Simple New Analog-RF Weak-Signal Receivers

Rick Campbell KK7B and Katlin Dahn KJ7DMF
Portland State University

A striking number of eminent VHF contributor biographies in recent Central States VHF Society Proceedings reference their first exposure to VHF technology using a Heathkit Twoer. Even more common in the 20th century RF designer-builder-experimenter community is experience with a crystal radio. 6th grader Richard Campbell K7XNK built an 80m crystal set with outdoor dipole and transistor audio amplifier, and then turned on a nearby 3.686 MHz Pierce oscillator (a “local” oscillator) to copy CW signals. Three decades earlier, his dad had hacked a three transistor Knight-Kit walkie talkie up onto the 10m amateur band to listen to hams thousands of miles away.

Crystal sets and superregenerative radios have only a few components, and invite modification by young experimenters. There is a direct relationship between components and schematics, and after building a Heathkit Twoer from a kit, the young radio technologist had the tools, skills, and beginnings of understanding to attempt improvements. Young radio amateurs from well to do families, who perhaps received a Collins S-Line for their 14th birthday upon upgrading to General class, grew up to be bank vice presidents. Young folks of limited means who had to make do with marginal, entry level kits, were perhaps more likely to develop technical critical thinking skills that served them well in scientific and technical professions...or at least that is a conclusion that might be reached from the CSVHF Society biographies.

A decade ago, Wes Hayward W7ZOI and his friend Bob Culter N7FKI were experimenting with high performance crystal radios. Exchanged emails served as inspiration to revisit the K7XNK childhood explorations. The elementary school 80m crystal set had copied CW signals, but what was the simplest receiver that would receive HF CW signals, and suppress the opposite sideband? On a whim, an IQ Crystal Set made the transition from back-of-the napkin sketch (literally, at a McMenamins pub) to breadboard, and ultimately connection to headphones and an antenna. The design attracted a cult “basement tapes” following, but performance is truly marginal except that it is dirt simple and draws almost no current from the 3 AAA cell supply.

Simpler versions are possible, using an all-passive baseband IQ combiner, followed by a simple 3 transistor audio amplifier as in Hayward and Bingham’s seminal paper [1].

Two features of the IQ Crystal set fermented for years, and inspired further development. The image-reject mixer used a previously unknown to the author configuration of hybrid coil and diode ring as an SPDT switch that alternately connects the I and Q signal paths to ground. Careful experiments at different frequencies using various switches resulted in an IEEE paper, IQ mixer with single SPDT switch [2]. The starved current analog baseband signal processor was further developed into one of those annoying little topologies that works nearly as well as prior art while drawing a tiny fraction of the current and using only a few transistors [3].

Figure 1 on the next page is the original 2009 IQ Crystal Set mixer and LO, and Figure 2 is the original baseband signal processor, using a venerable B&W 2Q4 audio frequency phase shift network. These circuits are interesting historical references, but anyone who would like to do further work is invited to study the IEEE and European Microwave Week references [2,3].

