Waveguide Cross-guide Directional Couplers

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When my new 47 GHz transverter arrived from DB6NT[1], the first goal was to put it on the air. I had no test equipment and couldn't find any of the right size WR-19 waveguide in the junk box. Lacking a waveguide switch for TR switching, I decided to make two separate horns and get it on the air.

At our local makerspace, The FoundryVT[2], I made a pair of Skobolev dual-mode horns[3] using a CNC lathe. The horns have an estimated gain of 23 dBi. I put them on the transverter breadboard, shown in Figure 1, and made some contacts. Best DX was 90 km, beyond line-of-sight over the ocean between the islands of Block Island, RI, and Martha's Vineyard, MA. In the 2019 10 GHz & Up contest, I increased it to 123 km, line-of-sight between Mt. Mansfield, VT and Mt. Washington, NH.

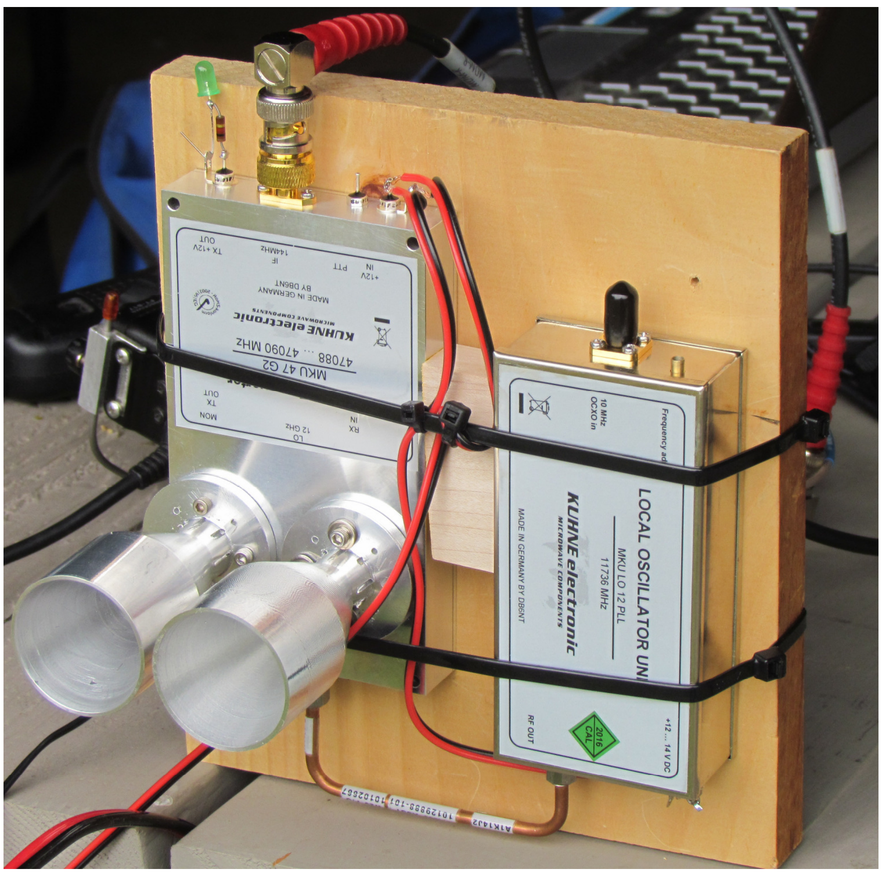

Figure 1 – 47 GHz DB6NT Transverter breadboard with separate horns

With the CNC machinery at the makerspace, I have been able to make a number of waveguide components in WR-19 and other sizes, including the OE9PMJ filters I described[4] at Microwave Update 2018. However, I have only been able to tune and test them at VHF conferences where a fancy VNA is available. Thanks to the suppliers of this equipment for making it available.

Waveguide Directional Couplers

I have found and used surplus waveguide directional couplers for 10 and 24 GHz and other frequencies, but never for 47 GHz. Could I make them for 47 GHz? I have seen three types: two with parallel waveguides, both broadwall and sidewall, and the other with crossed perpendicular waveguides; versions of all three types are shown in Figure 2. The parallel variety requires bends in one waveguide to access all four ports, an additional complication, so I decided on the cross-guide version, which could be machined in a block of aluminum.

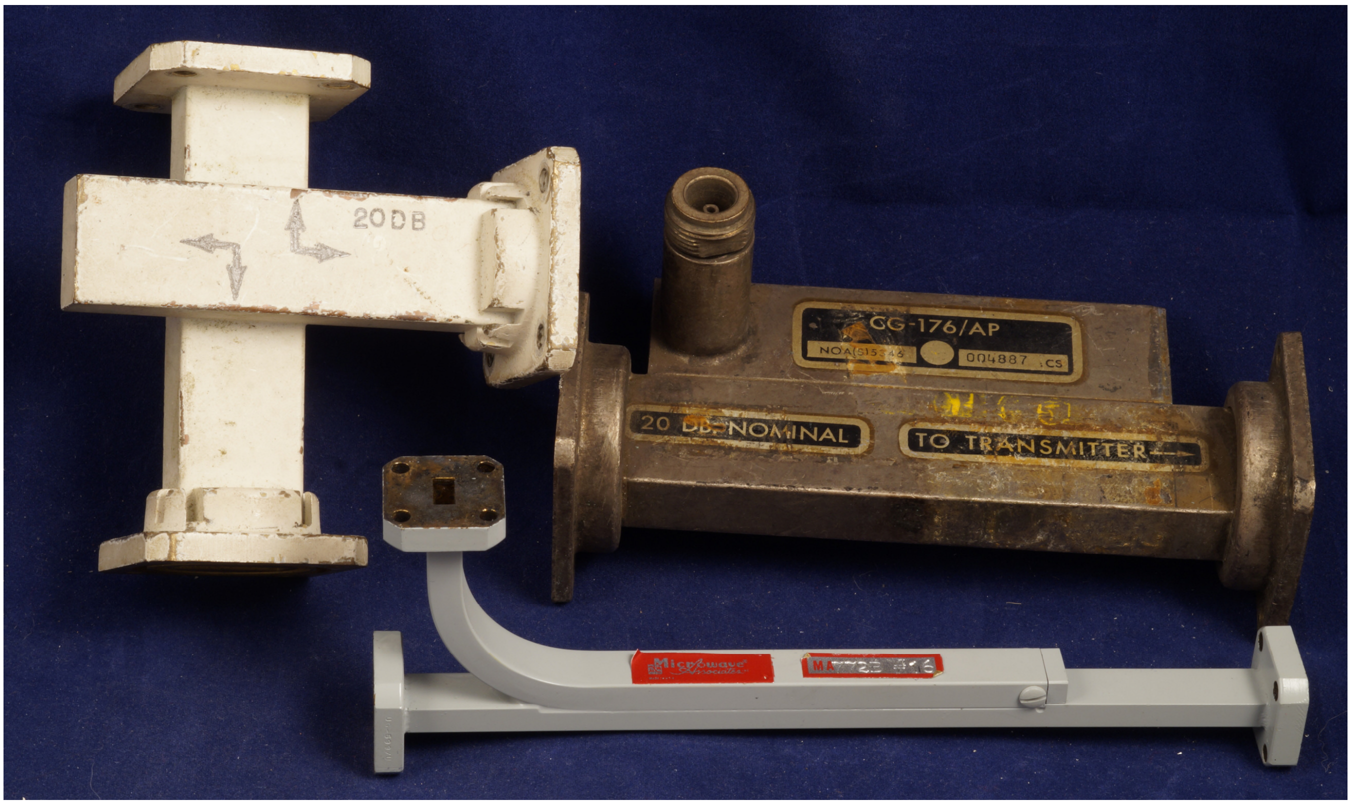

Figure 2 – Surplus waveguide directional couplers. Clockwise from left: cross-guide coupler in WR-75, sidewall coupler in WR-90, and broadwall coupler in WR-28.

