Design and Construction of Round Rod Interdigitated Filters
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Abstract

This paper describes, INTRFIL, a program intended to create bandpass filters using interdigitated round rod ¼ wavelength long resonators between a parallel ground planes (slab line). See Figure 1 for an example. A simulation technique synthesized from pairs of coupled lines in the open source circuit simulator QUCS (Quite Universal Circuit Stimulator) (1) is described. This simulation technique is useful for verifying a design. Test test filters for 2304 MHz and 5760 MHz are included as examples.

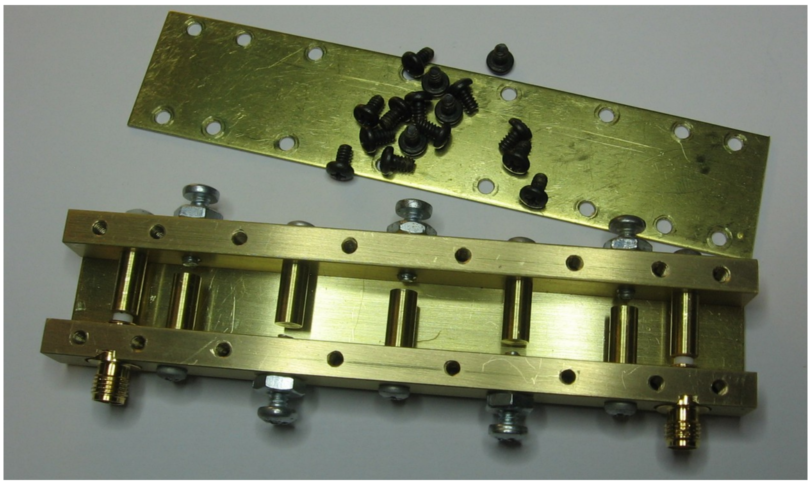

Figure 1: INTRFIL 5 resonator interdigitated filter. This filter was designed to have an approximately 35 MHz (3 dB points) bandwidth centered at 5760 MHz. The lid is 1.00 in wide. Note that there are 7 rods. The rods at the far ends of the filter are not resonators but coupling rods.

Introduction

INTRFIL began as an exercise to extend the interdigitated filer program that appeared in Ham Radio magazine in 1985 (2). That program appears to correctly calculate the rod spacing but the input/output tap points appear to be more problematic and its algorithms were not well documented. While this program produces very usable filters, your author had to adjust the end rod taps in order to get the passband and ripple correct. In addition, tapping the input/output lines becomes more difficult as the frequency increases. Attempts to make filters in the 6 GHz region were a disappointment.

There is no real upper/lower frequency limit for filters made with INTRFIL. 500-6000 MHz seems to be a reasonable range. The lower frequency is limited by how large you are willing to make the filter and the upper frequency limit is set by how small you can make the resonators. INTRFIL uses input/output coupling rods rather than tapped resonators for the input/output. This requires two extra rods beyond the number of resonators but it allows for more controlled input/output coupling particularly at higher frequencies. INTRFIL is intended to create a filter design that has a high probability of success if you follow its results carefully. The simulation and test filters in this paper are intended to verify the design.

The filters created by INTRFIL are more complex than those using pipe caps or hair pin PCB's. While relatively easy to construct and tune, these filters offer modest performance in the stopband. For several microwave bands this probably adequate as the mixing and LO spurious products from most transverters tend to fall in band. However, consider 2304 MHz. The LO and mixing products fall out of band for low side LO injection. These out of band emissions fall in the spectrum below 2300 MHz that is used by weak signal space and satellite systems. The example 2304 MHz filter in this paper is capable of suppressing the out of band 2248 MHz mixing product for a 28 MHz IF by over 60 dB.

INTRFIL is written in Pascal. Although Pascal is not as popular as it once was, the Free Pascal Complier (FPC) (3) is a modern cross platform complier. You can compile INTRFIL for Windows, MAC or Linux. In addition, there is a light weight, easy to use integrated development environment (IDE) called Geany (4) that makes running and/or editing INTRFIL source easy. INTRFIL's I/O is text in a terminal window with only minimal error checking. This is crude, but it works. My hope is someone with more advanced programming skills might write a nice GUI for INTRFIL.

The source code for INTRFIL is available (5) under General Public License (GPL). 32 bit Windows and Linux executables are available. While the GPL does not preclude commercial use, it means that INTRFIL is provided with no warranty, you use it at your own risk, and it can't disappear as some proprietary software. My intent is for anyone to be able to use it and it is not intended as a commercial product.

Running INTRFIL

Below is the typical input/output for INTRFIL. This is Figure 2 and it is the screen dialog for INTRFIL. The required input parameters are shown in bold (the bold is absent in the actual computer I/O). This example is for a 5 element 30 MHz wide (35 MHz is the bandwidth at 3 dB points) 0.05 dB ripple Chebychev filter for 5760 MHz. It is intended for a 5760 MHz transverter with a 28 MHz IF. While designed for 5760 MHz, it was actually tuned for 5770 MHz as will be explained later. An additional 2304 MHz filter will be presented as well.

INTRFIL: Interdigitated Filter Program Version 1.0
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Number of elements? 5
Center frequency (MHz) 5760
Butterworth (1) Chebychev (2) ? 2
Ripple Bandwidth (MHz) 30
Bandpass ripple (DB) 0.05
3 dB Bandwidth (MHz) = 35.26 Ripple Return Loss = 19.4 dB
Load impedance 50
ground plane spacing in = 0.375
rod dia in = 0.1875

d/h = 0.500 Slab Zo = 55.76 Co-ax Zo = 56.08

Calculated odd/even impedances and coupling coefficients

Zoo[0] = 46.81   Zoe[0] = 53.19   K = 0.0639
Zoo[1] = 49.62   Zoe[1] = 49.97   K = 0.0035
Zoo[2] = 49.67   Zoe[2] = 49.92   K = 0.0026
Zoo[3] = 49.67   Zoe[3] = 49.92   K = 0.0026
Zoo[4] = 49.62   Zoe[4] = 49.97   K = 0.0035
Zoo[5] = 46.81   Zoe[5] = 53.19   K = 0.0639

Odd/even impedances for fixed d/h = 0.500 with s/h rod spacings

Zoo = 51.92   Zoe = 59.01   s/h[01] = 0.5953   c - c = 0.411 in
Zoo = 55.45   Zoe = 55.84   s/h[12] = 1.4481   c - c = 0.731 in
Zoo = 55.51   Zoe = 55.80   s/h[23] = 1.5238   c - c = 0.759 in
Zoo = 55.51   Zoe = 55.80   s/h[34] = 1.5238   c - c = 0.759 in
Zoo = 55.45   Zoe = 55.84   s/h[45] = 1.4481   c - c = 0.731 in
Zoo = 51.92   Zoe = 59.01   s/h[56] = 0.5953   c - c = 0.411 in

Parameters for filter cavity length = wavelength/4

Ct = 0.2016 pf   Cf = 0.1251 pf   Cp = 0.0765 pf
l = 0.386 in   gap = 0.081 in   lamda/4 = 0.512 in

Cavity spacing width can be adjusted +/- 10% of wavelength/4
Spacing = (in) 0.5

Parameters for Filter cavity

Ct = 0.1845 pf   Cf = 0.1251 pf   Cp = 0.0593 pf
New Ct Rod Length = 0.395 in   New gap = 0.105 in   Rod + gap = 0.500 in

Estimated resonator Q = 1040.2   Filter Q = 192.0
Loss = 5.27 dB

Data for simulation model using coupled lines

Zs = 111.52

Zooprime = 80.66 Zoeprime = 101.71
Zooprime = 89.40 Zoeprime = 90.54
Zooprime = 89.55 Zoeprime = 90.39
Zooprime = 89.55 Zoeprime = 90.39
Zooprime = 89.40 Zoeprime = 90.54
Zooprime = 80.66 Zoeprime = 101.71

Ct = 0.1845 pf Bar length = 10.044 mm

Figure 2: INTRFIL input/output. **Required input information is printed in bold.**

In order to run INTRFIL, you need to provide the parameters for the desired filter. You specify the number of resonators (elements) and the center frequency of the filter. The end bars are not resonators but provide the input/output coupling so a 5 resonator filter will have 7 bars. You then specify a Butterworth or Chebychev response. For the a Chebychev filter, you will be asked for the bandwidth between equal ripple points and the bandpass ripple. The bandwidth for Chebychev filters is defined between equal ripple points and it is less than the 3 dB bandwidth. INTRFIL then calculates and reports the 3 dB bandwidth and the minimum in band return loss. If you specify a Butterworth filter, the bandwidth is the 3 dB bandwidth and no additional information is needed.

INTRFIL proceeds to requesting the load impedance. This is generally 50 ohms. INTRFIL then asks for the ground plane spacing and the rod diameter dimensions.

INTRFIL calculates and reports the diameter to ground plane spacing ratio, d/h, the impedance of the specified slab line and the impedance of an equivalent co-ax line. These data will be used later for the approximations that determine the rod capacitive loading and the resonator Q.

INTRFIL calculates rod coupling in terms of even and odd mode impedances. These impedances are depicted in Figure 12 below. The even/odd mode impedances for each set of coupled lines and the resulting coupling coefficient are calculated and printed. You could build a filter directly from these values but each set of lines will have a different rod diameter.

