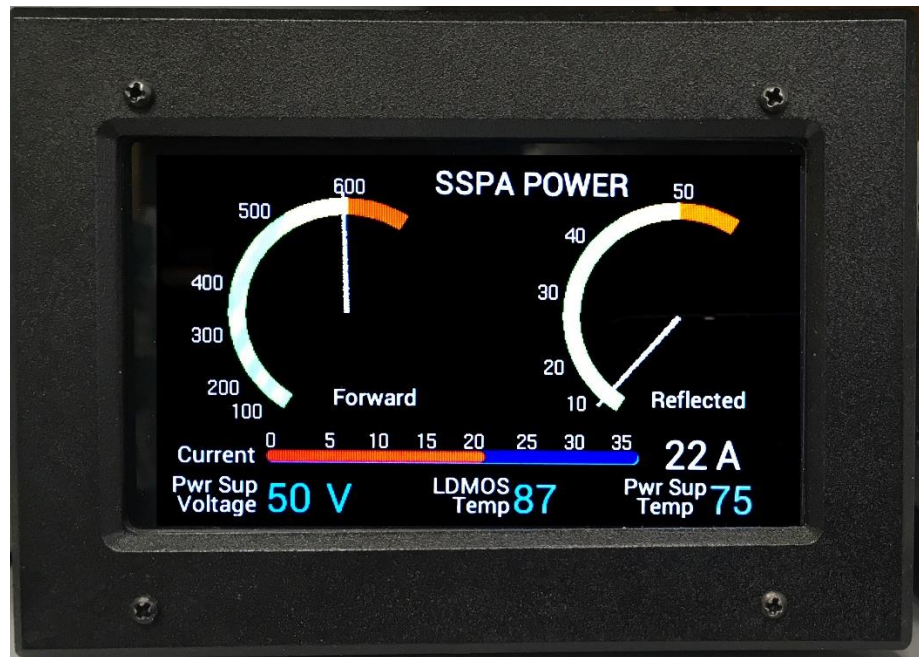


HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



Putting the cart ahead of the horse, I decided to see if I could create a graphical user interface to monitor the 600-Watt, 23 cm solid state power amplifier I am getting ready to build. After considerable effort, since I have no experience at all programming LCD displays, I came up with this 4.3-inch sunlight-readable LCD GUI that you see above. The display is a shield that plugs onto an Arduino Mega 2560 processor board.

Now that I have that running smoothly using a simulator, I need to come up with the sensors that will drive inputs on the Arduino's 8-bit A/D converter. They will consist of the following:

1. Forward SSPA power
2. Reflected SSPA power
3. Power supply current (high-side detector across a 30A/50mV shunt)
4. Power supply DC voltage (measured at the input of the SSPA on my tower)
5. Power supply temperature
6. SSPA temperature

In this write-up I will only start to deal with 1 and 2...

Accurately measuring forward and reflected power at high power levels is not easy. My first inclination when faced with the need to acquire or design and build a piece of equipment is to look on eBay. I'll be running an output of 600 Watts. That's a lot of power, and that eliminated all but one directional coupler. That was a unit made by Narda for a Motorola cellular system, but it had N-connectors. At the power level I'll be running, and at 23 cm, N-connectors are near the limit of their capabilities. I purchased one anyway. And since I know very little about EME, I thought it prudent to join the local 50 MHz and Up Ham club. I was soon convinced by experienced members that this coupler was not going to hack it at my power level and I needed to avoid N-connectors and switch to 7/16 DIN connectors,

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

which are much larger and can handle more power. The problem with Type-N connectors is the small center contact. It heats up and the solder can even melt. Not good!

It was shortly after making the switch to DIN connectors in my planning that I was sent an article titled, "High-Power Directional Couplers with excellent Performance that you can build" by Paul Wade, W1GHZ. Here's a link → http://www.w1ghz.org/antbook/conf/High-Power_Directional_Couplers_with_Excellent_Performance.pdf

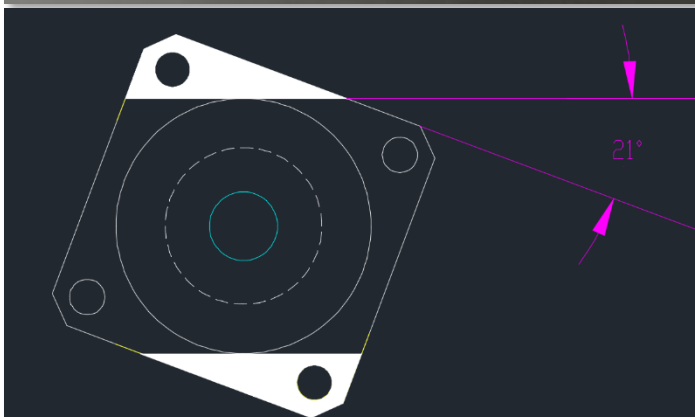
This is a fantastic article, and exactly what I needed. So now I'm attempting to replicate one of Paul's designs, but with DIN connectors instead of Type-N.



This coupler is built in a Hammond Engineering 1590B enclosure. The dimensions are extremely critical, and the stock 7/16 DIN bulkhead female connectors are too big for the enclosure. You can see that the mounting holes have nowhere to attach.

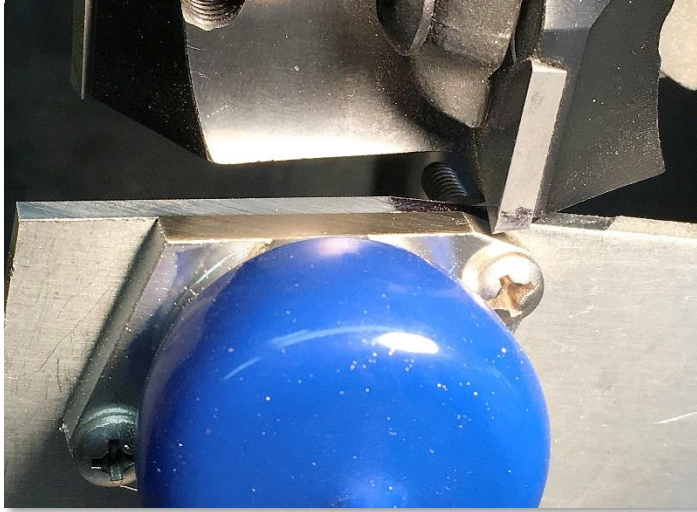
And you can't just scale up Paul's design to a bigger enclosure, so I had to find a way to mount the big DIN connectors...

After some thought it occurred to me that I could rotate the connectors and mill off two of the four corners, leaving two attaching screws.



By rotating the connector about 20 degrees, and milling off the part I've marked in white, I can reduce the footprint to 1-inch vertically and fit it on the side of the enclosure. This will allow the two remaining mounting screws room on the side of the case and keep them as far as possible from the critical transmission line. I'll trim their length so they're flush anyway, to this is not too important.

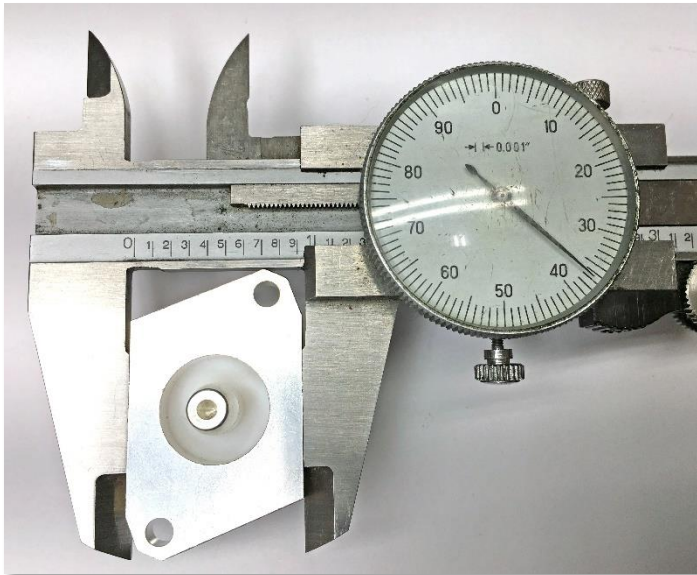
HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



I made this simple fixture to hold the connectors while I mill them. It's just a plate clamped into my mill vice with mounting holes for the connector.