The WWII RadLab series has 44 pages on directional couplers[5] in Volume 11, but most of them look rather difficult to make. Publications on waveguide have appeared frequently since then, but details for waveguide directional couplers are scarce. I found bibliographies[6,7,8,9] of all directional coupler papers between 1938 and 1966, but very little with useful details.

Two types of cross-guide couplers have been described – the Moreno type with two "X" shaped holes between the crossed waveguides[10], sketched in Figure 3, and one with three round holes between the crossed guides. The cross-guide coupler is of this type. The X-shaped holes are reasonably large at 10 GHz, but the dimensions are very small at 47 GHz, beyond my machining capabilities, while round holes are easy to make in any size.

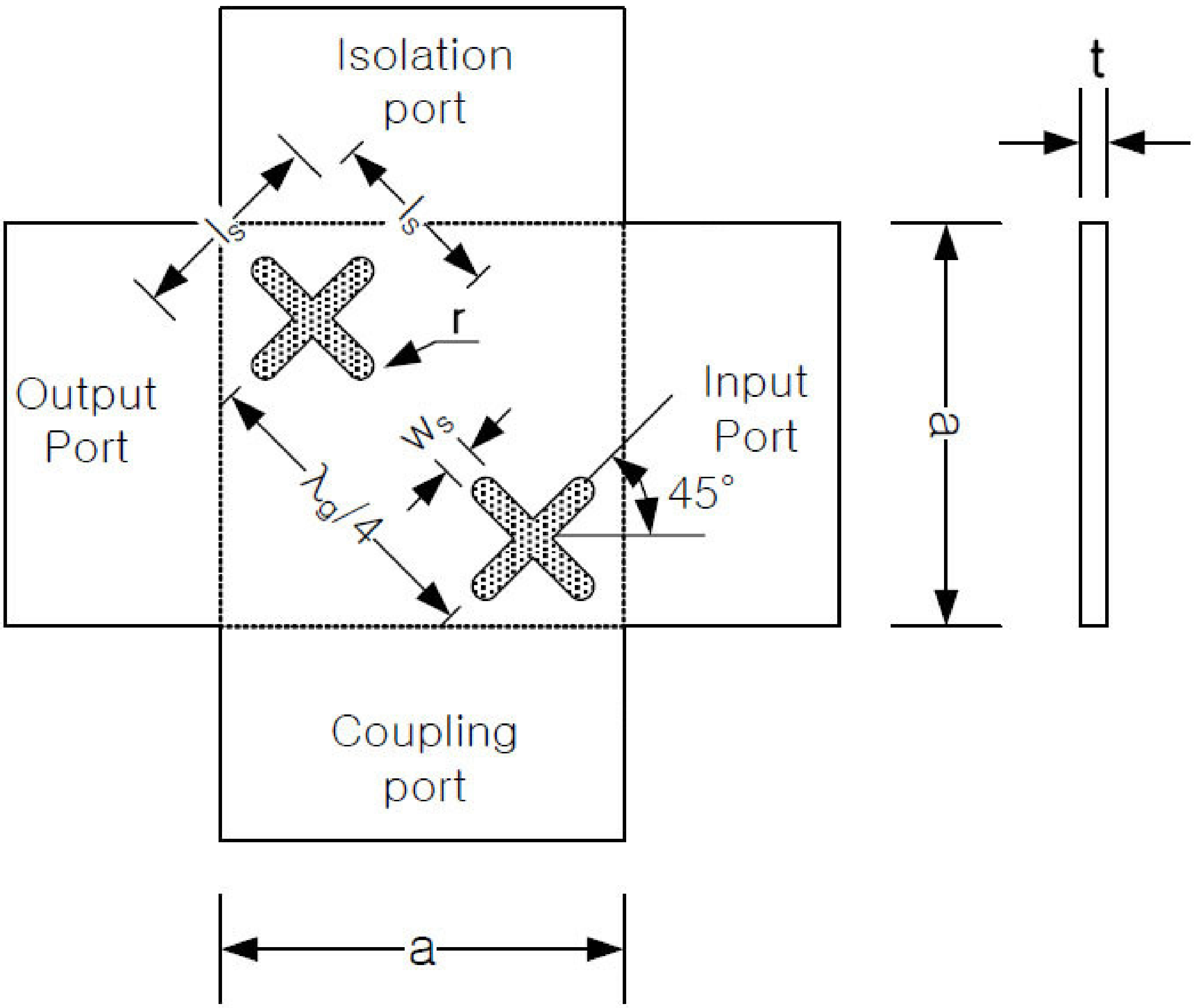

Figure 3 – Moreno cross-guide directional coupler sketch

The only publication I found for the round hole type is a single graph labelled "ROUND HOLE CROSS GUIDE DIRECTIONAL COUPLER" in the *Microwave Engineers Handbook* [11] attributed to Gershon J. Wheeler, showing two diagonally-placed holes plus a third, smaller, hole forming a triangle, with all holes λg/8 from the centerlines of both guides. The graph shows hole size vs coupling for couplings between 21 and 42.5 dB for the larger holes; the smaller hole is specified as 2/3 of this diameter.

I later found that Wheeler had patented[12] the three hole directional coupler, with the patent assigned to Raytheon. Figure 4 is a sketch of this coupler from the patent. The patent has expired, so we aren't going to infringe. The patent has lots of claims, but little useful information: "proven by empirical methods to increase directivity." One claim is that a third hole can improve the version shown in Figure 2 as well. Of course, the real details would have been proprietary information.

