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16-Bit 1-Gsps Digitizer Reference Design With AC and DC Coupled Variable Gain Amplifier

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Design Resources

TSW54J60EVM	Product Folder
ADS54J60EVM	Product Folder
LMH6401EVM	Product Folder
TSW54J60 Design Package	EVM Design Package
LMH6401 Design Package	EVM Design Package

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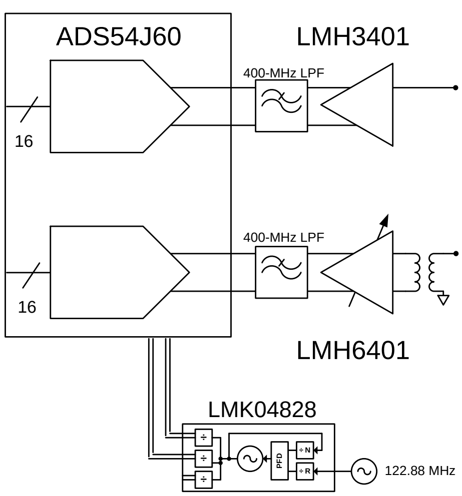
Design Features

- Flexible Transformer Coupled Analog Input on the LMH6401 Path to Allow for a Variety of Source and Frequencies
- Options for AC or DC Coupling, Single-Ended or Differential Inputs
- Easy to Use Software GUI to Configure the ADS54J60, LMH6401 and LMK04828 for a Variety of Configurations Through a USB Interface
- Quickly Evaluate ADC Performance Through High-Speed Data Converter Pro Software
- Simple Connections to TSW14J56EVM Capture Card

Featured Applications

- Radar and Antenna Arrays
- Broadband Wireless
- Cable CMTS, DOCSIS 3.1 Receivers
- Software Defined Radio (SDR)
- Digitizers



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1 Circuit Description

This reference design discusses the use and performance of the digital variable-gain high-speed amplifier, the LMH6401 to drive the high-speed analog-to-digital converter (ADC), the ADS54J60 device. Different options for common-mode voltages, power supplies, and interfaces are discussed and measured, including AC-coupling and DC-coupling, to meet the requirements for a variety of applications.

This type of circuit may be used in software defined radio, military communications, test equipment, cable headend receiver, radar receiver and digitizer applications.

2 Introduction

This reference design, the TSW54J60EVM, serves as a comprehensive summary of the performance and trade-offs when driving an ADC with high-speed amplifiers. A printed-circuit board was developed in order to test different setups in AC and DC coupled applications. This board consists of an ADS54J60 device, which is a dual-channel, 16-Bit, 1-GSPS ADC, and two high-speed fully-differential amplifiers: the LMH3401 (Fixed gain) and the LMH6401 (Digital variable gain). This board uses the LMH6401 amplifier to drive one channel of the ADC and a LMH3401 to drive the other channel. The board includes a jitter-cleaning clock generator (LMK04828), USB interface to allow operation with TI's High Speed Data Converter Pro GUI, and TI power solution LDO's and switchers. The JESD204B standard interface allows the EVM to be used with TI's TSW14J56EVM capture board or other JESD204B compatible platforms for data analysis.

The LMH6401 is a wideband, digitally-controlled, variable-gain amplifier (DVGA) designed for dc to radio frequency (RF), intermediate frequency (IF) and high-speed time-domain applications. The device is an ideal analog-to-digital converter (ADC) driver for dc- or ac-coupled applications that require an automatic gain control (AGC). The device supports both single- and split- supply operation for driving an ADC. A common- mode reference input pin is provided to align the amplifier output common-mode with the ADC input requirements.

The LMH6401 gain ranges from 26dB to -6dB in 1dB steps achieving a 32dB dynamic range. To reduce gain errors from one gain setting to the other, it is important to note that the change in input impedance or input return loss of the amplifier across gain steps should be minimal. The LMH6401 exhibits constant input impedance across gain settings making it suitable for wide-band automatic gain control (AGC) applications.

This document includes the general considerations when driving an ADC with an amplifier, such as common-mode voltages, power supplies, AC-coupling and DC-coupling, and filter interfaces. This document also includes a discussion of the measured performance of the LMH6401 and ADS54J60 interface. This includes IMD3 measurements as well as SNR and SFDR. This TIDesign will only focus on the LMH6401 channel driving the ADS54J60. Another TIDesign will feature the LMH3401 channel driving the ADS54J60. See the TSW54J60EVM User's Guide, SLAU649A, for more information regarding operation and testing of this EVM.

3 General Considerations

3.1 AC-Coupled Configuration

AC-coupling is the configuration that TI recommends if the application does not require processing of signals close to DC. The TSW54J60 uses a 1:2 (Zo = 50-Ω) transformer to convert single-ended input signals to 100 Ω differential signal for the LMH6401 device. This is required since the amplifier can only be used with differential inputs. A typical application would use a differential amplifier output to drive this device. For more information regarding this type of application, refer to TI Designs document TIDA-00654, titled "Cascaded LMH5401 and LMH6401 Reference Design". The board default configuration is AC-coupled, as shown in Figure 1. Note that the impedance seen on each input pin must be balanced with no DC offset voltage. Figure 1 shows the LMH6401 AC-coupled configuration.

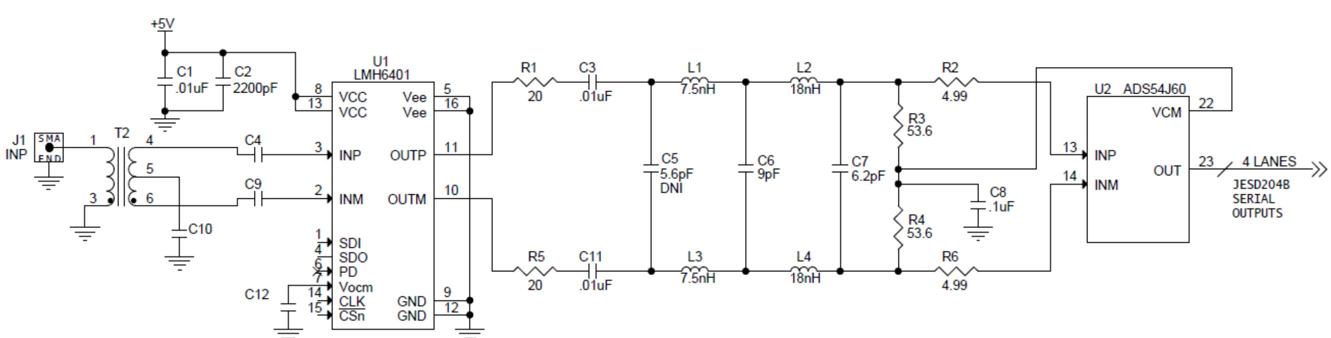

Figure 1. LMH6401 AC-Coupled Configuration

The output of the amplifier goes through a 370MHz low pass filter before connecting to the ADC. The specifications of the filter and data captured plots are shown later in this document. In AC-coupled configuration, the output common mode (CM) voltage of the amplifier output is isolated from the input CM of the ADC through the 0.01µF coupling capacitors. As a result, the output common control (VOCM) pin for the LMH6401 can be left floating or disconnected from the VCM pin of the ADS54J60. The LMH6401 output CM voltage defaults to mid-supply (2.5V in this case) if the VOCM pin is left floating. The amplifier and ADC interface has the best linearity performance when the output CM voltage of the amplifier is close to the mid-supply.

