Open-Loop Power Amplifier Characterization Using the ISL5239 Evaluation Board

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Description:

This application note presents tools and an example of open-loop power amplifier characterization. An open-loop characterization may be suitable for power amplifiers whose phase and amplitude characteristics are temperature insensitive. For other amplifiers, the tools and procedures described in this note could be used as a starting point for a closed-loop or iterative algorithm.

Hardware Description

An example hardware setup utilizing the ISL5239 Predistortion Linearizer (PDL) evaluation board to perform open loop characterization and correction of power amplifier (PA) gain and phase is shown in the block diagram of Figure 1. The setup consists of a test signal stimulus path from the evaluation board to the PA and a PA gain and phase characteristics measurement path from the PA output back to the evaluation board. The evaluation board is configured and controlled by a personal computer (PC) via the USB bus. Matlab M files included with the evaluation board software are run on the PC to instruct the hardware to perform the PA gain and phase characterization. The M files perform a scripted sequence of events. First, a test pulse waveform is generated by the evaluation board and applied to the PA. The evaluation board then captures the PA output response to the applied test pulse. Routines in the script files process the acquired response data and create lookup tables (LUTs) that are downloaded into the ISL5239 PDL chip on the evaluation board. The new LUTs allow the PDL to predistort the test pulse to compensate for the nonlinearity in the gain of the PA and to correct for phase. The response of the PA to the original and predistorted test pulse are displayed on the spectrum analyzer to allow measurement of decreased regrowth in the test pulse spectrum achieved by using the PDL to correct the PA gain and phase nonlinearity. Optionally, an ISL5217 digital up converter evaluation board can be added to the front end of the PDL evaluation board to enable the testing of the PDL and PA performance with stimulus signals conforming to any of the common cellular standards. The PDL evaluation board also has a wraparound mode through an onboard CPLD that allows the test signal stimulus to be wrapped back into the measurement path on the board, thus bypassing the actual path through the PA. This mode is useful when a software model of the PA response is available as described in the procedure.

Test Signal Stimulus Generation

The test signal stimulus path is designed to exercise the full dynamic range of the PA so that amplitude and phase distortion nonlinearities can be measured and corrected for with the PDL. The RF test signal stimulus for the PA is formed by up converting and amplifying quadrature baseband waveforms generated on the evaluation board. The baseband waveforms are constructed using the stimulus loop mode capability of the ISL5239 PDL on-chip memory. This stimulus mode allows the PDL to function as a 2K deep digital pattern generator operating at the PDL clock rate (125 MHz when the on board crystal is used as the clock source). The PC loads the PDL stimulus memory via the USB bus. The quadrature digital patterns generated by the PDL are then converted to differential analog waveforms on the evaluation board by the ISL5929 high speed, 14 bit, dual DAC. The analog waveforms are then filtered, DC biased, and buffered before being output from the evaluation board on SMA connectors J14 through J17.

The baseband quadrature analog outputs from the evaluation board are up converted to the desired RF frequency by inputting the waveforms to an analog quadrature modulator (AQM) along with a carrier from an RF signal generator. The evaluation board SMA outputs interface directly to AQM evaluation boards from either Sirenza or Analog Devices. An adjustable pot on the PDL evaluation board (R62) allows the DC bias on the baseband signals to be set at the level required by a particular AQM. Also, the PDL on the evaluation board has a functional block in the output data path that allows digital correction for AQM gain, phase, and dc-offset imbalance. By setting registers in the PDL to the proper values, carrier feed through and quadrature image can be reduced to negligible levels. Using the evaluation board GUI or Matlab script txbal.m on the PC, the PDL register values can be iteratively adjusted until adequate AQM balance is achieved.

A preamp and driver amp follow the AQM to provide gain to boost the RF signal to sufficient levels to drive the PA. The amplifiers chosen must have sufficient dynamic range and linearity so as not to add any significant regrowth to the spectrum of the test signal. A variable, continuous attenuator is included in the stimulus path for manually controlling the PA operating point. The attenuator should be set at a level that allows the PA to be driven between 2 and 2.5 dB into compression at the peak of the test pulse. This operating point is indicated on the spectrum analyzer by the appearance of spectral regrowth adjacent to the signal bandwidth that is about 10-15 dB below the level of the main signal.

PA Output Response Measurement

The PA measurement path involves attenuation of the PA RF output, down conversion of the RF signal back to baseband or a low IF frequency, filtering and analog-to-digital conversion (ADC) of the baseband waveform, and capture of the digital data pattern. Sampled snapshots of the digital data pattern are captured on the evaluation board by the PDL using 1K deep on-chip feedback memory. Collection and processing of the data is facilitated by use of the scripted Matlab routines.

