*设计指南：**TIDA-060021***
适合高阻抗应用的级联高增益有源低通滤波器 参考设计

说明

此设计使用 OPA2810 高速放大器来提供两个具有 1MHz 截止频率的多反馈 (MFB) 低通滤波器电路板。四阶电路板可提供一个具有高增益和陡峭滚降的四阶滤波器。高阻抗电路板 (High-Z) 是一种二阶滤波器，专门用于前一级中具有大输出阻抗的系统。此参考设计中的两种电路板均为工程师提供了重点将噪声和失真降至最低的高增益、宽电源电压范围滤波器。OPA810 是 OPA2810 器件的单通道型号。

资源

TIDA-060021	设计文件夹
OPA2810	产品文件夹
OPA810	产品文件夹
TINA-TI	工具文件夹
Filter-Pro	工具文件夹

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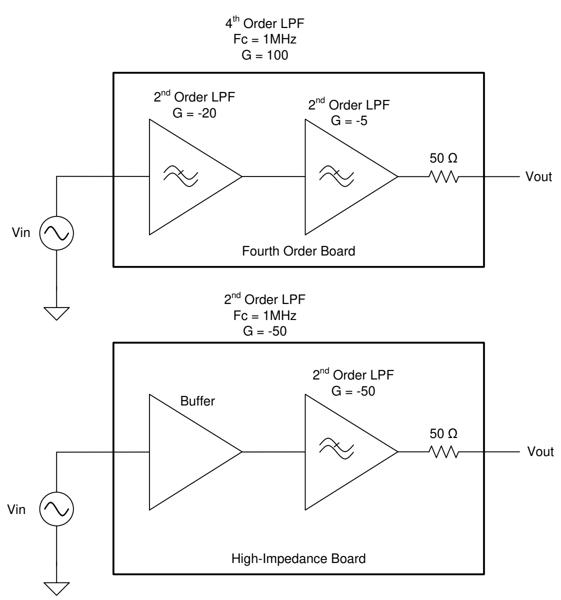
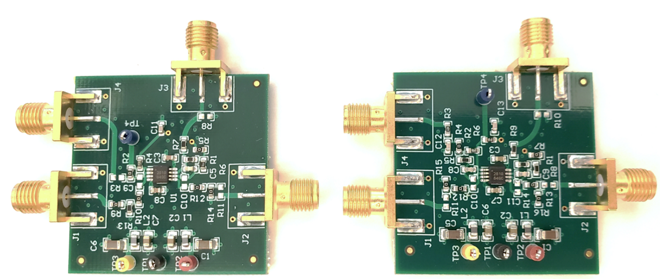
特性

- 可获得高达 40dB 的增益和 1MHz 截止频率的级联低通滤波器
- 多反馈拓扑，可用于四阶和二阶设计
- 紧凑型两级设计，适合高增益和二阶或四阶滤波器
- 稳定性高，可使过冲和振铃降至最低
- 低失真和低噪声设计
- 采用了 JFET 输入 OPA2810，可实现低输入噪声、高共模抑制比 (CMRR) 和快速压摆率
- 支持宽电源电压范围和高输出电压设计

应用

- 数据采集 (DAQ)
- 频谱和网络分析器
- 示波器
- 有源探头





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TIDUEH7 — http://www-s.ti.com/sc/techlit/TIDUEH7

1 System Description

With improvements in amplifier capabilities over time, active filters have become more common in higher frequency applications. Compared to passive filters, active filters can provide gain and also improve the size, cost, and flexibility of a design. With the right amplifier and configuration, active filters can prove useful in many filter applications.

Texas Instruments' FilterPro™ software tool was used in the design of both active filters featured in the TIDA-060021 boards. Each board has a different emphasis on its design, but both boards are made up of two stages:

- The High-Z board is made up of a buffer, followed by a 34-dB gain, MFB filter. The original input signal is inverted because the High-Z board only uses one MFB filter. The use of a buffer for the first stage allows the filter to have a large input impedance.
- The fourth-order design uses an MFB filter for both stages, leading to a greater gain of 40 dB, steeper roll-off and no inversion of the input. This design, however, does not use a buffer and therefore has an input impedance of only 412 Ω.

