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Baseband Quadrature Multi-Band Modulator

This baseband quadrature modulator operates over multiple amateur bands.

I have been looking for a way to experiment with and assemble a software defined transceiver using separate components such as the transmitter, receiver, local oscillator, and so on. For transmitting, I looked at discrete baseband IQ modulators, especially the Linear Technology LTC5598 baseband IQ modulator IC with a range of 5 to 1600 MHz. This range is met with proper local oscillator port matching to a range of

frequencies, but I've had reasonable success with a single match from 50 to 450 MHz.

This article describes the design and construction of an IQ modulator based on the LTC5598. The modulator takes baseband 'I' and 'Q' signals, such as from digital to analog converters or left and right output of a sound card, a local oscillator signal, and outputs an RF signal up to 1 mW. The RF output contains odd order harmonics, but with

filtering the output can then be amplified for transmitting on the ham bands. When used as an image-reject up-converting mixer, it is suitable as a modulator building block in a transmitter or transceiver for such things as APRS, beacons, and voice using SSB or FM. Other modulation modes are possible as well.[1]

Design

Figure 1 shows a block diagram of the LTC5598 modulator board. Two excellent
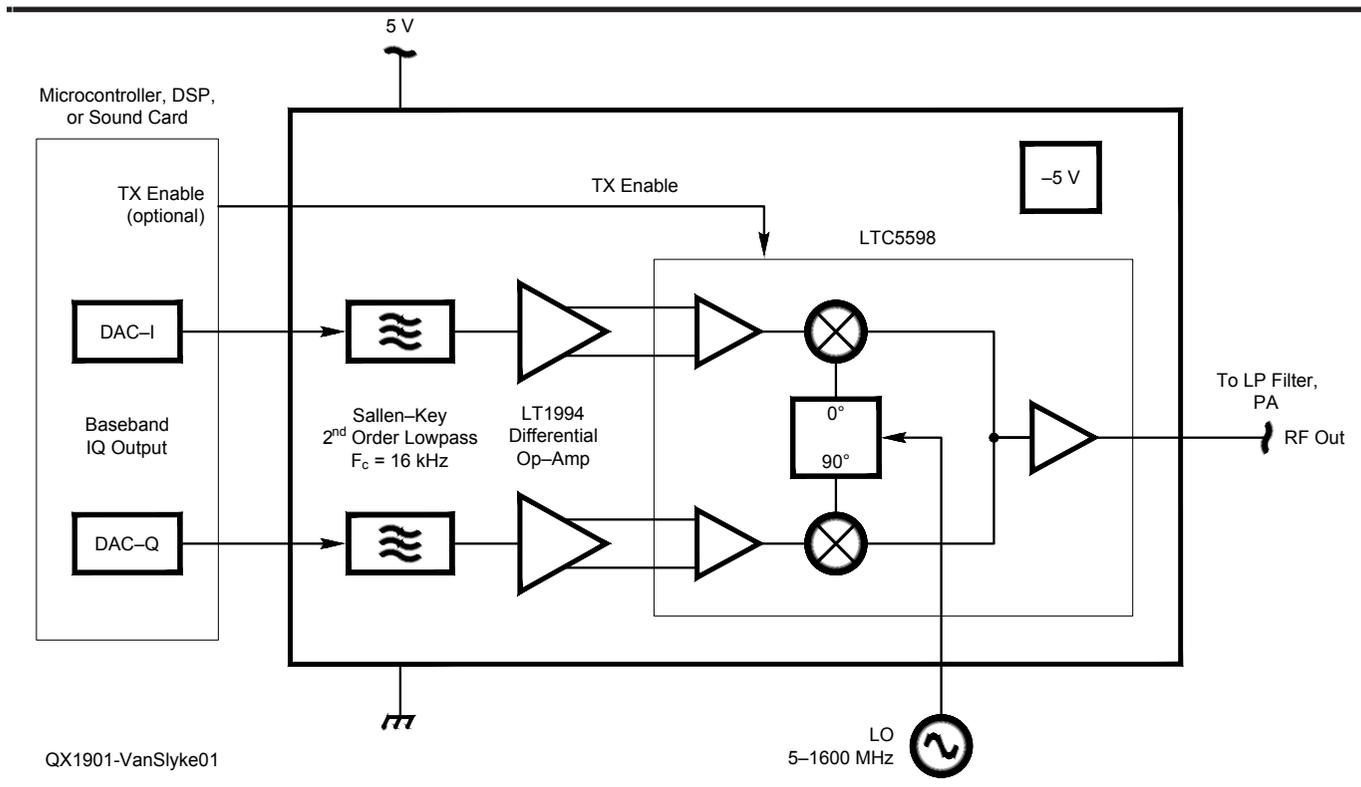
Figure 1 — Block diagram of the LTC5598 modulator board.

sources about IQ or quadrature modulation, are *Understanding the 'Phasing Method' of Single Sideband Demodulation* [2] and *Basics of IQ Signals and IQ modulation & demodulation – A Tutorial* [3]. I also encourage you to read the *SDR Simplified*, and *Hands On SDR* articles in previous *QEX* issues.

