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A Low Frequency Adapter for your Vector Network Analyzer (VNA)

This compact and versatile unit extends low frequency capability down to 20 Hz for your VNA using down/up conversion. It also generates clean signals from audio up to 5 MHz, and provides direct conversion receive capability plus a high impedance input compatible with scope probes to drive 50 Ω loads over a 60 MHz bandwidth.

I always wished my Hewlett-Packard Vector Network Analyzer (VNA) would be capable of going down to frequencies below 300 kHz. I was working on a project that necessitated frequency response tests in the audio range, but it could not be done with my HP machine. So I started designing a low frequency adapter that would retain the accuracy and linearity of my RF VNA. Figure 1 shows the basic diagram of my Low Frequency Adapter (LFA).

System Overview

The VNA generates frequencies from 10 MHz to 15 MHz on its port 1 when set in S_{21} mode. This mode allows measuring attenuation or gain as well as phase shift between ports 1 and 2. The above signal is mixed in a double balanced mixer (DBM), which has its local oscillator (LO) at 10 MHz. The difference signals from 20 Hz to 5 MHz go through a low-pass filter (LPF) and are available at the transmit (TX) output port for frequency response testing. The output of the device under test (DUT) is fed to a high impedance buffer and to a 5 MHz low pass filter before being re-multiplexed in the 10 to 15 MHz range by a second DBM.

The signal at the RF output of this mixer has double sidebands, above and below the 10 MHz LO frequency. The VNA synchronously demodulates the upper sideband and uses this signal to compute the attenuation or gain of the device under test in the S_{21} mode. Both the first and second 5 MHz filters (LPF1 and LPF2) provide attenuation of the 10 MHz LO signal, so it does not go thru the device under test path. These filters also greatly attenuate the sum frequencies in the 20 to 25 MHz range, which could decrease the accuracy if these were present at the second DBM IF input.

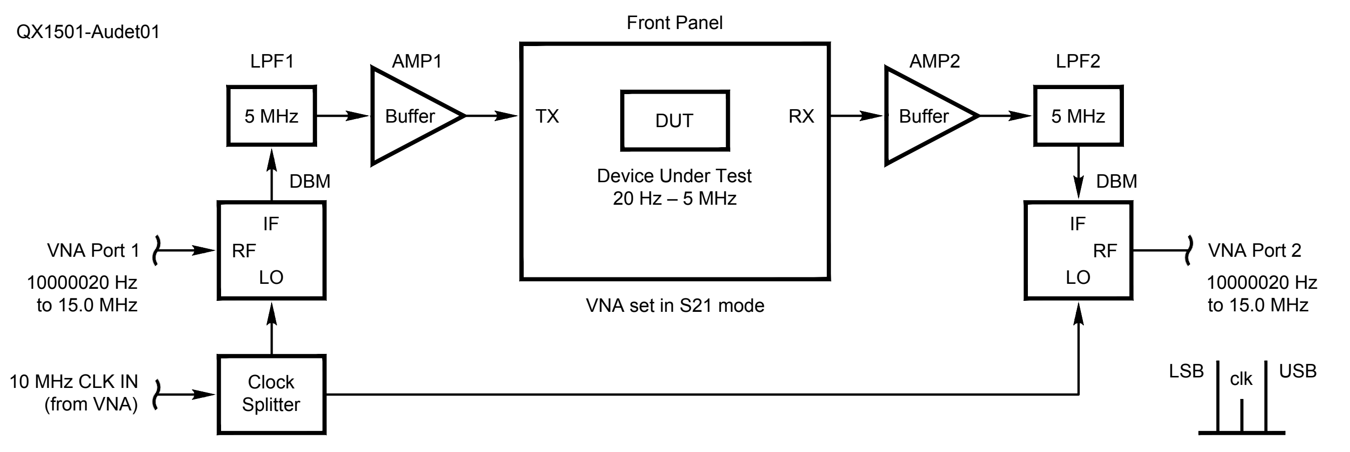

Figure 1 — Basic block diagram of the low frequency adapter (LFA).

