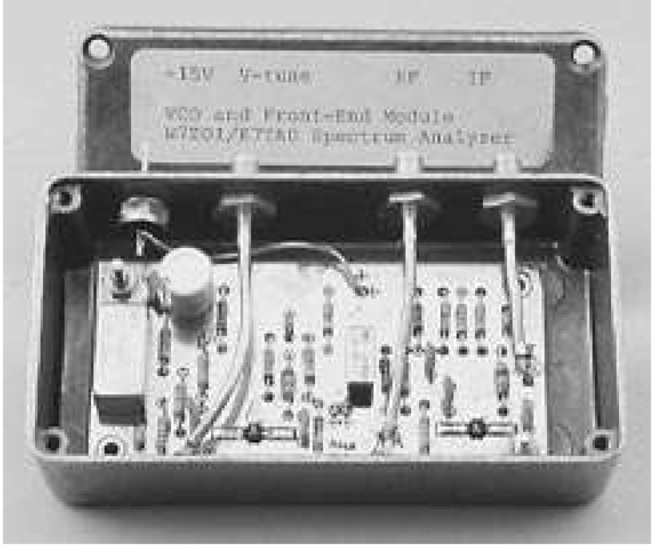
By Wes Hayward, W7ZOI, and Terry White, K7TAU

A Spectrum Analyzer for the Radio Amateur—*Part 2*

Here are some examples of procedures you can use to become familiar with your new spectrum analyzer.



In Part 1,[14] we described the design and construction of a simple, yet useful spectrum analyzer. This installment presents some applications and methods that extend the underlying concepts.

Amplifier Gain Evaluation

One use for a spectrum analyzer is amplifier evaluation. We can illustrate this with a small amplifier from the test-equipment drawer—an old module that has been pressed into service for a variety of experiments. This circuit, shown in Figure 11, is used for illustration only and is not presented as an optimum design. It's a project that grew from available parts and may be familiar to some readers. The circuit uses four identical 2N5179 amplifier stages. A combination of emitter degeneration and parallel feedback provides the negative feedback needed to stabilize gain and impedance. (Ideally, construction and measurement of a *single* stage should precede construction of the complete amplifier.)

We began the experiment by setting the signal generator at a known power level, –20 dBm. (If a good signal generator is unavailable, you can easily build a suitable substitute.[15] We used a surplus HP8654A for most of these experiments.) With the generator and spectrum analyzer connected to each other through 50-Ω coax cable, we set the generator to 14 MHz with 10-dB attenuation ahead of the analyzer. The amplifier was not yet connected. We adjusted the analyzer's **IF GAIN** control for a response at the top of the screen. Using a resolution bandwidth of 300 kHz allows for a fast sweep without distortion. In our case, the second harmonic was only 26 dB below the peak response. However, when we added a 15 MHz low-pass filter, the second harmonic dropped to –57 dBc.[16] The third harmonic is well into the noise. (It is not unusual for a signal generator to be moderately rich in harmonics.)

Next, we inserted the amplifier between the signal generator and the analyzer, keeping the low-pass filter in the generator output. The on-screen signal went well above the top as soon as the amplifier was turned on. Decreasing the signal generator output to –51 dBm produced the same –20 dBm analyzer signal that we saw before the amplifier was inserted. The gain measured 31 dB.[17] Increasing the analyzer attenuation by 10 dB (for a reference level of –10 dBm) and increasing the generator output to –41 dBm produced the same gain, but a growing harmonic output. The second-harmonic response was now at –43 dBc and a third harmonic appeared out of the noise at –60 dBc.

We continued the process—moving both step attenuators produced an amplifier output of 0 dBm with second and third harmonics at –28 and –36 dBc, respectively. The next 10-dB step, however, didn't work as well, producing gain compression. With a drive of –21 dBm, the output was only +4 dBm, a gain of only 25 dB instead of the small-signal value of 31 dB.