INTRFIL then calculates a new set of even and odd mode impedances where the rod diameter is fixed, ie: d/h is fixed. The algorithm uses the fixed d/h and the coupling coefficients calculated in the previous step to calculate the rod spacing, s/h. This is a compromise but it appears to work well for narrowband filters where the coupling between adjacent sets of rods is fairly weak. From s/h and the rod diameter, INTRFIL calculates the center-to-center (c-c) distance for each set of rods.

Using the ¼ wavelength at the center frequency as the cavity wall spacing, INTRFIL estimates the rod length. The actual rod length is somewhat less than a ¼ wavelength.   The rod is foreshorten by the fringing capacitance, Cf, formed by the open circuit at the end of the rod and by the parallel plate capacitance, Cp, formed by the gap between the end of the rod and the cavity wall, Cp. The total capacitive loading is the sum of these two capacitors. See Figure 3.

The ¼ wave dimension for the cavity may not be very convenient so you have the option of specifying a new cavity wall spacing. However, you are limited to a change of +/-10% from the ¼ wave dimension. In the example above, the actual ¼ wavelength is 0.512 inches. A more convenient dimension would be 0.500 inches. That paired with ¼ inch thick side bars will result in 1.0 inch wide top and bottom covers. Covers for the test filter were made with a 0.032” X 1.0” brass strip obtained from K&S Precision Metals. K&S material is available in many hobby shops. With this new value of cavity spacing, INTRFIL goes back and recalculates the gap, a new capacitive loading (Cp), and the resulting rod length. This is also shown in Figure 3.

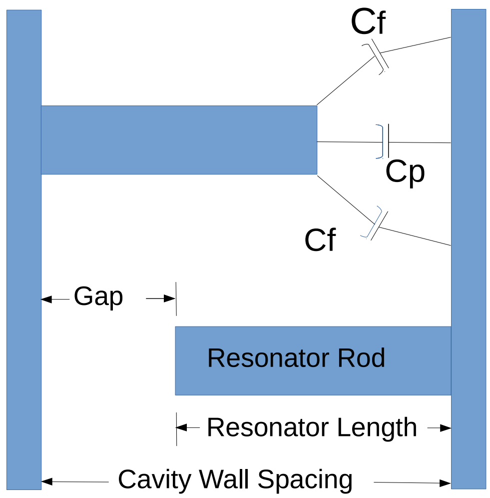


Figure 3: Fringing capacitance, Cf, and parallel plate capacitance, Cp, formed by the end of the resonator rod. The relation between the gap at the end of the resonator, the resonator length and the cavity wall spacing are shown. INRFIL adjusts the gap and resonator length for small changes in the cavity wall spacing so as to maintain the chosen center frequency.

An estimate of the resonator Q and filter loss is next reported. Measurement suggests that this estimate is optimistic but not unrealistic. Later in the paper is a discussion of the limitations of the loss estimate. INTRFIL also calculates a "filter Q". This the ratio of center frequency to specified bandwidth. A rule of thumb is that resonator Q should be 10 times the filter Q for reasonable loss performance. This is not a requirement but it provides insight into loss performance.

Finally INTRFIL creates data for a simulation model using coupled lines. These data can be used in simulators like QUCS to create a simulation. Any simulator that has a single coupled line model should be able to employ this data to create an array of coupled lines that mimics the interdigitated structure. Information for creating this simulation is provided later in the paper.

Center Frequency Approximation

The rods in interdigital filters are nominally a ¼ wavelength length long at the filter center frequency. However in practice, the rods must be slightly shortened because they are loaded by the fringing capacitance at the open end of the rod and the parallel plate capacitor formed by the end of the rod and the side wall of the filter. The INTRFIL algorithm used to correct the rod length is an approximation. There does not appear to be a model for the fringing capacitance for slab line. However the work of Nicholson (6) uses a mathematical concept called conformal mapping (7) to convert the slab line into an equivalent coax line and then estimates the fringing capacity of that coax line. A 5th order polynomial curve fit is used to approximate Nicholson's fringing capacitance. The data were obtained by measuring the capacitance plot in Nicholson's paper with digital calipers and then doing a polynomial curve fit. The curve fit coefficients were obtained with Octave's polyfit. This works surprisingly well as it almost exactly reproduces Nicholson's example.

There is good agreement between the center frequency reported by the simulator and the measured center frequency of a built filter but these results suggest that Nicholson's algorithm makes a filter that comes out high in frequency. This is fortuitous as the filter can be tuned down with screws at the open end of the rods. The 2304 MHz filter described later came out high in frequency as well.

As already noted, INTRFIL gives you the option to slightly adjust the cavity width. You are limited to a change of +/-10% from the ¼ wave dimension. With this new value of cavity spacing, INTRFIL goes back and recalculates the capacitive loading, a new rod length and the resulting gap between the rod end and the filter wall. To accomplish this, INTRFIL uses an iterative algorithm (8). It will return a "failed to converge after 40 iterations" error message if it is not successful. You should not see this error as this algorithm, while slower than the algorithm described later for s/h, is mathematically guaranteed to converge to an answer. If this error appears, it likely that the estimate falls outside the range that the algorithm can test. This suggests that you attempted too large a change in cavity width. The reason for the +/- 10% limit is to limit the range over which the algorithm will work. There is some error checking to enforce this +/- 10% limit so you should never see this error.

The test filter center frequency was tuned to 5770 MHz with the tuning screws. This is slightly high so 5760 MHz is at the lower end of the passband. This maximizes the LO and image rejection when using a 28 MHz IF.

The measured center frequency for the filter with the predicted 0.395" (10.044 mm) rods was 6034 MHz and the simulation reports 6017 MHz as the center frequency. See Figure 4 for a QUCS simulation and the measured results of the filter built to the computer specification. The rods for the test filter were then lengthened 2.5% from the predicted 0.395" to 0.406" (10.044 mm to 10.3 mm) to make tuning easier. Cf does not change although with the longer rods Cp will be slightly larger. The simulator was used to check the center frequency. With the longer 0.406" (10.3 mm) rods, the measured untuned center frequency is approximately 5869 MHz and the simulator reported the center frequency as 5895 MHz.

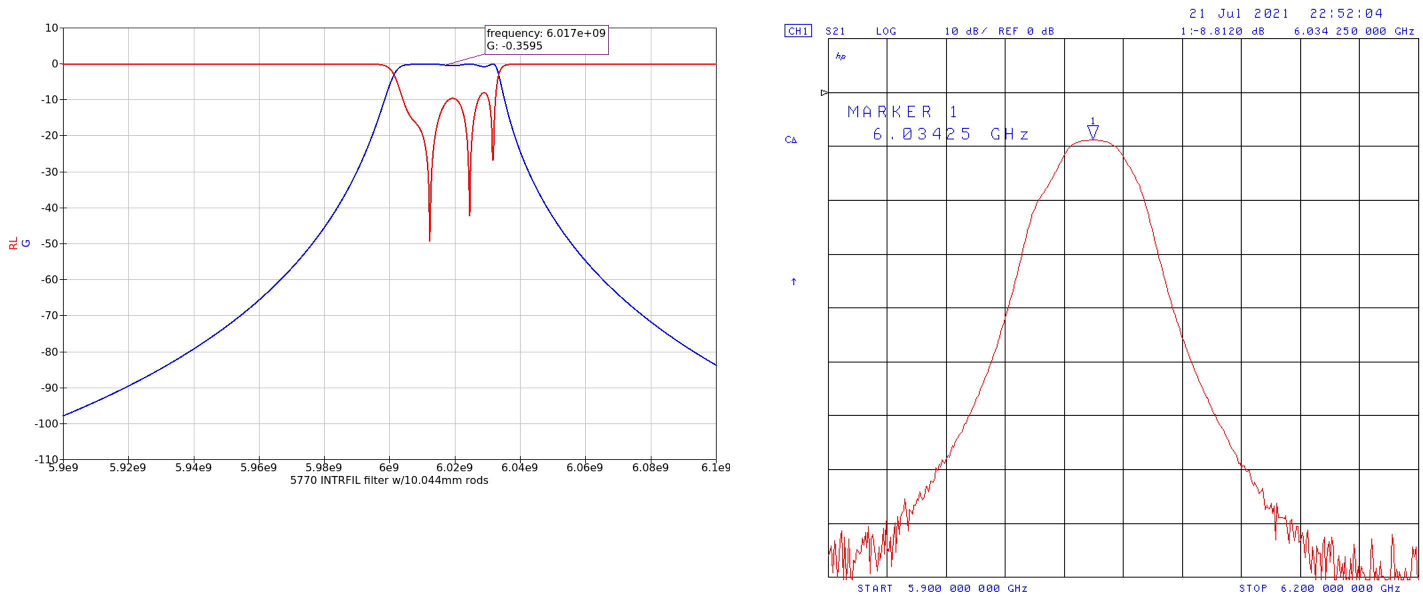


Figure 4: The simulator plot on the left is for 0.395” (10.044 mm) rods with 0.1845 pf capacitive loading. The simulator plot does not account for loss. The plot on the right is the measured filter with no tuning built to the same parameters. The simulated and measured center frequency is approximately 4.5% higher in frequency than requested. It was possible to tune this filter down to 5770 MHz but, in the final test filter, the rods were lengthened 2.5% to 0.406” (10.3 mm) to make for easier tuning.