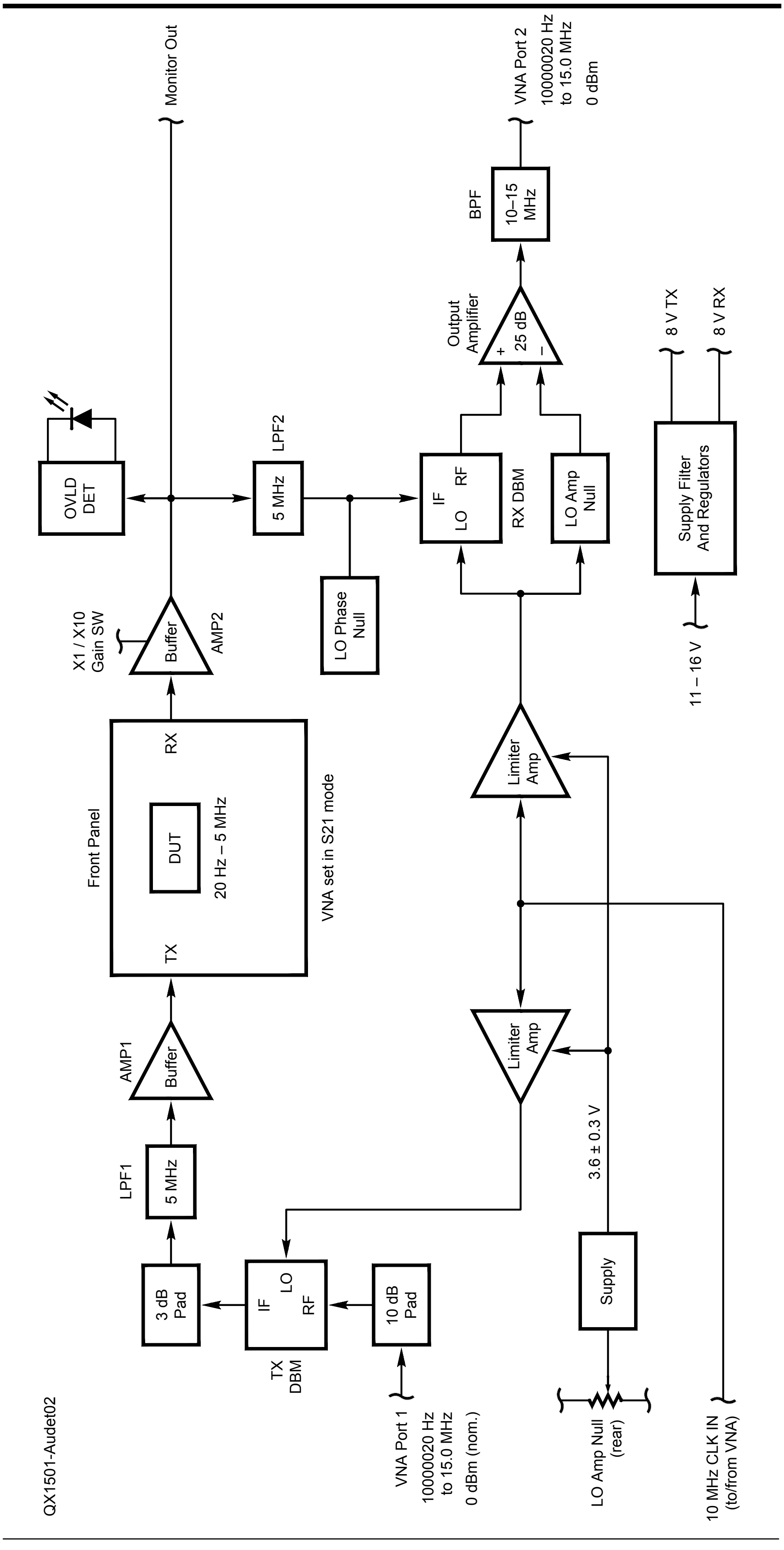

Figure 2 — Detailed block diagram of the low frequency adapter

Since the VNA does coherent detection of the signal (in order to measure the phase), it is necessary to have its internal clock synchronized with the low frequency adapter LO signal. This is normally done by using a common external 10 MHz clock feeding the VNA and the low frequency adapter. This also enables the low frequency adapter to do S_{21} phase measurements from 20 Hz to 5 MHz.

I wanted the low frequency adapter to be as transparent as possible to the VNA. This meant that the low frequency adapter should have unity gain from its input and output. Also the TX output port should have a 50 Ω impedance to be able to drive low impedance loads. On the receive side, the input impedance consists of 1 MΩ in parallel with 8 pF so that it is compatible with oscilloscope probes. An additional capacitor may be added to provide the same input capacitance as your scope input for instance, thus providing a flat frequency response with an external ×10 probe. This high impedance provides much flexibility for the user to terminate the device under test by shunting a parallel termination across the receive (RX) input.

Figure 2 shows a more detailed block diagram of the low frequency adapter.

Detailed Description

The VNA outputs its default-level 0 dBm signal, which is attenuated by 10 dB before reaching the RF port of the TX double balanced mixer. This is done to preserve the linearity at its IF output. The TX output level must track the VNA port 1 level in order to minimize generated distortion on the device under test signals and preserve the VNA capability to perform compression tests. Both double balanced mixers used are of level 7 type, requiring a nominal +7 dBm at the LO port. The 10 MHz clock is sent to a limiter amplifier that drives the two LO ports with a fast square wave, reducing the distortion at high levels and providing a constant LO drive with varying clock input levels. A 3 dB pad at the IF port provides a minimum termination for the TX DBM at both the upper and lower sidebands, helping to minimize distortion. A buffer amplifier (AMP1) provides about 17 dB of gain to compensate for the losses in the pads and the TX DBM, while providing an output level of 225 mV into a high impedance or 112 mV into 50 Ω (–6 dBm).