3.2 DC-Coupled Configuration

The LMH6401 path driving the ADS54J60 can be either dc- or ac-coupled at the inputs. The LMH6401 device provides excellent performance as a digitally-controlled fully differential amplifier down to DC. Figure 2 shows a typical DC-coupled configuration where a LMH6401 device is used to produce a balanced differential output signal for the ADS54J60 input.

In general, transformers are used to provide single-to-differential conversion, but these transformers are inherently band-pass in nature and cannot be used for DC-coupled applications. As a result, a common solution is to use a high speed amplifier in order to enable DC-coupling without affecting ADC performance at higher frequencies. Amplifiers offer a flexible and cost-effective solution when the application requires gain, a flat pass-band with low ripple, DC-level shifts, or a DC-coupled signal path.

In order to dc-couple the LMH6401 input path, care must be taken to ensure the common-mode voltage is set within the input common-mode range of the LMH6401. Please refer to the Electrical Characteristics table in the LMH6401 datasheet to set the input common-mode voltage within the device range. Since the LMH6401 is a fully differential amplifier, the path inputs must be driven differentially. For single-ended input source dc-coupled applications, care must be taken to select an appropriate fully-differential (such as the LMH3401 or LMH5401) that can convert single-ended signals into differential signals with minimal distortion.

When interfacing an amplifier to the ADC in dc-coupled application, it is required to match the output CM voltage of the amplifier close to the input CM voltage of the ADC. Best performance is achieved when the ADC input pins are at the same voltage as the ADC VCM pin or (INPADC + INMADC)/2 equals VCMADC. Interfacing the LMH6401 to the ADS54J60 is made easier by an option provided in the amplifier to control the output common-mode voltage using the VOCM pin of the amplifier. The LMH6401 device performance is optimal when the output common-mode voltage is within ±0.5 V of mid-supply and performance degrades outside the range when the output swing approaches clipping levels. For the ADS54J60, the input CM voltage to be maintained is close to 2.0V as specified in the ADC datasheet. The ADC input CM voltage of 2.0V makes it easier for the LMH6401 to be run on a single +5V supply and use the VOCM pin to set the output CM voltage to 2.0 V, since it is within ±0.5 V of mid-supply.

See the *TSW54J60EVM User's Guide*, section 5.2.1 of (SLAU649A), for more information regarding testing with this mode of operation.

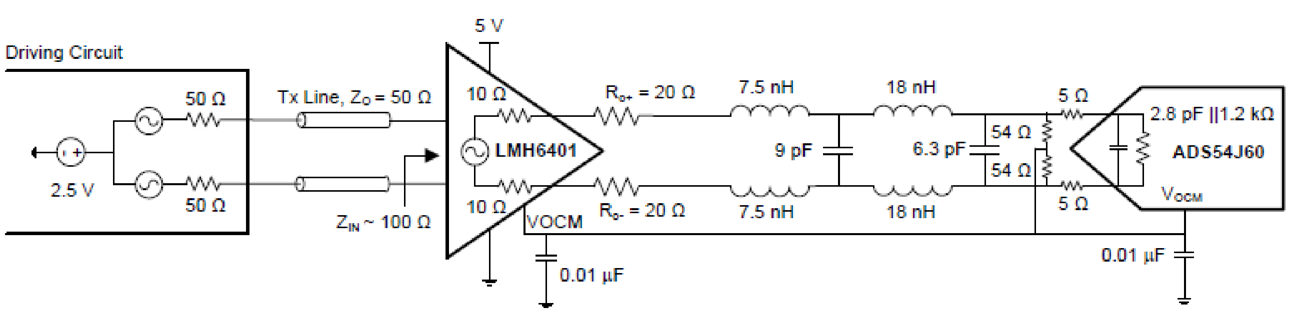

Figure 2. Interfacing LMH6401 With the ADS54J60 in the DC-Coupled Configuration

4 Common Mode Considerations

To achieve the best performance while DC-coupling an amplifier and an ADC interface, match the output CM voltage of the amplifier to the input CM voltage of the ADC. For DC-coupled applications, the LMH6401 provides an option to control the output common-mode voltage using the VOCM pin. Device performance is optimal when the output common-mode voltage is within ±0.5 V of mid-supply and performance degrades outside the range when the output swing approaches clipping levels. The LMH6401 can achieve a maximum output swing of 6 VPPD with the output common-mode voltage centered at mid-supply. Note that by default, the output common-mode voltage is set to mid-supply before the two 10-Ω, on-chip resistor. On a single-supply operation when DC-coupling the device outputs to an ADC using common-mode level-shifting resistors, the output common-mode voltage and resistor values being calculated must include the two internal 10-Ω resistors in the equation.

Figure 3 shows where a resistor network can be used to perform the common-mode level shift. This resistor network consists of the amplifier series output resistors and pullup or pulldown resistors to a reference voltage. This resistor network introduces signal attenuation that may prevent the use of the full-scale input range of the ADC. ADCs with an input common-mode closer to the typical 2.5-V output common-mode of the LMH6401 are easier to dc-couple, and require little or no level shifting

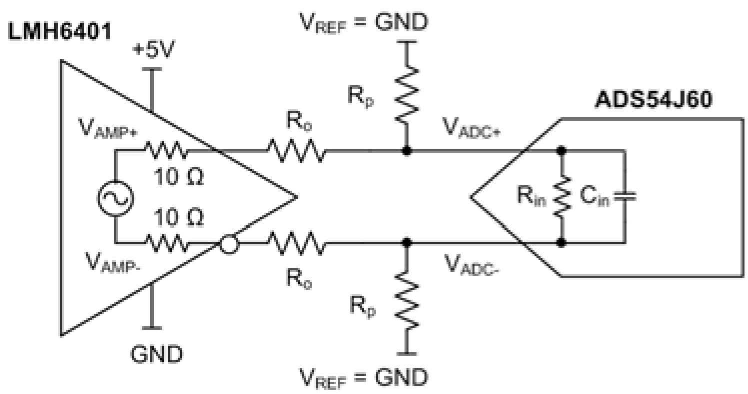

Figure 3. Resistor Network to DC Level-Shift

When operating the LMH6401 on split supplies and DC-coupling the outputs, TI recommends matching the output common-mode voltage of the LMH6401 with the input common-mode voltage of the ADC. A simple design procedure is to select the supply voltages (VS+ and VS-) such that the default output common-mode voltage being set is equal to the input common-mode voltage of the ADC.

To minimize the design complexity on the TSW54J60EVM, the LMH6401 uses a single supply (5VDC) instead of split-supplies which would be centered close to an output CM voltage of 2.5-V. This is done because the input CM voltage of the ADS54J60 is within the ±0.5 V of the LMH6401 mid-supply on a single 5-V supply.

