The Service Line

Build a Quality RF Sampler

by Don Jackson, W5QN

We know that it would be very handy to have an RF sampler to use with our Spectrum Analyzer (SA) or any other device with 50Ω input impedance.

You may ask why the frequency response need be as high as 90 MHz. For many HF measurements, we only need a 30 MHz response, but we may want to measure the harmonic content of a 30 MHz signal. In this case, we need a reasonably flat frequency response up to at least the 3rd harmonic, which is 90 MHz.

Let's summarize the specs for the sampler.

- 1500 Watt maximum input power
- Coupling Factor of 50 dB (for no damage to an SA)
- Frequency response from 2 MHz to 90 MHz
- Sample port source impedance of 50Ω
- Output port and sample port terminations are both 50Ω

We could purchase a commercial sampler, but they are quite pricey. So, let's look at building our own. David Knight's (G3YNH) article (http://www.g3ynh.info/zdocs/bridges/Xformers/part_1.html) has a great deal of design information, but his examples only consider circuits with a single terminating resistor of 50Ω. The use of a single resistor in the circuit is ok for many applications, but using two resistors (Rt and Rs) provides an additional degree of freedom in the design. This helps considerably, particularly with achieving good high frequency response. The schematic of the sampler is shown in Figure 1.

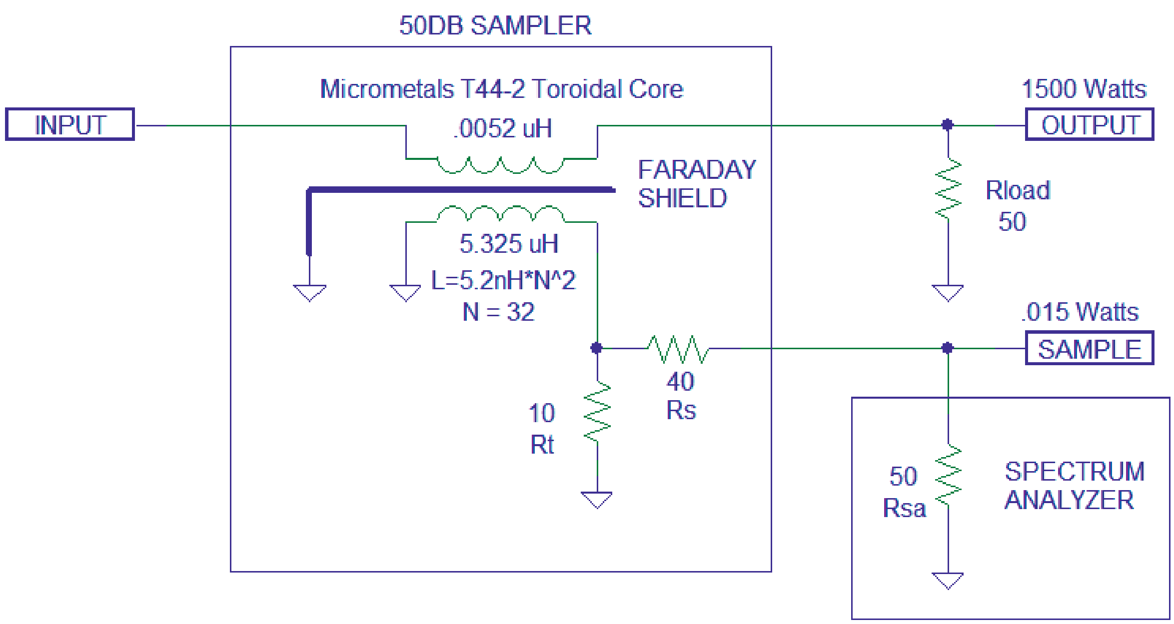


Figure 1 – Schematic Diagram

I set about deriving the equations for the sampler, expecting the result to be fairly complicated for determining values for the number of transformer turns, and the values for Rt and Rs. To my surprise, a page of equations boiled down to a very simple relationship:

Rt = 100*N*SQRT(Ps/Po)

Where N is the number of turns on the secondary of the current transformer, Po/Ps is the ratio of the main output power to the power at the sample port. The number of turns on the transformer primary is "1", since the main line simply passes through the center of the toroid core. The value for Rs is always (50 - Rt). Using this equation, and assuming N= 32 turns and Ps/Po is .00001 (-50 dB), we calculate Rt = 10Ω, and Rs = 40Ω. You may ask why two resistors are used instead of just a single 50Ω resistor. To answer this, let's solve the above equation for N:

N = (Rt/100)*SQRT(Po/Ps)

If Rt is 50Ω (Rs becomes zero) and Ps/Po is still .00001, N calculates to be about 158 turns. The number of turns has increased by almost a factor of 5. This is bad news for the high frequency response since the distributed capacitance is increased and the length of the wire is also increased.