For the example covered in this application note, in the stimulus path the baseband quadrature test pulse signal output from the evaluation board has a bandwidth of 4 MHz centered about a frequency of 15.625 MHz. Having the test signal centered about a low IF frequency allows up and down conversion of the pulse using the same RF source and a single ADC in the down conversion path. A tone at 31.25 MHz is included as part of the test waveform to provide a signal peak-to-average power ratio (PAR) of about 10 dB. After up conversion by the AQM with a 2140 MHz carrier, the test signal is located on the upper sideband of the carrier and centered at 2155.625 MHz. On the measurement path the RF signal is down converted to the low IF frequency using a mixer with the LO input supplied by the same RF source that is used in the stimulus path AQM up conversion. The low IF output signal from the mixer is then filtered, amplified, and sampled by a 14 bit ADC operating at 62.5 MHz. The clock for the ADC is available from the evaluation board at pin 19 on connector J10. The digital output from the ADC is input to the feedback capture port on the evaluation board at connector J8. This connector interfaces directly to many ADC evaluation boards. The recovery of the quadrature components of the baseband signal from the captured digital data is performed in software by the Matlab routines.

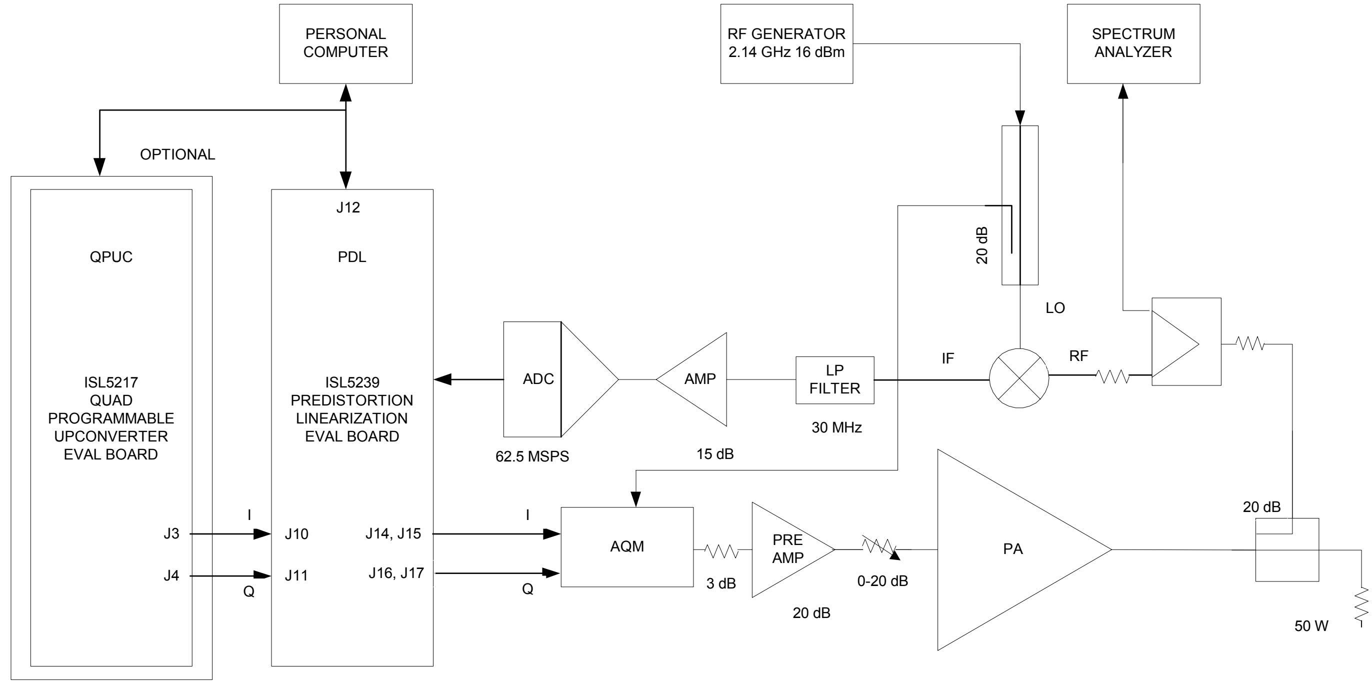

FIGURE 1. PA CHARACTERIZATION HARDWARE SETUP

Procedure

This section demonstrates the process of characterizing an amplifier using the hardware described above. The process is automated by the Matlab script open_loop_demo.m in conjunction with the Matlab interface library included in the evaluation board software. A description of the major sections of open_loop_demo.m is provided.