5 Filter Design

The TSW54J60EVM follows the LMH6401 with a 370MHz 4th order Chebyshev Low Pass Filter (LPF) filter to remove out-of-band noise and harmonics aliasing into the first Nyquist zone of the ADS54J60. The filter has been designed for less than 2dB pass-band ripple with cut-off frequency at 370MHz, and stop-band attenuation of 30dB at 1GHz. The circuit is appropriately biased to match the ADC common-mode level by connecting the VCM output to the common mode termination. Figure 4 shows the filter simulated response is shown in, and Figure 5shows he measured performance of this filter.

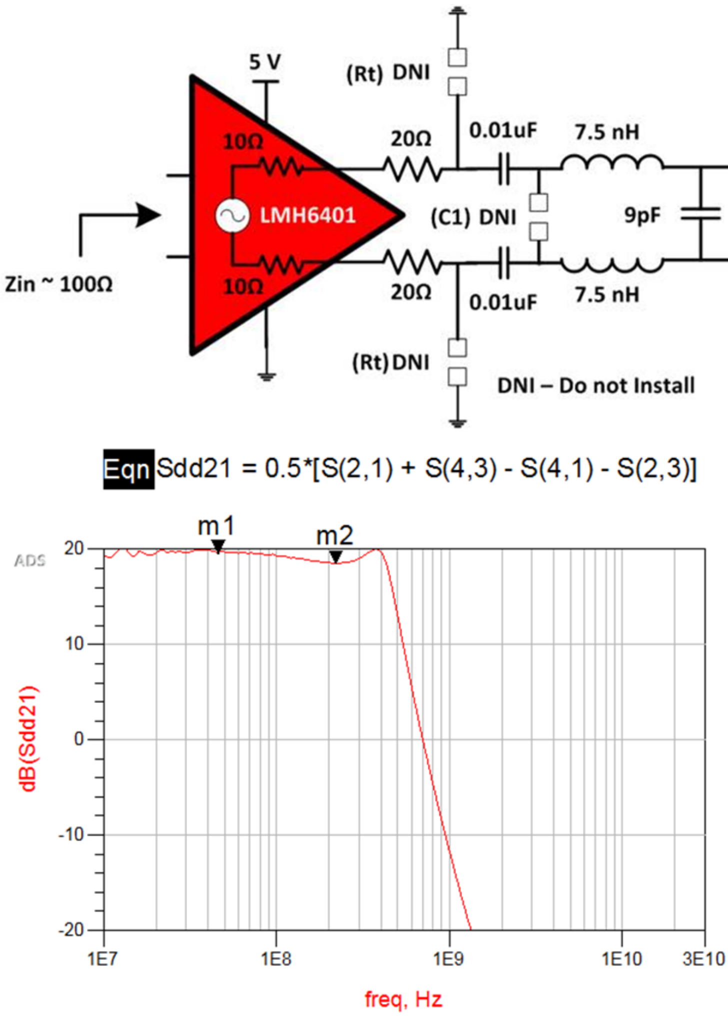

Figure 4. 370 MHz Low-Pass Filter and Simulation Response

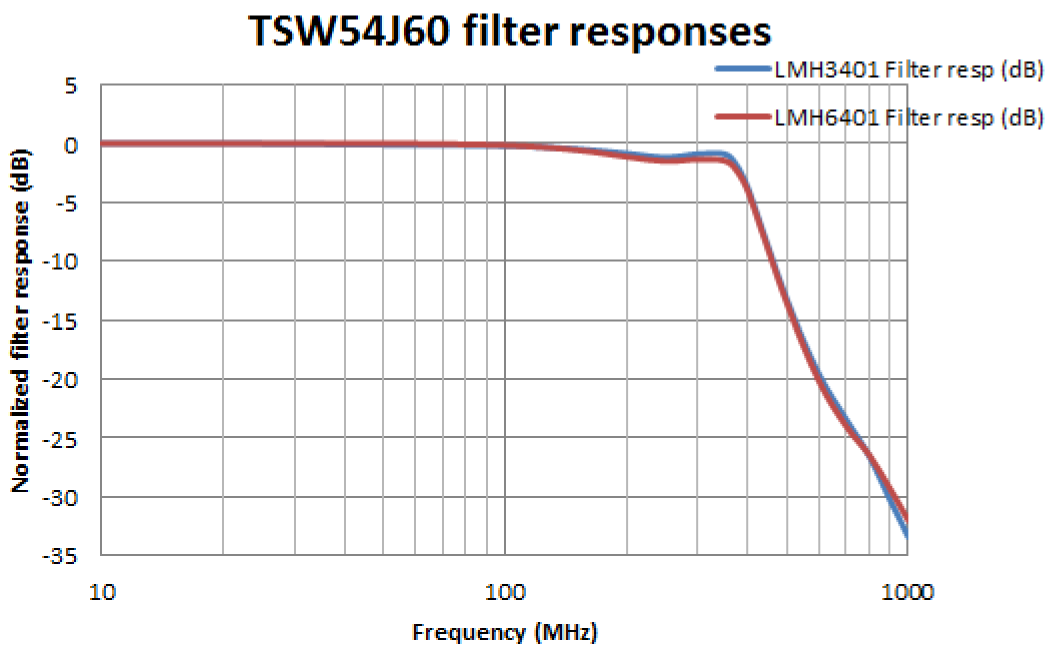

Figure 5. 370 MHz Low-Pass Filter Measured Responses

The LMH6401, as with most RF amplifiers, has two 10-Ω, on-chip resistors on each output leg to provide isolation from board parasitic at the output pins. When designing a filter between the amplifier and the interfacing circuitry (ADC), the filter source impedance must be calculated by taking into account the two 10-Ω, on-chip resistors. Table 1 shows the calculated external source impedance values (R_{O+} and R_{O-}) required for various matched filter loads (RL). An important note is that the filter design between the LMH6401 and the ADC is not limited to a matched filter, and source impedance values (R_{O+} and R_{O-}) can be reduced to achieve higher swing at the filter outputs. Achieving lower loss in the filter source impedance resistors or higher swing at the filter outputs is often desirable because the amplifier must reduce the output swing to maintain the same full-scale input at the ADC and, thus, better linearity performance.

The 370-MHz, un-matched, low-pass filter between the LMH6401 and ADS54J60 is illustrated in Figure 4, with (R_{O+} and R_{O-}) set to 20 Ω and RL set to 100 Ω. Since the ADC input impedance (RL) is set to 100 Ω and the termination resistors including the two on-chip 10-Ω resistors on LMH6401 output is 60 Ω, the termination loss (or insertion loss) between the LMH6401 and ADS54J60 is close to 4-dB (or 2-dB). The termination loss is calculated by the voltage division between the ADC input and the termination resistors at the amplifier output.

$$VIN_{ADC}(diff) = Loss \times VOUT_{AMP}(diff) \quad (1)$$

For the LMH6401 and ADS54J60 interface, use:

$$Loss(dB) = 20 \times \log 10\left(\frac{R_L}{R_L + R_{0+} + R_{0-} + 20}\right) \quad (2)$$

Table 1 shows the load component values.