1.1 Key System Specifications

表 **1. Key System Specifications**

PARAMETER	SPECIFICATIONS (High-Z)	SPECIFICATIONS (4th Order)
Filter order	2nd-order	4th-order
Gain	34 dB	40 dB
Input impedance	12 GΩ	412 Ω
Cutoff frequency	1.04 MHz	1.04 MHz
Pass-band ripple	< 1 dB	< 1 dB
Stop-band attenuation	34 dB	40 dB
Stop-band cut-off frequency	15.16 MHz	4.53 MHz
Q-factor (first stage)	n/a	0.556
Q-factor (second stage)	0.599	1.06
Total supply voltage (min)	4.75 V	4.75 V
Total supply voltage (max)	27 V	27 V

2 System Overview

2.1 Block Diagrams

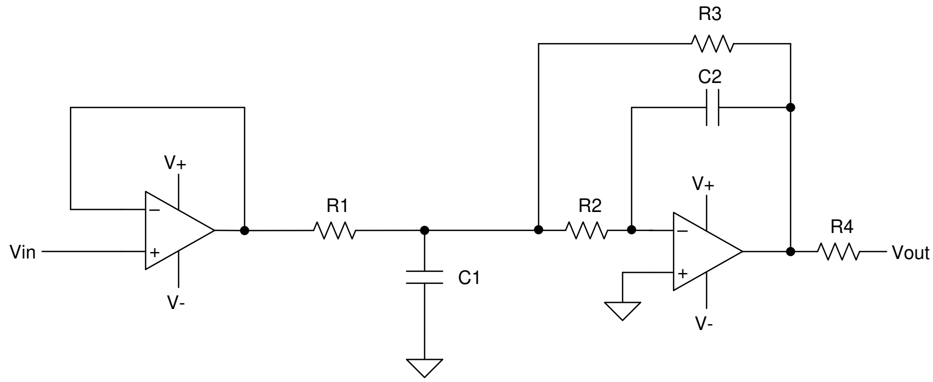

图 1. High-Z, 2nd-Order Filter Circuit

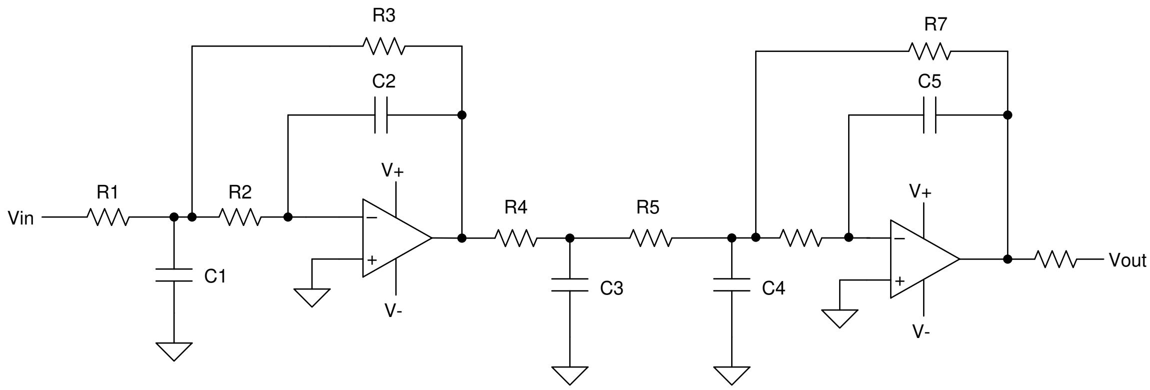

图 2. 4th-Order Filter Circuit

2.2 Design Considerations

2.2.1 Filter Topology

A multiple-feedback (MFB) topology was chosen for both designs because of its reliability in high-gain and high-frequency applications. To provide gain to a Sallen-Key filter, two resistors must be added to the typical configuration. However, an MFB filter uses fewer components to provide both higher gains and better stop-band rejection. Another issue with Sallen-Key filters is their high-pass like effects at higher frequencies. To mitigate this effect, larger resistances are needed, leading to greater noise in the overall system.