Needless to say at 5.7 GHz a few thousandths of an inch make a difference but the simulator is useful in predicting the center frequency. The filter still needs to be tuned to get a flat passband. Filters this narrow will never be “no tune” although the filter with the 0.395” long rods has a surprisingly well formed passband with no tuning. Inevitably filters such as this must be tuned but their predicted center frequency should be close enough to allow for predictable tuning. It is even better if they have a reasonably formed passband without tuning. That way they can be tuned with a simple signal source. Figures 5 and 6 are the measured and simulated results respectively for the completed filter tuned to 5770 MHz. Figure 9 below in a complete mechanical drawing for the 5760 MHz filter.

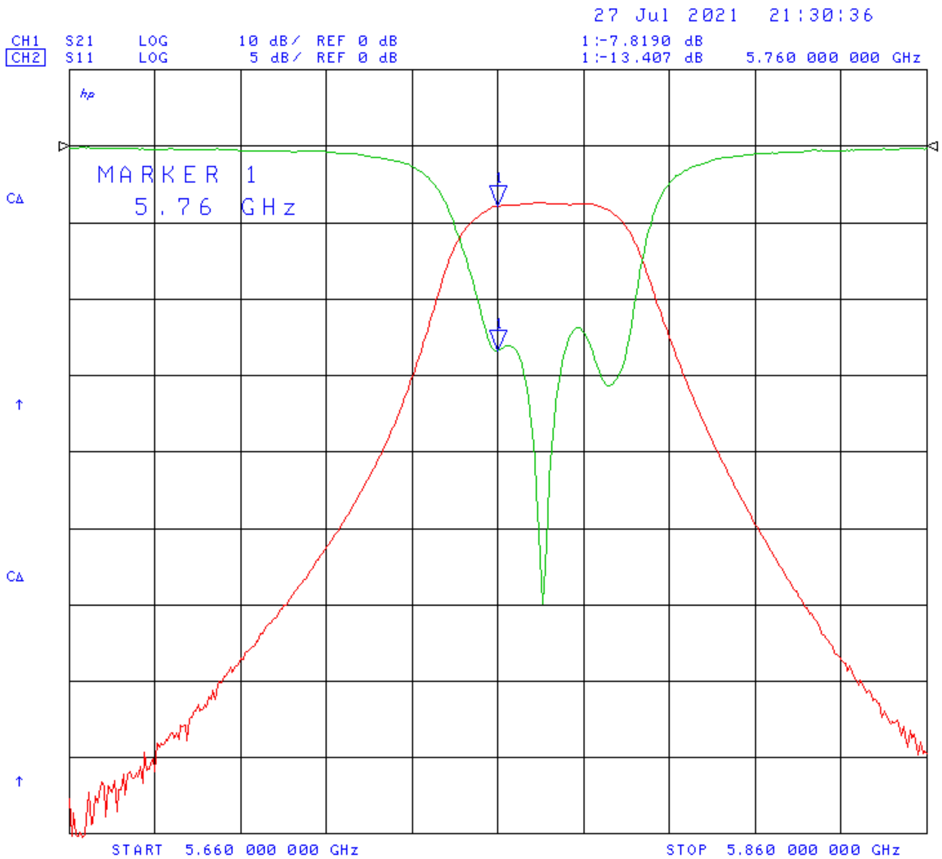


Figure 5: Measured results for the completed filter. The red trace is the filter insertion loss (10 dB/division) and the green trace is the return loss (5 dB/division). The measured 3 dB bandwidth is 36.96 MHz and the midband insertion loss is 7.5 dB. This filter was tuned to 5770 MHz so 5760 MHz is at the bottom of the passband. This filter is 33.4 dB down at 28 MHz removed from 5760 MHz and 56.5 dB down at 56 MHz removed. A return loss of 10 dB corresponds to a VSWR of approximately 1.9:1.

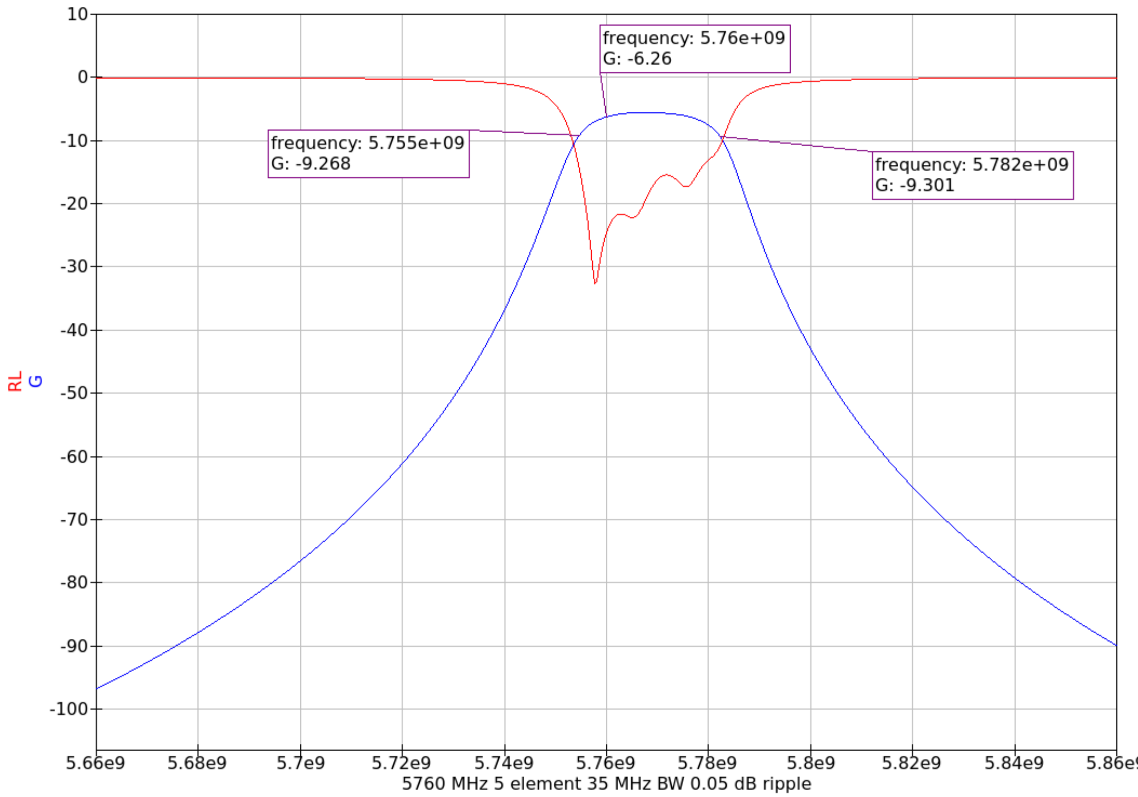


Figure 6: Simulated results for the completed filter. The loading capacitors were trimmed on the simulator to move the frequency down to agree with the measured filter. The 3 dB bandwidth is 27 MHz. Filter loss was adjusted to reflect the loss predicted by the computer synthesis. Loss narrows the bandwidth as it tends to affect the edge of the passband more than the center. Without the loss, the simulated 3 dB bandwidth is 31 MHz. The QUCS simulation model is shown in Figure 14 below. The filter rods were lengthened to 0.406” (10.3 mm) from the 0.395” (10.044 mm) reported for the simulation data in Figure 2.

Chebychev Bandwidth Specification

The bandpass for Chebychev filters is defined between equal ripple points and that is less than the 3 dB bandwidth. When a Chebychev filter is specified, INTRFIL calculates the 3 dB bandwidth and the minimum in band return loss for the specified ripple. For passive lossless networks, power is either transmitted through the network or reflected from it. Formally this is:

$$1-|S_{21}|^2=|S_{11}|^2$$

$|S_{11}|^2$ is the ratio of the reflected power to the incident power. It is often referred to as return loss and given in dB units. Since the ripple you specify for a Chebyshev filter is actually an insertion loss and given the lossless assumption, there will be a corresponding reflection. If you are lucky enough to have access to a network analyzer, return loss is a very sensitive way to tune filters. Note that “return loss” is often specified as positive number of dB and, the larger the number, the better match. It is important to remember that it is actually a numerical ratio less than one and you need to know when to include the negative sign in dB calculations.

Resonator Q and Loss Approximation

INTRFIL estimates the resonator Q and calculates an approximate loss for the center of the passband. The Q approximation was developed by Nicholson (9) and it uses the equivalent coax line created by conformal mapping. Resonator Q is estimated on the basis of brass as the filter material but it is possible to edit INTRFIL to accommodate other materials. Brass is more lossy than silver but brass, copper and aluminum will probably be the most common construction materials. There is a note in the INTRFIL source code that tells you how to edit the code to accommodate a different construction material.

Resonator Q is used to estimate filter loss. 5.27 dB is the predicted loss for the 5.7 GHz test filter. The actual measured midband loss is approximately 7.5 db. It is not surprising that the accuracy of this prediction degrades as the frequency increases. The loss estimate is more accurate for the 2.3 GHz filter described later.

Construction Thoughts

The easiest and most accurate way to create a filter is to use a lathe and a milling machine. The CNC machines available in some Makerspaces would be ideal but not all amateurs have access to such equipment. Your author has a manual table-top milling machine and a 60+ year old Atlas lathe (sold under the Sears Roebuck name!). The lathe has a set of 3AT collets which allow for precisely drilling and tapping the end of the small diameter rods used for the resonator rods.

