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The Polar Explorer

You may never look at your "linear amplifer" the same way again.

If you're like me, you have a love/hate relationship with your linear amplifier. While this piece of "big iron" has cranked out the legal limit for almost 20 years, it also presents some significant challenges. It seems to take forever to warm up — especially when sitting down to work an all-time new one! Because of the size and weight, it occupies its own piece of reinforced furniture in the shack. I have to keep it within easy reach because it doesn't tune automatically. New tubes are not available, so the dwindling supply of matched pairs on the "new old stock" (NOS) market is driving up the price, even though they aren't guaranteed to last. Rather than simply spending several thousand dollars to replace this venerable sidekick of my 100 W transceiver, I decided to explore the feasibility of using a technique called *polar modulation* to reduce the size, weight and cost of a legal-limit ham transmitter, hence the moniker, "Polar Explorer."

The Cost of RF Power

The high cost of high power is rooted in the evolution of ham radio technology and equipment. Figure 1A shows the traditional modulation process of a high-power output stage operating at the carrier frequency with the modulation process at the high power output stage. Figure 1B shows the single sideband modulation process moved away from that high-power output stage back to an intermediate frequency (IF) operating at a very low power level. SSB signals generated at less than one watt at the IF are heterodyned to the carrier frequency and passed through three or more stages of amplification to reach levels useful for reliable communication over long distances with average antennas. Unlike CW and AM, SSB and other quadrature amplitude modulated signals must undergo a relatively inefficient *linear* amplification to increase signal levels without distortion. To balance cost and performance, slightly nonlinear Class AB amplifiers[1] are often used, requiring low-pass filters between stages to remove harmonic distortion products, and adding cost to the transmitter without adding value to the signal.

Since the VFO and IF circuitry — including the expensive electromechanical sideband filter — can be shared between the transmit and receive, manufacturers increasingly combined the formerly separate receiver and transmitter into a single "transceiver" to keep equipment prices within reach of a the ham population. But, this marriage of convenience came at a price. Transmitter improvements have been largely outpaced by receiver improvements, as advances in silicon technology integration spawned digital integrated circuits that supplanted analog circuits in a number of performance-critical roles.

A "pay as you go" power upgrade path was provided in what came to be known as a "linear amplifier" to augment the comparatively low output power of an affordable SSB transceiver. Because more efficient nonlinear amplifiers cannot be used to amplify SSB signals, about 40% more dc power needs to be provided to the "linear" amplifier to produce the same output power as a Class-C amplifier of a CW or AM transmitter.

As the convenience of no-tune solid-state amplifier technology displaced vacuum tube circuits, the single high-Q band-switched tank circuit gave way to a switched bank of five or six low-pass filters to control spurious emissions. Each filter section requires several custom-wound inductors and ceramic capacitors that can sustain high RF currents, once again adding cost without adding value to the signal.

In today's era of concern over energy efficiency, it's easy to lose track of the fact that a significant fraction of the total cost of an RF power amplifier is driven by the need to generate nearly twice as much dc power as the RF power that will be sent up the transmission line, and the need to dissipate the difference. This inefficiency also requires RF transistors to be made with exotic insulating materials that can survive high energy densities, plus high-conductivity heat sinks and fans to remove the heat produced by the dissipated power.

Efficiency and Amplifier Classes

Amplifiers traditionally employed in amateur RF amplifiers - classes A, AB, B and C - operate the active device in its linear region for some part of the RF cycle. This means that there is voltage across the device while there is current flowing through the device, resulting in power dissipation in the device. By contrast, amplifier in the switch-mode classes D, E, F and their variants [superscript 9-11" switch the active device between cutoff - zero current through the device - and saturation - zero voltage across the device. Switching amplifiers minimize power dissipated in the active device by minimizing the overlap of the periods of nonzero current and nonzero voltage, resulting in higher efficiency. The output networks of the switching amplifier classes are designed to optimize this behavior.

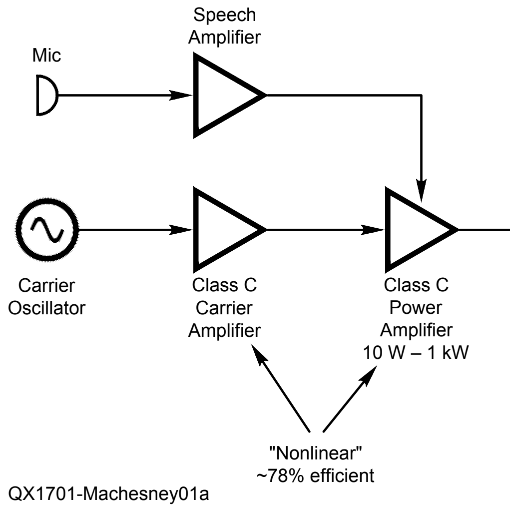

Figure 1A — AM transmission was accomplished by directly modulating a relatively efficient, high-power Class C output stage.