Consider this short review of IQ baseband modulator basics. Transmitting a tone signal, for instance 600 Hz, would be designated as the 'I', or in-phase signal. The quadrature signal, designated 'Q', is the 'I' signal phase shifted -90° from the 'I' signal. In digital signal processing a Hilbert Transform is commonly used to phase shift the in-phase signal, and by definition, shifts each frequency components of the 'I' signal by -90° to produce the quadrature signal. Any time/sample delay introduced by the Hilbert transform into the quadrature signal must be matched in the in-phase signal. The in-phase signal can be any arbitrary waveform such as voice. These 'I' and 'Q' signals form the baseband input. The local oscillator (LO) frequency is then set to be the transmit frequency, for instance, 144.270 MHz. At this point, a plot of the RF spectrum output at 144.270 MHz would show one upper-sideband (USB) signal, at 144.270 MHz plus 600 Hz. For the sake of this discussion let's ignore odd-order harmonic products. To create a lower-sideband (LSB) signal at 144.270 MHz minus 600 Hz just invert the 'Q' signal by multiplying by -1. That is, the phase of the 'Q' signal is shifted to be +90° to that of the 'I' signal.

A few key characteristics of the LTC5598 should be summarized. First, the LTC5598 requires the quadrature input signal to be differential, rather than single-ended. The data sheet states[4] "The baseband inputs should be driven differentially; otherwise,
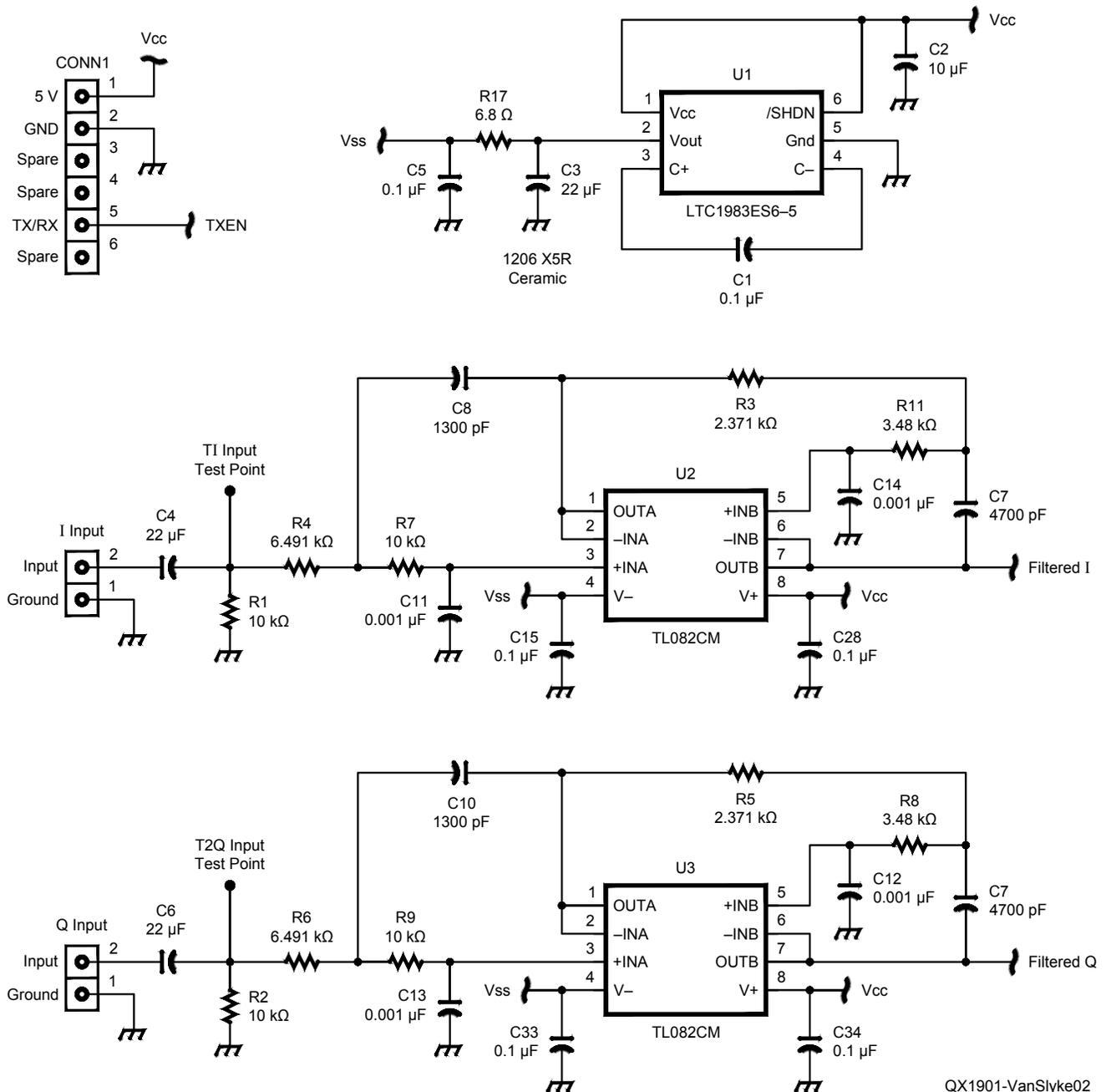
Figure 2 — Schematic of the modulator board showing anti-aliasing filters and the negative 5 V supply.

the even-order distortion products may degrade the overall linearity performance." Single-ended signals have a conductor and a ground, whereas differential signals have two conductors and ground, where the signals on the conductor are 180° apart. This project provides single-ended to differential conversion, so that single-ended DACs or sound card outputs can be used.