It may be possible to get around the lack of machine shop facilities. Your author published a paper on making waveguide bandpass filters in Microwave Update 1989. (10) A technique was outlined in that paper for precisely placing the posts in the waveguide using only a drill press and a set of calipers. Your author hasn't tried it but that technique might be adapted for making INTRFIL filters. A good set of calipers is a must. The rod length can be increased by the wall thickness and the filter wall drilled for the rod diameter. The rods can then be soldered in the side wall negating the need to drill and tap the end of the rod. However, getting the rod length accurate this way is more difficult. Find a friend with a lathe!

Most of the test filters were made with brass rods and copper/brass side walls. Standard sized material was used where possible. d/h = 0.5 is a convenient dimension and it creates slab lines close to 50 ohms. Material can be obtained on line. Most of the author's material came from Online Metals (11) but there are other vendors. The top and bottom plates in most of the test filters were made with brass K&S metal strips, printed circuit board (PCB) material or 0.05" aluminum sheet. PCB material results in a copper wall. The PCB top and bottom plates were trimmed to size with the milling machine. A word of caution when working with PCB material. The glass epoxy is very abrasive and it will quickly dull a file or a high speed steel mill cutter. Your author uses a solid carbide mill cutter. More expensive but up to task.

Depending on rod size, the end of the rods are drilled and tapped for 2-56, 4-40 or 6-32 screws. 4-40, 6-32 and 8-32 screws were used for tuning screws. The top and bottom plates are held on with 4-40 screws. A lid screw is place half way between each rod. Some early 5.7 GHz test filters used smaller 2-56 screws. Avoid these if possible as 2-56 taps are more expensive and VERY easy to break! There are a lot of holes and, if you break that small tap, it usually means you have to start over.

The ends of the filter are left open. If the side walls and top/bottom plate extend for a couple of rod diameters beyond the last rod, closing the end should have little effect. This doesn't seem to be critical.

Input/output can be done through either 0.085/0.141 semi-rigid coax soldered into the side wall, see Figure 7, or SMA connectors. If the side wall is more than 0.375” wide, you can drill and tap for an SMA connector. The connector should be threaded continuously over its entire length so it can be screwed into the side wall. See Figure 8. SMA connectors have a ¼-36 thread. While this thread is somewhat uncommon, taps are available. They can be found on eBay or at machinist supply houses like Victor Machinery Exchange (12).

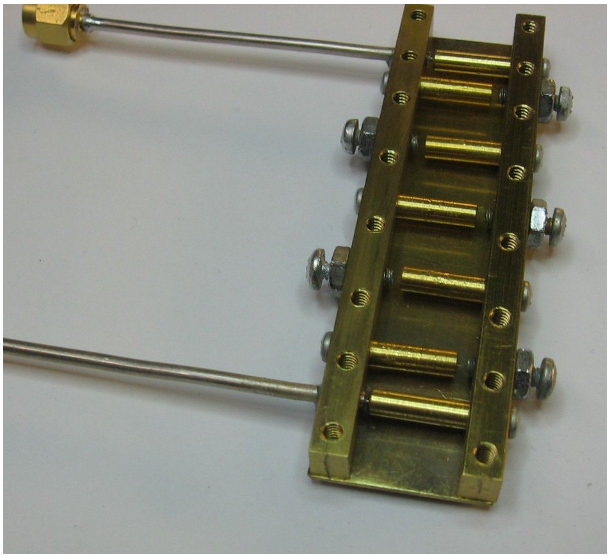
Be sure the connector is long enough to go through the side wall, accommodate a lock nut and the SMA plug. It appears that SMA connectors threaded over their entire length are getting harder to find. A header rear mount connector from Jameco (13) part number 153286 was used for the 5760 MHz test filter. The side bar is 0.25” thick so the ¼-36 mounting hole had to be counter sunk about 0.06” to allow the end of the connector to came through. A close examination of Figure 1 shows the counter sink.

Connectors similar to the Jameco part can be found on eBay. However, be careful of eBay connectors. Their insulation may not be PTFE. As a result they may be very lossy at microwave frequencies or they may have unexpected discontinuities.

The one end of an end coupling rod will be drilled and tapped for a screw to hold it to the side wall. The other end is drilled with a small center drill (#0) so the center pin of the SMA connector or the center conductor of the coax can be soldered into the hole. That way the connector or the coax can be connected to the coupling rod with a minimum of discontinuity. Since the coupling rod is a not a resonator, its length is less critical. Adjusting its length is one way to optimize the connector projection. A close examination of the mechanical drawing in Figure 9 shows that coupling rods were lengthened from 0.406” to 0.420”.

Internal to INTRFIL, all dimensions are calculated in cm but the dimensions are reported in inches. (My apologies to my metric colleagues.) You can obtain metric dimensions by editing everywhere INTRFIL has 2.54 and replacing it with 1 and replacing all the “in” labels with “cm”. INTRFIL reports the rod length in mm in the simulation data because the QUCS coupled line model specifies the line length in mm.

Figure 9 is the mechanical drawing created for the 5760 MHz test filter. It is dimensioned in such a way that it uses the bar end as the reference and the dimensions are accommodated by advancing the mill table. The mill has a digital readout that makes this accurate and relatively easy.



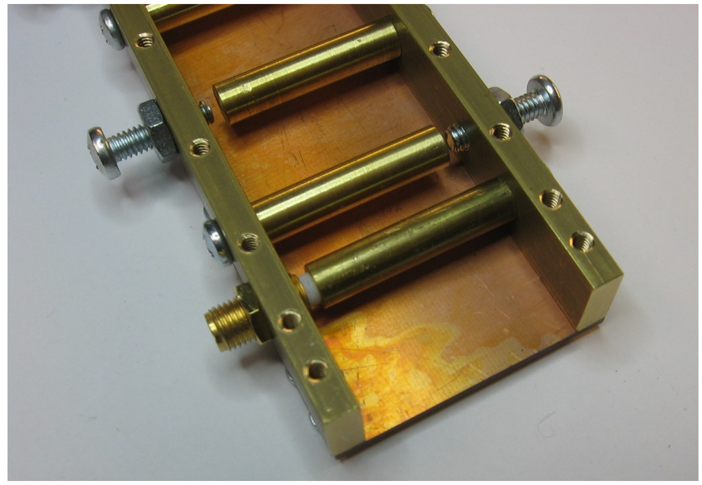


Figure 7: 5.7 GHz filter fed with 0.085” semi-rigid cable soldered into the filter wall. This early filter was done with 0.125” rods secured with 2-56 screws.

Figure 8: 2.3 GHz filter fed with a SMA connector. The rods are 0.25” in diameter.

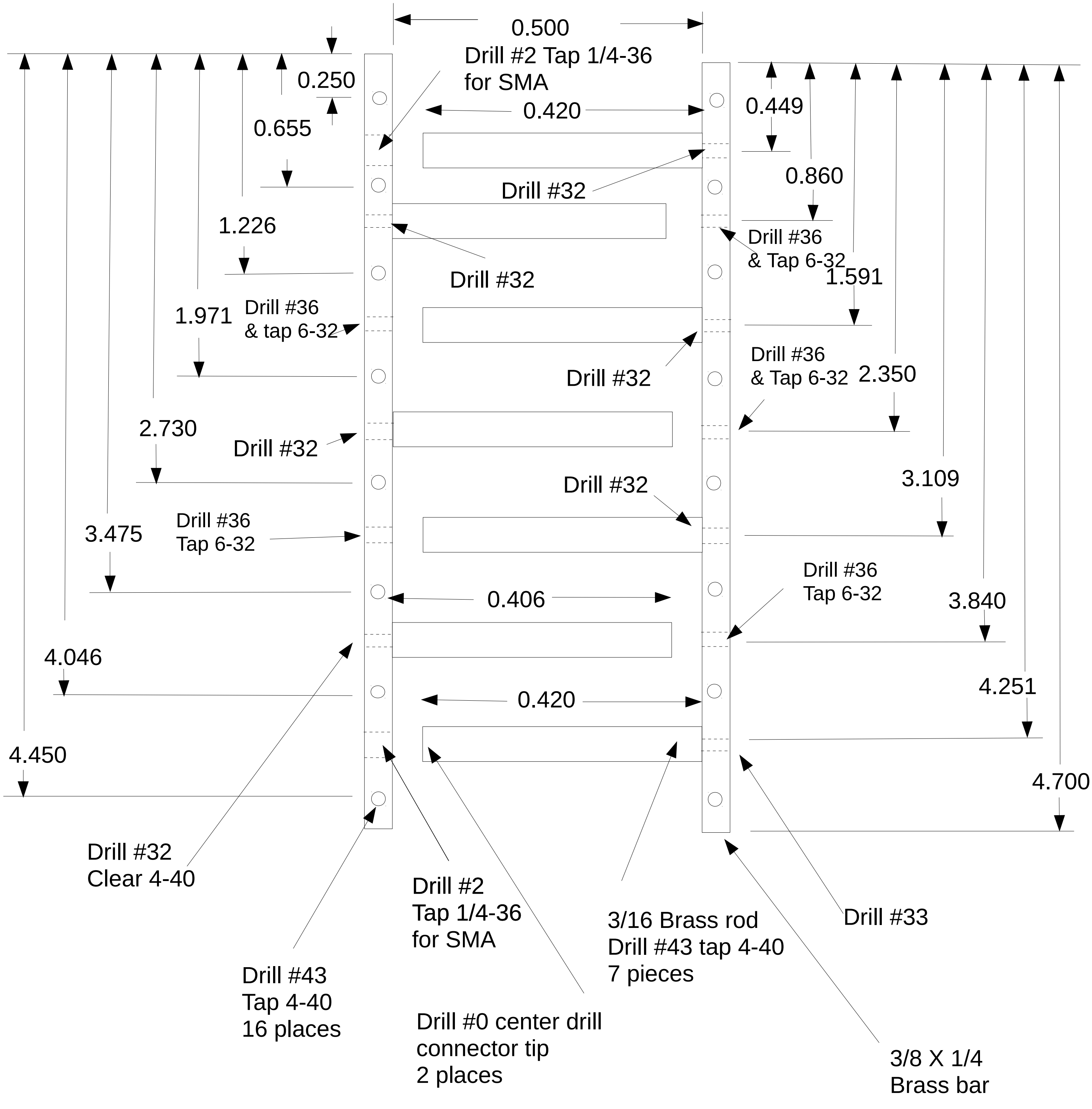


Figure 9: Mechanical drawing for 5760 MHz test filter. While not specified in the drawing, the edge and side bar holes are located along the bar and side center line.