Operating Mode

Open_loop_demo.m uses a variable called demo_mode to demonstrate power amplifier (PA) linearization using a mathematical model in place of an actual PA. Set demo_mode = 1 in the file to enable demo mode, or to 0 (normal mode) to work with an actual PA. Note that the evaluation board is still required in demo mode. In both modes, a stimulus is loaded into the input capture memory.

In normal mode, the stimulus input is set to loop to provide the PA with a continuous signal. The CPLD is set to route data from the external feedback connector (J8) to the ISL5239's feedback capture bus. J8, as shown above, is connected to the A/D converter.

In demo mode, the stimulus input is set to single. The CPLD is first set to route the ISL5239's I output back to the feedback capture bus. A trigger starts the stimulus data through the part to be captured by the feedback capture memory after a certain delay (accounting for CPLD and other pipeline delays). The CPLD is then set to route Q data back, and a 2nd trigger is generated. This captured data is then run through the PA model and its output is processed as detailed.

Configure the ISL5239 Evaluation Board

The script begins with resetting the hardware, initializing registers to a known power-up state.

Next, input section and Interpolator settings are loaded. The default values in this example are appropriate for connection to an ISL5217 upconverter evaluation board on J10 (I data in) and J11 (Q data in).

The lookup table (LUT) and predistorter settings are then initialized. During characterization, the LUT is bypassed to allow the stimulus pulse through unchanged.

Correction filter file invsinc.cf is loaded and enabled. This filter compensates for the D/A converter’s sin(x)/x rolloff. The reconstruction filter response is not taken into consideration by invsinc.cf. For characterization of bandwidths wider than the 4 MHz of this example, it may be desirable to correct for this rolloff as well. In demo mode, a unit impulse response is loaded into the correction filter.

The output data conditioner (ODC) is configured for offset binary output and loads the I-to-I, I-to-Q, Q-to-I, Q-to-Q, I DC offset and Q DC offset settings provided in the top of open_loop_demo.m. These settings are unique to each evaluation board and analog quadrature modulator (AQM), and should be determined experimentally using the evaluation board software GUI or Matlab tool txbal.m.

Finally, the input stimulus data are loaded. The input mode is set to loop in normal mode and idle in demo mode (it will later be set to single in demo mode).

During this reset and initialization step it is recommended that the PA be powered-down to prevent damage. The open_loop_demo.m script will prompt you to turn off the PA before the above procedure, and tell you when it is complete so that the PA may be brought back up. The PA should be brought up carefully -- start with more attenuation between the D/A converters and the PA than you expect to need for the desired drive level.

Characterization

The stimulus pulse in this example consists of two sinc pulses, first a positive pulse and then a negative one, followed by a windowed CW burst to raise the average power level. It is designed to allow the power amplifier to be driven well into its non-linear region during the peaks of the sinc pulses (ideally, up to the point of saturation) while maintaining a safe average power level. The stimulus file used in this example, 4MHz_10p2par_test_pulse, has a bandwidth of 4 MHz centered on a 15.625 MHz carrier (D/A rate of 125 MHz) and a peak to average ratio of 10.2. It is plotted in Figure 2. Use the script file make_pulse_with_ballast.m to create other stimulus pulses if desired.