Second, odd-order harmonics of the modulated signal are present at the LTC5598 output, and those must be filtered prior to transmitting. Third, the local oscillator must be a sine wave, or images can occur. Images are unwanted signals present on the other side of the LO frequency from the desired signal. "The third-harmonic rejection on the applied LO signal is recommended to be equal or better than the desired image rejection performance since third-harmonic LO content can degrade the image rejection severely. Image rejection is not sensitive to second-harmonic LO content".[5] Lastly, the 'I' and 'Q' inputs of the LTC5598 can be up to 300 MHz in bandwidth. My design does not use nearly that wide a bandwidth, but is limited to 16 kHz, which is sufficient for audio and low data rate operations.

Design

The schematic for the modulator is shown in Figure 2 and Figure 3. I have a DSP evaluation board with dual DACs, which I wanted to use to produce the 'I' and 'Q' inputs to the modulator. The DAC outputs do not have anti-aliasing filters, so anti-aliasing filters are part of the board design. To design the filters, I used the Texas Instrument Filter Designer Tool[6] specifying a passband frequency of 16 kHz, a stop-band frequency of 80 kHz, unity gain in the passband, and selecting the "Linear Phase 0.05 deg" design option. The filter topology is Sallen-Key.

The maximum 'I' and 'Q' input voltage before the output begins to distort is 2 V P-P. The voltage limit is a function of the gain of the differential driver stages. The LTC5598 puts out a little over 0 dBm (1 mW) at this level.

The left and right speaker outputs from a sound card can also be used as the 'I' and 'Q' inputs to the modulator. If speaker outputs are used, the low-pass filter circuits on the modulator board could be omitted or replaced with a gain circuit using a single op-amp. Sound card line-level output voltages are generally too small, but they too could be used by changing the gain of the filters or by replacing with a single op-amp having a specific gain. An example using GNU Octave to generate baseband FM and SSB 'I' and 'Q' signals and outputting the signals to a sound card is shown in the sample Octave code *basebandIQ.m* on the **arrl.org/**

QEXfiles web page.

The op-amp and differential driver design requires a negative voltage supply. The modulator needs a differential signal with a common mode voltage of 0.5 V. The differential driver requires a negative voltage supply of at least 1.1 V below the common mode voltage to function properly.

The negative supply uses an LTC1983-5 100 mA regulated charge pump inverter that provides -5 V. Pay attention to the LTC1983 data sheet regarding layout; under General Layout Considerations: "You will not get advertised performance with careless layout".[7] I built a separate negative power supply using dead-bug construction on top of a grounded copper plane on a separate PCB. My latest PCB layout has a ground plane around the chip and short connections from power supply lines with capacitors to ground. It gives good performance with spurs at ±280 kHz at -66 dB relative to the carrier.

The LTC5598 requires differentially driven 'I' and 'Q' signals. A number of ADCs provide differential outputs, but my specific ADCs do not, and neither do PC sound cards. To create the differential signals, I used a pair of LT1994 fully differential input/output amplifier driver ICs. The IC uses typical plus and minus inputs as does a standard op-amp, but it also includes a common-mode voltage input pin that allows setting the common-mode output voltage independent of the input common-mode voltage. A voltage divider sets the common-mode output voltage to 0.5 V.

I had an issue with setting the gain of the driver using the gain equations from the data sheet. The output of the differential driver should be,

$$V_{out} = 0.5\,V_{in}\,\frac{R_f}{R_{in}}$$

The 0.5 accounts for the gain split between the two differential outputs. With $R_f = 806\ \Omega$ and $R_{in} = 619\ \Omega$, the gain should be $V_{out} = 0.65$, but empirically I found about 0.5. I can't explain this discrepancy, but for the time I'll just document the difference. Linear Technology makes single-ended to differential driver converters, which in retrospect might have been a better choice.

Looking at the 'I' signal path in Figure 3, the output of the anti-aliasing filters is coupled to the driver through capacitor C17, and connected to the drive negative input resistor R14. Resistor R13 connects the node between C17 and R14 to ground, and is used to prevent leakage current from building a up charge on C17.

Potentiometer R19 is the driver positive input resistor and is tied to ground. For equal differential balancing, its value must be that of R13 in parallel with the source (anti-aliasing

filter) resistance, and in series with R14. The source resistance of the anti-aliasing filter is in the hundreds of kΩ, so the value of R19 is very close to that of R13 in series with R14. Imbalance between the resistances on the positive and negative inputs will result in LO leakage. Instead of using a potentiometer, I used a series combination of R13 and R14 at the positive input, with 1% resistors, that results in LO leakage about 40 dB below the primary output signal.