Both designs are given topologies where a combination of the desired filter gain, quality factor, and corner frequency determine the component values of the design. 公式 1 shows the transfer function of a low-pass MFB filter using the second stage of the High-Z board in 图 1.

$$A(s) = \frac{\dfrac{-1}{C_1 C_2 R_1 R_2}}{S^2 + \dfrac{R_1 + R_2\left(1 + \dfrac{R_1}{R_3}\right)}{C_1 R_1 R_2} + \dfrac{1}{C_1 C_2 R_2 R_3}} \tag{1}$$

2.2.2 Filter Properties

A 0.05° equiripple linear phase filter was chosen for the type of response for both the High-Z and fourth-order designs. A linear phase filter displays characteristics between that of a Bessel and Butterworth response. By introducing slight ripple into the phase response of the filter, a faster roll-off rate and bandwidth than that of a Bessel filter can be achieved. This linear-phase filter has more overshoot than a Bessel filter but less than that of a Butterworth response. 表 2 shows the quality factors of each filter stage. For more information on the types of low-pass filter responses and their comparisons, see the *How to compare your circuit requirements to active-filter approximations* technical brief.

表 2. Quality Factor of Filter Designs

BOARD	STAGE 1	STAGE 2
High-Z	—	0.599
4th-order	0.556	1.06

2.2.3 Noise

In order to minimize the total noise of each filter, op amp noise must be the dominating factor in both designs. The OPA2810 voltage noise is the dominant source of amplifier noise because the OPA2810 is a FET-input device. Components are the largest factor in achieving a lower noise solution because the properties of the OPA2810 are fixed. As a result, noise must be considered when determining component values, along with the quality factor, gain, and cutoff frequency of the filter. 图 3 and 图 4 compare the total simulated integrated noise results of both filters, with an equivalent circuit using noiseless resistors. This comparison provides insight to the noise contribution of both the amplifiers and components to the overall system noise.

