Application Report
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A Differential Op-Amp Circuit Collection

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ABSTRACT

All op-amps are differential input devices. Designers are accustomed to working with these inputs and connecting each to the proper potential. What happens when there are two outputs? How does a designer connect the second output? How are gain stages and filters developed? This application note answers these questions and gives a *jumpstart* to apprehensive designers.

1 INTRODUCTION

The idea of *fully-differential op-amps* is not new. The first commercial op-amp, the K2-W, utilized two dual section tubes (4 active circuit elements) to implement an op-amp with differential inputs and outputs. It required a ±300 V_{dc} power supply, dissipating 4.5 W of power, had a corner frequency of 1 Hz, and a gain bandwidth product of 1 MHz(1).

In an era of discrete tube or transistor op-amp modules, any potential advantage to be gained from fully-differential circuitry was masked by primitive op-amp module performance. Fully-differential output op-amps were abandoned in favor of single ended op-amps. Fully-differential op-amps were all but forgotten, even when IC technology was developed. The main reason appears to be the simplicity of using single ended op-amps. The number of passive components required to support a fully-differential circuit is approximately double that of a single-ended circuit. The thinking may have been “Why double the number of passive components when there is nothing to be gained?”

Almost 50 years later, IC processing has matured to the point that fully-differential op-amps are possible that offer significant advantage over their single-ended cousins. The advantages of differential logic have been exploited for 2 decades. More recently, advanced high-speed A/D converters have adopted differential inputs. Single-ended op-amps require a problematic transformer to interface to these differential input A/D converters. This is the application that spurred the development of fully-differential op-amps. An op-amp with differential outputs, however, has far more uses than one application.

2 BASIC CIRCUITS

The easiest way to construct fully-differential circuits is to think of the inverting op-amp feedback topology. In fully-differential op-amp circuits, there are two inverting feedback paths:

- Inverting input to noninverting output
- Noninverting input to inverting output

Both feedback paths must be closed in order for the fully-differential op-amp to operate properly.

When a gain is specified in the following sections, it is a differential gain—that is the gain at V_{OUT+} with a V_{OUT-} return. Another way of thinking of differential outputs is that each signal is the return path for the other.

2.1 A New Pin

Fully-differential op-amps have an extra input pin (V_{OCM}). The purpose of the pin is to set the output common-mode voltage.

The V_{OCM} pin can be connected to a data converter reference voltage pin to achieve tight tracking between the op-amp common mode voltage and the data converter common mode voltage. In this application, the data converter also provides a free dc level conversion for single supply circuits. The common mode voltage of the data converter is also the dc operating point of the single-supply circuit.

The designer should take care, however, that the dc operating point of the circuit is within the common mode range of the op-amp + and – inputs. This can be achieved by summing a dc level into the inputs equal or close to the common mode voltage, or by employing pull-up resistors as shown in Reference 6.

2.2 Gain

A gain stage is a basic op-amp circuit. Nothing has really changed from the single-ended design, except that two feedback pathways have been closed. The differential gain is still R_f / R_{in} a familiar concept to analog designers.

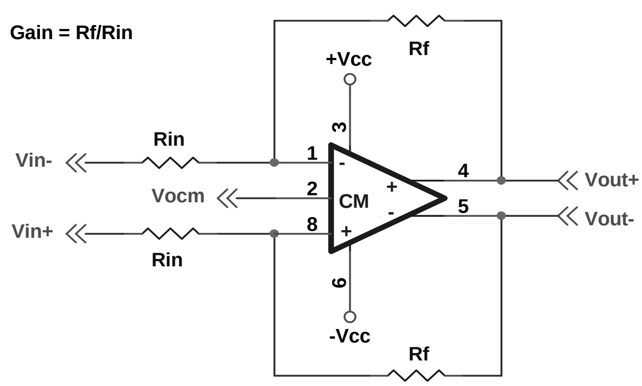


Figure 1: Differential Gain Stage

NOTE: Due to space limitations on the device schematics, the Vocm input is designated as "CM"

This circuit can be converted to a single-ended input by connecting either of the signal inputs to ground. The gain equation remains unchanged, because the gain is the differential gain.

2.3 Instrumentation

An instrumentation amplifier can be constructed from two single-ended amplifiers and a fully-differential amplifier as shown in Figure 2. Both polarities of the output signal are available, of course, and there is no ground dependence.

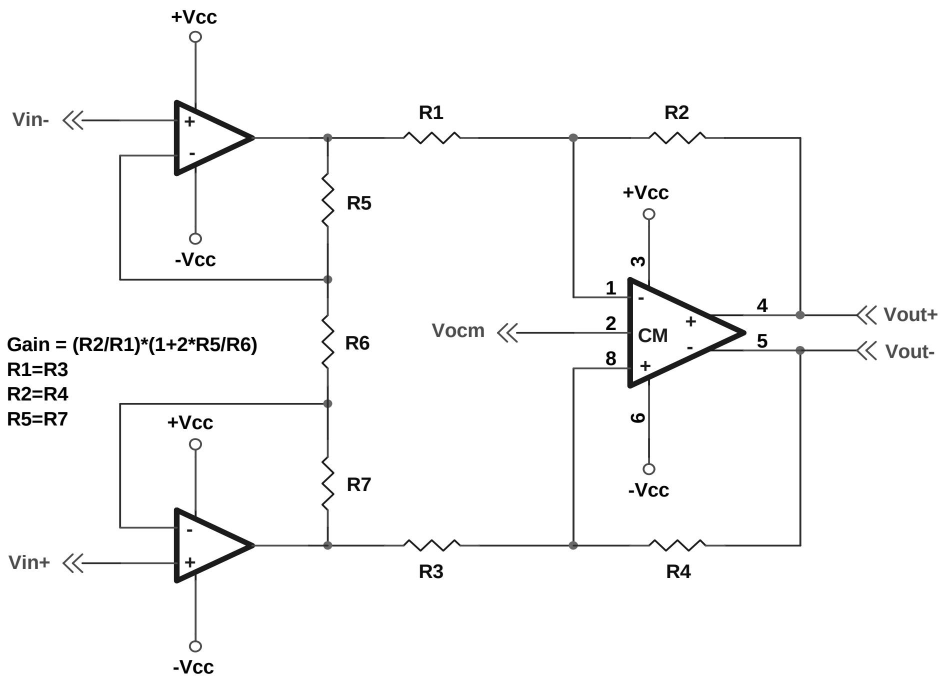


Figure 2: Instrumentation Amplifier

3 FILTER CIRCUITS

Filtering is done to eliminate unwanted content in audio, among other things. Differential filters that do the same job to differential signals as their single-ended cousins do to single-ended signals can be applied.