Amplifier Intermodulation Distortion

Next, we measured intermodulation distortion (IMD). The setup for these experiments is shown in Figure 12. Two crystal-controlled sources[18] at 14.04 and 14.32 MHz are combined in a 6 dB hybrid combiner (return-loss bridge),[19] applied to the 15 MHz low-pass filter and a step attenuator having 1 dB steps. This composite signal drove the amplifier, with its output routed to the spectrum analyzer. For this measurement, we dropped the resolution bandwidth to 30 kHz. (The video filter was turned on and the sweep rate reduced until the signal amplitude was stable.) The analyzer's attenuator, set for a reference level of –10 dBm at the top of the screen, was confirmed with a calibration signal from the signal generator. We adjusted the **IF GAIN** to compensate for changes in analyzer bandwidth and for log-amplifier drift.

The output of the two-tone generator system was adjusted to produce a spectrum analyzer response of –10 dBm per tone. The IMD responses were readily seen, now 47 dB below the desired output tones. The output intercept is given by

$$IP3_{out} = P_{out} + \frac{IMDR}{2}$$

where P_{out} is the output power of each desired tone (–10 dBm) and IMDR is the intermodulation distortion ratio, here 47 dB. The output intercept for this amplifier measured +13.5 dBm. This is well in line with expectations for such a design.

When performing IMD measurements, it's a good idea to change the signal level while noting the resultant performance. Dropping the drive power by 2 dB should cause a –2 dB response in the desired tones, accompanied by a 6 dB drop in distortion-product tones. The output intercept

[14] Notes appear on page 40.

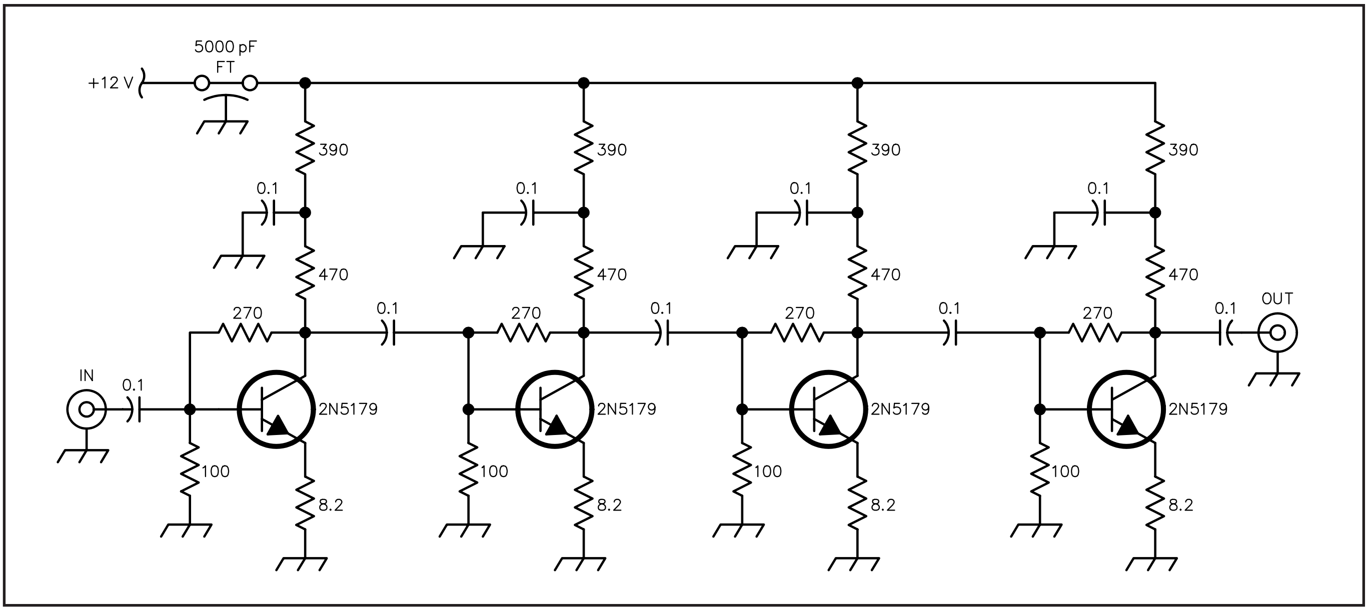


Figure 11—Sample wideband amplifier used to illustrate amplifier measurements.

