TI Designs
High-Q Active Differential Band-Pass Filter Reference Design for Instrumentation Qualification

Description

High quality filters are a critical component in the test and measurement of high-precision data acquisition (DAQ) systems. However, realizing a high-quality filter at low frequencies with passive components requires large inductors that are both size and cost prohibitive. The TIDA-01036 analyzes the benefits and tradeoffs of using an active sixth order multi-feedback architecture using TI's high performance fully differential THS4551 amplifier. All key design theories are described guiding users through the schematic, board layout, and hardware testing. Measured results demonstrating better than a 16-bit performance are also presented in Section 3.3.

Resources

TIDA-01036	Design Folder
THS4551	Product Folder
OPA376	Product Folder
THS4551 EVM-PDK	Associated Design
TINA-TI™	Product Folder

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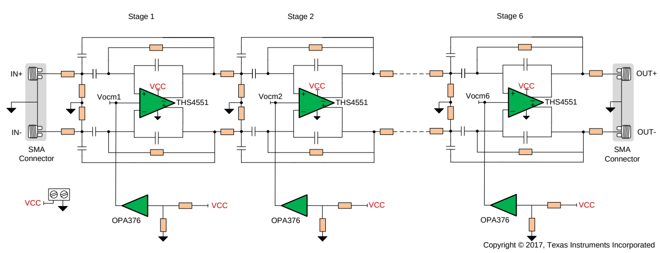
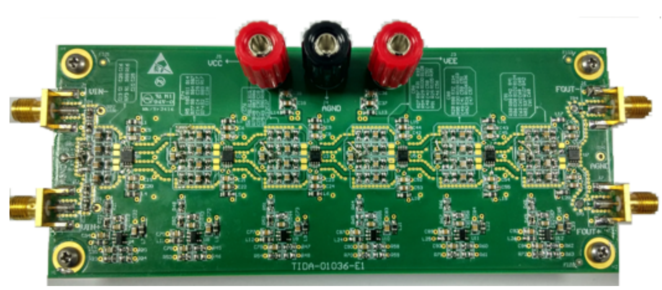
Features

- Differential Input Band-Pass Filter Suitable for 16-Bit Systems (16.6 ENOB at 2 kHz)
- Supports up to 100-kHz Center Frequency With System ENOB Better Than 14 Bits
- Multiple Feedback Filter Topology for Achieving High Filter Quality Factor
- Uses THS4551 Fully Differential Amplifier (FDA) for Low Distortion and High SNR
- Compact Solution That Replaces Bulky High Order Passive Filter Suitable for DAQ Module Testing
- Includes Theory, Calculations, Component Selection, PCB Design, and Measurement Results

Applications

- Data Acquisition (DAQ)
- Lab Instrumentation
- High-Performance Device Characterization (ADC and DAC) and Validation
- Signal Conditioner for Analog Front-End (AFE)
- Signal Generator
- Baseband Filter





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1 System Overview

A filter is a device that passes electrical signals at a certain frequency range with no or little attenuation and rejects other frequency components. The applications of filters are wide in nature. In the field of telecommunication, band-pass filters are used in audio frequency range (0 to 20 kHz) for modem and speech processing. High frequency band-pass filters (greater than several MHz) are used in RF transmit and receive applications for channel selection. The low-pass anti-analyzing filters is used in front of data convertors and noise filters are used in nearly all signal chain applications such as data acquisition (DAQ) systems. In power supplies, band-reject filters are used to suppress a 50- to 60-Hz line frequency.

1.1 System Description

Filters can be classified as passive or active. Passive filters are made of only passive components such as resistors (R), capacitors (C), and inductors (L) requiring no external power. Typically, passive filters are used in high frequency applications (> 1 MHz) and are called passive LRC filters. For low-frequency applications (< 1 MHz), these passive filters require very large inductors, which increase system size and cost. In such applications, active filters are often preferred in order replace large inductors. Active filters require an external, but usually small power source to power an operation amplifier (op amp) that is used to replace the inductor and achieve similar performance to passive filters.

The filters can be classified according to their characteristics:

- Low-pass filter
- High-pass filter
- Band-pass filter
- Band-stop filter or band-reject filter
- All-pass filter (used to introduce constant time delay or linear phase delay)

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Number of channels	1
Differential	Differential
Input range	±5-V fully differential
Input impedance	600 Ω
Center frequency F_C	2 kHz
Band-pass region (–3-dB BW)	250 Hz
Band-pass ripple	< 1 dB
Stop band attenuation	80 dB
Stop band (BW)	1.29 kHz
Selectivity (Q-factor)	10
System performance (ENOB)	16 bits
Operating temperature	0°C to 60°C
Storage temperature	–40°C to 85°C
Connectors	SMA connector for input and output
Power	5-V DC, 200 mA
Form factor	145 mm × 60 mm

1.3 Block Diagram

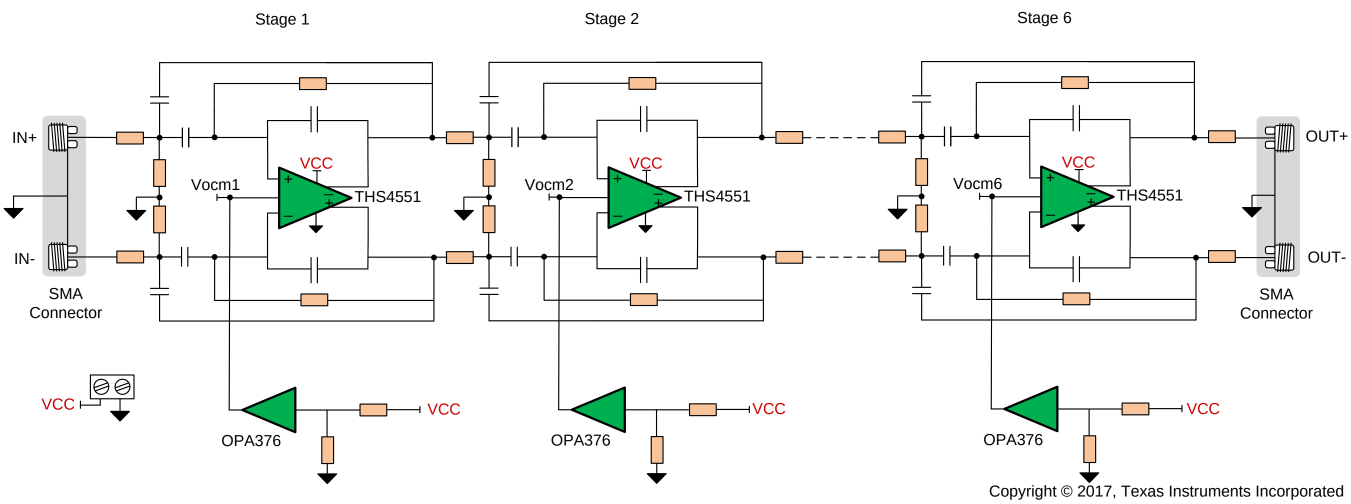


Figure 1. TIDA-01036 System Block Diagram

1.4 Highlighted Products

This TI Design contains a number of highlighted parts that determine the overall system performance:

- THS4551: The THS4551 fully differential amplifier offers an easy interface to the high-precision and high-speed differential ADC. This device has very low DC error and drift support for the emerging 16- to 20-bit SAR ADC input requirement. With the exceptional DC accuracy, low noise, and robust capacitive load driving capability, this device is well suited for DAQ systems where high precision is required along with the best signal-to-noise ratio (SNR) and spurious-free dynamic range (SFDR) through the amplifier and ADC combination.
- OPA376: The OPA376 op amp offer low noise with outstanding DC and AC performance. The device's very low offset (25 µv max), low noise (7.5 nV/√Hz), low quiescent current makes it an ideal choice for low power and portable applications. The device supports rail-to-rail input/output with a 5-V single supply operation.

1.5 Design Considerations

1.5.1 Multiple Feedback Topology (MFT)

Multiple feedback filters are popular configurations for band-pass filters because they possess a very high quality factor (Q) and sensitivity. It is because of these characteristics a multiple feedback filter topology was selected. MFTs use op amps as an integrator, thus the filtering characteristics are then dependent on the op amp transfer function. The open loop gain of the op amp should be at least 20 dB (×10) greater than the amplitude response at the resonant (or cutoff) frequency, including Q induced filter peaking. Figure 2 illustrates a single-stage single-end band-pass MFT. The single-stage fully differential equivalent is shown in Figure 3. Note that the output phase will be inverted from the input 180°.

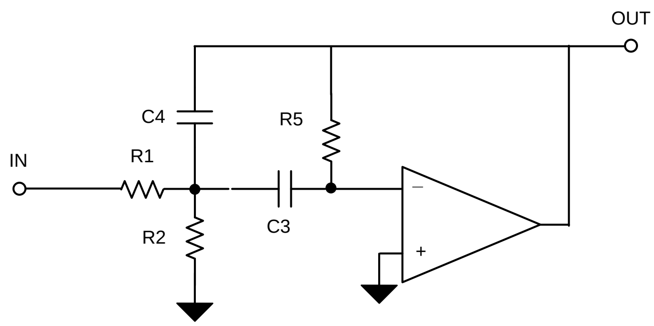


Figure 2. Multiple Feedback Band-Pass Filter (Single-Ended)

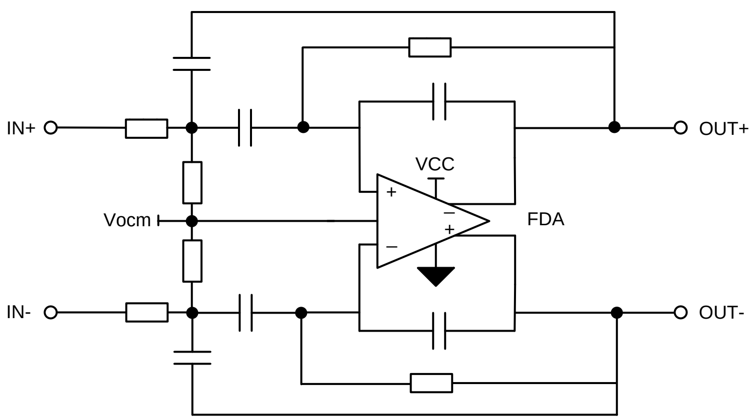


Figure 3. Multiple Feedback Band-Pass Filter (Fully Differential)

1.5.2 High-Q Filter Requirement

Very high-performance test applications require harmonic free signal sources. Despite quality designing and manufacturing, many high quality signal sources possess seven harmonics, which is not acceptable for the characterization of high performance electronics such as amplifiers, data convertors (ADC or DAC), filters, and DAQ modules. In order to minimize the impact of non-ideal sources, typically, high-Q filters are used to remove unwanted harmonics, improving THD and ultimately SNR. The TIDA-01036 design demonstrates how to implement an active sixth-order multiple feedback filter using TI's THS4551 fully differential amplifier (FDA) capable of replacing bulky and expensive passive filters that are used to characterize the 16-bit and higher signal paths.

Figure 4 shows how the TIDA-01036 design can be used to filter a source supply required for testing a high-performance signal chain. Here, the active filter is connected between the signal source generator and device under test (DUT). Typically, the DUT will be an amplifier, data converter, or DAQ system of some verity. As shown in Figure 4, the source signal quality is significantly improved by filter nearly all higher-order harmonics before being applied to the DUT.