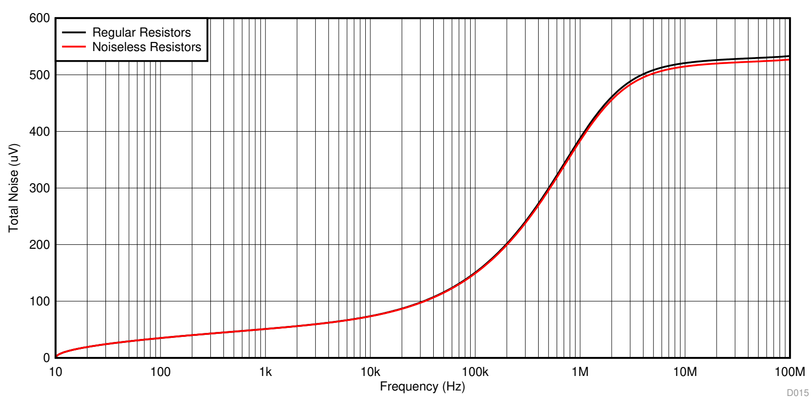

图 3. Noise Comparison for the High-Z Board

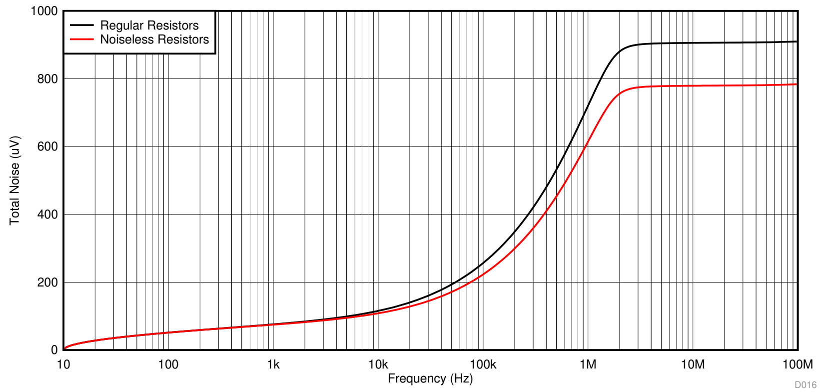

图 4. Noise Comparison for the 4th-Order Board

Appendix A of *Design Methodology for MFB Filters in ADC Interface Applications* application report describes the effect of each noise source on the final output of an MFB filter. The noticeable resistor noise in the fourth-order filter is a cause of the feedback resistance of the first stage. By lowering this resistance, resistor R1 must also be lowered, reducing the input impedance of the filter even further. If low input impedance is not a concern, the noise of the fourth-order board can be reduced by reducing these gain resistors and adjusting other components of the first stage to maintain the same quality factor and cutoff frequency.

2.3 Highlighted Products

2.3.1 OPA2810

The OPA2810 is a dual-channel, field-effect transistor (FET)-input, voltage-feedback operational amplifier with low input bias current. The OPA2810 is unity-gain stable with a small-signal unity-gain bandwidth of 105 MHz, and offers excellent DC precision and dynamic AC performance at a low quiescent current (I_Q) of 3.6 mA per channel (typical). The OPA2810 is fabricated on Texas Instrument's proprietary, high-speed silicon germanium (SiGe) bipolar CMOS (BiCMOS) process and achieves significant performance improvements over comparable FET-input amplifiers at similar levels of quiescent power. With a gain-bandwidth product (GBWP) of 70 MHz, slew rate of 192 V/µs, and low voltage noise of 6 nV/$\sqrt{Hz}$, the OPA2810 is well suited for use in a wide range of high-fidelity data-acquisition and signal-processing applications.

The OPA2810 is characterized to operate over a wide supply range of 4.75 V to 27 V, and features rail-to-rail inputs and outputs. The OPA2810 amplifier delivers 75 mA of linear output current, suitable for driving optoelectronics components and analog-to-digital converter (ADC) inputs or buffering digital-to-analog (DAC) outputs into heavy loads.

2.3.2 OPA810

The OPA810 is a single-channel variant of the OPA2810, and could also be used in this design.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The various hardware inputs and outputs of the TIDA-060021 boards are provided below:

- Terminals TP1, TP2, and TP3 provide inputs to power the board (GND, VCC, and VEE, respectively)
- SMA connectors J1 and J4 provide filter inputs for the High-Z and fourth-order boards, respectively
- SMA connector J3 provides the filter output

3.2 Testing and Results

3.2.1 Test Setup

节 3.1.1 describes the inputs and outputs required to power and run each of the TIDA-060021 boards. Each board is powered with a dual power supply of ±12 V with output swings dependent on the type of test. The test results are taken at a free-air operating ambient temperature value (T_A) of 25°C with no forced air regulating temperature of the EVM, unless otherwise noted in the results.

3.2.2 Test Results

3.2.2.1 Frequency Response

As shown in 图 5 and 图 6, the frequency response results closely resemble the data returned during simulations. A large-signal response with an output voltage of 6 V_{PP} is used for the measured data whereas the simulated curve is a small-signal response. Both responses illustrate that at larger outputs, the OPA2810 slew limit is not reached and there is minimal loss in the frequency response of both filters. This minimal loss illustrates that the measured response also matches simulations at lower output levels.