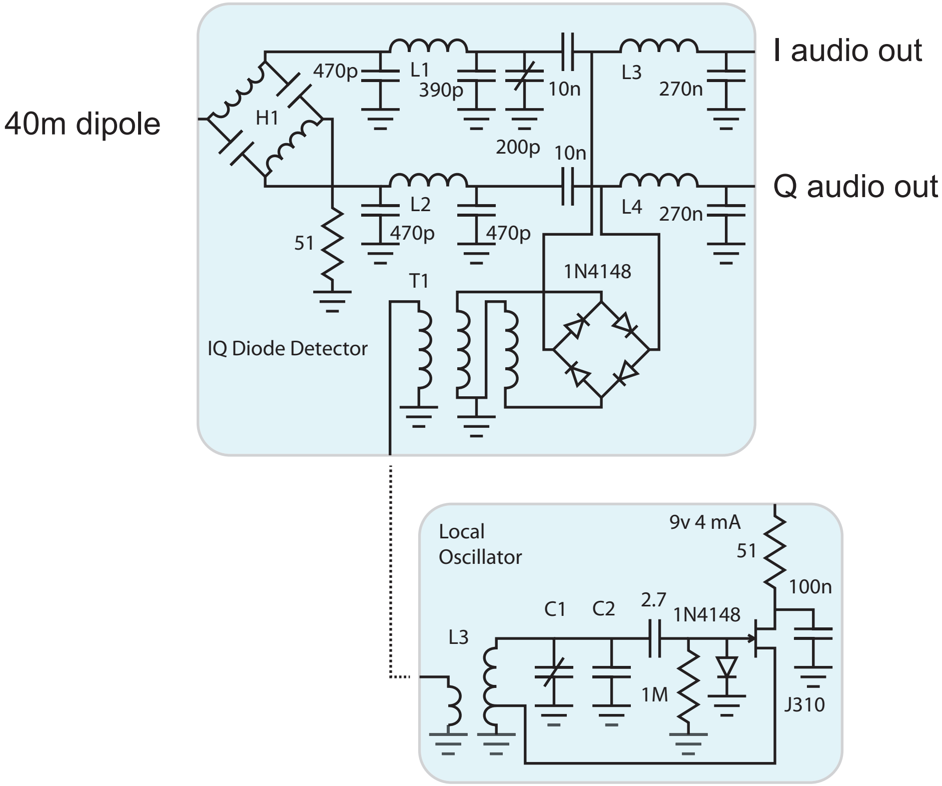

Figure 1 40m IQ Crystal Set front-end

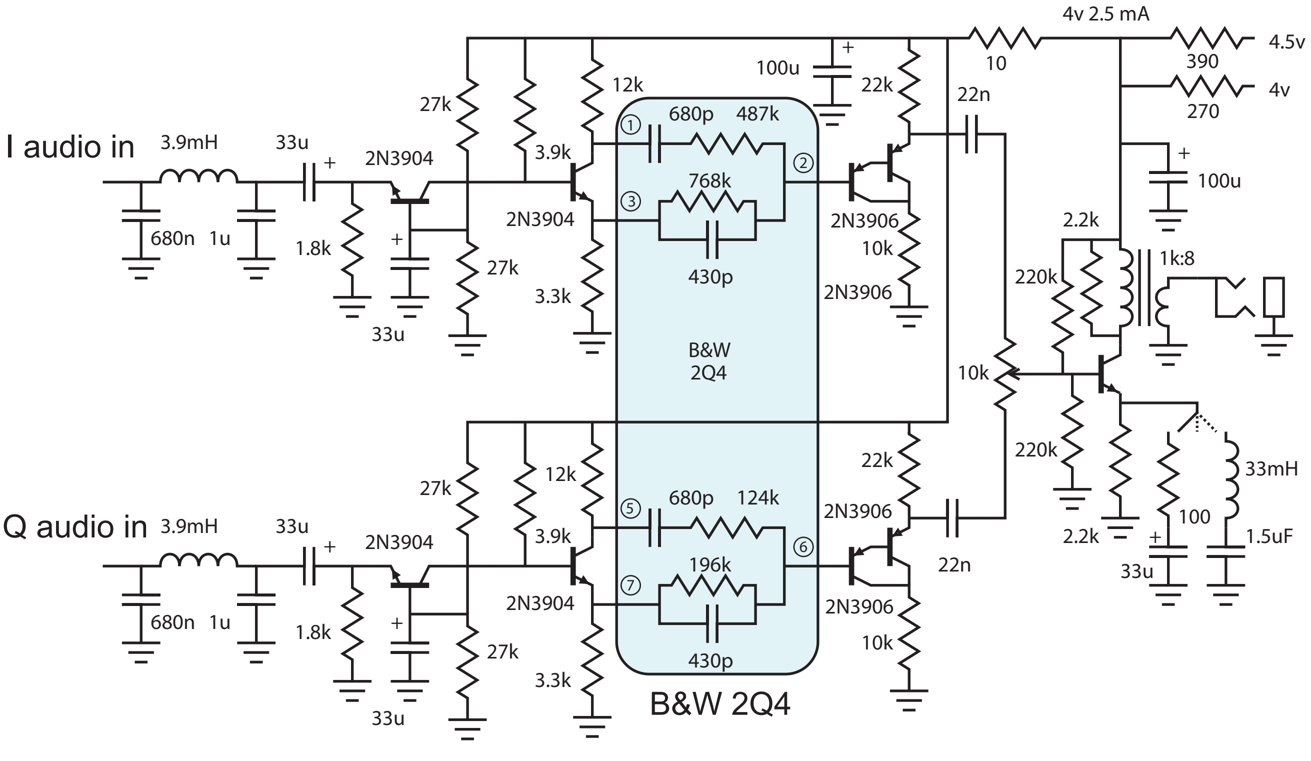

Figure 2 IQ Crystal Set analog baseband signal processor

The photos in Figures 3 and 4 show the carefully built experimental version of the IQ mixer with single SPDT switch described in Campbell [2]. Performance is acceptable for many low power applications, as the SPDT switch with four Schottky diodes and trifilar ferrite transformer works well with only a few mW of drive. A