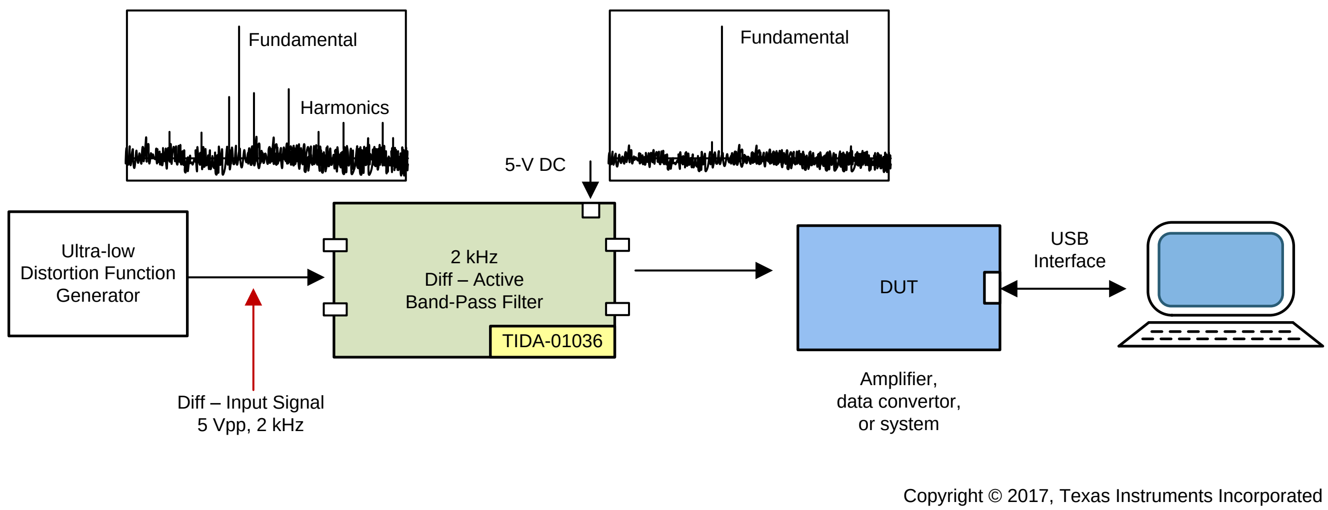


Figure 4. System or Device Characterization Test Setup With TIDA-01036

1.5.3 Circuit Design

1.5.3.1 Band-Pass Filter Stage

Figure 5 shows the first stage of differential filter, and Table 2 shows associated passive feedback network component terms. The TIDA-01036 design has up to six stages, each containing a THS4551 FDA with a resistor and capacitor feedback network containing different values. Using a higher filter order increases selectivity (Q-factor) and stops band roll-off rate.

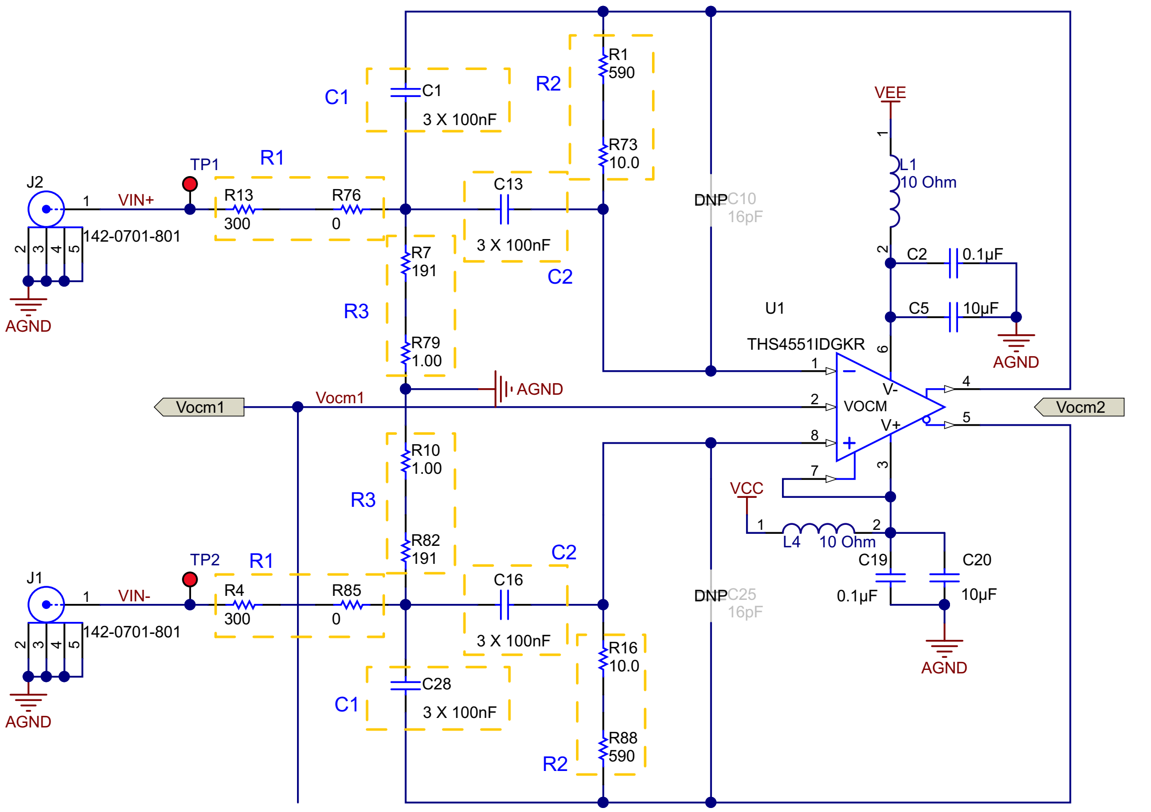


Figure 5. Differential Band-Pass Filter

The single stage transfer function is given in Equation 1 where the corresponding passive elements are highlighted in Figure 5.

$$\frac{-\left(\frac{s}{R1\times C2}\right)}{s^2+\frac{s(C1+C2)}{C1\times C2\times R2}+\frac{R1+R3}{C1\times C2\times R1\times R2\times R3}} \qquad (1)$$

Table 2. Feedback Component Terms

REFERENCE	DESCRIPTION
R1	Input resistor
R2	Feedback resistor
R3	Gain resistor
C1	Capacitor
C2	Capacitor

1.5.3.2 Output Common-Mode (V_{OCM}) Generation

The FDA common-mode voltage (V_{OCM}) should be maintained at mid-supply to achieve maximum output dynamic range. The V_{OCM} generation is achieved using a supply voltage resistive divider network as shown in Figure 6. This mid-supply voltage is buffered using the OPA376 op amp with in the loop compensation method. This configuration has good stability when driving larger capacitive loads.

Resistor R22 is an isolation resistor that is connected in series between the op amp output and the capacitive load to provide isolation and improve stability. Feedback capacitor, C31, becomes the dominant AC feedback path at higher frequencies. This configuration allows heavy capacitive loading while keeping the loop stable. The combination of resistor R21 and capacitor C33 forms low-pass filter with a cutoff frequency of 159 Hz, effectively suppressing ripple and noise.

