Quarter Wave Cavity Filters Using Copper Pipe

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There are a number of documents on the web concerning filters of this type. This document was written to detail my experience with this type of filter. The filter is very effective and easy to build with common tools available in the home workshop. The filter is practical to build for frequencies between 500 to 1500 MHz.

The basic design of this type of filter is a quarter wave rod, grounded at one end, inside of a larger enclosure creating a coaxial structure. In this case the inner rod was round brass tubing and copper pipe served as the enclosure. Tuning of the filter is accomplished by sliding a smaller brass tube up the center of the inner tube. The total length of the inner tube will approach a quarter of a wavelength. The tube will be slightly shorter than a quarter wavelength because of the capacitance present in the structure. An alternative tuning method would be a brass screw in the end of the outer tube to provide a variable capacitance. The effect of the sliding tube or brass tuning screw is to reduce the resonant frequency of the filter. If you make the inner tube too long you will not be able to increase the resonant frequency.

Ideally the characteristic impedance of the coaxial structure of the assembly should be 77-ohms for best unloaded Q. In the home shop the limiting factor will be available materials in construction of the cavity. Try to find material to get as close to 77 ohms as possible. Good results will still be achieved with characteristic impedance from 50 to 100 ohms.

The critical factor in building this filter will be the input and output coupling. If multiple stages are required then the inter-stage coupling is another critical factor. This paper will focus on the single cavity. We will leave the multiple cavity filters for another time.

The input and output coupling can take on two forms. The first is a loop which consists of the inner conductor of the input (or output) coax line going directly to ground. The second configuration is a short tap from the incoming (or outgoing) coax line directly connected to the inner tube. The connection would be made at some fraction of a wavelength above the ground end. Calculating the loop size or tube connection can be difficult and is normally done by experimentation. I found it best to come up with a mechanical design to permit an adjustable coupling. The coupling was too critical to consistently come up with the correct filter response even when duplicating filters using the same construction technique.

I found the coupling loop to ground provided the filter response I was looking for. The direct connection to the inner tube provided a wide filter with little insertion loss. There is a trade off here. A sharper filter requires more insertion loss. A 1296 MHz filter I constructed was so broad that I don’t think there would be many applications for it. It did have the best return loss measurements of all the filters. The return loss was better than 25 DB throughout the 1296 MHz band. The loops to ground provided a much sharper filter but at a cost of insertion loss. Using adjustable coupling loops I was able to make the trade off between sharpness and insertion loss. I could set the insertion loss from a DB or two with a wide bandwidth up to a 10 DB loss with a very sharp bandwidth. In the case of a 738 MHz filter described here I had a 1.3 MHz bandwidth with a 7 DB insertion loss.

The Design

Figure 1 shows the general design values, expressed in wavelengths. I chose to use the sliding inner rod as this provides the smoothest tuning. Tuning screws are somewhat noisy as the screw does not make a good connection passing through the threads. If you have to go this route use a block of Teflon to lock down the screw rather than a lock nut. Drill the Teflon using the proper tap drill for the screw. Let the screw cut its own threads the first time you insert it into the Teflon block.