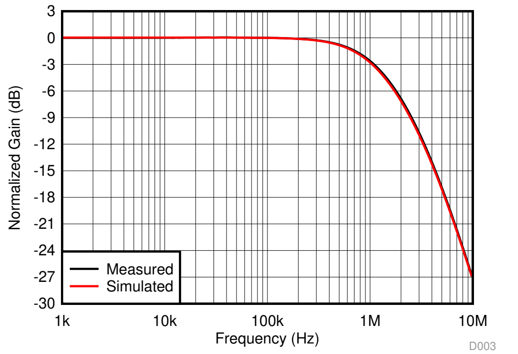

图 5. Frequency Response for the High-Z Board

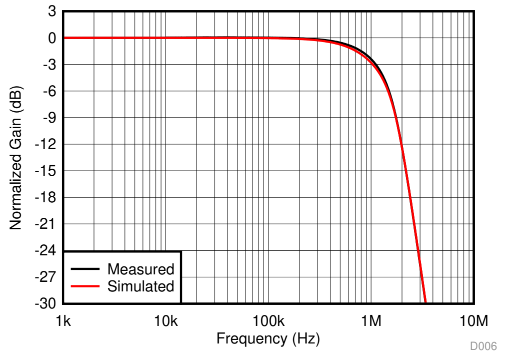

图 6. Frequency Response for the 4th-Order Board

3.2.2.2 Noise

For both boards, the measured noise matched the simulated results. Differences in noise can be attributed to a deviation from of the OPA2810 typical noise specifications and from component tolerances that are then amplified by the high gain of the board. 图 7 and 图 8 show noise test results for the High-Z and fourth-order boards, respectively.

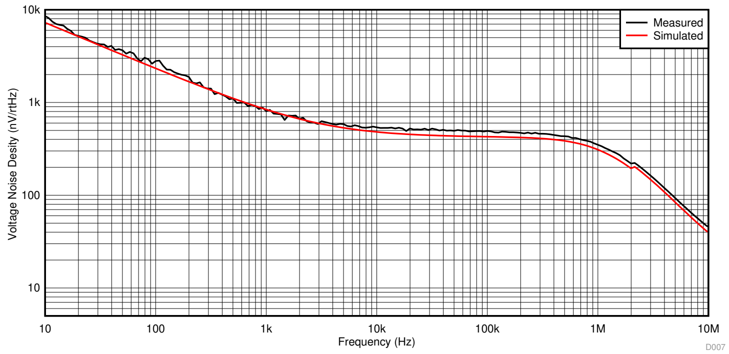

图 7. Noise Test Results for the High-Z Board

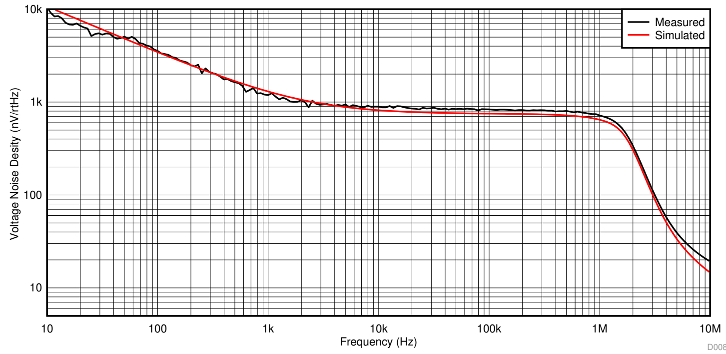

图 8. Noise Test Results for the 4th-Order Board

3.2.2.3 Distortion

图 9 through 图 12 show the harmonic distortion of both boards. There is increased distortion between these figures and the distortion figure of the OPA2810 data sheet. The data sheet results, however, use a low-gain-test configuration to measure distortion. 图 13 and 图 14 display the total harmonic distortion plus noise (THD+N) results of each board, which remain relatively constant over the measured frequency range. This constant result represents the noise floor of each board and illustrates that noise is the dominating factor of THD+N in the frequency range of these figures. 图 13 and 图 14 also illustrate that THD+N is improved at larger output voltages because the signal-to-noise ratio (SNR) increases when noise is kept constant when the output signal level increases.