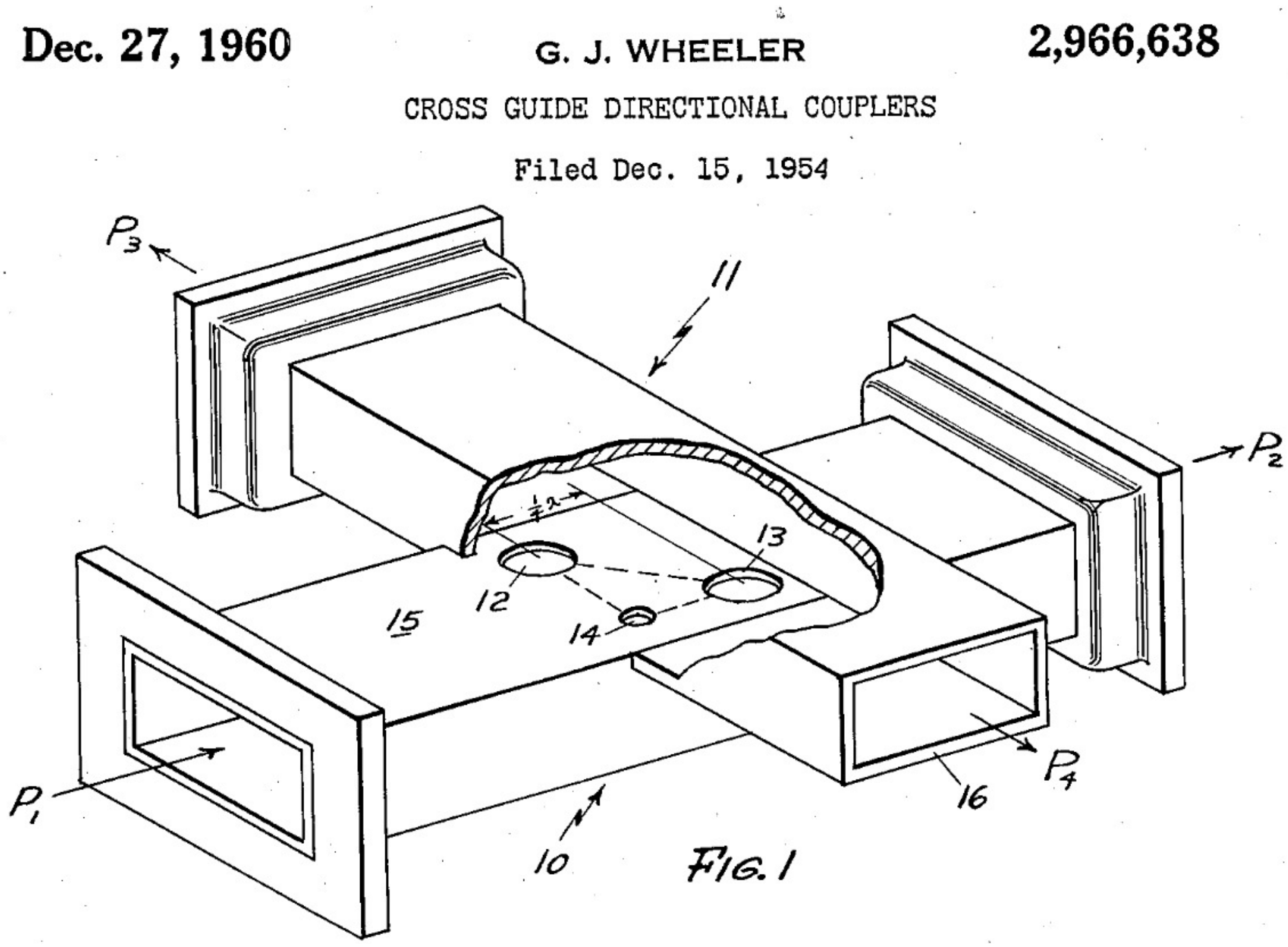

Figure 4 – Round hole cross-guide directional coupler sketch

What wasn't mentioned in the graph is the thickness of the wall between the crossed waveguides that the holes pass through. The patent says the holes are in the wall of one waveguide, with the wall of the other cut away. Since I machine both guides out of a single block of aluminum, leaving the wall between them, 0.5 mm seemed like a comfortable thickness.

The graph seemed like a good starting point. Since I don't have any 47 GHz test equipment, starting with a WR-42 coupler at 24 GHz seemed like a good way to prove the concept, with the wall thickness scaled to 1 mm. I did an HFSS[11] simulation of a 30 dB WR-42 coupler with the published dimensions – the results, shown in Figure 5, were not too promising, with only about 12 dB directivity. This result plus the round numbers for hole locations suggest that the graph is only a first order calculation, probably based on the proverbial "thin" wall. However, simulations with thinner walls only improved directivity a couple of dB, but the coupling increased with thinner walls, bracketing the 30 dB target, as shown in Figure 5.

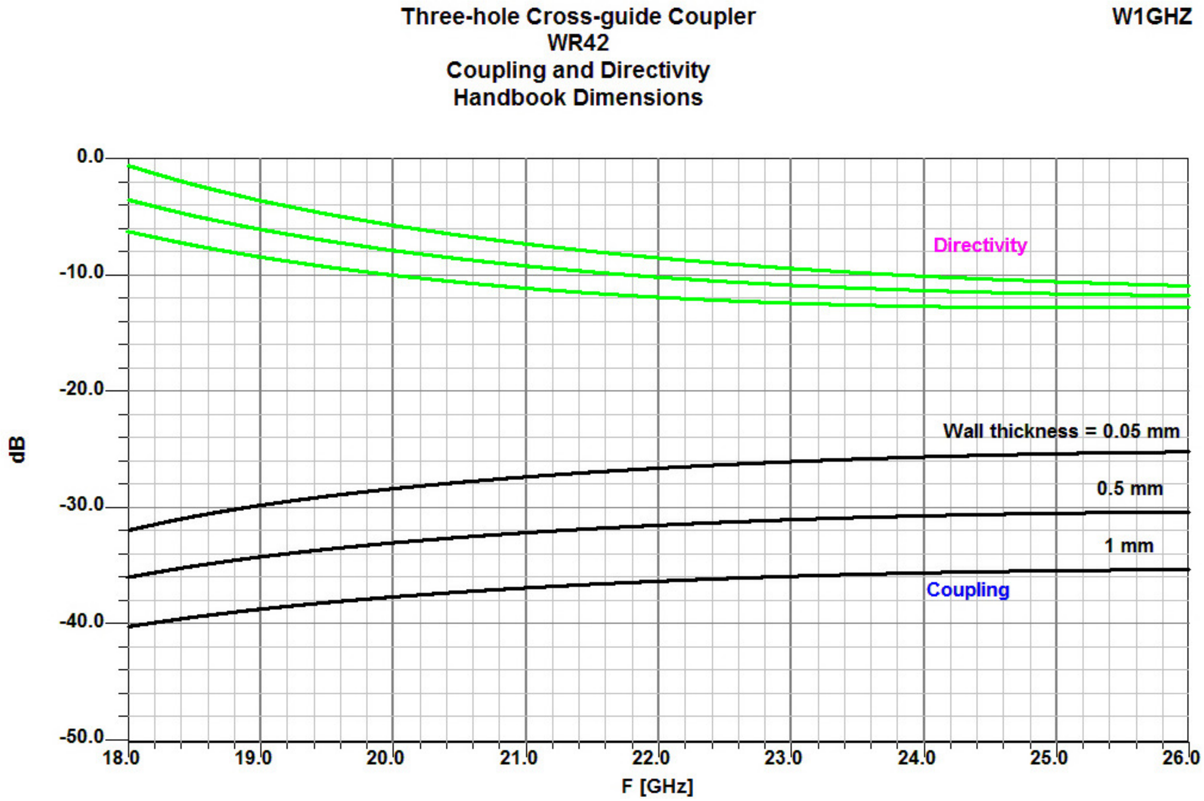

Figure 5 – Simulation of 30 dB round hole cross-guide directional coupler with dimensions from Wheeler graph

Directivity

A directional coupler with only 12 dB of directivity isn't very useful. Directivity is the difference between coupled forward power and coupled reflected power with a perfect termination; in other words, leakage into the reflected port. This means that the indicated Return Loss with a perfect load would be 12 dB. Any reflected power from different terminations would add or subtract from the leakage, depending on phase, giving bogus readings. Forward power indication also includes leakage, so that could vary by +/-6% (-12 dB) from true power. Note that hams bragging about -35 dB return loss (or 1.036 VSWR) had better know the directivity of their test equipment.