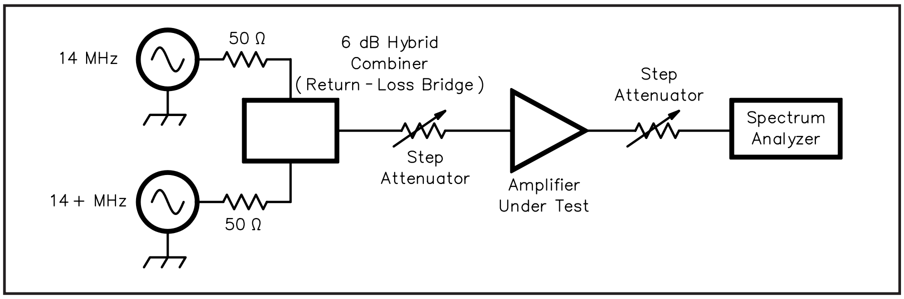


Figure 12—Equipment setup for evaluation of amplifier intermodulation distortion.

should remain unchanged.

The IMD in the preceding example was 47 dB below the desired output tones, a value that we obtained by simply reading it from the face of the ’scope, possible because we use a log amplifier that has moderate log fidelity. If the log amplifier was not as accurate as it is, we could still get good measurements. In this example, you would note the location of the distortion products on the display. Then, using the step attenuator, decrease the desired tones until they are at the noted level. The result would be –47 dBc for the distortion level, a measurement that depends solely on the accuracy of the attenuator. This illustrates the profound utility of a *good* step attenuator, an instrument that can be the cornerstone of an excellent basement RF laboratory.

During the third-order output-intercept determination just described, we assumed that the distortion was a characteristic of the amplifier under test. This may not be true. It is important to determine the IMD characteristics of the spectrum analyzer used for the measurements before the amplifier measurements are fully validated. Specifically, for results to be valid, the input intercept of the analyzer should be much greater than the output intercept of the amplifier under test.

The spectrum analyzer input intercept is easily measured with the same equipment used to evaluate the amplifier. The two tones are applied to the analyzer input with no attenuation present at the analyzer front end. Then, the input tones are adjusted for a full-screen response. In this condition, there should be no trace of distortion. Although this is generally an adequate test, it *does not* establish a value for the input intercept. To do that, we must overdrive the analyzer, using signals that exceed the top of the screen.

The following steps were used to measure the analyzer input intercept:

- We calibrated the analyzer for a reference level of –30 dBm with a 30-kHz resolution.
- Confirmed the lack of on-screen distortion with two tones at the reference level.
- Increased the drive of each tone by 10 dB to provide a pair of –20 dBm tones to the analyzer. This higher-than-reference-level input produced distortion products 66 dB below the reference level, or –96 dBm. The input signals producing this were each –20 dBm, so the IMD ratio is (–20) – (–96) = 76 dB. Following the earlier equation, the input intercept was +18 dBm.
- A 2-dB drive increase produced the expected 6-dB distortion increase. If this had not occurred, distortion measurements under overdrive would be suspect. The +18-dBm value seems to be a good number. This analyzer generally seems happy with signals 20 dB above the top of the screen, but not much more.

The intercept for the analyzer with attenuation in place is the measured value with no pad plus the attenuation. Hence, with 20 dB of attenuation, the input intercept will be +38 dBm, and so forth.