similar circuit with a pair of ADE-1 diode ring mixers requires +10 dBm (10 mW) drive.

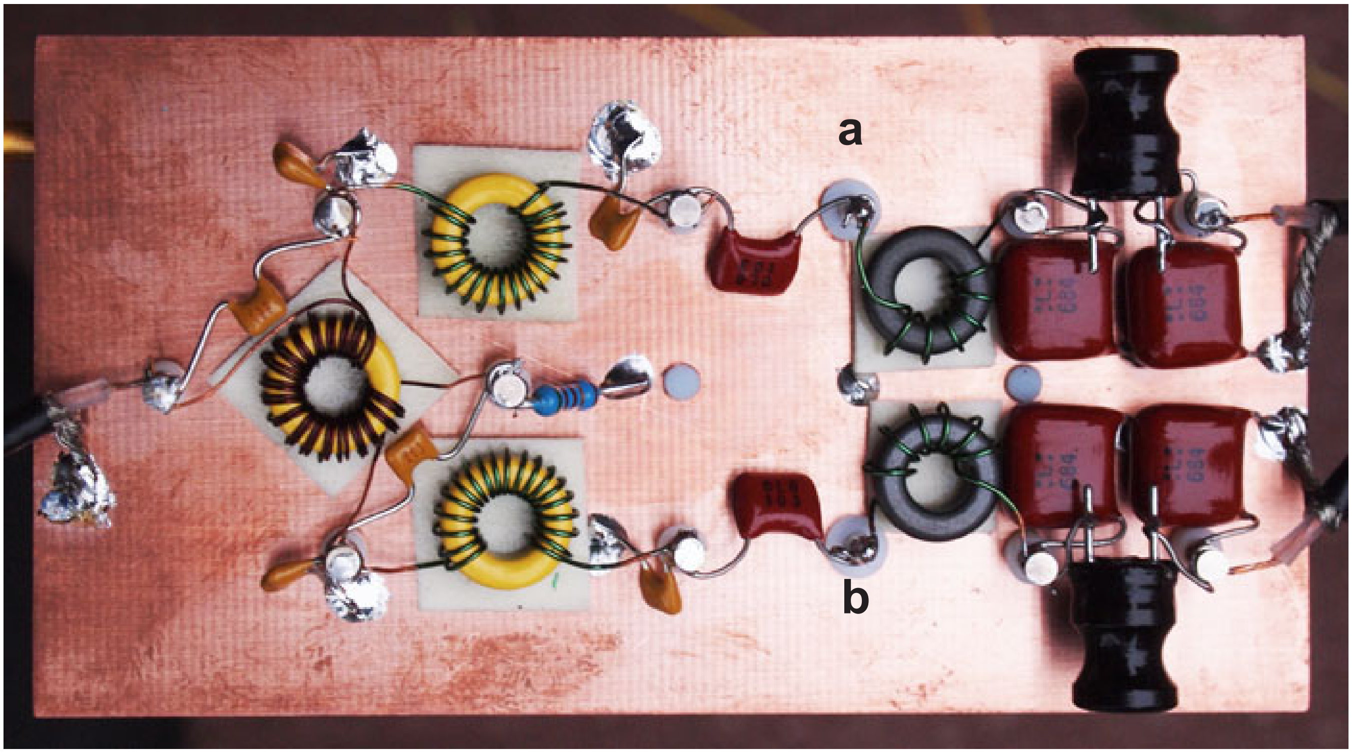

Figure 3 7 MHz IQ mixer from Campbell [2]

Construction with the signal paths on one side of the circuit board and LO on the opposite improves RF-LO isolation and facilitated experiments with FET and diode switches reported in [2]

The circuitry in these photographs was modified by adding a diode frequency doubler and LO-RF trim circuitry as shown on the next two pages.

