



*Next step solutions in calibration...improving productivity and enabling new markets*

## **Simplifying Circuit Calibration With Electrically-Adjustable Resistors**

Dr. Les M. Landsberger

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### **The Need for Adjustment in Analog Electronics**

In the field of analog electronics, the pain of achieving precision is the need for calibration. In general, electronic circuits, systems and solutions, both integrated and discrete, are prone to variations in parameter values of their components. These may be variations in the as-manufactured component values, or may be variations over time or temperature. In any case, these variations may degrade circuit performance, and/or reduce fabrication yield. As a result, analog electronics relies on a variety of circuit design, calibration and adjustment techniques, to overcome these variations, and achieve the required performance and precision. Typically, circuit calibration is done by adjusting (“trimming”) a resistance element, and the industry relies heavily on a variety of such resistance trimming techniques. Manual trim pots, laser trimming, digital potentiometers, fusible arrays, and other programmable active devices, are each used in certain circumstances.

However, each of these techniques has one or more limitations. For example, they may have limited frequency range, may have limited precision, may not behave like a resistor unless separate power and ground are present, may be adjustable only once or only in one direction, or may be adjusted only during manufacturing before packaging using expensive equipment. Designers of analog and mixed-signal circuits, with even modest requirements for precision, must always consider how the circuit will be adjusted, and which limitation will be the least painful.

Microbridge’s **Rejistor™** (electronically readjustable resistor) is a passive, VLSI- and MEMS-compatible adjustable micro-resistor. It is non-volatile (i.e. doesn’t need any power to hold its adjustment), and it is re-adjustable many times, bi-directionally, to very high precision (e.g. 0.1% to 0.002%, depending on a variety of factors), using only electrical signals. Rejistors can also be Temperature Coefficient matched with other Rejistors, or can be used in-circuit to compensate for offsets and Temperature Coefficient variations in other analog circuit elements, again using only electrical signals. All adjustments can be carried out at low voltage and low current before and/or after packaging.

### **Rejistor Technology Overview**

The **Rejistor** technology is based on standard CMOS chip technology, with post-processing to create and protect passive released microstructures. During the basic

CMOS part of the process, 1-3 Rejustor-specific dopant implant masks may be required to tailor the resistor film (typically resistor-poly in the host CMOS process). The implanted dopants are typically standard CMOS dopants. Typically (but not necessarily) the functional resistance element is made in a different resistor film layer than the heater-resistor which receives the electrical adjustment signals, in order that the respective resistor values and properties may be optimized separately.

At the end of the CMOS process (for example, after the bond-pads are opened), the microstructures are typically released by a bulk-silicon etch process, leaving them suspended over a cavity. This offers enhanced thermal isolation and low thermal mass, which enables localized, controllable and rapid thermal cycling of resistance elements embedded in the microstructures. Finally, if permanent protection is required for the microstructures, such as to protect them during plastic packaging, then wafer-scale capping is applied, prior to dicing.

The adjustment of a thermally-isolated functional resistance element is accomplished by locally annealing (heating) the resistance element, gently changing the physical properties of the resistance element with each heat cycle. The algorithms to apply the heat cycles are adaptive, involving a repeating sequence:

- measuring (or inferring in-circuit) the functional resistance at room temperature,
- computing pulse parameters for the next temperature cycle,
- applying the high-temperature sequence,
- measuring or inferring the resulting functional resistance at room temperature,
- and so on, until the resulting room temperature resistance is within the desired tolerance.

This adaptive approach would be impractical without the capability to rapidly heat and cool the microstructure, so that many cycles can be applied in a short time, without requiring high temperature furnace operations, and without affecting other circuitry closely adjacent on the same chip.

### **Polysilicon High-Temperature Instability and Adjustability**

The *Rejustor* technique is based on the inherent instability of certain materials at high temperatures. In standard CMOS IC technologies, polycrystalline CVD-deposited silicon is one example of such a high temperature-mutable material. Instability at any temperature is typically seen as a disadvantage, but in this case it is used advantageously to allow high-precision trimming.

