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Abstract

Most electronics engineers are proficient in using operational amplifiers to design signal conditioning circuits—such as summers, amplifiers, and active filters. But fully differential amplifiers are often less common. In reality, fully differential amplifiers can also perform functions like signal summation, filtering and current-to-voltage conversion. In certain scenarios, using fully differential amplifiers for signal processing can actually simplify the circuit design, thereby reducing system costs. Furthermore, thanks to the inherent characteristics of differential amplifiers, circuits utilizing them naturally offer superior noise immunity. This article introduces how to use fully differential amplifiers for signal conditioning.

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1 Introduction

Fully differential amplifiers (FDA) are increasingly used in modern electronic systems; however, many engineers limit their application to converting single-ended input signals into differential output signals typically to drive differential-input ADCs or performing differential amplification within differential circuits. In reality, fully differential amplifiers can also perform signal summation, subtraction, active filtering, current-to-voltage conversion, and more. In certain scenarios, using a fully differential amplifier for signal processing offers distinct advantages over a traditional operational amplifier. For instance, in medical ultrasound Doppler imaging systems, the analog front-end often incorporates 1~16 AFE chips such as the [AFE58JD48](#) or [AFE58JD28](#) or similar to receive and demodulate Doppler shift signals. The resulting Doppler output is typically a differential current signal. The system must sum the Doppler signals from all analog front-end units before feeding them into a precision ADC for conversion to digital signals and subsequent processing. A simplified diagram is shown in [Figure 1-1](#).