The RX side provides unity gain from its input to the monitor and VNA outputs. The gain may be increased by 20 dB (×10) using a front switch to improve the system dynamic range. The monitor output has approximately 80 MHz bandwidth in ×1 mode and 60 MHz in ×10 mode. It can be used to monitor the

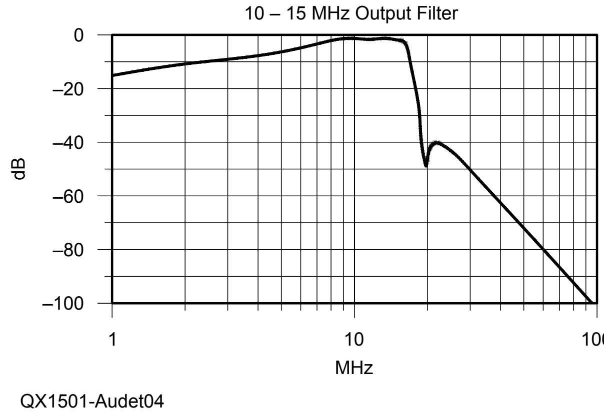

Figure 4 — Band-pass filter frequency response.

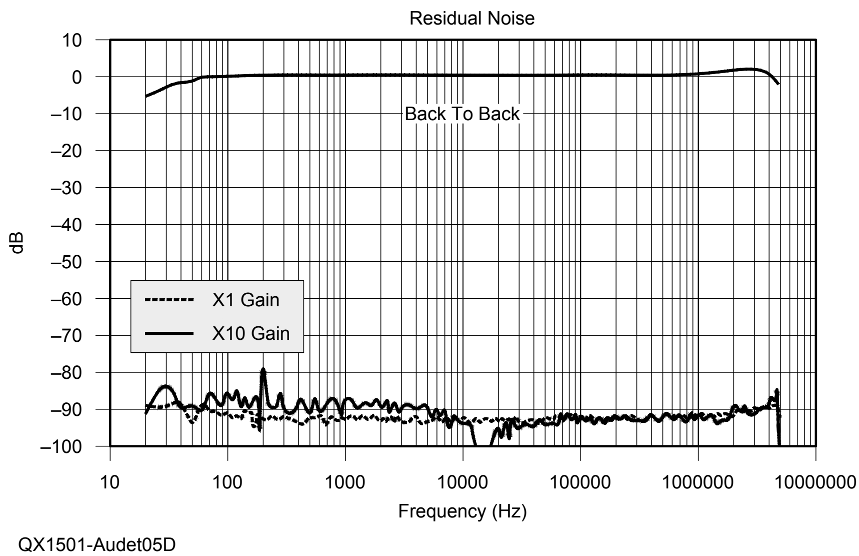

Figure 5 — System measured back-to-back frequency response and residual noise level.

device under test output with an oscilloscope or to provide a high impedance buffer for the VNA, compatible with oscilloscope probes. An overload detector turns on a red LED when the input exceeds +5 dBm. The same LED is normally green and indicates that the low frequency adapter is powered on. A buffer amplifier (AMP2) also drives a 5 MHz low pass filter, which feeds the IF of the second double balanced mixer. The filter is designed for a 30 Ω load, since this is the impedance that I measured at the IF port when the LO is present.

The signal fed at VNA port 2 consists of the two sidebands and some 10 MHz LO carrier leak.

The second double balanced mixer (RX DBM) must provide a high degree of rejection of the LO signal. This is important at the lowest frequencies, from 20 Hz to 1000 Hz. The LO appears as a spurious signal at the VNA port 2, even more than the undesired LSB signal. For this reason, it is necessary to use the lowest IF bandwidth at the VNA (10 Hz for the HP 8753x). This will require slowing down the sweep speed.

The selected RX DBM provides excellent LO rejection from the LO port to the RF port (typically 70 dB). This was not enough at the lowest frequencies, and limited the dynamic range to 60 to 70 dB, however. The expected dynamic range is 90 dB, which occurs above 2 kHz. With an LO at +7 dBm, and 70 dB of LO-RF isolation, –63 dBm will appear at the RF port. This signal is then amplified by the output amplifier, which has 25 dB of gain. This brings the LO to –38 dBm at the VNA port 2. This high level will reduce the dynamic range at the lowest frequencies. We need to reduce the LO feedthrough below –70 dBm at port 2 to restore the 90 dB dynamic range below 100 Hz.

The external LO nulling circuit uses the LO to feed an adjustable voltage divider connected to the inverting input of the output amplifier. Every double balanced mixer has its own LO to RF phase shift characteristics, however, so a variable phase shifting circuit is required. I found that adding bias current in the order of a few microamps to the double balanced mixer IF port did shift the phase. A few double balanced mixers, out of the 40 units I tested, had their initial phase too far and could not be used on the RX side. They can be used as a TX double balanced mixers, however.