Could the directivity of the cross-guide couplers be improved by adjusting the holes? Some trial and error suggested that the center frequency of the coupler was too high, so the holes should be further from the center line. Directivity improved by making the smaller hole a bit larger, but only over a relatively narrow bandwidth. Coupling is fairly flat over a wider bandwidth, but not good directivity. Fine tuning of hole placement and size produced 30 dB and 40 dB couplers in WR-42 with flat coupling and excellent directivity from 24.0 to 24.5 GHz. An attempt at increasing the hole diameters to produce a 20 dB coupler was not successful – large holes that graze the waveguide wall only resulted in 23 dB coupling.

Final dimensions after simulation suggest that Wheeler's graph for coupling was reasonably close, but the other dimensions are not as good. The hole distance from guide centerlines is closer to $\lambda g/6$ rather than $\lambda g/8$, and the small hole diameter providing best directivity is around 0.8 D rather than 2/3 D. Actual dimensions of couplers that I made and measured are shown in Table 1.

24 GHz

I machined both 30 dB and 40 dB WR-42 cross-guide couplers on a CNC milling machine. Hole location is controlled by the CNC using the same indexing as the waveguide cuts, and hole diameter is tested and fine-tuned using pin gauges. Figure 6 is a photo of one side with waveguide and holes, and an assembled coupler. Twenty tapped holes are required for assembly and waveguide flanges – all the holes would never line up without CNC. An additional complication is that the threaded holes intersect with the joint between metal blocks.

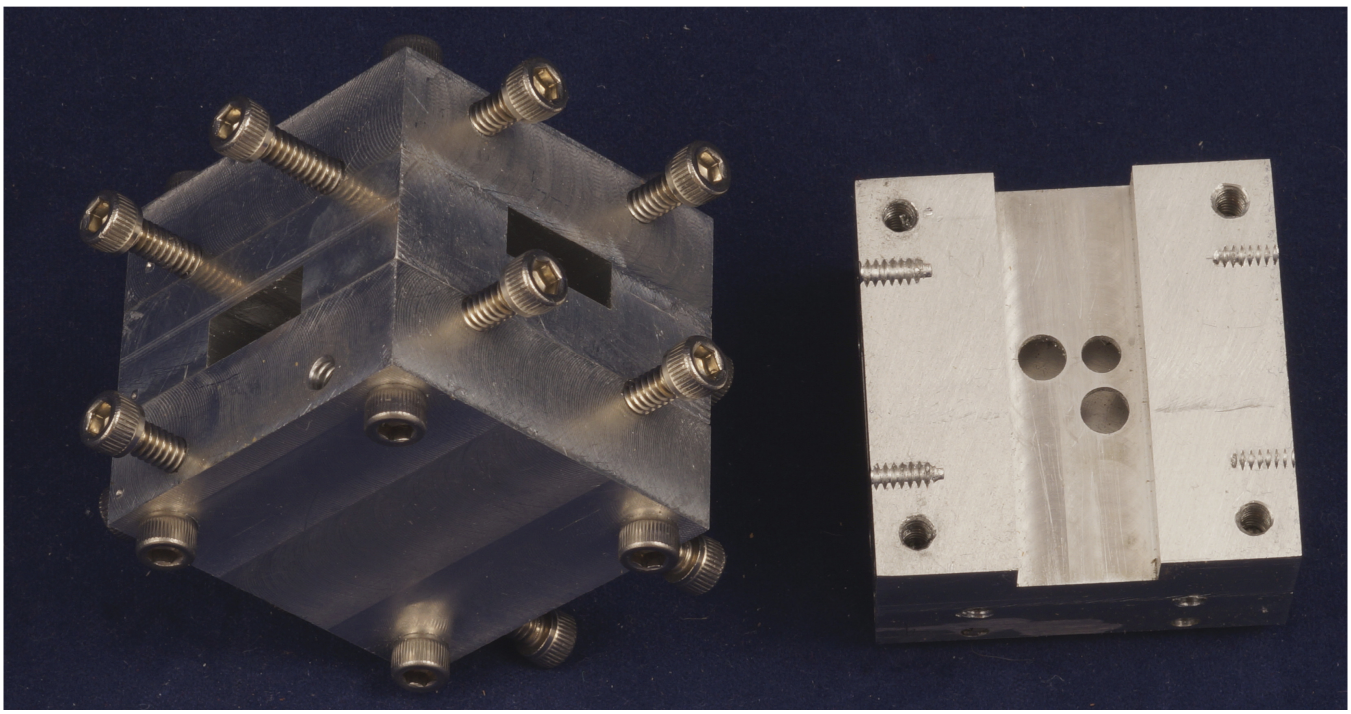

Figure 6 – Machined round hole cross-guide coupler for 24 GHz in WR-42 waveguide

I got a chance to test one of the finished couplers at Microwave Update 2017 on an Anritsu VNA with full waveguide calibration; coax transitions add uncertainty and usually degrade directivity. Thanks for to Anritsu for providing this equipment and to Jeffrey Pawlan, WA6KBL, for the waveguide calibration. The results, shown in Figure 7 are very good, with 35+ dB directivity from 24.0 to 24.5 GHz. Coupling is 38.3 dB, slightly less than the target 40 dB.

The measured results are compared with simulation in Figure 8. The measured coupling is slightly stronger than simulated, and the measured directivity is best at 24 to 24.5 GHz while the simulated directivity is best at a bit higher frequency – a fortunate difference.

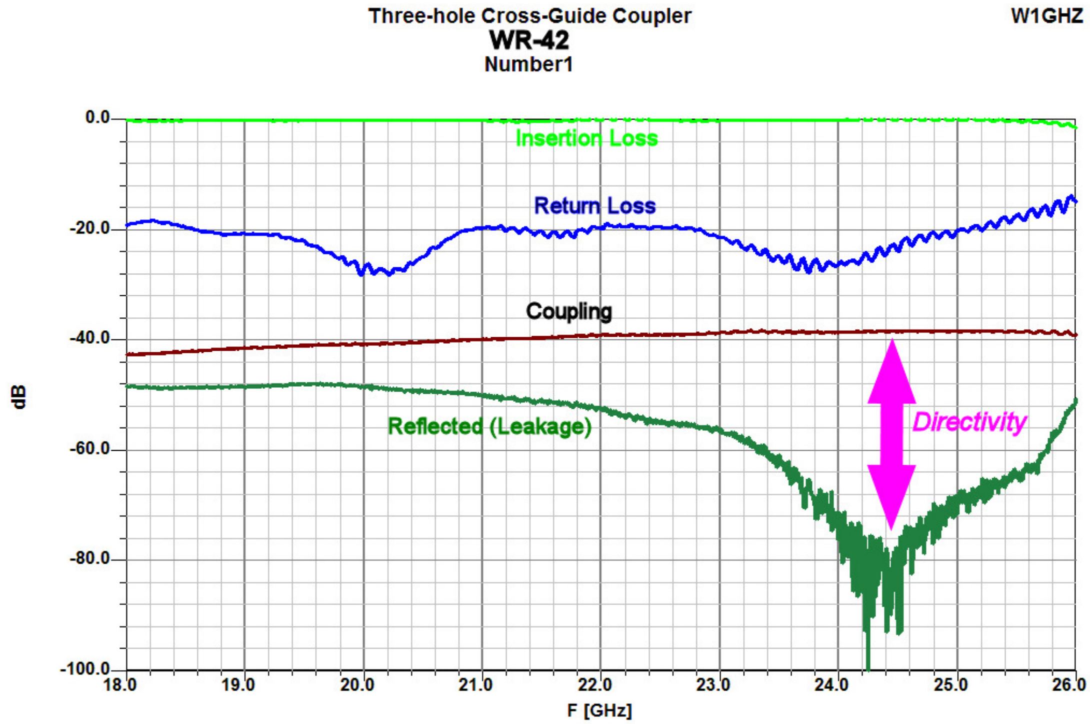

Figure 7 – Measured performance of round hole cross-guide 40 dB directional coupler for 24 GHz in WR-42 waveguide