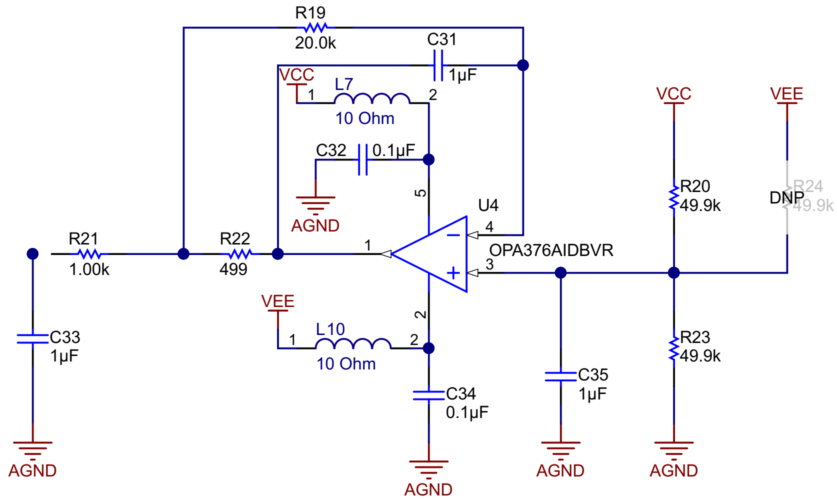
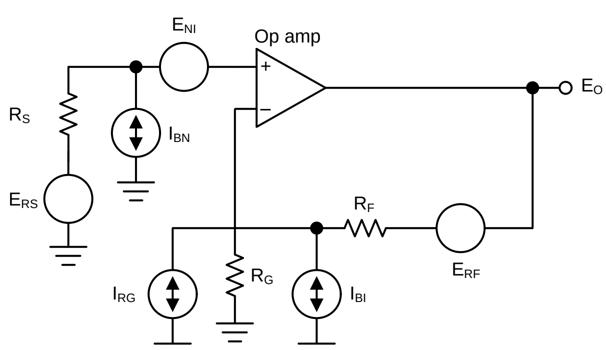


Figure 6. V_{OCM} Generation

1.5.3.3 Noise Analysis

The op amp noise model and its corresponding noise source definitions are given in Figure 7. The detailed noise analysis of operational amplifiers can be found in application notes *Noise Analysis in Operational Amplifier Circuits*[1] and *Op Amp Noise Theory and Applications*[3].



$$4kT = 16E-20J \times \frac{T}{290°K}$$

where:

T is temperature in Kelvin

E_{NI} = Op amp non-inverting input noise current

I_{BI} = Op amp inverting noise current

E_{RS} = Source resistor noise voltage = $\sqrt{4kTR_S}$

E_{RF} = Feedback resistor noise voltage = $\sqrt{4kTR_F}$

I_{RG} = Gain setting resistor noise current = $\sqrt{\frac{4kT}{R_G}}$

Figure 7. Noise Model for Non-Inverting Configuration

Normally, the resistor noise terms are considered to have a constant noise voltage (or current) density over frequency; however, along with this Johnson noise, there is also a low-frequency component, excess noise, that is dependent on the DC voltage across the resistor.

Computing the total output noise assuming:

$(1 + R_F/R_G) \equiv G_N$ = Noise gain (identically equal to the op amp non-inverting signal gain). First, find the gain to the output for each voltage or current noise term by superposition:

Table 3. Noise Term

NOISE TERM	GAIN
E_{NI}	G_N
I_{BN}	$R_S \times G_N$
E_{RS}	G_N
I_{BI}	R_F
E_{RF}	1
I_{RG}	R_F

$$E_O = \sqrt{(E_{NI}G_N)^2 + (I_{BN}R_SG_N)^2 + 4kTR_SG_N^2 + (I_{BI}R_F)^2 + 4kTR_F + \frac{4kT}{R_G}R_F^2} \tag{2}$$

Equation 2 helps to find out noise terms for both stage 1 and stages 2 through 6 and are shown in Table 4.

Table 4. Noise Term (2-kHz Frequency)

NOISE TERMS	STAGE 1	STAGE 2 TO 6	GAIN	STAGE 1	STAGE 2 TO 6
E_{NI}	3.300000	3.300000	G_N	1	1
I_{BN}	0.000500	0.000500	$R_S \times G_N$	300 Ω	1000 Ω
E_{RS}	2.191430	4.001000	G_N	1	1
I_{BI}	0.000500	0.000500	R_F	600 Ω	600 Ω
E_{RF}	0.181989	0.332265	1	1	1
I_{RG}	0.000536	0.001230	R_F	600 Ω	600 Ω
Eo (nV/√Hz)	3.992000	5.857000	—	—	—

1.5.4 Simulation

The filter is designed to achieve a center frequency of 2 kHz in a fully differential configuration. The pass band of the filter is expected to be near 250 Hz to achieve a quality factor near 10 and the band-pass ripple is targeted to be less than 1 dB as is the characteristic of a Butterworth filter.

1.5.4.1 Theoretical Calculation

Equation 3 to Equation 7 help to find out component values, pass-band gain, and cutoff frequency.

$$\text{Input Resistance R1} = \frac{Q}{G \times 2\pi f \times C} \tag{3}$$

$$\text{Attenuator Resistance R2} = \frac{Q}{(2Q^2 - G) \times 2\pi f \times C} \tag{4}$$

$$\text{Feedback Resistance R3} = \frac{Q}{\pi f \times C} \tag{5}$$

$$\text{Pass-Band Gain G} = \frac{1}{\frac{R1}{R3} \times 2} \tag{6}$$

$$\text{Center Frequency } F_C = \frac{1}{(2\pi \times C) \times \sqrt{\frac{R1 + R2}{R1 \times R2 \times R3}}} \tag{7}$$

1.5.4.2 Target Specification

The target specification is derived to obtain the 16-bit performance is listed in Table 5.

Table 5. Band-Pass Filter Target Specification

PARAMETER	SPECIFICATIONS
Input impedance	600 Ω
Center frequency F_C	2 kHz
Band-pass region (–3-dB BW)	250 Hz
Band-pass ripple	< 1 dB
Stop band (BW)	1.29 kHz
Selectivity (Q-factor)	10

1.5.4.3 Component Value Obtain for Targeted Specification

Assume Gain (G) = 1, Frequency (Fc) = 2 kHz, Capacitor (C) = 300 nF, and Q-factor (Q) = 1.13 for the first stage. Substituting in Equation 3 to Equation 7, the results obtained are as follows:

Table 6. First Stage Component Value

RESISTOR		FIRST STAGE
Input resistor (Ω)	R1	300.0
Attenuator resistor (Ω)	R2	192.5
Feedback resistor (Ω)	R3	600.0

Similarly, find other stages with Gain (G) = 1, Frequency (Fc) = 2 kHz, Capacitor (C) = 300 nF, and Q-factor (Q) = 3.77 for the second to sixth stage.

Table 7. Second to Sixth Stage Component Value

RESISTOR		SECOND TO SIXTH STAGE
Input resistor (Ω)	R1	1000.0
Attenuator resistor (Ω)	R2	36.5
Feedback resistor (Ω)	R3	2000.0

1.5.4.4 TINA Simulation Result

Figure 8 and Table 8 show the filter response obtained from the TINA simulation.