In this picture, the corner has been milled down to very slightly below the radius of the connector body, which is 1.000 inches in diameter.

To do the opposite side I simply unscrew the connector and swap ends. A few swipes with a jewelers file to remove burs and the connector is ready to go.

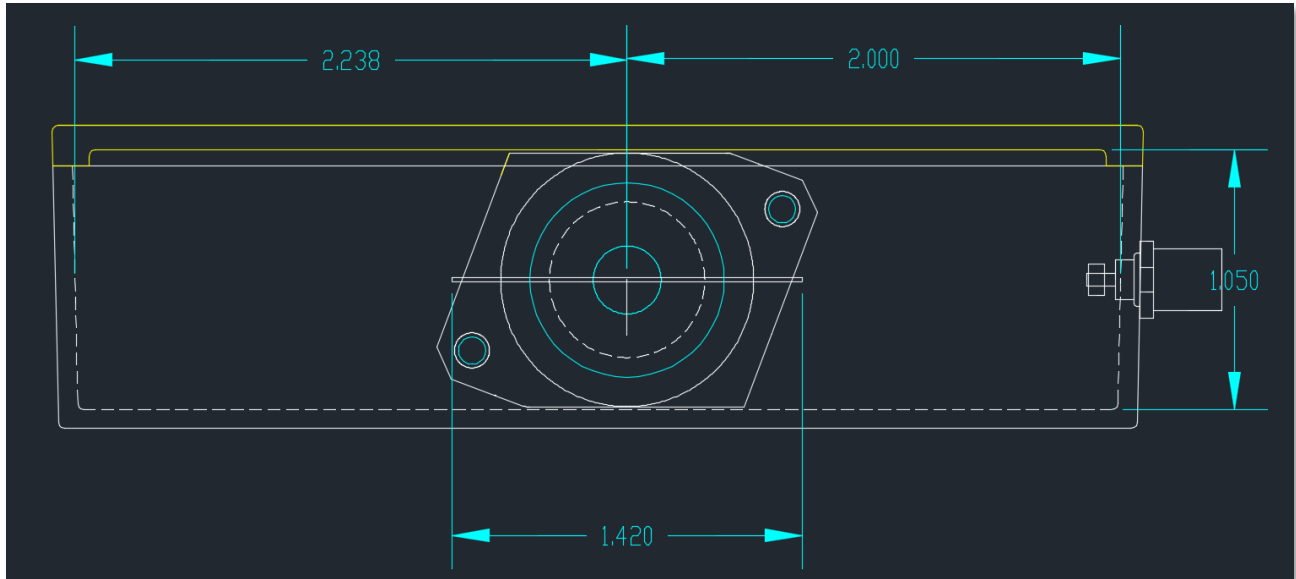


Here's a finished connector. The sides are parallel, and the height will now allow it to be mounted with room to spare.

The exact dimension is not critical if it will not stick out above or below the enclosure and the screws have a wall to mount to that is not too close to the top edge or the bottom.

The enclosure is cast aluminum and very soft. Since I'm down to only two screws I will pay close attention to my tapped 6-32 holes. I'll be using expensive coated taps and a lot of care to insure a tight fit. No hardware store taps!

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

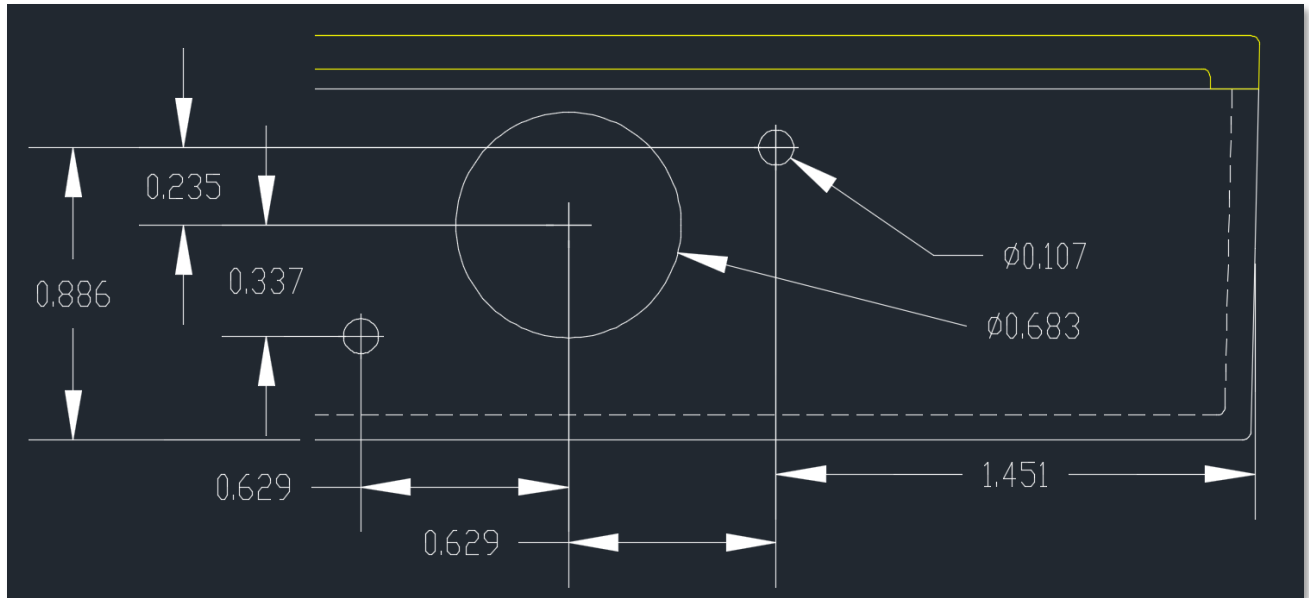


Here's a side view of the enclosure, showing the location of the modified DIN connectors, the 1.420-inch wide transmission line, and the small coupled line at the right side of the box. It's mounted using two SMA female bulkhead connectors.

Notice that the DIN connectors are not centered on the side of the box. The centerline of the pins needs to be exactly 2.000 inches from the right-hand side wall. This distance determines the coupling between the transmission line and the sense line.

Everything is complicated by the fact that this is a cast enclosure and the sides are tapered, so that 2.000 dimension is to the vertical center of the side.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

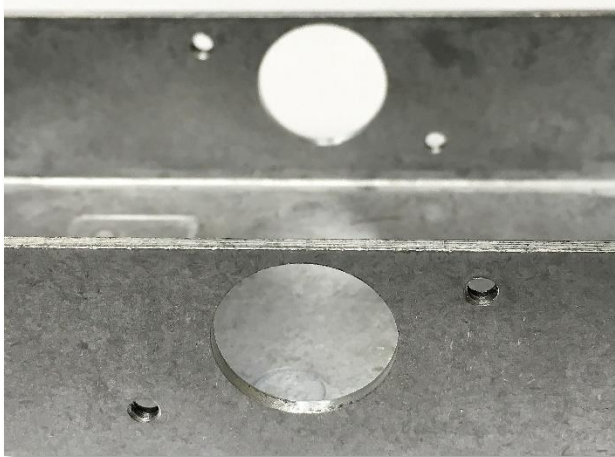


OK. Time to drill some holes... As I mentioned, the sides are tapered so my X-axis measurements have to be taken from the center of the side and not the top or bottom. Adding to the difficulty is the fact that the edges are radiused, so finding an exact edge is difficult. Lastly, my mill has a lot of slop in the X-axis, so I don't want to change directions. Once I find an edge all of my measurements will be relative to the last one. That way I don't have to go back and find the edge more than once.