By setting the 'I' and 'Q' inputs to 0 V (or just disconnecting them), and setting the LO to a frequency within an anticipated operating range, the potentiometers can be adjusted to minimize the LO leakage. This method results in LO leakage at or better than 55 dB below the primary output signal. A ball park approximation can be done by measuring the dc voltage on each differential output and adjusting the potentiometers so that the voltages match as closely as possible.

For the circuitry that supports the LTC5598, I used the schematic for the LTC5598 demo board as a reference, part number DC1455A.[8] According to the documentation, the demo board design targets frequencies from 80 MHz to 1300 MHz. I found that the design works at 50 MHz as well. The negative LO input "LOM" is tied to ground through a 50 Ω resistor. The positive LO input requires between 0 and -10 dBm input power. LO levels below -10 dBm will result in poor image rejection. Document DC1455A, section: "Application Note – LO Input Interface" Table 2 lists LO input matching component values *vs*. LO input frequency range. This table allows the designer to optimize the LO circuit matching for a specific range of frequencies. The single-ended RF output is internally matched to 50 Ω over the entire operating range. Resistors R32 and R33 are used to prevent voltage supply ringing.

Construction

The assembled board is shown in Figure 4. The PCB is a double-sided 2.2" by 3.2" board with mostly surface-mount components. I used *DesignSpark* for the schematic and PCB Gerber file generation. The files for the *DesignSpark* project, as well as the Gerbers can be found on the **arrl.org/ QEXfiles** web page. I used PCP GOGO[9] to create the PCB in FR-4 board material.

Aside from the ICs, the parts are fairly common and can be ordered from Digikey or Mouser. The resistors used have a 1% tolerance, and the capacitors, except for the 22 µF on the negative power supply, are ceramic NPO types. The Linear Technology parts can be ordered directly from Analog Devices. Linear Technology has a two component minimum when purchasing, but
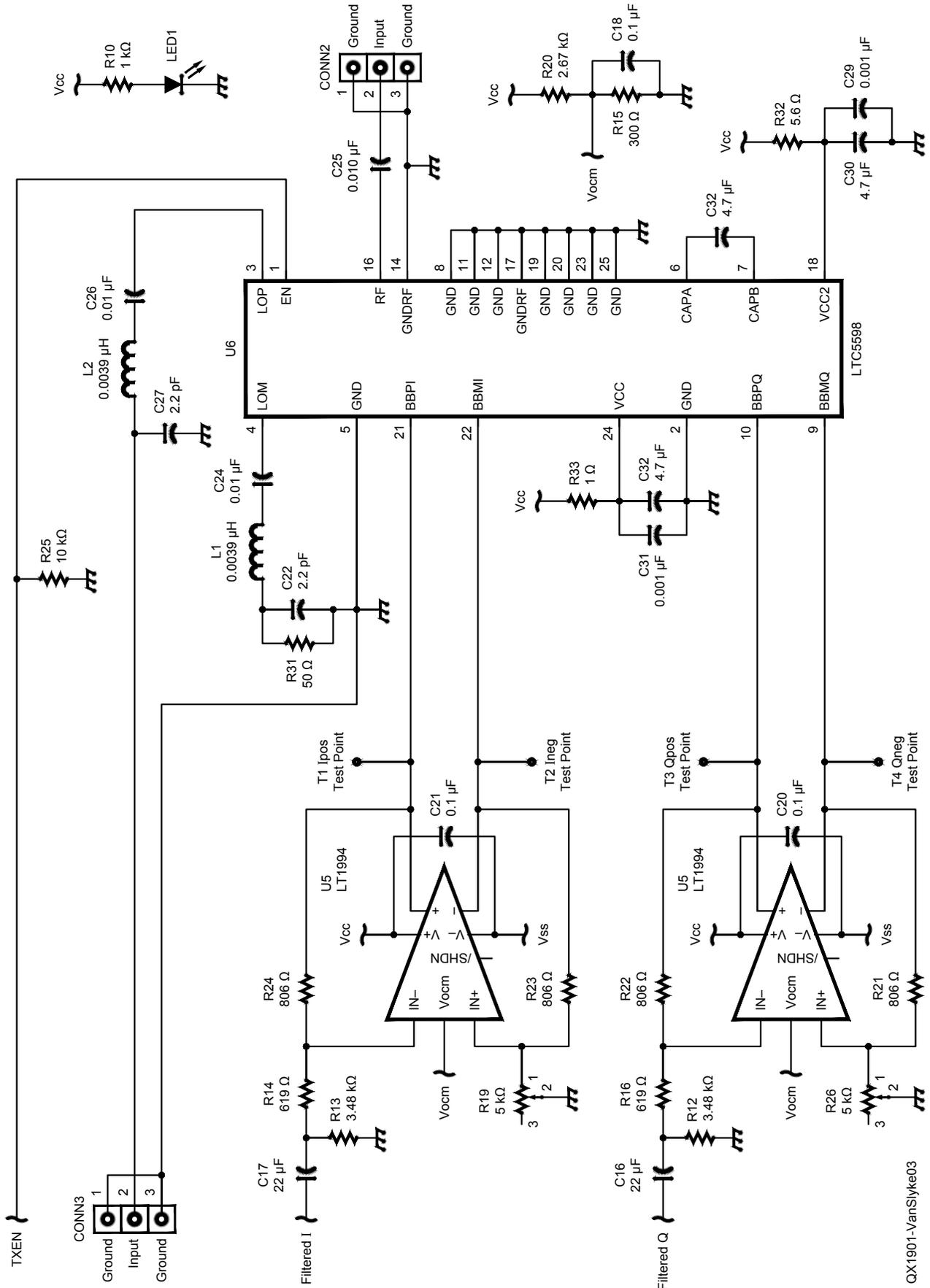
Figure 3 — Schematic of the modulator board showing single-ended to differential drivers.