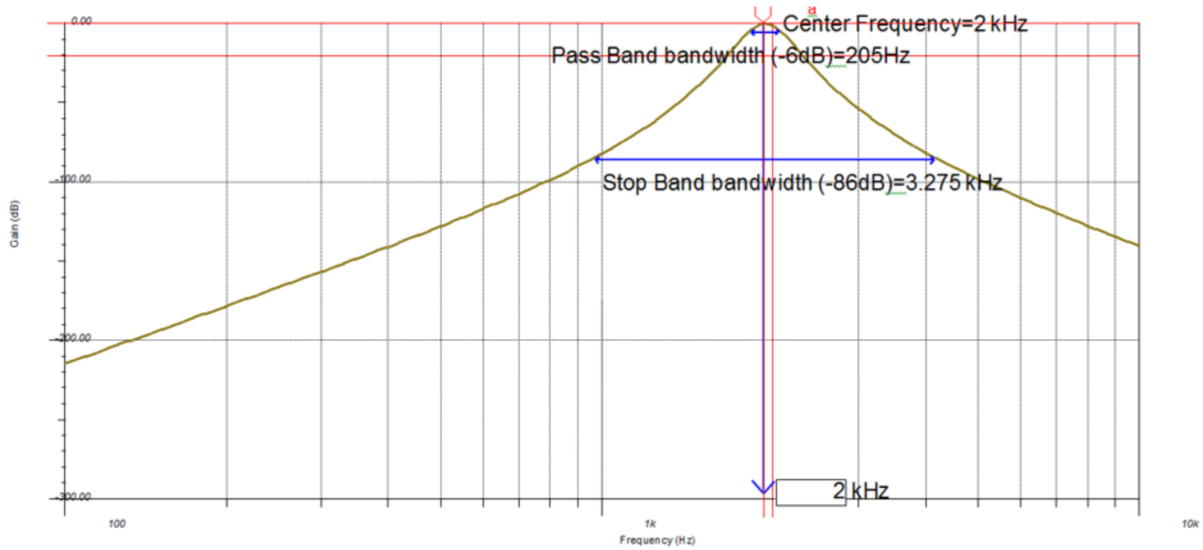


Figure 8. TINA Simulation—Frequency Response

Table 8. TINA Simulation Result

PARAMETER	EXPECTED	SIMULATED
Gain	0 dB	–0.1 dB
Center frequency	2 kHz	2 kHz
Bandwidth	215 Hz	205 Hz
Q factor	9.28	9.75
Stop band attenuation	> 80 dB	–86 dB

Figure 9 and Table 9 show the noise analysis obtained from the TINA simulation.

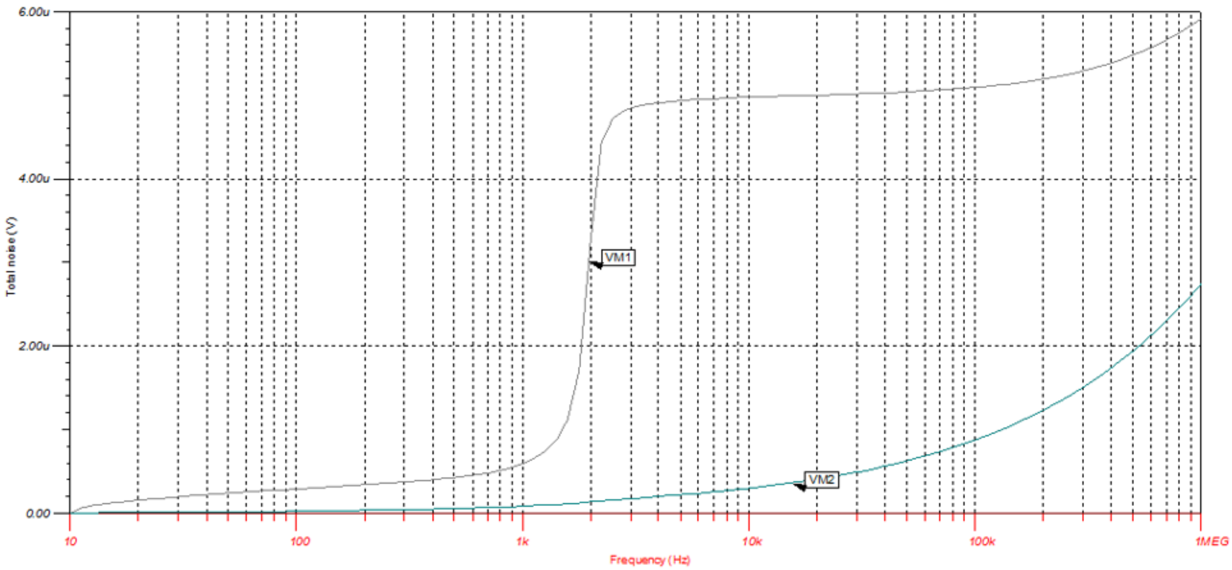


Figure 9. TINA Simulation—Phase Response

Table 9. TINA Noise Result

PARAMETER	SIMULATED
Signal amplitude	1 Vpp
Noise	6 µV
SNR	104 dB

2 Getting Started Hardware and Software

2.1 Hardware

Figure 10 highlights various hardware inputs and outputs of the TIDA-01036 board:

1. Connector J3, J4, and J5 accept the power supply (+5V, GND, and –15 V, respectively)
2. SMA connector (J1,J2) accepts differential input signal
3. SMA connector (J5,J6) outputs differential filtered output