Inside INTRFIL

INTRFIL is built around the algorithm published by Matthaei (14) for an edge coupled filter as shown in Figure 10. The resonators are ½ wavelength long and their ends are grounded. The Matthaei paper also has an algorithm for the dual of this filter where the ends of the resonators are open circuited. That topology is probably more common in amateur use.

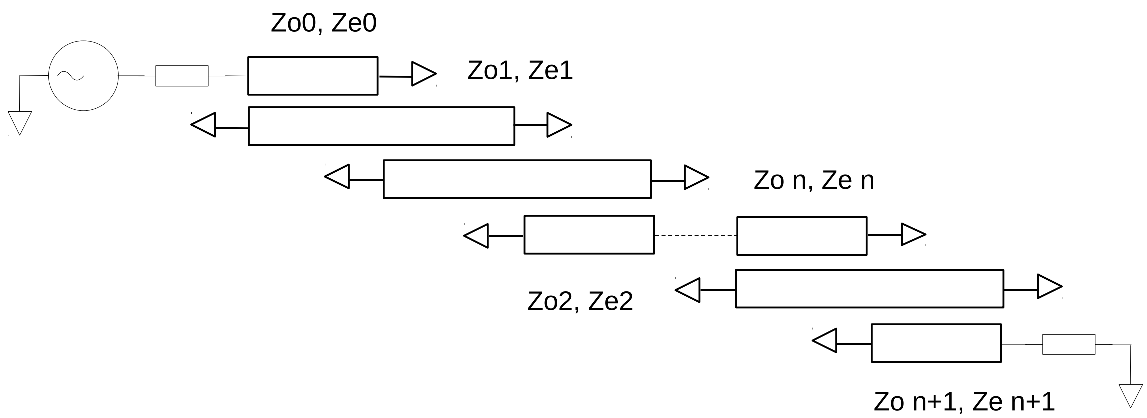


Figure 10: Half wave edge coupled filter with grounded ends.

An examination of this structure suggested that it might be modified to make an interdigitated filter by folding it in half. This is shown in Figure 11.

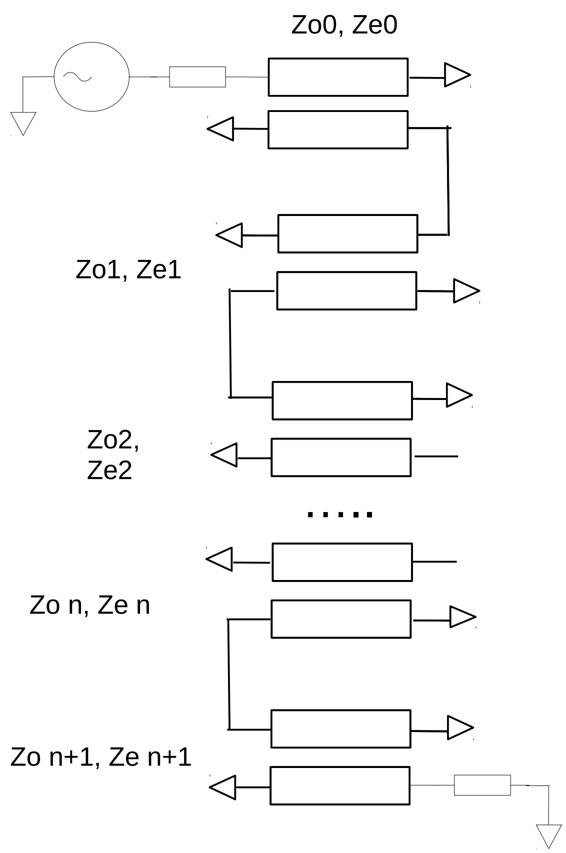


Figure 11. Folder filter. Elements 0 and n+1 are the input/output coupling bars.

While not immediately obvious, this doubles the bandwidth because the filter impedance is cut in half. The ¼ wave sections that were once in series are now in parallel. This was discovered almost by accident while simulating the interdigitated implementation of this filter. To correct for this, INTRFIL simply divides the bandwidth you specify by two.

The dimensions for an interdigitated filter are usually determined by the capacity to ground and the rod to rod capacity of each set of rods. The classic way to do this is from the graphs of E. G. Cristal (15). Unfortunately this creates different sized rods for each resonator and the graphs do not lend themselves to computer aided design. Vadopalas and Cristal (16) suggest that approximations for even and odd mode impedances could be used to analytically synthesize the rod to ground and rod to rod capacitance. This could be the basis for a computer algorithm.

INTRFIL does not require this step. The folded version of INTRFIL is already defined by its even and odd mode impedances. The definition of even and odd mode impedance is shown in Figure 12.

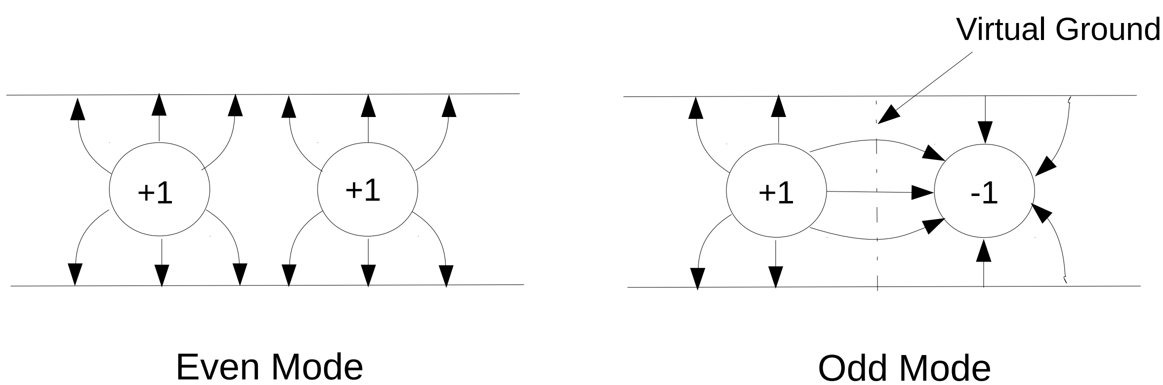


Figure 12: Even and Odd Modes. With the even mode, each line is charged to the same potential and is has a characteristic impedance Zoe and for the odd mode they are charged to opposite potentials and the impedance is Zoo.

Using the even and odd mode impedances, INTRFIL calculates the coupling coefficient, K, between pairs of rods:

$$K=\frac{Zoo-Zoe}{Zoo+Zoe}$$

It is possible to enforce equal diameter rods and adjust rod spacing, s/h, to obtain new even and odd mode impedances that produce the same value of K. However, this compromises the internal impedance of the filter. Simulation suggests that this has little effect for narrowband filters where the coupling between rods is relatively weak and where the difference between the two different sets of impedances is not that great. Exactly where this approximation breaks down is not known. Filters for amateur use tend to be fairly narrowband. Some 5 element 5% BW filters made for 1900 MHz exhibited an unexpected decrease in return loss (poorer match) in the center of the passband. The narrowband test filter did not show this decrease in return loss. This suggests that the internal coupling in the wider band filters may not be correct. The bandwidth and response of these wider band filters were very close to the prediction and they were still quite usable filters. Similar 3 element filters did not exhibit this effect. It is not clear if this is related to the filter synthesis, to the tuning or to construction anomalies. This might be an exercise for the simulator.

A computer algorithm that calculates the even and odd mode impedance of a pair of coupled lines from d/h and s/h is implemented in INTRFIL (17). This algorithm relates Zoo/Zoe to the filter dimensions. The result is an array of equal diameter rods that form the filter.