I'll be using a 0.1065 diameter drill for my 6-32 threaded holes. That should give me 75% threads in aluminum. I'm paying a lot of attention to these two holes because the connector is very large and a lot of force could be applied during mating and demating. I'll want to take great care when I attach my right-angle antenna feed line connector and secure the coax with a clamp.

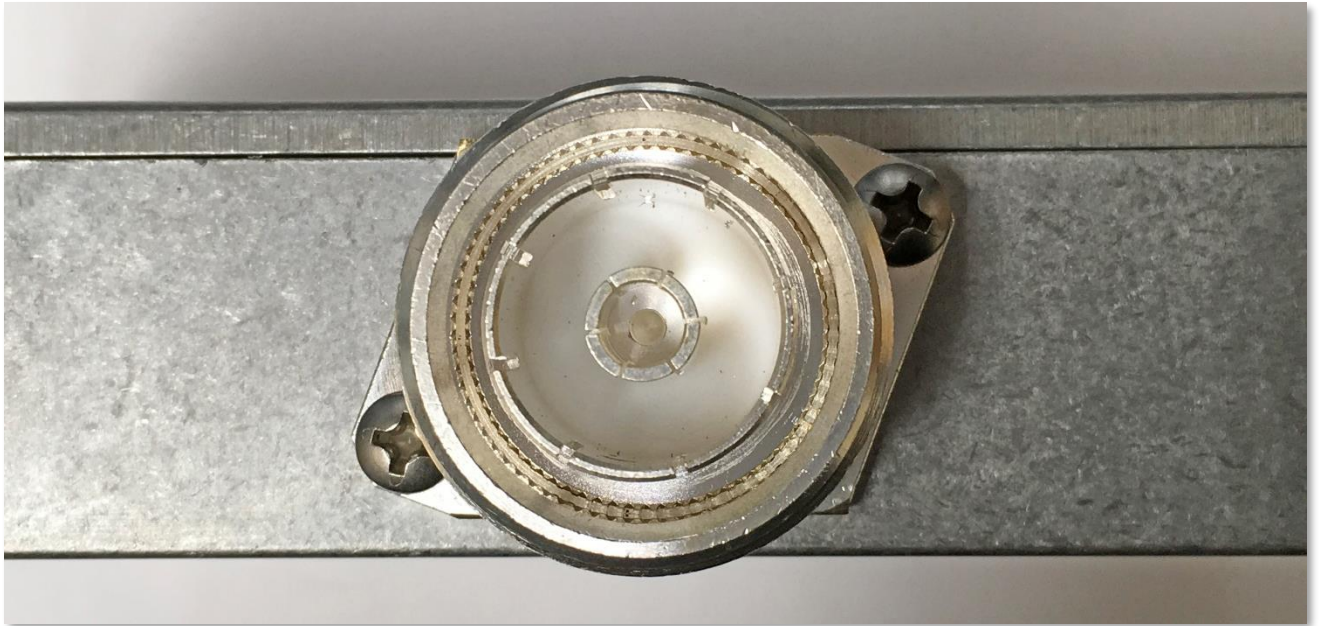
You may notice that the large center hole is offset slightly. I'll explain the reason for that later.

And most important of all, I need to remember to reverse all my measurements when I do the opposite side so I don't end up with offset connectors (Remember – they are not in the center of the enclosure).



So far, so good. You can see how thin the sides are (about .080 inches). As I mentioned, there isn't much thread there to securely mount such a big connector. I could extend the screws into the enclosure enough to add a nut, but I would rather not intrude into the space for fear of adversely impacting performance.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



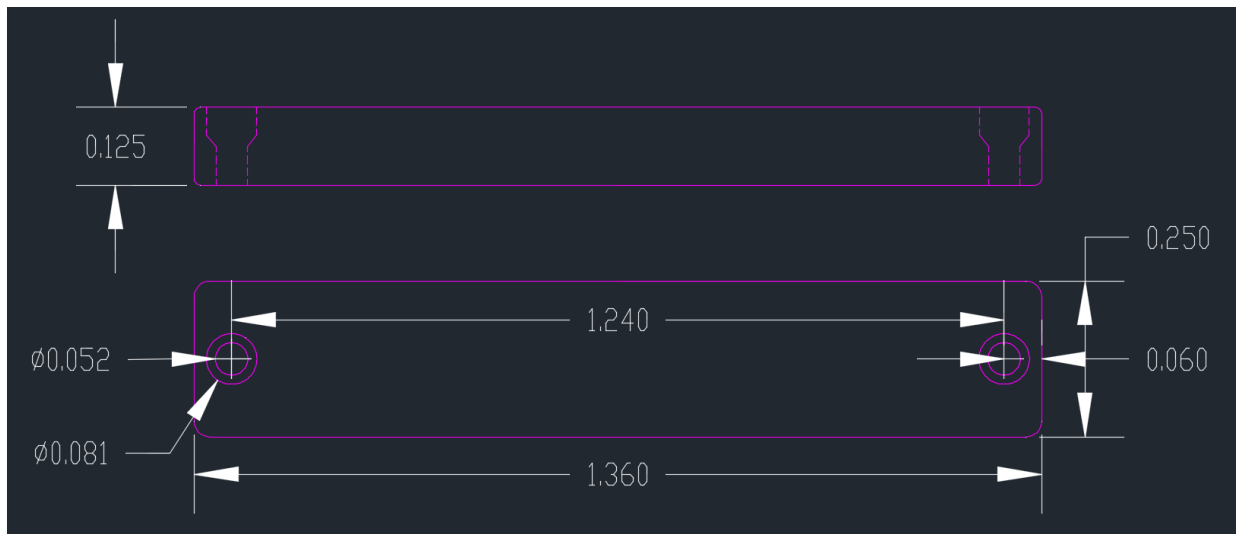
Here are a few pictures of the 7/16 DIN Females mounted on the enclosure. The next step is to drill the holes for the coupled Sense Line's two SMA connectors.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

The next step is to lay out the coupled sense line. Paul calls for 0.250 x 0.125 rectangular brass stock for rigidity. The spacing between this line and the wall is critical, and so is everything else. There can't be any sharp edges or irregularities. Everything needs to be smooth. The critical length is 1.360, based on Paul's computer modeling. If this isn't perfect the directivity will suffer.

In my first attempt, I used rectangular tubing with square ends. In Paul's N-connector version of this coupler he achieved a directivity of 32.1 dB, which is fantastic. This is why I chose this design. Gary, K6MG was kind enough to test my first attempt with his Vector Network Analyzer. He measured a respectable 23 dB. Not bad, but not what we expected. I consulted with Paul and he stressed that there can be no sharp edges. So I removed the line and radiused all the edges and resoldered. This time I attempted to apply the solder inside the tubing. The result was a disappointing drop to only 15 dB.

My theory is that there is no way to get a really clean end using hollow stock, so I ordered solid stock and this is my second attempt. Normally I would just replace the coupled line, but I also mistakenly mounted the DIN connectors in the center of the box instead of two inches from the wall on the coupled line side. That resulted in less than the anticipated coupling.