their cost is much less per piece than buying from Mouser or Digikey. At the time of this writing, the modulator, the charge pump inverter and the driver, when purchased in quantities of two, costs about $24 from Linear Technology (excluding postage). Samples are an option as well, although I have found delivery time takes longer.

Performance and Results

The board current consumption when transmitting is 220 mA at 5 V. My goal when I started this project was to get the modulator working then optimize power consumption later. The LTC5598 alone consumes about 170 mA while transmitting. A similar part, the LTC5599, draws only 28 mA, but it is not a drop-in replacement to the LTC5598.

My local oscillator signal is the output from a Silicon Labs Si5338 into a low-pass filter. The output from the filter is a single sine wave at -10 dBm with third-harmonic attenuated more than 50 dB. The 'I' and 'Q' inputs are generated by software running on a TMS320F28377S configured to use two of its 12-bit DACs to create the 'I' and 'Q' signals to the modulator board. The power output of the modulator in the present configuration is about 0 dBm CW, and is fed into a dummy load with a Rigol DSA815 Spectrum Analyzer tapped into the output via a 20 dB attenuator.

The first test creates an upper sideband signal using an LO of 144.270 MHz and a tone at 2000 Hz. The spectrum analyzer output in Figure 5 shows the 144.272 MHz tone at slightly less than 0 dBm output power. The local oscillator leakage is seen to be down approximately -60 dB, and the image rejection at 144.278 MHz is at approximately -50 dB. Image rejection can be further reduced if desired by adjusting the gain and/or phase of the 'I' channel relative to the 'Q' channel.

Figure 6 shows the same signal but the span is increased 1 MHz. The spurs from the LT1994 are seen at ±288 kHz from the LO, making their way into the LTC5598. If the output of this modulator were to be used to drive an amplifier, then attention must be paid to these spurs especially if the operating frequency causes the spurs to be out of band. Bob Allison, WB1GCM, points out[10] how out of band spurs, or harmonics, must be minimized so that they do not exceed 25 μW(-16 dBm) output. That suggests the output of the modulator could be increased to (-16 dBm) – (-65 dB) = 49 dBm (79 W) before needing further filtering of the out-of-band spurs.

