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Demystifying the Operational Transconductance Amplifier

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ABSTRACT

Operational transconductance amplifiers (OTAs) are often among the least understood analog components. However, these devices serve a very useful function that is being implemented on a regular basis in many integrated circuits as an element for more advanced purposes; the current feedback amplifier is among the most prominent example. The purpose of this application report is to show how this building block operates. It also develops several examples of how this type of component can be put to good use for many applications.

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1 Operational Transconductance Overview

OTAs are versatile building blocks that intrinsically offer wide bandwidth for many types of amplifiers. The OTA, or voltage-controlled current source, can be viewed as an ideal transistor. As the transistor model, it has three terminals: a high input impedance (base, or ***B***); a low-impedance input/output (emitter, or ***E***); and a current output (collector, or ***C***). However, unlike a bipolar transistor, the OTA is self-biased and has bipolar output, meaning that the output current source can either source or sink the output current. The output current is zero for a zero base-emitter voltage. AC-inputs centered on zero produce an output current that is bipolar and also centered on zero. The transconductance element is traditionally adjustable with an external resistance, allowing trade-offs in bandwidth, quiescent current, and gain. Used as a basic building block, an OTA element simplifies designs of automatic gain control (AGC) amplifiers, light-emitting diode (LED) driver circuits, fast-pulse integrators, control loops for capacitive sensors, and active filters, as well as other applications.

1.1 Definitions

Over the years and depending on the writer, an OTA has been referred to as a *diamond transistor*, a *voltage-controlled current source*, a *transconductor*, a *macro transistor*, and a *positive second-generation current conveyor* or CCII+. Figure 1 illustrates these terms and the corresponding symbols generally used to represent each.

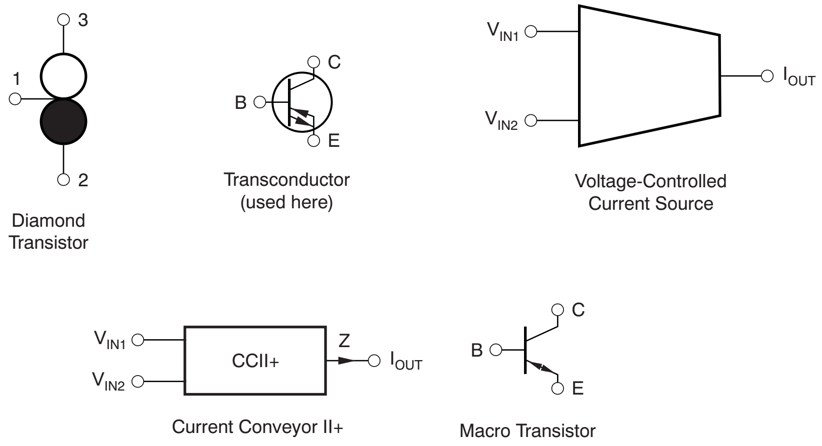


Figure 1. Typical OTA Elements and Accepted References

Regardless of how it is illustrated or defined, the OTA has a high impedance terminal (B); a low impedance terminal (E) that can be considered either as an input or an output depending on the circuit; and a output current source terminal (C). The output current source terminal is high impedance. Looking at the transconductor, any voltage that appears between B and E will generate a current that flows out of C. For the balance of this document, however, we will consider circuits. The first circuit that demonstrates how an OTA operates is shown in Figure 2.

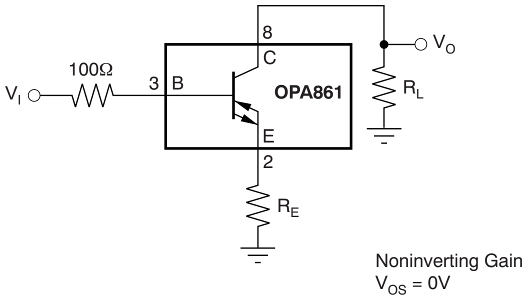


Figure 2. Basic OTA Circuit Architecture

Looking at the internal architecture of the OTA as shown in Figure 2, a buffer is present between the B-input and the E-output. This buffer places a copy of the input voltage to the E-output. The voltage present on the E-output generates a current through the R_E resistor. The current flowing out of the R_E resistor is then duplicated and flows out of the C-output. This current is converted back to a voltage by passing through the load resistance. The total gain for the circuit illustrated in Figure 2 is set by R_L/R_E. The input is high impedance and the output impedance is set by the load resistance. Note that a 100Ω resistance is placed in series with the B-input. This resistance helps isolate the parasitic input capacitance of the OTA from the earlier voltage-mode stage to help ensure stability. A value ranging from 25Ω to 100Ω is normally recommended. If a current-mode stage is used, this series resistor is not needed.