For differential filter implementations, the components are simply mirror imaged for each feedback loop. The components in the top feedback loop are designated *A*, and those in the bottom feedback loop are designated *B*.

For clarity decoupling components are not shown in the following schematics. Proper operation of high-speed op-amps requires proper decoupling techniques. Proper operation of high-speed op-amps requires proper decoupling techniques. Typically, a 6.8 µF to 22 µF tantalum capacitor placed within an inch (or two) of the power pins, along with 0.1 µF ceramic within 0.1 inch of the power pins is generally recommended. Decoupling component selection should be based on the frequencies that need to be rejected and the characteristics of the capacitors used at those frequencies.

3.1 Single Pole Filters

Single pole filters are the simplest filters to implement with single-ended op-amps, and the same holds true with fully-differential amplifiers.

A low pass filter can be formed by placing a capacitor in the feedback loop of a gain stage, in a manner similar to single-ended op-amps:

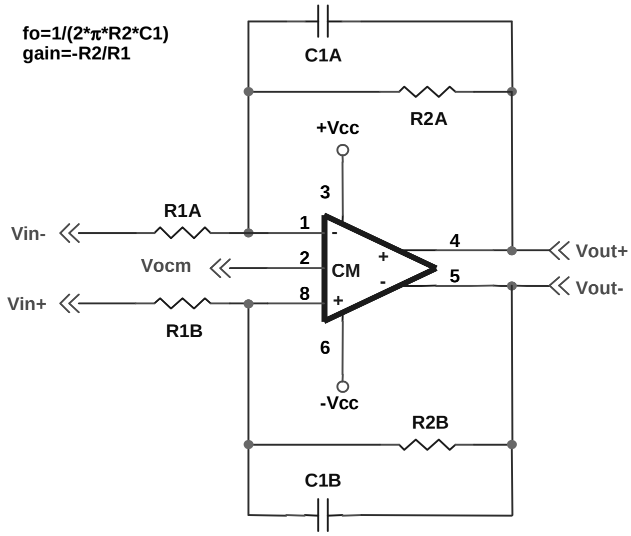


Figure 3: Single Pole Differential Low Pass Filter

A high pass filter can be formed by placing a capacitor in series with an inverting gain stage as shown in Figure 4:

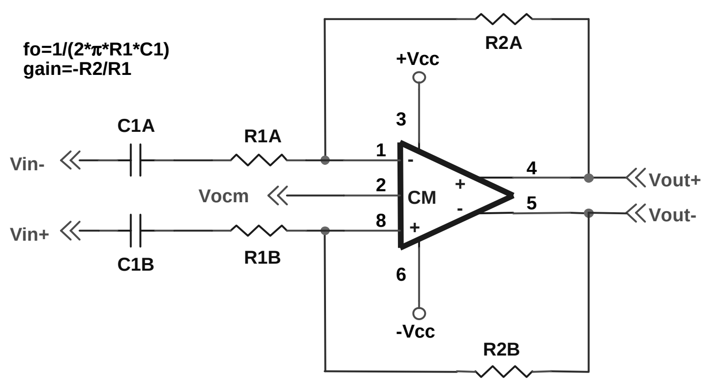


Figure 4: Single Pole Differential High Pass Filter

3.2 Double Pole Filters

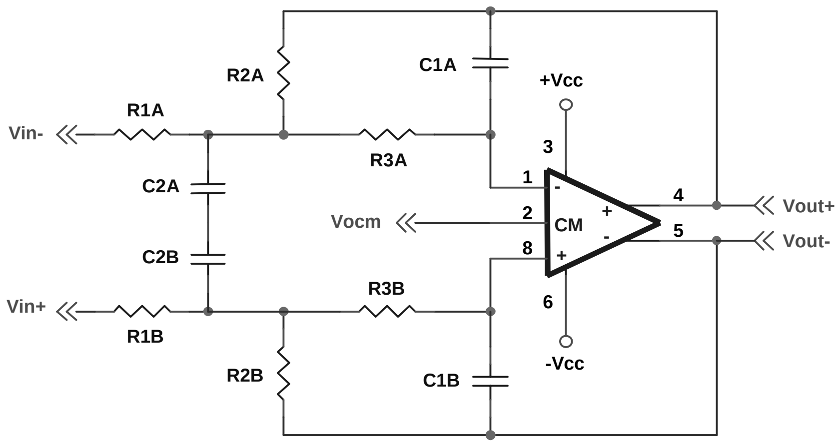
Many double pole filter topologies incorporate positive and negative feedback, and therefore have no differential implementation. Others employ only negative feedback, but use the noninverting input for signal input, and also have no differential implementation. This limits the number of options for designers, because both feedback paths must return to an input.

The good news, however, is that there are topologies available to form differential low pass, high pass, bandpass, and notch filters. However, the designer might have to use an unfamiliar topology or more op-amps than would have been required for a single-ended circuit.

3.2.1 Multiple Feedback Filters

MFB filter topology is the simplest topology that will support fully-differential filters. Unfortunately, the MFB topology is a bit hard to work with, but component ratios are shown for common unity gain filters.

Reference 5 describes the MFB topology in detail.