Table 1. Load Component Values

LOAD (R_L)	R_{O+} AND R_{0-} FOR A MATCHED TERMINATION	TOTAL LOAD RESISTANCE AT AMPLIFIER OUTPUT	TERMINATION LOSS
50 Ω	15 Ω	100 Ω	6 dB
100 Ω	40 Ω	200 Ω	6 dB
200 Ω	90 Ω	400 Ω	6 dB
400 Ω	190 Ω	800 Ω	6 dB
1 kΩ	490 Ω	2000 Ω	6 dB

6 Power Supply Consideration

The LMH6401 device can operate with either a single or dual supply, and with either DC coupling or AC coupling. The advantage of AC-coupling over DC-coupling is to offer more freedom of choice in regard to power supply. The main concern with DC coupling is ensuring that the input common-mode voltage does not violate the device operating conditions. By AC-coupling the input of the driver, the input self-biases at the level set by the output CM (V_{CM}) pin which ensures optimal operation.

If a single supply is used, AC-coupling the amplifier when driving an ADC is easier in relation to common-mode settings. The TSW54J60EVM uses a 5-V single supply configuration for both the LMH6401 and LMH3401 amplifiers.

If DC-coupling must be used with a single supply, the common-mode output of the driver must operate at VS+/2 (in this case, 2.5 V) and then DC level shifting must be used to match the common mode of the ADC. The appropriate common mode is set by using a voltage divider as described in the Section 4 section. The drawback is this method results in a loss of signal power because the amplifier must drive a larger voltage to overcome the attenuation of the voltage divider, which results in degraded performance.

The input common-mode voltage (V_{ICM}) of the DC-coupled driver input must also be considered. While the output common-mode voltage (V_{OCM}) is set at V_{CM}, V_{ICM} can have a small delta compared to V_{OCM} based on the internal feedback resistors. This delta can generate a flow-back current that wastes power in the feedback resistors. Also, based on the signal source, the delta can cause issues in some applications that may require a buffer amplifier before the fully-differential amplifier.

7 Loop Filter Component Selection

The TRF3765 requires an external loop filter for proper operation. The loop filter design is critical for achieving low closed-loop phase noise. For this design the synthesizer is operating in Fractional-N mode with a PFD (phase frequency detector) frequency of TBD. The charge pump current is set to 1.95 mA to minimize noise. The loop filter component values are given in Table 2, and are referenced to designators in .

If the application uses a split supply, an advantageous approach is to use a non-symmetric supply operation. For example, non-symmetric supply operation with a DC-coupled application driving an ADC that requires an input common mode of 2.0 V. Using +4.5 V and -0.5 V supplies will allow to set the amplifier output CM to 2.0 V.

The following summarizes the AC-coupling and DC-coupling differences between a single-supply operation and a split-supply operation.

Single Supply Operation (5 V):

- **AC-coupling:**
  - The CM is biased at 2.5 V at the output of the amplifier.
  - Easily adapts to any required ADC input CM.
  - Filter design between the amplifier and ADC interface is easier because the DC level shifting is not required.
- **DC-coupling:**
  - The input CM of the amplifier may differ from the output CM, which leads to current leakages.

Split-supply Operation:

- **AC-coupling:**
  - The CM is biased at the output of the amplifier.
  - Easily adapts to any required ADC input CM.
- **DC-coupling:**
  - Best solution if the supply is set to match the required input CM of the ADC.
  - Voltage divider is not required, which leads to an easier interface configuration.
  - Increases the number of supplies, which increases board space and cost.

Table 2. TRF3765 Loop Filter Components

Fpfd (MHz)	C1	C2	R5	C3	R6
1.6	47 pF	560 pF	10 K	4.7 pF	4.99 K

If a modification to the PFD frequency or operational mode is required, then the loop filter may need to be modified. The Loop_Filter-CALC program available on the TI website is a great resource in determining the proper loop filter component values.

8 Results

The measured results below were made using a TSW54J60 connected to a TSW14J56EVM and the HSDC Pro GUI. Two signal generators, band pass filters, and 3dB attenuators were used along with a power combiner for the two tests. Data was collected using frequencies ranging from 70MHz to 250MHz and LMH6401 Gain settings from 2dB to 26dB (max gain). Figure 6 shows show captured data in two formats. The two tones were separated by 1MHz. Table 3 lists the two tone test results across several frequency and gain settings. Figure 6 shows the two tone test results across several frequency and gain settings.

Table 3. Two Tone Test Results Across Several Frequency and Gain Settings Table

GAIN (dB)	70 M	125 M	150 M	220 M	250 M
2	-77.5	-85.3	-76.2	-74.4	-68.06
6	-79/4	-77.9	-79	-75.3	-69.42
11	-79.9	-77.9	-80.5	-75.9	-69.77
15	-81	-79.4	-82.9	-77.6	-71.33
18	-81.1	-78.9	-81.9	-76.1	-70.32
22	-82.6	-79.1	-81.8	-77.3	-71.98
26	-81.5	-79.1	-79.5	-76.5	-70.05

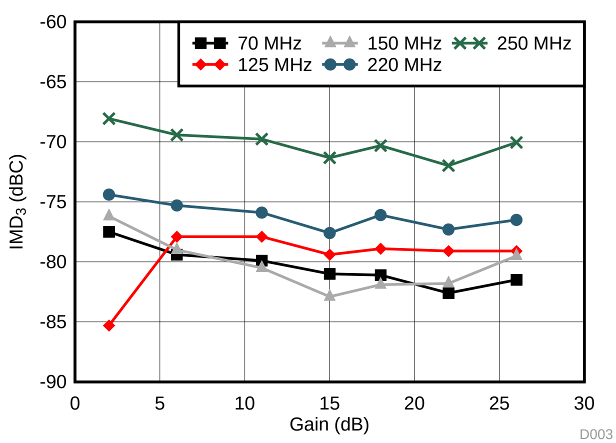

Figure 6. Two Tone Test Results Across Several Frequency and Gain Settings

Figure 7 is a screen shot from HSDC Pro GUI of a two tone test using (169.5 MHz and 170.5 MHz) with a LMH6401 gain setting of 16 dB.