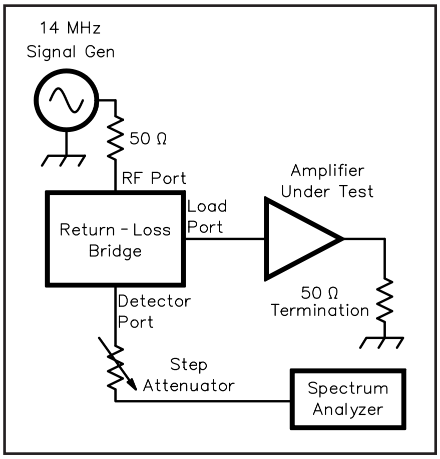


Figure 13—Test setup for impedance-match measurements with return-loss bridge.

Return-Loss Measurements

The next amplifier characteristic that we measured was the input impedance match, or return loss, performed with the setup shown in Figure 13. With the signal generator set for a 14-MHz output of about –30 dBm, we set the analyzer for full-scale response with the **LOAD** port of the return-loss bridge open circuited. Placing a 50-Ω termination momentarily on the **LOAD** port, produced a 38-dB signal drop. This is a measure of the bridge directivity. A 38-dB directivity is more than adequate for casual measurements.

Then, we removed the termination from

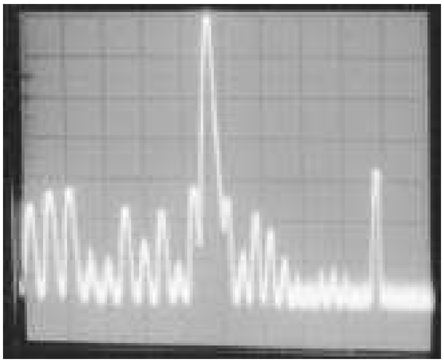


Figure 14—Output of a typical QRP transceiver kit. The 1-W plus output at 7 MHz is the dominant signal; all others are spurious outputs more than 40 dB down, currently meeting FCC specifications.

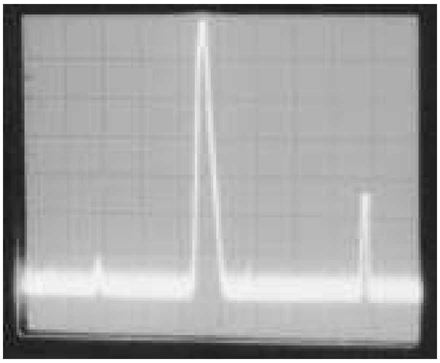


Figure 15—Output of a simple homemade QRP rig. The desired signal is the large pip at the center of the trace. Two measurable spurious responses exist, one to the left and one to the right of the main signal. The response to the left is 3.5 MHz feedthrough from the VFO at –64 dBc; the response to the right of the desired signal is a second harmonic at –44 dBc.

the bridge and placed it on the amplifier output. A short length of cable connected the bridge load port to the amplifier input with power applied to the amplifier. The result was a response 20 dB below the top of the display; 20 dB is the return loss for the amplifier input, an excellent match for a general-purpose amplifier.[20] The match improved slightly when the output load was removed, an unusual situation.

The next variation measured the output match for the amplifier. The load was transferred to the amplifier input and the cable from the bridge **LOAD** port was moved to the amplifier output, producing a reading 15 dB below the screen top. This match was virtually unchanged when the input termination was removed. The weak dependence of both amplifier return losses is the result of a four-stage design. A single-stage feedback amplifier will have port impedances that depend strongly on the termination at the opposite port.

The –30 dBm drive from the generator provides an available power of –36 dBm from the bridge **LOAD** port. This is low enough that the amplifier is not over-driven. The match measurements should be done at a level low enough that the amplifier remains linear. In this case, we saw no difference in the results with drive that was 10 dB higher.

When performing return-loss measurements—and indeed, most spectrum-analyzer measurements—it is wise to place at least 10 dB of attenuation ahead of the spectrum-analyzer mixer. When this attenuation is switched in, the reference level changes from the top of the screen to a point down screen a bit. Return loss is then measured as a decibel difference with regard to the new reference.

