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An All Purpose High Gain Antenna for 2400 MHz

Roger shows an easy to fabricate circular horn antenna that can be built using copper plumbing pipe and sheet copper.

For those interested in a relatively easy way to build antenna for the 2400 MHz band, the design described here might be the answer. It features high gain, good capture area, and shielding from strong local signals. The antenna will operate in either vertical or horizontal polarization as a function of mounting. Design data with complete construction and tuning procedures take the guesswork out of building this wonder antenna, out of a simple copper pipe.

This article provides a simple step-by-step procedure for the design and construction of a horn antenna. This horn will work as a stand-alone antenna (boasting nearly 9 db-d of gain) or a feed horn for a parabolic dish. The possibilities for using this antenna are limited by your imagination. Point to point communication of data and voice has been done over several miles. If you are lucky enough to have a shack in the back yard, two of these provide a great data link with the house. The author has not tried this antenna as a feed horn with a dish but there is no reason why it would not work. Attention should be given to f/d ratio and parabola illumination in that application. With a simple hood addition, this copper wonder will provide 12 db of gain, now that's 17 times!

Figure 1 – Side view of the completed horn antenna.

According to Kraus[1] a horn antenna is regarded as an opened up waveguide. The function of this arrangement is to produce an in-phase wave front thus providing signal gain in a given direction. Signal is injected into the waveguide by means of a small probe that must be critically placed. The type of horn described in this writing is known as a cylindrical horn. It was chosen for simplicity of construction utilizing available copper pipe.

[1]Notes appear on page 46.

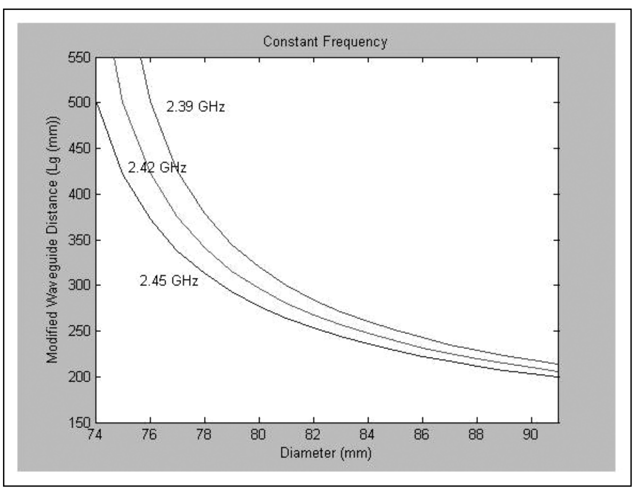

Figure 2 – Graph of Guide Wavelength (Lg) vs Horn diameter for 13 cm Band.

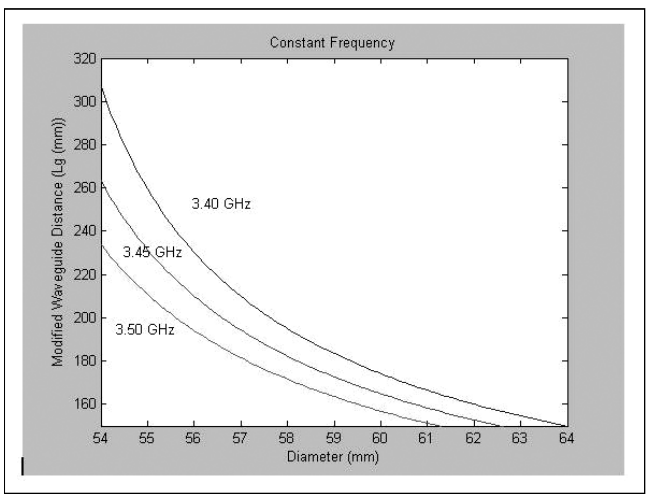

Figure 3 — Graph of Guide Wavelength (Lg) vs Horn diameter for 9 cm Band.

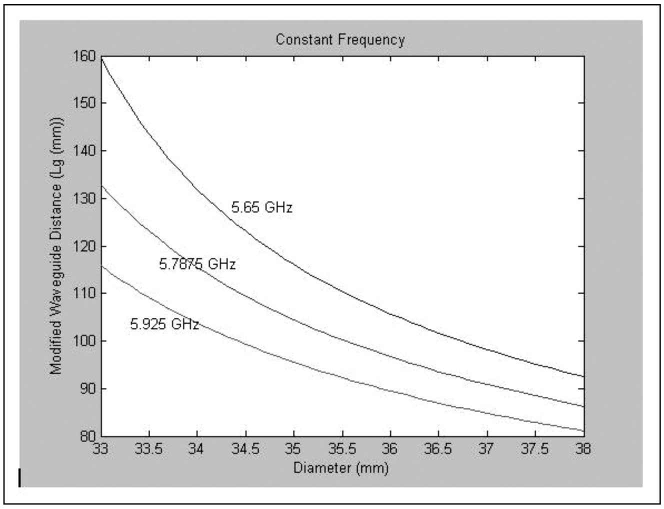

Figure 4 — Graph of Guide Wavelength (Lg) vs Horn diameter for 6 cm Band.

Figure 6 — Raw cylinder ready to be cut.