So here is my second generation design, using solid brass stock. The diameter of the SMA connector pins I'm using is 0.050. I'll drill a 0.052 clearance hole as close to the ends as possible, using a #55 drill. Then I'm going to drill half way down using a larger #46 drill (0.081). My plan is to shave off the SMA pins so they are slightly recessed with the side of the line, when it is spaced properly in the box. Then I'll feed solder into the cups I've created with the larger drill. Once that's done I'll use solder wick to remove any excess solder from the surface of the line. Before I mount the line I'll radius all edges and polish it. I think that is as good as I can make it, and I hope the result will be a coupler that matches Paul's test results.

If you look at the LCD GUI display on page-1, you'll see that I want to display reflected power on a 0-60 Watt scale with a resolution of one watt. To do that I need a directivity of close to 30 dB. Anything less will add errors since RF from the forward direction mixes with reflected RF in unpredictable ways and introduces plus or minus errors. If I can limit those errors to a watt or two I'll be very happy.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



Here's the original coupled Sense Line fabricated from hollow stock. I made a special point to make the ends as square as I could. It yielded an isolation of 23 dB – good, but not great.



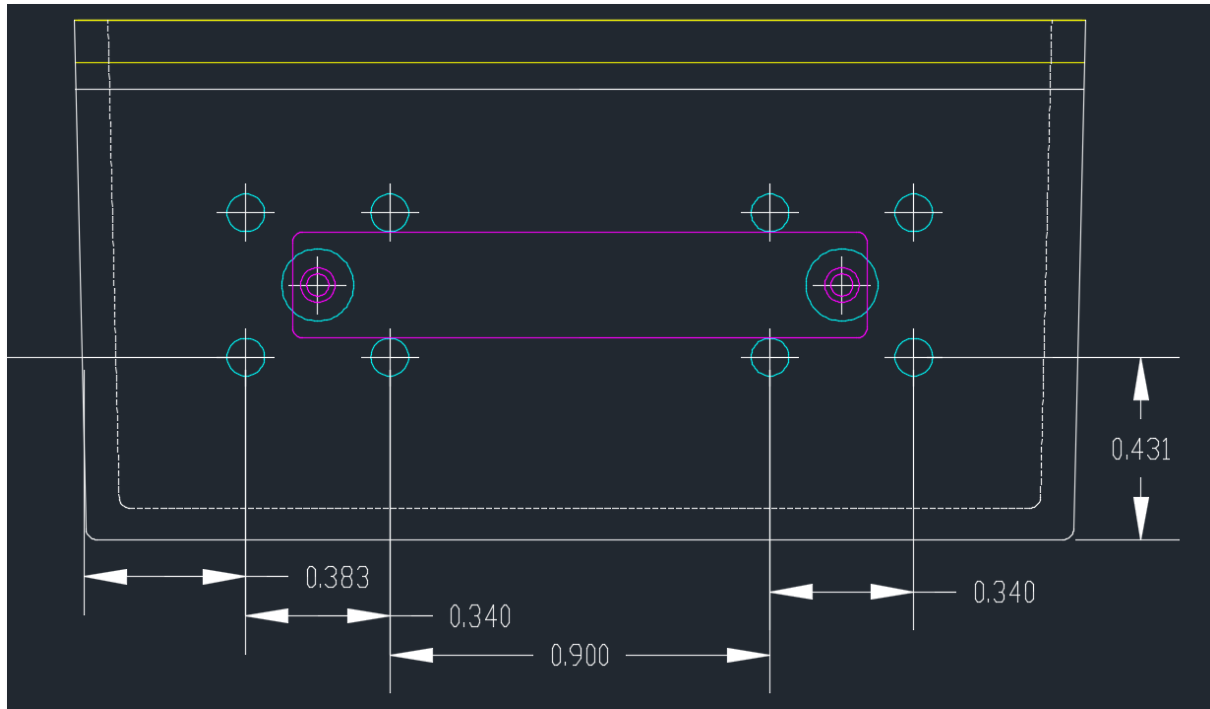
Per Paul's suggestion, I rounded off the ends. Unfortunately, that decreased the isolation to 15 dB. I may have overdone it.



Here's my rev 2.0 solid version. It's a definite improvement from a mechanical perspective, but will it improve performance?

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

Now that the coupled line has been fabricated, it's time to lay out the connectors to match the line's hole spacing and the vertical alignment in the enclosure.



Between the sloped sides, and the slop in my mill's X-axis, deciding how to do this took some thought...

I've decided to break it down into three separate operations, working up from the bottom of the enclosure. This drawing only shows the left to right path I'll use to drill the four lower 4-40 tapped mounting holes. Then I'll reset and do the SMA center holes, then reset again and do the upper set of mounting holes. Each pass has to take the slope into account.

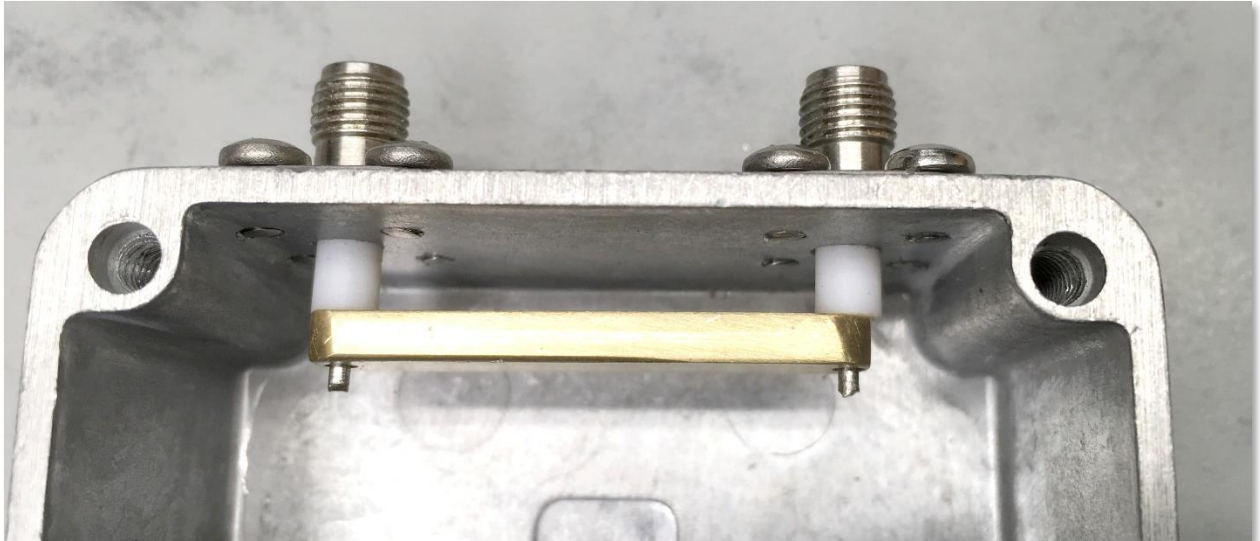
Just over the vertical distance between the upper and lower mounting holes, the sides slope out 0.008. I suppose I could live with that much error, but I want to do the best job I can, so this is my plan. If I had no slop in my X-axis I wouldn't need to go to this much trouble, but changing directions in that axis adds a lot of uncertainty, so repeatedly finding an edge on that rounded side is still the best approach I think. If the connector holes all line up, and the coupled line drops on to the SMA pins, I'll know it worked.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



Here's how I find an edge on a curved corner. I use a laser that creates a very small spot. I sneak up on the side of the case until I see a fairly long line of light. And as I mentioned, in the vertical axis I have to do this half way between the top and the bottom of the case, as you see.