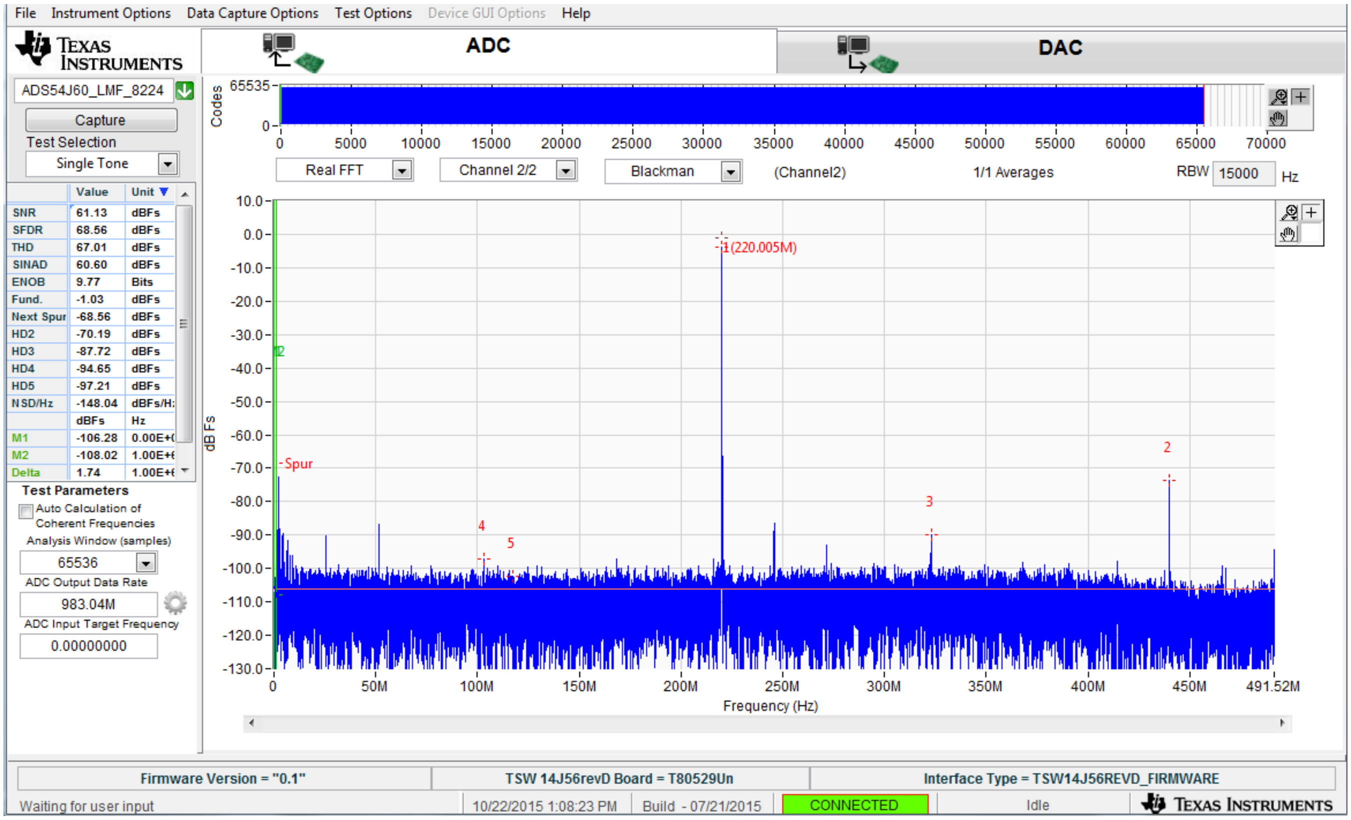

Figure 7. FFT of the Two Tone Test, Gain of 16 dB

The following three figures show a 220MHz single tone captured using different LMH6401 Gain settings. This setup used a signal generator, a band pass filter, and 6dB attenuator between the filter and SMA connector INBP (J3) to provide a robust 50-Ω source impedance. Figure 8 shows a 220MHz IF, AC-Coupled, LMH6401 Gain = 26dB (max).

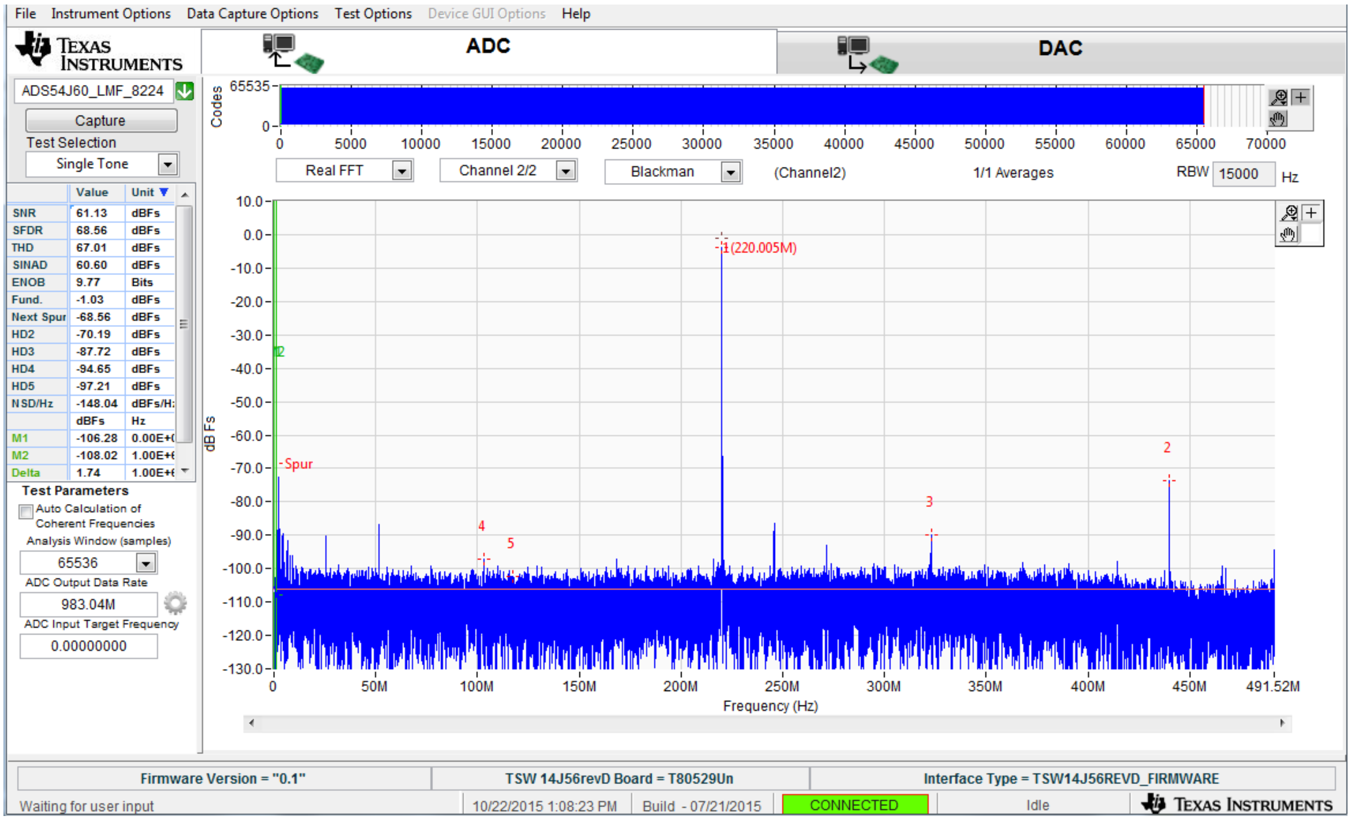

Figure 8. 220 MHz IF, AC-Coupled, LMH6401 Gain = 26dB (max)

Figure 9 shows the 220 MHz IF, AC-Coupled, LMH6401 Gain = 21 dB.