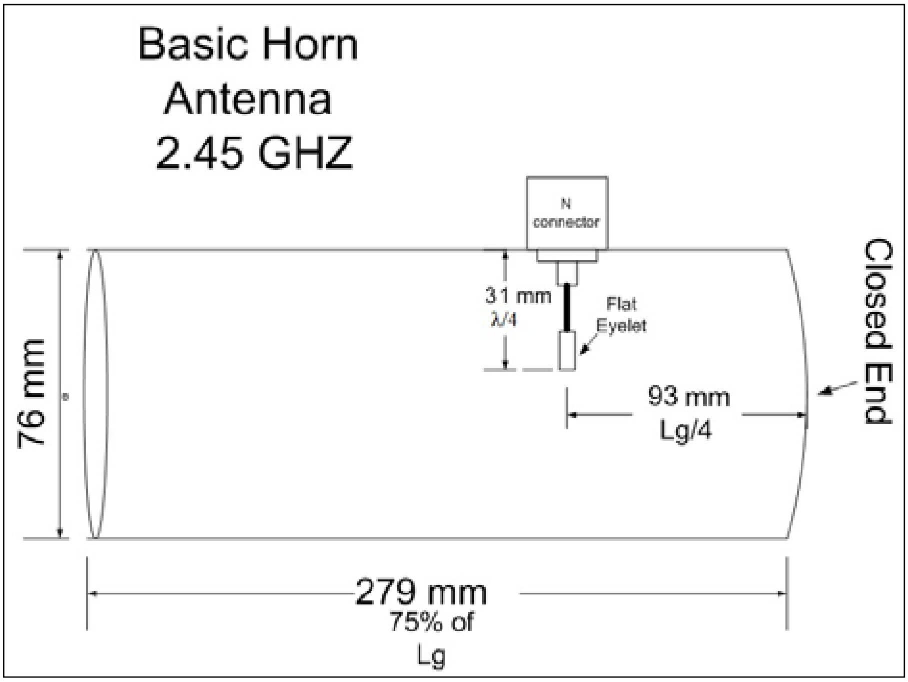

Figure 5 — Basic Horn Antenna Design.

Sometimes relationships that appear to be relatively simple are in-fact very complex. This is certainly the case for the horn antenna. First, only the cylinder diameter determines the lowest and highest frequency that can be used with this arrangement. They are referred to as the cut off frequencies because below and above performance deteriorates rapidly. Secondly, there is a critical optimum location for a probe that excites the waveguide horn cylinder. Finally, the length of the tube, shorted on one end, is a modified version of a wavelength, but not the free space wavelength.

What goes on inside a waveguide is complex to say the least. Instead of propagating in straight lines, the energy bounces off the walls of the cylinder causing constructive interference due to multiple reflections. The wavelength inside the closed cylinder is a compressed version of a free space wavelength. The reasons for the compression are due to in-phase and group velocities within the cylinder. The critical placement of the injection probe reinforces these wave fronts within the pipe waveguide thus providing signal gain out of the open end of the cylinder. This cylindrical waveguide is physically closed on one end and can be thought of similarly to a shorted piece of coaxial cable.

Designing your Antenna

To begin our design, a suitable cylinder must be found. The author used three inch I.D. copper pipe since it was surplus from the local public TV station. Cut pieces of rigid hard line work well and so does copper plumbing pipe. Any type of cylinder will work including coffee cans, but thin walled tin does not seem too stable or surface conductive compared to copper. Larger diameter copper pipe sections can be obtained from plumbing and heating contractors usually working on larger projects. Many commercial boilers utilize 3-4 inch diameter copper pipe. There are always small cut-off pieces (under two feet) that could be available for the asking. No matter what material you want to use, it must pass the frequency cut-off tests. If the diameter is too large or too small, the pipe may not function in the waveguide mode at your frequency of choice. The lowest frequency where this cut-off phenomenon occurs is known as the horn low cut-off diameter.[2] Without getting into propagation modes, let's refer to this number as the low cut-off frequency. There is also a high cut-off frequency, but we will deal with that later. This low cut-off frequency can be found using the equation below.[3]

$\lambda_C = 3.412 * r$

λ_C is the low cutoff wavelength, and r is the radius of the cylinder. By dividing the constant in half, this formula (in terms of diameter) becomes:

λ_C (mm) = 1.706 * diameter (mm) [Eq 1]

The low cut-off frequency is then found by using the standard wavelength formula.

F (GHz) = 300/ λ_C [Eq 2]

The author chose to use metric measure-

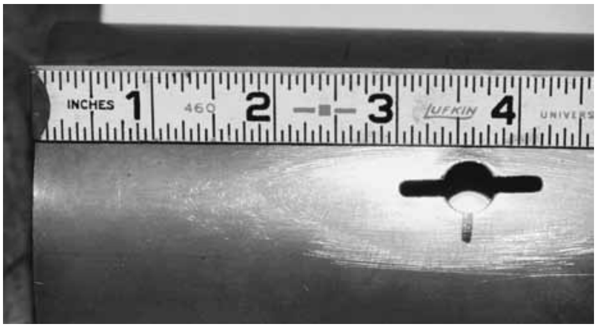

Figure 7 — Drilled opening for type "N" connector probe assembly. The slot was tried to be able to move the probe for best results. No difference was found and the slot was eliminated on later models.

ment for the equations not only for ease of calculations, but also for use in an evaluation program where metric units are used.

The low cut-off frequency is only a function of the diameter of the pipe, therefore, measure each pipe's inside diameter and crank out the above equations (one and two) until the cutoff frequency (λ_C) is slightly lower than the frequency range that you are planning to operate. Step one is to calculate the low frequency cut-off. In the author's particular case, the 76 mm (3 inches) diameter copper pipe from equation one became:

$\lambda_C = 1.706 * 76\text{mm}$
$\lambda_C = 130$ mm
F = 2.31 GHz = 300/130

This is the lowest critical frequency that the 76 mm diameter pipe will operate. Anything below 2.31 GHz and the pipe will stop functioning like a waveguide.

