Keywords: BiCMOS, IC transistors, operational amplifier, op amp, zero temperature coefficient, resistors, precision arrays, binning, tolerance grade, bandwidth, frequency response, summing amp

APPLICATION NOTE 4301

The Zero-Transistor IC, a New Plateau in IC Design

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Apr 01, 2013

Abstract: We can apply a BiCMOS integrated circuit with only resistors and no transistors to solve a difficult design problem. The mythically perfect operational amplifier's gain and temperature coefficient are dependent on external resistor values. Maxim precision resistor arrays are manufactured together on a single die and then automatically trimmed, to ensure close ratio matching. This guarantees that the operational amplifier (op amp) gain and temperature coefficient are predictable and reliable, even with large production volumes.

A similar version of this article appeared in the March 1, 2013 issue of *Electronics World* magazine.

Introduction

This article explains how a BiCMOS integrated circuit with only resistors and no transistors can solve a difficult design problem. It examines how the mythically "perfect" operational amplifier's gain and temperature coefficient are dependent on external resistor values. It then examines some precision resistor arrays which are manufactured together on a single die and then automatically trimmed to ensure close ratio matching. This process guarantees that the op amp's gain and temperature coefficient are predictable and reliable, even with large production volumes.

The Perfect and Practical Op Amp

A BiCMOS IC without transistors, that's different! Now that we have your attention, we are trying to make a point. Why would anyone want an integrated circuit (IC) without transistors? Would anyone spend good money for a BiCMOS mask set without transistors?

For the answers, we must visit the land of practical operational amplifier (op amp) applications. And while there, we need to remember the old saying "a chain is only as strong as its weakest link." The mythical, perfect, million-dollar op amp has infinite gain and a zero temperature coefficient. In **Figure 1**, that perfect op amp is configured to provide noninverting amplification of an input signal.

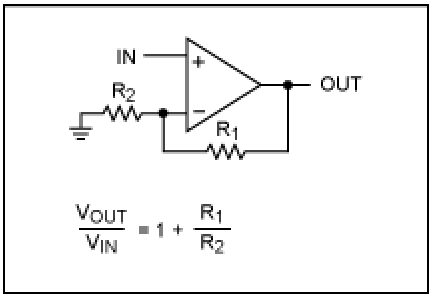

Figure 1. A perfect op amp noninverting amplifier circuit.

What controls amplifier gain? More significantly, what controls the gain tolerance and the temperature coefficient? Is it the op amp or the resistors? The op amp will be no better than the resistors. Similarly, it is the resistors that dominate the temperature coefficient. Thus, precision resistor arrays can have an impact on op amp performance. We will use some arrays and op amps from Maxim to provide some as specific examples.

Tolerance in Precision Resistors: Averaging in Manufacturing and What Can Go Awry

Common op amps offer different operating bandwidths (**Table 1**) and each device can benefit from the precision resistor arrays. The close specifications of the precision resistors are transferred to the amplifier system. Among the transferred specifications are tight gain (as low as 0.035%), and a low temperature gain coefficient (1ppm/°C (typ)). Now the importance of precision resistors is becoming clear—chains do have weak links.

Table 1. Common Op Amps*		
Part	**Description**	**Unity Gain BW (MHz, typ)**
MAX9619–MAX9620	Ultra-low power, zero-drift precision op amps in SC70 packages	1.5
MAX9636	3V/5V low-power, low-noise, CMOS, rail-to-rail I/O op amp	1.5
MAX44251	20V, ultra-precision, low-noise op amp	10
MAX9632	36V, precision, low-noise, wide-band amplifier	55
MAX44260	1.8V, 15MHz low-offset, low-power, rail-to-rail I/O op amp	15
MAX9613/MAX9615	Low-power, high-efficiency, single/dual, rail-to-rail I/O op amps	2.8
MAX9912	Dual, 200kHz, 4µA, rail-to-rail I/O op amp	0.2
MAX9916	Dual, 1MHz, 20µA, rail-to-rail I/O op amp in SOT23	1
MAX4036	Single, low I_{BIAS}, 1.4V/800nA, rail-to-rail op amp	0.004
MAX4239	Ultra-low offset/drift op amp ($A_V \geq 10$) in SOT23 package	6.5
MAX4232	High-output-drive, 10MHz, 10V/µs, rail-to-rail I/O dual op amp	10
MAX4236	Very high precision, 3V/5V, rail-to-rail op amp (unity gain stable) in an 8-pin µMAX® package	1.7
MAX4472	Quad, 1.8V/750nA, rail-to-rail op amp in TSSOP package	0.009
MAX4253	Low-noise/distortion, low-power, rail-to-rail op amp	3

*For the latest information, refer to the device's data sheet.