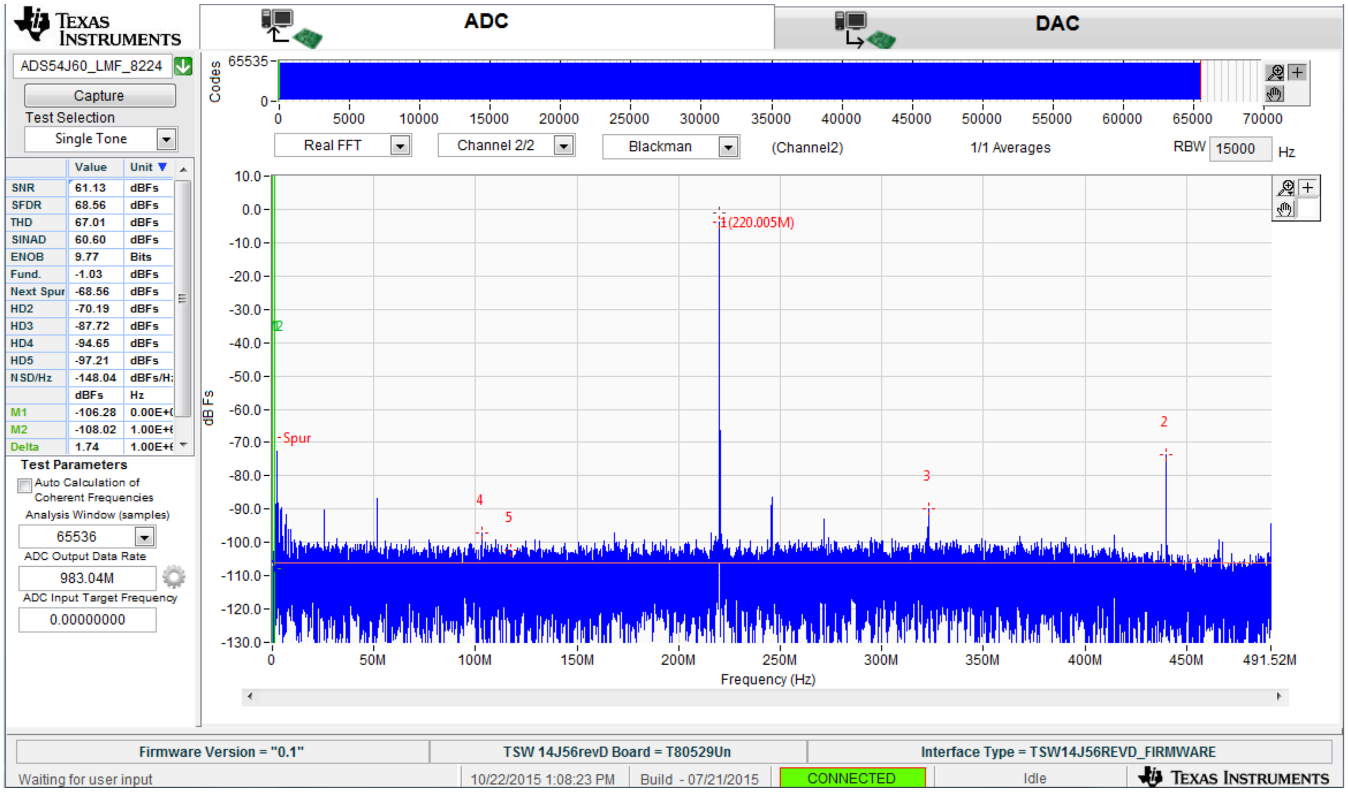

Figure 9. 220 MHz IF, AC-Coupled, LMH6401 Gain = 21dB

Figure 10 shows the 220 MHz IF, AC-Coupled, LMH6401 Gain = 16 dB.

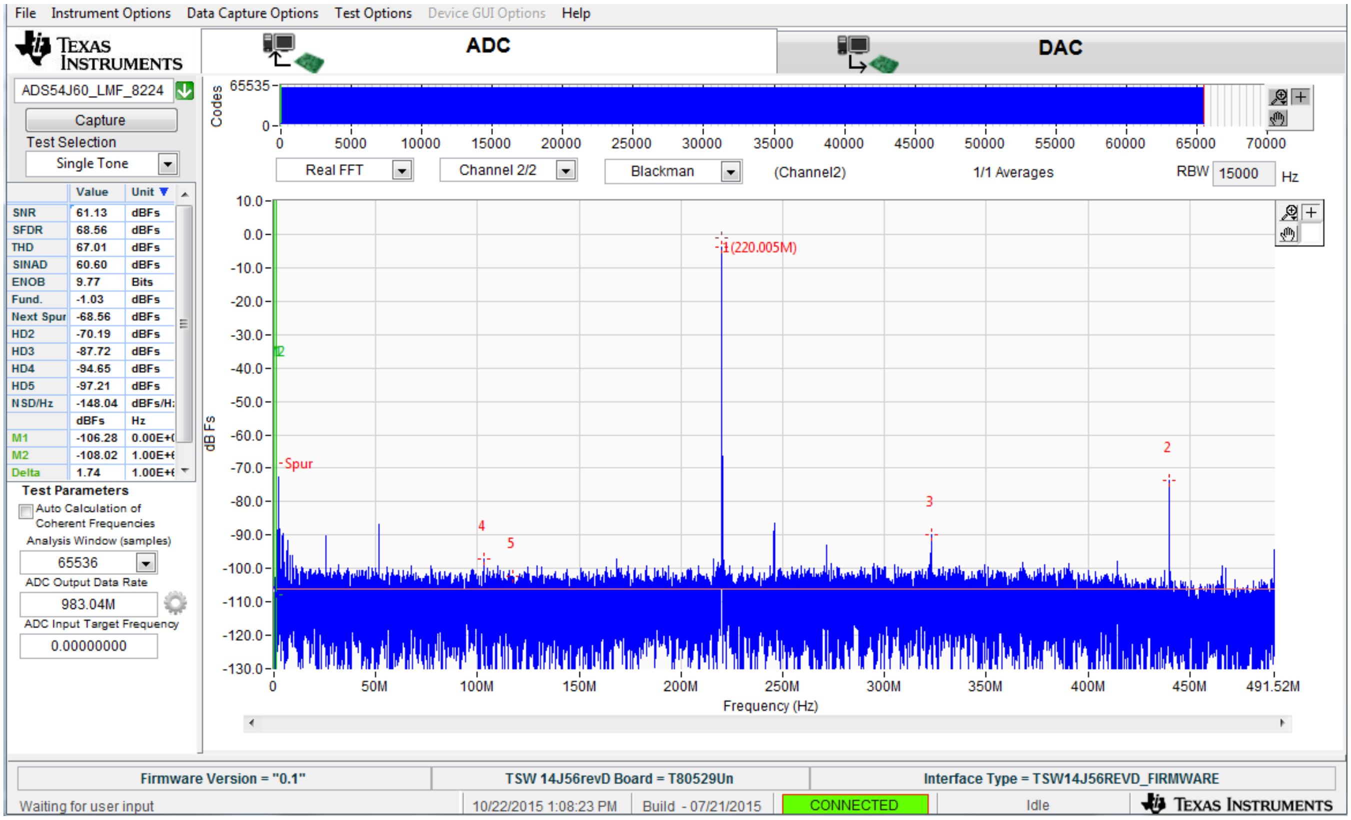

Figure 10. 220 MHz IF, AC-Coupled, LMH6401 Gain = 16 dB

The measured results show that the LMH6401 device is a good solution to drive a high-speed ADC such as the ADS54J60 device for high speed, wide input voltage range digitizer applications. The LMH6401 device can be set in either DC-coupled or AC-coupled configuration. An important consideration is proper common-mode biasing. One difficulty with the DC-coupling case is the need to provide the optimal common-mode voltage at the amplifier output pins and the ADC input pins. Another challenge with DC coupling is the need to level shifted the DC source to the amplifier's input common mode voltage.