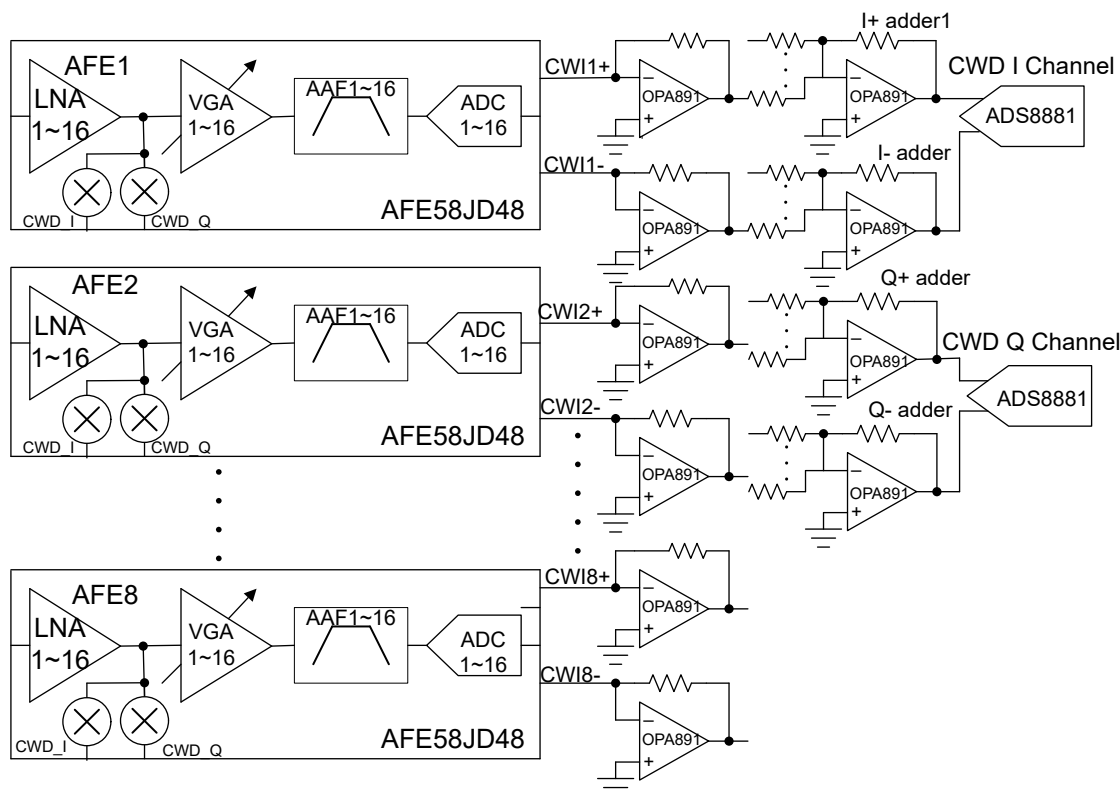


Figure 1-1. Diagram of an Ultrasound CWD Imaging System

A traditional approach involves using standard precision operational amplifiers such as the [OPA2891](#) to first convert current signals into voltage signals, followed by signal summation using precision op-amps. With this method, a 128-channel ultrasound imaging system would require at least 36 operational amplifiers; the count would be even higher if the chosen analog front-end featured only eight receive channels. In contrast, using fully differential amplifiers for signal processing allows the design requirements to be met with just two such devices. Consequently, the appropriate use of fully differential amplifiers can simplify circuit design, enhance system performance, and reduce both system cost and PCB area.

1.1 Basic Knowledge of Fully Differential Amplifier

[Figure 1-2](#) shows a fully differential amplifier. Unlike an operational amplifier, a fully differential amplifier has two output terminals. [Figure 1-3](#) illustrates a typical application circuit for a fully differential amplifier. For a differential amplifier, the input is defined as the voltage at the non-inverting input terminal minus the voltage at the inverting input terminal, as shown in Equation 1. The output is defined as the non-inverting output voltage minus the inverting output voltage, as shown in Equation 2. The input common-mode voltage is defined as half the sum of the voltages at the non-inverting and inverting input terminals, as shown in Equation 3. Similarly, the

output common-mode voltage is defined as half the sum of the voltages at the non-inverting and inverting output terminals, as shown in Equation 4.

$$v_{id} = (V_{IN+} - V_{IN-}) \dots (1)$$

$$v_{od} = (V_{OUT+} - V_{OUT-}) \dots (2)$$

$$v_{ic} = \frac{(V_{IN+} + V_{IN-})}{2} \dots (3)$$

$$v_{oc} = \frac{(V_{OUT+} + V_{OUT-})}{2} \dots (4)$$

Let $a(f)$ be the open-loop transfer function of the fully differential amplifier; then, the relationship between the input voltage and the output voltage is as shown in Equation 5.

$$v_{od} = a(f) \times v_{id} \dots (5)$$

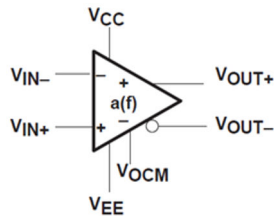


Figure 1-2. Fully Differential Amplifier

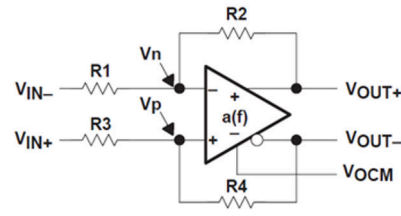


Figure 1-3. Typical Amplification Circuit Using FDA

As shown in [Figure 1-4](#), for a fully differential amplifier, the internal common-mode voltage is designed to operate in feedback mode; therefore, the output common-mode voltage is always equal to the output common-mode voltage set by the user on the actual chip. Refer to Equation 6.

$$V_{OC} = V_{OCM} \dots (6)$$

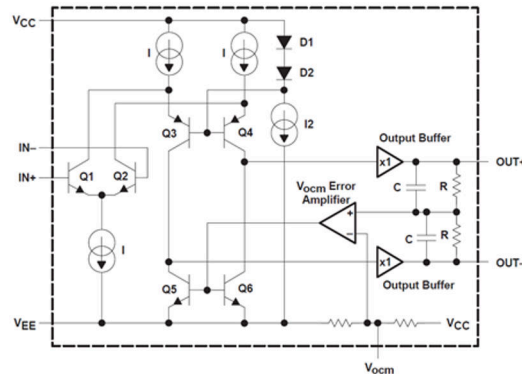


Figure 1-4. Simplified Diagram of a Fully Differential Amplifier

1.2 Advantages of Fully Differential Amplifiers

The main advantages of fully differential amplification are:

- Strong anti-interference capability

Let v_n be the interference affecting the fully differential circuit; then, the output voltage is

$$v_{od} = k((v_{in+} + v_n) - (v_{in-} + v_n)) = k(v_{in+} - v_{in-}) \dots (7)$$

It is evident that the interference signal has been removed from the output signal.

- Under the same supply voltage, the output voltage range is doubled

Assuming the fully differential amplifier is powered by a symmetrical dual power supply, since the output voltage at the non-inverting input is at its maximum when the output voltage at the non-inverting input is at its minimum, and vice versa, therefore we have:

$$V_{EE} \leq V_{\text{output}+} \leq V_{CC} \dots (8)$$

$$V_{CC} \geq V_{\text{output}-} \geq V_{EE} \dots (9)$$

$$V_{EE} - V_{CC} \leq V_{\text{output}+} - V_{\text{output}-} \leq V_{CC} - V_{EE} \dots (10)$$

It is evident that the dynamic range of the output voltage has doubled under the same voltage conditions.

- Improved even-order harmonic distortion performance

Assuming distortion is present in the output voltage, the voltages at the non-inverting and inverting output terminals are given by the following equations:

$$V_{\text{output}+} = k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 + \dots (11)$$

$$V_{\text{output}-} = k_1 (-V_{in}) + k_2 (-V_{in})^2 + k_3 (-V_{in})^3 + \dots (12)$$

The output voltage is

$$V_{od} = V_{\text{output}+} - V_{\text{output}-} = 2k_1 V_{in} + 2k_3 V_{in}^3 + \dots (13)$$

It is evident that there is no even-order harmonic distortion in the output voltage.

- Low EMI, low interference.

Since the two signal lines of the fully differential signal are routed close to each other and have opposite phases, the external electromagnetic radiation of the two lines is very small. There is less interference to other signals.

2 Fully Differential Signal Conditioning Circuit

Based on the brief introduction above, we have gained a basic understanding of differential amplifiers. Just as with operational amplifiers, the effect of feedback verifies that the voltage at the non-inverting input of a fully differential amplifier equals the voltage at the inverting input. This principle can be used to determine the relationship between the circuit's output and input. Furthermore, in practical designs, the two feedback resistors in a fully differential amplifier are typically chosen to have equal values to simplify calculations.

2.1 Fully Differential Adder Circuit

The fully differential adder circuit is shown in [Figure 2-1](#). The **THS4551** fully differential amplifier is used here as an example. However, users can readily employ other fully differential amplifiers to achieve similar functionality in their specific designs. The **THS4551** is a fully differential amplifier recommended by TI for ultrasonic Doppler signal processing, offering advantages such as low noise, high bandwidth, and extremely low output offset voltage. Let V1 and V3 represent differential signal 1, and V2 and V4 represent differential signal 2. Applying Kirchhoff's Current Law to the non-inverting and inverting terminals yields Equations 14 and 15.