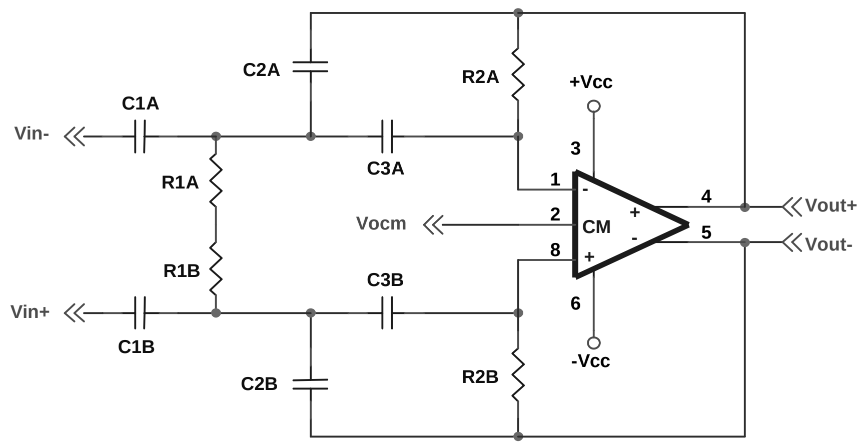
Bessel
Fo=1/(2πRC)
R1=R2=0.625R
R3=0.36R
C1=C
C2=2.67C

Butterworth
Fo=1/(2πRC)
R1=R2=0.65R
R3=0.375R
C1=C
C2=4C

Chebyshev 3 dB
Fo=1/(2πRC)
R1=0.644R
R2=0.456R
R3=0.267R
C1=12C
C2=C

Note: Chebyshev characteristics are for 1 dB ripple in this document.

Figure 5: Differential Low Pass Filter



Bessel	Butterworth	Chebyshev
Fo=1/(2πRC)	Fo=1/(2πRC)	Fo=1/(2πRC)
R1=0.73R	R1=0.467R	R1=3.3R
R2=2.19R	R2=2.11R	R2=0.215R
C1=C2=C3=C	C1=C2=C3=C	C1=C2=C3=C

Figure 6: Differential High Pass Filter

There is no reason why the feedback paths have to be identical. A bandpass filter can be formed by using nonsymmetrical feedback pathways (one low pass and one high pass). Figure 7 shows a bandpass filter that passes the range of human speech (300 Hz to 3 kHz).