The prototype construction method shown here encourages experiments.

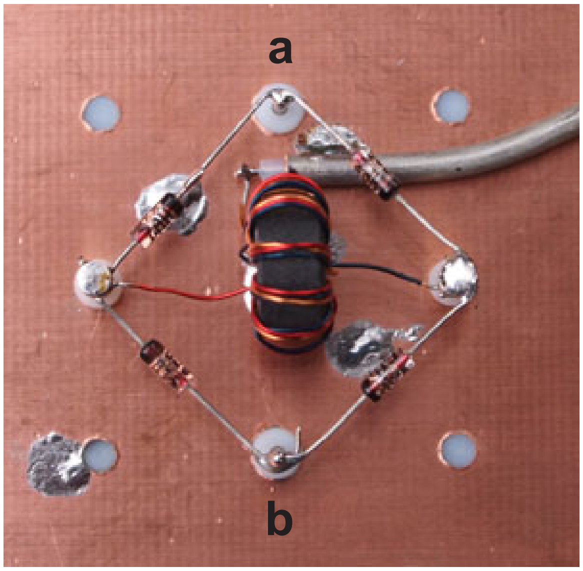

Figure 4 Back of circuit board showing SPDT switch from Campbell [2]

The IQ Crystal Set is a direct conversion receiver, and as discussed at length in Chapter 8 of Experimental Methods in RF Design, performance is limited by the need for a local oscillator on the same frequency as the RF input. A classic cure is operating the LO at half frequency, with a frequency doubler as either the last stage, or integrated into the IQ mixer. Figure 5 is the schematic of the experimental IQ mixer with single SPDT switch from [2], with added diode doubler to drive the SPDT switch. The frequency doubler generates a little offset voltage at point c, which is used with trimpots to obtain I and Q variable offset voltages d and e.