In step two, we must calculate the highest cut off frequency (λ_H) that this diameter pipe will operate as a waveguide antenna.[4]

$\lambda_H = 1.3065 * \text{diameter (mm)}$

Using the author's 76 mm example:

$\lambda_H = 1.3065 * 76$ mm

$\lambda_H = 99.3$ mm is the critical upper wavelength of this 76 mm pipe. Using equation two again, we find that critical upper frequency

Frequency (GHz) = $300/\lambda_H$
F = 300/99.3

Upper critical frequency for λ_H is 3.02 GHz.

You now have the critical lower and upper frequencies where your given pipe will operate as a circular waveguide antenna. In the author's case, this was 2.31 GHz through 3.02 GHz. This pipe will work for the 2.39-2.45 GHz microwave bands. Repeat this process for every diameter pipe you measure until you find one that will operate in the frequency range you desire. The lower cut-off must be below the frequency on which you want to operate. The high cut-off must be above the

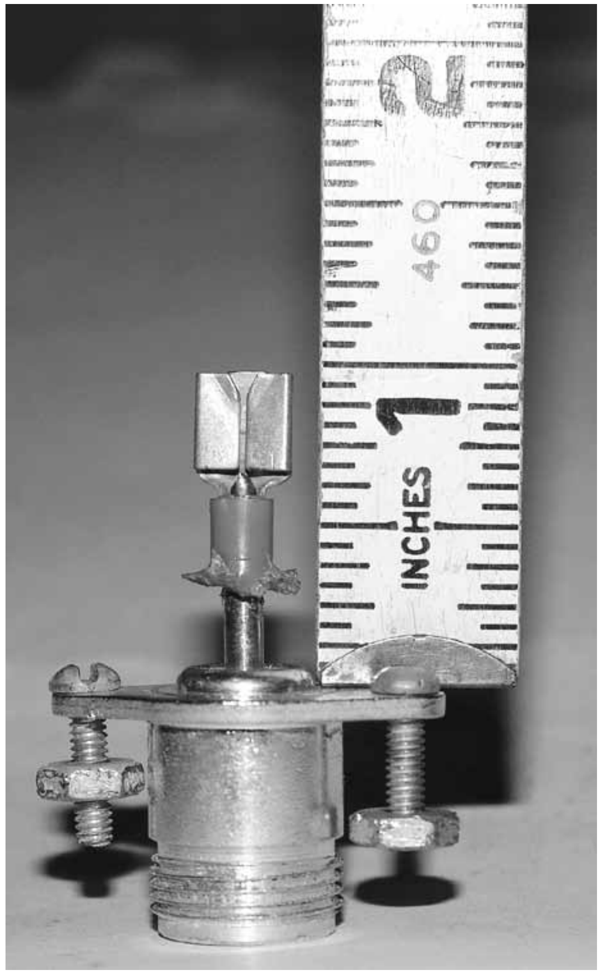

Figure 8 — Probe details including the flat eyelet soldered to the #12 wire on the "N" connector. Carefully measure to the end of the eyelet.

Figure 9 — Materials ready for assembly. The cut cylinder, copper plate for closing the end of the pipe, and the probe assembly.

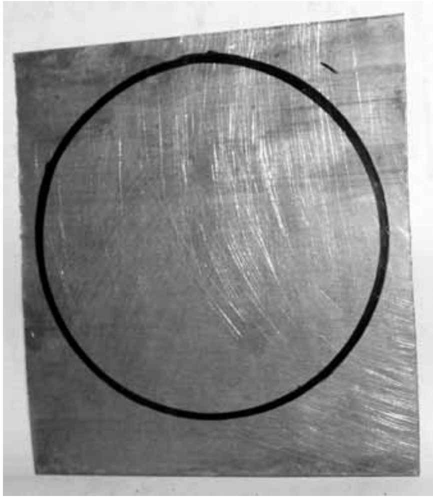

Figure 10 — Using the cylinder end, scribe a circle onto the PC board.

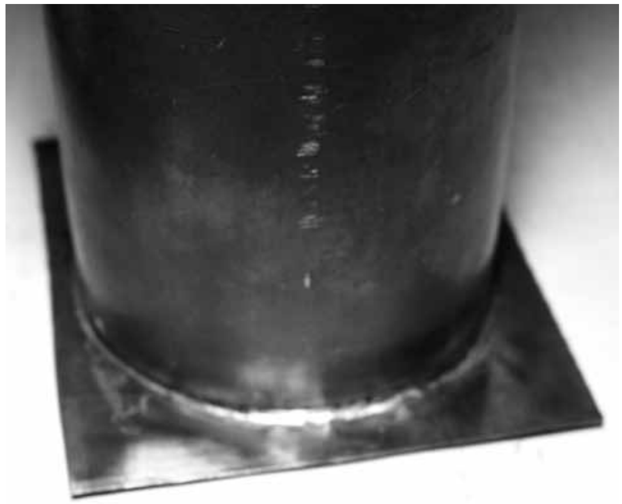

Figure 11 — PC board soldered to the end of the cylinder. The corners need not be trimmed since it will not affect the operation of the antenna.