There are two amplitude nulling adjustments, one located on the circuit board and the other at the rear. The phase adjustment is located at the rear. Doing so allows easy tweaking of LO null before low frequency (below 1 kHz) response tests are done.

During the testing phase, I found that I had some intermodulation problems at the VNA. Looking at the spectrum, I discovered that high levels of harmonics were present at the RX double balanced mixer RF output. See Figure 3.

A band-pass filter was added at the output to clean up these spurs and get rid of all intermodulation problems. Figure 4 shows the filter frequency response.

Figure 5 plots the system back-to-back frequency response and residual noise level, showing a 90 dB and 110 dB dynamic range in the ×1 and ×10 modes respectively.

Figure 6 shows a picture of the completed unit. Part A shows the font panel, while Part B shows the rear panel. Figure 7 is a picture of the assembled circuit board. The detailed circuit schematic for the low frequency adapter is not printed in the article, but can be downloaded from the author's website and the ARRL *QEX* files website.[1, 2] The adapter

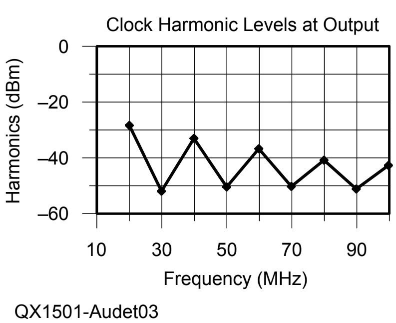

Figure 3 — Measured harmonic Levels of the 10 MHz LO at the output of the RX DBM mixer. Note the strong levels at all even multiples of the LO frequency.

[1]Notes appear on page 16.

Figure 6 — The low frequency adapter is built in a standard Hammond extruded aluminum cabinet. The front and rear panels are pictured.

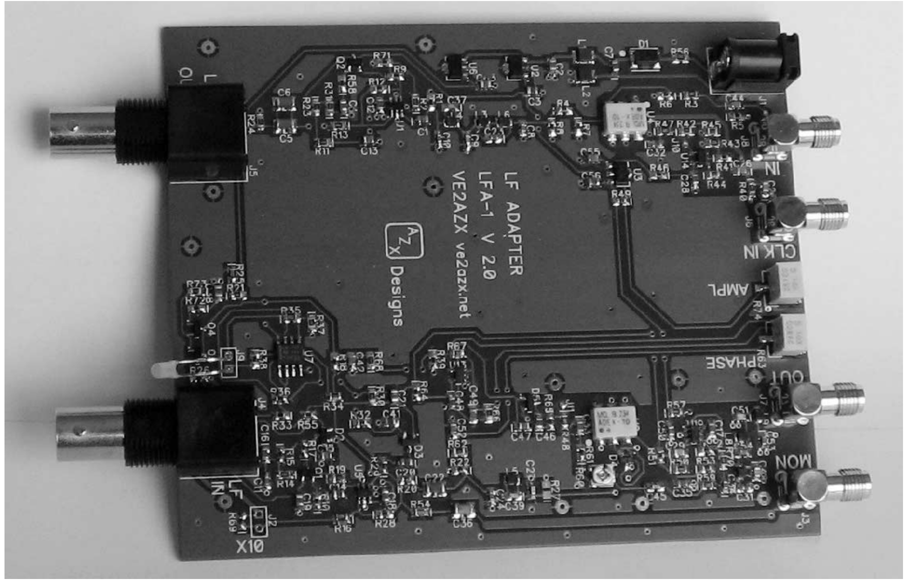

Figure 7 — The assembled circuit board. The R, L and C components are of 0805-size, surface-mounted. Smaller 0603 components will also fit on the pads.

is built on a 3.9 × 4.68 inch (9.9 × 11.89 cm) circuit board, using surface-mounted components on the top surface. It uses a power supply Pi filter and separate regulators for the TX and RX sides, to enhance isolation. The amplifiers used are of the current feedback type, with stable gain that is set by resistors. Two low noise +4 V DC references, consisting of emitter followers, provide a constant output impedance and a flat frequency response. The board may be assembled in approximately five hours.

Low Frequency Adapter Basic Capabilities

All S_{21} measurements are performed within the 10 to 15 MHz frequency range of the VNA. The low frequency measurements include:

- S_{21} magnitude and phase,
- Group Delay,
- Compression point at a single frequency.
- TRU Calibration, with the device under test bypassed with a short circuit, to set a reference amplitude and phase frequency response.

Figure 8 shows the linearity and accuracy in measuring S_{21} magnitude.