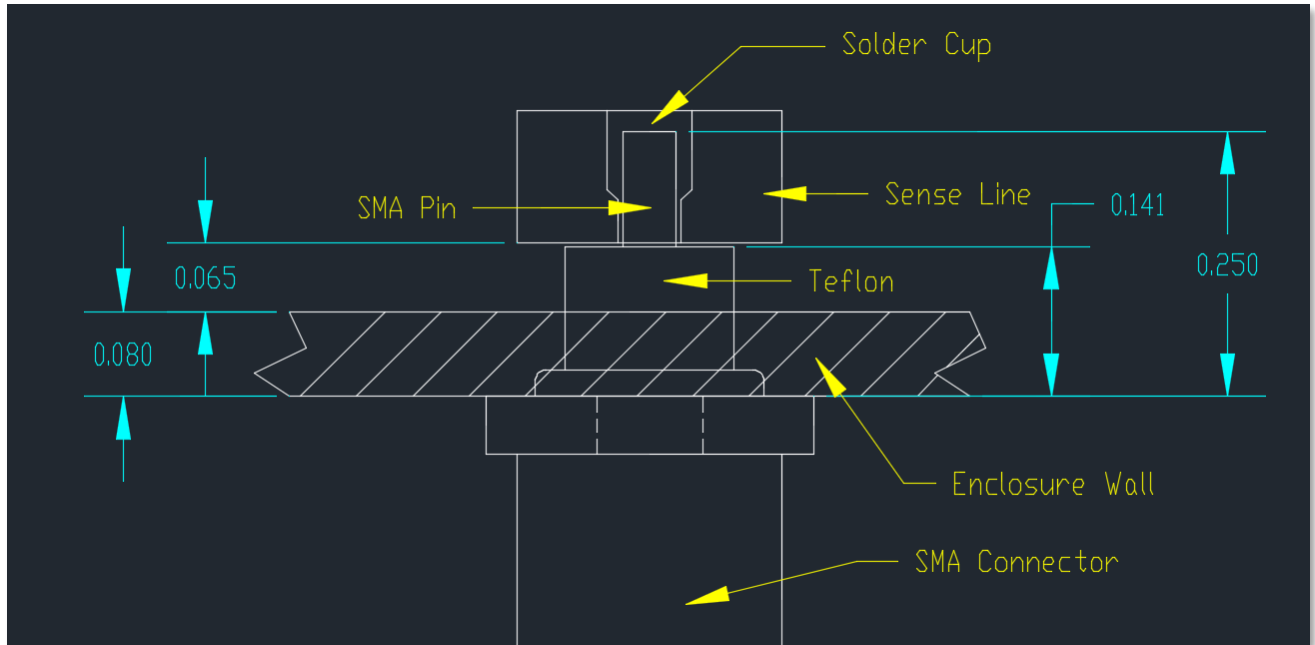
The difference between no light hitting the box and what you see here is about 0.010, and that's close enough for this project. It's very subjective.



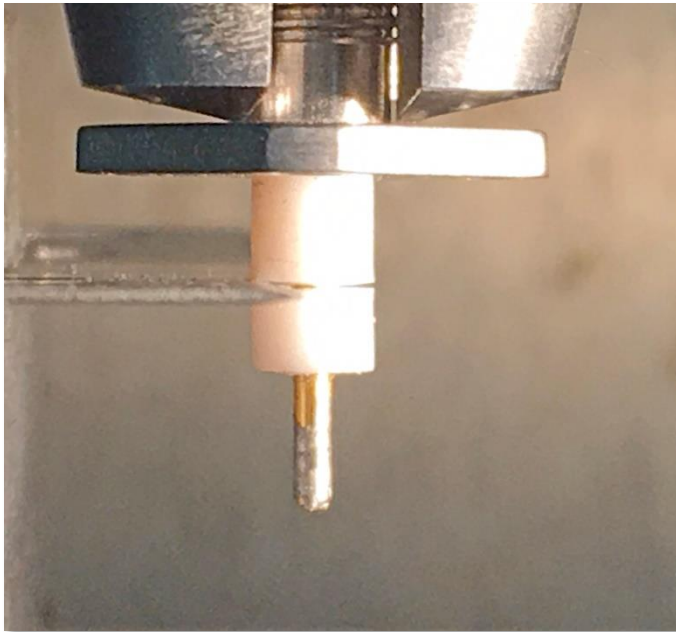
That exercise went well. All the holes lined up, and the Sense Line's holes line up perfectly with the SMA connector pins. The gap between the Sense Line and the back wall of the enclosure is critical. It determines the impedance of the line. Paul's simulation and testing show that this needs to be exactly 0.065, so I'll need to trim the Teflon back. Then I'll trim the SMA pins so that they are slightly lower than the outer surface of the line. The last step will be to try to solder the line to the pins as cleanly as I can without leaving any solder above the surface.

I've also cut and smoothed the length of the screws so that they don't protrude into the enclosure's interior.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



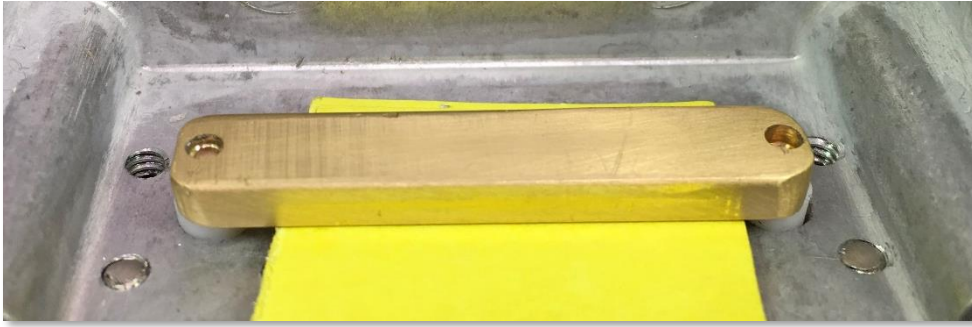
Here's my plan for the Sense Line. I'll cut the Teflon back to about 0.140, so it is not limiting the gap between the inner surface of the line and the enclosure wall. Paul had a great suggestion for setting that gap – use a Post-It pad. Remove pages until you have a width of exactly 0.065. Then use that as a shim. Next, I'll trim the SMA pins to a length of 0.250, so they sit slightly below the surface of the line. The last step will be to try to solder the line to the pins without getting solder on the outer surface. I'll use solder wick is needed to clear up the surface, so it is as flat as I can make it.



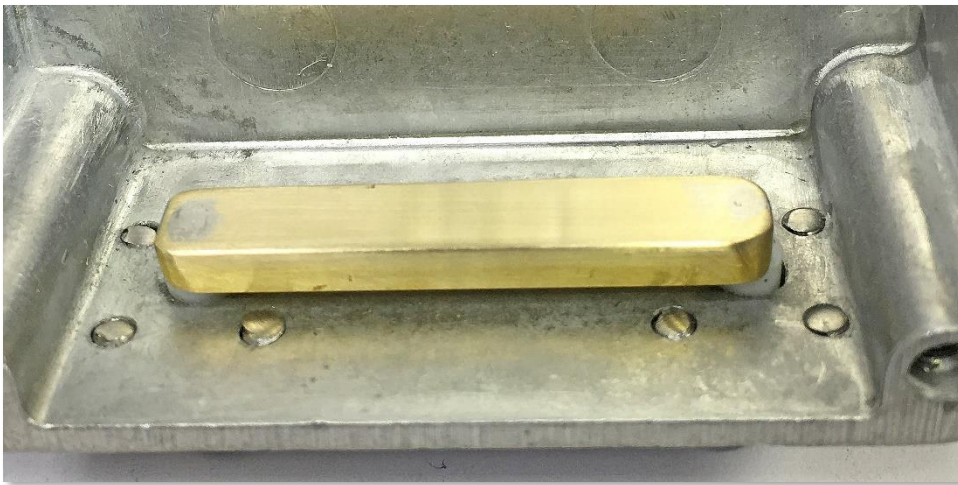
I clamped a razor blade down horizontally and lightly chucked each SMA connector up, eye-balled the offset from the bottom of the Teflon, and sliced part way. I finished them off by hand, so as not to get carried away and nick the pin. Both ended up at 0.130, which is close enough. The main thing was to make sure the Teflon wasn't too long.