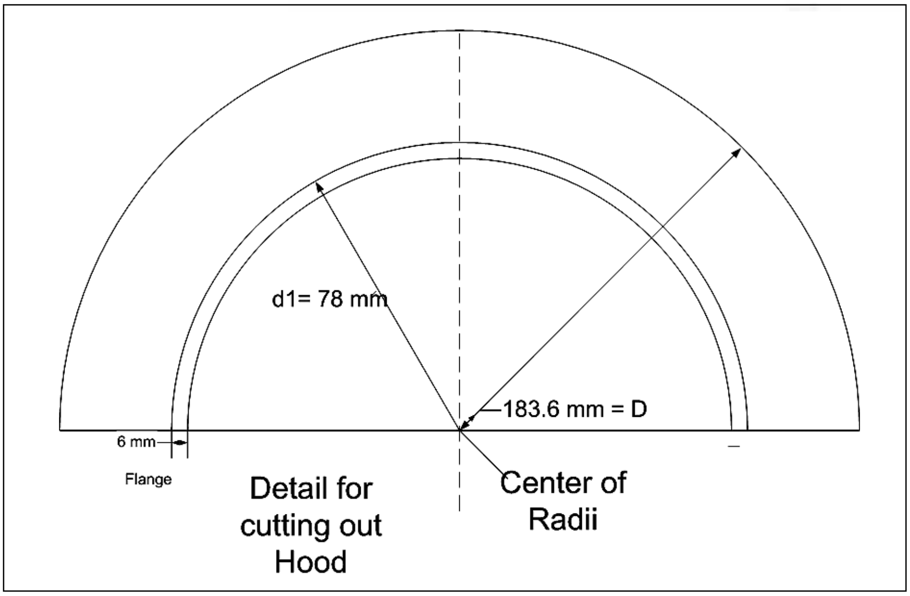

Figure 12 — Layout the hood radius as indicated. Note all semicircles come from the same point. The inner most radius is a flange for soldering.

frequency on which you want to operate.

We have to choose a design frequency within this critical frequency range that you intend to operate this antenna. Let's decide on a design frequency of 2.45 GHz for our example. It is at the top end of the 2.4 GHz band and allows some crossover into the Wi-Fi world. In step three, we calculate free space wavelength for your design frequency:

λ = 300/Freq (GHz) [Eq 3]

λ = 300/2.45 = 122 mm

Next, in step four, the overall cylinder length of the horn antenna must be calculated. The traveling waves inside the tube travel slower than the speed of light. Therefore, a slightly more complex formula must be used to figure the physical length dimensions of the tube. This modified wavelength distance will be called Lg, the wavelength inside the waveguide. The cylinder length is cut to 75% of Lg.[5]

$$L_g = \frac{1}{\sqrt{\left[\frac{1}{\lambda}\right]^2 - \left[\frac{1}{\lambda c}\right]^2}} \qquad \text{[Eq 4]}$$

λ = 122 mm
λ_C = 130 mm
Lg = 372 mm

cylinder length = 0.75 * Lg [Eq 5]

The cylinder length should be 279 mm which is about 11 inches long and closed at one end. If you don't like the inverse math, Lg can be obtained from the graphs in Figures 2 through 4.

Now that we know the critical dimensions of your ready-made cylindrical waveguide, some means of feeding this antenna is needed. The behavior of microwaves inside the waveguide is similar to that of a shorted coaxial cable. The excited signal inside the cylinder reflects off the closed end of the tube and sets up standing waves that travel through the cylinder toward the opening and are radiated out. If a means of putting some sort of voltage measuring device (signal probe) inside along the length of the cylinder were set up, we would see points of signal maximums and minimums. Starting at the closed end, the voltage would be zero and maximum at odd quarter wave intervals all along the distance of Lg. If a probe is put into the cylinder at one quarter of the guide wavelength from the closed end, this would be the best place to excite this waveguide antenna. The probe is placed at the first signal maximum from the closed end. Now, we have to find this distance.[6]

Calculating the distance so a suitable "N" connector can be installed on the side of the cylinder is done with the equation below.[4]

Probe Distance Lg/4 = 372/4 = 93 mm [Eq 6]

An "N" female chassis connector will be mounted on the side of the cylinder at 93 mm from the closed end with a stiff 12 AWG wire soldered to the connector's center conductor. This wire is a quarter wavelength in free space at the operating frequency 2.45 GHz.

Probe Depth = λ/4 = 122/4 = 31 mm [Eq 7]

The necessary calculations have now been completed. Our final dimensions are as follows:

Frequency 2.45 GHz (design frequency)
Free space wavelength λ = 122 mm
Wavelength inside tube Lg = 372 mm
Cylinder length ¾ Lg = 279 mm
Probe distance Lg/4 = 93 mm
Probe depth λ/4 = 31mm

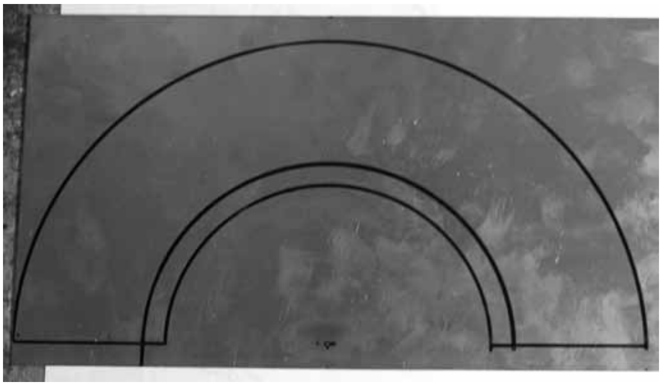

Figure 13 — Scribe the semicircles onto a copper sheet to be cut-out to form the hood.

Figure 14 — Cut out segments around the inner most semicircle to aid in soldering to the outer cylinder.