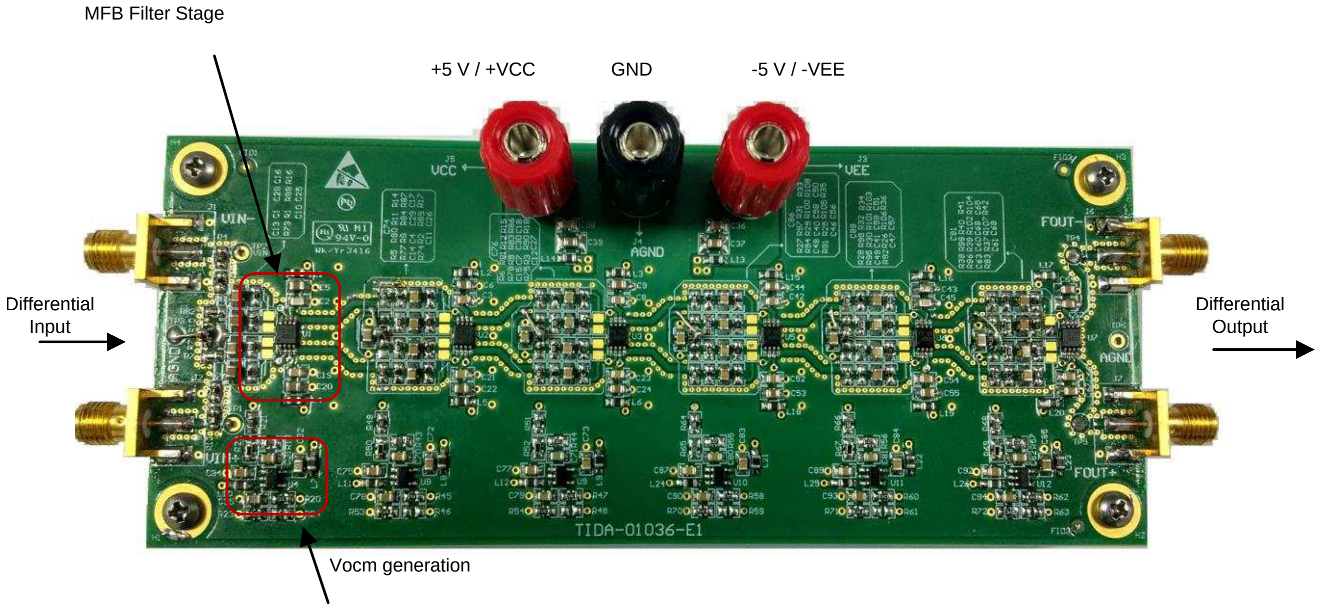


Figure 10. TIDA-01036 Hardware

2.2 Application GUI

The PHI GUI software, which is based on the LabVIEW™ platform, validates the TIDA-01036 hardware using either the TIDA-00732 or TIDA-01035 reference design. Figure 11 shows the available test options in PHI GUI.

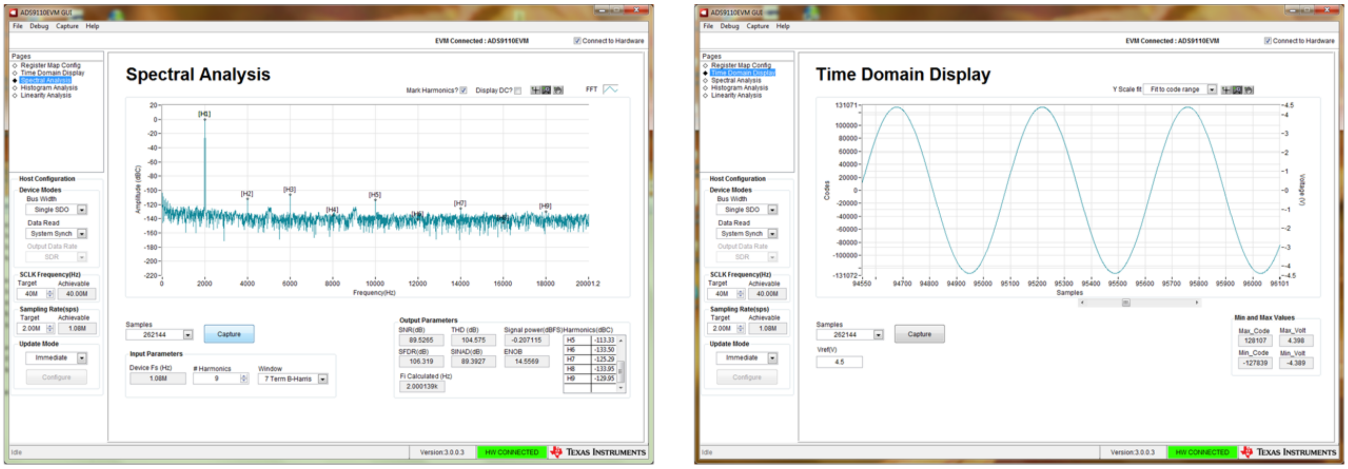


Figure 11. PHI GUI Demonstrate AC Parameter Analysis (Spectral, Time Domain)

The PHI GUI can be used to validate the following system key specifications:

1. Spectral analysis
   - SNR
   - THD
   - SFDR
   - SINAD
   - ENOB
2. Linearity analysis
   - DNL
   - INL
   - Accuracy
3. Histogram analysis
   - Effective resolution

Find the PHI GUI software at the ADS9110 product page.

3 Testing and Results

The validation can be done with two test methods:

1. Frequency response test
2. System and device characterization

3.1 Frequency Response Test

Figure 12 shows the frequency response test setup where the Standard Research Systems DS360 precision, ultra-low distortion waveform generator is used as a generator and is capable of generating a sine pattern with a signal frequency range of 10 mHz to 200 kHz. The device needs high precision with very low ripple power supply to power the entire system. This TI Design requires 9- to 12-V DC at 250 mA with high precision and low ripple power. The 12-V DC voltage is generated using the Keithley triple output power supply (2230G). It is capable of generating up to 30 V with 0.03% of voltage accuracy and 0.1% of current accuracy with simultaneous voltage and current indication.

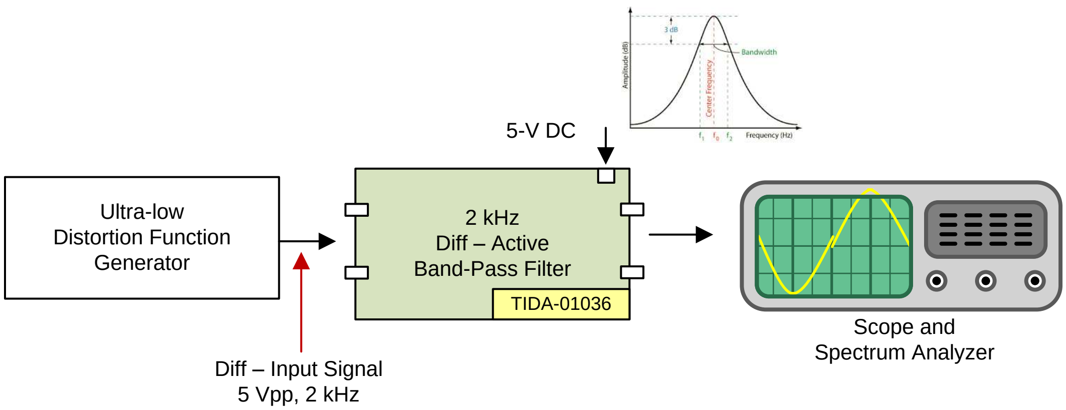


Figure 12. Frequency Response Test Setup

1. Connect 5-V DC of power to the TIDA-01036 board. Ensure the positive terminal is connected to the positive input (J5-VCC) and the negative terminal is connected to the negative input (J4-GND and J3-VEE).
2. Connect the differential output of the function generator to the differential input terminal (J1 and J2 SMA connector) of the TIDA-01036 board.
3. Connect the differential output of the TIDA-01036 (J7 and J8 SMA connector) to CH1 and CH2 of the oscilloscope.
4. Configure the scope in math function mode and set to calculate difference of channel 1 and 2.
5. Set the function generator output as 1Vpp, output source impedance as 600 Ω, and both channels set to AC coupling mode.
6. Vary the frequency from 500 Hz to 4 kHz in steps of 50 Hz and note down corresponding filter output at (J7 and J8).
7. Find the lower cutoff (F_1) and upper cutoff (F_2) frequency points from 6 dB apart from the center frequency (F_C).
8. Calculate the pass band and quality factor using Equation 8 and Equation 9:

$$\text{Pass-Band Bandwidth}\,(6\ \text{dB}) = (F_2 - F_1) \quad (8)$$

$$\text{Q-factor} = \frac{F_C}{\text{Pass-Band Bandwidth}\,(6\ \text{dB})} \quad (9)$$

9. Plot amplitude versus frequency to get filter frequency response plot.

Table 10 and Figure 13 shows frequency response test result of the TIDA-01036.

Table 10. Frequency Response Test

PARAMETER	VALUE
Lower cutoff frequency F_1	1930 Hz
Upper cutoff frequency F_2	2140 Hz
Pass-band bandwidth at 6 dB ($F_2 – F_1$)	210 Hz
Center frequency F_C	2040 Hz
Q-factor	9.71

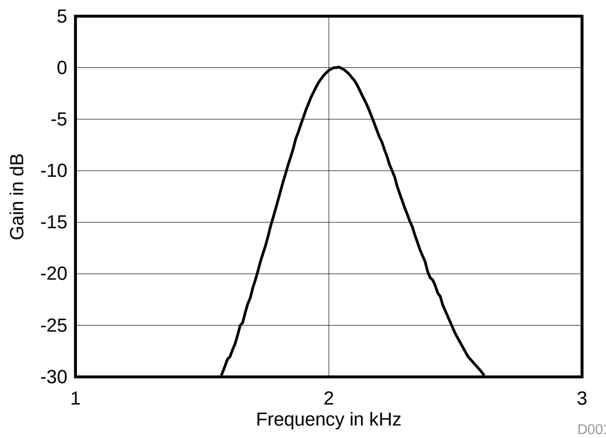


Figure 13. Frequency Response Result Graph

3.2 System and Device Characterization

Figure 14 demonstrates how the TIDA-01036 can be used as a high quality filter for characterizing high-performance DAQ systems. In this example, the DAQ module is a high-speed, 1-MSPS, high-resolution, 20-bit data bath. The Standard Research Systems DS360 precision ultra-low distortion waveform generator is used as a generator and is capable of generating a sine pattern with a signal frequency range of 10 mHz to 200 kHz. The device needs high precision with very low ripple power supply to power the entire system. This TI Design requires 9 to 12-V DC at 250 mA with high precision and low ripple power. The 12-V DC voltage is generated using Keithley triple output power supply (2230G). It is capable of generating up to 30 V with 0.03% voltage accuracy and 0.1% current accuracy with simultaneous voltage and current indication.

The data capturing is established using a USB 2.0 interface. The testing computer must have one USB port and support USB 2.0 specification.

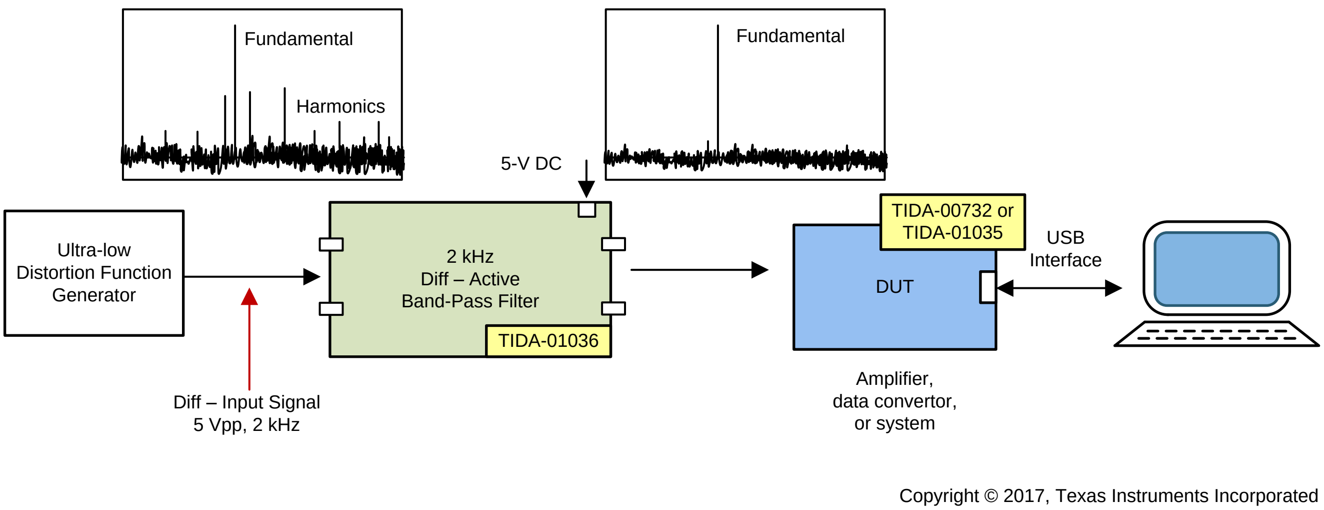


Figure 14. System and Device Characterization Setup

Install the PHI GUI software in the host computer before testing:

1. Plug the PHI interface board to the Samtec connector (J18).
2. Connect 12-V DC of power to the J5 connector of the TIDA-01035. Ensure the positive terminal is connected to the positive input (Pin 2 of J5) and the negative terminal is connected to the negative input (Pin 1 of J5).
3. Connect 5-V DC power to the TIDA-01036 board. Ensure the positive terminal is connected to the positive input (J5-VCC) and the negative terminal is connected to the negative input (J4-GND and J3-VEE).
4. Connect the differential output of function generator to the differential input terminal (J1 and J2 SMA connector) of the TIDA-01036 board.
5. Connect the differential output of the TIDA-01036 (J7 and J8 SMA connector) to (J7 and J8) of the TIDA-00732 board or J8 and J9 of the TIDA-01035 board.
6. Also, make sure both differential signals are balanced and configured as shown in Table 11.
7. Connect the PHI module to the PC or laptop using a microUSB cable.
8. Switch on the power supply.
9. Switch on the signal source and set the signal source parameter. Then, enable the output.
10. Run the PHI GUI software, go to spectrum analysis tab, and capture the results (SNR, THD) for various input signal frequencies.
11. Repeat the test without the TIDA-01036 and compare the results.