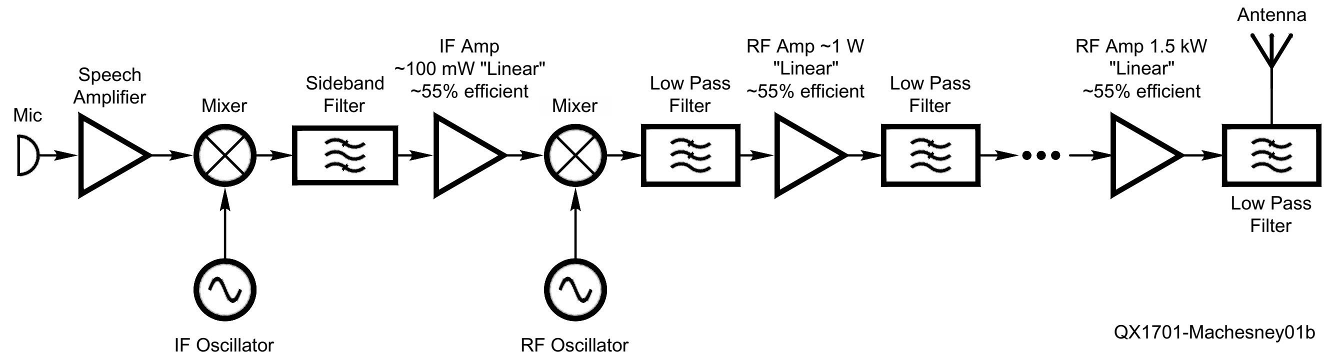

Figure 1B — The filter approach to SSB transmission generates a low-power waveform at an IF and heterodynes the waveform to the transmitting frequency, achieving high power levels through a series of relatively inefficent linear amplifiers.

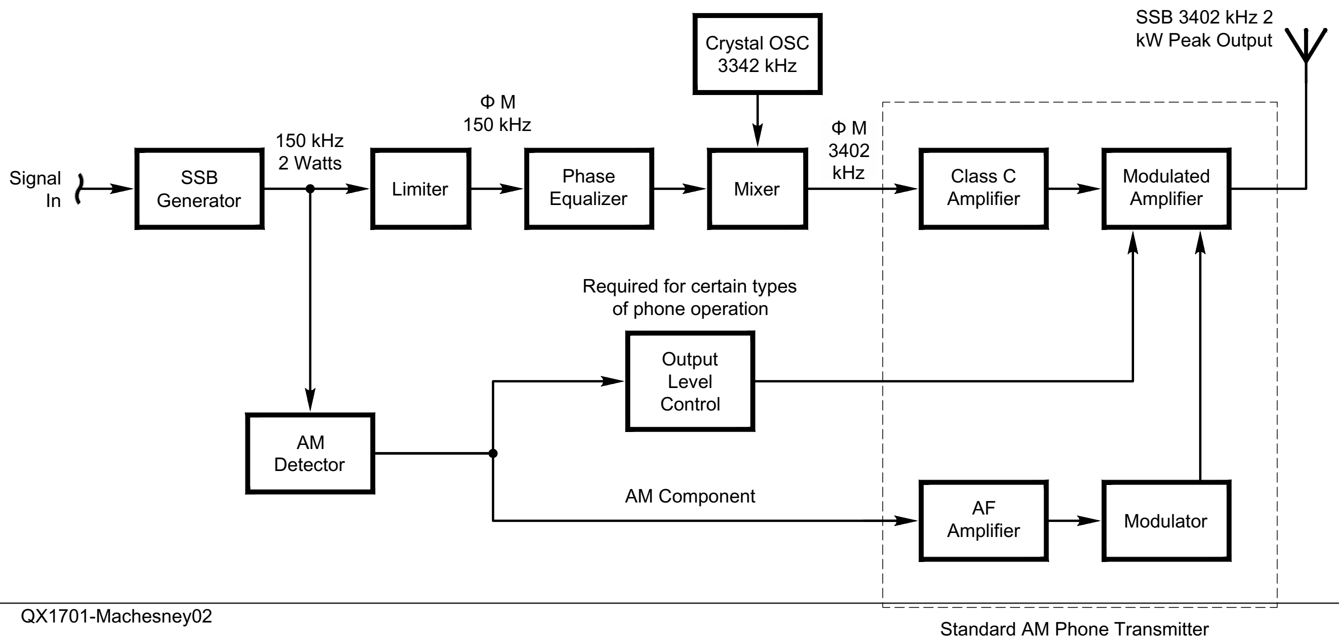

Figure 2 — A block diagram of the Kahn EER system to generate SSB.