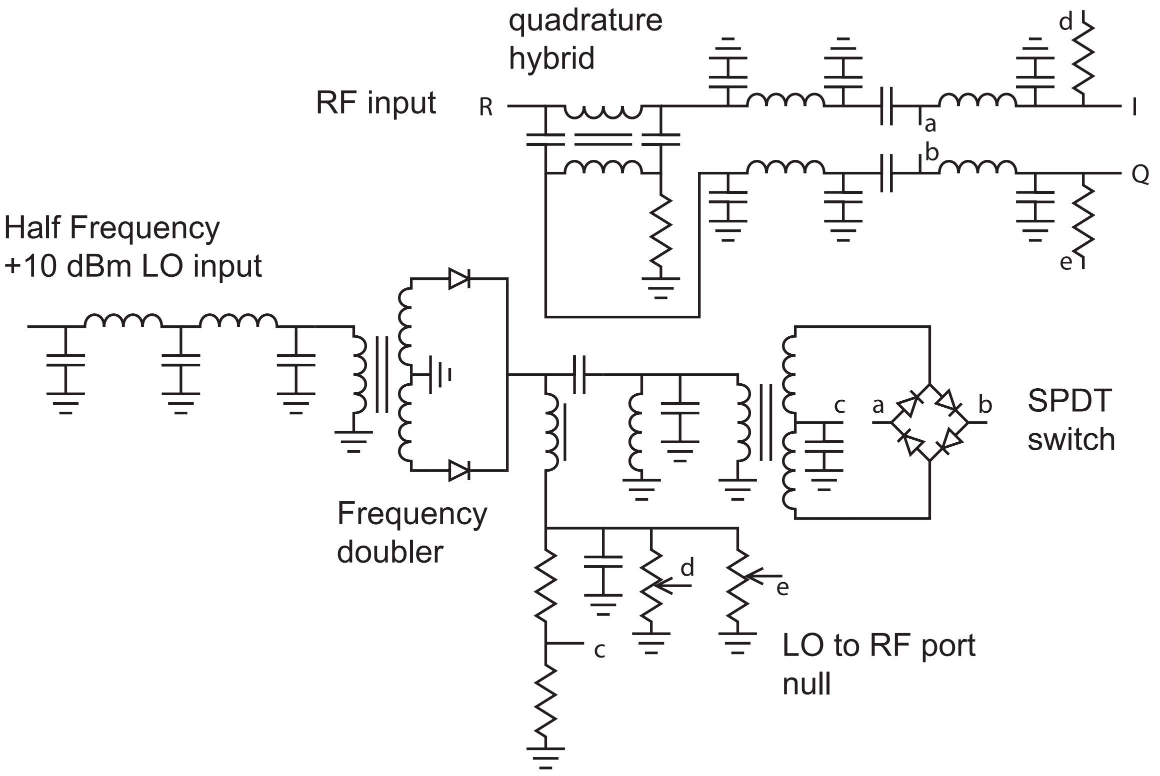

Figure 5 SPDT IQ Mixer with diode doubler

Points a and b are alternately connected to ground at the doubled LO frequency. Trimming the dc offsets d and e may be used to either null the residual LO output at the RF port R, or to achieve improved 2nd order distortion performance from the I Q mixer. That may be achieved by introducing an off-frequency AM signal into the RF port, and nulling the output with d and e.

Component values are not included in Figure 5, as this schematic may be designed at any RF and I and Q output frequencies where passive components and diodes are reasonably well behaved. Figure 6 has complete component values for a 7 MHz example with audio I and Q outputs.