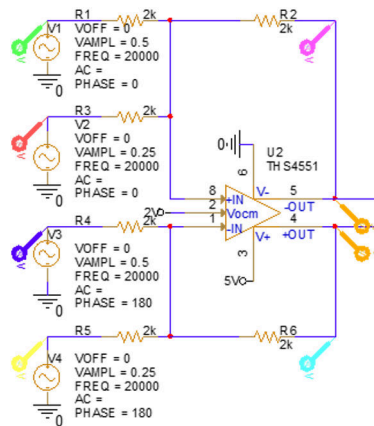


Figure 2-1. Voltage Adder Circuit Based on a Fully Differential Amplifier

$$\frac{V_1 - V_{IN+}}{R_1} + \frac{V_2 - V_{IN+}}{R_3} = \frac{V_{IN+} - V_{OUT+}}{R_2} \dots\dots (14)$$

$$\frac{V_3 - V_{IN-}}{R_4} + \frac{V_4 - V_{IN-}}{R_5} = \frac{V_{IN-} - V_{OUT-}}{R_6} \dots\dots (15)$$

Due to feedback, $V_{IN+} = V_{IN-}$. At the same time, for simplicity of calculation, the resistance values of all resistors are equal. Then we can get formula 16.

$$V_{out+} - V_{out-} = (V_1 - V_3) + (V_2 - V_4) \dots\dots (16)$$

It is evident that the circuit performs the function of summing the input differential signals. The simulation results are shown in [Figure 2-2](#). Input signals $v_1 = 0.5V$, $V_2 = 0.25V$, $V_3 = -0.5V$, $V_4 = -0.25V$, The expected output voltage is 1.5V. Simulation shows the output voltage is a 1.5V sine wave.

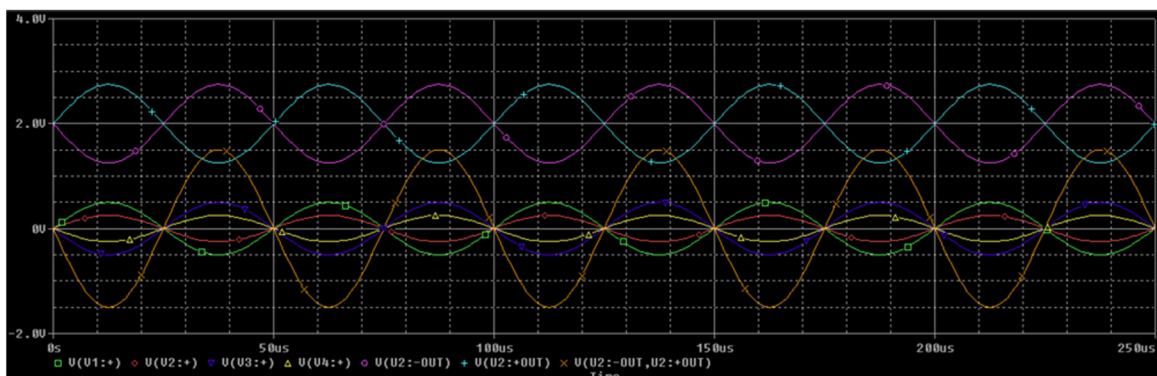


Figure 2-2. Simulation Results of the Voltage Adder Based FDA

Designers can readily derive the calculation formulas for the adder circuit under conditions where the resistors are unequal. The derivation process is entirely analogous and is not repeated here. However, note that, in general, the input resistances at the non-inverting and inverting terminals of the differential amplifier—as well as the two feedback resistors—should be matched; this results in simpler formulas. If the corresponding input resistances are unequal, the resulting formulas become more complex.

Similarly, if the input signals are current signals—as shown in [Figure 2-3](#), where I1 and I3 constitute differential signal 1, and I2 and I4 constitute differential signal 2—Equations 17 and 18 can be derived using Kirchhoff's Current Law.