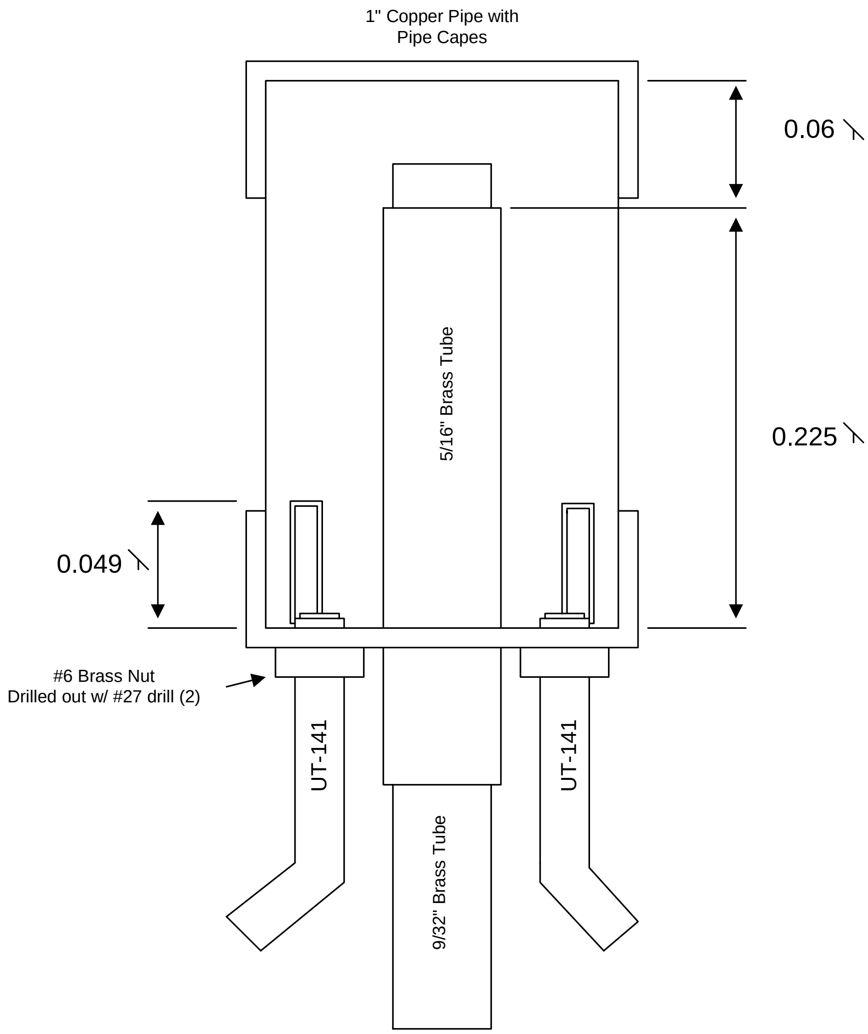

Figure 1 – Filter layout

The sliding tube was made using brass tubing from the hobby shop. The tubing is designed to telescope into the next size up or down. To calculate the diameter of the inner tube use the following formula. Remember we are looking to achieve 77 ohm characteristic impedance.

$$Z = 138 * Log \frac{D}{d}$$

D = Inside diameter of outer tube
d = outside diameter of inner tube

It may help to enter this formula into a spreadsheet to try various combinations depending on what materials are available to you. In my case a 1" copper water pipe served as the outer tube. Running the spreadsheet I ran various diameters of brass tubing available at my local hobby shop. I found a 5/16" inner tube provided 72 ohm impedance. Measure the actual diameter of your parts. The water pipe was slightly larger than 1" (1.03125"). A 9/32" tube telescoped nicely into the 5/16" tube.

I used free space calculations for the wavelength:

$$\lambda = \frac{11808}{Fmhz} \text{ (inches) or } \lambda = \frac{300{,}000}{FMhz} \text{ (millimeters)}$$

For this design the desired frequency was 738 MHz used in a local oscillator chain. The wavelength is 406.5 mm.

The parts list and measurement of cut pieces based on Figure 1:

1. Distance from inner tube to top cap = 24mm
2. Inside length of inner tube = 91mm
3. Allow for 15mm of inner tube to stick out the bottom of the cavity making the total length of the 5/16" inner tube = 106mm
4. Length of 9/32" sliding tube = 145mm. This length is arbitrary. Just have enough to hold onto when the tube is fully inserted.
5. Length of 1" outer tube = 91 + 24 = 116mm
6. UT-141 semi-rigid coax for input and output lines = 90mm
7. Two 1" copper pipe caps will be needed. The bottom cap is drilled to accommodate the inner tube and coax lines.
8. Two SMA solder connectors for UT-141.
9. Two #6 brass nuts

The length of the UT-141 will depend on how you intend to connect the lines. Allow enough length to form the loops. In my case the loops were 0.049λ long, or 20mm. I need about 5mm extra to form around the shield of the line and solder for the lower ground point. Total line required for the loop was 45mm. I added an extra 45mm to extend out of the filter where SMA connectors were attached. See loop photograph for details.