Figure 7 shows a full-span plot. Odd-order harmonics, a product of mixing, can be seen at 144.27 × 3, ×5, ×7, and ×9. Odd-order harmonics are to be expected, and can be easily filtered prior to amplification.
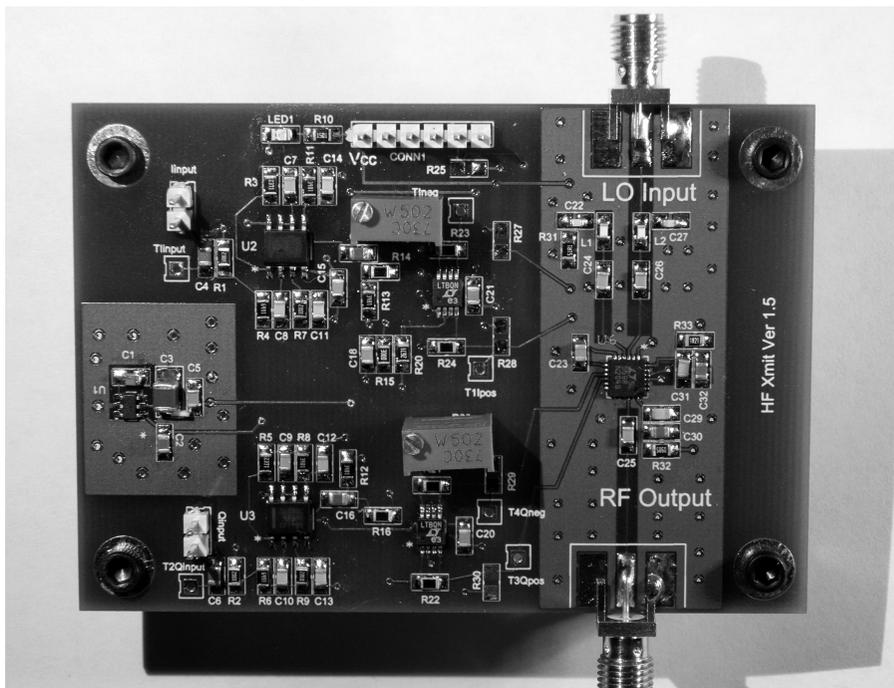
Figure 4 — The assembled LTC5598 modulator board.
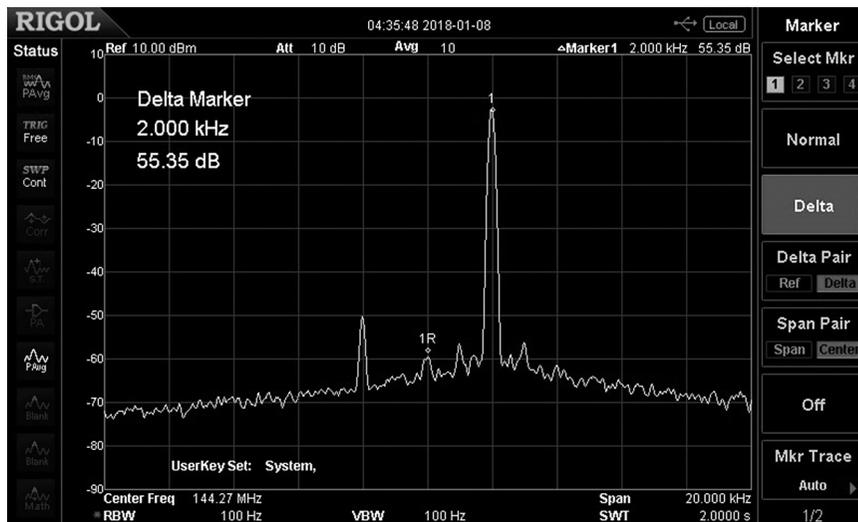
Figure 5 — Spectrum analyzer plot of USB 2000 Hz tone at 144.270 MHz, span is 20 kHz.
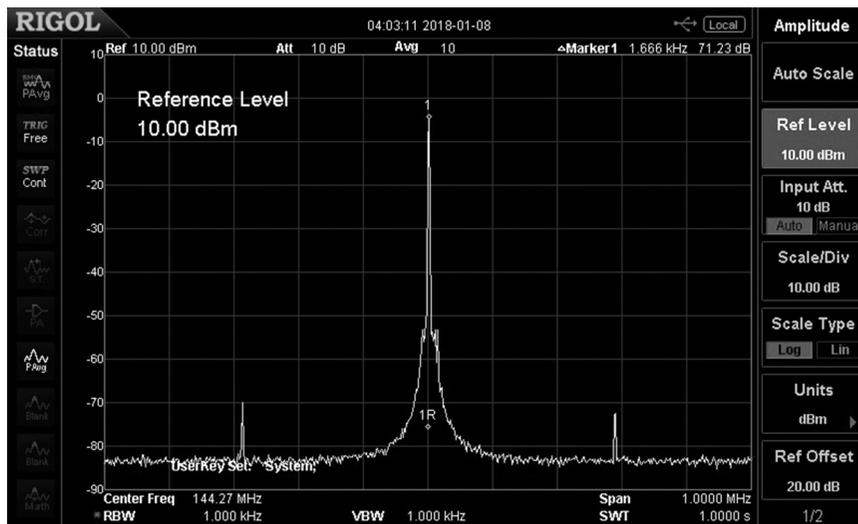
Figure 6 — Spectrum analyzer plot of USB 2000 Hz tone at 144.270 MHz, span is 1 MHz.

Switching to lower sideband is as simple as changing the polarity of the Q signal, that is, multiplying by -1, prior to DAC output. Figure 8 shows the lower sideband output 2 kHz below the suppressed carrier frequency of 144.27 MHz. Figure 9 shows a lower sideband signal with the tone below the LO set frequency of 440 MHz. Again, results are very similar to when the LO is set to 144.270 MHz. Results are similar for 50 MHz, with the output slightly lower than 0 dBm even though the LO match isn't optimized for that frequency.

I used an older Wavetek 3520 to generate an output signal at 1290 MHz, albeit with more phase noise than with the Si5338. Figure 10 shows an upper sideband plot at 1290 MHz, which shows that the device should be useable up to the 23 cm band.

Figure 11 shows the output of a frequency modulated (FM) tone. FM modulation with the LTC5598 is relatively straightforward. In the DSP, a 10 kHz cosine wave carrier is modulated with a tone — a voice signal will work just as well. The modulated 10 kHz signal is converted into a composite signal with 'I' and 'Q' outputs, these 'I' and 'Q' signals are sent to separate DAC channels. The DAC outputs go to the modulator board. In this case I applied a 1.9 kHz signal with a modulation index of 5.54, resulting in the expected suppressed carrier. This same tone can be picked up by my two-meter handheld radio with no apparent distortion in the audio.

Conclusion

The LTC5598 is an inexpensive and easy way to modulate baseband signals using SSB, FM, and other modulation methods. With the proper local oscillator, the chip will easily modulate baseband signals from the 6 m band up to 23 cm with an output power up to 1 mW. With the addition of a Raspberry Pi, USB sound card, and filter/amplifier, it could form the core of a beacon or APRS transmitter. It could be used as the modulator for a multi-mode transceiver for operation on the lesser-used 33 cm and 23 cm bands.