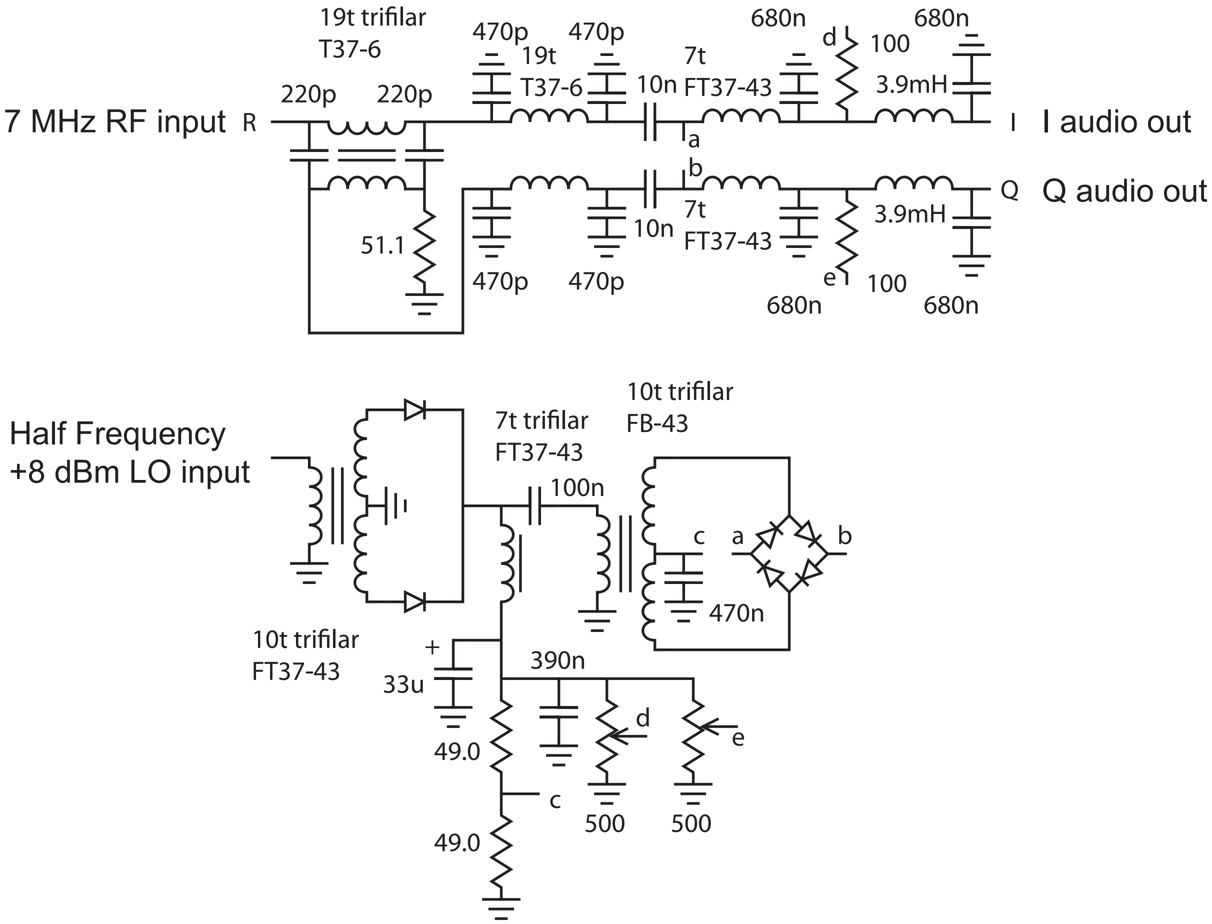

Figure 6 7 MHz example IQ mixer with frequency doubler and LO-RF trim

An unintended consequence of deriving the offset voltage for the LO-RF trim adjustments d e from the frequency doubler is that I Q performance becomes LO drive level dependent. As measured in [2], the IQ mixer with SPDT switch using a diode ring has performance that is remarkably stable with variations in LO drive. After adding the clever circuitry shown in figures 5 and 6, the opposite sideband suppression in our 40m experimental receiver varied from 20 dB to >40 dB as LO drive level changed by only a few dB either side of +8dBm at 3.5 MHz.

The analog baseband signal processor using the B&W 2Q4 shown in Figure 2 continues to evolve. This version was described in [3], with the I and Q paths mirror imaged across the center line. The I section uses NPN transistors, and the Q section uses PNP devices in an identical, but upside down circuit.

The whole analog signal processor draws less than 3mA from a 9v battery.

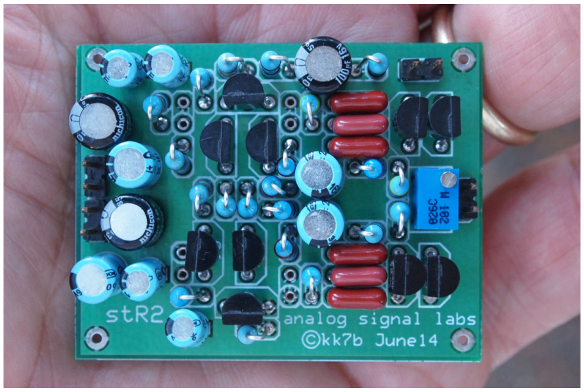

Figure 7 Analog Baseband Signal Processor

The basic IQ mixer may be built with components for any frequency where passive elements and diodes are available. A photograph and some preliminary measurements were included in Campbell [2]. The small circuit board in figure 8 includes all of the components from the figure 1 original circuit, scaled to 144 MHz and a 455 kHz IF.