In terms of SNR and SFDR, the performance can be improved if time is spent to optimize the interface circuit and filtering, likely further than what is shown in this document. One way of improving the SFDR performance is by designing the output filter with lower termination resistor values at the amplifier output and keeping the same ADC input impedance. Such an output filter design lowers the amplifier output swing for the same full-scale input at the ADC and would result in lower SFDR. The limitation in terms of SFDR performance is the second harmonic coming from the LMH6401 device when driven by a transformer. The HD2 performance can be improved by using a high performance balun such as a Marki BAL-0010 in front of the amplifier to do the conversion from single-ended to differential, however this can only be used when AC coupling is allowed. An additional high speed differential amplifier could also be used in front of the LMH6401, such as a LMH5401 to provide DC level shifting and single-ended to differential conversion.

9 Design Files

9.1 Bill of Materials

Table 4 lists the bill of materials.

Table 4. Bill of Materials

ITEM	QTY	PART REFERENCE	VALUE	PCB FOOTPRINT	MANUFACTURER NAME	MANUFACTURER PART NUMBER	NOTE
1	4	C1, C3, C14, C16	.01 uF	0306	Murata	LLL185R71E103MA01L	
2	4	C2, C4, C15, C17	2200 pF	0306	Murata	LLL185R71H222MA01L	
3	14	C5, C10, C13, C18, C24, C27, C101, C104, C197, C198, C200–C203	.01 uF	0402	Murata	GRM155R71H103JA88D	
4	0	C6, C19	5.6 pF	0402	AVX Corp	MK02275R6BAT2A_DNI	DNI
5	2	C7, C20	9 pF	0402	Murata	GJM1555C1H9R0CB01D	
6	2	C5, C10, C13, C18, C24, C27, C101, C104, C197, C198, C200–C203	6.2 pF	0402	Murata	GJM1555C1H6R2CB01D	
7	32	C6, C19	.1 uF	0402	Murata	GRM155R71C104KA88D	
8	2	C7, C20	9 pF	TANT_A	AVX	TPSA106K010R0900	Low ESR or equivalent
9	38	C8, C21	.1 uF	0201	Murata	GRM033R61A104KE15D	
10	16	C9, C12, C23, C26, C35, C65, C73–C75, C79–C84, C86–C91, C93, C95, C97, C117–C119, C122–C124, C132, C133	.01 pF	0603	AVX	06035C103JAT2A	
11	0	C11, C25	.68 pF	0402	Murata	GRM155R71C104KA88D_DNI	
12	2	C28–C34, C36–C62, C66, C67, C70, C71	47 pF	0201	TDK	C0603X5R1A103K030BA	
13	1	C63, C147–C149, C158–C160, C171–C173, C182–C184,C193–C195	3900 pF	0402	Murata	GRM155F50J684ZE01D	
14	3	C64, C72	100 pF	0402	Murata	GRM1555C1H470FA01D	DNI
15	1	C68, C69	10 uF	0402	Murata	GRM155R71H392KA01D	
16	2	C76	2200 pF	0402	AVX Corp	06031A101GAT2A	
17	4	C77, C120, C121	10 pF	0603	TDK	C1608X5R1C106M080AB	
18	1	C78	1 uF	0402	Murata	GRM155R71E222KA01D	

Table 4. Bill of Materials (continued)

ITEM	QTY	PART REFERENCE	VALUE	PCB FOOTPRINT	MANUFACTURER NAME	MANUFACTURER PART NUMBER	NOTE
19	1	C85, C92	10 pF	0402	Murata	GRM1555C1H100JA01D	
20	9	C99, C102, C105, C108, C112–C116	1 uF	0402	TDK	C1005X5R1C105K050BC	
21	4	C100, C103, C129, C136	10 uF	3528	Kemet	T520B106M016ATE100	Low ESR or equivalent
22	0	C106, C107, C109-C111	.01 uF	0402	Murata	GRM155R71H103JA88D_DNI	DNI
23	1	C125	47 uF	TANT_B	AVX	TPSB476K010R0250	
24	16	C126, C140, C145, C150, C151, C156, C161, C164, C169, C174, C175, C180, C185, C186, C191, C196	10 uF	0805	Murata	GRM21BR61E106KA73L	
25	4	C128, C135, C139, C163	22 uF	0603	TDK Corp	C1608X5R0J226M080AC	
26	7	C130, C137, C141, C152, C165, C176, C187	0.1 uF	0603	AVX	0603YC104KAT2A	
27	2	C131, C199	1000 pF	0603	Kemet	C0603C102K3RACTU	
28	10	C142, C146, C153, C157, C166, C170, C177, C181, C188, C192	1 uF	0603	TDK	C1608X7R1E105K080AB	
29	5	C143 C154 C167 C178 C189	47 uF	1206	Murata	GRM31CR61A476ME15L	
30	5	C144, C155, C168, C179, C190	33 uF	TANT_B	AVX	TPSB336K016R0350	
31	4	D1-D4	LED Green	LED_1206	Lite On	LTST-C150KGKT	DNI
32	0	F1	FUSE 10 A 63 V FAST	1206	TE Connectivity	1206SFF200F/63-2_DNI	
33	16	FB1-11, FB13-FB17	120 Ω at 100 MHz	1206	Murata	BLM31PG121SN1L	
34	1	FB12	1 k Ω at 100 MHz	1806	Murata	BLM41PG102SN1L	
35	2	FLT1, FLT2	FILTER LC HIGH FREQ, .2 uF	1806_BEAD_NFM41P	Murata	NFM41PC204F1H3L	
36	5	J1-5	CONN, SMA, JACK, 50 Ω, EDGE MNT	SMA_SMEL_DUAL_PSF-S01_250x215	Johnson Components	142-0711-821	
37	1	J6	CONN, SMA, JACK, 50 Ω , THVT	SMA_THVT_312x312	Johnson Components	142-0701-201	
38	1	J7	CON, SMVT, HS, FIELD ARRAY, 400POS, MALE	SMA_THVT_312x312	Samtec	SEAM-40-02.0-S-10-2-A-K-TR	
39	1	J8	CONN, USB MINI AB, SMT	CON_SMRT_USBMNE20_F	Wurth ELektronik	651305142821	
40	1	J9	CONN, JACK, PWR, MINI, R/A, TH	CON_RAPC722_JACK_THVT_3	Switchcraft	RAPC722X	

Table 4. Bill of Materials (continued)