So now that the hard work is done, let's start construction of this new horn antenna. Since the diameter of your cylinder was determined by the cut-off equations in steps 1 and 2, the tube you select is fixed for the frequency of interest. In our example the diameter was 76 mm. The next step in construction is to cut this cylinder to the correct length which is 279 mm. Utilizing a hack saw, cut the cylinder to length. (See Figure 6)

Next, the hole for the probe should be measured and drilled. In the prototype, the end plate was soldered first but it was quickly learned that this only made it very difficult to put the screws on the connector inside the cylinder. First, measure the quarter wave distance from the closed end of the tube to the center of your "N" connector. This would be the probe distance of 93 mm. Mark this point and drill out the hole starting with a pilot drill then widen the opening to fit the inner edge of the "N" connector. In the prototype, a slot was made to move the connector for best output. After testing, there was no improvement in signal within a quarter inch of the exact quarter wave point. (See Figure 7)

At this point, the probe must be carefully fabricated to fit into the cylinder hole with the exact length specified. In our example, this would be 31 mm which is the result of equation 7 (see Figure 8). A small #12 wire will do an excellent job. Note the small crimp connector soldered to the top of this wire. In experimenting with the probe depth and SWR, the flat crimp-on connector improved the match over a plain wire. Please make sure that the overall length is exact to the end of the crimp connector and solder all connections. Everything is ready for assembly. (See Figure 9) Now place this entire "N" connector assembly into the hole and secure with bolts and nuts. Note that the bolt head should be inside the cylinder and the nut on the outside. When things are secure, it is time to solder the end plate.

Scribe the cylinder end onto a flat copper stock or PC board. (See Figure 10) Place the cylinder over the plate and solder neatly. (See Figure 11) The corner excess copper can be trimmed after the plate has cooled but leaving the plate square will have no negative effect on the operation of the antenna. It may take quite a bit of heat.

The antenna is now ready for testing and can be used in its present form. It will boast a good match and offer about 9 db of gain with a good directional pattern. Why not double your signal output with just one small addition to this antenna, a capture hood. A capture hood is not necessary for operation and the antenna will work quite well as a straight cylinder. But, if you want to increase the gain of your antenna by 3 dB, add this funnel to the front of your cylinder to increase the capture area and double your signal output. You are effectively collecting signal from a larger area to provide additional signal gain. Think of this as a funnel collecting rain water into a barrel. You will always get more water with a funnel.

So the question becomes how large does this funnel need to be to fit over the end of the cylinder? We go back to the drawing board for a moment and some geometry to find the right size hood for this particular frequency and antenna. What needs to be done is calculating the radius and diameter of a copper flange that will be soldered to the front of your antenna. The actual hood will end up as a curved copper strip soldered to the outside of the antenna's open end.

Calculating the Hood size

Step one is to determine D, the outer diameter of the hood. The outer diameter of the hood should be 1.5 times the free space wavelength λ.[7] The previously calculated value of λ at 2.45 GHz is 122 mm.

$$D = 1.5 * \lambda \quad \text{or} \quad 1.5 * 122 \text{ mm} = 184 \text{ mm}$$

D1 is the measured outside diameter of the cylinder or 76mm(id) plus the thickness of the copper pipe times two in our case. D1

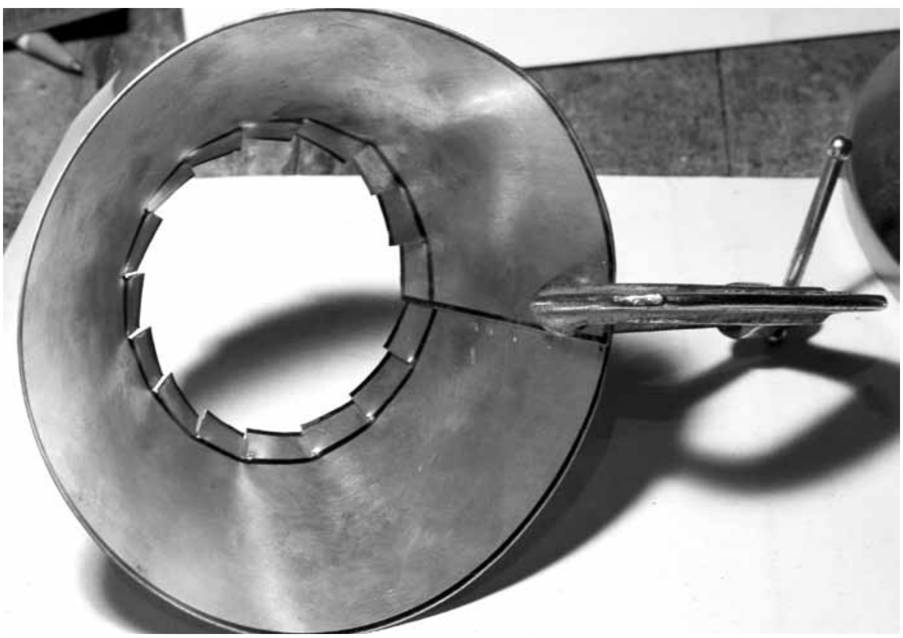

Figure 15 — Bend the flange into a circle, holding with vise grips, solder the seam.