Impedance Measurements

The unit as such does not provide for measuring the reflection coefficient S_{11}. The problem of measuring impedances with a return loss bridge is that the accuracy decreases rapidly when the unknown impedance is more than five times above or below the

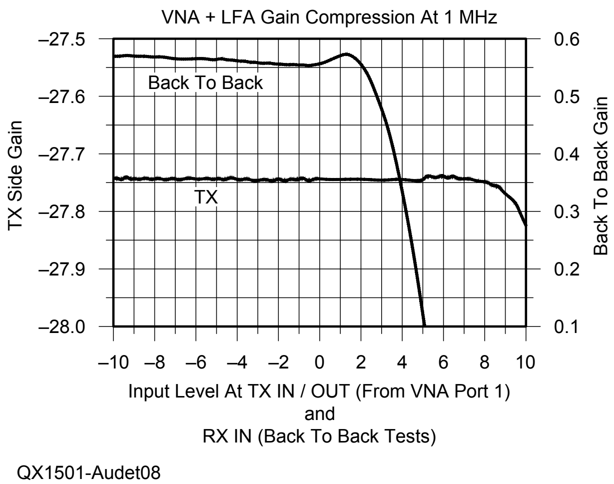

Figure 8 — Linearity / Gain Compression test results. The TX output gain rolls off less than 0.1 dB at +10 dBm, while the RX side gain compression measures ±0.05 dB up to +3 dBm input.

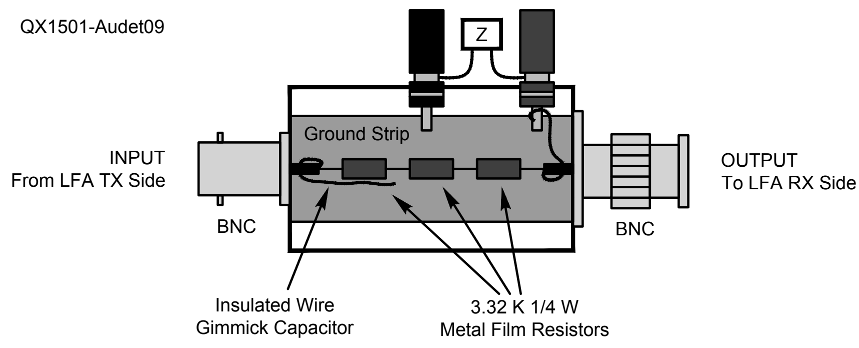

Figure 9 — Here is the shunt impedance adapter physical layout used for impedance measurements. Note the three resistors connected in series to reduce the overall shunt capacitance.

reference impedance. At low frequencies, we are generally interested in measuring a wide range of impedances, from say 0.1 Ω to 1 MΩ. This measurement is best handled by a series or shunt transmission circuit, where S_{21} is measured as a complex value and used to compute the impedance value, including the reactance, inductance, capacitance, and resistance in the series or parallel models. I have created an *Excel* spreadsheet that performs these computations.[3]

Note that the low frequency adapter provides 1 MΩ impedance on the RX side, which gives the user more flexibility in doing shunt impedance measurements. When the device under test cannot be floated, then the shunt configuration must be used. With the normal 50 Ω source and load impedances, the maximum value of shunt impedance that can be measured does not exceed about five times 50 Ω, or 250 Ω. Adding resistors in series with the 50 Ω source (TX) and load (RX) will increase the accuracy in measuring higher impedances at the expense of reducing the dynamic range. For example adding 1000 Ω in series at both the TX and RX sides will give about 32 dB of attenuation when the shunt device under test is unconnected.

With the low frequency adapter, the RX impedance is raised from 50 Ω to 1 M Ω, the attenuation will be about 0 dB with the shunt device under test unconnected, and no reduction in the dynamic range will occur. The *Excel* spreadsheet performs these calculations. Figure 9 shows the layout of the shunt impedance adapter that I used. It provides impedance measurements from < 1 Ω to over 20 kΩ, from 20 Hz to 10 MHz. Photo A shows the completed shunt impedance adapter.

Table 1
Using external probe and attenuator allows large signal capability.

Maximum Input Amplitude	*Setup*
50 mV rms	×10 Gain on LFA, improves dynamic range
500 mV rms	×1 Gain on LFA
5 V rms	×1 Gain + ×10 probe
50V rms	×1 Gain + ×100 attenuator 1 MΩ in/out
500 V rms	×1 Gain + ×100 attenuator + ×10 probe