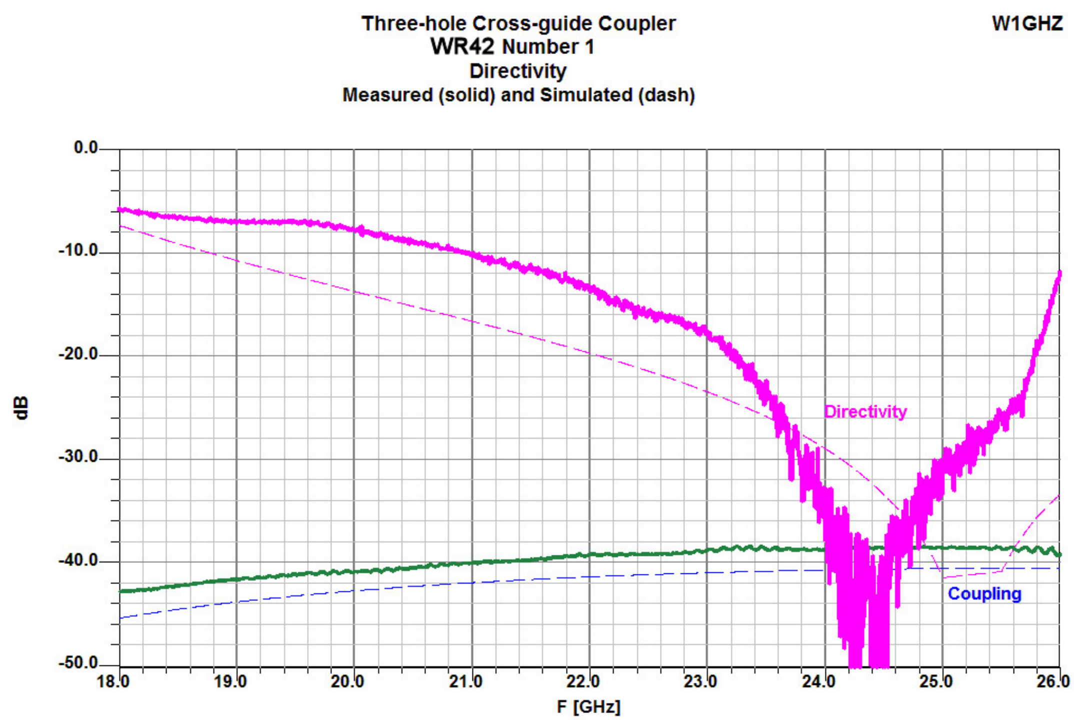

Figure 8 - Measured performance comparison to simulation of round hole cross-guide 40 dB directional coupler for 24 GHz in WR-42 waveguide

The second WR-42 coupler, targeted at 30 dB coupling, was measured in coax with homebrew transitions on a Rohde & Schwarz ZVA67 VNA at the 2018 Eastern VHF/UHF Conference thanks to Greg Bonaguide, WA1VUG. Results were not as good – the homebrew transitions appear to have significant mismatch which compromised the results. Coupling was about -29 dB, slightly stronger than the target.

47 GHz

Encouraged by the 24 GHz results, I machined three WR-19 cross-guide couplers, two with 30 dB nominal coupling and one with 40 dB nominal coupling. I was only able to measure these couplers in coax using WR-19 to SMA transitions that I made, at Microwave Update 2018. SMA connectors are way beyond their specified range at 47 GHz, and a pair of transitions show about 2 dB loss, adding uncertaintly to the coupling. The results for one of the 30 dB couplers, shown in Figure 8, are not great, but the coupling is close to the 30 dB target. The other two couplers showed similar results.

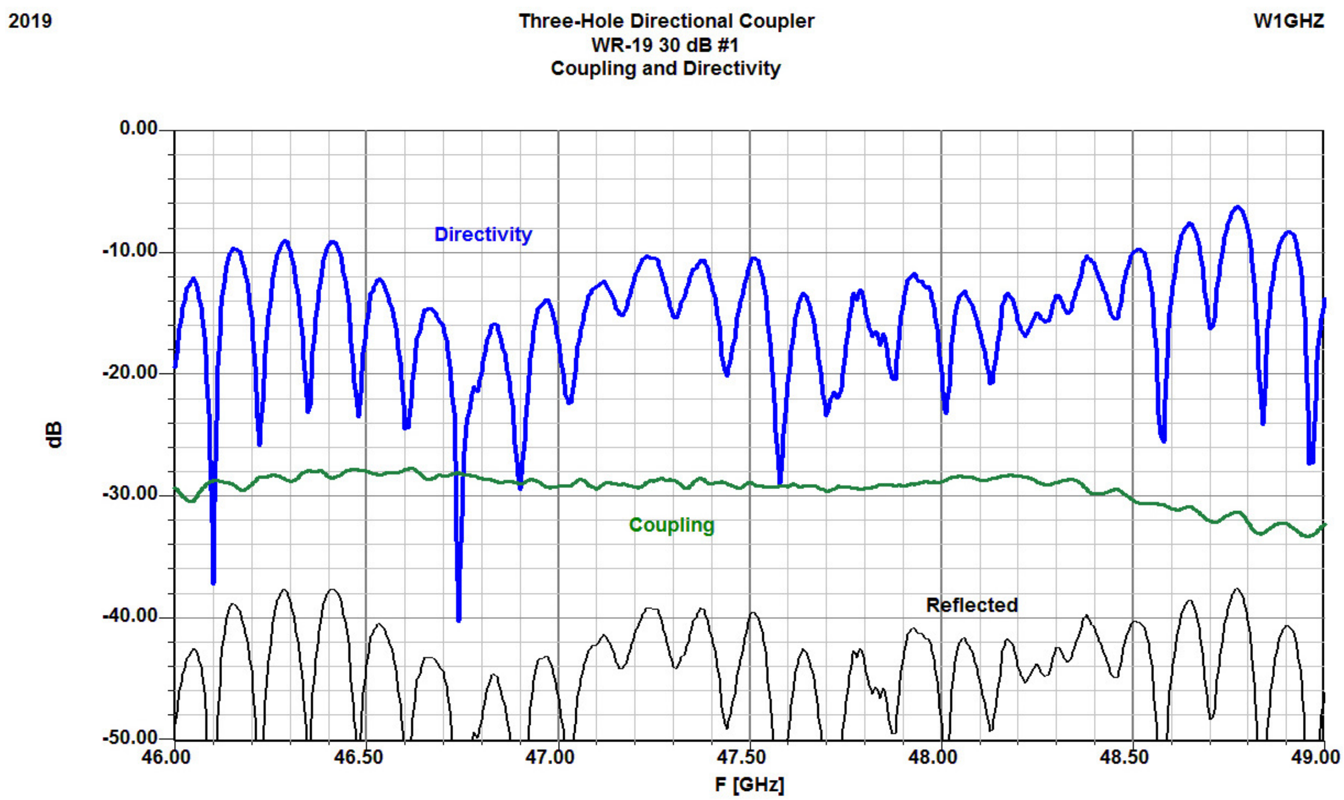

Figure 9 - Measured performance of round hole cross-guide 30 dB directional coupler for 47 GHz in WR-19 waveguide

I am not ready to buy a 47 GHz amplifier from DB6NT, and my transverter output is only 30 or 40 milliwatts, so the 30 and 40 dB couplers aren't much use yet. A 20dB coupler would be useful, but the strongest possible coupling in simulation is about 23 dB. However, all the measured couplers have slightly stronger coupling than expected, and making the wall between the waveguides thinner also increases the coupling. Making these changes might get close to 20 dB coupling.