Figure 16 — Cylinder with flange fitted over pipe ready to solder. This may take quite a bit of heat.

is 78 mm. Step two is to draw out two radii on a sheet of copper. Make D the radius of the outer hood semicircle and D1 is the radius of the inner semicircle. Using a compass, measure from a reference line 184 mm and draw the outer arc on the copper sheet. Along the same reference line, measure 78 mm and draw the inner arc. Move down below this inner arc 6 mm and draw a small arc. This will allow about 6 mm (¼") tabs on the shorter radius for soldering to the outer cylinder end. (See Figures 12 and 13). Cut out the outer and inner lines of the copper hood with tin snips. Make small strip cuts into the 6 mm (¼") flange to aid in soldering the hood to the cylinder. (See Figure 14) Roll the strip into a semi-circle. Hold the flange together with vice grips and solder the strip into a circle. (See Figure 15)

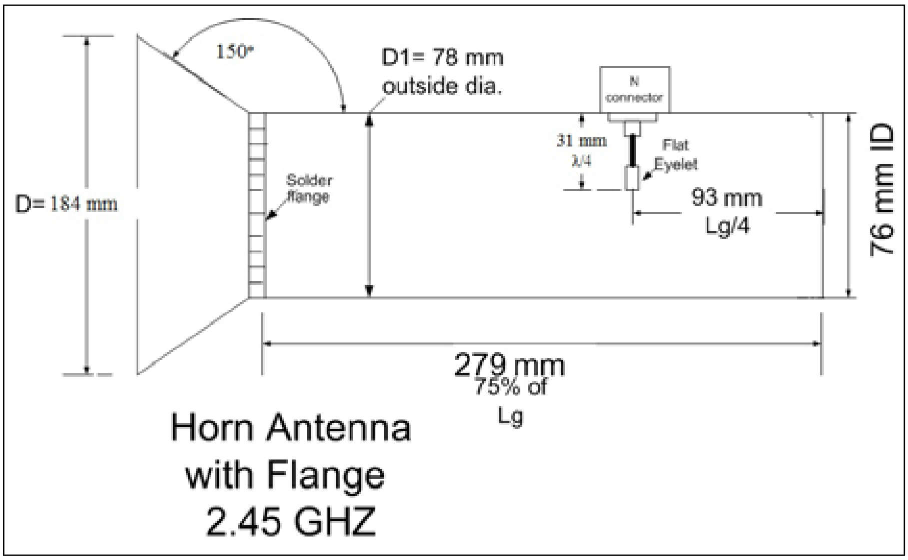

Figure 17 – Diagram of Complete Hooded Horn antenna.

Figure 18 — A practical yet easy to make a mounting bracket for the horn antenna.

When you are ready, mold the flange over the end of your cylinder and carefully solder the tabs onto the cylinder. (See Figure 16) It may take a lot of heat since copper conducts very well. Your flange hood is now part of the antenna and you are almost ready to test the new antenna. The completed horn antenna with hood is diagrammed in Figure 17.

To complete the project, some form of mount is required to attach your high gain horn antenna to a tower or building. After some consideration, bending a one inch width of aluminum stock worked out well. Bend the flat stock over the horn, then around a "form", the same diameter as your tower leg. Drill several holes for mounting hardware and wing nuts. You now have a ready-made custom horn mounting bracket. (See Figure 18) A suitable cover for the mouth of this antenna can be found from any plastic cap that will fit and pass the microwave test. After one minute in the microwave oven, there should be very little heat internal to the cover.

Testing and Measurements

Once you have finished your horn antenna, it is time to see it operate in action. The author had access to an HP 8714 Network analyzer that has 3 GHz capability. Stand the horn upright with the opening away from all metal surfaces by at least 4 feet. (See Figure 19) Connecting the horn antenna for return loss measurement provided a really nice curve showing a very good match of 1.08 SWR at 2.45 GHz. The useable SWR bandwidth under 1.6:1 was 2.40 GHz to 2.51 GHz. Putting your hand over the front of your antenna hood will cause the reading to change drastically. It is a crude indication that there is an energy field focused in front of the horn. The author also verified these measurements with a 1W transmitter operating on 2.44 GHz using a Bird 43 wattmeter and a 2.5 GHz slug. (See Figure 20)

To show some of the other parameters of this antenna, the author employed a little known program called *SABOR*. This program is a product of the Universidad Politécnica de Madrid Engineering department and fortunately is offered as freeware on the internet. The program was initially written to evaluate several types of waveguide horn antennas. It is perfect for calculating maximum gain, bandwidth, phase center and generating a plotted pattern of your antenna for evaluating the power gain at some beam width.

To use *SABOR*, go to **www.gr.ssr.upm.es/sabor.htm** and download the freeware version of the program, *SABOR* 1.0. The program can be downloaded as freeware but if you're going to use it a lot, the University asks for a $25 donation. The files will unzip into a folder. Click on the blue icon, SABOR.EXE.

The program opens up with a welcome

page from Madrid, Spain. Hit the OK button at the bottom. You will now see many horn antenna designs. The program covers six different types of horn designs. You will need to choose what type of design you want. The program is written in centimeters so conversion from mm to cm is necessary. Use the upper menu icons along the top of the opening page to navigate the program. The initial page should be a horn design. If not, go under the menu and select HORN. Under horn, you will be viewing three options in a drop down menu. We want to select CIRCULAR. You will now see the screen change to a conical circular diagram similar to the one we just built. Next move over on the top toolbar to