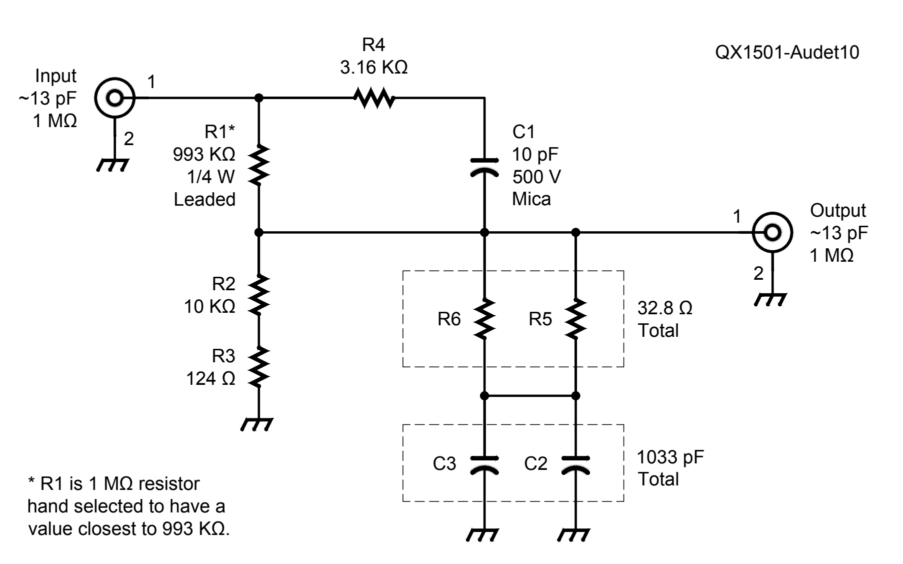

Figure 10 — The schematic diagram for the ×100 divider/attenuator.

Photo A — This photo shows the assembled shunt impedance adapter. The female BNC connector accepts the signal from the low frequency adapter TX connector. The male BNC connector is the output signal, which goes to the low frequency adapter RX connector.

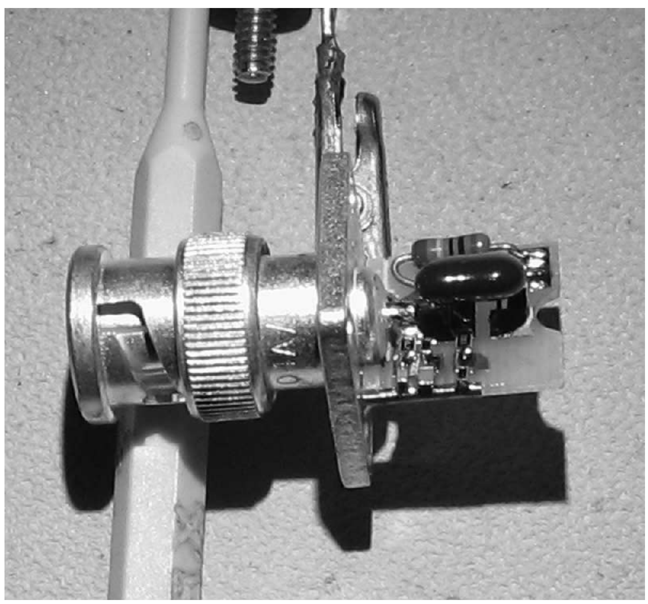

Photo B — Here is the male BNC connector, with the ×100 attenuator circuit board attached. A short wire from the female BNC connector goes to the circuit board pad at the top right corner before placing that end into the square aluminum extrusion.

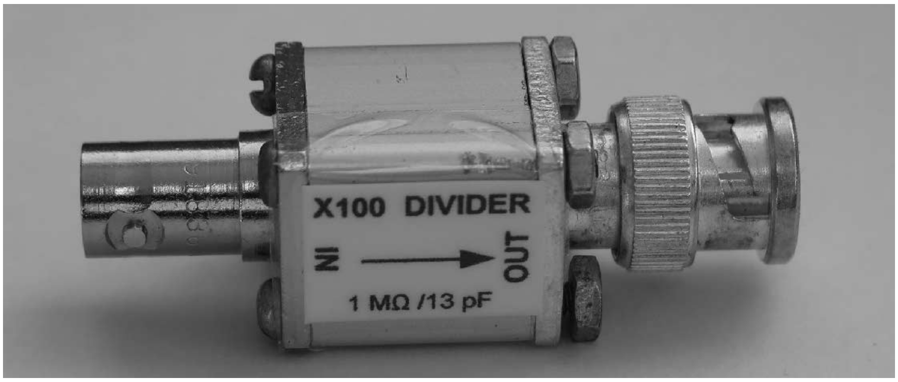

Photo C — This photo shows the completed ×100 attenuator unit.

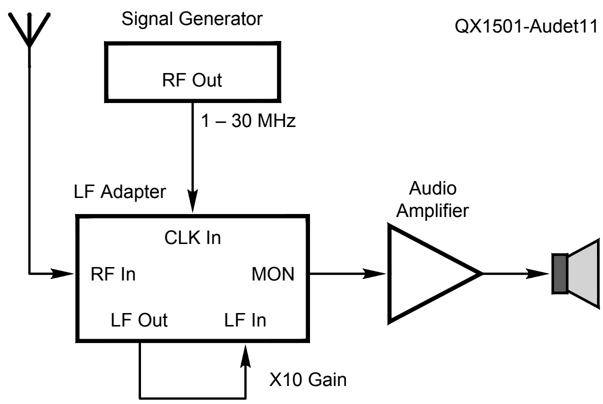

Figure 11 — Setup for an HF direct conversion receiver. The monitor output uses ×10 gain to improve the signal to noise ratio.