Next I trimmed the length of the pins to 0.250. Again, this was done by eye and the main thing was not to have the pins sticking above the surface of the sense line.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



My goal is to fill up those solder cups I created by drilling the oversized hole half way through the solid line. Any slop will be removed using solder wick.

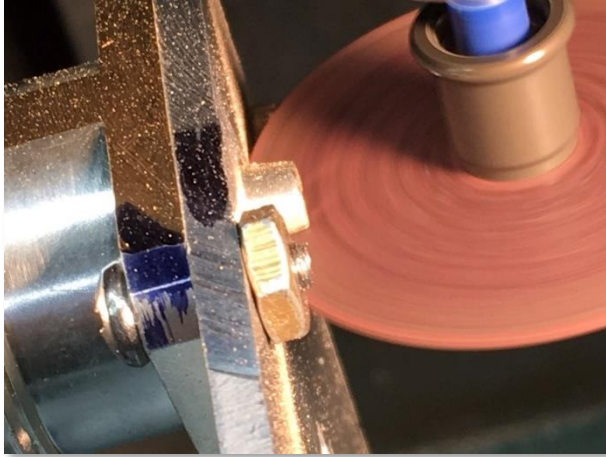


I'm really happy with the results, especially when you see my prior effort with the hollow rectangular tubing!



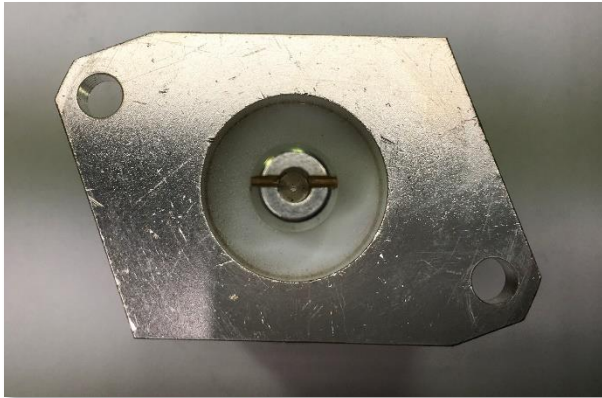
Believe it or not, this is the line that achieved a directivity of 23 dB. When I made this first one I didn't realize how critical all the small details were, like sharp edges, and lumps and bumps. I'm expecting big things from this new coupler!

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

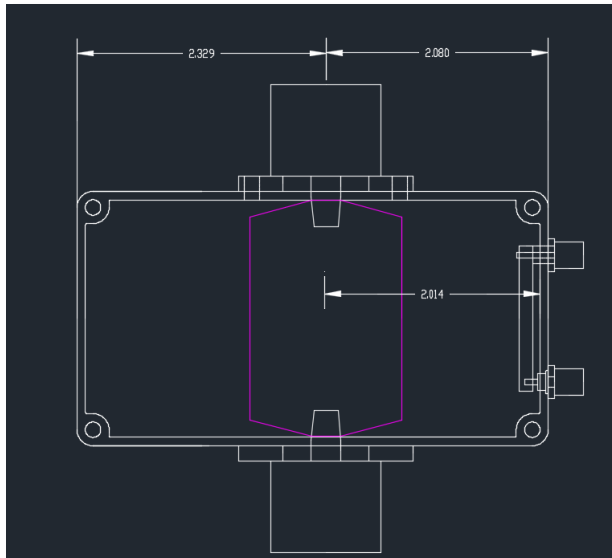


OK... Back to work. Now it's time to move on to the transmission line. The first step is to cut slots in the 7/16 DIN connector center pins to receive the transmission line which is formed from .021 copper sheet.

This Dremel cutting wheel was advertised to cut a .020 thick slot. Wrong! It cuts .030 slots which became a major pain later as the Transmission Line will be free to slide, making precise alignment difficult.

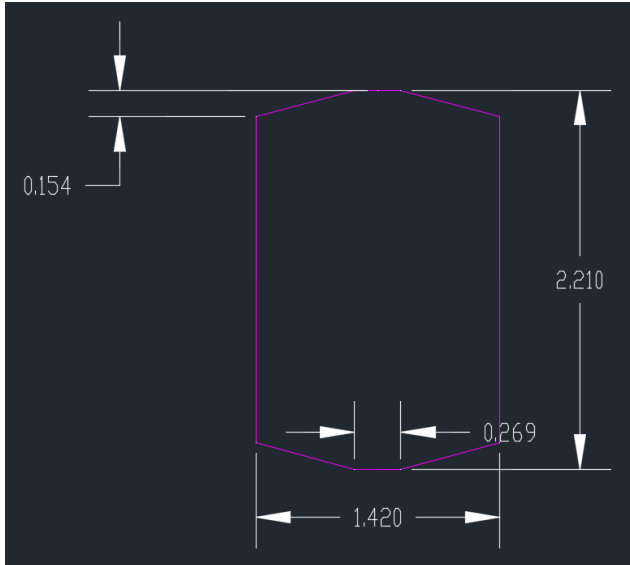


Here's the cut. The cutting wheel cuts through the pins like butter.



Here's a top view of the enclosure showing both lines. The 2.014 dimension from the center of the transmission line to the inside surface behind the coupled line is at the top. At the center, where the coupled Sense Line is located, it's 2.000.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



This is the transmission line. I'm making the end-to-end dimension .012 less than the width of the enclosure at that depth. That's so I can slide it in without jamming.

Paul's design calls for a taper of 0.016, so that explains my taper dimension of 0.154. It's 0.154 to the edge of the line but adding in a 0,006 gap on either side yields a taper of 0.160 to the wall. Of course, trying to hold these tolerances and achieving symmetry with the Transmission Line free to slide around is nearly impossible. I'll face that challenge once the line is fabricated.



To cut out the critical shape of the transmission line tapers, I lay out the part 1:1 using AutoCAD and print it on my digital printer as a full-scale print. I can then cut it out and use it as an overlay to create the part.