ITEM	QTY	PART REFERENCE	VALUE	PCB FOOTPRINT	MANUFACTURER NAME	MANUFACTURER PART NUMBER	NOTE
41	2	JP1. JP2	HDR, THVT, 2POS, .100	HDR_THVT_1x2_100_M	Samtec	HTSW-102-07-G-S	
42	4	L1. L3, L5, L7	7.5 nH	ind_0603	Coilcraft	0603CS-7N5XGEU	
43	4	L2 L4 L6 L8	18 nH	ind_0603	Coilcraft	0603CS-18NXGEU	
44	1	L9	1.5 uH	2016	Toyo	1286AS-H-1R5M	
45	2	MT1, MT2	STANDOFF, FEMALE, 4-40 X 1 3/16", AL	MFG125_PLATED	Raf	1648-440-AL	
46	0	PP1	PROBE POINT	PROBE_POINT_30PAD	N/A	N/A	
47	1	Q1	CSD17313Q2	mosfet_8_2mmx2mm_0p65	Texas Instruments	CSD17313Q2	
48	4	R2, R14, R17, R25	4.99	0402	Vishay Dale	CRCW04024R99FKED	
49	0	R3, R10	129	0402	Panasonic	ERJ-2RKF1270X_DNI	DNI
50	0	R4, R15, R19, R26	A/R	0402	DNI	DNI	DNI
51	4	R5, R9, R20, R23	53.6	0402	Panasonic	ERA-2AEB53R6X	
52	9	R7, R21, R38, R39, R41, R64, R67, R119, R125	0	0402	Panasonic	ERJ-2GE0R00X	
53	0	R11	365	0402	Panasonic	ERJ-2RKF3650X_DNI	DNI
54	6	R12, R18, R22, R42, R49, R51	49.9	0402	Panasonic	ERJ-2RKF49R9X	
55	4	R16, R24, R29, R33	20	0402	Panasonic	ERJ-2RKF20R0X	
56	5	R27, R28, R30, R31, R74	1 k	0402	Panasonic	ERJ-2RKF1001X	
57	2	R32, R34	100	0201	Panasonic	ERJ-1GEF1000C	
58	1	R36	240	0402	Panasonic	ERJ-2GEJ621X	
59	1	R37	0	0402	Panasonic	ERJ-2GEJ393X	
60	0	R40	100	0402	Panasonic	ERJ-2RKF1000X_DNI	DNI
61	4	R43, R44, R46, R47	750	0402	Panasonic	ERJ-2RKF2400X	
62	0	R45, R54, R55, R57, R120-R124, R126, R131, R132	2.1 k	0402	Panasonic	ERJ-2GE0R00X_DNI	DNI
63	2	R48, R58	100	0402	Panasonic	ERJ-2RKF1000X	
64	3	R50, R52, R53	750	0603	Vishay Dale	CRCW0603750RFKEA	
65	1	R56	2.1 k	0402	Panasonic	ERJ-2RKF2101X	

Table 4. Bill of Materials (continued)

ITEM	QTY	PART REFERENCE	VALUE	PCB FOOTPRINT	MANUFACTURER NAME	MANUFACTURER PART NUMBER	NOTE
66	1	R59	48.7 k	0402	Panasonic	ERJ-2RKF4871X	
67	3	R60–R62	4.75 k	0402	Panasonic	ERJ-2RKF4751X	
68	0	R63, R82, R84, R85, R89, R91, R92, R99, R102, R104, R106, R109, R111, R113–R115, R117, R118	0	0603	Panasonic	ERJ-3GEY0R00V_DNI	DNI
69	3	R65 R69 R70	22.1	0402	Panasonic	ERJ-2RKF22R1X	
70	14	R68, R83, R86, R87, R90, R93, R94, R100, R101, R103, R107, R108, R110, R116	0	0603	Panasonic	ERJ-3GEY0R00V	
71	1	R76	1.05 M	0603	Vishay Dale	CRCW06031M05FKEA	
72	1	R77	200 k	0603	Panasonic	ERJ-3EKF2003V	
73	5	R78, R88, R95, R105, R112	47.5 k	0603	Panasonic	ERJ-3EKF4752V	
74	1	R80	590 k	0603	Panasonic	ERJ-3EKF5903V	
75	2	R81, R98	162 k	0603	Panasonic	ERJ-3EKF1623V	
76	1	R96	301 k	0603	Panasonic	ERJ-3EKF3013V	
77	0	SJP1	JUMPER_L_0603_SMT	JUMPER_SMD_L_0603	DNI	DNI	
78	0	SJP2	SOLDER JUMPER, 0603	JUMPER_SMT_1x2_0603	DNI	DNI	Shunt 1–2
79	0	SJP3	JUMPER_L_0603_SMT	JUMPER_SMD_L_0603	DNI	DNI	Shunt 2–3
80	1	SW1	SWITCH, SMT, PUSHBUTTON, SPST	SW_SMVT_SPST_EVQPJX_2	Panasonic	EVQ-PNF04M	
81	1	T1	JTX-2-10T+	XFMR_6_310X280_100	Mini-Circuits	JTX-2-10T+	
82	1	T2	JTX-2-10T+	XFMR_6_310X280_100	Mini-Circuits	JTX-2-10T+	
83	9	TP1, TP7–TP10, TP13–TP16	Red	TESTPOINT_62DRILL_THM	Keystone	5000	
84	7	TP2–TP6, TP11, TP12	Black	TESTPOINT_62DRILL_THM	Keystone	5001	
85	1	U1	LMH3401	QFN_14_98x98_0P50MM	Texas Instruments	LMH3401IRMS	
86	1	U2	LMH6401	UQFN_16_118x118_0P5mm_RMZ	Texas Instruments	LMH6401IRMZ	
87	1	U3	ADS54J60	QFN_72_10MMX10MM_0P50MM_PWRPAD	Texas Instruments	ADS54J40IRGC	
88	1	U4	LMK04828	QFN_64_360X360_0P50MM_PWRPAD	Texas Instruments	LMK04828BISQ/NOPB	

Table 4. Bill of Materials (continued)

ITEM	QTY	PART REFERENCE	VALUE	PCB FOOTPRINT	MANUFACTURER NAME	MANUFACTURER PART NUMBER	NOTE
89	1	U5	SN65LVDS4	QFN_10_81X61_RSE	Texas Instruments	SN65LVDS4RSET	
90	2	U6, U8	TXB0104	VQFN_14_138x138_0P50_RGY	Texas Instruments	TXB0104RGYR	
91	1	U7	FT245RL	SSOP_28_413x220_26	FTDI Chip	FT245RL-REEL	
92	1	U9	TPS63050	DSBGA_12_1P56MMx1P16MM_YFF	Texas Instruments	TPS63050YFF	
93	2	U10	TPS2400	DBV5	Texas Instruments	TPS2400DBVT	
94	2	U11, U15	TPS82085	uSIL_8_3MMx2p8MM_0p65mm	Texas Instruments	TPS82085SIL	
95	5	U12–U14, U16, U17	TPS7A8300	VQFN_20_138x138_0P50_RGR	Texas Instruments	TPS7A8300RGR	
96	1	Y1	122.88 MHz	VCXO_6_CUSTOM	Crystek	CVHD-950-122.880	
97	1		BARE BOARD, TSW54J60		TTM	TSW54J60 REV B	
98	2		SCREW, 4-40 X 3/4", PHIL, SS		Building Fasteners	PMSSS 440 0075 PH	Screw for standoff
99	2	SEE NOTE 3	SHUNT-JUMPER-0603		Panasonic	ERJ-3GEY0R00V	Shunt for jumper

9.2 Software Files

To download the software files, see the design files at TSW54J60EVM

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