Here is where INTRFIL has to do some heavy computing. You have K and d/h but not the rod spacing, s/h. K is a function of Zoo/Zoe which are a complex function of d/h and s/h:

$$K = f(Zoo, Zoe) = f(d/h, s/h)$$

Given the complexity of the Zoo/Zoe algorithm there is no direct way to solve for s/h. INTRFIL uses an iterative numerical technique (18) that creates values for s/h until the difference between the computed value of the coupling coefficient K and the original value of K is less than a specified error. For some values of d/h, s/h or K, this algorithm may not converge properly to an answer. The resulting s/h and Zoo/Zoe may still be usable but with reduced precision. The simulator can validate the results. INTRFIL returns a "failed to converge" error if the algorithm does not converge correctly. This error shouldn't occur very often but slight changes in bandwidth and/or ripple usually correct the problem.

Simulation

The ability to simulate a filter was an important part of the development of INTRFIL and it is useful for verifying the results generated by INTRFIL. It allows trimming the resonator length and/or the loading capacitors and checking filter bandwidth. Design followed by simulation followed by construction and measurement was the work flow. Good agreement between simulation and measurement gives one confidence in the design. Once there is confidence in the design, filters can be built without sophisticated test equipment.

Simulators such as QUCS have a model for a single pair of coupled lines. It is necessary to create an array of coupled lines that model the filter. This can be done with the technique outlined in (19).

Single coupled lines are connected in parallel to create the array. The even and odd mode impedances are adjusted to accommodate this parallel connection. INTRFIL calculates these new impedances for the parallel connection as Zooprime and Zoeprime:

$$Zs = slab\,Zo$$

$$Z'oe = \frac{1}{\left(\frac{1}{Zoe} - \frac{1}{2\,Zs}\right)}$$

$$Z'oo = \frac{1}{\left(\frac{1}{Zoo} - \frac{1}{2\,Zs}\right)}$$

The model requires an extra transmission line at the input/output to balance the array. Its impedance is given by:

$$Z's = 2\, slab\, Zo$$

slab Zo the impedance of the slab line reported by INTRFIL for the specified by d/h.

The array is shown in Figure 13. As part of the synthesis process INTRFIL calculates all required values for the simulation. An implantation of a QUCS simulation is shown in Figure 14.

The simulation is based on all the pairs of lines being the same impedance as the specified slab line. This can be checked by:

$$slab\ Zo = \sqrt{(Zoo)(Zoe)}$$

The largest error occurs for the end pair of rods since they are the tightest coupled. However, the error is only a few tenths of an ohm.

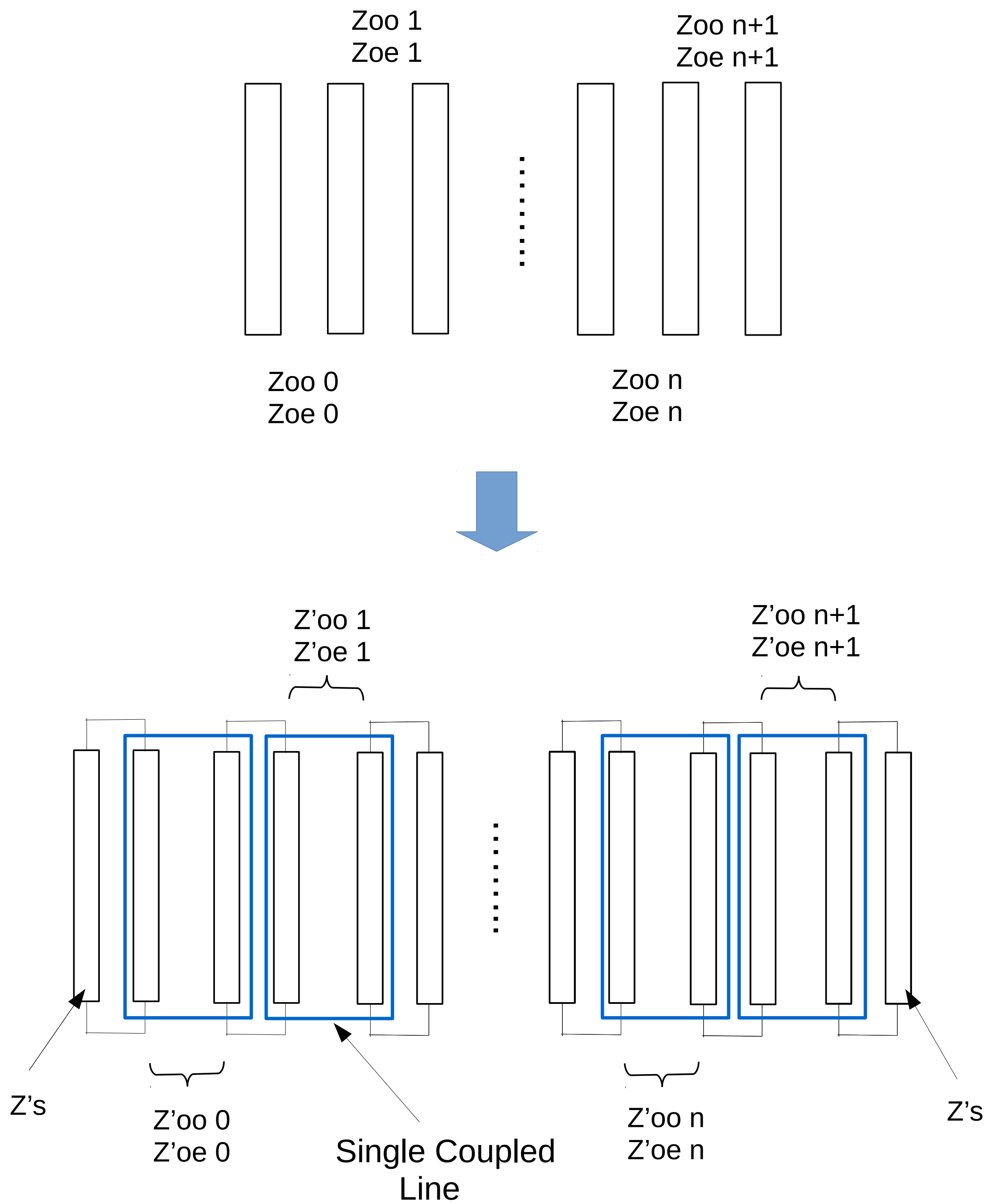


Figure 13: Synthesis of coupled line model for simulating an interdigitated filter.

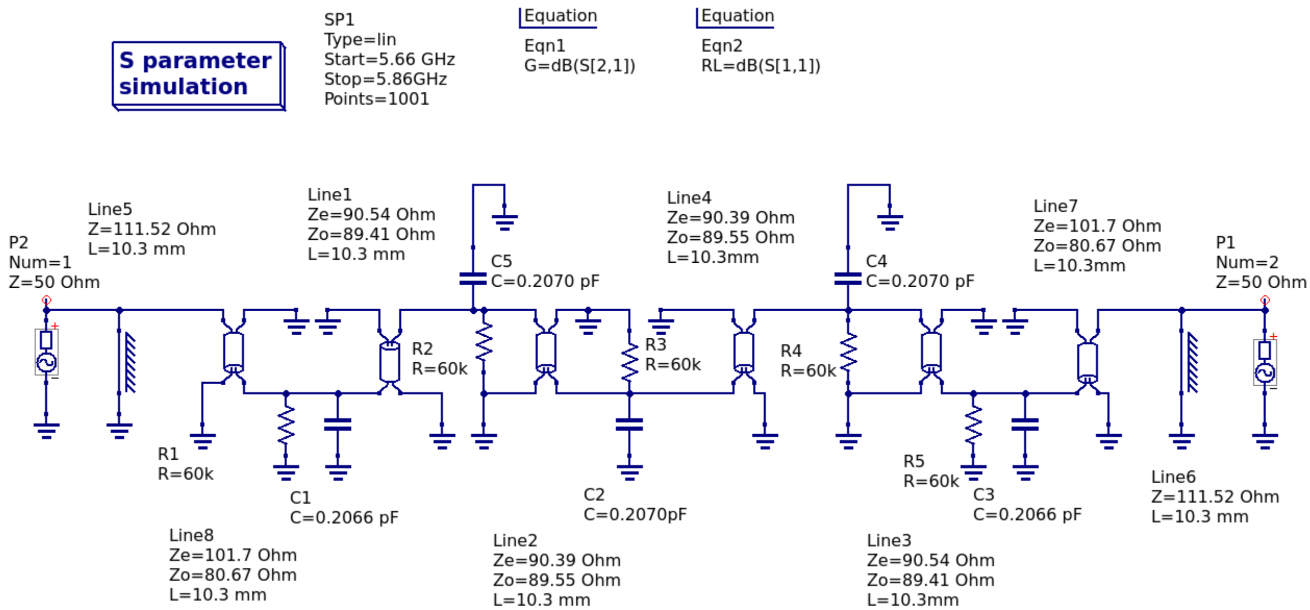


Figure 14. QUCS simulation for the 5 element 5760 MHz filter example using an array of parallel coupled lines. The line impedances for this simulation were obtained from the "Data for simulation model using coupled lines" in Figure 2 above. C1-C5 are the rod end capacitances and they were manually adjusted to tune the filter. You can use the value Ct reported by the computer as starting point. R1-R5 simulate loss although there is a line loss parameter in the QUCS coupled line model that could be used instead. The resistor values were adjusted empirically to simulate the loss calculated by INTRFIL. This is the simulation use to create Figure 6 above.