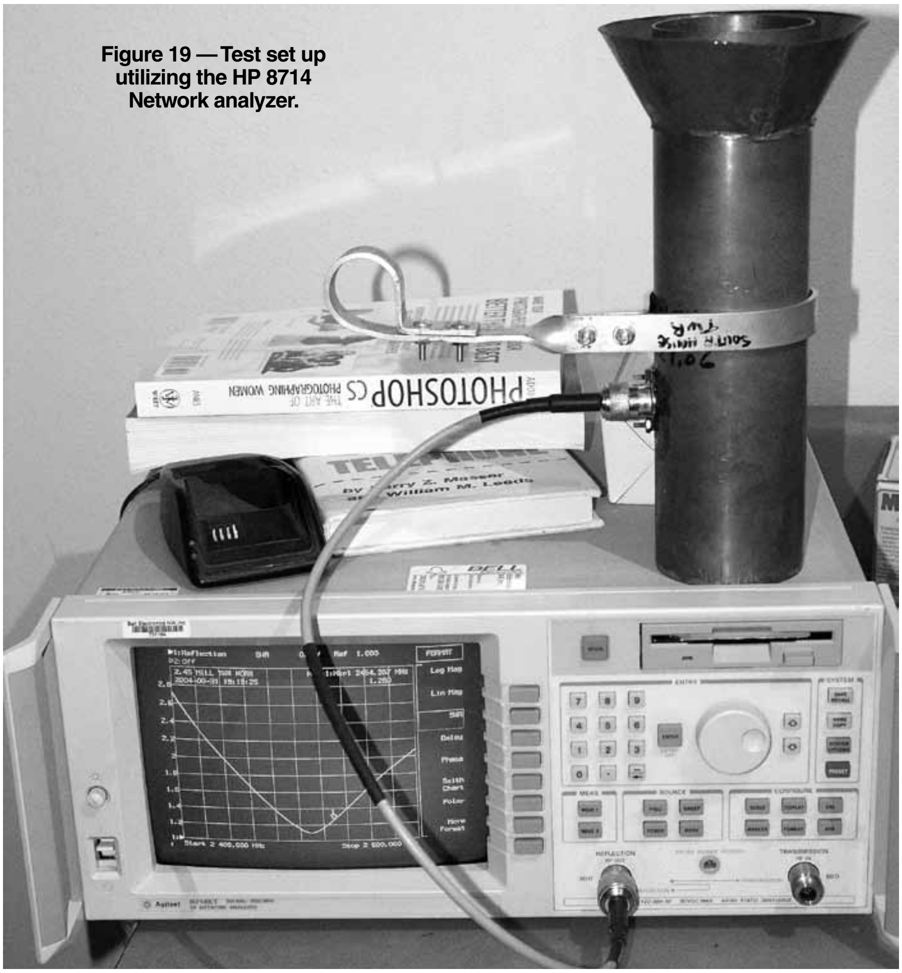

Figure 19 — Test set up utilizing the HP 8714 Network analyzer.

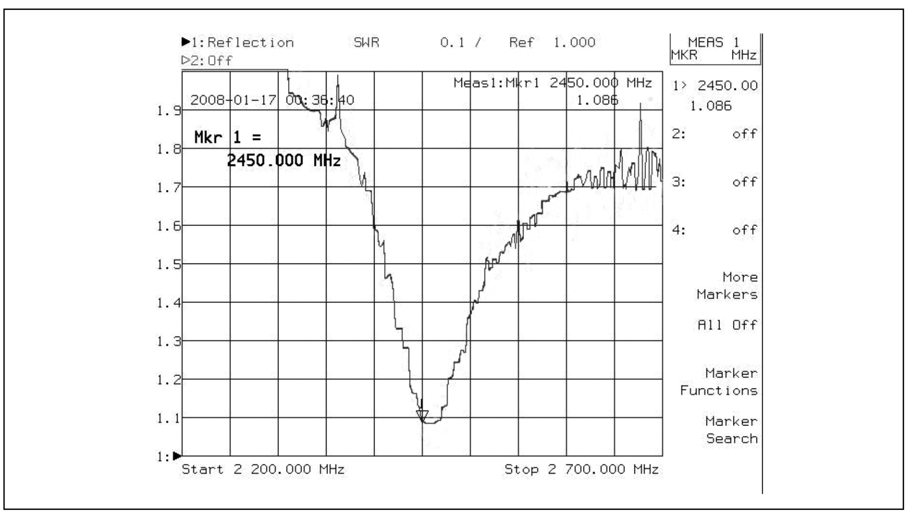

Figure 20 — Actual screen shot of SWR bandwidth boasting 1.086 at 2.45 GHz.

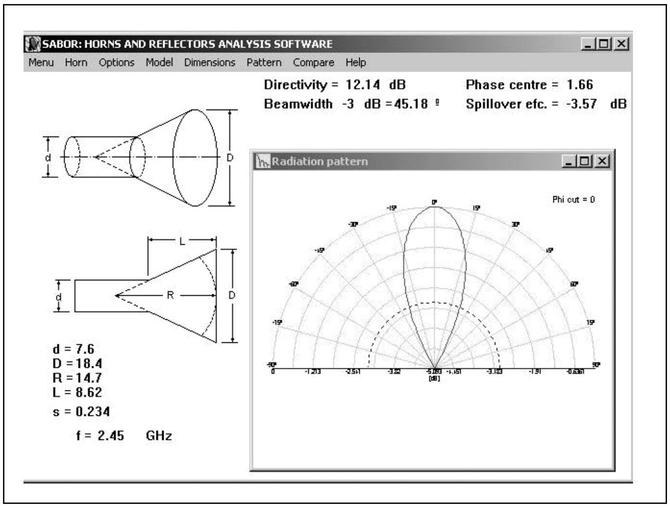

Figure 21 — Polar Plot of the radiation pattern from the *SABOR* program.