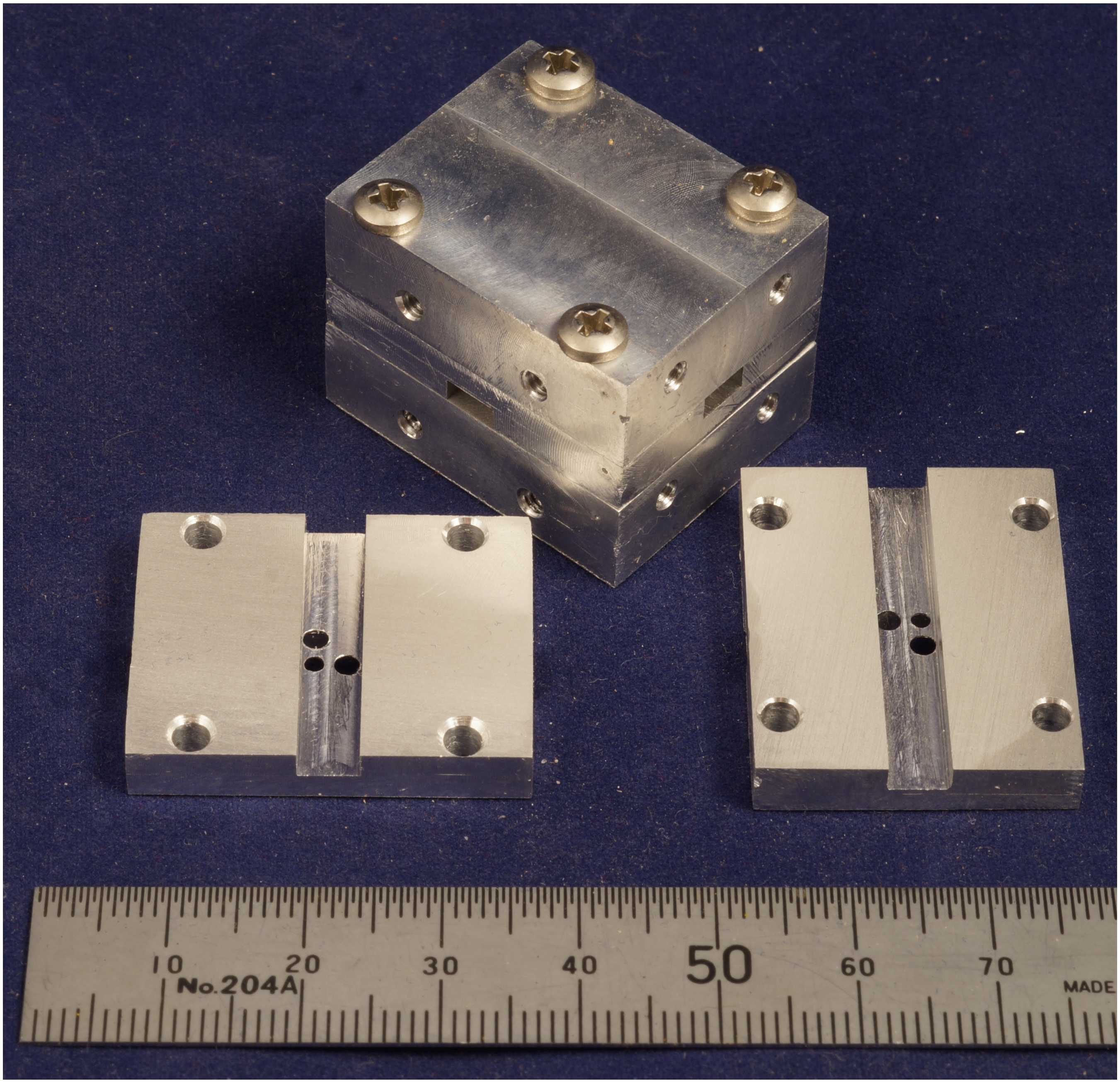

Figure 10 - Machined round hole cross-guide 20 dB directional coupler for 47 GHz in WR-19 waveguide

I machined two more WR-19 couplers with large holes and a thin wall, which ended up somewhere between 5 and 10 mils thick – WR-19 waveguide is too small to fit a micrometer inside. The large holes may be seen in Figure 10. Measurements were made at the 2019 Super VHF Conference, with results shown in Figure 11. Both have about 22 dB coupling including coax transitions; a pair of transitions alone has about 2 dB loss, so the actual coupling may be close to 20 dB. Directivity is very good, at least 30 dB from 47 to 47.5 GHz. These couplers are actually useful for measuring Return Loss with an HP432 power meter.