Antenna Measurements

It is interesting to look at some other impedance values while the return-loss bridge is attached to the signal generator and spectrum analyzer. The obvious choice is the station antenna system, especially if it is connected through a Transmatch. Playing with the tuning will readily demonstrate that the return-loss bridge and sensitive detection system will allow adjustments to accuracy unheard of with traditional diode detector systems. Although such tuning accuracy is not needed in a normal antenna installation, it is interesting to see what *can* be measured when the need does arise.

Transmitter Evaluation

Another obvious application for a spectrum analyzer is in transmitter evaluation. Figure 14 shows the output of a typical QRP transceiver kit. The 1-W plus output at 7 MHz is the dominant signal, with all others being transmitter spurious outputs. All spurs are more than 40 dB down, which meets current FCC specifications. On the other hand, significantly better performance is easily obtained, especially if the builder has the facilities to measure them. Figure 15 is a photograph of a simpler QRP rig with two measurable spurious responses. One is the 3.5-MHz feedthrough from the VFO at –64 dBc; the second is a harmonic at –44 dBc.

The output available from a typical QRP rig (and certainly higher power rigs) is enough to damage the spectrum-analyzer input circuits. Attenuators that we generally build are capable of handling 0.5 to 1 W input without damage, while commercial attenuators are rated at from 0.5 to 2 W input. The mixers used in this analyzer can be damaged with as little as 50 to 100 mW signals. Two methods can be employed to view the output of a high-power transmitter without causing damage to the spectrum analyzer. In one, the transmitter output is run through a directional coupler with weak coupling to the sampling port—perhaps –20 to –30 dB. The majority of the output is dissipated in a dummy load. The second method uses a fixed, high-power attenuator. Figure 16 shows an attenuator that will handle about 20 W while providing 20-dB attenuation. The design is not symmetrical.

Spectrum Analysis at Higher Frequencies

Although the 70-MHz spectrum analyzer is extremely useful, we constantly wish that it covered higher frequencies. Not only do we want to experiment on the VHF and UHF bands, but we need to examine higher-order harmonics of HF gear. One method we can use with a regular receiver is a converter, usually crystal controlled. The same can be done with a spectrum analyzer, although crystal control is not needed. We can build a simple block converter, consisting of nothing more than a 100 to 200 MHz VCO (just like that used in the analyzer) and a diode ring mixer. A Mini-Circuits POS-200 VCO with a 3 dB pad will directly drive a Mini-Circuits SBL-1 or TUF-1 mixer to produce a block converter with a nominal loss of 10 dB. (One of the spectrum analyzer front-end boards could be used, with slight modification, for the block converter.)

This block converter allows analysis of much of the VHF spectrum. With the converter VCO set at 100 MHz, frequencies from 100 to 170 MHz are easily studied. The 70 to 100-MHz image is also available—it can also lead to confusion, as a few minutes with a signal generator will demonstrate. With the converter VCO up at 200 MHz, the 200 to 270 MHz spectrum is also available. Clearly, there is nothing special about the particular VCO used in the converter. All that is required to convert other portions of the low UHF spectrum to the analyzer range is a different VCO, and perhaps, a higher-frequency mixer. We will soon build similar block converters to allow analysis of the 432-MHz area. One of the popular little UHF frequency counters is quite useful with these converters. The block converters should be well shielded and decoupled from the power supply.

Even without the analyzer, the block converter is a useful tool. For example, it can be used with a 10 MHz LC band-pass filter and an amplifier to directly drive a 50-Ω-terminated oscilloscope. This can serve as a sensitive detector for the alignment of a 110-MHz filter.

As useful as the block downconverter is, it has image-response problems that can greatly confuse the results. The preferred way to get to the higher frequencies is with a spectrum analyzer—just like the one we have described—but having higher-frequency oscillators and front-end filters. If you're careful, you can build helical resonator filters for the 500-MHz region, or higher, with sufficiently narrow selectivity to allow a second conversion to 10 MHz. A more practical route uses a third IF. Such a triple-conversion analyzer is shown in Figure 17, where a 1 to 1.8 GHz VCO moves signals in the 0 to 800-MHz spectrum to a 1 GHz IF. This signal is still easily amplified with available monolithic amplifiers. Building a 1 GHz filter should not be too difficult, for a narrow bandwidth is not required. A bandwidth of 20 or 30 MHz with a three-resonator filter would be adequate. The resulting signal is then heterodyned to a VHF IF (such as 110 MHz) where the remaining circuitry is now familiar.