The loop coupling must be adjustable at least initially. After the desired response is achieved the loops can be soldered into place. To provide for this adjustment a hole was drilled into the bottom pipe cap for each coax line using a #27 drill. This is just about 0.141" in diameter. A #6 brass nut was drilled out using the same #27 drill bit. The nut was soldered to the bottom of the pipe cap. This provided a more stable surface to hold the coax line during adjustment. The hole could be snugged up by using a spring loaded center punch to dimple the edge of the hole to tighten the grip around the UT-141.

Assembly

Once the parts are cut to length file any rough edges. Polish with a very fine steal wool. For a final cleaning use a copper cleaner even on the UT-141. For soldering consider using a solder paste such as Solder-It SP7 (http://www.solder-it.com). See suggested source at the end of the paper. Solder paste is stronger than conventional solder and melts at a lower temperature. Use a small butane torch on the UT-141 connectors. When soldering the brass tubes or UT-141 to the pipe cap a conventional plumbing propane torch may be needed. The small pencil butane torch many not be large enough. Do not hit the solder paste directly with the flame. Heat around the solder paste. You first want the flux to flow then move in a little closer to bring the temperature up to the melting point. Let the pieces cool before trying to move them. The copper pipe retains a lot of heat. I know from the burns on my fingers!

I encountered a problem with the sliding tubing. I used a very small pipe cutter for the brass tubing. This resulted in the cut edge being rounded a bit. This prevented the inter tube from sliding past the cut edge of the outer tube. I had to use a 9/32" twist drill and the 5/16" cutting edge of a step drill to open this up. Some filing with a small rat tail file also helped to open the tube back up.

Construct the loops by stripping off 45mm of outer conductor of the UT-141. Take smaller sections rather than try to pull off 45mm. You might break the center conductor if you try to pull off too much at one time. Once the center is exposed form the loop as shown in the photograph. Solder the ground end of the loop to the outer conductor of the UT-141 as close to the edge as possible. It helps to try to bend that last 5mm around the coax line. The center conductor is very stiff so this will not be easy. Don't let too much stick out on the ground connection as there is not much room between the center rod and the inside edge of the pipe cap. Do not attach the SMA connectors at this point. You need to slide the UT-141 into the pipe cap first.

Drill the bottom pipe cap to accommodate the 5/16" inner tube and two UT-141 lines. Drill the 5/16" hole using a step drill. The step drill will be more accurate than using a twist drill. Use a spring loaded center punch and then a centering drill to make the initial hole. The 5/16" hole is in the center of the pipe cap. The UT-141 #27 holes are between the edge of the center hole and inside edge of the pipe cap. This works out to be about 4mm from the edge of the center hole. The coax lines are directly opposite each other with the center tube in the middle between them.

Finding the center of the pipe cap can be a problem. The edges are rounded and I had trouble measuring the center. I found a simple way to determine where the center is located. Stuff some steal wool into the open end of the pipe cap. Hold the cap in one hand and the steal wool with the other hand. Spin the cap around several times. The steal wool will carve groves into the inside surface of the pipe cap. They will look like rings on a cut tree trunk. The center ring will be a small round circle. Pop the middle of this circle with the center punch. You found your center. Drill this dimple with a centering drill. The centering drill should drift less than using just the twist drill. Copper is a hard material so the drill tends to move away from the center if you are not careful.

Use a vise to hold the inner rod then place the pipe cap over the tube so 15mm sticks out the bottom. The bottom of the pipe cap will be facing up. The tube must be 90-degrees to the bottom edge of the pipe cap. I aligned the tube with a small square prior to setting the pipe cap in place. Use very little pressure from the vise to hold the tube. The brass can be crushed if too much pressure is used. If it is crushed the inner tube will not slide into the outer tube. Also add the #6 nuts over the #27 holes. A piece of UT-141 will be necessary to align the nuts with the holes. Leave the UT-141 in place during the solder process otherwise the nuts will drift out of alignment. Use a small amount of solder paste. You don't want to solder the UT-141 to the nuts! Spread a bead of paste around the 5/16" tube where it mates to the pipe cap. Heat the pipe cap and let the solder paste flow. Allow to cool. With any luck you did not solder the UT-141 to the nuts.