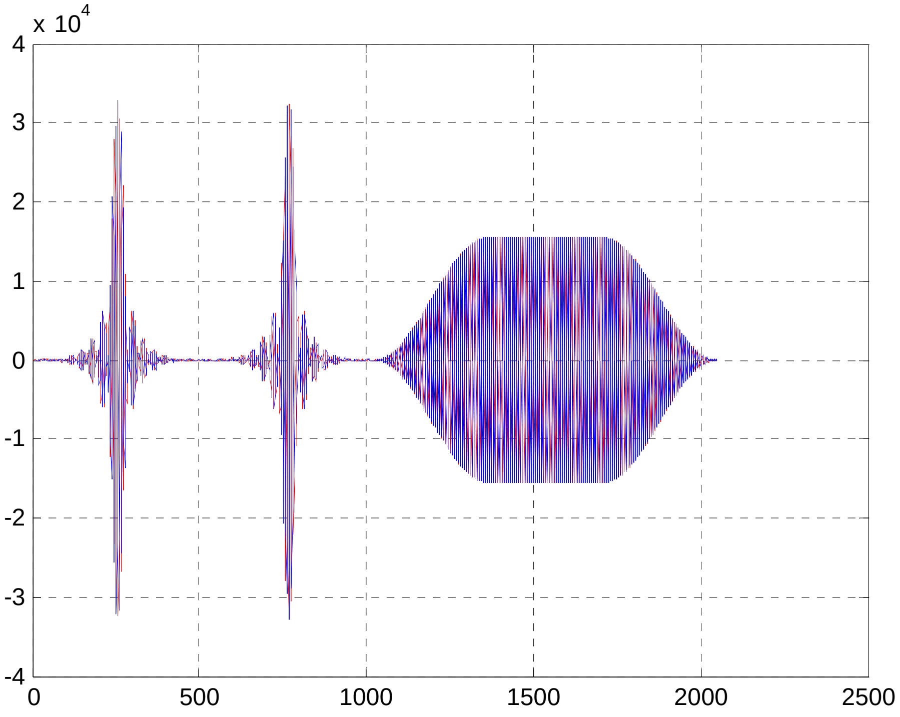

FIGURE 2. STIMULUS PULSE: I DATA IN RED, Q DATA IN BLUE

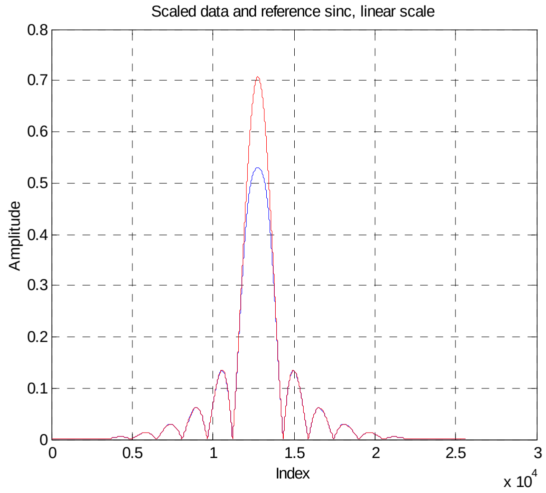

FIGURE 3. AVERAGED SINC PULSES FROM PA MODEL (BLUE) SCALED FOR COMPARISON TO REFERENCE SINC PULSE (RED). LINEAR SCALE

In demo mode, the drive level for the PA model is already set to an appropriate level. For normal mode, the attenuation will need to be set to allow for a sufficient level of nonlinearity. The idea is to push the PA to the edge of its operating limits to obtain the data needed to generate a LUT. When the drive level is set as desired, press a key to continue and 1K sample snapshots of the PA output are taken and processed.

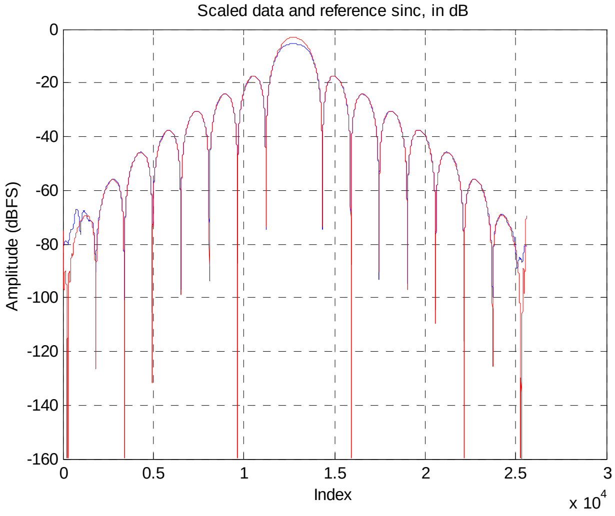

FIGURE 4. AVERAGED SINC PULSES FROM PA MODEL (BLUE) SCALED FOR COMPARISON TO REFERENCE SINC PULSE (RED). dB SCALE

In demo mode, only one capture is required since the model behaves the same each time. The capture, unchanged stimulus data, is scaled and routed through the PA model. Five captures are performed in normal mode to get 10 sinc pulses to average over. The down conversion, filtering and correlation process is repeated 5 times and an average is taken to prepare the data for LUT generation.