Clearly, there are several ways to attack the project. Recent technology offers some help in the way of interesting band-pass filter structures, as well as high-performance, low-noise VCOs. Time spent with some cata-

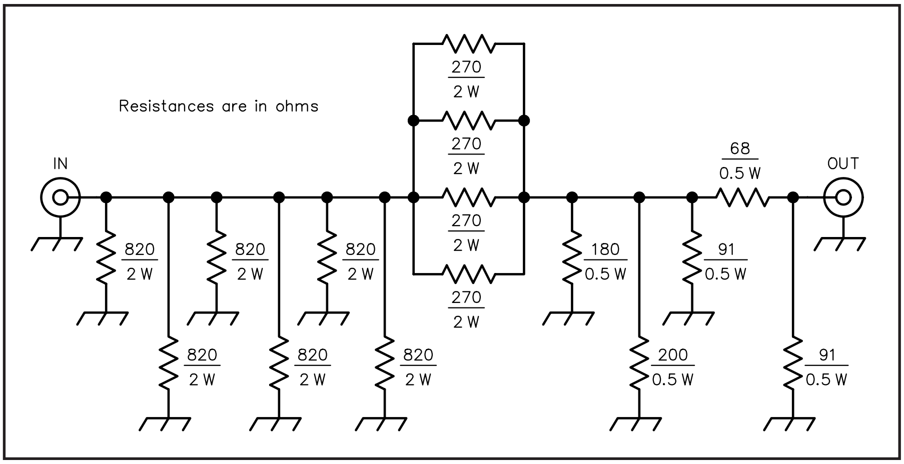


Figure 16—A 20-W, 20-dB attenuator for transmitter measurements.

An inside view of a prototype VHF band-pass filter. See Figure 7.

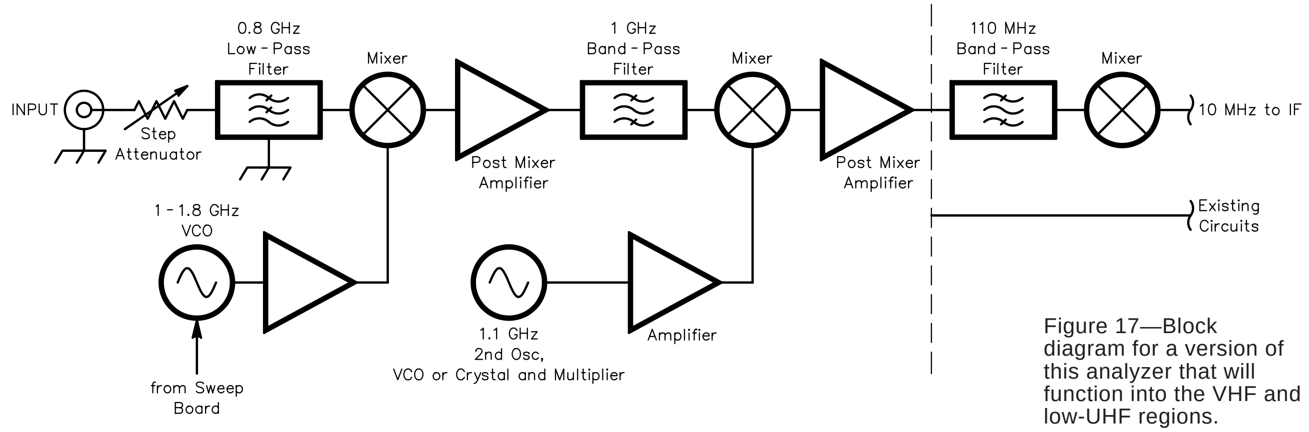


Figure 17—Block diagram for a version of this analyzer that will function into the VHF and low-UHF regions.

logs and a Web browser could be very productive in this regard. Just as important is the experience that the lower-frequency analyzer will provide. Not only is it the tool (perhaps supplemented with block converters) that is needed to build a higher-frequency spectrum analyzer, but it is the vehicle to provide *the confidence* needed to tackle such a chore.