For several decades, researchers and patent authors have reported that polysilicon (embedded in typical integrated circuits or in suspended microstructures), became thermally unstable at high temperatures. The prior art has shown that the resistance of polysilicon can be adjusted by passing current through it, or, in general, by heating it to high temperatures. It was also demonstrated that one could decrease resistance quickly, by using high-temperature pulses, and increase resistance more slowly by heating at temperatures lower than those required for resistance decrease.

## Thermally-Isolated Microstructures: Practical Bidirectional High-Precision Trimming

While many researchers have noticed high temperature instability, most of the prior art on intentional thermal adjustment of resistors has addressed simple integrated resistors which were not thermally-isolated on microstructures. Figure 1 shows an example of a pair of polysilicon resistors, (a functional resistor,  $R_f$ , and a heater,  $R_{th}$ ), designed to be suspended over a rectangular bulk-silicon-etched cavity.

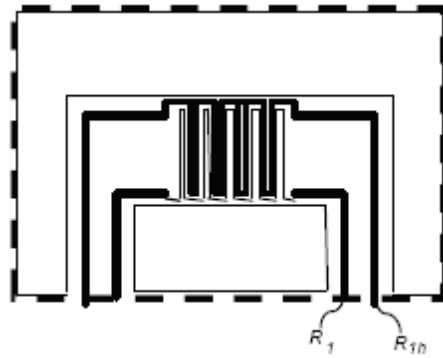


Fig. 1: Top view of a typical layout of a pair of resistors, which may be suspended over a bulk-silicon-etched cavity having outer edge indicated by the dashed line.

The table below compares electrical tests of two such structures, identical except that one has the bulk-etched cavity etched beneath it, while the other does not. The temperature increases were estimated through the known temperature coefficient of resistance of the polysilicon.

	Applied Voltage	Dissipated Power	Temperature Increase	Temperature on chip, 270 $\mu$ m away	Cooling time
Etched	2.5 V	~ 8 mW	~300 °C	~ 0.1°C	< 0.003 s
Un-etched	10 V	~ 100 mW	~10 °C	~ 2 °C	> 2 s

The un-etched structure needs 10V to apply roughly a tenth of a watt. This achieves only about 10 degrees of temperature rise at the resistor itself, because most of the heat goes to warming the substrate, as evidenced by the significant temperature rise 270 $\mu$ m away. Of course, the high thermal mass of the substrate prevents rapid cooling.

The etched structure, on the other hand, needed only a quarter of the applied voltage (about one sixteenth of the applied power), to reach 30x greater temperature rise. This was feasible because the thermal isolation was much higher ( $\sim 50^\circ\text{K}/\text{mW}$  vs. less than  $1^\circ\text{K}/\text{mW}$  for the unetched structure). Accordingly, the rest of the chip experienced negligible temperature rise. Very rapid heating and cooling were evidently attainable, because the thermal mass being heated was far smaller (only the microstructure vs. the entire chip).

Microbridge's techniques rely on this rapid heating and cooling, as a foundation for adaptive algorithms to apply calibration signals. With rapid heating and cooling, one has precise control of heat cycles, as well as the ability to adapt from one cycle to the next. Several cycles can be adaptively applied in a short time period (a few seconds), and one can attain better adjustment precision than would otherwise be practical. Microbridge's innovations in microstructure geometry, combinations of Rejistor elements having different temperature coefficients, and electrical calibration algorithms allow repeatable, reversible adjustment in a few seconds or less, over a range of tens of percent of the as-manufactured resistance value.

## Simple Applications Example: Op Amp Offset and Gain Calibration

Figure 2 shows a simple analog op amp circuit, where trimmable elements are typically used to adjust amplifier gain and offset. When *Rejutors* are tested as shown in this circuit, referred-to-input offsets of a few  $\mu\text{V}$ , and gain control of better than 0.1%, are readily attainable.