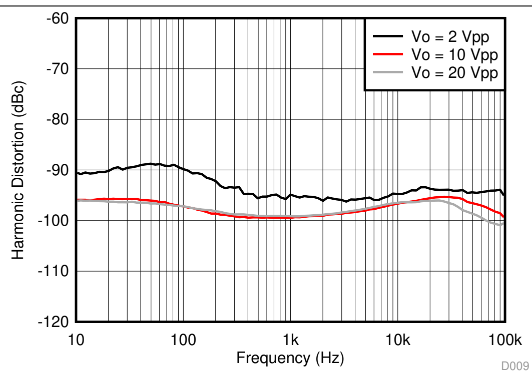

图 9. 2nd-Harmonic Distortion for the High-Z Board

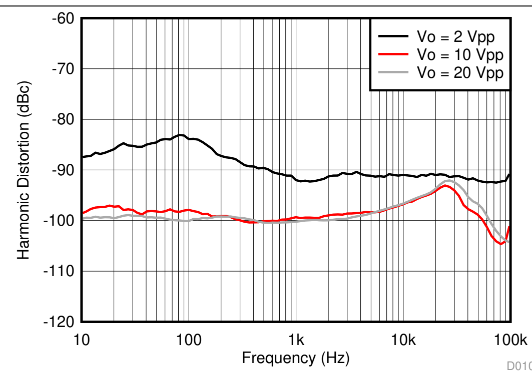

图 10. 2nd-Harmonic Distortion for the 4th-Order Board

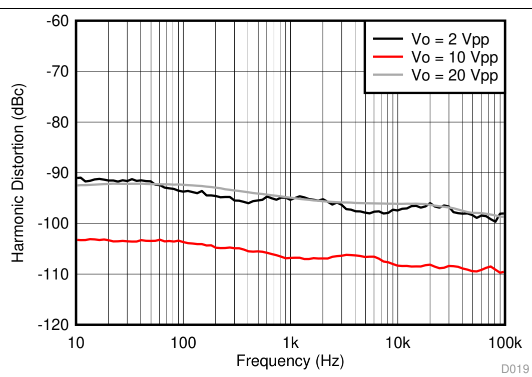

图 11. 3rd-Harmonic Distortion for the High-Z Board

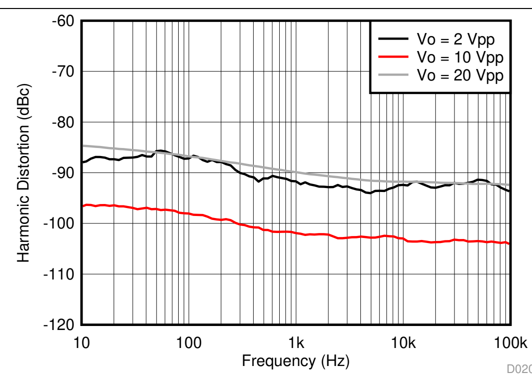

图 12. 3rd-Harmonic Distortion for the 4th-Order Board

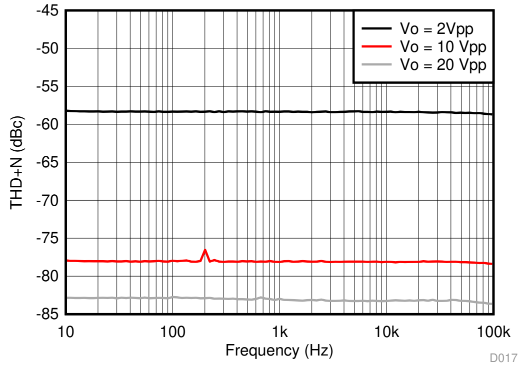

图 13. THD+N Results for the High-Z Board

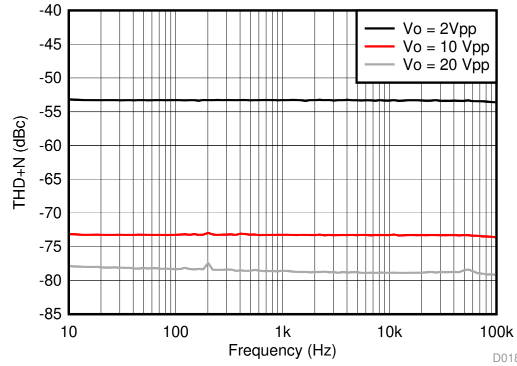

图 14. THD+N Results for the 4th-Order Board

3.2.2.4 Step Response

图 15 through 图 18 show the step responses for the High-Z and fourth-order boards. Although the High-Z board displays an underdamped response, the fourth-order board response is slightly overdamped. In both cases, the quality factor is between that of a Bessel and Butterworth response. The difference in the type of response can be attributed to constraints in component selection and tolerances. This design used FilterPro™ software and E96 resistors. If tighter tolerance resistors are used, similar responses can be achieved for both boards.