Summary

This analyzer has been a useful tool for over 10 years now. It was a wonderful experience and fun to build HF and VHF CW and SSB gear with the "right" test equipment available. We have built special, narrow-tuning-range analyzers to examine transmitter sideband suppression and distortion. The equipment uses the same concepts presented.

There are many ways that this instrument can grow. One builder has already breadboarded a tracking generator. (Let's see that in *QST*!—*Ed.*) Many builders will want to interface the analyzer with a computer instead of an oscilloscope. A recent *QST* network analyzer paper suggests circuits that may provide such a solution.[21]

A recent *QST* summary of WRC97[22] outlines new specifications regarding spurious emissions from amateur transmitters. Generally, the casual specifications that we have enjoyed for many years are being replaced by new ones that are more stringent—and more realistic in safeguarding the spectral environment and reflecting the sound designs that we all strive to achieve. Equipment such as the spectrum analyzer described here can provide the basic tool needed to meet this new challenge.

Acknowledgments

Many experimenters had a hand in this project and we owe them our gratitude. Jeff Damm, WA7MLH, and Kurt Knoblock, WK7Q, built versions of the analyzer and have garnered several years of use with them. Their experiences have been of great value in our efforts. Barrie Gilbert of Analog Devices Northwest Labs suggested the AD8307 log amplifier and provided samples and early data needed for evaluation measurements. Many of our colleagues within the Wireless Communications Division at TriQuint Semiconductor have helped us with filter measurements: Thanks go to George Steen and to Don Knotts, W7HJS. Finally, special thanks go to our colleague in the receiver group at TriQuint, Rick Campbell, KK7B, who provided numerous enlightening discussions and suggestions regarding the preparation of the paper and the role of measurements in amateur experiments.

Notes

[14] Wes Hayward, W7ZOI, and Terry White, K7TAU, "A Spectrum Analyzer for the Radio Amateur," *Part 1*, *QST*, Aug 1998, pp 35-43.

[15] The wide-range oscillator presented in Fig 68, Chapter 7 of *Solid-State Design for the Radio Amateur* (Newington: ARRL, 1997) is still intact and still often used.

[16] The term dBc refers to dB attenuation with respect to a specific *carrier*.

[17] Formally, this is the transducer gain, or 50-Ω insertion gain. There are many different parameters that are called "gain."

[18] The signal sources used are updated versions of the circuits shown in Fig 66, p 168, in the Note 15 referent.

[19] See page 154, *Solid-State Design for the Radio Amateur*.

[20] A 20-dB return loss corresponds to a voltage reflection coefficient of 0.1, or an SWR of 1.222. See Wes Hayward, W7ZOI, *Introduction to RF Design* (Newington: ARRL, 1994), p 120.

[21] See, for example, Steven Hageman, "Build Your Own Network Analyzer," *QST*, Jan 1998, pp 39-45; *Part 2*, Feb 1998, pp 35-39.

[22] Larry Price, W4RA, and Paul Rinaldo, W4RI, "WRC97, An Amateur Radio Perspective," *QST*, Feb 1998, pp 31-34. See also Rick Campbell, KK7B, "Unwanted Emissions Comments," Technical Correspondence, *QST*, Jun 1998, pp 61-62.

◊ Please refer to Wes Hayward, W7ZOI, and Terry White, K7TAU, “A Spectrum Analyzer for the Radio Amateur—*Part 2*, *QST*, Sep 1998, p 40, Fig 16. The six 2-W input resistors for the 20-dB pad should be 620 Ω units, not 820 Ω as originally specified.—*Wes Hayward, W7ZOI (tnx EA2SN)*