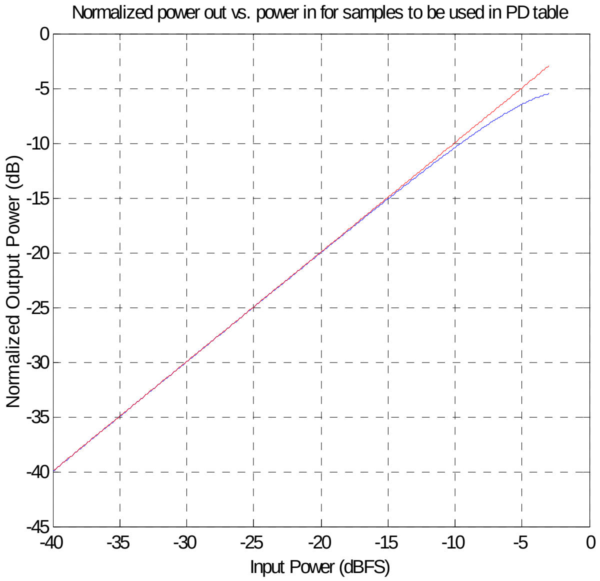

FIGURE 5. MAGNITUDE INFORMATION FROM PA MODEL. RED SHOWS NORMALIZED LINEAR RESPONSE, BLUE IS ACTUAL RESPONSE.

First, the capture is down converted to DC. Then the negative real image is filtered off. The filter cutoff in this example is 5 times the one-sided bandwidth of the signal (4 MHz / 2 = 2 MHz in this example) plus 25%. This gives all the 5th order intermodulation products, plus 25% extra to allow for filter rolloff. The default filter is a 200 tap linear-phase FIR filter.

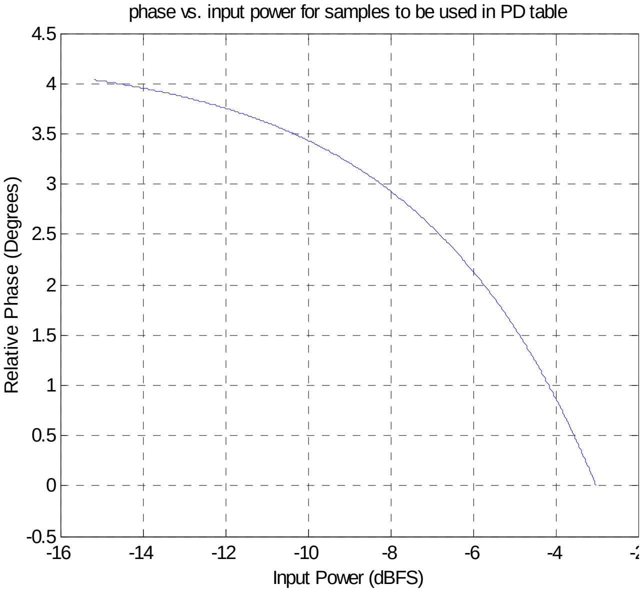

FIGURE 6. PHASE INFORMATION FROM PA MODEL.

Interpolation by a factor of 50 is then performed to increase the time resolution so that the delay in the mixed signal and analog portions of the system can be more closely accounted for.

Location of the sinc pulses in the captured data is done with correlation. Correlation peaks indicate the centers of the sinc pulses, allowing them to be extracted from the interpolated data. Each 1K capture yields two sinc pulses which can be extracted. The unwrapped phase (angle) and magnitude information of each pulse is then averaged.

Next, the magnitude of the averaged pulse is scaled for comparison to the reference sinc pulse. PA compression will flatten the sinc pulse's central lobe, but will not affect the side lobes as much because they are in the PA's linear region. The power scaling in this example assumes that samples with power below 10% (-10 dB) of the peak amplifier output power are linear. The sampled signal is scaled so that these samples have the same signal power as their counterparts in the reference sinc pulse. The resultant scaling in the demo mode example is shown in Figure 3 and Figure 4 in linear and dB scale. The reference pulse is in red while the compressed PA output is shown in blue.