Slide the inner tube into the outer tube and make sure it moves freely. There should be some tension to aid in keeping the rod in place once set. Insert the UT-141 coax lines into the cap. Make sure you can spin them around without hitting the side of the inner tube or pipe cap. You only need 180-degrees of rotation. Normally the ground end of the loop will stay toward the pipe cap. Now the SMA connectors can be attached. Leave the coax lines straight until final tuning and soldering of the lines is finished.

Insert the 1" tube into the bottom pipe cap. Insert the top cap also. You don't really need the top cap as the tube is long enough that the missing cap will not affect the performance. I like to use the cap to keep dirt out of the filter. Don't solder them at this time. Once the filter is finished the bottom can be soldered on if desired just to hold everything together.

Alignment

The coupling loops will have minimum coupling when the plane of the loop is broadside to the inner tube. Maximum coupling will be with the plane of the loop perpendicular to the inner tube and the ground end of the loop towards the edge of the pipe cap.

The best equipment to tune the filter is a tracking generator. This will allow you to see the total picture. You want to adjust the loops for the bandwidth and insertion loss desired. Too much coupling will result in a very low insertion loss but a wide response with little roll off. There will also be a sharp notch above the center frequency. This notch will disappear and the overall response will improve as the coupling is reduced. Too little coupling will result in an excessive insertion loss without any narrowing of bandwidth. With the tracking generator you can see the attenuation skirt improve as the coupling is reduced. Then you will see a sharp increase in insertion loss at the peak as the filter becomes under coupled. The coupling loops should be adjusted so they are the same position relative to the center rod. It helps if the end cap is off to see the loop position. You will also adjust the sliding inner tube to keep the center frequency where desired. Once final loop configuration is found the UT-141 lines can be soldered to the brass nuts. I marked the UT-141 lines in relation to nuts then remove the coax cables connecting the analyzer. I repositioned the lines with the marks then applied solder. Unfortunately something slipped as the final insertion loss was higher than my final adjustment. I had around 6 DB insertion loss before soldering and 9 DB after. It would have been better to keep the coax cables attached to minimize moving the adjustments for soldering.

Silver plating the inside of the tube and the rods may improve performance somewhat. Studies have shown the plating must be of proper type and thickness to be effective. I have used a plating process from Caswell that is inexpensive (http://www.caswellplating.com/kits/plugnplate.htm). Unfortunately this is not what would be considered an effective plating process. Testing has shown the plating did not improve the unloaded Q of these cavities or the final insertion loss. The plating did not hurt the measurements either. The plating makes the project look better than letting the copper corrode so I continue to use it. Plating was not applied to filters shown in the photographs below.