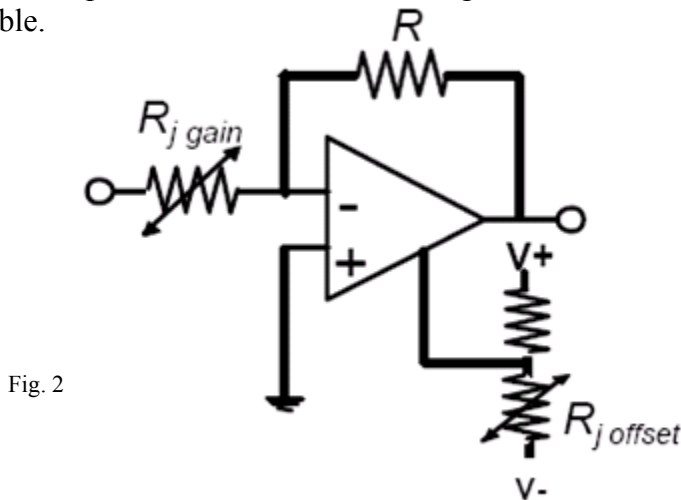


Fig. 2

### Higher Precision Enhances The Importance of TCR Matching

The ability to do high precision trimming raises the issue of Temperature Coefficient of Resistance (TCR) which may not be important at lower precision. The TCR's of electronic components and resistive sensing elements may vary widely (e.g. from zero up to  $\pm$  thousands of ppm per K of temperature change). To understand why this may cause

problems in the context of high-precision calibration, one only has to consider the following example. If the TCR of an individual resistor in a circuit were, say, 1000ppm/K, and if one trims resistance to within a precision of 100ppm, then in order to stay within roughly 100ppm of a trimmed value, one would need to control the operating temperature of the device to within  $\sim 0.1^\circ\text{C}$  – a challenge! For mainly this reason, many resistors in many electronics circuits are used as matched pairs, where the TCR's of the resistors are attempted to be matched as well as possible, so that their *relative* TCR (RTCR), is as close to zero as possible. Even so, non-idealities and mismatches remain, routinely frustrating analog designers.

### eTC Technique for Adjusting R and TCR to Independent Values

In the industry at present, the TCR of a material is widely viewed as a given, and never trimmed at the level of an individual device. Microbridge's Rejistor with eTC technology not only electronically adjusts resistance to high precision, but can electronically adjust the TCR to high precision as well. This is an industry first.

Consider a pair of eTC Rejutors in a 1:1 voltage divider configuration powered by an input voltage  $V_{in}$ . By adjusting the resistance ratio of the two *Rejutors*, one can fine-calibrate the output voltage (e.g. to exactly  $V_{in}/2$ , or to  $V_{in}/2 + \Delta V$ , where  $\Delta V$  is a small offset voltage corresponding to a mismatch in *Rejistor* resistances). Next, by adjusting the relative TCR's of the two *Rejutors*, one can further establish a particular temperature-coefficient of that output voltage (e.g. +25ppm/K, -70ppm/K, 0ppm/K, etc.) The adjustment of output voltage and its TC are independent within certain ranges. See Fig. 3 below, for an example of the available adjustment ranges in the space of TC-offset vs. offset. Fig. 4 shows examples of divider output voltage vs. temperature, for several adjustment states of the eTC divider.

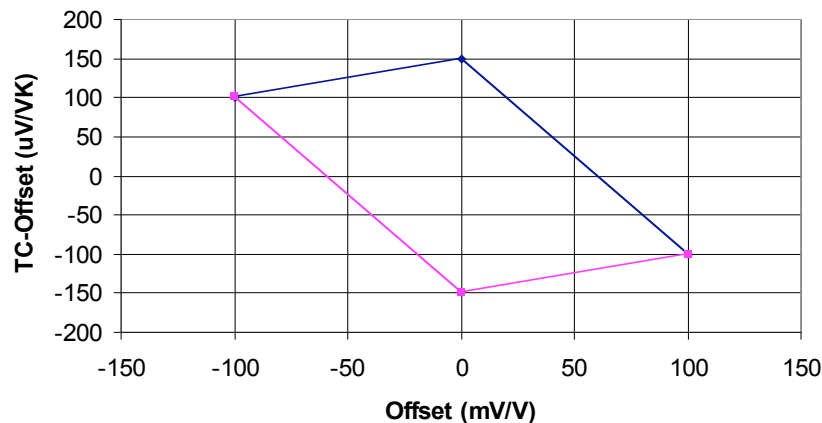


Fig. 3: Shows a typical adjustment range of an eTC voltage divider, as a parallelogram-shaped region in the space of TC-offset vs. offset.