Service Line (Cont'd)

That's enough background information. How do we build the sampler? One consideration is to make the physical distance between the input port and output ports as small as practical. The connection between these two ports is not a 50Ω transmission line, so the shorter we make the distance, the less inductance is present, and the better the high frequency performance. Although not super-critical, I found the shortest practical distance between the two Type-N connector flanges to be about .8". Therefore, that defined the width of the enclosure for my sampler. A width much smaller than .8" will make it difficult to install the toroidal transformer and Faraday shield. The length of the enclosure need only be long enough for Rs and a BNC connector. Figure 2 is an external view of the sampler, while Figures 3 and 4 are close-ups of the internals that will hopefully help you in construction. You might notice that my Rs is actually a parallel combination of 270Ω and 47Ω, which I happened to have in my junk box. A value of 39Ω will work fine though.

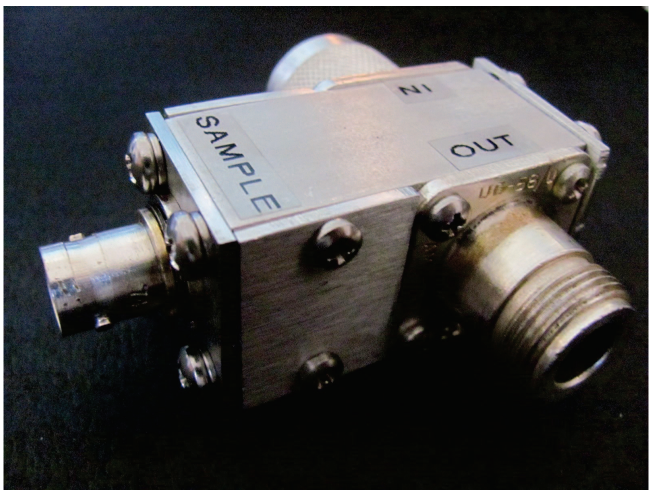
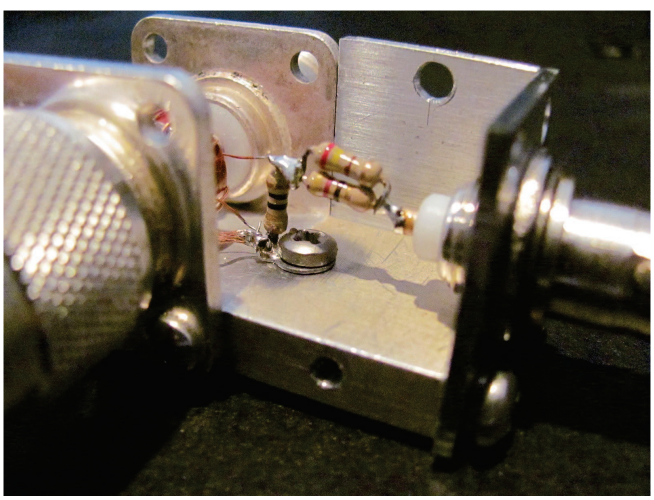


Figure 2 – Sampler External View
Figure 3 – Sampler Side View



The transformer is constructed by winding 32 turns of 30AWG enameled magnet wire on a Micrometals 44-2 powdered iron core. This core can be ordered online from Amidon Corporation. Wind a single layer of wire on the core, taking reasonable care to leave a little space between each winding. This will help minimize the distributed capacitance of the transformer.

The Faraday shield is an important feature in the design. We would like the sampler output signal to be dependent only on the magnetic coupling of the transformer. However, at higher frequencies, there is electrical coupling from the main line to sample port due to capacitance between the transformer windings and the main line. We want tight magnetic coupling in the transformer, but not the capacitive coupling. This is where the Faraday shield comes in. It provides electric field isolation without affecting the magnetic coupling. In G3YNH's article, he shows an implementation of the shield using 50Ω flexible coax. Note that only ONE END of the coax shield is connected to ground, so don't be fooled into thinking you have a 50Ω transmission line from input to output. However, his implementation is meant for lower frequencies than we want, so I used a slightly different implementation. My sampler uses a short piece of RG-402 (.141 inch O.D.) semi-rigid coax, which allows more precise control over construction of the Faraday shield. Cut a piece of RG-402 so that the center conductor of the coax can be soldered to the input and output connectors. (Do not solder the RG-402 in place yet.) You will find that the transformer is a bit of a loose fit over the RG-402. It is best if the transformer fits snuggly over the RG-402, so build up the gap by wrapping layers of Teflon pipe thread tape around the RG-402. The desired result is that the transformer will hold itself in place when inserted over the RG-402. If you like, you can add a drop of polystyrene "Q-Dope" (from GC Electronics) to hold the transformer in place. Set the transformer/Faraday shield assembly aside for the moment.

