonator spacings and the tap-point dimensions are the critical ones, so I calculated a filter with 75 MHz bandwidth using 1/4-inch-diameter resonators, then built it with threaded standoffs. It took less than an hour to complete. A quick measurement showed nearly 3 dB loss at 3456 MHz,

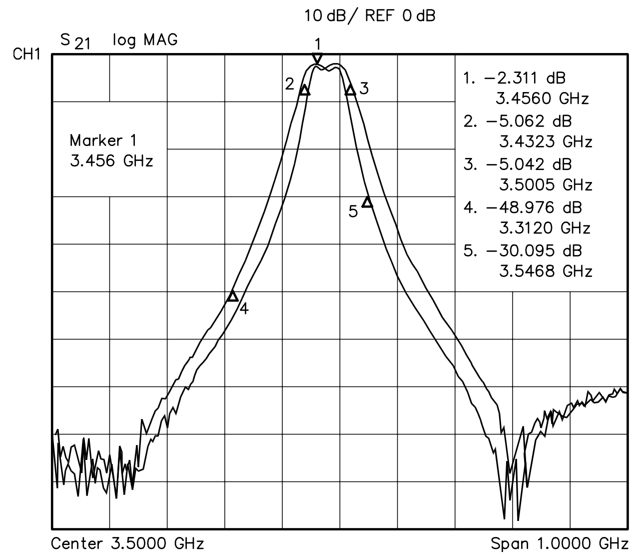

Fig 6—Performance of 3456 MHz filter built with threaded standoffs in WR-90 waveguide (lower frequency response is after tuning).

Table 2: Waveguide Interdigital Filter Examples

Waveguide	*WR-229*	*WR-137*	*WR-90*	*WR-90*	
Target Frequency	*1289*	*2304*	*3456*	*3456*	*MHz*
Bandwidth	*50*	*75*	*108*	*79*	*MHz*
Resonator (Designed for waveguide λ/4)					
Diameter	0.375	0.25	0.1875	0.25	inches
End Length	1.983	1.099	0.732	0.727	inches
Interior Length	1.971	1.095	0.73	0.728	inches
Tap Point	0.23	0.127	0.089	0.089	inches
λ/4 Frequency	1289	2155	3280	3280	MHz
Bandwidth	same	70	100	75	MHz
Resonator (Designed for target frequency)					
Diameter	″	0.25	0.1875	0.25	inches
End Length	″	1.187	0.777	0.773	inches
Interior Length	″	1.183	0.775	0.772	inches
Tap Point	″	0.136	0.093	0.095	inches
Spacing 1-2,3-4	1.47	0.864	0.58	0.653	inches
Spacing 2-3	1.632	0.951	0.636	0.709	inches
Compromise Dimensions					
Resonator					
Diameter	same	0.25	0.1875	0.25*	inches
End Length	″	1.144	0.756	0.75*	inches
Interior Length	″	1.14	0.752	0.75*	inches
Tap Point	″	0.132	0.09	0.092	inches
Loss, Calculated	0.2	0.3	0.4	0.6	dB
Loss, Measured	0.45	1.25	0.8	2.3	dB
Bandwidth, Measured	58	70	100	68	MHz
LO Frequency	1152	2160	3312	3312	MHz
LO Rejection, Calculated	–59	–47	–34	–45	dB
LO Rejection, Measured	–75	–49	–36	–49	dB

* = threaded standoff

however, so I took it apart to add tuning screws to see if I could improve it. Careful tuning only reduced the loss to 2.4 dB, versus 0.8 dB for the filter with machined brass resonators. Fig 6 shows the response before and after tuning. The response is slightly higher in frequency before tuning, but otherwise there is little difference. I attribute the higher loss to three factors:

- I arbitrarily designed this version for a 75 MHz (2%) bandwidth, compared to a 108 MHz (3%) bandwidth for the other 3456 MHz filter. As previously mentioned, filters with narrow bandwidths tend to be more lossy.
- The threaded standoffs are plated with nickel, a lossy metal.
- The standoffs are chamfered at the ends, so the contact area is smaller at the shorted end where currents are highest.

Performance

The waveguide interdigital filters exhibit excellent performance (as shown in Figs 2, 3, 4, and 6) with low insertion loss in the passband and high rejection of undesired frequencies. Steep skirts provide good rejection of possible spurious signals, such as LO leakage only 144 MHz away from the operating frequency. LO rejection is much greater for the 1296 MHz filter (–75 dB) than for the others (–49 dB at 2304 MHz and –36 dB at 3456 MHz) because the relative LO separation is much greater at 1296 MHz. It's 9% of the operating frequency at 1296 MHz, versus 6% at 2304 MHz and 4% at 3456 MHz.

Table 2 lists the filter dimensions and compares the measured performance with the design values, as calculated by ***INTFIL***. The measured performance is quite close to the design values. The dimensions shown are for the two designs for each filter, plus the compromise values that I fabricated, to illustrate the design procedure.