1.2 Recommended OTA Devices

Texas Instruments offers three devices that include an OTA:

- OPA860 (an OTA and a closed-loop buffer)
- OPA861 (an OTA)
- OPA615 (a wide-bandwidth dc restoration circuit that contains an OTA and a switching OTA, or SOTA)

Information on these products is available through the TI web site at http://www.ti.com.

2 Direct Use of an OTA

Most circuits for the OTA section of a given application consist of variations on a few basic types. These variations are best understood by analogy to a typical transistor. When used in voltage mode, the OTA section can operate in one of three basic states: common emitter, common base, and common collector. In current mode, the OTA can be used for analog computation such as a current amplifier, a current differentiator, a current integrator, and a current summing device. This section discusses the use of an OTA in either voltage mode or current mode.

2.1 Voltage Mode

Figure 3 through Figure 5 illustrate the options for using an OTA in voltage mode.

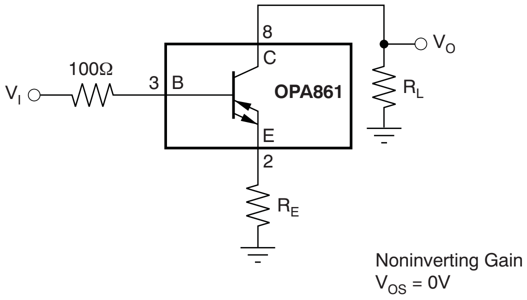


Figure 3. Voltage Mode: Common-E Amplifier

The gain for the common-E amplifier configuration is set by Equation 1, and the transconductance shown in Equation 2. Note that a new term appears in the equation, g_m. This term is the transconductance of the OTA stage. It may be best understood as the output impedance of the E-terminal with a value of $1/g_m$.

$$G = \frac{R_L}{\frac{1}{g_m} + R_E} \tag{1}$$

$$g_{m\_deg} = \frac{1}{\frac{1}{g_m} + R_E} \tag{2}$$

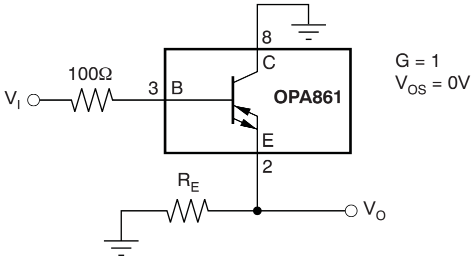


Figure 4. Voltage Mode: Common-C Amplifier

The gain for the common-C amplifier configuration is set by Equation 3, and the output impedance shown in Equation 4.

$$G = \frac{1}{1 + \frac{1}{g_m \times R_E}} = 1 \tag{3}$$

$$R_O = \left(\frac{1}{g_m} \middle\| R_E\right) \tag{4}$$

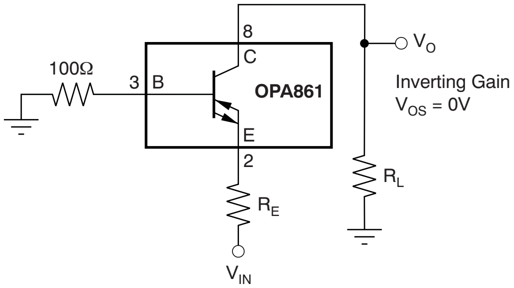


Figure 5. Voltage Mode: Common-B Amplifier

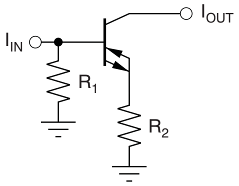
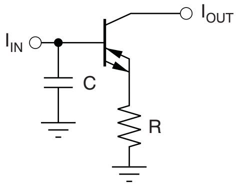
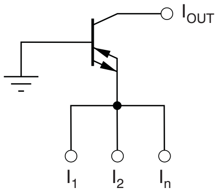
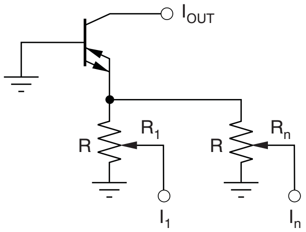
The gain for the common-B amplifier configuration is set by Equation 5.

$$G = \frac{R_L}{R_E + \frac{1}{g_m}} = -\frac{R_L}{R_E} \tag{5}$$

2.2 Current Mode

The different current-mode OTA circuits are summarized in Table 1.