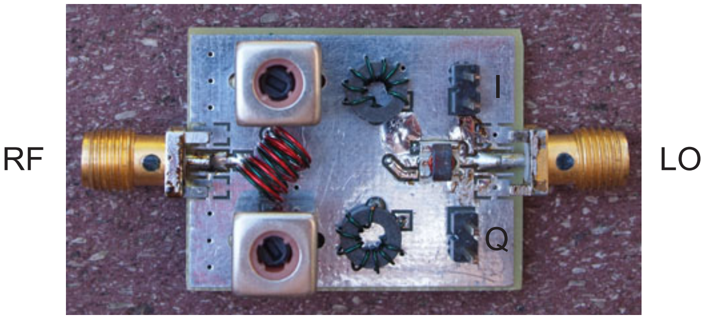

Figure 8 144 MHz IQ Mixer

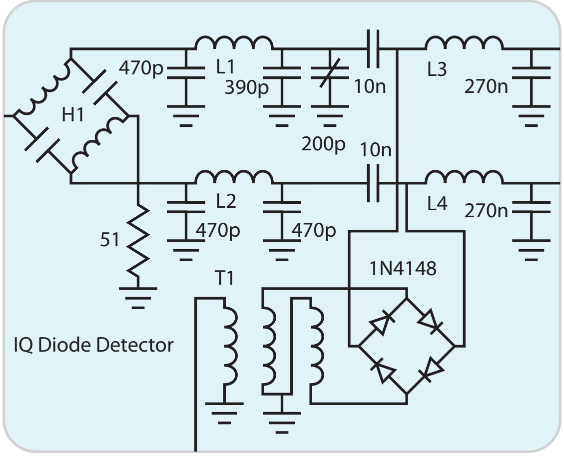

Figure 9 IQ mixer components

Figures 10 and 11 are detail photos that may be compared with figure 9 to see how the circuit is scaled from 7 MHz to 144 MHz.

An IQ mixer at 144 MHz allows an image-reject front-end to any IF, not just the audio range common in single-signal direct conversion receivers. For example, an image-reject front end at 144 MHz may be used in a single conversion receiver with a 455 kHz IF. Receivers with an unusually low frequency IF have significant response at the image. A combination of front-end selectivity, image-reject mixing, and strategically placing the image band is necessary for acceptable performance. For example, single conversion 72 MHz radio control receivers with 455 kHz IF simply accepted that the image would be present, but designed the frequency and band plan such that interfering signals at the image frequency were unlikely.

A 144 MHz receiver for the weak signal range from 144.0 to 144.320 MHz with 455 kHz IF and low-side injection has an image band from 143.090 to 143.410 MHz. A few evenings listening in the Portland Oregon metro area revealed zero signals in the image band, above the local noise floor. With no signals in the image band, a receiver with 40 dB image rejection is more than adequate.

The initial plan for the Near Zero IF 144 MHz receiver was for an ultra-simple 2m AM receiver, a 2019 variation on the original Heathkit Twoer concept. 2m AM turns out to be an ideal mode for low-power classroom explorations where students design and build every single block of the wireless communication system, down to the individual device level. It also turns out to be a hot topic in 2019, as envolope modulation is a key element of high efficiency linear power amplifier architectures. A dirt simple 2m AM receiver with IQ mixer and 455 kHz IF using a one chip AM radio was built, and it worked, but it didn't have the high fidelity audio embraced by the KK7B aesthetic. So the IQ front-end was taped (literally) on top of a prior KK7B project, a high performance 472-479 kHz instrumentation receiver prototype.

Note the air-core bifilar inductor in the quadrature hybrid.

The slug-tuned low pass coils permit limited adjustment of relative amplitude and phase between the I and Q signal paths.

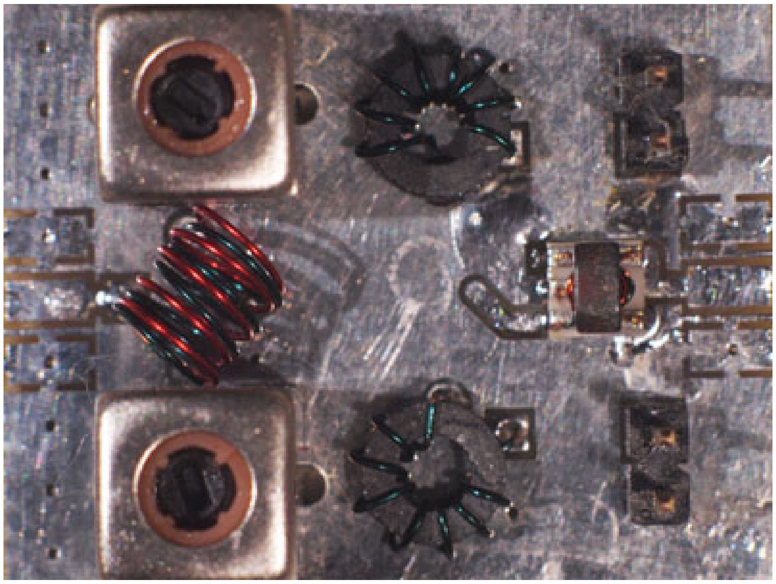

Figure 10 144 MHz IQ mixer top

The components in the IQ mixer are entirely passive, and only the diode ring uses semiconductors.