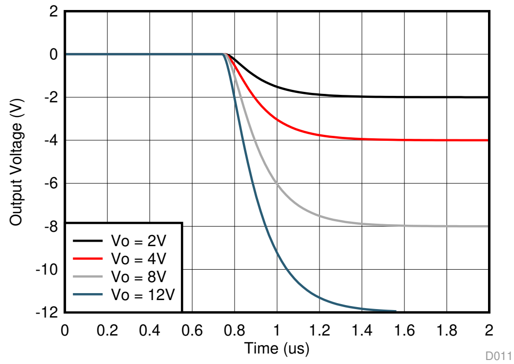

图 15. Step Response Simulations for the High-Z Board

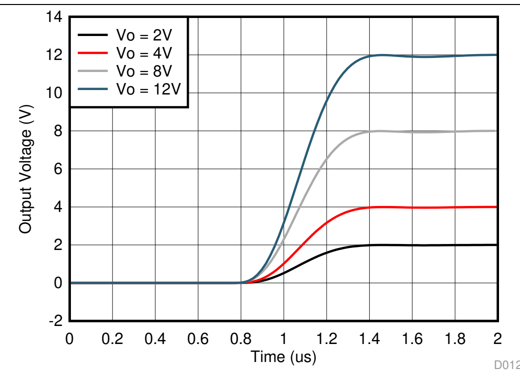

图 16. Step Response Simulations for the 4th-Order Board

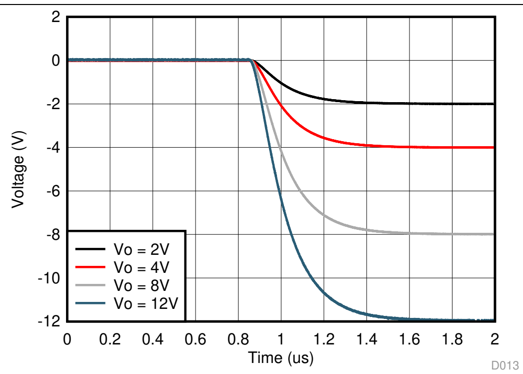

图 17. Step Response Results for the High-Z Board

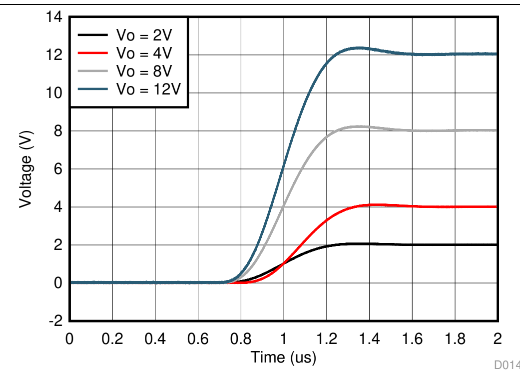

图 18. Step Response Results for the 4th-Order Board

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-060021.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-060021.

4.3 PCB Layout Recommendations

This design follows the guidelines found in the *Layout* section of the OPA2810 data sheet.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-060021.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-060021.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-060021.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-060021.

5 Software Files

To download the software files, see the design files at TIDA-060021.

6 Related Documentation

1. Texas Instruments, *How to compare your circuit requirements to active-filter approximations* technical brief
2. Texas Instruments, *Active low-pass filter design* application report
3. Texas Instruments, *Design methodology for MFB filters in ADC interface applications* application report
4. Texas Instruments, *OPA2810 Dual-channel, 27-V, rail-to-rail input/output FET-input operational amplifier* data sheet

6.1 商标

7 About the Author

Sima Jalaleddine is an applications engineer intern in TI's high-speed amplifiers team. She is pursuing her masters degree in Electrical and Computer Engineering at the University of Arizona.

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修订历史记录

注：之前版本的页码可能与当前版本有所不同。

Changes from A Revision (March 2019) to B Revision	Page
• 已添加 OPA810 产品文件夹	1

Changes from Original (March 2019) to A Revision	Page
• Replaced 4th-Order Filter Circuit with High-Z, 2nd-Order Filter Circuit	3
• Replaced High-Z, 2nd-Order Filter Circuit with 4th-Order Filter Circuit	3

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