A High Efficiency Amplifier Approach

The weaknesses in the arguments favoring SSB were not lost on RF practitioners of the day. In 1952, Leonard Kahn published a technical paper explaining how to make SSB transmissions by envelope elimination and restoration.[2] As shown in Figure 2, Kahn separated the amplitude and phase components of a low-level SSB signal, then amplified and applied the components to a more-efficient conventional Class-C AM transmitter, reproducing the original SSB signal at higher power. David Cripe, NMØS, used this approach in his award winning 5 W to 50 W 40-meter SSB amplifier costing just $32.[3] His secret was to use short lengths of copper wire as a heat sinks for his amplifier. Because the high efficiency amplifier dissipated very little power, very little heat needed to be removed.

Advances in semiconductor technology introduce opportunities to modernize Kahn's approach. As shown in Figure 3, a digital signal processor (DSP) chip can generate the envelope signal, which is then amplified with a high-efficiency circuit similar to the audio amplifier in modern entertainment equipment. Likewise, a DSP can generate the phase modulation signal at a baseband frequency, followed by a quadrature digital upconverter (QDUC) that numerically heterodynes it to the carrier frequency. By generating the envelope- and phase-modulation signals numerically, rather than separating them from an existing SSB signal, it is reasonable to anticipate improvements in output signal quality.

In this hybrid approach to Kahn's architecture, the number of inter-stage low pass filters can be dramatically reduced to cut cost. The substantially lower power dissipation resulting from use of a high efficiency switch-mode power amplifier operated in Class D, E or F allows the use of inexpensive transistors in plastic packages intended for other high-volume markets. The same is true for the modulator and power supply, cutting the size, weight and cost of heat sinks and fans for thermal management. It may soon be possible for transmitter

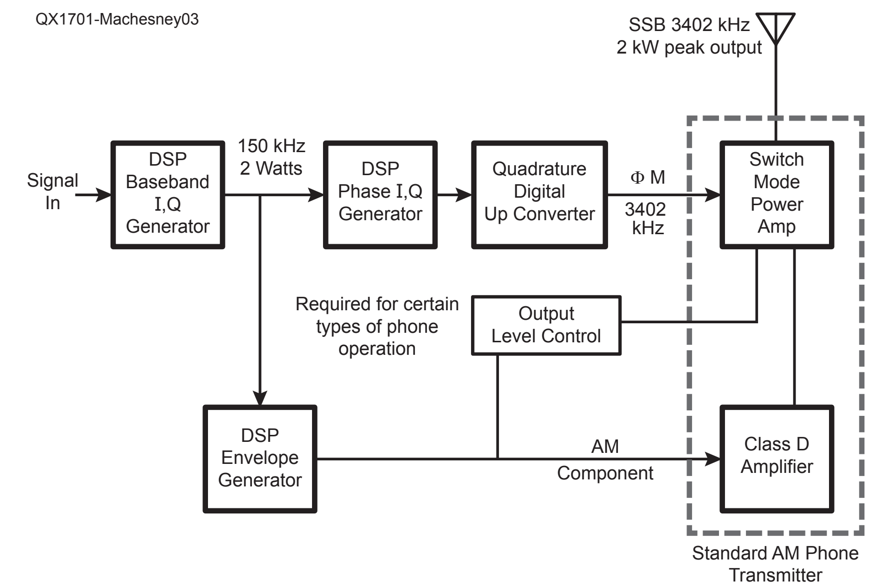

Figure 3 — Direct generation of envelope and phase signals using modern silicon devices.

Quadrature Digital Upconverter

As shown in the functional block diagram of the Analog Devices AD9957 in Figure A, a QDUC converts baseband digital I and Q signals to an analog signal at a carrier output frequency.

Normalizing the I and Q inputs to the envelope amplitude results in an analog output from the QDUC, which has the constant peak amplitude required by the phase-modulation input of Polar Explorer Class E amplifier. The digital outputs of the numerically controlled oscillators (NCO) represent the sine and cosine values of a carrier at the programmed frequency. The QDUC combines the results from a pair of high-speed digital multipliers, which heterodynes interpolated up-samples of the input, then converts the result to analog. By choosing whether the combining of I and Q is additive or subtractive, the output signal is upper sideband (USB) or lower sideband (LSB).