2304 MHz Filter

A second test filter was constructed using INTRFIL. Figure 15 below is the INTRFIL input/output for this filter. It is a 5 element 30 MHz wide (@ equal ripple points) 0.05 dB ripple Chebychev filter for 2310 MHz. It is intended for a 2304 MHz transverter with a 28 MHz IF. It is tuned to 2310 MHz so 2304 MHz is at the low end of the passband. This maximizes the attenuation of the LO and image frequencies. The simulated and measured response of this filter are Figures 16 and 17 respectively. Figure 18 is a mechanical drawing.

INTRFIL: Interdigitated Filter Program Version 1.0
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Number of elements? 5
Center frequency (MHz) 2310
Butterworth (1) Chebychev (2) ? 2
Ripple Bandwidth (MHz) 30
Bandpass ripple (DB) 0.05
3 dB Bandwidth (MHz) = 35.26 Ripple Return Loss = 19.4 dB
Load impedance 50
ground plane spacing in = 0.5
rod dia in = 0.25

d/h = 0.500 Slab Zo = 55.76 Co-ax Zo = 56.08

Calculated odd/even impedances and coupling coefficients

Zoo[0] = 44.97 Zoe[0] = 55.03 K = 0.10056
Zoo[1] = 49.07 Zoe[1] = 49.93 K = 0.00871
Zoo[2] = 49.18 Zoe[2] = 49.81 K = 0.00643
Zoo[3] = 49.18 Zoe[3] = 49.81 K = 0.00643
Zoo[4] = 49.07 Zoe[4] = 49.93 K = 0.00871
Zoo[5] = 44.97 Zoe[5] = 55.03 K = 0.10056

Odd/even impedances for fixed d/h = 0.500 with s/h rod spacings

Zoo = 49.67 Zoe = 60.78 s/h[01] = 0.4607 c - c = 0.480 in
Zoo = 55.14 Zoe = 56.11 s/h[12] = 1.2009 c - c = 0.850 in
Zoo = 55.28 Zoe = 55.99 s/h[23] = 1.2854 c - c = 0.893 in
Zoo = 55.28 Zoe = 55.99 s/h[34] = 1.2854 c - c = 0.893 in
Zoo = 55.14 Zoe = 56.11 s/h[45] = 1.2009 c - c = 0.850 in
Zoo = 49.67 Zoe = 60.78 s/h[56] = 0.4607 c - c = 0.480 in

Parameters for filter cavity length = wavelength/4

Ct = 0.2674 pf Cf = 0.1668 pf Cp = 0.1005 pf
l = 1.103 in gap = 0.110 in lamda/4 = 1.277 in

Cavity spacing width can be adjusted +/- 10% of wavelength/4
Spacing = (in) 1.25

Parameters for Filter cavity

Ct = 0.2485 pf   Cf = 0.1668 pf   Cp = 0.0817 pf
New Ct Rod Length = 1.115 in   New gap = 0.135 in   Rod + gap = 1.250 in

Estimated resonator Q = 1058.1   Filter Q = 77.0
Loss = 2.08 dB

Data for simulation model using coupled lines

Zs = 111.52

Zooprime = 75.36 Zoeprime = 108.63
Zooprime = 87.61 Zoeprime = 90.40
Zooprime = 87.97 Zoeprime = 90.03
Zooprime = 87.97 Zoeprime = 90.03
Zooprime = 87.61 Zoeprime = 90.40
Zooprime = 75.36 Zoeprime = 108.63

Ct = 0.2485 pf Bar length = 28.322 mm

Figure 15: INTRFIL run for the 2310 MHz test filter. The cavity width was adjusted to 1.25” from the ¼ wave dimension of 1.277”.

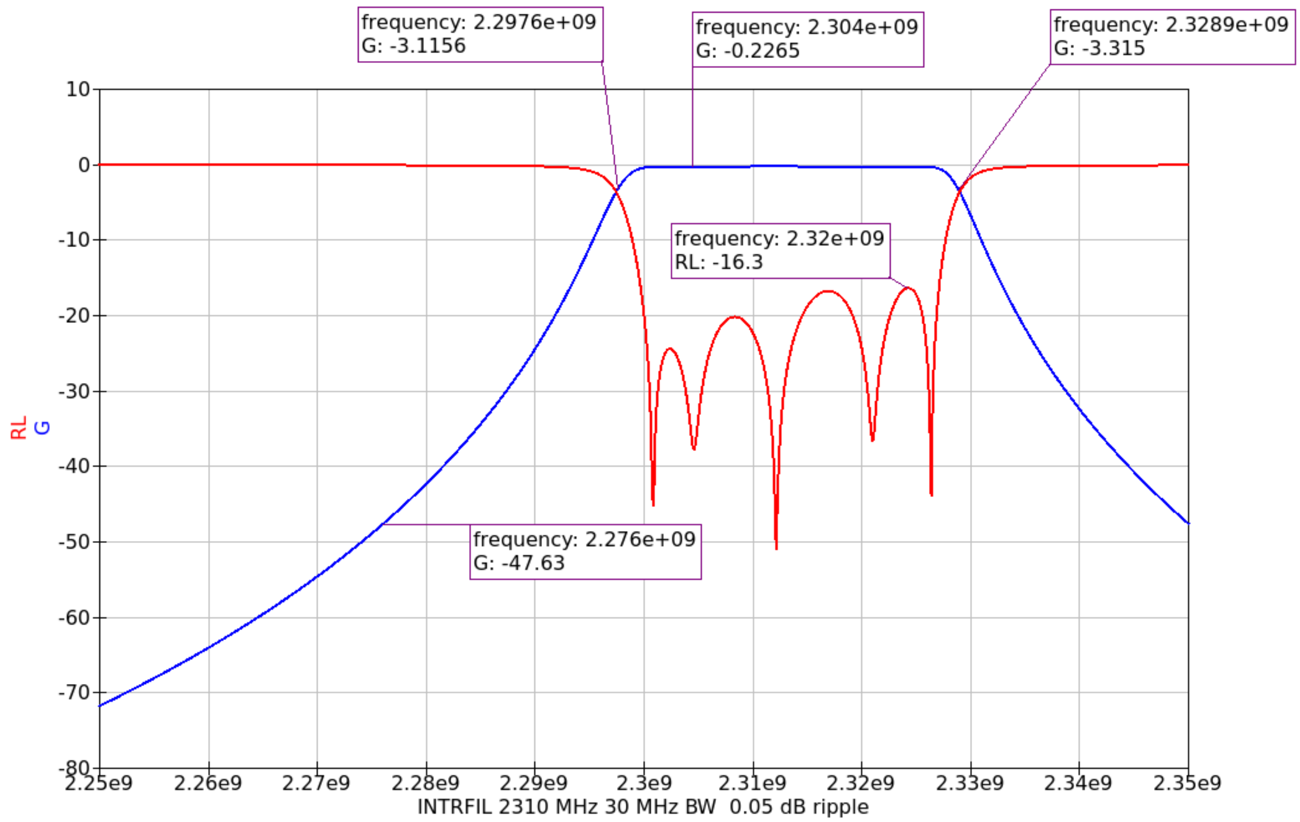

Figure 16: The simulated response of the 2310 MHz test filter. The simulated 3 dB BW is 31.3 MHz. The rods were lengthened approximately 0.009” to 1.124” (28.55 mm) and the loading capacitors trimmed. This increase in rod length is approximately 1%. No loss was added to this simulation. With the 1.115” rods originally predicted by the computer (and no tuning), the simulated center frequency was approximately 2371.0 MHz and the actual measured center frequency of the test filter without tuning was 2359 MHz. This is ~2.0% high. Even with 1.115” rods this filter tuned down to 2310 MHz easily.

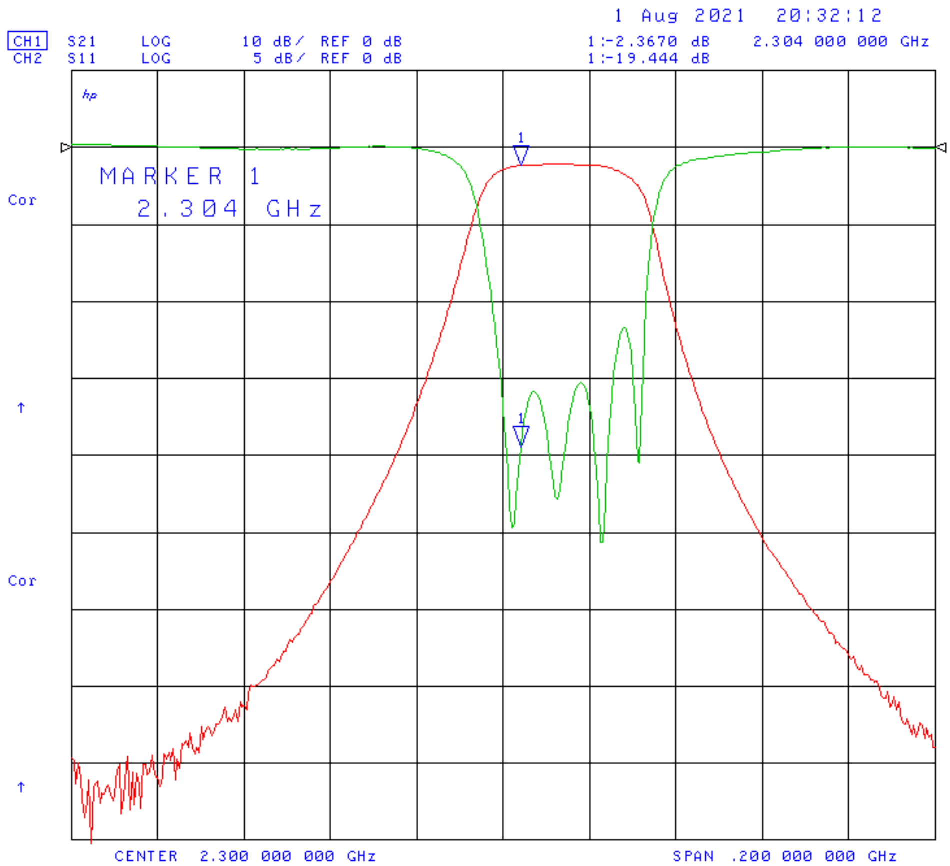

Figure 17: The measured response of the 2310 MHz test filter. The red trace is the filter response and the green trace is the return loss (at 5 dB/division). The measured 3 dB bandwidth is 35.92 MHz and the midband loss is 2.17 dB. The LO at 2776 MHz for a 28 MHz is attenuated 36.5 dB. The image frequency at 56 MHz below 2304 MHz is attenuated 63.5 dB.