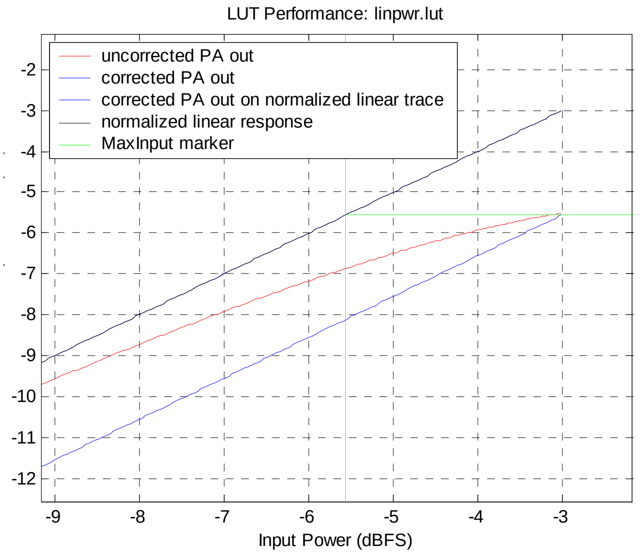

FIGURE 7. LUT PERFORMANCE PLOT

Only the main lobe of the sinc pulse is used for LUT generation. It contains the full range of output power needed for the calculation. The central lobe is isolated and the power levels are sorted in order of increasing power. Because the left and right halves of the central lobe are symmetric, the sorted power data occurs in pairs. These pairs are averaged and replaced by their average value, generating a single curve of output power vs. input power using points from both the left and right halves of the central lobe.

Polynomial fitting is now performed on the phase and magnitude data. In this example, both are 20th order and are fitted using a least-squares error method. Lower order polynomials also work well and may provide better stability for noisy signals. Since phase information becomes increasingly noisier as input level decreases, code has been included to determine the maximum usable range for the data. This sets the range for the polynomial fit. For magnitude fitting, the range is hard-coded to start at -55 dBFS (dB relative to full scale) while only -40 dBFS and higher is actually used. These values should be altered if necessary for a particular lab configuration. Figure 5 and Figure 6 show the magnitude and phase information from the PA model in demo mode. In the power out vs. power in (magnitude) figure, the red trace represents the normalized linear response while the blue trace shows the model's non-linear response.

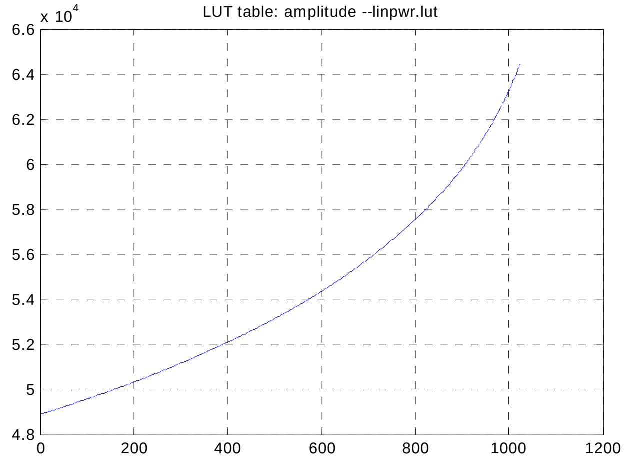

FIGURE 8. MAGNITUDE COMPONENT OF GENERATED LUT. X AXIS IS LUT ADDRESS (0-10 23).

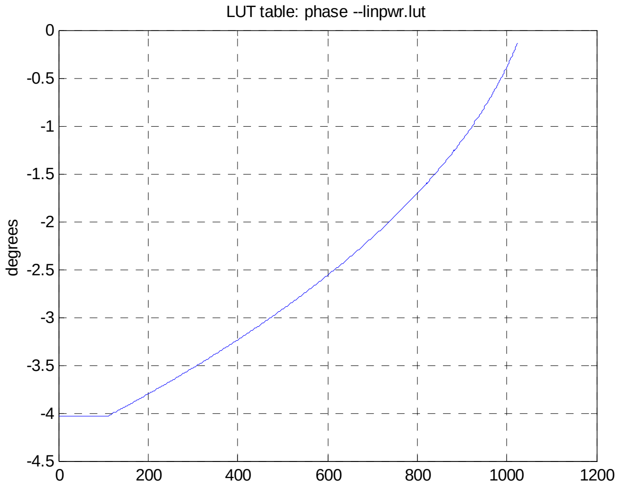

FIGURE 9. PHASE COMPONENT OF GENERATED LUT. X AXIS IS LUT ADDRESS (0 - 1023).

LUT Generation

At this point make_lut.m is called by the script to generate the actual LUT from the polynomial coefficients just generated. Make_lut.m also requires a ranges matrix which maps a dBFS input power to a LUT table entry. Range matrices can be generated using the find_LUT_power_ranges.m script. Matrices for the default linear power, log power and linear voltage modes are already included. In the linear power and linear voltage matrices, a scale factor of 256 and offset factor of 0 was used. For log power, the scale factor is 3449 and offset is 0. These are reflected in the filenames: “ranges_s3449_o0_m0.mat”, “ranges_s256_o0_m1.mat” and “ranges_s256_o0_m2.mat” for log power, linear voltage and linear power modes, respectively. These scale factors and offsets set the top of the LUT at -3 dBFS (input powers greater than -3 dBFS will saturate to LUT address 1023).