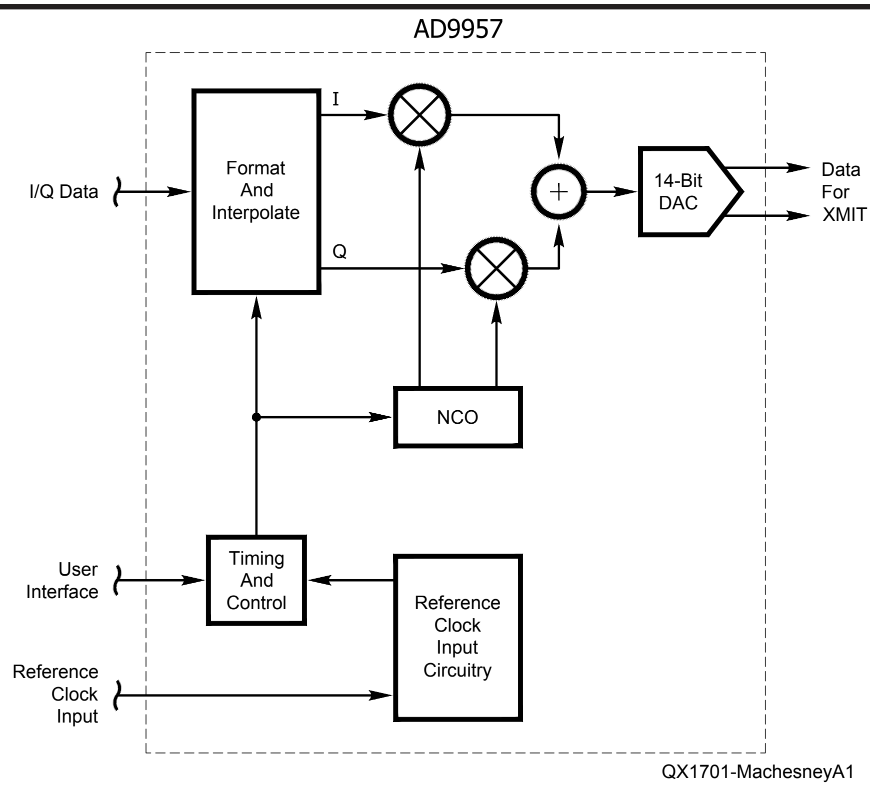

Figure A — Functional block diagram of the Analog Devices AD9957.