Let's look at a simple example in which we will use two 10% tolerance resistors. While our prototype may have typical center-value resistors, we know that the production run will eventually encounter a situation with R_1 and R_2 at opposite ends of the tolerance bands. During the design, we have to consider these worst-case corners to ensure that the final complex system meets specifications. To deal with this, designers should create an error budget that assigns acceptable errors for each stage. By staying within the budget, you can assure specification compliance for the whole system.

One trick is to form each resistor from several larger-value parallel resistors. This uses the normal distribution of a manufacturing process to average the tolerance values, thus increasing the probability of maintaining the proper value. Of course, this is only true if the normal distribution pattern actually exists. This is a dangerous assumption if one does not control the manufacturing process. For example, resistor manufacturer A makes or trims the resistor at one edge instead of at the center value. This could happen as a result of a chemistry error, or perhaps the trimming machine is out of tolerance. Worse, resistor manufacturer B makes the resistors that follow the normal distribution curve; however, they sort or bin the results. **Figure 2** illustrates the normal distribution and the sort selection. Note that each of the bins except 1% are really two bins, one for higher than nominal value and a minus bin for parts lower than nominal.

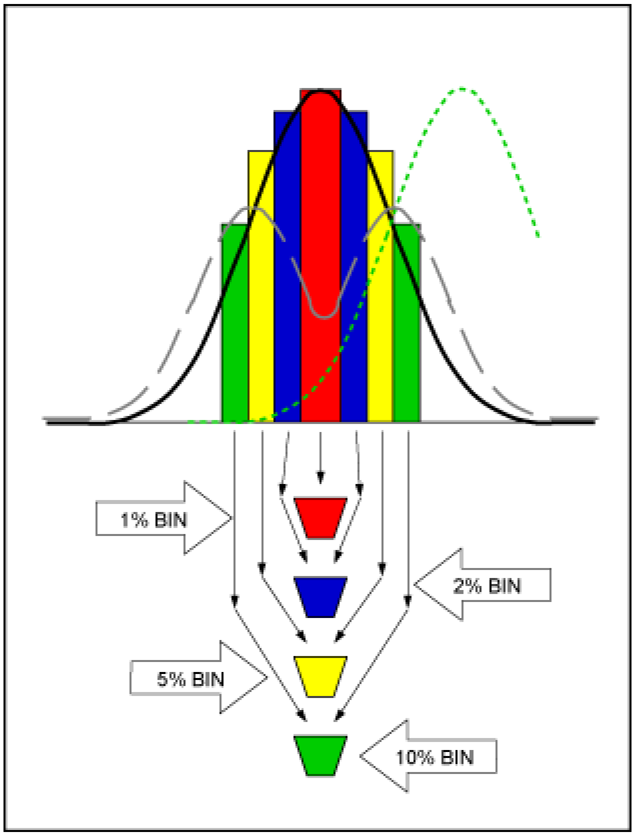

Figure 2. Binning or sorting of manufacturing tolerances.

The solid (black line) curve in Figure 2 looks good in a perfect world. However, where we live, not much is perfect. As the manufacturing tolerances move, the number of parts in each bin changes. The tolerance could move to the right (illustrated by the green dotted line), resulting in no yield at 1% tolerance. It could be bimodal (illustrated by the gray dashed line) with many 5% and 10% tolerance parts and few 1% and 2% tolerance parts.

More importantly, this method seems to make sure that the 2% tolerance parts are only from minus 1 to minus 2 and plus 1 to plus 2 (no 1% parts). It also appears to remove any 1% and 2% tolerance parts from the 5% bin. We say "seems to" and "appears to," because sales volume and human nature also control the mix. For instance, the plant manager needs to ship 5% tolerance resistors, but he does not have enough to meet the demand this month. He does, however, have an overabundance of 2% tolerance parts. So, this month he throws them into the 5% bin and makes the shipment. Clearly deliberate, human intervention skews the statistics and method, but that plant manager gets his performance bonus. Such is the importance of the human factor.