Braddon (Brad) Van Slyke, ACØZJ, received his Amateur Extra class license in 2011 and has been obsessed with building and testing anything related to radio ever since. He lives in Arvada, Colorado with his wife and four boys, and is a Digital Signal Processing Engineer employed at LGS Innovations, Inc. He holds undergraduate and graduate degrees in Electrical Engineering from the University of Wyoming and Texas A&M respectively. Brad had been writing software for medical devices including pulse oximeters and surgical generators for over 20 years, then recently switched to writing software for wireless applications.
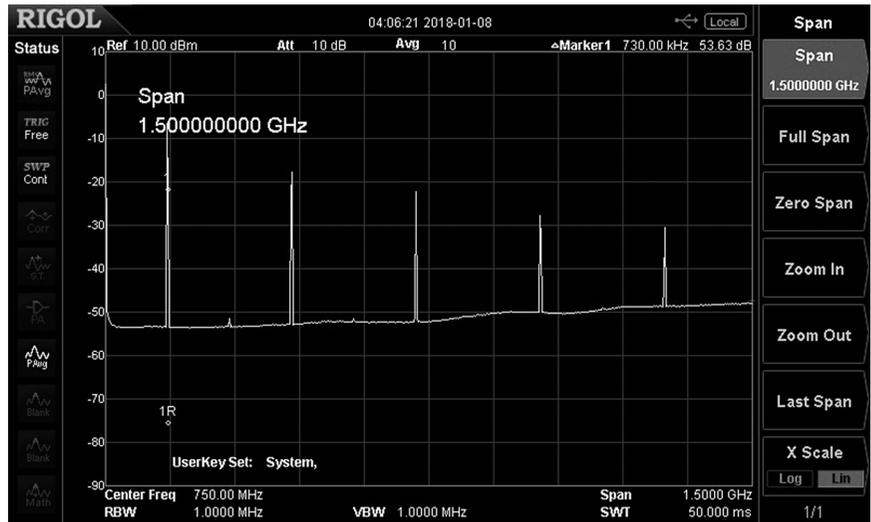
Figure 7 — Spectrum analyzer plot of USB 2000 Hz tone at 144.270 MHz, full span of 1.5 GHz.
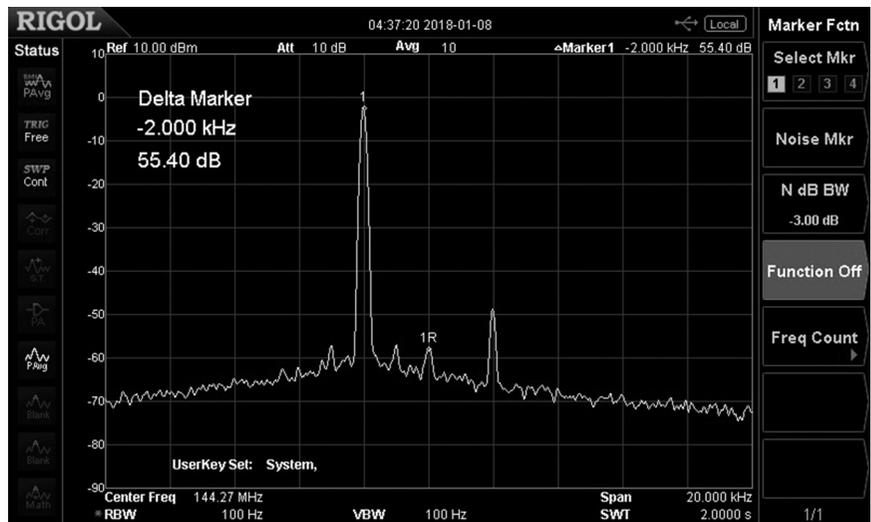
Figure 8 — Spectrum analyzer plot of LSB 2000 Hz tone at 144.270 MHz, span is 20 kHz.
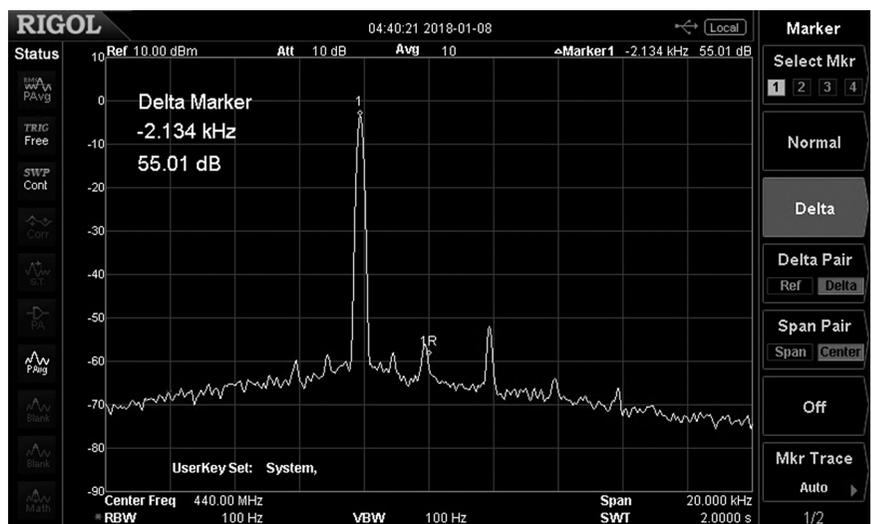
Figure 9 — Spectrum analyzer plot of LSB 2000 Hz tone at 440 MHz, span is 20 kHz