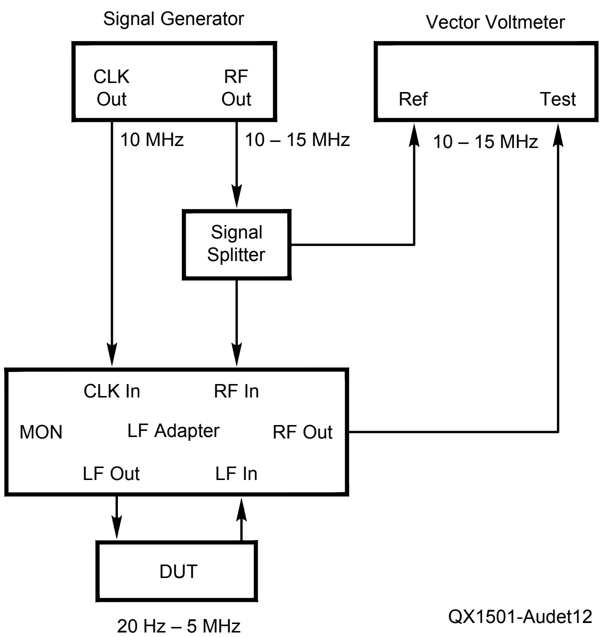

Figure 12 — Setup for using the vector voltmeter at low frequency, using a synthesized RF signal generator. While I have not tried this setup, a very similar arrangement is described in Note 5.

Other Applications of this Low Frequency Adapter

• **Probe Buffer / Amplifier** using the monitor output. It provides an 80 MHz bandwidth in ×1 mode and a 60 MHz bandwidth in ×10 mode.

Using a ×100 attenuator at the low frequency adapter RX input, and/or a ×10 probe provides the ability to handle a very wide range of amplitudes, as shown in Table 1. Figure 10 shows the schematic diagram of the ×100 1 MΩ wideband attenuator that I designed. Photo B is a picture of the circuit board and BNC male connector for the output side of the attenuator. A BNC female connector is used for the input side, and that attaches to the circuit board with a single wire to the circuit board pad between the 933 kΩ and 3.16 kΩ resistors. Photo C is the complete, assembled attenuator. For more details about this ×100 attenuator see the file **Divider-100.pdf** that is part of the **1x15_Audet.zip** file on the ARRL *QEX* files website.[4]

• **Low Frequency Signal Generator**, using your RF signal generator.

The generator clock output provides the clock signal for the low frequency adapter. Its frequency is set from 10.00002 MHz to 15 MHz, to generate an output from 20 Hz to 5 MHz. The low frequency adapter output amplitude tracks the generator output up to +10 dBm.

• **Direct Conversion Receiver**

The low frequency adapter may be used as a simple wideband direct conversion receiver with a well-defined 5 MHz bandwidth. Both sidebands will be detected. Using a low phase noise signal generator allows testing the phase noise of an oscillator using a computer soundcard as a spectrum analyzer. Another possible use is for calibrating the signal generator time base against WWV or CHU, for off the air frequency measurements. Figure 11 illustrates how the low frequency adapter can be connected to an antenna, an RF signal generator and an audio amplifier to create a direct conversion receiver.

• **Vector Voltmeter Operation at Low Frequency**

Figure 12 illustrates the basic operation of the low frequency adapter with a vector voltmeter, for making low frequency measurements. The 10 to 15 MHz signal generator output connects to a signal splitter, so the same signal is going to the RF In port on the low frequency adapter and also to the reference input of the vector voltmeter. Notice that a 10 MHz clock reference signal also connects from the signal generator to the Clock In port on the low frequency adapter. The RF Output, or RX port on the adapter connects to the Test signal input port on the vector voltmeter. The device under test connects to the LF In and LF Out ports on the front of the low frequency adapter. I have not tried this setup, but a very similar arrangement is described in a Feb 1972 *IEEE Transactions on Instrumentation and Measurements* article.[5]

Conclusion

The Low Frequency Adapter described here adds low frequency capability to a Vector Network Analyzer, as well as adding audio frequency generation, 1 MΩ probe amplified interface, and direct conversion receiver capability. In the VNA application, an IF bandwidth of 10 Hz must be used to extend the lowest frequency down to 20 Hz. The low frequency adapter has allowed me to measure R, L and C components down to 20 Hz, using my Hewlett Packard 8753D VNA. I have also been able to accurately characterize and document the response of many audio type amplifiers that otherwise would have required tedious measurement methods. I wish to acknowledge the help and encouragement of my good friend Bertrand Zauhar, VE2ZAZ, who did the beta testing on this project. Readers seeking more information (component procurement, circuit schematic, updates, and so on) should visit my website at **http://ve2azx.net/technical/LFA/LowFreqAdapter.htm**.