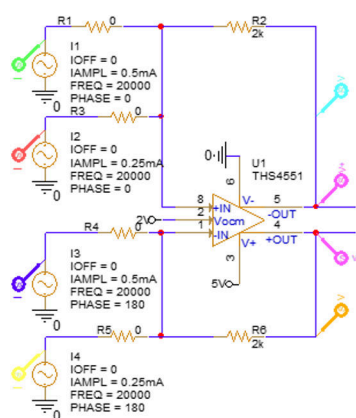


Figure 2-3. Current Adder Circuit Based on a Fully Differential Amplifier

$$V_{IN+} - v_{out-} = (I_1 + I_2) \times R_2 \dots (17)$$

$$V_{IN-} - v_{out+} = (I_3 + I_4) \times R_6 \dots (18)$$

Due to feedback, $V_{IN+} = V_{IN-}$. At the same time, for the sake of calculation simplicity, we set $R_2 = R_6$. Thus, Equation 19 is obtained.

$$v_{out} = (v_{out+} - v_{out-}) = ((I_1 - I_3) + (I_2 - I_4)) \times R_2 \dots (19)$$

Therefore, fully differential amplifiers can also perform current summation. The simulation results are shown in [Figure 2-4](#) and [Figure 2-5](#).

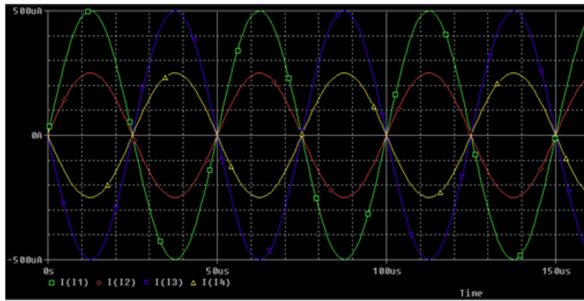


Figure 2-4. Input Current

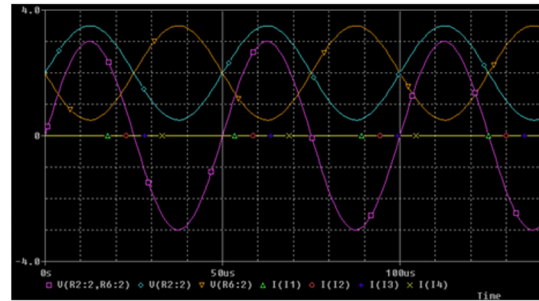


Figure 2-5. Output Voltage

2.2 Single-Ended Input Fully Differential Adder Circuit

In Figure 4, if V3 and V4 are set to 0V, the fully differential input signal becomes a single-ended input signal. In this case, resistors R8 and R11 are in parallel, allowing the designer to replace them with a single equivalent resistor. The fully differential adder thus becomes an inverting single-ended signal adder, as shown in Figure 2-6.

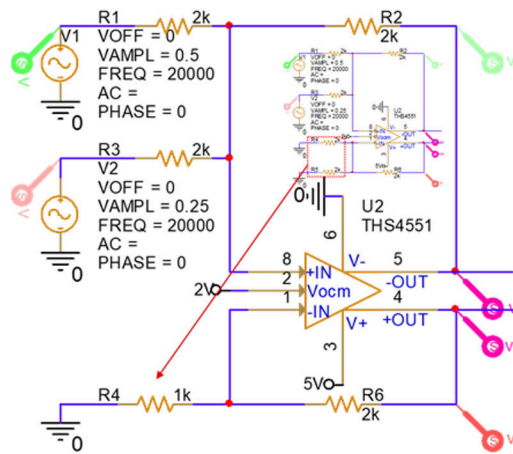


Figure 2-6. Single-Ended Signal Adder Based on a Differential Amplifier

The circuit analysis process is the same as that for the fully differential summing circuit, and Equations 20 and 21 can likewise be obtained.

$$\frac{V_1 - V_{IN+}}{R_1} + \frac{V_2 - V_{IN+}}{R_3} = \frac{V_{IN+} - V_{OUT-}}{R_2} \dots\dots (20)$$

$$\frac{0 - V_{IN-}}{R_4} = \frac{V_{IN-} - V_{OUT+}}{R_6} \dots\dots (21)$$

From Equations 20 and 21, it can be obtained that.

$$v_{out} = v_{out+} - v_{out-} = v_1 + v_2 \dots\dots (22)$$

The simulation results are as follows:

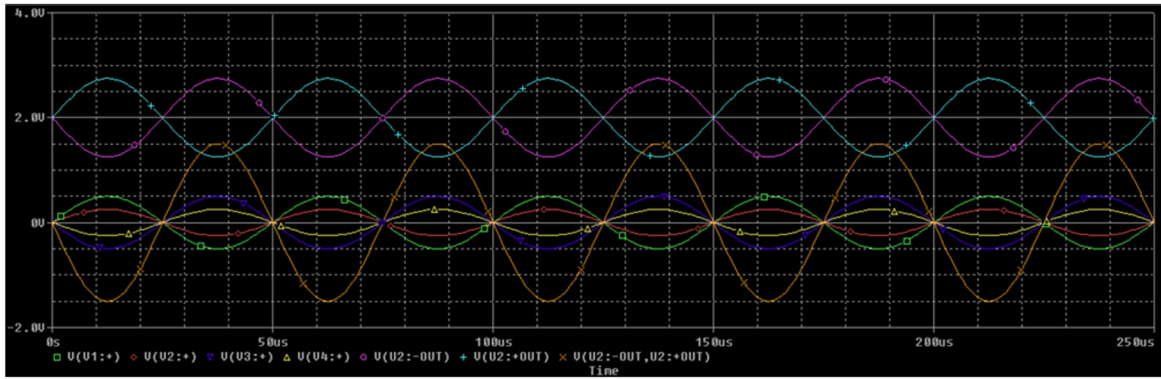


Figure 2-7. Simulation Results for the Single-Ended Signal Adder

2.3 Fully Differential Current-to-Voltage Conversion Circuit

In optical communication and ophthalmic OCT systems, the output from a photodiode (PD) is typically a weak current signal; the electronic system generally requires converting this current signal into a voltage signal for further processing. To enhance circuit sensitivity, designers can employ a fully differential amplifier as the front-end circuit to directly convert the PD's output current into a differential voltage. The circuit configuration is shown in Figure 2-8. In designing such circuits, minimizing the amplifier's bias current is desirable to reduce system errors. The **THS4567** is a fully differential amplifier well-suited for this application, featuring a bias current as low as 20pA.

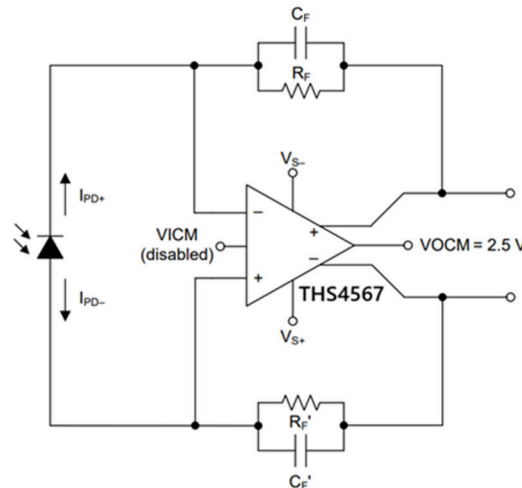


Figure 2-8. Circuit Configuration

Let the current of PD be I_{PD} , then for the non-inverting and anti-inverting terminals respectively, we have:

$$v_{IN-} - v_{out+} = -I_{PD} \times R_F \dots (23)$$

$$v_{IN+} - v_{out-} = I_{PD} \times R_F \dots (24)$$

From Equations 23 and 24, it can be obtained that

$$v_{out} = v_{out+} - v_{out-} = 2I_{PD} \times R_F \dots (25)$$

As shown by Equation 25, using a differential amplifier as the TIA circuit can double the system's sensitivity, which helps increase the signal-to-noise ratio.

2.4 Fully Differential Active Filter Circuit

In practical circuit design, designers sometimes wish to incorporate active filtering capabilities into a fully differential amplifier to improve the system's signal-to-noise ratio and filter out noise and interference, as shown in Figure 2-9.