Table 1. Current-Mode Analog Computation Using an OTA Circuit

Functional Element	Transfer Function Equation	Implementation with an OTA Circuit
Current Amplifier	$I_{OUT} = \frac{R_1}{R_2} \times I_{IN}$	
Current Integrator	$I_{OUT} = \frac{\int I_{IN} dt}{C \times R}$	
Current Summer	$I_{OUT} = 1_j \sum_{j=1}^{n} I_j$	
Weighted Current Summer	$I_{OUT} = 1_j \sum_{j=1}^{n} I_j \times \frac{R_j}{R}$	

3 Advanced Uses of OTA Architecture

This section describes several advanced uses of an OTA element in typical applications.

3.1 Current-Feedback Amplifier (CFB)

Combining a transconductance amplifier with a buffer and then adding negative feedback produces the architecture of a current-feedback (CFB) amplifier. Figure 6 shows a typical CFB block diagram.

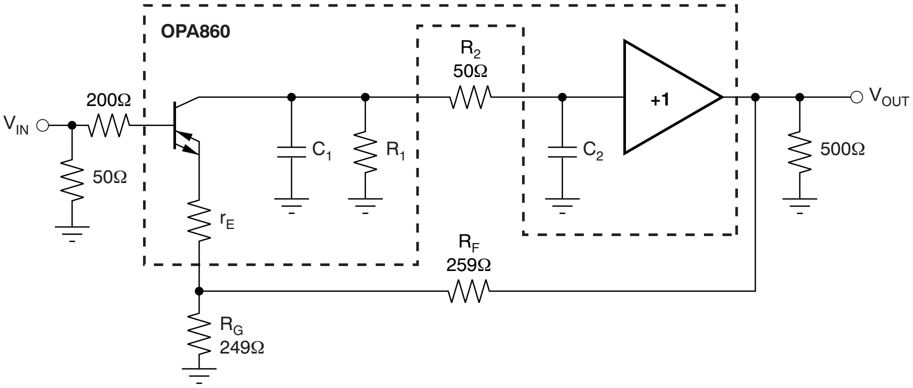


Figure 6. Typical CFB Amplifier Block Diagram

The circuit shown in Figure 6 makes use of the OPA860 because this device integrates both a buffer section and an OTA section. Notice that the E-input/-output is normally defined as *inverting input* in operational amplifier nomenclature. The B-input is the noninverting input and the output of the buffer is the operational amplifier output. The C-output of the OTA is connected to the high impedance input of the buffer. Note that R_1, C_1, and C_2 are parasitic components of both the OTA and the buffer. R_2 is an optional component that may help de-Q a potential RLC network as a result of component and package parasitics. If a slower amplifier were desired, to select the frequency response a capacitor in parallel with C_2 can be added. Alternatively, the feedback resistor R_F can be increased.

3.2 Control-Loop Amplifier

The input stage of the control-loop amplifier shown in Figure 7 is composed of two OTAs. This combination provides a high input impedance as well as excellent rejection to any common-mode signals. One C-output is left unconnected and the other C-output of the input stage is connected to an RC network, in effect forming an integrator from dc to the frequency defined by the RC time constant. A second integrator stage is then used before isolating the C-output of the second stage with a buffer to ensure ac performance and to drive subsequent output stages.

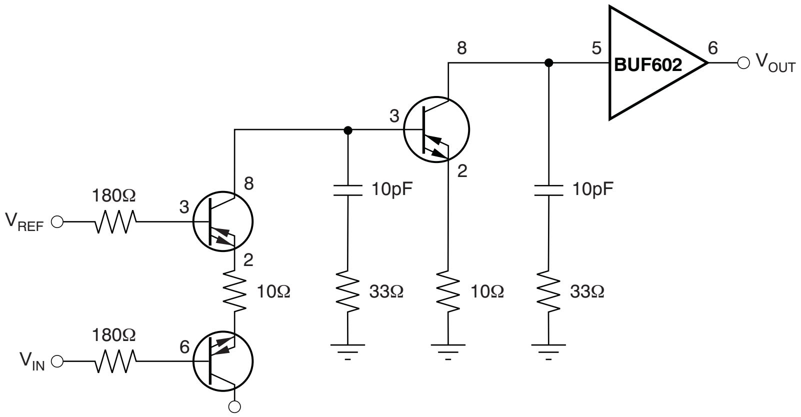


Figure 7. Control-Loop Amplifier Circuit Model

3.3 DC-Restore Circuit

Multiple dc-restore circuits can be developed using a modular OTA element. The circuit illustrated in Figure 8 uses a SOTA to restore the signal when it is triggered. This architecture allows a precise selection of the dc-restore point. For this purpose, we used the OPA615.