Jacques Audet, VE2AZX, became interested in radio at the age of 14, after playing with crystal radio sets and repairing old receivers. At age 17, he obtained his first ham license. In 1967 he obtained his BS degree in electrical engineering from Laval University. He then worked in engineering functions at Nortel Networks, where he retired in 2000. He worked mostly in test engineering on a number of products and components operating from dc to light-wave frequencies.

His areas of interest are in RF simulations, filters, duplexers, antennas and using computers to develop new test techniques in measurement and data processing. Jacques is an ARRL Member.

Notes

[1]For the complete circuit schematic, as well as any updated information, see the file named **LFA-V2-Schematic.pdf** on my web site: **ve2azx.net/technical/LFA/LowFreqAdapter.htm**.

[2]The complete circuit schematic, as well as other files associated with this article are available for download from the ARRL *QEX* files website. Go to **www.arrl.org/qexfiles** and look for the file **1x15_Audet.zip**.

[3]The *Excel* spreadsheet that I created to perform these calculations is available for download on my web site: **ve2azx.net/technical/Series_Parallell-Impedance_with_VNA-Re_Im.xls**. This spreadsheet is also included in the **1x15_Audet.zip** file available for download on the ARRL QEX files website.

[4]There is more information about the ×100 1 MΩ wideband attenuator included in the file **Divider-100.pdf**, which is part of the **1x15_Audet.zip** file on *QEX* files website.

[5]R. Lane and J. Butler, "LF Adaptor Extends Vector Voltmeter Magnitude and Phase Measurements down to 10 Hz," *IEEE Transactions on Instrumentation and Measurements*, Feb 1972. A copy of this

Appendix
Low Frequency Adapter Specifications

Supported VNA Mode: S_{21}.

LFA Frequency Range: 20 Hz to 5 MHz.

In the VNA application, an IF bandwidth of 10 Hz must be used to extend the lowest frequency down to 20 Hz.

Clock Input: 10 MHz, 0 to +12 dBm, 50 Ω. Clock must be synchronized to the VNA reference clock.

Input to LFA from VNA Port 1: 10.000 020 MHz to 15.000 MHz, 0 dBm nominal, Max +6 dBm, 50 Ω (at rear).

Output from LFA to VNA Port 2: 10.000 020 MHz to 15.000 MHz, 0 dBm nominal, Max +6 dBm, 50 Ω (at rear).

Low Frequency Output: 20 Hz to 5 MHz, 50 Ω, AC coupled, –6 dBm (112 mV RMS into 50 Ω) or 225 mV nominal into an open circuit.

Return Loss: > 40 dB below 5 MHz.

Harmonics at 1 MHz Out / 0 dBm: –65, –70, –50, –70 dBc for the 2^{nd}, 3^{rd}, 4^{th},5^{th} harmonics.

Spurs Measured Under No Input From VNA Port 1: – 85, –97, –101, –102, –104 dBm at 10, 30, 50, 70, 90 MHz.

Source Linearity (Up to +9 dBm Out): < 0.05 dB

Low Frequency Input: 20 Hz to 5 MHz, 1 MΩ in parallel with 8 pF, AC coupled, 0 dBm nominal input level (front panel).

Overload Level: ~ +5 dBm, as indicated by a red LED on the front panel.

Damage Level: 20 V RMS.

Loopback of Low Frequency Output to Low Frequency Input: Yields ~ 0 dBm output to VNA port 2 at ×1 Gain.

Frequency Response Uncorrected: –3 db at 35 Hz and 5 MHz, ±1.5 dB from 100 Hz to 4 MHz.

A front panel switch provides ×10 gain to compensate for ×10 scope probe attenuation.

Back-to-back linearity, including HP 8753D VNA: Up to +3 dBm in: < ±0.05 dB.

Two rear adjustments potentiometers allow for tweaking the LO carrier balance to improve dynamic range below 1000 Hz.

Dynamic range: better than 90 dB from 100 Hz to 5 MHz, when used with a VNA having more than 100 dB of dynamic range. Improves by 20 dB at ×10 gain.

Sweep time: For a 170 point log sweep, from 20 Hz to 5 MHz: 50 seconds on the HP 8753D, using 10 Hz IF Bandwidth and LIST frequency mode.

Monitor Output: 50 Ω, AC coupled, open circuit level equals input level ±1 dB.

Frequency response –3 dB into 50 Ω: 200 Hz to > 80 MHz at ×1 and > 60 MHz at ×10 gain.

Maximum Output Level: + 6 dBm into 50 Ω

Power input: +11 V to +16 V DC at < 80 mA (at rear). A balanced Pi filter at the input cleans up the DC source from any switching power supply noise.

Size: 10.5 cm (W) × 15 cm (L) × 3.5 cm (H).