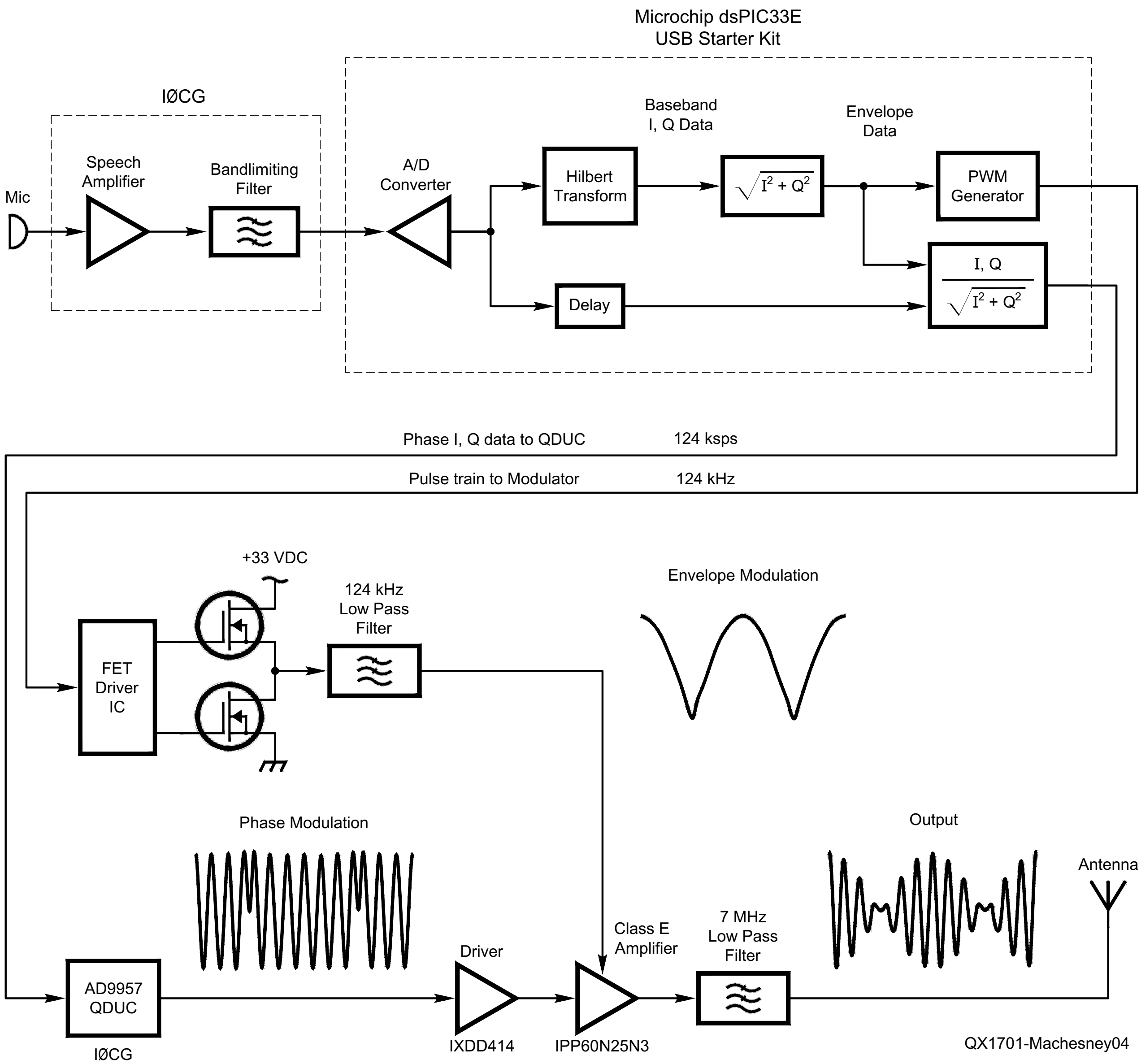

Figure 4 — The polar explorer block diagram.

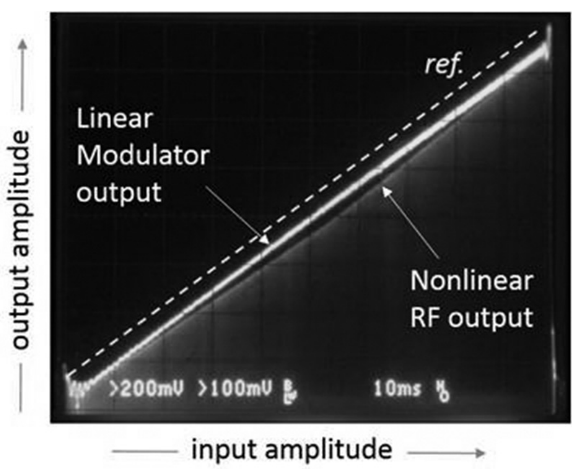

Figure 5A — The uncompensated power amplifier gain sags by about 5% in the middle of its range.

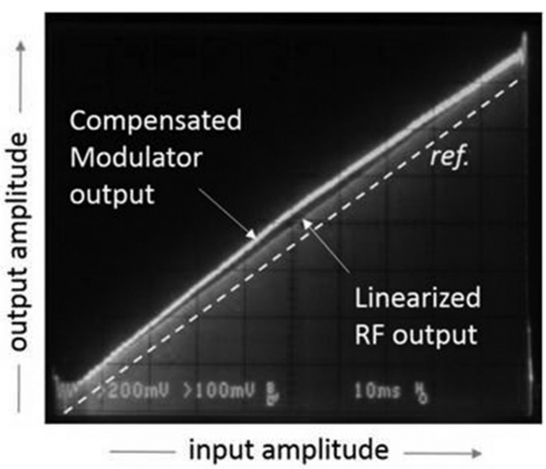

Figure 5B — Linearized power amplifier RF output.

technology improvements to catch up with receivers. Together with the recent influx of highly capable "software defined radios" (SDR), the flexibility of separate units will be restored. See *Sidebar–1: Efficiency and Amplifier Classes*.

Polar Modulation Basics

First dubbed "quadruplex telegraph," what we now call polar modulation was invented by Thomas Edison in 1874 as a means of allowing the simultaneous transmission of four telegraph signals on a single wire. Single sideband is a special case of quadrature modulation, whereby the quadrature (Q) component of the signal is derived from the in-phase (I) component by the mathematical operation of a Hilbert transform.[4] Applying the trigonometry of a right triangle, the amplitude of the signal is the square root of the sum of the squares of the I and Q components of the SSB signal, while the phase angle is derived from their ratio. These and other calculations take advantage of the unique architecture of a DSP to develop the baseband envelope and phase modulating signals at very low cost.

As seen in Figure 3, the phase modulation to the switch-mode power amplifier must operate at the RF carrier frequency. The baseband phase modulation is heterodyned to this frequency by a quadrature digital up-converter (QDUC). Whereas the QDUC would produce SSB from the baseband I and Q signals, polar modulation requires a phase modulation signal of constant amplitude. This is accomplished by dividing each I and Q value by the corresponding envelope value before sending to the QDUC.