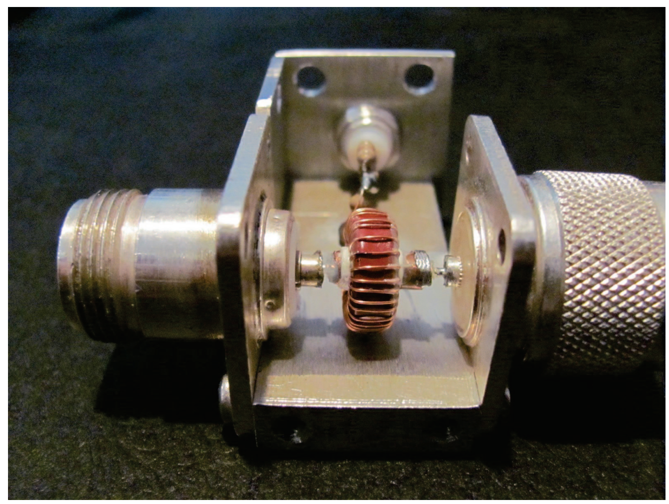


Figure 4 – Sampler End View

Install the input, output and sample port coaxial connectors onto your chosen enclosure. I used female N (Mouser 523-82-368) for the output connector and a male N (Mouser 523-49000) for the input, but you can use other suitable RF connectors. Now you can install Rt and Rs in place, taking care to make all connections as short as possible. A good method is to install an insulated standoff (with good RF characteristics) at the point where the transformer leads will be. Install a short ground lug under the standoff, where one of the transformer leads and the ground end of Rt can be soldered. At the top of the standoff, Rt, Rs and the other transformer lead will be connected. (Note: I didn't have a standoff short enough to fit, so I used the junction of Rt and Rs as a "standoff".) IMPORTANT! I learned the hard way that both Rt and Rs must be installed so that they have no parallel mechanical component with reference to the main line. Figures 3 and 4 will help understand the correct method. If you do not install them properly, the resistor will form a coupler to the main line. If you have the instrumentation, I suggest that you test your installation before proceeding with the sampler assembly, using the following method. Temporarily install a straight piece of wire between the input and output connector pins. (Do not place the transformer on this wire.) Connect a signal generator to the input port, and set it for a level around +10 dBm and a frequency of 30MHz. You should terminate the output port with a good 50Ω load. Connect a Spectrum Analyzer to the sample port. If the resistors are properly installed, you should see a signal at the sample port that is at least 90 dB lower than the signal generator level. On my sampler, I measured 104 dB. By the way, with Rt erroneously installed nearly parallel to the main line, the isolation was closer to 50 dB. Lesson learned!

Now it is time to install the transformer with the Faraday shield. Carefully drop it into place, soldering the center conductor of the RG-402 to the input and output connectors. Solder a short piece of braid from the shield of the RG-402 (nearest the INPUT port) to the ground lug. I used a piece of size .030" solder wick from Chemtronics for good conductivity and mechanical flexibility. Note that it is the connection of this braid that determines which of the N connectors becomes the input port.

Lastly, connect the transformer wires, one to the standoff, and one to the ground lug. You are now ready to perform some preliminary tests. The first is to ensure the coupling factor is close to 50 dB. Assuming Rt is accurate, the coupling factor is determined only by N, the number of turns on the transformer secondary. In my case, the coupling factor was within .1dB of the 50 dB design target. Another good test is what I call the "load/no load" test. Ideally, if you disconnect the 50Ω termination from the output port, the output at the sample port should drop to zero. This is because no current should be flowing in the main line, thus there should be no output at the sample port. However, due to a variety of things, but primarily capacitive coupling from the main line to the transformer windings, energy is present at sample port, even with no termination on the output port. This phenomenon worsens with increasing frequency, and is the main reason for the Faraday shield. As a test, connect a signal generator to the input port, set for 30 MHz and +10 dBm output. Terminate the sampler output port with 50Ω and measure the sample port output with a spectrum analyzer. Remove the termination and note the drop in the sample port output. As a reference, my experiments showed a 12 dB drop in a sampler without the Faraday shield installed. With the Faraday shield, the drop improved to about 38 dB. A final check on operation is to short the output port to ground. If the signal generator has a 50Ω source impedance, grounding the output should double the current, so the signal at the sample port should increase by about 6 dB.