Then there are other relevant human factors. If an operator is interrupted while unloading the bins, anything can happen. When he (a rhetorical "he" here, as we know that women hold these positions too) returns to working, will he remember to put the parts back in the proper bin? When a few parts spill, the operator does not want to be penalized (or yelled at), so the parts might go back into the most convenient bin. It is human nature and besides, who will ever know?

Then there are human factors when the board is stuffed. The part wanted is 2.52K. The operator is confused—does the correct reel say 2520, 2.533, or 2531? Is the nearest reel the proper one? Alternatively, during rework if some resistors are dropped, will he pick up the correct part, or will he pick up the resistors that he dropped last time? Will the operator admit a mistake or ask for help, taking the risk of some penalty? Human nature says no.

Packaging Resistor Arrays in a Zero-Transistor IC

With so many things to consider, how can a design engineer protect a design from errors? The zero-transistor IC (IC-packaged precision resistor arrays) comes to the rescue. In these integrated arrays, the resistors are very controlled. They have narrow tolerances and, most importantly, the ratio between the two resistors is accurately controlled (after all, it is the ratio that determines the gain). Furthermore, the temperature coefficient is well known and the resistors will track each other, since they are integrated close together on a single die and in a single package.

The resistor arrays are also manufactured together on the same wafer and are typically automatically tested and trimmed together. Yes, test escapes do happen—an operator can dump parts from the bad bin into the good bin. But the places where this can happen are minimized to just one station instead of many. Using automatic test equipment (ATE), it is very common to see a physical lock on the bad bin. Such an operating procedure ensures that the good parts are removed from the test floor and stowed in inventory, before the bad parts are unlocked and discarded.

As the boards are manufactured, the chance of assembly errors is also reduced, since one package now replaces several discrete resistors. It also requires just a single insertion, rather than multiple components being inserted into the PC board.

If the discrete resistors used in Figure 1 are replaced by a pair of MAX5490 precision resistors (**Figure 3**), the schematic is basically the same. However, the physical co-integration of the resistors provides excellent resistance matching.

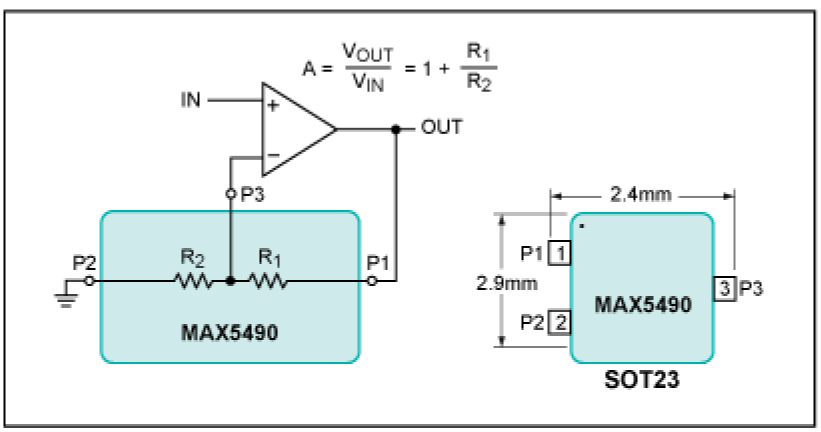

Figure 3. The MAX5490 precision resistor pair.

In fact, resistor arrays often offer a choice of 0.035% (A grade), 0.05% (B grade), and 0.1% (C grade) tolerances. At one part per million, the temperature drift of the devices is extremely low. It is the resistance ratio (effectively gain stability) that is guaranteed to be less than 1ppm/°C (typ) over -55°C to +125°C. The end-to-end resistance of the pair is 100kΩ. Five standard and other custom-resistance ratios from 1:1 to 100:1 are available from tiny 3-pin SOT23 packages. The operating voltage across the resistors is greater than most op amps—up to 80V across the sum of R1 and R2. Additionally, the resistance-ratio long-term stability is typically 0.03% over 2000 hours at 70°C.

The MAX5490 precision-resistor pair allows the use of normal op-amp application circuits. **Figure 4**, **Figure 5**, and **Figure 6** illustrate the simplest common circuits. To show the typical range of resistor arrays commonly available, **Table 2** sums up Maxim's family of arrays. Such arrays can support and simplify system designs, based on instrumentation amplifiers, current-to-voltage converters, filters, adders, level shifters, impedance converters, load isolators, and more.