The Hardware

It was time to bring Kahn's approach to the 21st century of Amateur Radio. I invited Tony Brock-Fisher, K1KP, to partner with me on the development of Polar Explorer, a platform for experimentation with polar modulation and switching amplifiers. Figure 4 shows its 'building block' circuit boards, some of which we designed and others that we obtained elsewhere. Giuliano Carmignani, IØCG, kindly supplied us with bare circuit boards from his software defined transmitter project.[5] One of his boards amplifies and band-pass filters the incoming audio, which is then sampled at 15.5 kilo-samples per second (ksps)by the 12-bit A/D converter on a Microchip dsPIC33E USB Starter kit.

The dsPIC applies a Hilbert transform to the sampled audio, producing the baseband analytic I and Q signal pair, then computes the envelope and the I and Q pairs for the phase modulation signals. Interpolation filters in the dsPIC up-sample the phase and envelope signals to 124 ksps. The phase modulation I and Q data is sent to another IØCG board, which uses an Analog Devices AD9957 QDUC chip to numerically heterodyne the phase modulation signal to the RF carrier frequency and convert it to analog with an on-chip D/A converter. See *Sidebar–2 Quadrature Digital Upconverter*. The output of the AD9957 is amplified and applied to the gate input of the Class E switching amplifier.

The dsPIC also converts the envelope signal to a 124 kHz pulse width modulated (PWM) wave train with 8 ns resolution. This digital signal is sent to a Class D switching modulator and low-pass filter that removes the 124 kHz component and passes baseband audio. The 33 V (peak) modulated drain voltage for the Class E switching amplifier produces peak RF output of about 55 W.

The Numbers

As described earlier, the audio information sampled at 15.5 ksps is used by the DSP to calculate the phase modulation I and Q data. Those I and Q pairs are up-sampled by a factor of 8 to produce interpolated phase modulation data for the AD9957 QDUC at 124 ksps. The programmable QDUC hardware up-samples the phase modulation data a further factor of 1008, to 125 MHz. Why all this up-sampling? Because the final rate, in this case 125 MHz, determines the spacing between the spurious replicas (aliases) of the input data that result from the sampling process. This high sample rate pushes the spurs outside the pass bands of the low-pass filters used between the amplifier output and the antenna.

The goals of the project include generating legal-limit output power as cleanly, efficiently and cheaply as possible. Modern receivers combine advanced digital and analog design to achieve very high performance with regards to receiver intermodulation distortion (IMD). Rob Sherwood, NCØB, has documented extensive measurements of this parameter across a large number of commercial transceivers.[6] He estimates that a receiver operating in a band crowded with strong signals needs to have at least 80 dB of close-in (2 kHz) IMD dynamic range for CW, but only 70 dB for SSB.

Sherwood observes that contemporary transceivers have so much IMD on their *transmitted* signals that the ultimate performance of our equipment is limited by our transmitters, not our receivers.

While receivers have made giant strides in performance over the past three decades, transmitters, in particular the power output stages, have not fundamentally changed or improved since the 1970s.

Prototype Results

The goal of the first Polar Explorer prototype was to produce 100 W with low transmitted IMD on any HF Amateur Radio frequency up to 30 MHz. While it served as an excellent platform for experimentation, we quickly discovered some design shortcomings. Contrary to the performance of its SPICE simulation model, the IXDD614 driver chip for the PA MOSFET did not work above 14 MHz. Once we had Polar Explorer working on 40 meter SSB, we made a few contacts and received welcome compliments on how good it sounded! We tried many different approaches to the software calculations and the hardware implementation, and learned a tremendous amount about changes for future revisions.

We measured output power directly with a Telepost LP-100A watt meter. PA input power was calculated by multiplying the modulator output voltage by the current measured through a 0.5 Ω resistor inserted between the modulator and the drain of the Class E PA MOSFET. Dividing the output power by the input power, we routinely observed efficiencies above 90%. The highest efficiency we observed was a staggering 97%! The temperature of the output device and its heat sink barely rose above room ambient temperature. Compare that to what you would expect to feel if you touched a 40 W incandescent light bulb, which dissipates about the same amount of heat you would expect from a Class AB amplifier producing 55 W.

The situation was not so rosy for the quality of the transmitted signal. Using SpectrumLab software[7] and a sound card generator, the ARRL standard 700 Hz and 1900 Hz tones[8] were injected at the Polar Explorer audio input. Intermodulation distortion products were measured by tuning an Icom 756Pro2, with 3000 Hz DSP filter and with AGC disabled, to an attenuated sample of the RF output. Receiver audio was routed back to the sound card input and analyzed with SpectrumLab.