Make_lut.m uses the ranges matrix along with the polynomial coefficients to generate tables to correct the magnitude and phase. Magnitude lookup tables are generated by searching for a power Pin2 which gives an output Pout2 = Pout1, where Pout1 is the desired linear output for an input Pin1. In Figure 7, the black line represents a normalized linear response from the PA. The red line is the actual (non-linear) response from the PA. If we wanted to get a linear response from an input level of -5.6 dBFS, we would need to use an actual power level of about -3.2 dBFS (follow the green lines from -5.6 dBFS to the red non-linear trace, then back down to get -3.2 dBFS).

With the information given in this plot (the red PA trace ends at -3 dBFS), it is seen that the maximum linearizable input power is about -5.5 dBFS since there is no level shown which could given a linear output for inputs greater than -5.5 dBFS. This value is backed off by 0.05 dB and referred to in the Matlab scripts as “Max Input”, and shown on Figure 9 as the vertical green line.

For the input level of -3.2 dBFS, a gain of about 2.4 dB would be needed to linearize the point. The ISL5239’s predistorter, however, works in attenuations. This is possible because a D/A to PA attenuation setting sufficiently low enough to drive the stimulus pulse’s -3 dBFS peak into the PA’s saturation region would require attenuation (back off) in the LUT for the ISL5239’s full scale input to be linearized. Referring again to Figure 9, a maximum ISL5239 input of -3 dBFS could simply be passed with 0.2 dB of attenuation to get the same output a linear PA would give at an input level of -5.6 dBFS. Continuing to build the magnitude correction table in this manner gives a LUT which linearizes the amplifier and provides -3.2 - -5.6 = 2.4 dB of attenuation. The blue curve is the resultant PA output with the LUT applied. It parallels the normalized linear curve (black) with 2.4 dB of attenuation. This attenuation is simply a mapping of the maximum allowing ISL5239 input (-3 dBFS in this example) to the Max Input value determined in the characterization processing -- i.e. a -3 dBFS value into the ISL5239 with this LUT applied will give the largest linearizable output from the PA. Although the LUT as a whole provides 2.4 dB of attenuation, the attenuation for a given input power level varies from (in this example) 0.2 dB at the top of the LUT to 2.4 dB at the lowest power entry.

For the phase correction table, the phase polynomial is used to determine the phase shift at the adjusted output level. This phase shift is negated for the table to undo the undesired shift the PA is about to perform.

The magnitude and phase correction tables are combined into a single I Q table compatible with the LUT memory. This single table corrects magnitude and phase simultaneously.

The magnitude and phase components of the actual 1K LUT are shown in Figure 8 and Figure 9. The magnitude curve shows that attenuation decreases with power since the PA’s compression also decreases. Positive phase shifts in the PA are met with negative phase shifts in the LUT to compensate.

Using the Newly Generated LUT

In normal mode, the open_loop_demo.m pauses with “press any key to load LUT into the ISL5239” before downloading and enabling the new LUT. After pressing a key, the PA’s output spectrum should show a substantial improvement (actual improvement will depend on how far into the non-linear region the PA was being operated during characterization).

Demo mode produces Figure 10. The blue trace is the PA model’s output during characterization. The results of the LUT on the PA’s output are shown in red. For comparison, the green trace shows the response of an ideal linear PA with the same gain as the PA model. A zoom of the signal’s pass band shows that the LUT introduces about 1 dB of attenuation with respect to the PA’s output during characterization. This differs from the expected 2.4 dB because the amplifier is well into compression (about 2.5 dB) during characterization. The 2.4 dB of attenuation introduced by the LUT is with respect to the ideal linear PA’s output (green trace). This can be seen in the zoomed plot, Figure 11.

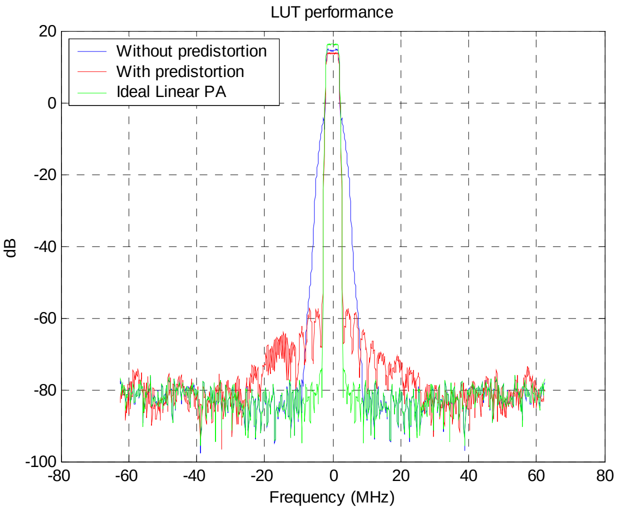

FIGURE 10. LUT PERFORMANCE ON PA MODEL.