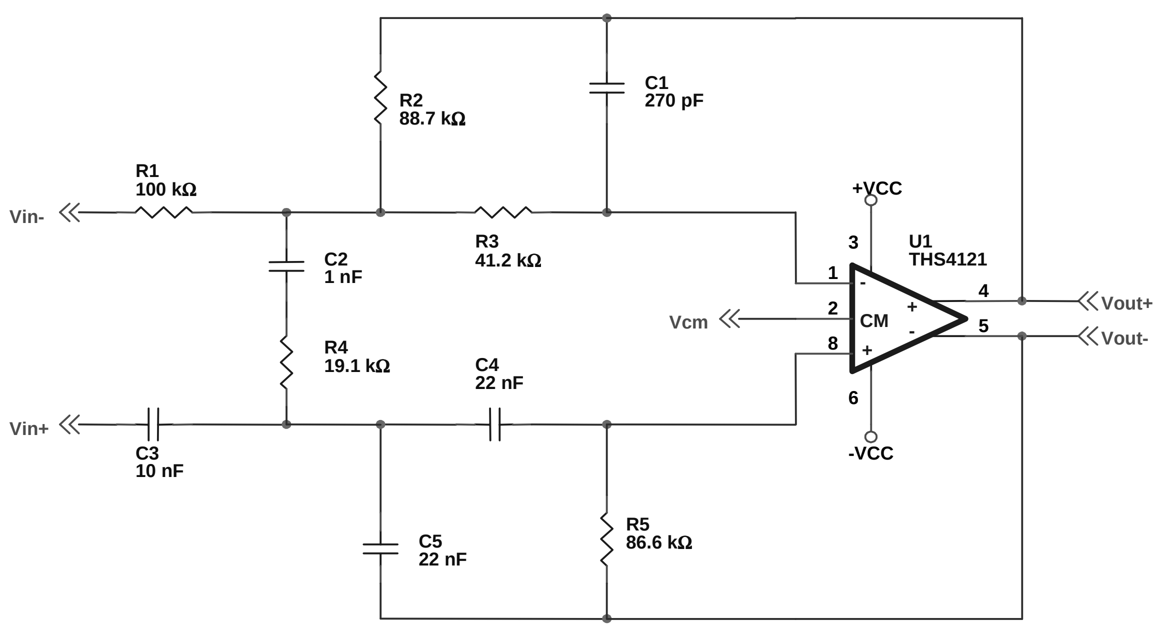


Figure 7: Differential Speech Filter

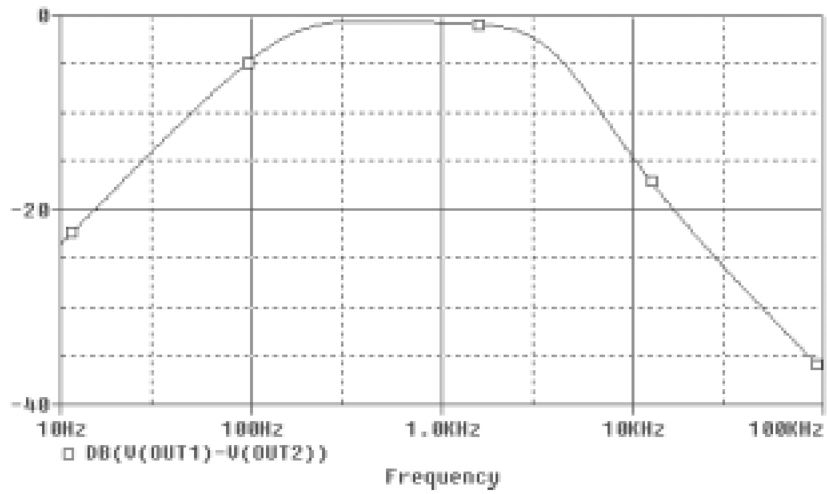


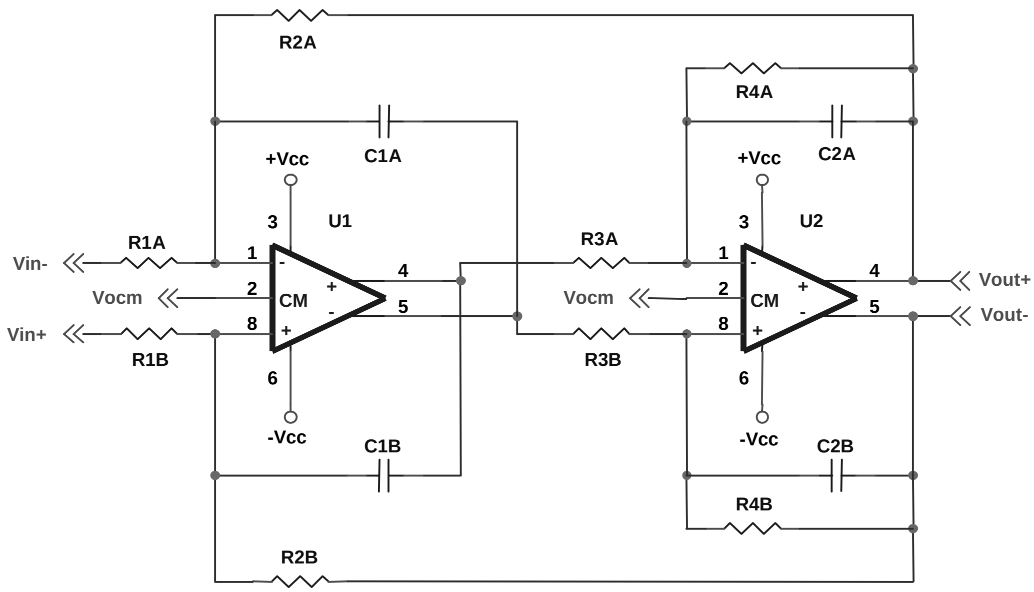
Figure 8: Differential Speech Filter Response

Some caveats with this type of implementation:

- Because the input is non-symmetrical, there will be almost no input common mode rejection
- Proper DC operating point must be set for both feedback pathways.

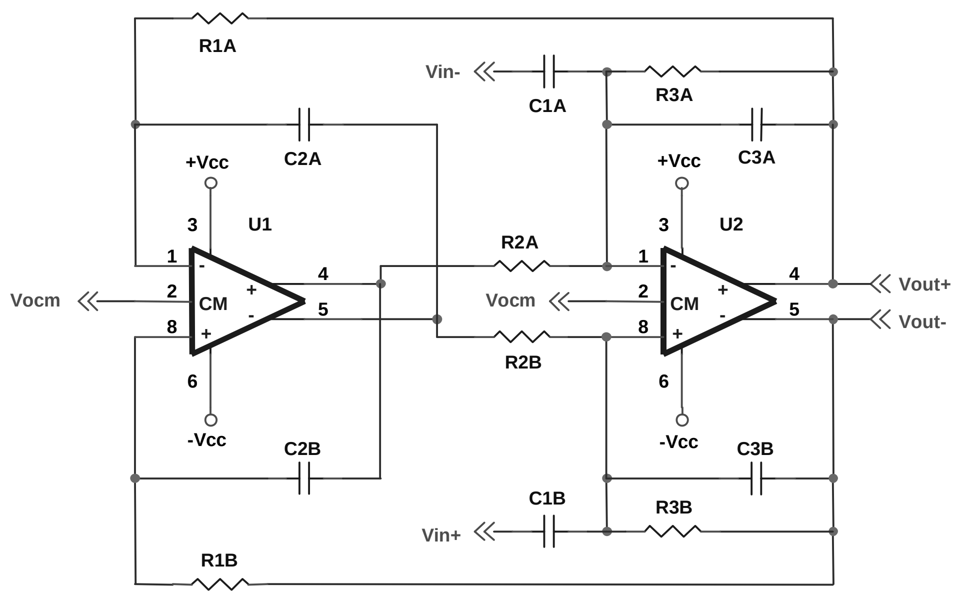
3.2.2 Akerberg Mossberg Filter

Akerberg Mossberg filter topology (see Reference 7) is a double pole topology that is available in low pass, high pass, band pass, and notch. The single ended implementation of this filter topology has an additional op-amp to invert the output of the first op-amp. That inversion in inherent in the fully-differential op-amp, and therefore is taken directly off the first stage. This reduces the total number of op-amps required to 2:



Bessel	Butterworth	Chebyshev
Fo=1/(2πRC)	Fo=1/(2πRC)	Fo=1/(2πRC)
R2=R3=0.786R	R2=R3=R	R2=R3=1.19R
R4=0.453R	R4=0.707R	R4=1.55R
C1=C2=C	C1=C2=C	C1=C2=C
Gain: R/R1	Gain: R/R1	Gain: R/R1

Figure 9: Akerberg Mossberg Low Pass Filter



Bessel	Butterworth	Chebyshev
Fo=1/(2πRC)	Fo=1/(2πRC)	Fo=1/(2πRC)
R1=R2=1.27R	R1=R2=R	R1=R2=0.84R
R3=0.735R	R3=0.707R	R3=1.1R
C2=C3=C	C2=C3=C	C2=C3=C
Gain: C1/C	Gain: C1/C	Gain: C1/C