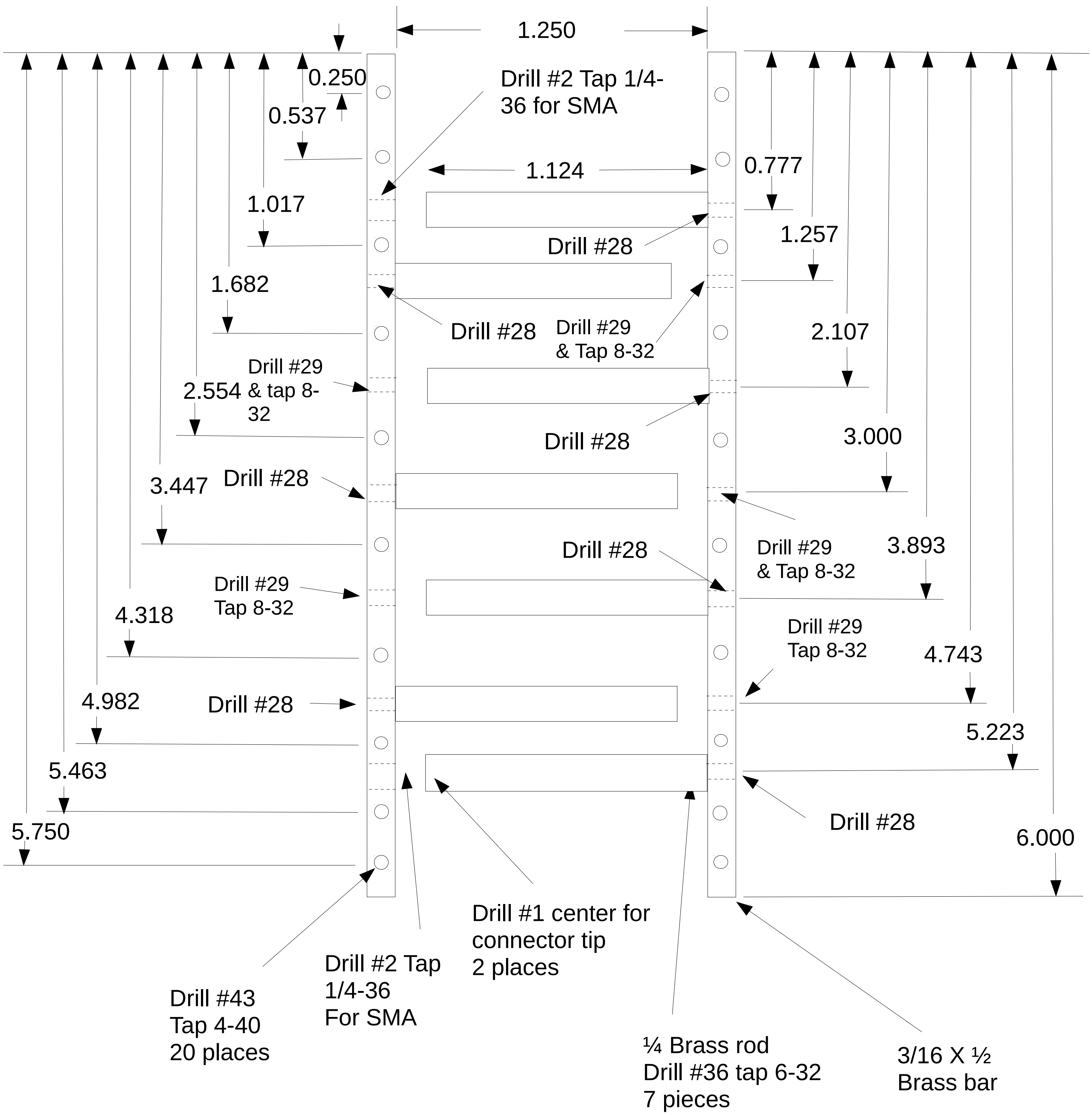

Figure 18: Mechanical drawing for 2310 MHz test filter. While not specified in the drawing, the edge and side bar holes are located along the bar edge and side center line.

Conclusion

INTRFIL creates interdigitated bandpass filters using ¼ wavelength long round rods between parallel ground planes. Table 1 and 2 summarize the designed, simulated, and measured results for the two test filters, one for 5760 MHz and the other for 2310 MHz.

Table 1: 5760 MHz Test Filter

	Design	Simulation	Measured
3 dB bandwidth	35.26 MHz	31.0 MHz w/o loss	36.96 MHz
Loss	5.27 dB		7.5 dB
Center frequency	5760 MHz	6017 MHz (6034 MHz measured)	Tuned to 5770 MHz
Rod Length	0.395”	0.395”	0.406”

Table 2: 2310 MHz Test Filter

	Design	Simulation	Measured
3 dB bandwidth	35.26 MHz	31.3 MHz w/o loss	35.92 MHz
Loss	2.08 dB		2.17 dB
Center frequency	2310 MHz	2371 MHz (2359 MHz measured)	Tuned to 2310 MHz
Rod Length	1.115”	1.115”	1.124”

The 5760 MHz filter had significantly higher loss than predicted but the agreement between design, simulation and measurement is encouraging. The 5760 MHz filter has a passband at 6034 MHz with the shorter rods and no tuning. The 2310 MHz filter with the short 1.115” rods had an almost perfectly formed passband centered on 2359 MHz with no tuning. All the rods were +/-0.001” of the 1.115”. Precision is important but the results were encouraging enough that you could build a filter from the computer design and have confidence in its performance without sophisticated test equipment.

This paper shows how to use INTRFIL and obtain useful results. It provides some insight into how INTRFIL operates. Finally, a simulation technique is presented. Network simulators like QUCS offer a way to build your filter in the computer and verify its performance.

INTRFIL should be useful in designing filters in the 500 to 6000 MHz range that will satisfy almost any amateur need.

References

(1) QUCS: Quite Universal Circuit Simulator. There appears to be three flavors of QUCS, the original QUCS (http://qucs.sourceforge.net/), Qucs-S: Qucs with SPICE (https://ra3xdh.github.io/) and QucsStudio (http://dd6um.darc.de/QucsStudio/). All three are available for free download but their licensing and development trajectories are different. QucsStudio appears to be the most developed. It has a nonlinear simulator, an em simulator and a neat "tuning" function with sliders. However, it does not appear to be open source and it is currently available only for Windows. The others have a Windows, MAC and Linux variant and are available under General Public License (GPL). QUCS has a fairly steep learning curve but there are on line tutorials. The simulations in this paper were all generated using the original QUCS as your author is primarily a Linux user.

(2) Hinshaw, Jerry, N6JH and Shahkrokh Monemzadeh, computer-aided interdigital bandpass filter design, Ham Radio, January 1985, pp. 12-26.

(3) https://www.freepascal.org/

(4) http://www.geany.org/

(5) The source code and compiled versions are available from the Blue Ridge Microwave Society (BRMS) group site groups.io/g/brms. Look under the "Files" tab and then "Microwave Filters." The WGFIL waveguide filter program mentioned below is also available there.

(6) Nicholson, B.F., "The Resonant Frequency of Interdigital Filter Elements," IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-14, No. 5, May 1966, pp. 250-251.

(7) Hui, Huang, Liu Xinmeng and Lv Sin, "Optimal Design of Precision Slab-line for N Type Coaxial Automatic Tuner," 79th ARFTG Microwave Measurement Conference, Montreal, Canada, 22-22 June 2012.

(8) Flannery, Teukolsky, Vetterling, *Numerical Recipes in Pascal*, Cambridge University Press, Cambridge, 1989, p. 277.

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(12) https://www.victornet.com/

(13) https://www.jameco.com/

(14) Matthaei, George L., “Design of Wide-Band (and Narrow-Band) Band-Pass Microwave Filters on the Insertion Loss Basis,” IRE Transaction on Microwave Theory and Techniques, November 1960, pp. 580-593.

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(16) P. Vadopalas, P and E.G. Cristal, “Coupled Rods Between Ground Planes (Correspondence), “ IEEE Transaction on Microwave Theory and Techniques, March 1965, Vol. MTT-13, Issue 2, pp. 254-255.

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