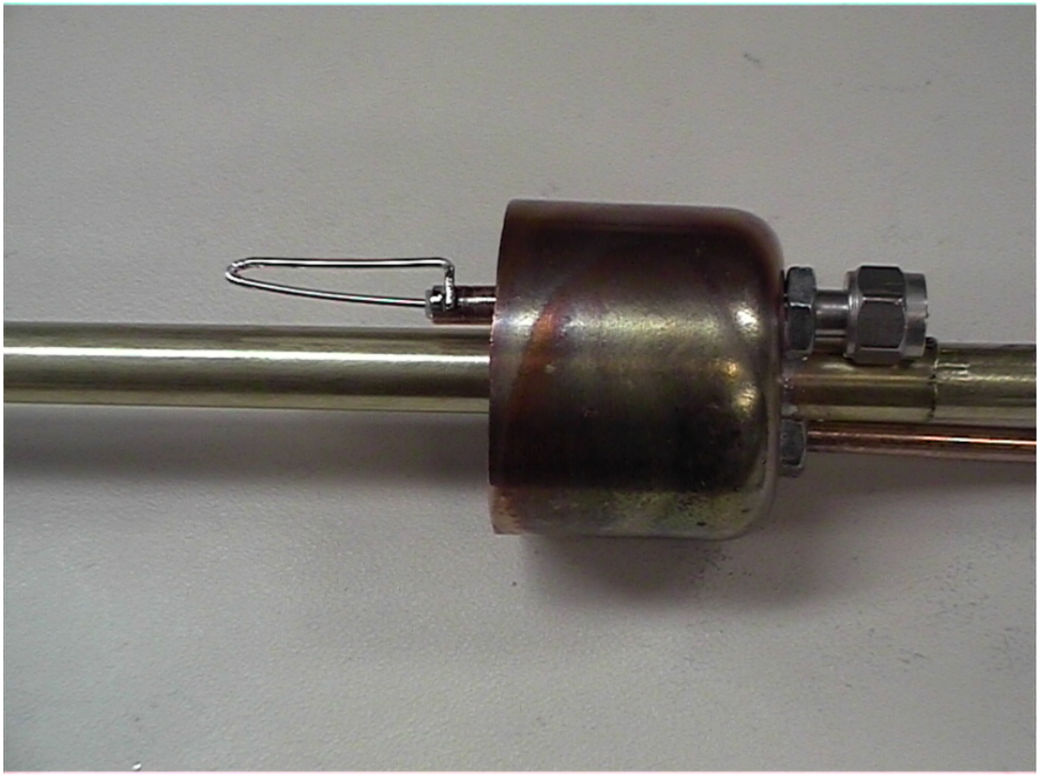

Figure 2 - Coupling loop detail

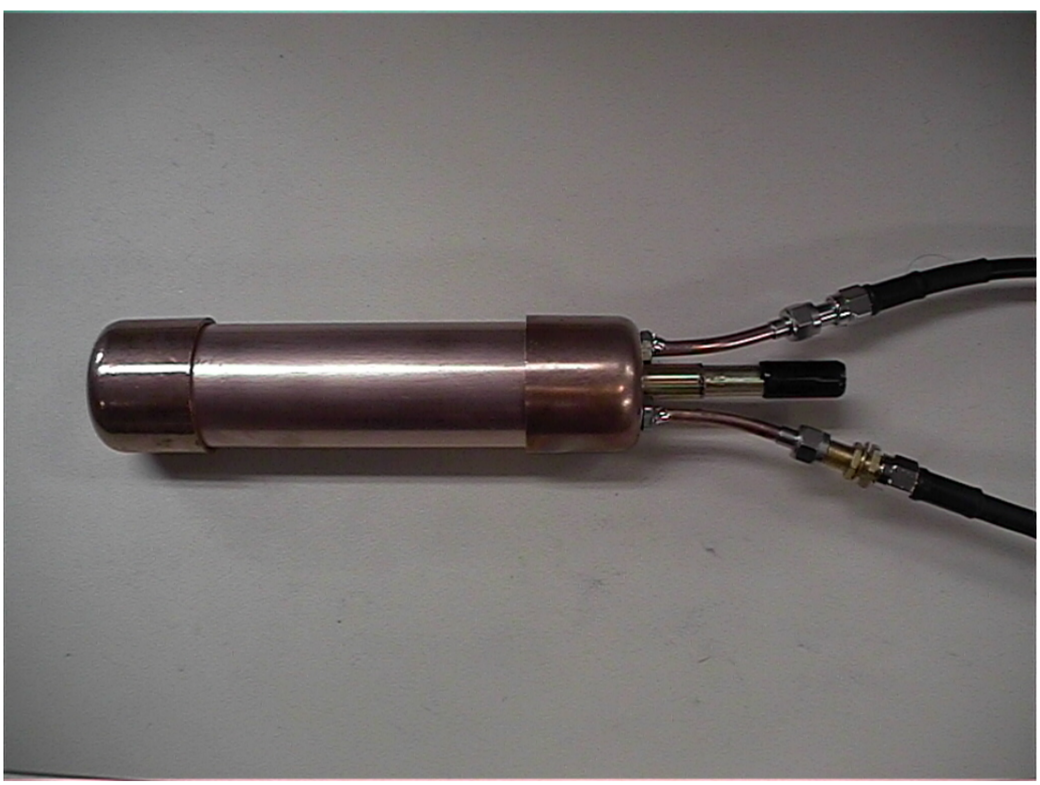

Figure 3 - Completed Filter

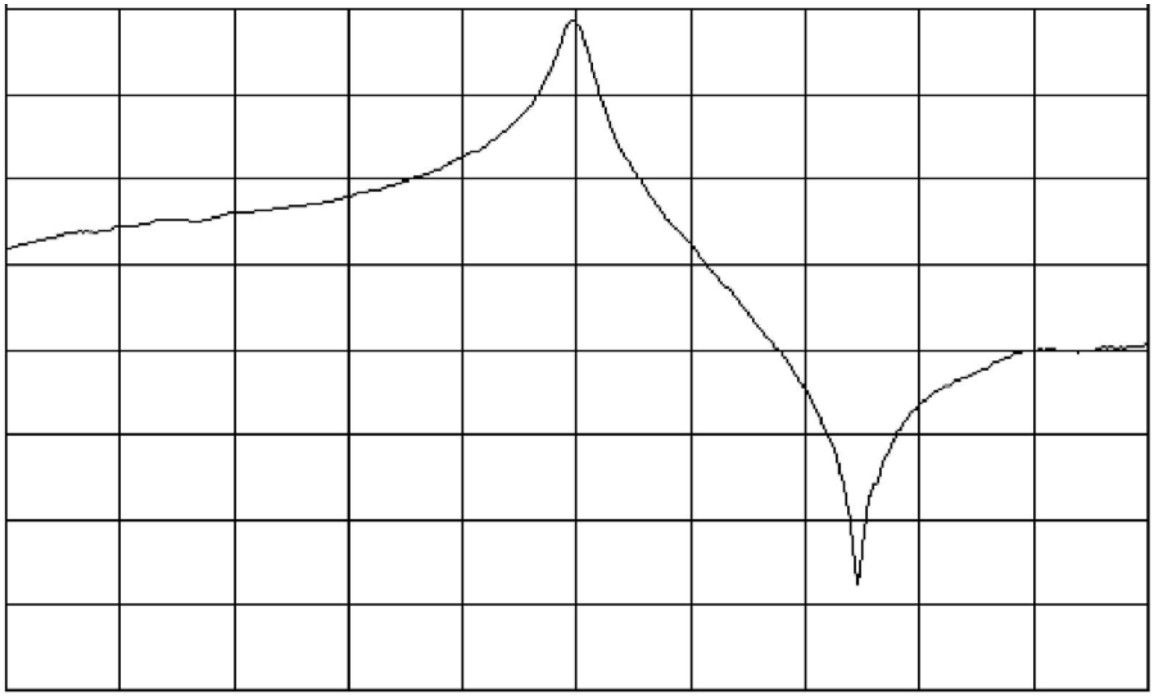

Figure 4 - Over coupled filter response. Center frequency 738 MHz, top reference line 0 DBm, span 100/MHz division horizontal, 10-DB/div vertical