Figure 10: Akerberg Mossberg High Pass Filter

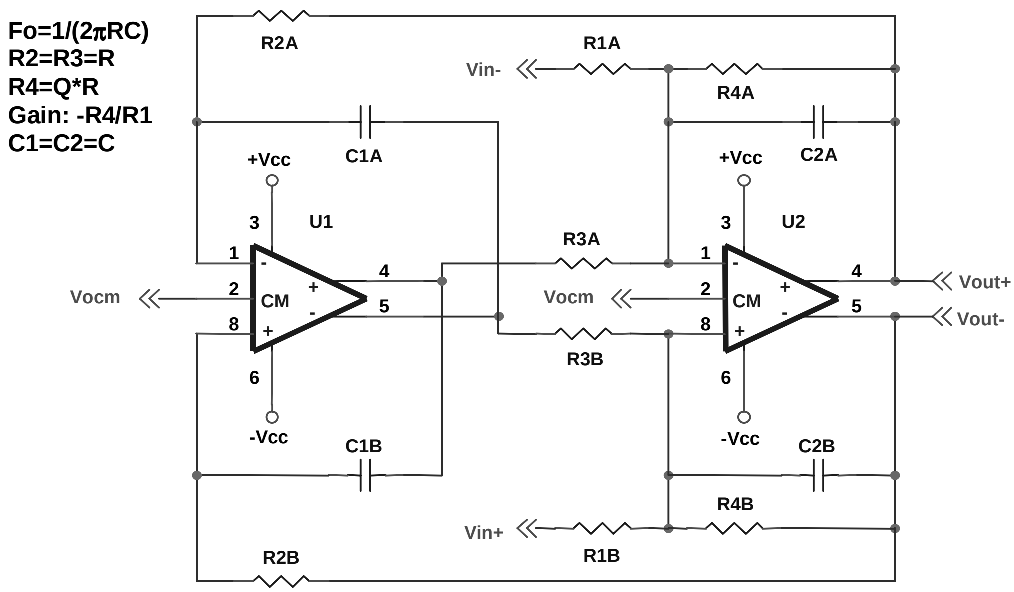


Figure 11: Akerberg Mossberg Band Pass Filter

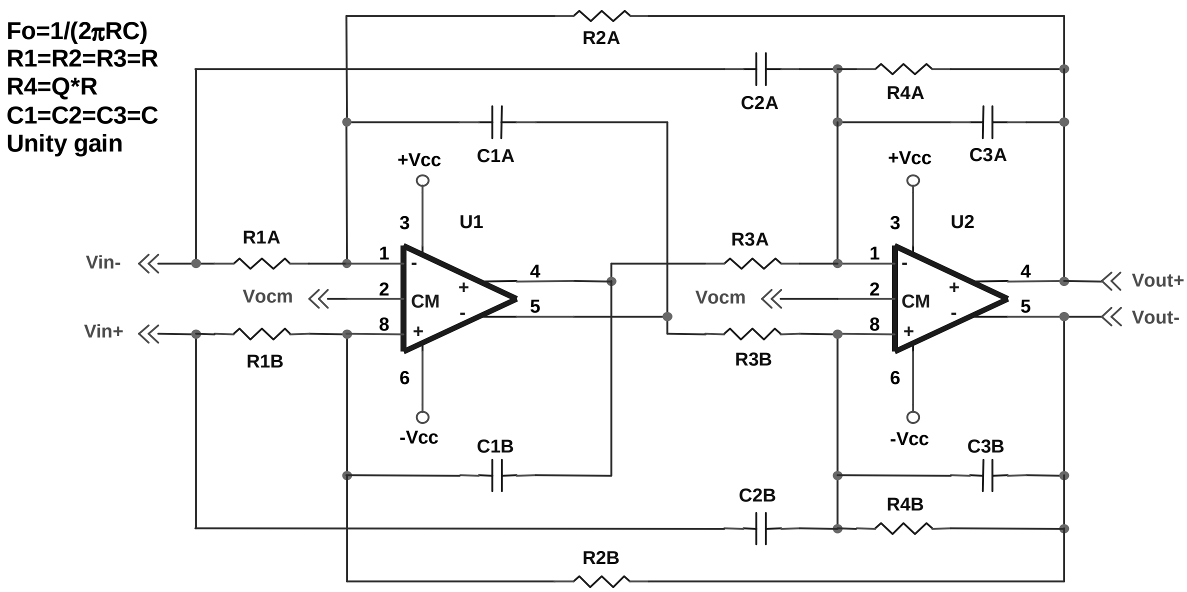
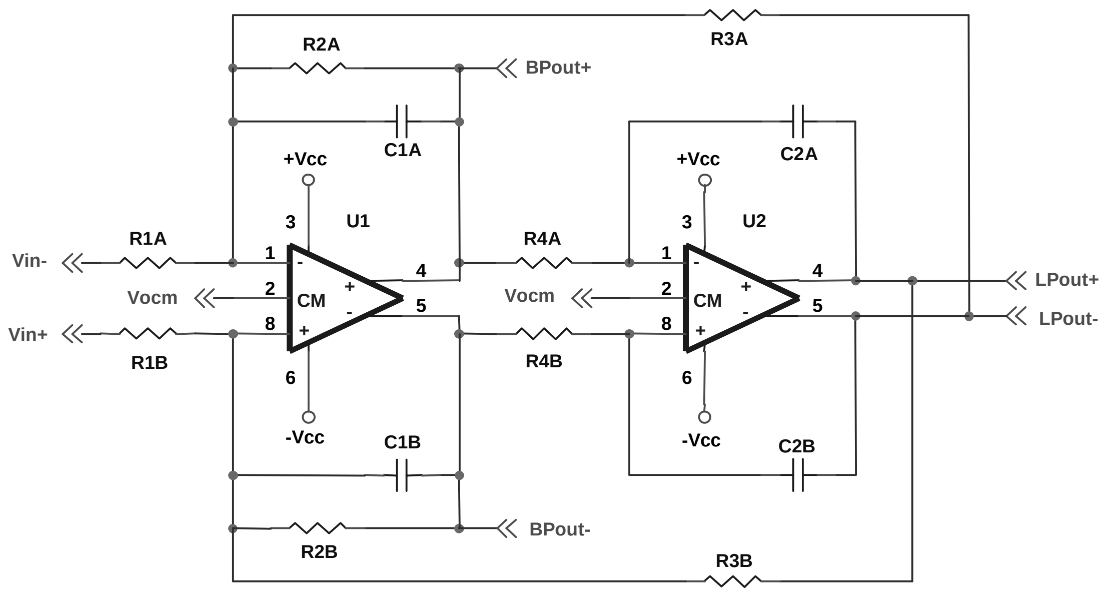


Figure 12: Akerberg Mossberg Notch Filter

3.2.3 Biquad Filter

Biquad filter topology is a double pole topology that is available in low pass, high pass, band pass, and notch. The highpass and notch versions, however, require additional op-amps, and therefore this topology is not optimum for them. The single-ended implementation of this filter topology has an additional op-amp to invert the output of the first op-amp. That inversion is inherent in the fully-differential op-amp, and therefore is taken directly off the first stage. This reduces the total number of op-amps required to 2:



BANDPASS		LOWPASS	
	Bessel	Butterworth	Chebyshev
Fo=1/(2πRC)	Fo=1/(2πRC)	Fo=1/(2πRC)	Fo=1/(2πRC)
R3=R	R3=0.785R	R3=R	R3=1.19R
C1=C2=C	R2=0.45R	R2=0.707R	R2=1.55R
Gain= -R2/R1	Gain: -R2/R1	Gain: -R2/R1	Gain: -R1/R2
R2=Q*R	C1=C2=C	C1=C2=C	C1=C2=C

Figure 13: Differential BiQuad Filter

4 Driving Differential Input Data Converters

Most high-resolution, high-accuracy data converters utilize differential inputs instead of single-ended inputs. There are a number of strategies for driving these converters from single-ended inputs.