NOTE: The same process can be easily repeated using DAQ TI Designs TIDA-00732 or TIDA-01037 where the TIDA-01036 is used to replace the in-line passive filter used for characterization.

Table 11. Test Conditions

PARAMETER	VALUE
Pattern	Sine
Voltage	7.88 Vpp (adjust to –1 dB full scale)
Frequency	2 kHz
Source impedance	600 Ω

By default, the TIDA-01035 analog front-end is configured as unity gain and increased gain to 4 for TIDA-01036 testing. To increase gain, change the resistor values R82, R83 as 250 Ω, 1%; the location of the components in the TIDA-01035 are shown in Figure 15.

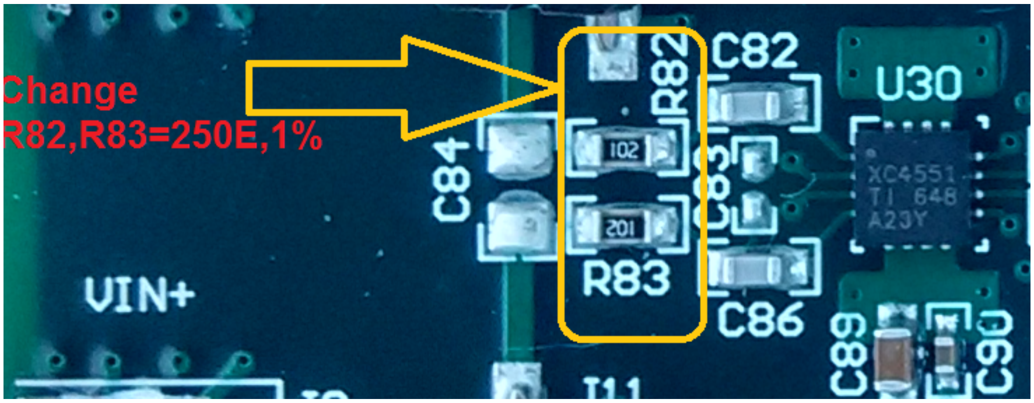


Figure 15. TIDA-01035 Resistor Change Location

3.3 Performance Test Result

Table 12 shows the performance test results of system and device characterization with and without the TIDA-01036 design. The test results show almost 9 dB of improvement in SNR and 2 dB of improvement in THD performance.

Table 12. Test Result—System and Device Characterization

PARAMETER	WITHOUT TIDA-01036	WITH TIDA-01036
FIN (kHz)	2	2
SCLK (MHz)	45	45
Sample rate (MSPS)	1	1
SNR (dB)	92.02	101.5
THD (dB)	–109.9	–122.06
ENOB	14.98	16.56

Figure 16 and Figure 17 shows the spectrum of the TIDA-01035 design with and without the TIDA-01036 differential high Q filter.

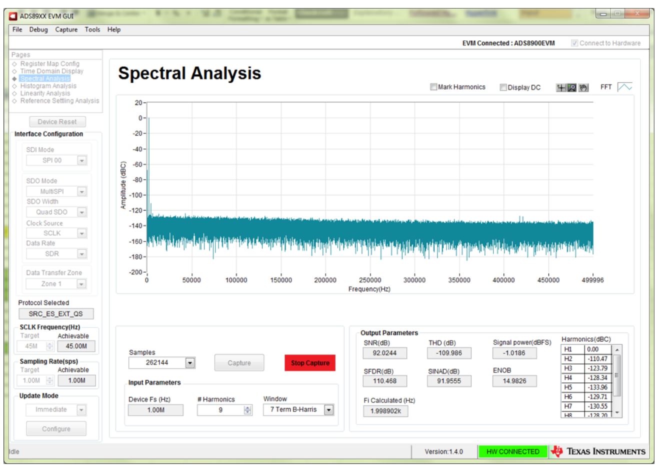


Figure 16. Spectrum Without TIDA-01036 Filter

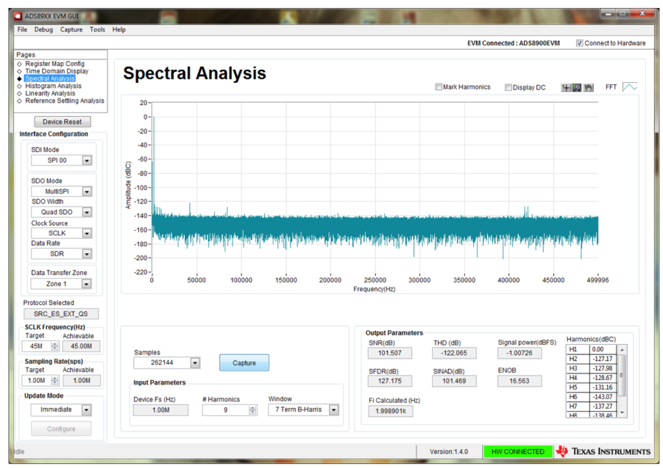


Figure 17. Spectrum With TIDA-01036 Filter

Table 13 summarizes the test results measured from the TIDA-01036 compared with the target specification.

Table 13. Summary of Measured System Results

PARAMETER	SPECIFICATIONS	MEASURED
Center frequency F_C	2 kHz	2.04 kHz
Band-pass region (–3-dB BW)	250 Hz	210 Hz
Band-pass ripple	< 1 dB	0.06 dB
Selectivity (Q-factor)	10	9.64
System performance (ENOB)	16 bit	16.56

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01036.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01036.

4.3 Layout Prints

To download the layer plots, see the design files at TIDA-01036.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01036.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01036.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01036.

5 Related Documentation

1. Texas Instruments, *Noise Analysis in Operational Amplifier Circuits*, Application Report (SLVA043)
2. Texas Instruments, *Fully-Differential Amplifiers*, Application Report (SLOA054)
3. Texas Instruments, *Op Amp Noise Theory and Applications*, Excerpted from *Op Amps for Everyone* (SLOA082)
4. Texas Instruments, *Active Filter Design Techniques* , Application Report (SLOA088)
5. Texas Instruments, *A Basic Introduction to Filters - Active, Passive, and Switched Capacitor*, Application Report (SNOA224)

5.1 Trademarks

6 About the Authors

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Revision A History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (October 2016) to A Revision	Page
• Changed language and images to fit current style guide	1

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