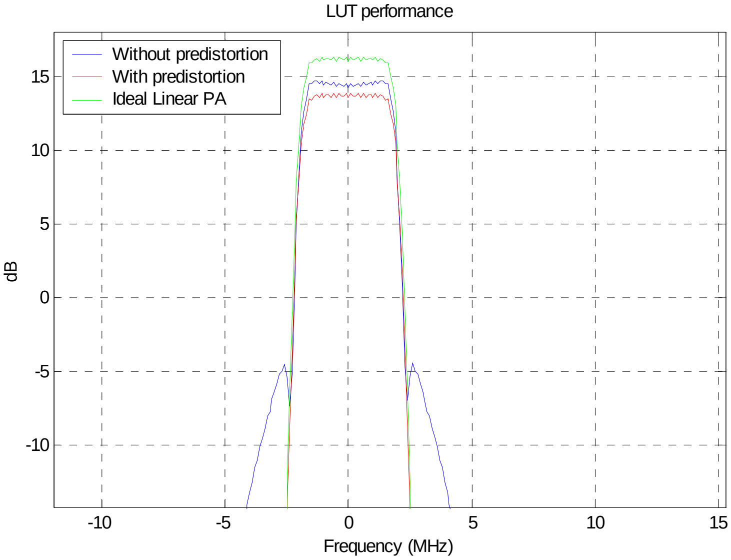

FIGURE 11. LUT PERFORMANCE ON PA MODEL (ZOOMED AROUND SIGNAL PASS BAND).

Figure 12 shows results obtained from characterization of a PA in the lab using the 4 MHz bandwidth pulse from the example. An ACLR reduction of 15 to 20 dB is seen over the 20 MHz sweep bandwidth. The traces have been normalized here for ease of comparison.

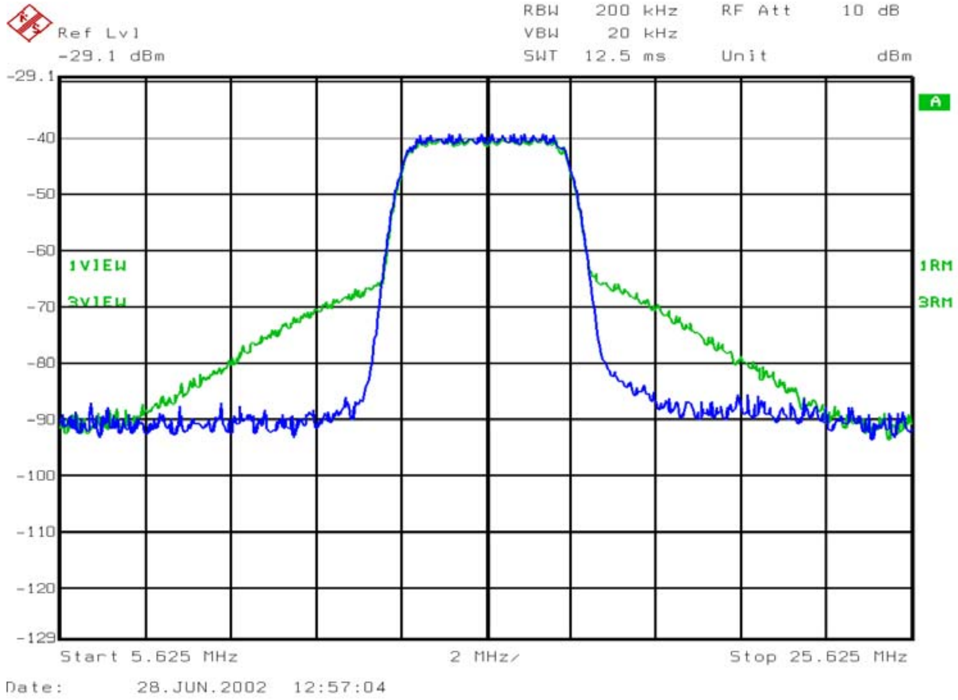

FIGURE 12. ACTUAL LUT PERFORMANCE FROM LAB MEASUREMENTS