There is a small amount of asymmetry to the design created by the grounding of the Faraday shield. What I mean by this is that the input and output ports are not perfectly interchangeable. Swapping the input and output ports reduces the high frequency response somewhat, but the response is still adequate for most monitoring applications. Figure 5 shows the high frequency response of my sampler with normal input/output connections.

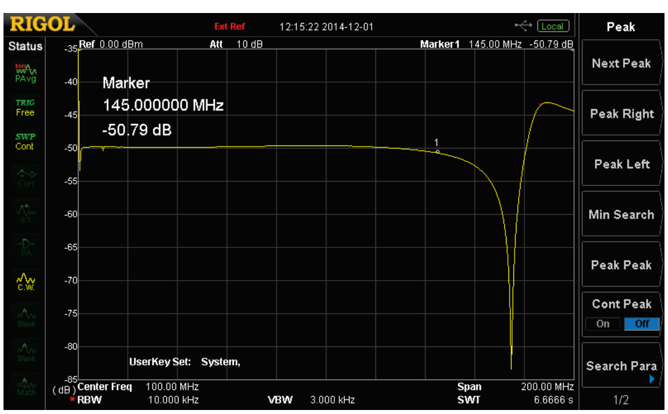


Figure 5 – High Frequency Response of Sampler

The response at the sampled port is 1dB down from 50dB at a frequency of 145 MHz, which is easily good enough for HF work.

The low frequency response of the sampler is shown in Figure 6. The 1dB down frequency on the low end is about 580 kHz, very close to the calculated value.

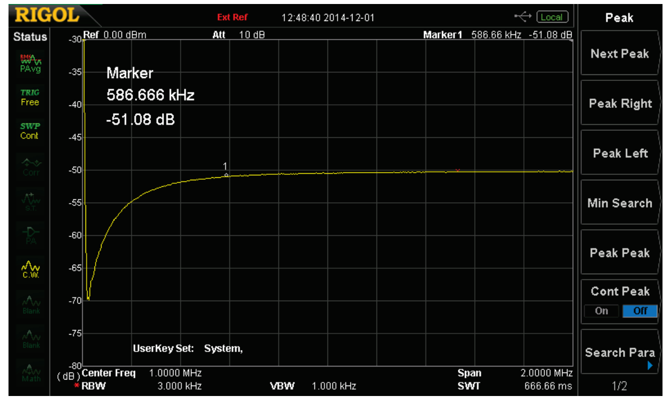


Figure 6 – Low Frequency Response of Sampler

Figure 7 below shows the insertion loss of the main line. Note that the scale is .1dB/division.

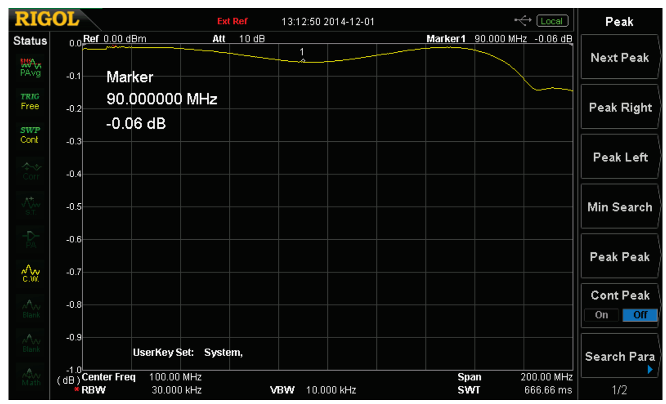


Figure 7 – Main Line Insertion Loss

Resistors Rt and Rs should be carbon film for good RF performance and small size. At 1500 Watts input, the power dissipated in Rt is only about 300 mW, even under the "worst case" condition when there is no termination at the sample port. So, a 500 mW resistor rating is fine. The power dissipated in Rs is considerably less than that of Rt.

Although calculations of magnetic flux density in the transformer core indicate it is operating well within the limits of the core, even at 1500 Watts, I do not have the equipment to quantify distortion that might be added by transformer core saturation affects. I've used the sampler to measure harmonics at the output of my 30L-1 and don't see any obvious problems. However, it would be great to measure the harmonic content of a 1500 Watt CW carrier using the sampler, then compare that to a measurement using a high power resistive attenuator. If anyone has the equipment to do that, I'd love to hear the results.

I created an Excel spreadsheet that allows you to choose different parameters for the sampler, including different powdered iron core sizes. It also calculates many other parameters should you be inclined to design a sampler with different characteristics. Let me know if you'd like a copy via email.

Have fun and treat that SA with care!
de Don, W5QN

- - - - - - - - - - - - - - CCA - - - - - - - - - - - - - -