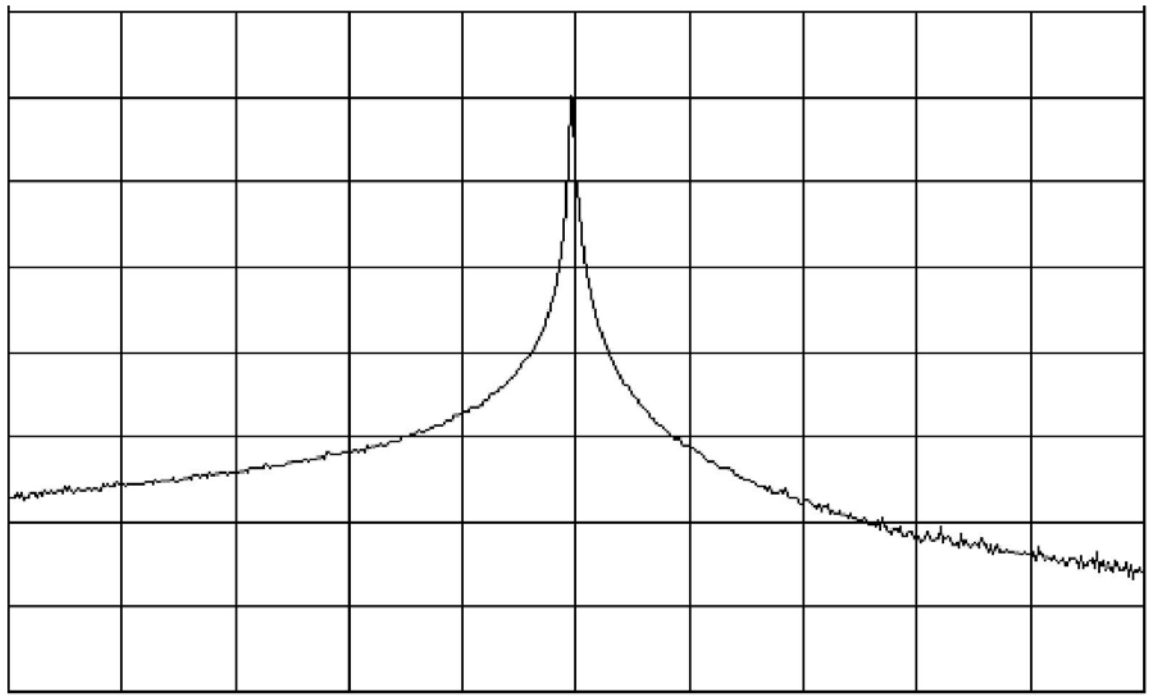

Figure 5 - Response after adjusting coupling loops but loops moved during soldering as insertion loss increased from 6 to 9 DB. 3-DB bandwidth is 1.3 MHz. Loops were adjustable for less insertion loss and wider bandwidth. Center frequency 738 MHz, top reference line 0 DBm, span 50 MHz/division horizontal, 10-DB/division vertical.

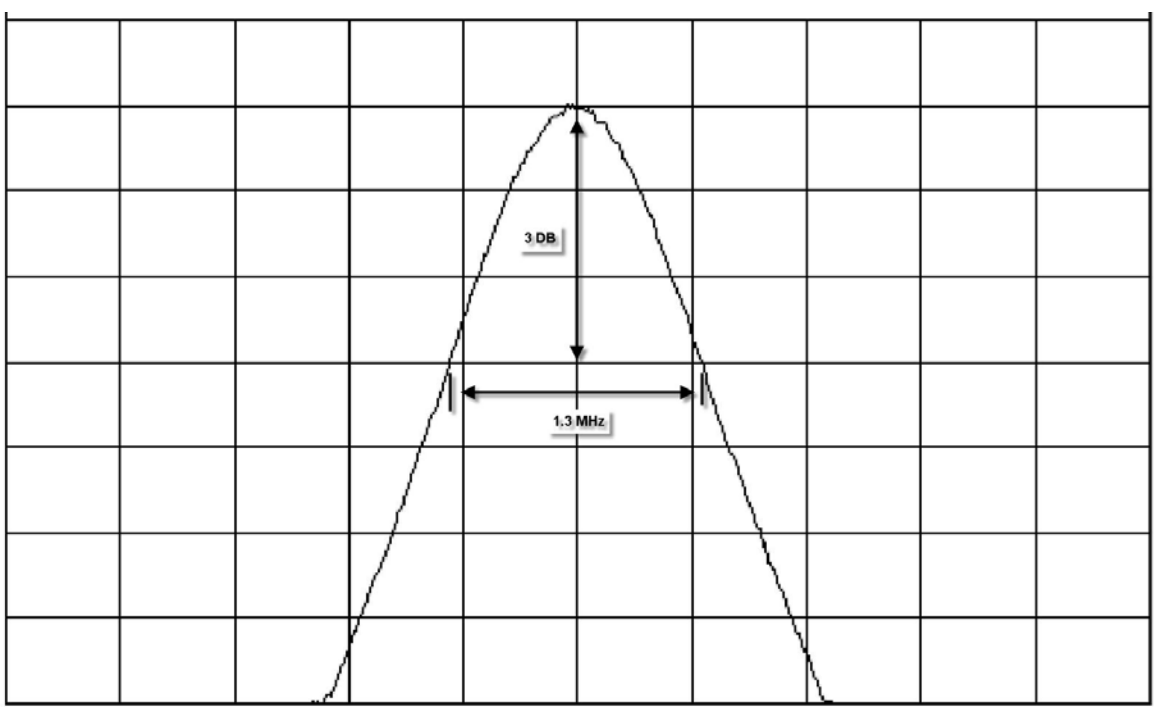

Figure 6 - Filter 3-DB bandwidth. Center frequency 738 MHz, span 500 KHz/div horizontal, 1-DB/div vertical