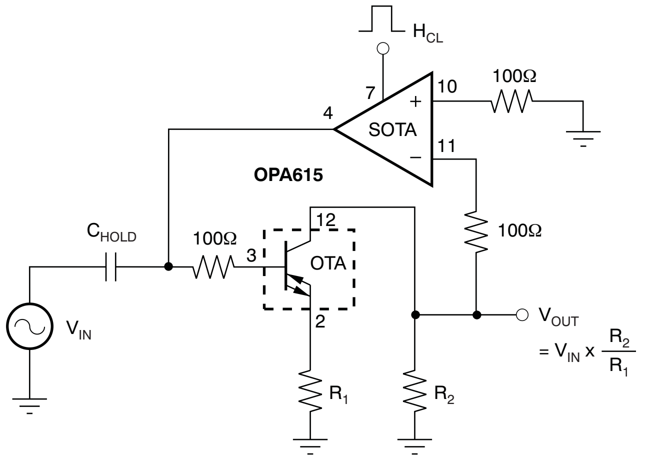


Figure 8. DC-Restore Circuit Example with the OPA615

In this example, the C_{HOLD} capacitor is being charged by the sampling OTA (SOTA), triggered at the exact point of interest. The OTA provides a means to amplify the signal. Note that because of the very high input impedance of the OTA, a small C_{HOLD} capacitor can be used for higher frequency applications; or, if a large C_{HOLD} is desired, a very low-frequency high-pass filter can be defined. The OPA615 is the fastest OTA offered by Texas Instruments with a bandwidth in excess of 700MHz. This circuit can easily be adapted to operate continuously without any trigger requirements by adding a capacitor on the SOTA inverting input. This capacitor will form, with the 100Ω series resistance at the input, a low-pass filter that allows the SOTA to charge and discharge the hold capacitor only in relation to the low frequency.

Figure 9 shows another possible implementation of a dc-restore circuit using a current conveyor Type 2 (CCII) OTA.

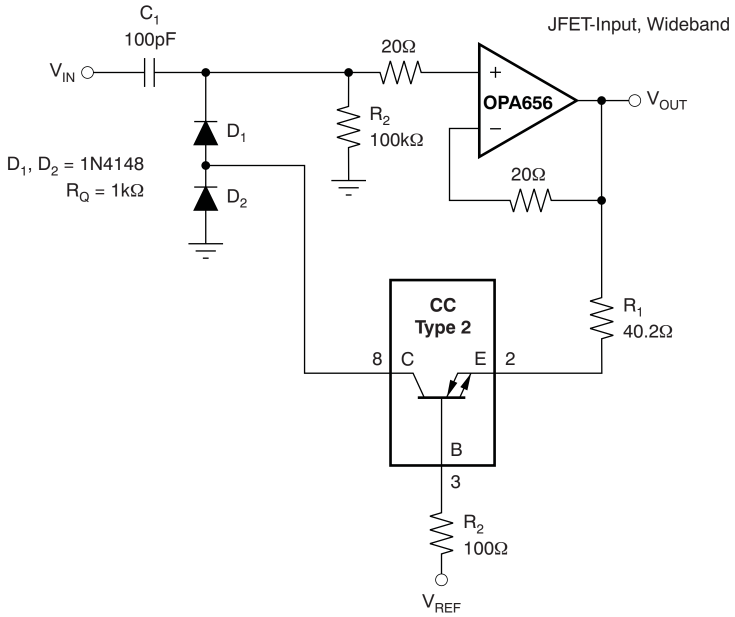


Figure 9. DC-Restore Circuit Example (CC Type 2) with the OPA656

Here, the OTA amplifier works as a current conveyor (CCII), with a current gain of 1. R_1 and C_1 set the dc restoration time constant. D_1 adds a propagation delay to the dc restoration. R_2 and C_1 set the decay time constant.

The output voltage of the operational amplifier (in this case, an OPA656), is compared to a reference level. When the signal is below the level, a current is driven into the noninverting input of the amplifier, thereby raising the dc level.

3.4 Sample/Hold Circuit

The OPA615 can also be reconfigured as a sample/hold circuit using the approach presented in Figure 10.