### Examples of Divider Offset V vs. Temp

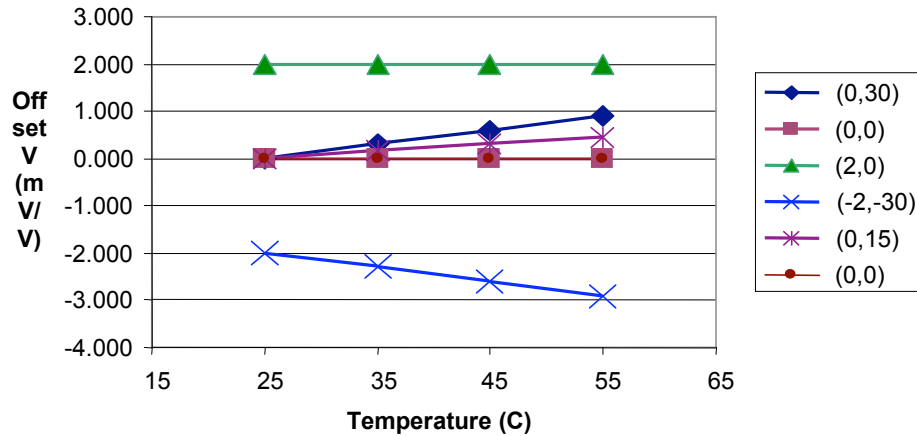


Fig. 4: Shows offset-V (mV/V) vs. T curves for several different examples of settings of [offset, TC-offset], as listed in the legend at the right side of the figure.

### What Can You Do With The *Rejistor*: Wheatstone Bridge Sensor Circuits

Many sensors are used in a Wheatstone Bridge circuit, as shown generically in Figure 5. With no sensor stimulus (e.g. pressure, noxious gas or magnetic field) present, and at a constant temperature, the resistive sensing element (labeled “*Sensor*”), has a nominal resistance value. The other three resistors in the bridge are designed such that, when the sensor is in its quiescent state, the mid-points of the two voltage dividers maintain the same voltage, such that the bridge is “balanced”. For example, the four resistors, “*Sensor*”,  $R_1$ ,  $R_{j0}$ ,  $R_{jt}$ , can be designed to all have the same resistance value, such that the divider midpoints ride at half of the bridge supply voltage. In general, when the sensing element responds to a stimulus, its resistance changes, thereby unbalancing the two bridge mid-points. Fine differences between these two voltages are then amplified, typically with substantial gain. The sensor response may be small, and in principle this type of scheme allows for robust amplification and handling of subtle sensor signals.

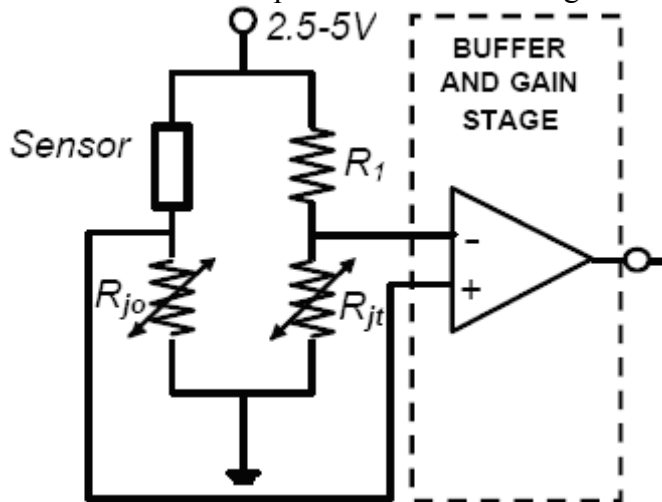


Fig. 5: Typical Wheatstone Bridge circuit with amplification stage.

In practice, however, Wheatstone Bridges are prone to being unbalanced by factors other than the desired sensor response. If, due to minor component variations, the quiescent sensor resistance and its three partner resistances are not related such that the divider mid-points are perfectly matched, then there can be substantial spurious zero-stimulus output. And if the TCR's of the four resistances are not matched, there can be a substantial temperature variation of this quiescent response. Furthermore, the amplification stages are prone to needing offset and gain adjustments.