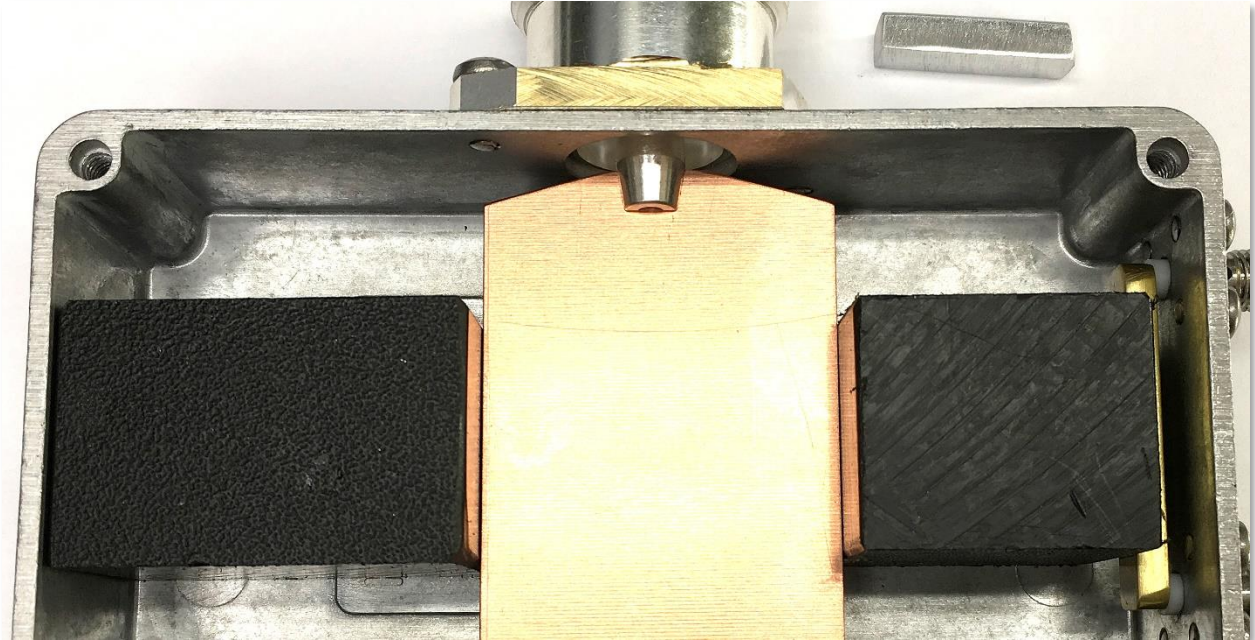
After multiple tries, I finally got close by simply cutting along the printed lines. The last step is to clean up any sharp edges with a buffing wheel, a file or sandpaper.

I haven't developed a good plan for the remaining portion of this project yet. Here's a list:

- 1) Center the Transmission Line in both planes so that all 4 tapered corners are exactly 0.160 from the walls.
- 2) Secure the line so it will not move while soldering it into place.
- 3) Solder the upper side of the line to the connector pins.
- 4) Remove the connector mounting screws, slide the assembly away from the bottom to clear the Transmission Line and rotate it 180 degrees.
- 5) Slide back into position, secure the connectors and solder the opposite sides.

There's just a few problems with that list... Positioning the line precisely and securing it will not be easy. And after soldering one side, as the assembly is slid away from the bottom so the Transmission line will clear as it's rotated, the sides slope away from each other and the assembly will jam. I'll sleep on it and maybe I'll think of something...

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



I machined two shims from engineering plastic to secure the Transmission Line in the left/right axis, and a small 0.160 aluminum piece (upper right in picture) to gauge distance from the edges of the tapers to the wall. I found that the accumulation of small errors resulted in the tapers being off very slightly. The symmetry is not bad, considering those cuts were all done by eye. If I adjust the up/down direction to get one side exactly right, the other side is off about 0.020. I'll touch that up with a file.



For the first nail biter, I soldered one pin then unscrewed the connectors, slid the soldered connector up as far as it would go, to see if I could clear the bottom and rotated it 180 degrees. That's the reason for the offset hole that I mentioned earlier. On my first attempt I didn't do that, and the Transmission line didn't quite clear and I had to bend it slightly. So far, so good...

After flipping the line over, reattaching the connectors, and reinstalling the shims, or at least trying to, I realized that the line was not exactly centered on the pin. Part of this error was caused by the fact that plastic melts. Something like Teflon would have made much better shims, but this is all I have. I could have used aluminum, but it would conduct heat and make soldering next to impossible. I think the other factor is that my connectors are not exactly where they need to be. This accumulation of minor errors resulted in an offset of about .060.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

My last coupler was off a quarter of an inch because I misread Paul's dimensions, and it still worked well. The distance from the transmission line to the Sense Line impacts the coupling. That quarter-inch error caused a difference of 3.2 dB between his results and mine (-43.8 dB Vs -47.0 dB).

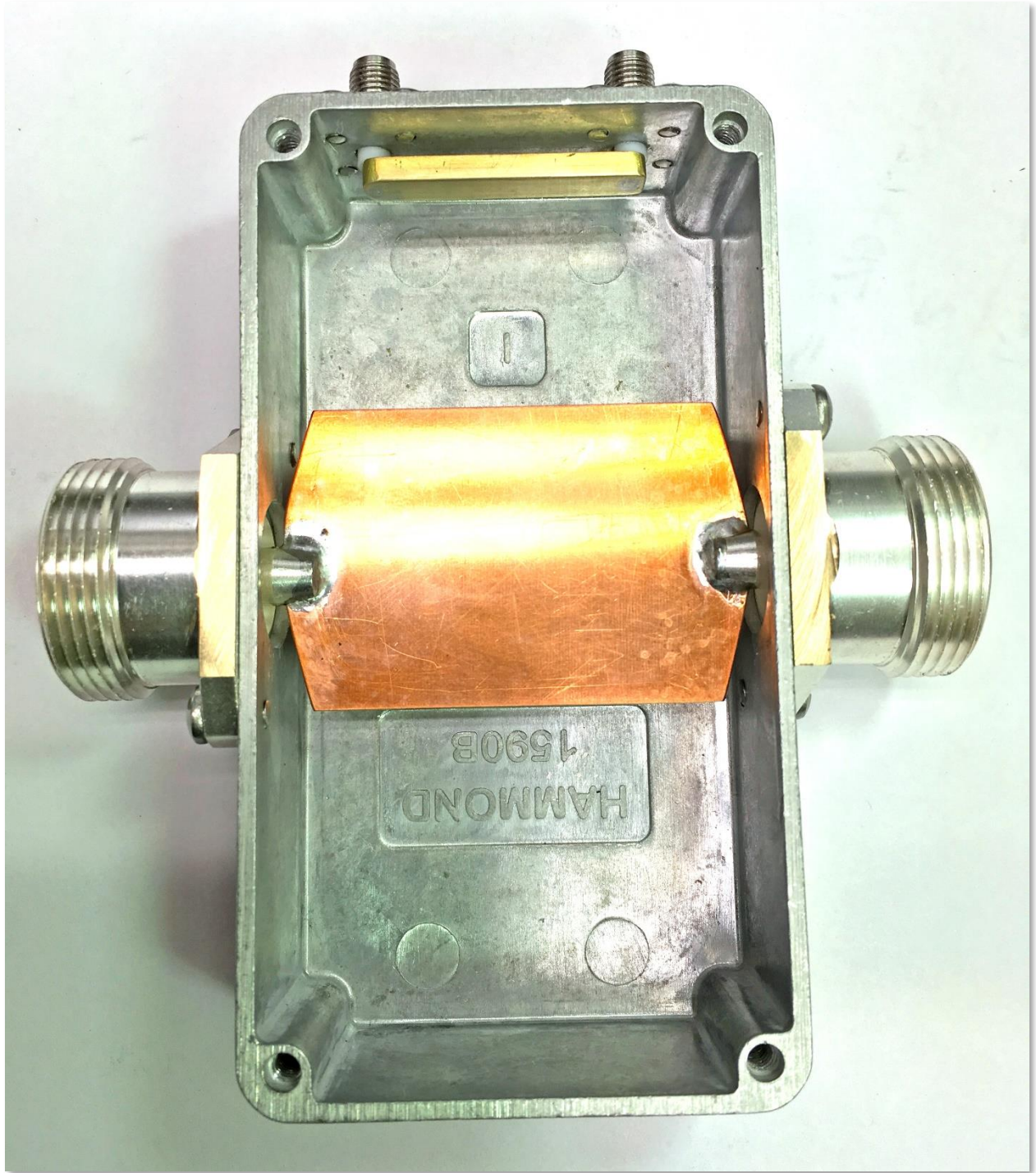
After flipping everything over and re-shimming, I soldered the other side of that first connector. Now it gets a tad unwieldy... You can't just solder the other side because you won't be able to flip it again to get the back of that second connector – the assembly will jam up due to the sloped sides.