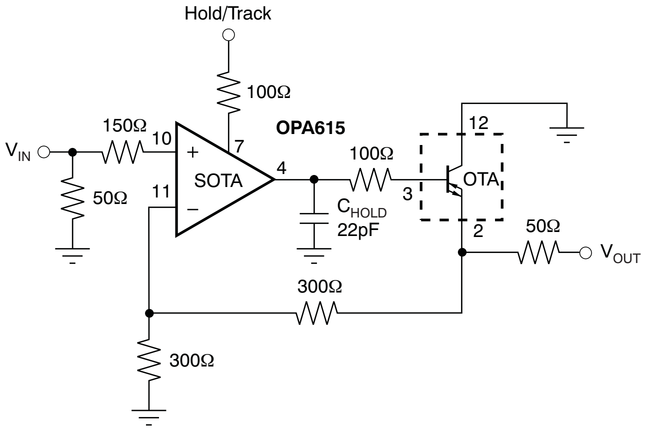


Figure 10. Sample/Hold Circuit Example

Ignoring the hold/track control of the SOTA for now, or considering that the SOTA is in a track mode, you may recognize a voltage-feedback amplifier architecture. The SOTA is used as the input stage, with the OTA (in a buffer configuration) to play the output stage role of a traditional voltage-feedback architecture. You can see that for any change of voltage at the input, the output will track the input with a gain of 2V/V.

Activating the hold mode, the SOTA C-output is now disconnected. The charge held by the hold capacitor is set and droops only as a result of the B-input bias current of the OTA. The output voltage is set. The E-output of the OTA will then see a total load of (600Ω ∥ Load).

As you go from track mode to hold mode, you effectively realize a sample/hold application. With a 2.5ns control delay and greater than 700MHz bandwidth, the OPA615 answers several medium- to high-speed sample/hold needs.

3.5 Instrumentation Amplifier

Figure 11 shows an instrumentation amplifier using three OPA861s to form the high-impedance front-end. Two OTAs are used to create the differential input stage. The third OTA is present to invert the current flowing out of the IN_2 OTA. Remember that the current is flowing out of the C-output. Ground V_{IN2} for a moment and set a positive voltage on V_{IN1}. This method generates a current that flows across R_G from top to bottom, exiting the IN_1 OTA and entering the IN_2 OTA. The current flowing out of the C-output then flows out of the IN_1 OTA and into the IN_2 OTA, indicating that both currents will be of same amplitude but 180° out of phase. To be able to add the currents together at the inverting pin of the operational amplifier, one of the input stage current must be inverting. That function is realized by the third OTA. To compensate for the propagation delay of the second amplifier, an RC network was used. Having two currents with the same amplitude and phase, we can simply add them together and drive a transimpedance amplifier.

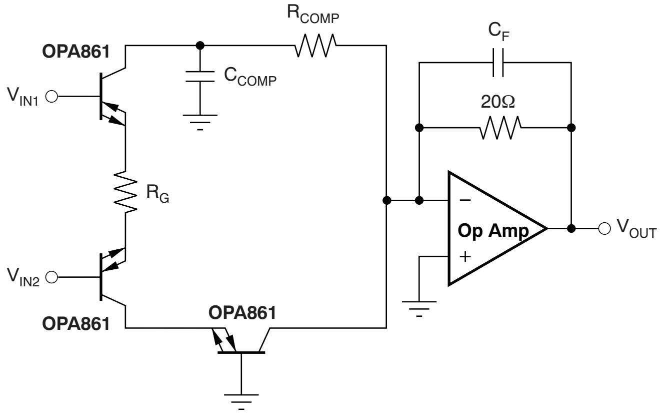


Figure 11. Instrumentation Amplifier Approach with the OPA861

Because any common-mode signal will try to generate the same opposing currents across the gain resistor, this circuit exhibits very good common-mode rejection.

4 Advanced OTA Circuits

From a conceptual standpoint, filtering applications using an OTA element are the most challenging because thinking in a current-mode approach is not a popular technique. However, current-mode amplifiers allow more bandwidth for a reduced quiescent current in most cases. This section describes a simple filtering circuit as well as a high-performance filter developed on an OTA element.

4.1 Simple Filtering Circuit

The low-pass filter circuit illustrated in Figure 12 achieves filtering through the use of a negative impedance converter.