Initially, the third-order IMD product was just 24 dB down from peak output, considerably worse than nearly all contemporary ham transceivers. After some research into the literature on the subject, we analyzed the system amplitude and phase distortions in search of improvement.

Figure 5A shows that the uncompensated PA gain sags by about 5% in the middle of its range. In Figure 5B the compensated PA has a linearized output. Figure 6 shows that the uncompensated PA phase varies by 56 degrees across the output range. We incorporated an Analog Devices AD8302 gain and phase detector chip into the circuitry to provide a means of correcting these errors. This chip compares the input and output of the PA to provide error measurements to the DSP. On command, the DSP programs the RF output to span across 60 discrete amplifier levels and records the exact gain and phase

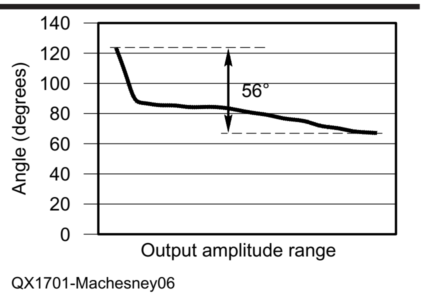

Figure 6 — The uncompensated power amplifier input vs. output phase varies by 56 degrees across the output range.

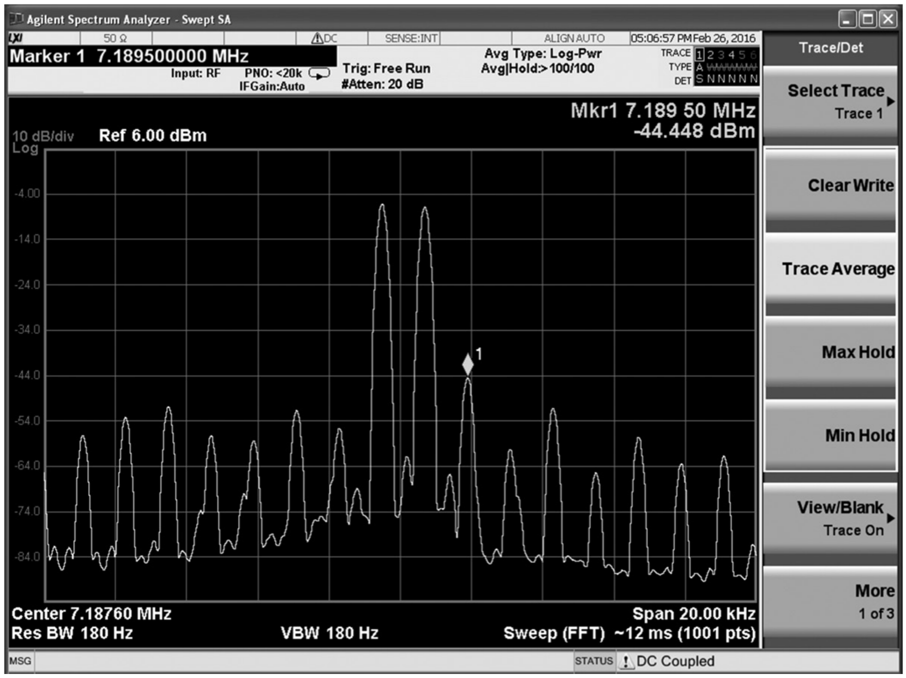

Figure 7 — Polar Explorer transmitted spectrum.

response of the PA. These recorded values are then used to pre-distort the gain and phase of the signals being applied to the PA. The phase correction is applied to the data sent to the AD9957, and the gain correction is applied to the signal sent to the pulse-width modulator.

The effects of these corrections on transmitted IMD were very interesting. Applying the gain correction by itself made a barely perceptible improvement, while applying the phase correction by itself reduced third-order IMD by over 12 dB. Applying the gain and phase corrections together made a significant additional improvement of 3 dB. Further refinements in the correction data of the prototype shown in Figure 8 led to the competitive final value of 39 dB down, relative to peak output, shown in Figure 7.

Further Work

We plan to continue our explorations of polar modulation and we encourage others to take up the quest. Our next revision aims to achieve the original goals of producing 100 W at up to 30 MHz, including the ability to band switch the PA output filter. Our ultimate goal is to produce 1500 W output with a single RF output stage and a single set of RF low-pass filters, thus realizing our dream of a cleaner, cheaper, smaller, lighter and quieter legal-limit Amateur Radio transmitter.