*Rejustors* with *eTC* adjustment capability can be readily used in the above configuration. A pair of TCR-adjust-able *Rejustors* can be used as  $R_{jo}$  and  $R_{jt}$ , and another pair can be used to precisely set, and temperature-compensate, the gain of the amplification stage. If needed, further *Rejustors* can be used to regulate the offset of the amplifiers.

## Using the *Rejustor*

There are two principal ways in which *Rejustor* technology may be implemented: as a discrete chip-resistor, or designed into a larger analog or mixed-signal CMOS integrated circuit. The modes of use can range from simple adjustment of a discrete component, such as where a manual trim potentiometer may otherwise be used, to the other end of the spectrum, integrated into a system-on-chip (SoC) IC. In between, it may be assembled onto a printed circuit board, module, or thickfilm circuit.

Since the adjustment signal sequence is adaptive, logic processing and digital/analog/digital conversion (ADC and DAC) must be present. The DACs need 8-to-10-bit resolution, in order to apply the calibration signals, and the quality of the ADCs depends on the precision needed for the application and circuit in question. These elements of the technique may be implemented in a variety of ways, the most common mode being as part of the test and measurement apparatus used to adjust or calibrate the analog system within which the *Rejustor* (discrete or integrated) is functionally embedded. *Rejustor* calibration is most commonly done post-packaging, and after assembly of the larger analog system, by applying the adjustment signal sequences to the calibration pins.

## *Rejustor* Benefits

In most cases the elimination of laser-trimming in the manufacture of an integrated circuit can offer a significant cost reduction (\$1-8mm per run as indicated in Michael Quirk and Julian Serda's book [Semiconductor Manufacturing Technology](#)). When wafer yield is high, wafer sort may be eliminated, all die could be packaged without exhaustive probing, and calibration may be done at final package test.

In sensor applications electrical calibration may be done after packaging, compensating for both as-manufactured across-wafer variations, and variations due to the stresses typically incurred in assembly processes. This provides not only a cost saving by reducing or eliminating pre-package test/calibration, but also a performance enhancement.

## ***Analog pots (Manual Mechanical Trimpots)***

### **Analog pots Limitations**

- Cost (0.10\$ to several dollars per unit in volume depending on adjustment resolution)
- Large form factors
- Limited adjustment accuracy (5-1%) and poor matching
- Prone to drift under vibration and temperature
- Require manual adjustment
- Limited high-frequency range (inevitable inductance)

### **Microbridge Rejutors vs. Analog pots**

- Competitive cost for dual Rejutors in volume
- Small form factors (SO & QFN packages)
- Superior adjustment accuracy and matching (0.1% or better)
- Improve precision and reliability under vibrating conditions (<0.01% change with vibration)
- Temperature compensation possible
- Eliminate manual or mechanical operation
- Higher frequencies (~1GHz or higher)

## ***Digital pots (Configurable Resistor Arrays)***

### **Limitations of Digital pots (Configurable Resistor Arrays)**

- Cost (0.50-3.00\$ per unit in volume depending on # of bits of resolution)
- Adjustment accuracy depends on # of bits of resolution (7bits~0.8%, 10bits~0.1%) - discrete adjustment
- Not passive components
- Limited resistance values (typically 10Kohm or higher) due to wiper resistance
- Limited high-frequency range (~1MHz)
- Dissipates power (needed for normal operation)
- Requires non-volatile technology to maintain settings (e.g. E2PROM) with potential associated reliability issues

### **Microbridge Rejutors vs. Digital pots**

- Competitive cost for dual Rejutors in volume
- Superior adjustment accuracy (0.1% or better)
- True passive operation
- Wide range of resistance values possible (no 'wiper' Resistance)
- Higher frequencies (~1GHz or higher)
- Low power (no power required during operation, only 2-5V, 2-5mA during trimming)
- Rejutors are a non-volatile device
- Smaller layout footprint versus DPOT when integrated on chip
- Potential for multi-order temperature compensation

## ***Digital Conditioning***

### **Limitations of Sensor/Signal Conditioning**

- Cost (0.50-3.00\$ per unit in volume depending on accuracy)
- Adjustment accuracy depends on # of bits of resolution used - discrete compensation fit
- Not passive components
- Complex configuration by users required
- Dissipates power (needed for normal operation)
- Requires non-volatile technology to maintain settings (e.g. E2PROM) with potential associated reliability issues