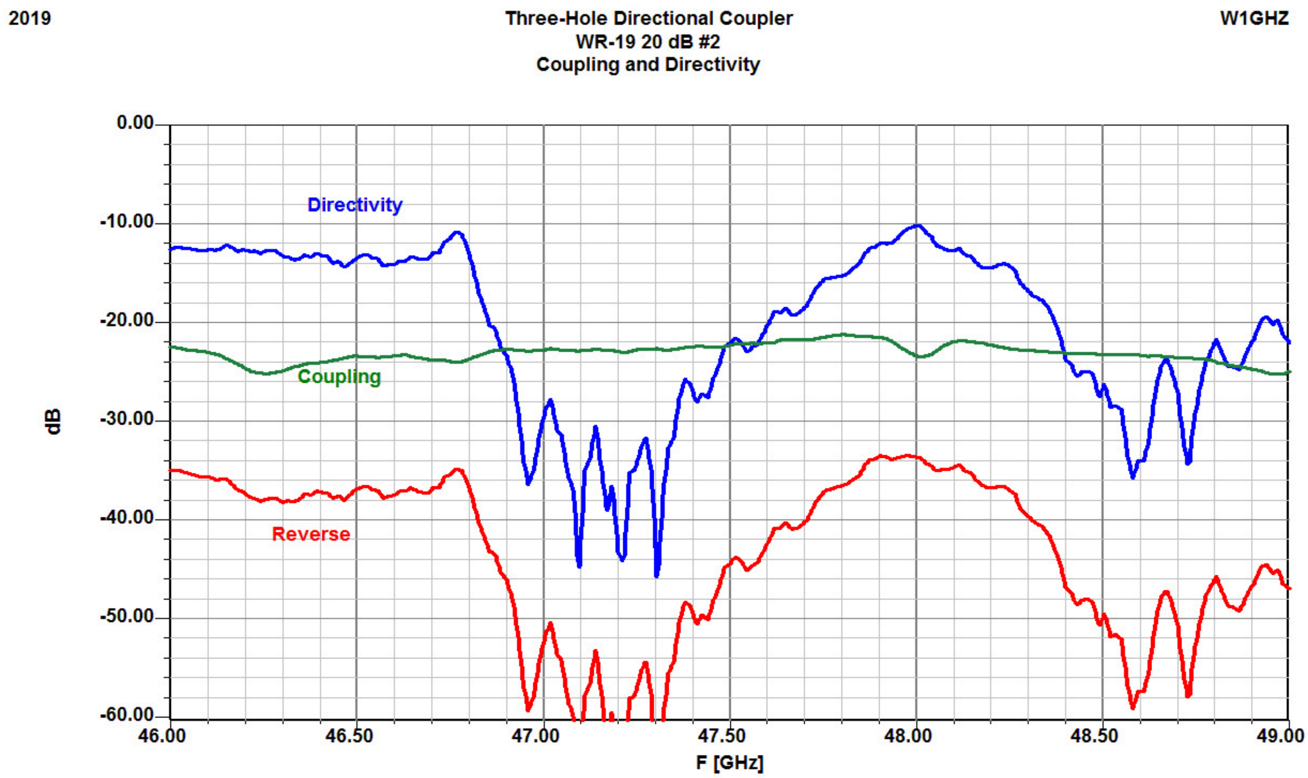

Figure 11 - Measured performance of round hole cross-guide 20 dB directional coupler for 47 GHz in WR-19 waveguide

Construction

I machined the 24 and 47 GHz directional couplers as three aluminum blocks: a center section with both waveguides, separated by the wall containing the coupling holes. The waveguides are simply rectangular grooves in the center block, with flat top and bottom pieces forming the fourth wall of the waveguides. The two perpendicular waveguides are offset vertically by the wall thickness, so the screw holes for the waveguide flanges are asymmetric. Tapping the threads for 4 flanges plus assembly screws, a total 20 threaded holes, is rather tedious.

A possibly better way to produce these directional couplers would be to photo etch the holes into a thin metal plate, to be placed between two metal blocks. Each block would have a waveguide machined into it, with opposite sides of the metal plate forming the fourth wall of both waveguides. Alignment pins would control placement of the coupling holes. Companies offering precision photo etching have displays at microwave trade shows.

10 GHz

Some serious EME stations run real power at 10 GHz, and waveguide is required – SMA connectors aren't good for much more than 50 watts. Directional couplers for 10 GHz, in WR-90 waveguide, are occasionally found in surplus. A quick check of ebay finds a number of 10 and 20 dB couplers, but nothing at 30 dB or higher. For instance, at least 40 dB is needed for 100 watts. I worked out hole dimensions for both 40 and 50 dB of coupling in WR-90.

Rather than machine large blocks of aluminum, I used surplus pieces of ordinary WR-90 waveguide with the holes drilled in one piece and a window cut out in the other, as shown in Figure 12, then soldered them together. To make alignment easier, the wall with the holes was notched slightly to hold the guide with the window in place. As a result, the wall was thinned slightly, to about 1mm. I made the holes, notch, and window using CNC so they fit perfectly, but WR-90 is large enough that a coupler could be built with hand tools with some care.

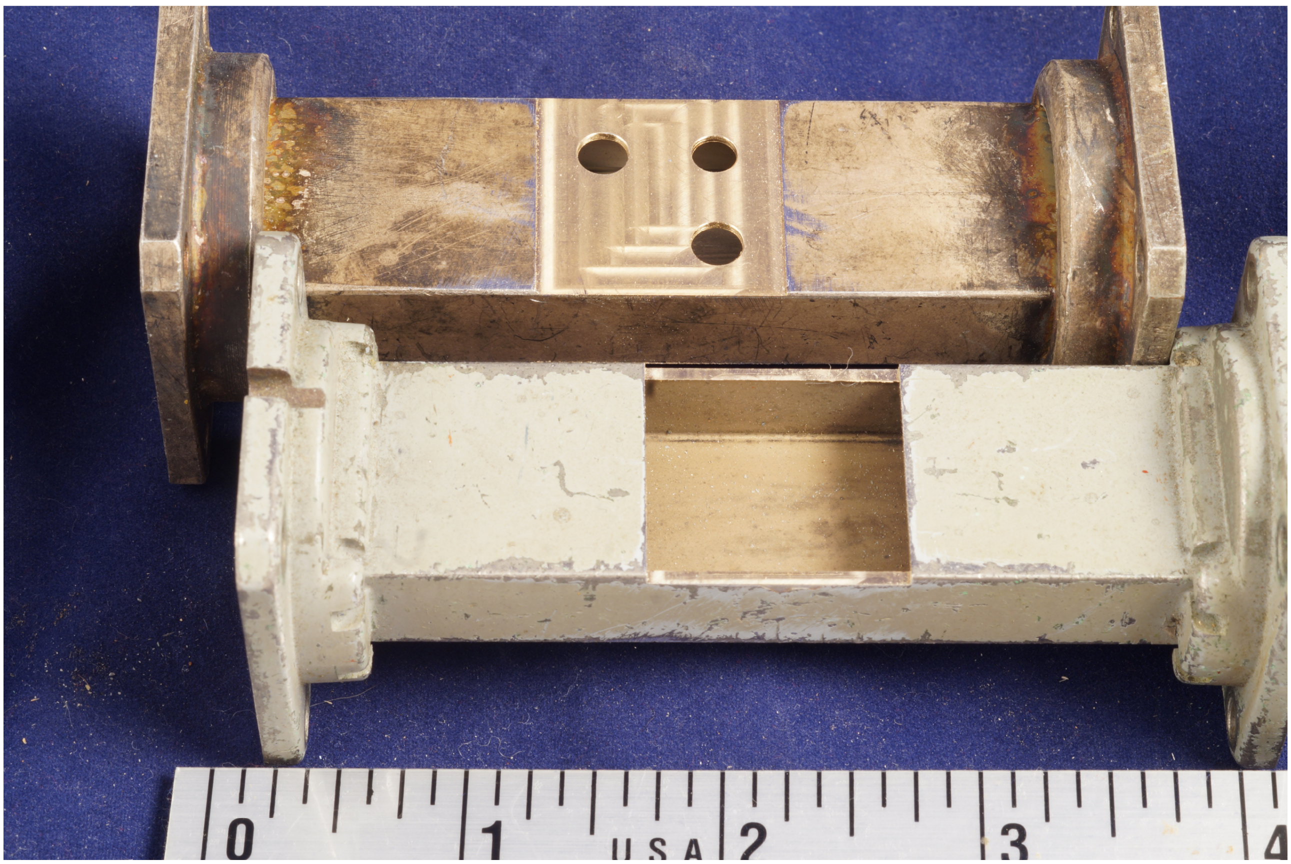

Figure 12 - Round hole cross-guide directional coupler for 10 GHz in WR-90 waveguide fabrication from surplus waveguide before soldering together.

The couplers, shown complete in Figure 13, were measured at the 2019 Super VHF Conference. Measuring the couplers required waveguide to coax transitions for the VNA. I don't have enough professional transitions, so some homebrew ones were used as well. These are good enough for ham rigs, but not for precision measurements with the >80 dB range required for a 50 dB directional coupler.