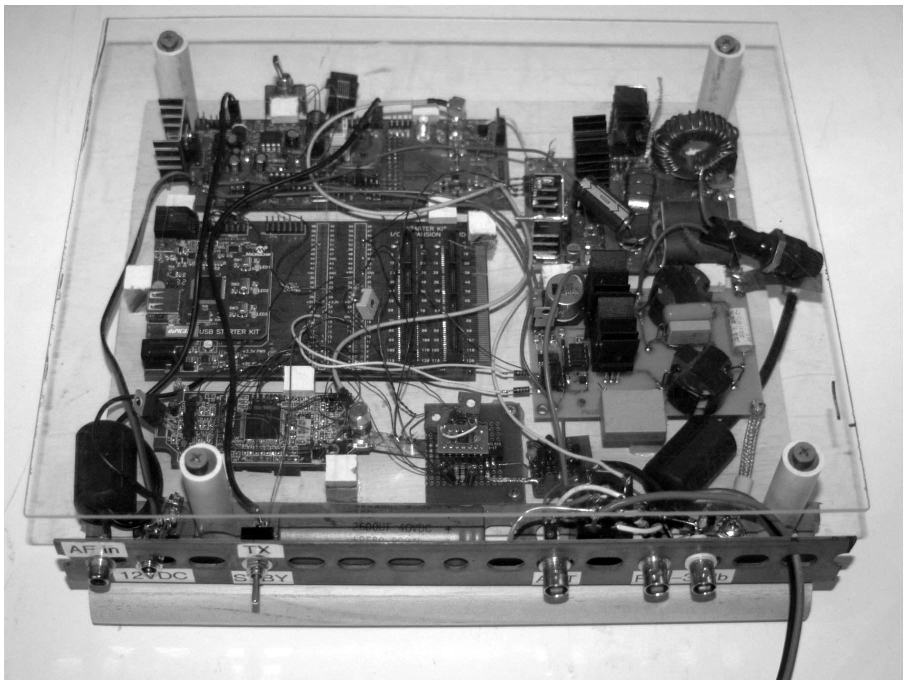

Figure 8 — Polar Explorer prototype hardware.

Brian Machesney, K1LI, was first licensed at the age of 10. His interest in ham radio was kindled by reading his father's (Ward, K1DXB, SK) back issues of QST throughout the 1950s and 1960s. After graduating from Rensselaer Polytechnic Institute with a BSEE in 1979, he spent more than three decades in both the R&D and business aspects of the semiconductor industry, where he was awarded 14 US patents. Brian has recently turned his radio fascination from DXing and contesting to technical projects that he hopes will address important challenges faced by many hams around the world.

Tony Brock-Fisher, K1KP, was originally licensed in 1967 as WA1IKP and upgraded to Amateur Extra class license in 1976. He has a BS in Physics and an MS in Ocean Engineering. Tony retired from Philips Electronics in 2013 following a 35 year career in medical ultrasound design. He currently serves as president of Yankee Clipper Contest Club. Tony enjoys contesting, DX, and station construction projects, as well as writing for QST!

Notes

[1]Amplifier classes are discussed in the "Types of Power Amplifiers" section of the Transmitters and Transceivers chapter of the *ARRL Handbook for Radio Communications,2017,* ARRL item no. 0628, available from your ARRL dealer, or from the ARRL Store, Telephone toll-free in the US 888-277-5289, or 860-594-0355, fax 860-594-0303; **www.arrl.org/shop/**; **pubsales@arrl.org**.

[2]L. R. Kahn, "Single-Sideband Transmission

by Envelope Elimination and Restoration", Proceedings of the IRE, 1952, Vol. 40, Issue 7, pp 803-806.
[3]D. Cripe, NMØS, "Homebrew Challenge II Co-Winner — The Lowest Cost Entry", *QST*, Oct 2010, pp 37-41.
[4]For a complete discussion of analytic signals, see the chapter on DSP and Software Design in the *ARRL Handbook for Radio Communications, 2017*.
[5]**www.i0cg.com/ad9957_dds.htm**.
[6]Sherwood Engineering Inc., **www.sherweng.com/**.
[7]DL4YHF Amateur Radio Software: Audio Spectrum Analyzer (Spectrum Lab), **www.qsl.net/dl4yhf/spectra1.html**.
[8]Bob Allison *et al.*, ARRL "Test Procedures Manual," Rev. L (2011), **www.arrl.org/files/file/Technology/Procedure%20Manual%202011%20with%20page%20breaks.pdf**.
[9]F. H. Raab, W1FR, "High efficiency RF power amplifiers", *Ham Radio*, Oct 1974, pp 829.
[10]F. H. Raab, "Power-conserving drive-modulation method for envelope-elimination-and restoration (EER) transmitters", U.S. Patent 6,256,482, July 3, 2001.
[11]F. H. Raab, W1FR, M. F. Gladu, N1FBZ, and D. J. Rupp, "Complementary class-D power amplifier for LF and MF", *QEX*, Mar/Apr 2006, pp 9-13.