Table 2. Maxim Resistor Arrays*

Part	Description	End-to-End Resistance (kΩ)	Resistance Tolerance (%)	Temp. Coefficient (ppm/°C, typ)
MAX5492	10kΩ, ±2kV ESD precision-matched resistor-divider	10	0.025	35
MAX5491	30kΩ, ±2kV ESD precision-matched resistor-divider	30	0.025	35
MAX5490	100kΩ, ±2kV ESD precision-matched resistor-divider	100	0.025	35
MAX5426	Digitally programmable resistor and switch network for instrumentation amps	15	0.025	35
MAX5431	±15V digitally programmable precision voltage-divider and switch for programmable gain amplifiers (PGAs) with input bias resistor	57	0.025	—
MAX5430	Digitally programmable precision voltage-divider and switch for PGAs	15	0.025	—
MAX5421	Digitally programmable precision voltage-divider and switch for PGAs with input bias resistor	15	0.025	—
MAX5420	Digitally programmable precision voltage-divider and switch for PGAs	0.025	0.025	—

*For the latest information, refer to the device's data sheet.

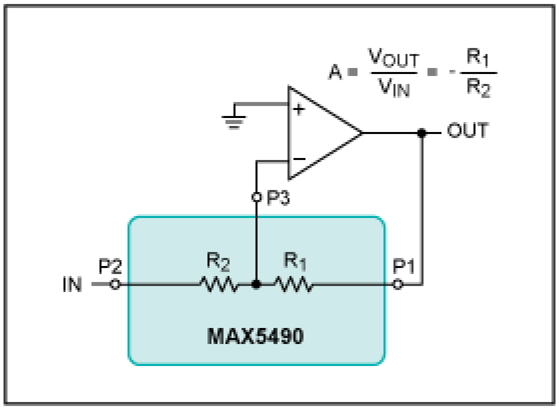

Figure 4. Inverting input op amp.

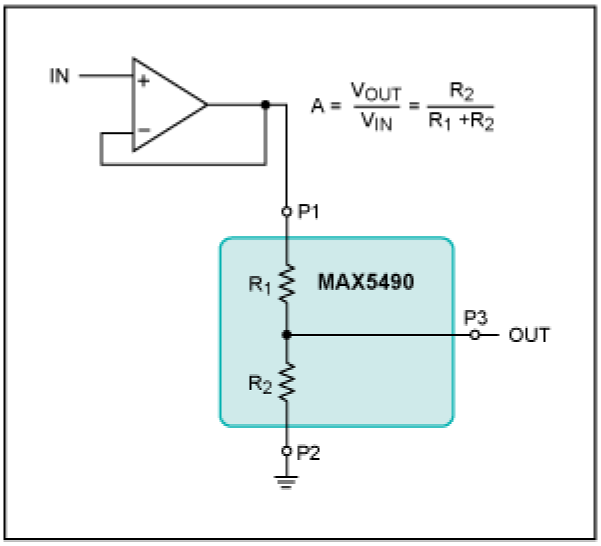

Figure 5. Buffered input attenuator.

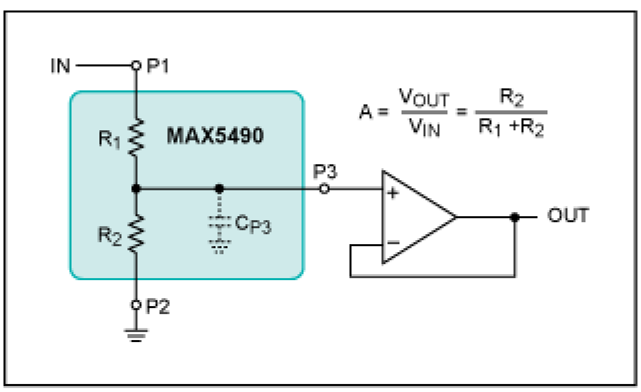

Figure 6. Buffered output attenuator.

The data sheet for the MAX5490 tells you to calculate bandwidth by using $\frac{1}{2\pi RC}$ where C = CP3 and $R = \frac{R_1 \times R_2}{R_1 + R_2}$. CP3 is 2pF, so the bandwidth is 3MHz. This assumes that the op amp has sufficient bandwidth to support the resistor bandwidth.