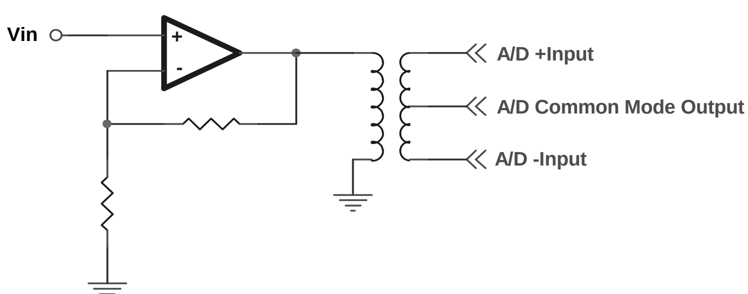


Figure 14: Traditional Method of Interfacing to Differential-Input A/D Converters

In Figure 14, one amplifier is used in a noninverting configuration to drive a transformer primary. The secondary of the transformer is center tapped to provide a common-mode connection point for the A/D converter V_{ref} output.

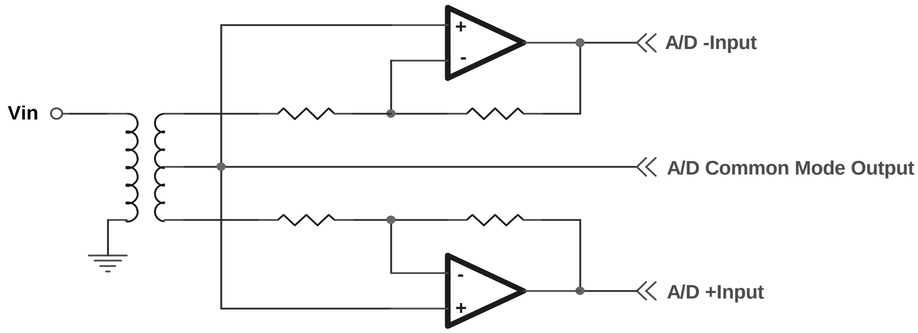


Figure 15: Differential Gain Stage With Inverting Single-Ended Amplifiers

Gain can be added to the secondary side of the transformer. In Figure 15, two single-ended op amps have been configured as inverting gain stages to drive the A/D Inputs. The non-inverting input inputs are connected to the transformer center tap and A/D V_{ref} output.

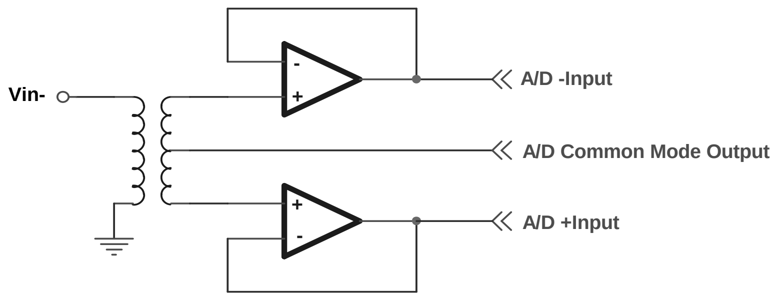


Figure 16: Differential Gain Stage With Noninverting Single-Ended Amplifiers

Figure 16 shows how single-ended amplifiers can be used as noninverting buffers to drive the input of an A/D. The advantage of this technique is that the unity gain buffers have exact gains, so the system will be balanced.

Transformer interfacing methods all have one major disadvantage:

- The circuit does not include dc in the frequency response. By definition, the transformer isolates dc and limits the ac response of the circuit.

If the response of the system must include dc, even for calibration purposes, a transformer is a serious limitation.

A transformer is not strictly necessary. Two single-ended amplifiers can be used to drive an A/D converter without a transformer:

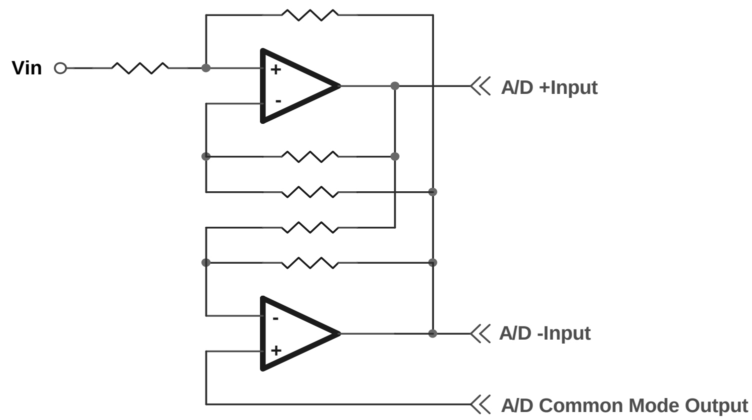


Figure 17: Differential Gain Stage With Noninverting Single-Ended Amplifiers

Although all of the methods can be employed, the most preferable method is the use a fully-differential op-amp:

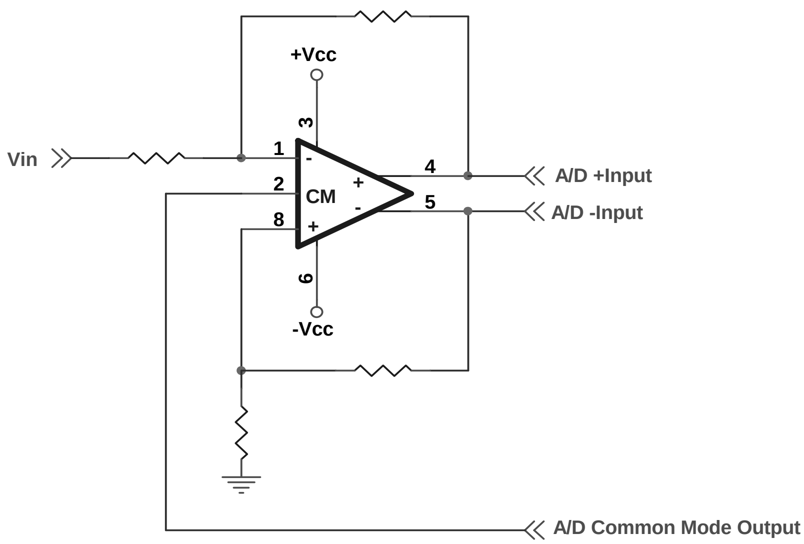


Figure 18: Preferred Method of Interfacing to a Data Converter

A designer should be aware of the characteristics of the reference output from the A/D converter. It may have limited drive capability, and / or have relatively high output impedance. A high-output impedance means that the common mode signal is susceptible to noise pickup. In these cases, it may be wise to filter and/or buffer the A/D reference output:

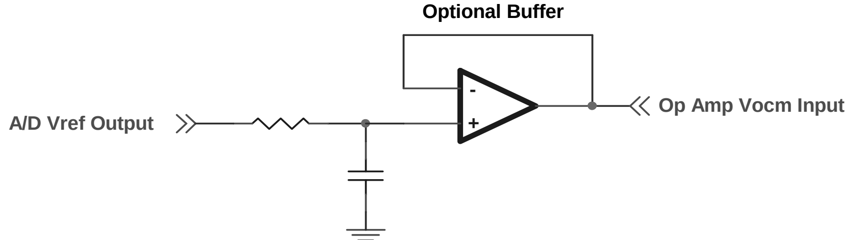


Figure 19: Filter and Buffer for the A/D Reference Output

Some A/D converters have two reference outputs instead of one. When this is the case, the designer must sum these outputs together to create a single signal as shown in Figure 20:

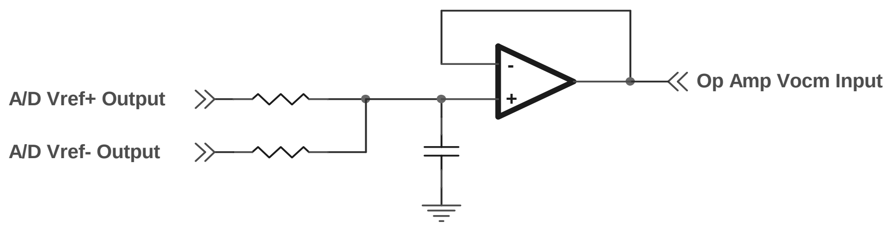


Figure 20: Filter and Buffer for the A/D Reference Output

5 Audio Applications

5.1 Bridged Output Stages

The presence of simultaneous output polarities from a fully-differential amplifier solves a problem inherent in bridged audio circuits – the time delay caused by taking a single-ended output and running it through a second inverting stage.

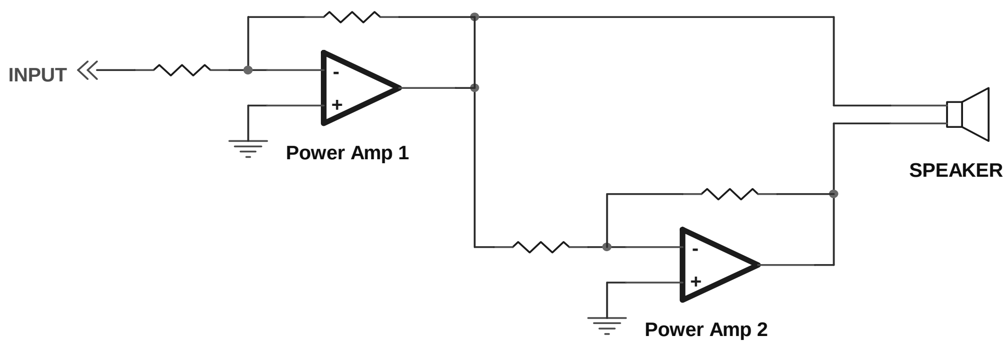


Figure 21: Traditional Bridge Implementation

The time delay is nonzero, and a degree of cancellation as one peak occurs slightly before the other when the two outputs are combined at the speaker. Worse yet, one output will contain one amplifier's worth of distortion, while the other has two amplifier's worth of distortion. Assuming traditional methods of adding random noise, that is a 41.4% noise increase in one output with respect to the other, power output stages are usually somewhat noisy, so this noise increase will probably be audible.

A fully-differential op-amp will not have completely symmetrical outputs. There will still be a finite delay, but the delay is orders of magnitude less than that of the traditional circuit.

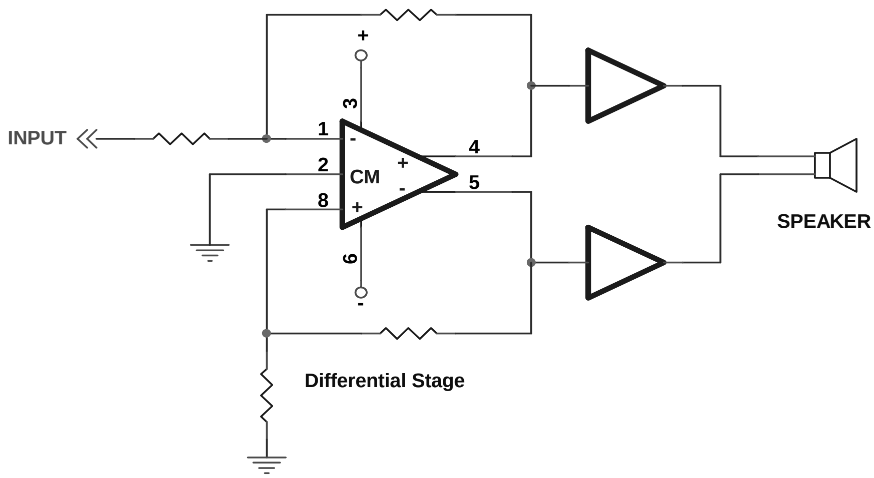


Figure 22: Improved Bridge Implementation

This technique increases component count and expense. Therefore, it will probably be more appropriate in high end products. Most fully-differential op-amps are high-speed devices, and have excellent noise response when used in the audio range.