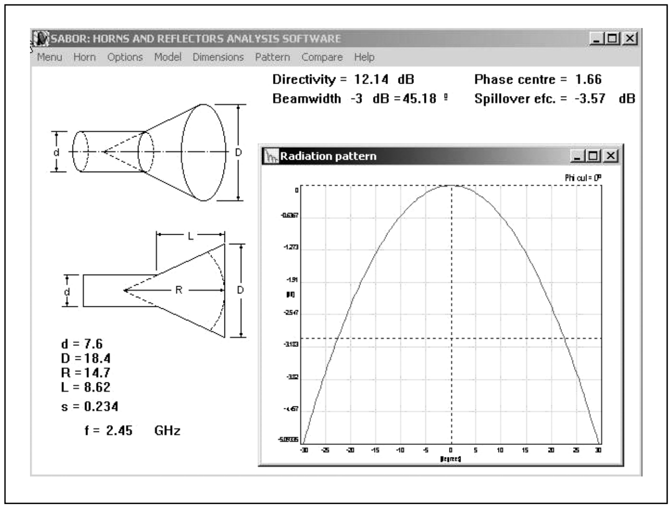

Figure 22 — SABOR X-Y Plot of the pattern. Gain is 12.14 db and the 3 db beam width is 45 degrees.

OPTIONS. The drop down menu will show frequency on top. Click on FREQUENCY and enter the operating frequency. In our example, the author chose 2.45 GHz. Move over on the top menu to DIMENSIONS. Several parameters are requested but we have already determined two of the three. *SABOR* asks for Wave-g, Horn radius and a radius value for R1. Knowing our example hood dimensions, D1 = 76 mm, D = 184 mm, will be all that is necessary to utilize *SABOR*.

Wave-g is half the cylinder diameter (d = 76 mm). In our case, 76 mm/2 = 38 mm or 3.8 cm. Horn Radius is half of the hood diameter (D = 184 mm) and in our case 184/2 = 92 mm or 9.2 cm. R1 is found by D/1.25, so it is 184/1.25 = 147 mm or 14.7 cm. Enter waveg = 3.8 cm. (Refer to the left side of Figure 21 to see these values in *SABOR*.) Given this information, the pattern and gain figures can now be calculated. Move back to the OPTIONS drop down menu and click AUTOMATIC and xy. Now move to the PATTERN icon and click. This is the X-Y plot of your antenna. The gain for our example is over 12 db and the beam width is 45 degrees. To see a polar plot of your antenna, go back to the OPTIONS drop down menu and click POLAR. The display will now change to the familiar directional pattern. (See Figures 21 and 22.)

Applications.

This antenna is currently in use to link the author's radio shack with the home, a distance of 600 feet. A pair of these horn antennas can easily link data services using 10 mW access points. The antenna can be used for any 2.4 GHz point to point communication. A 1W Amateur television signal has been sent over a pair of these horn antennas at a distance of six miles with good A5 results.

Table 1
Standard Type L Copper Pipe Dimensions (Inches)

Nominal Size Inside Diameter	*Actual Dimensions Outside Diameter*	*Wall Thickness*
¼	0.375	0.035
⅜	0.50	0.049
½	0.625	0.049
⅝	0.750	0.049
¾	0.875	0.065
1	1.125	0.065
1¼	1.375	0.065
1½	1.625	0.072
2	2.125	0.083
2½	2.625	0.095
3	3.125	0.109
3½	3.625	0.120
4	4.125	0.134
5	5.125	0.160
6	6.125	0.192
8	8.125	0.271

This horn antenna could be utilized to illuminate a dish antenna. Polarization is a function of the direction of the probe. Up and down is vertical and 90 degrees to that is horizontal. Your imagination is the limiting factor in applications for this antenna.

Here are dimensions for a 2.40 GHz version of this horn antenna using a 76 mm diameter copper pipe. The cut off frequencies remain the same since the diameter is 76 mm.

Design Frequency is 2.40 GHz
¾ = 125 mm
Lg = 470 mm
Cylinder length = 352 mm
Probe distance from closed end = 118 mm
Probe depth = 31 mm
Hood dimensions D = 188 mm, D1 = 78 mm

There are potential designs for 5 GHz utilizing 38 mm (1.5 inch) diameter copper pipe and 3.4 GHz using 2 inch diameter pipe. Let's experiment. You get a lot of gain for a small amount of effort and the horn antenna is very directional with a clean pattern. To aid in the hunt for copper tubing, Table 1 shows typical ID and OD sizes for commercial plumbing pipe.

The author would like to express his gratitude to Dustin Larson who fabricated prototypes of this antenna during the development and testing phases and Jeremy Vogel for his assistance in the graphing programs.

Notes

[1]John Kraus, *Antennas*, McGraw-Hill, 1988, pp 644-653.
[2]Gershon Wheeler, *Introduction to Microwaves*, Prentice-Hall, 1963, pp 60-63.
[3,4]Jessop, G. R., *VHF-UHF Manual*, 4th edition, Radio Society of Great Britain, 1985, p 9.27.
[5]Barter, Andy, *International Microwave Handbook*, Radio Society of Great Britain, 2002, p 58.
[6]Norm Foot, "Cylindrical Feed Horn," *Ham Radio*, May 1976, p18.
[7]Richard Kolbly, "Low Cost Microwave Antenna," *Ham Radio*, November 1969, p 52.

Photos by the author

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He is a practicing Broadcast Engineer and owns several broadcast stations. You can contact him at ***rogerp@paulbunyan.net.***

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