Notes

1Linear Technology "LTC5598 5MHz to 1600MHz High Linearity Direct Quadrature Modulator", **cds.linear.com/docs/en/datasheet/5598f.pdf**.
2R. Lyons, "Understanding the 'Phasing Method' of Single Sideband Demodulation", **https://www.dsprelated.com/showarticle/176.php**.
3A. Wolke, W2AEW, "Basics of IQ Signals and IQ modulation & demodulation – A tutorial", **https://www.youtube.com/watch?v=h_7d-m1ehoY**.
4Note 1 p. 9.
5Note 1 p. 12.
6Texas Instruments Filter Design Tool, **www.ti.com/design-tools/signal-chain-design/webench-filters.html**.
7Linear Technology, "LTC1983 – 100 mA Regulated Charge-Pump Inverters in ThinSOT," p. 10, **cds.linear.com/docs/en/datasheet/1983fc.pdf**.
8Linear Technology, "Quick Start Guide For Demonstration Circuit 1455A 5MHz To 1600MHz High Linearity Direct Quadrature Modulator, " p. 7, **cds.linear.com/docs/en/demo-board-manual/dc1455A.pdf**.
9PCB GOGO, **www.pcbgogo.com**.
10Bob Allison, WB1GCM, *Technical Correspondence*, "ARRL Laboratory Handheld Transceiver Testing", *QST*, Nov. 2015, pp 74-76.
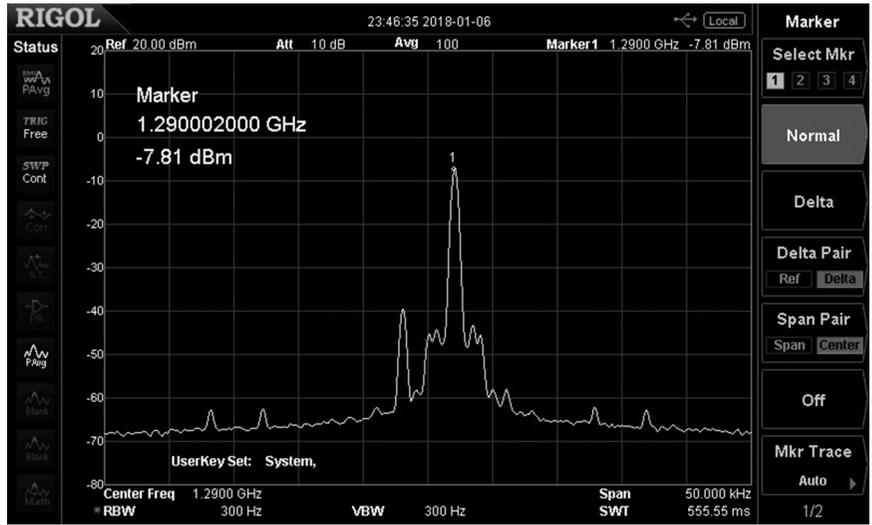
Figure 10 — Spectrum analyzer plot of USB 2000 Hz tone at 1290 MHz using a Wavetek 3520 for local oscillator, span is 50 kHz.
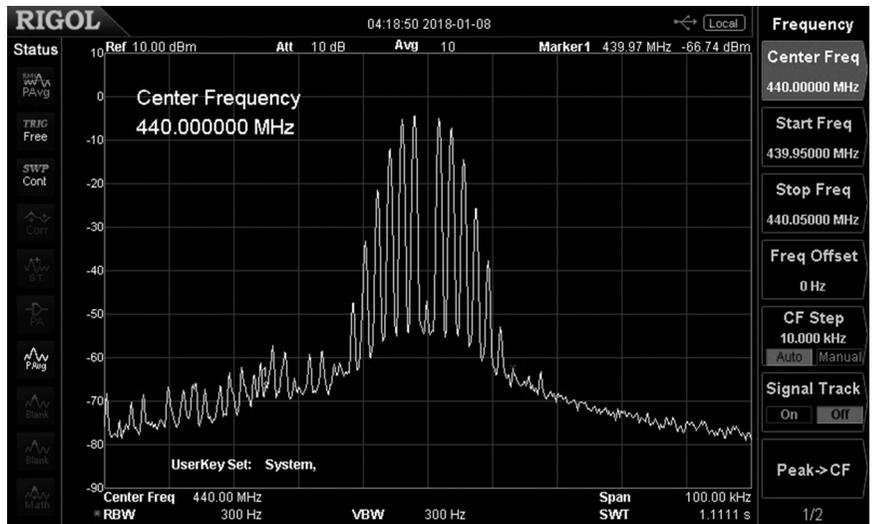
Figure 11 — Spectrum analyzer plot of FM 1.9 kHz tone with a modulation index of 5.4 at 440 MHz.