5.2 Stereo Width Control

Fully-differential amplifiers can be used to create an amplitude cancellation circuit that will remove audio content that is present in both channels.

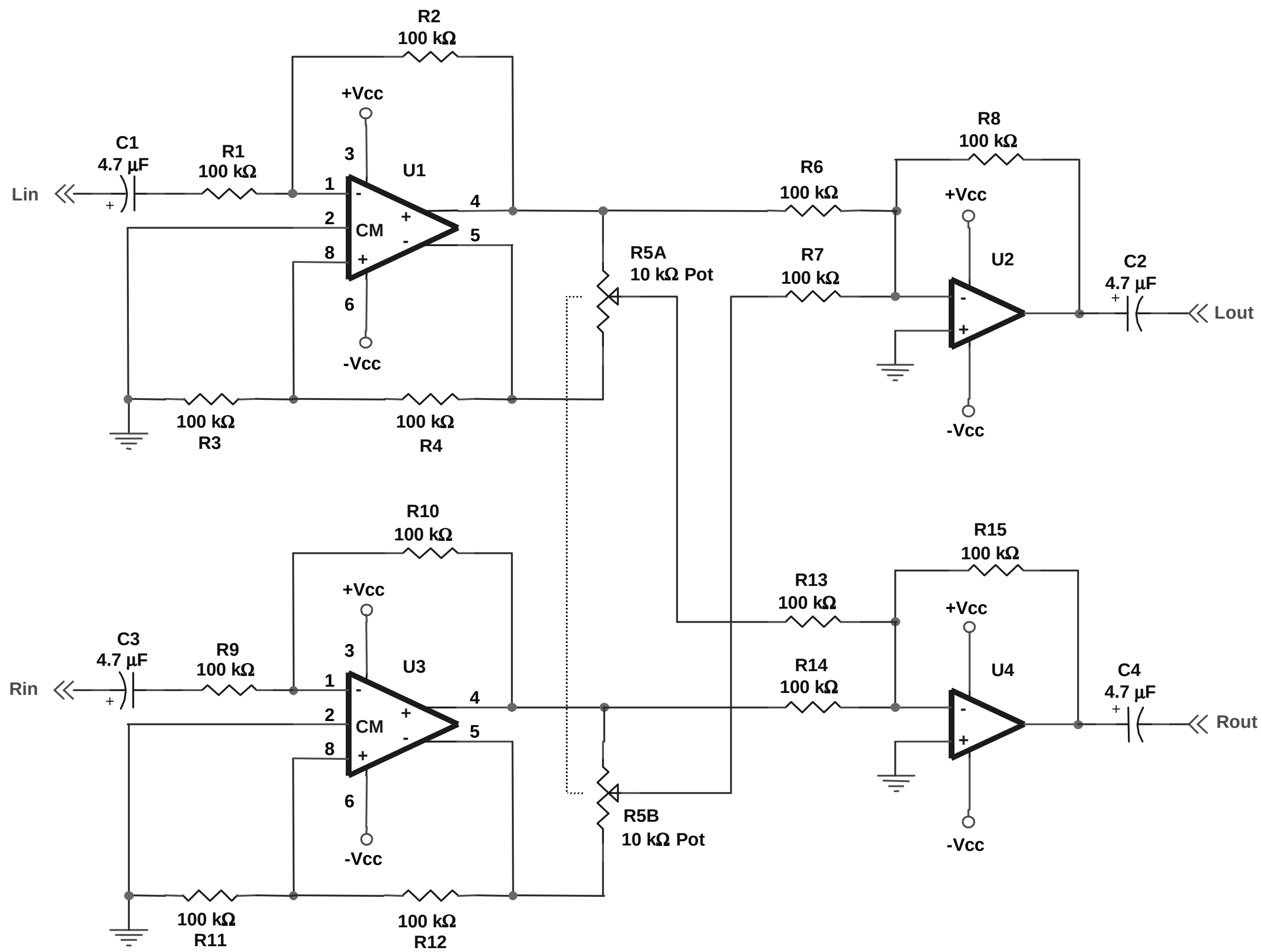


Figure 23: Stereo Width Control

The output mixers (U2 and U4) are presented with an inverted version of the input signal on one input (through R6 and R14), and a variable amount of out-of-phase signal from the other channel.

When the ganged pot (R5) is at the center position, equal amounts of inverted and noninverted signal cancel each other, for a net output of zero on the other input of the output mixers (through R7 and R13).

At one extreme of the pot (top in this schematic), the output of each channel is the sum of the left and right channel input audio, or monaural. At the other extreme, the output of each mixer is devoid of any content from the other channel – canceling anything common between them.

This application differs from previous implementations by utilizing fully-differential op-amps to simultaneously generate inverted and noninverted versions of the input signal. The usual method of doing this is to generate an inverted version of the input signal from the output of a buffer amp. The inverted waveform, therefore, is subject to two op-amp delays as opposed to one delay for the non-inverted waveform. The inverted waveform, therefore, has some phase delay which limits the ultimate width possible from the circuit. By utilizing a fully-differential op-amp, a near perfect inverted waveform is available for cancellation with the other channel.

6 Summary

Fully-differential amplifiers are based on the technology of the original tube-based op-amps of more than 50 years ago. As such, they require design techniques that are new to most designers. The performance increase afforded by fully-differential op-amps more than outweighs the slight additional expense of more passive components. Driving of fully-differential A/D converters, data filtering for DSL and other digital communication systems, and audio applications are just a few ways that these devices can be used in a system to deliver performance that is superior to single-ended design techniques.

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