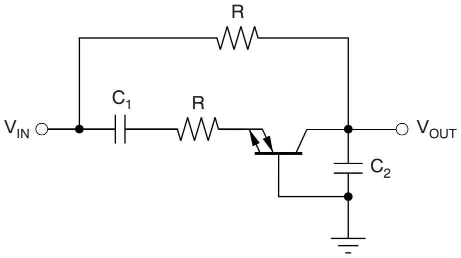


Figure 12. Low-Pass Filter Circuit Example

Equation 6 provides the design equation of the filter.

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1 + sC_2R + s^2C_1C_2R^2} \qquad (6)$$

with:

$$\omega_o = \frac{1}{\sqrt{C_1C_2}R}$$

$$Q = \sqrt{\frac{C_1}{C_2}}$$

This circuit may require some buffering, because the input impedance is set as shown in Equation 7.

$$Z_{IN} = \frac{1}{2sC} + R\frac{1 + sRC}{1 + 2sRC} \qquad (7)$$

4.2 Advanced Filtering Circuit

A universal active filter can be achieved with an OTA using an integrator, as Figure 13 shows. Note that not all OTAs are required for different filtering functions (such as low-pass filters, high-pass filters, or band-pass filters). This circuit implements a second-order filter. Higher-order filters are possible by simply adding an additional integrator stage with its two corresponding, current-weighted OTAs.

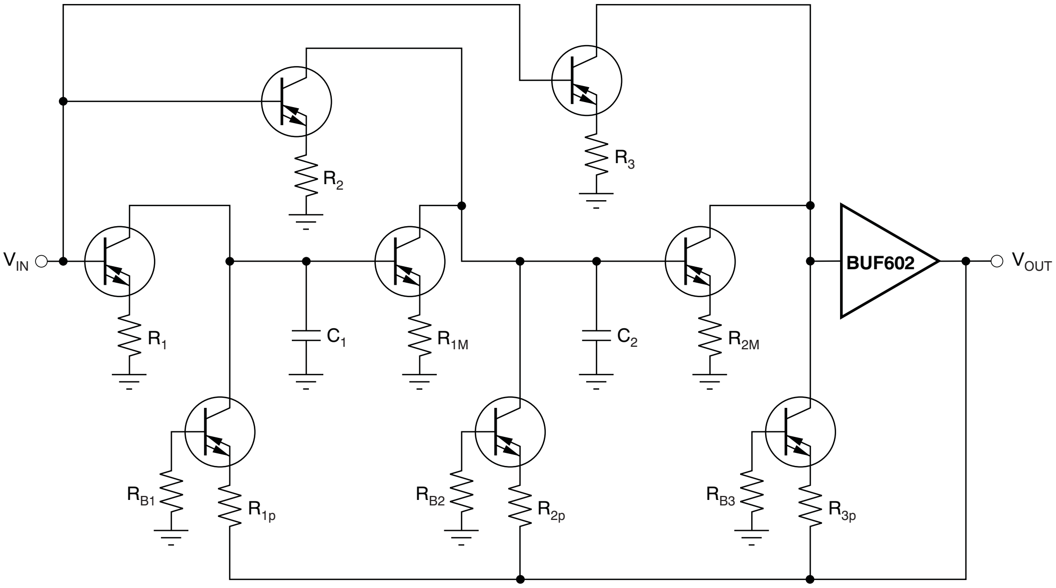


Figure 13. Universal Active Filter with OTA Architecture

With 80MHz OTAs, filter bandwidths as high as 50MHz have been achieved without considering any parasitics for predistortion reasons. These 50MHz/80MHz results compare favorably with the ratio of 50MHz/1GHz that is achieved when traditional operational amplifier circuits are considered.

Equation 8 gives the design equation for the filter shown in Figure 13.

$$F(s) = \frac{V_{OUT}}{V_{IN}} = \frac{s^2C_1C_2R_{1M}\frac{R_{2M}}{R_3} + sC1\frac{R_{1M}}{R_2} + \frac{1}{R_1}}{s^2C_1C_2R_{1M}\frac{R_{1M}}{R_{3p}} + sC1\frac{R_{1M}}{R_{2p}} + \frac{1}{R_{1p}}} \qquad (8)$$

4.2.1 Filter Characteristics

Five filter types can be designed with this structure. These five types include the following:

- For a low-pass filter, set $R_2 = R_3 = \infty$
- For a high-pass filter, set $R_1 = R_2 = \infty$
- For a bandpass filter, set $R_1 = R_3 = \infty$
- For a band rejection filter, set $R_2 = \infty$, and $R_1 = R_3$
- For an all-pass filter, set $R_1 = R_{1p}$; $R_2 = R_{2p}$; and $R_3 = R_{3p}$

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