The only performance flaw for these filters is poor harmonic rejection. At frequencies much higher than the operating frequency, the waveguide enclosure behaves as a waveguide rather than just an enclosure. This behavior is not unique to the waveguide interdigital filters—all conductive enclosures will propagate waveguide modes at frequencies above the cutoff frequencies for the interior dimensions. Fig 7 shows the transmission characteristics of the 3456 MHz filter from 50 MHz to 20 GHz. Out-of-band rejection is excellent (> 70 dB) below

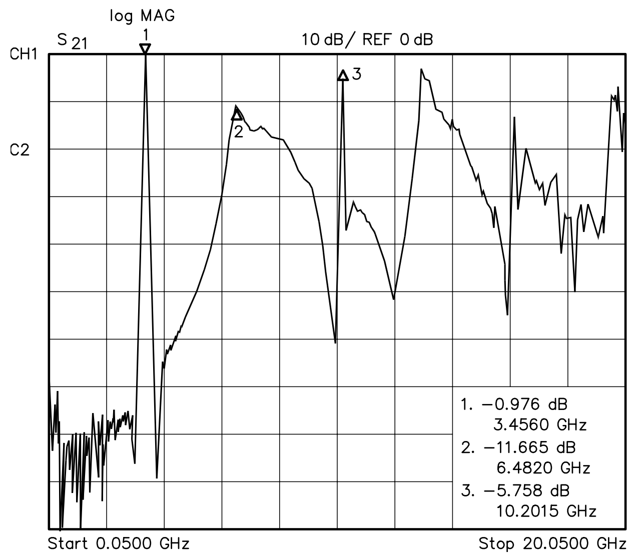

Fig 7—Wide-range performance (0 to 20 GHz) of 3456-MHz filter—WR-90 waveguide.

Tools for Interdigital Filter Construction

I use a small metal lathe to trim the interdigital-filter resonators to length. A lathe is the ideal tool for this work, but is a luxury for most hams. Some other tools are great for homebrewing, however, and inexpensive imports have made them quite affordable. The two that I find almost indispensable are a drill press and a dial caliper.

A drill press is a sturdy drill on a stand, with an adjustable table to hold the work. For the interdigital filters, it drills the holes square and true. The mounting holes in the resonator rods can be first drilled and then threaded, by chucking a screw tap in the drill press and feeding it *by hand* (power off!), with the rod held in a vise. Imported tabletop drill presses are available for less than $60.[A, B] I used and abused one of these constantly for 16 years before splurging on a larger floor-mounted model; the old one is still in use for local "Elmer" sessions.

A dial caliper is a measuring instrument capable of resolving dimensions to a precision of 0.001 inches on a dial. Most of the dimensions in the interdigital filters, and for much microwave work, must be more precise than I can measure with a ruler, so my dial caliper also sees constant use. I even scribe dimensions directly with the caliper tips—a gross abuse of the tool that I justify by its low replacement cost. Imported 6-inch dial calipers are available for less than $20,[C, D] a very modest investment compared to the alternative: eyestrain and frustration.

Everything else can be done with common hand tools—plus patience. A hacksaw and file can cut the waveguide to length and trim the resonators, measuring frequently with the dial calipers. The holes are carefully marked, center-punched, and drilled to size with a drill press. A set of "number-sized" drills provides many more choices of hole size than ordinary fractional sizes, and is available at reasonable cost from any of the suppliers already mentioned.—*W1GHZ*

A modest investment in tools—inexpensive, but not cheap—can add to the pleasures of homebrewing and improve the results.

Sources

[A]Harbor Freight Tools, 3491 Mission Oaks Blvd, Camarillo, CA 93011; tel 800-423-2567; **http://www.harborfreight.com**

[B]Grizzly Industrial, Inc, 1821 Valencia St, Bellingham, WA 98226; tel 800-523-4777; **http://www.grizzlyimports.com**

[C]MSC Industrial Supply Co, 151 Sunnyside Blvd, Plainview, NY 11803; tel 800-645-7270; **http://www.mscdirect.com**. The street address is for the corporate offices. Call for a location near you.

[D]Eastern Tool & Supply, 149 Grand St, New York, NY 10013; tel 800-221-2679.

the passband and good above the passband up to about 6 GHz. Above 6 GHz, various waveguide modes are propagated and limit the attenuation.

Conclusion

Good filters are important for operation in locations with RF pollution, and are recommended when no-tune transverters are followed by broadband power amplifiers. Interdigital filters offer excellent performance for the lower microwave bands. The filters are easily constructed in a waveguide housing without extensive machining and require little tuning, resulting in a robust, high-performance filter.

Notes

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

[2]P. Wade, N1BWT, "A Dual Mixer for 5760 MHz with Filter and Amplifier," *QEX,* August 1995, pp 9-13.

[3]R. Fisher, W2CQH, "Interdigital Bandpass Filters for Amateur VHF/UHF Applications," *QST*, March 1968, p 32.

[4]J. Hinshaw, N6JH, and S. Monemzadeh, "Computer-Aided Interdigital Bandpass Filter Design," *ham radio*, January 1985, pp 12-26.

[5]R. Dean Straw, N6BV, Editor, *The ARRL Handbook for Radio Amateurs,* ARRL, 1997. See pp 30.22 and following.

[6]G. Matthei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks, and Coupling Structures*, McGraw-Hill, 1968.

[7]W.S. Metcalf, "Graphs Speed Design of Interdigital Filters," *Microwaves*, February 1967, pp 91-95.

[8]M. Dishal, "Alignment and Adjustment of Synchronously Tuned Multiple-Resonator-Circuit Filters," *Proc. IRE*, November 1951, pp 1448-1455.

[9]G. Matthei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks, and Coupling Structures*, McGraw-Hill, 1968, pp 668-673.

□□