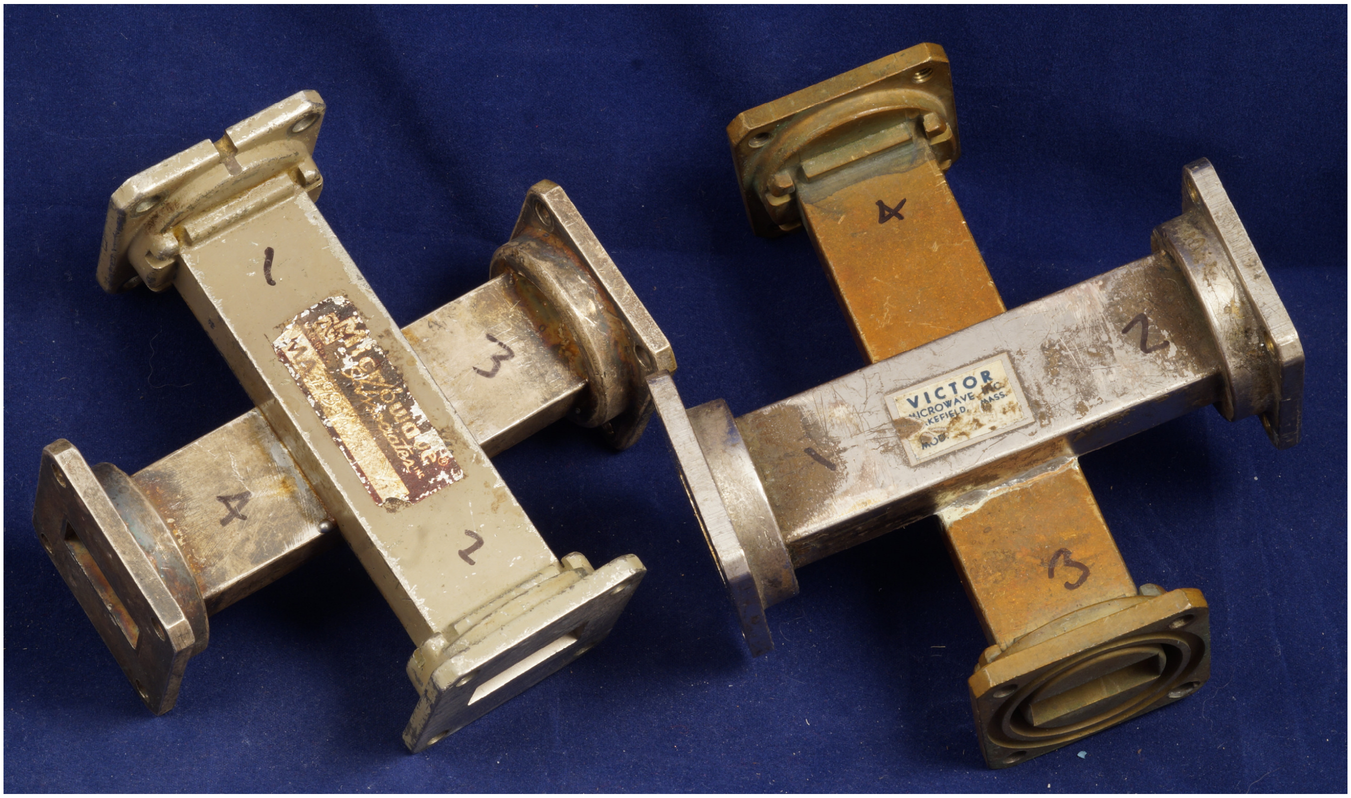

Figure 13 - Round hole cross-guide directional couplers for 10 GHz in WR-90 waveguide

Measurement results are not completely available – I apparently did something wrong in saving the S-parameters, so I only have screenshots of the plots. Like the higher frequency couplers, coupling at 10.368 GHz is slightly stronger than predicted by simulation: 37.3 dB for the nominal 40 dB coupler, and 46.3 dB for the 50 dB one. Directivity is not as good as expected, ~20 dB for the nominal 40 dB coupler, and ~16 dB for the 50dB one; this is probably limited by the coax transitions. These couplers are useful for measuring QRO power: with a power meter like the HP432, limited to 10 milliwatts, — 46.3 dB coupling allows measurement of up to 426 watts.

Summary

Waveguide directional couplers with good directivity were made for 47, 24 and 10 GHz. These couplers can be used to measure high power directly in a waveguide system, and as instrumentation to measure Return Loss. Hole dimensions for all of these directional couplers are shown in Table 1, to enable others to replicate the couplers. Not included, but available on request, are some other simulated dimensions.

I do not plan to produce and sell any of these directional couplers, but would be willing to assist any ham who wishes to produce his or her own or to make them for sale.

Acknowledgements

Very little of this machining would have been possible without the assistance and mentoring of Tom Bishop of The FoundryVT and other members of this fine Makerspace.

Measurements of these directional couplers made possible by the availability of test equipment at conferences from Rohde & Schwarz, courtesy of Greg Bonaguide, WA1VUG; Agilent; and Anritsu, with assistance from Jeffrey Pawlan, WA6KBL.

References

1. www.kuhne-electronic.com
2. www.TheFoundryVT.org
3. Paul Wade, W1GHZ, "Optimized Dual-Mode Feedhorns," ***DUBUS***, 3/2009, p. 46. http://www.w1ghz.org/antbook/conf/optimized_dualmode_feedhorns.pdf
4. Paul Wade, W1GHZ, "Understanding the OE9PMJ Microwave Filter," *Proceedings of Microwave Update 2016*, ARRL, 2016, pp. 162-173.
5. R. L. Kyhl, "Chapter 14 – Directional Couplers," in *Technique of Microwave Measurements*, Carol G. Montgomery, editor; Volume 11 of *MIT Radiation Laboratory Series*, Louis N. Ridenour, editor in chief, McGraw-Hill, 1947, pp. 854-897.
6. R.F. Schwartz, "Bibliography on Directional Couplers, 1935-1953" *Transactions of the IRE Professional Group on Microwave Theory and Techniques*, July 1954, pp. 58-63.
7. R.F. Schwartz, "Adenda to 'Bibliography on Directional Couplers'," *Transactions of the IRE Professional Group on Microwave Theory and Techniques*, April 1955, pp. 42-43.
8. W.E. Caswell, R.F. Schwartz, "The Directional Coupler - 1966", *IEEE Transactions on Microwave Theory and Techniques*, February 1967, pp. 120-123.
9. S.B. Cohn, R. Levy, "History of Microwave Passive Components with Particular Attention to Directional Couplers", *IEEE Transactions on Microwave Theory and Techniques*, September 1984, pp. 1046-1054.
10. Theodore S. Saad, *Microwave Engineers Handbook, Volume 2*, Artech House, 1971, p.9,
11. Theodore S. Saad, *Microwave Engineers Handbook, Volume 2*, Artech House, 1971, p. 11.
12. G. J. Wheeler, "Cross Guide Directional Couplers," *US Patent 2.966,638*, Dec. 27, 1960.

Three-hole Cross-guide Directional Coupler Dimensions

W1GHZ
2019

Waveguide	Coupling Target dB	Coupling actual dB	Wall thickness inches	Large hole Diameter inches	Small hole Diameter inches	off CL distance inches
WR-42	30	29.7	0.045	0.146	0.120	0.089
	40	38.3	0.045	0.122	0.098	0.089
WR-19	21.8	~21	~.010	0.079	0.062	0.050
	30.4	~30	0.029	0.078	0.062	0.0484
	40	~39	0.029	0.062	0.050	0.0484
WR-90	40	37.3	0.04	0.209	0.184	0.228
	50	46.3	0.04	0.158	0.138	0.225

Table 1