In our example we used a pair of 50kΩ resistors with the expected low currents. However, as the resistance ratio changes, the current levels rise, causing self-heating. Obviously this must be considered when evaluating the temperature coefficient; the data sheet details the needed calculations to minimize this effect.

While the MAX5490 consists of a center-tapped 100kΩ resistor, parts that have other resistor values are available, such as the MAX5491 (with a 30kΩ end-to-end resistance) and the MAX5492 (with a 10kΩ end-to-end resistance). Any of these values will be an aide in the design of a summing amplifier.

Summary

Thus, a zero-transistor IC is not such a ridiculous idea after all, especially when it produces resistors with extremely good tolerances. As a practical matter, great amplifiers depend on the tight resistor-pair ratios guaranteed by the MAX5490, MAX5491, and MAX5492.

Related Parts		
MAX4036	Low I_{BIAS}, +1.4V/800nA, Rail-to-Rail Op Amps with +1.2V Buffered Reference	Free Samples
MAX4128	Single/Dual/Quad, Wide-Bandwidth, Low-Power, Single-Supply Rail-to-Rail I/O Op Amps	Free Samples
MAX4232	High-Output-Drive, 10MHz, 10V/µs, Rail-to-Rail I/O Op Amps with Shutdown in SC70	Free Samples
MAX4236	SOT23, Very High Precision, 3V/5V Rail-to-Rail Op Amps	Free Samples
MAX4239	Ultra-Low Offset/Drift, Low-Noise, Precision SOT23 Amplifiers	Free Samples
MAX4253	UCSP, Single-Supply, Low-Noise, Low-Distortion, Rail-to-Rail Op Amps	Free Samples
MAX4291	Ultra-Small, +1.8V, µPower, Rail-to-Rail I/O Op Amps	Free Samples
MAX4327	Single/Dual/Quad, Low-Cost, UCSP/SOT23, Low-Power, Rail-to-Rail I/O Op Amps	Free Samples
MAX44251	20V, Ultra-Precision, Low-Noise Op Amps	Free Samples
MAX44260	1.8V, 15MHz Low-Offset, Low-Power, Rail-to-Rail I/O Op Amps	Free Samples
MAX4472	Single/Dual/Quad, +1.8V/750nA, SC70, Rail-to-Rail Op Amps	Free Samples
MAX4483	Single/Dual/Quad, Low-Cost, Single-Supply, Rail-to-Rail	Free Samples

	Op Amps with Shutdown	
MAX4488	SOT23, Low-Noise, Low-Distortion, Wide-Band, Rail-to-Rail Op Amps	Free Samples
MAX5420	Digitally Programmable Precision Voltage Divider for PGAs	Free Samples
MAX5421	Digitally Programmable Precision Voltage Divider for PGAs	Free Samples
MAX5426	Precision Resistor Network for Programmable Instrumentation Amplifiers	Free Samples
MAX5430	±15V Digitally Programmable Precision Voltage-Dividers for PGAs	Free Samples
MAX5431	±15V Digitally Programmable Precision Voltage-Dividers for PGAs	Free Samples
MAX5490	100kΩ Precision-Matched Resistor-Divider in SOT23	Free Samples
MAX5491	Precision-Matched Resistor-Divider in SOT23	Free Samples
MAX5492	10kΩ Precision-Matched Resistor-Divider in SOT23	Free Samples
MAX9613	Low-Power, High-Efficiency, Single/Dual, Rail-to-Rail I/O Op Amps	Free Samples
MAX9615	Low-Power, High-Efficiency, Single/Dual, Rail-to-Rail I/O Op Amps	Free Samples
MAX9619	High-Efficiency, 1.5MHz Op Amps with RRIO	Free Samples
MAX9620	High-Efficiency, 1.5MHz Op Amps with RRIO	Free Samples
MAX9632	36V, Precision, Low-Noise, Wide-Band Amplifier	Free Samples
MAX9636	3V/5V Low-Power, Low-Noise, CMOS, Rail-to-Rail I/O Op Amps	Free Samples
MAX9912	200kHz, 4µA, Rail-to-Rail I/O Op Amps with Shutdown	Free Samples
MAX9916	1MHz, 20µA, Rail-to-Rail I/O Op Amps with Shutdown	Free Samples

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