The diode ring in this case uses two HSMS 2812 nose-to-tail diodes, center right in this photo.

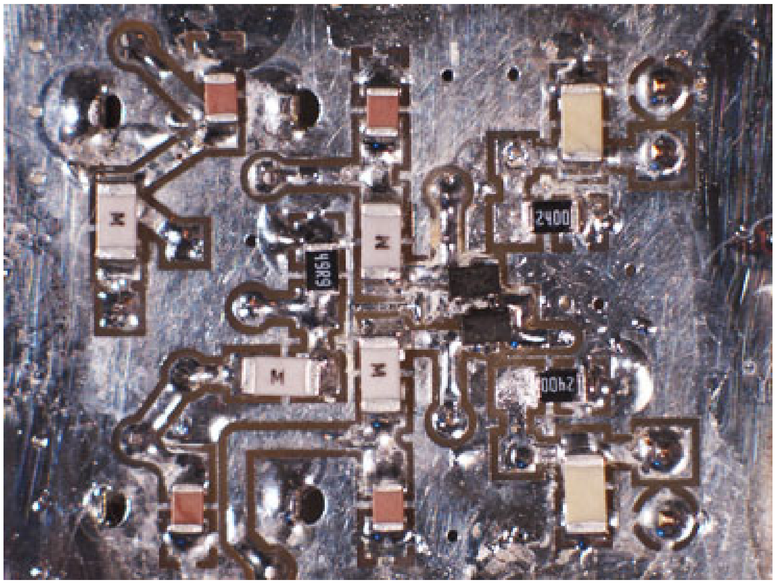

Figure 11 144 MHz IQ mixer bottom

The 472-479 kHz instumentation receiver described by Campbell and Davey in [4] was tuned to 455 kHz to serve in the venerable Q-5er function with a lovely old HQ-150 receiver in the KK7B vintage station. It worked so well that a matched pair was built, one for USB and the other for LSB. The prototype sat in a box until the disappointing performance of the 2m AM receiver described in the previous paragraphs. The IQ front-end was simply taped to the top of the 455 kHz Q-5er, and performance was good enough for some instrumentation applications with students at Portland State University. Yes, in case you were wondering, that's the same Campbell and Davey who brought you no-tune transverters in the 1980s.

Figure 12 shows the new 144 MHz instrumentation receiver sitting in the place of honor next to the Johnson 6N2 transmitter. The lower two diecast aluminum boxes are the 455 kHz IF system described by Campbell and Davey [5], and a 453.5 kHz stable BFO in the smaller box. The upper two boxes are a VXO on the left that tunes from 143.790 to 143.870 MHz, for a receive tuning range of 144.245 to 144. 325 MHz. This covers the experimental range used by Portland State University students in micro power instrumentation, and the 2m Beacon band.

Figure 12 144 MHz NZIF Instrumentation Receiver

The rear panel interconnects are all SMA using UT-085 semi-rigid cable for good shielding. The receiver hears nothing with the antenna port open. The tuning control is the large black upper left knob, the volume control is the smaller knob on the bottom, and just above the small black knob is a 30 dB input attenuator switch. The front panel RCA phono jack connects to a speaker and laptop running audio frequency waterfall plot software. Frequency stability of the receiver is good enough for 1 Hz bandwidth coherent integration, and there is 80 dB receive noise floor-to clipping head room. Gain is constant and the passband is flat to within a few tenths of a dB, permitting accurate measurements of both signal levels and frequency shifts.

References:

1. Wes Hayward and Dick Bingham, “Direct Conversion, A Neglected Technique,” QST November 1968
2. Rick Campbell, HF-VHF-UHF IQ mixer with a single SPDT switch, in Proceedings of the IEEE MTT-S International Microwave Symposium Proceedings, 2015, pp. 1-4
3. Richard L. Campbell, Branimir Pejcinovic, “Project-based RF/microwave education,” 2015 European Microwave Conference Proceedings (EuMC), 2015 pp. 1307 - 1310
4. Richard Campbell and James Davey, Instrumentation Receiver for Medium Frequency Propagation and Noise Measurements, in Proceedings of the IEEE MTT-S International Microwave Symposium 2017, pp. 1738-1741