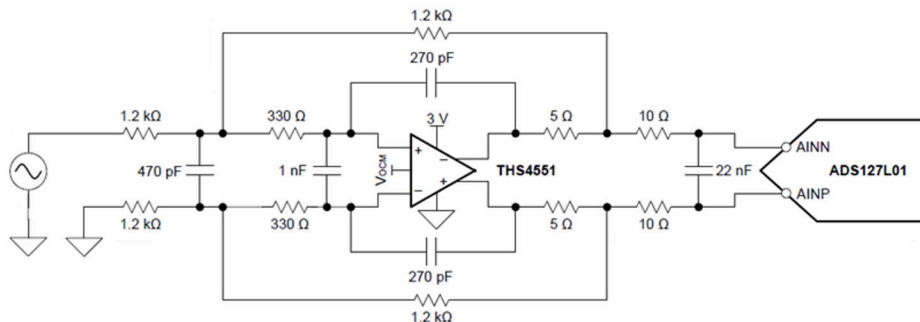


Figure 2-9. 500kHz Multiple Feedback Filter Interface to the ADS127L01

The design of the fully differential active filter shown in Figure 2-9 can generally be divided into three steps:

- First, use auxiliary software or other tools to design a single-ended filter based on a standard operational amplifier according to requirements, as shown in Figure 2-10.
- Then, create two copies of the designed single-ended filter to filter each of the differential input signals, as shown in Figure 2-11.
- Replace the standard operational amplifier with a differential amplifier and incorporate a series capacitor or series resistor, as shown in Figure 2-12.

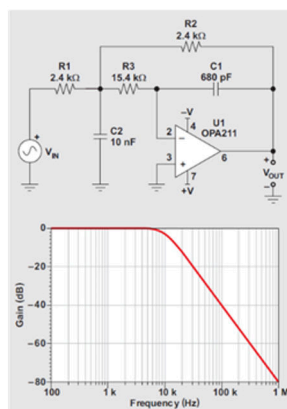


Figure 2-10. Step 1

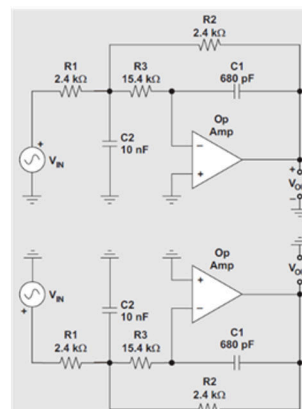


Figure 2-11. Step 2

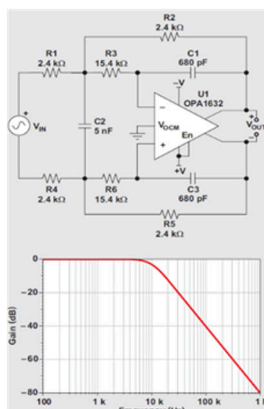


Figure 2-12. Step 3

By following the aforementioned steps, a differential active filter with the desired characteristics can be obtained.

3 Summary

This article briefly discusses the fundamental characteristics of fully differential amplifiers and their associated signal processing circuits. The proper use of these circuits can simplify system design and enhance system performance. In particular, when handling differential signals, the appropriate application of these signal processing circuits can simplify circuit design, improve performance, and reduce system costs.

4 References

- Texas Instruments, [Fully-Differential Amplifiers](#) application report
- Texas Instruments, [Continuous Wave Doppler Signal Chain Designs for TI's Ultrasound AFE](#) application note
- Texas Instruments, [Introduction to FDAs and differential signaling](#) video
- Texas Instruments, [Using the infinite-gain MFB filter topology in fully differential active filters](#) analog applications journal
- Texas Instruments, [THS4567](#) product page
- Texas Instruments, [OPA2891](#) product page
- Texas Instruments, [THS4551](#) product page

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