This is the very last step and there is room for improvement with all of this. I attached the connector with .040 thick washers as spacers and soldered the pin. Then I unscrewed everything, removed the washers, and flipped the assembly back over. I tightened down the first connector and loosely attached the second one (that was spaced away from the wall because of the washers). After reinstalling the shims, I heated up the remaining side of that last pin until I could melt solder. Then I screwed the connector in tightly and completed the solder joint. The solder on the bottom side was reheated by this last step.



Since the shims prevented the Transmission Line from sliding around while I attempted to solder it, I was able to do reasonably clean joints and maintain the alignment of the tapered ends.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



The completed High-Power, 23cm, Dual Directional Coupler

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



To test the coupler, we need serious test equipment and specialized expertise. Fortunately, Gary, K6MG, has both and offered to help me through this process. Here he is checking out the coupler on his vector network analyzer. VNA's are extremely sophisticated pieces of test equipment and are essential analytic tools for a job like this.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT

Here's the results:

	Paul Wade's	My 1st Attempt	My 2nd Attempt	Copper Foil Added to Lid	Copper Foil Replaced with EMI Gasket
COUPLING	-43.8 dB	-47.0 dB	-42.8 dB	-42.8 dB	-43.2 dB
DIRECTIVITY	32.1 dB	23.0 dB	15.0 dB	-27.0 dB	33.3 dB
INSERTION LOSS	0.10 dB	0.086 dB	0.06 dB	0.06 dB	0.06 dB

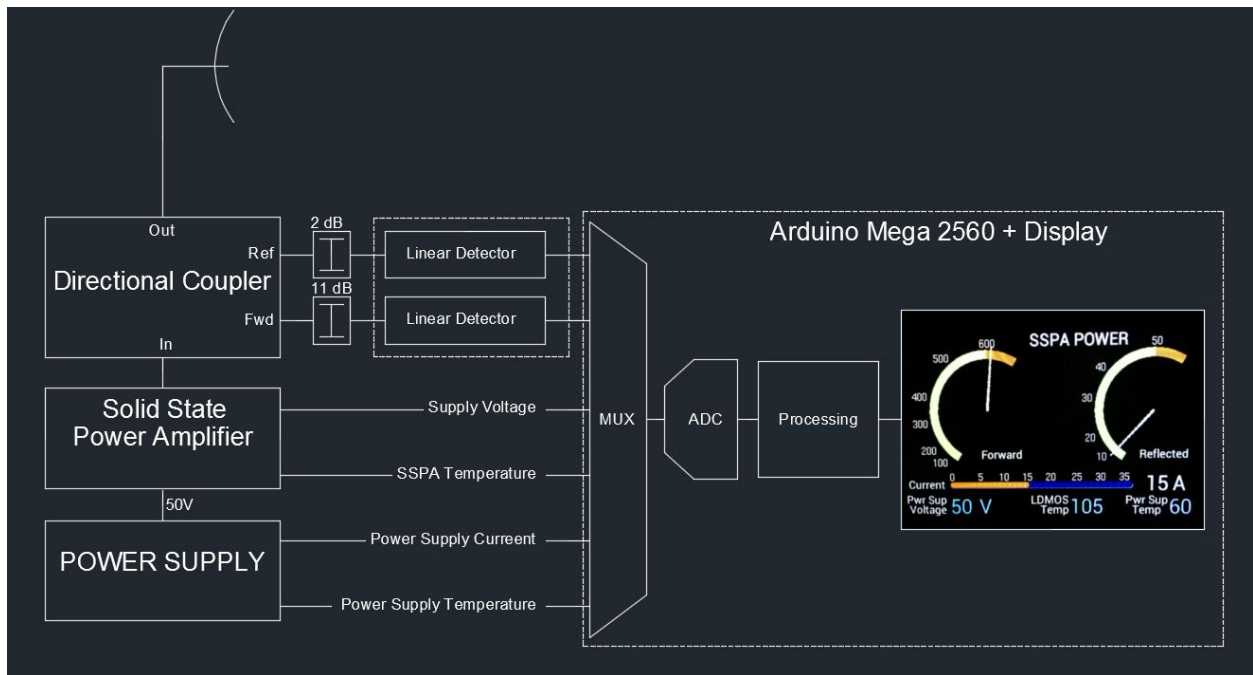
What just happened?? I did the best job I knew how, and that critical coupled Sense Line was a huge improvement – at least mechanically, but the directivity is horrible! Could the much larger size of the DIN connector pins have changed things for the worse?

While I was building up this new coupler, Gary had been experimenting with my first attempt and had greatly improved the directivity by doing several tweaks to the innards with sticky-back copper foil. He showed me, that simply pressing down on the lid changes the reflectivity substantially. That fact caused him to line the lid's lip with that copper foil. We decided to try that simple mod on the new coupler and see what impact it had. The change was huge. That simple step increased the directivity from a meager 15 dB to a very respectable 27.0 dB. I have no idea why neither of my attempts came close to Paul's amazing 32.1 dB directivity, but I will ask and add his comments later.

Clearly, the enclosure is not a good RF tight box. If you look at any of my pictures you can see how rough the top of the enclosure itself is. I thought to smooth and flatten that out using a very flat surface and a piece of wet and dry sandpaper, but I forgot. That might have helped, but the lid is a more complex shape and does not lend itself to smoothing it this way.

On the next page you'll see my overall plan for my SSPA data acquisition subsystem. The weak link is the 8-bit analog to digital converter on the Arduino board. I wanted to simply attach a 12-bit differential ADC shield between the Arduino and the LCD display, but it is not possible, so I'm stuck with only 8-bits of resolution. With 27 dB of directivity, and 600 Watts out, I'll have 1.2 Watts showing up in the reflected power port that shouldn't be there. It will add algebraically to the actual reflected power in an unknown way, depending on phase. So, my 0-60 Watt reflected power scale will be +/- one Watt in accuracy, at least coming out of the reflected power port on the coupler. That RF signal then gets processed by a logarithmic detector which should add little additional error, inverted, level-shifted, and amplified before reaching the input of the 8-bit ADC. Assuming a reasonable voltage span for the forward power, and identical circuitry on the reflected side, I'll only be using one tenth of the available bits – instead of close to 1000, I'll be resolving that output with only 100 bits.

HIGH-POWER 23cm DIRECTIONAL COUPLER PROJECT



Now that the High-Power Directional Coupler is completed, here's a block diagram of the whole SSPA data acquisition subsystem.

- 1) As RF power passes through the coupler, a portion is coupled to the Sense Line. The Sense Line has directivity and two outputs – Forward Power, and Reflected Power.
- 2) Those outputs drive the two attenuators. Their purpose is to bring the RF levels down into the linear range of the following linear Detectors, and to provide perfect 50-Ohm loads to the Sense Line, which will improve directivity.
- 3) This takes full advantage of the 8-bit analog to digital converter that follows the multiplexer.

Everything to the left of the Multiplexer will be housed in a weatherproof enclosure on my tower. The multiplexer and everything to the right is housed in a small box at my operating position. The items shown inside the dashed lines will be housed in an EMI shielded box.

My write-up on the GUI display picks up from here...