### **Microbridge Rejutors vs. Sensor/Signal Conditioning**

- Competitive cost for dual Rejutors in volume
- Offers precision offset and gain adjustment and temperature compensation as part of pre-conditioning solution
- Potential for multi-order temperature compensation
- Can compensate for sensor aging and drift at the source
- Low power (no power required during operation, only 2-5V, 2-5mA during trimming)
- Rejutors are a non-volatile device
- Smaller layout footprint when integrated with semiconductor sensor
- Complementary with and can be added to current sensor/signal conditioning to improve performance and yield

## ***Fusible Passive Resistor Arrays***

### **Limitations of Fusible Passive Resistor Arrays**

- Not used for precision
- Trim adjustment accuracy depends on # of resistors and fuses - discrete adjustment
- Generally trim only in one direction
- One time adjustment
- High power to 'blow' fuse
- Potential reliability issues
- Potential large unused layout footprint

### **Microbridge Rejustors vs. Fusible Passive Resistor Arrays**

- Superior adjustment accuracy (0.1% or better)
- Bi-directional adjustability with chip level voltage and current (2-5V, 2-5mA to adjust)
- Multiple adjustments before or after packaging
- Possibility of user-initiated adjustment
- Small form factor (similar in size to poly or thin film micro-resistor)
- Temperature compensation possible

## ***Laser Trimming (Thick Film - Hybrid)***

### **Limitations of Laser Trimming (Thick Film - Hybrid)**

- Trimmed in one direction only
- One time adjustment, typically before final assembly
- Limited trim adjustment accuracy (1-0.5%)
- Technology experience required
- Manually intensive setup
- Expensive capital investment (\$200K/laser)
- Can only trim one resistor at a time
- Resistor must be large enough for laser alignment and trim to desired tolerance

### **Microbridge Rejustors vs. Laser Trimming (Thick Film - Hybrid)**

- Offers adjustability in both directions
- Multiple adjustments before or after assembly
- Superior adjustment accuracy (0.1% or better)
- Networks of resistors and Rejustors possible
- Temperature compensation possible
- Possibility of user-initiated adjustment
- Automated adjustment with standard test equipment, no lasers
- Can trim multiple devices simultaneously
- Trim at temperature as part of production test
- Low TCR material (0±100ppm/oK)
- Small form factor (die SO & SOT packages) suitable for hybrid assembly

## ***Laser Trimming (Thin Film – Integrated Circuit)***

### **Limitations of Laser Trimming (Thin Film – integrated circuit)**

- Trimmed in one direction
- One time adjustment before packaging
- May change during final packaging
- Technology experience required
- Manually intensive setup of wafers
- Expensive capital investment (\$0.5-1M/laser)
- Can only trim one resistor at a time
- Resistor must be large enough for laser alignment and trim to desired tolerance

### **Microbridge Rejustors vs. Laser Trimming (Thin Film – integrated circuit)**

- Offers adjustability in both directions
- Multiple adjustments before or after packaging
- Superior adjustment accuracy (0.1% or better)
- Temperature compensation possible
- Possibility of user-initiated adjustment
- Automated adjustment with standard IC test equipment, no lasers
- Can trim multiple devices simultaneously
- Different TCR materials possible (+, -, zero)
- Similar in size to laser trimmable resistor



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### **About The Author**

Dr. Les M. Landsberger



Dr. Landsberger is the CTO and a Founder of Microbridge. Dr. Landsberger has been active in Microsystems fabrication research and development since 1991. He holds a Ph.D. in Electrical Engineering from Stanford University and is a member of the IEEE. The author of this article can be reached via his media contact, Joe Romano, at 781-279-1320 x 208 or [jromano@highgroundinc.com](mailto:jromano@highgroundinc.com)

### **About Microbridge**

Microbridge is the leading manufacturer and licensor of next step electronic calibration products and solutions in the consumer, automotive, medical and other industries that need to improve manufacturing yields and productivity, and enter new markets. Microbridge's resistor calibration products (*Rejustor*<sup>TM</sup>) and enabling technology are the first integrated calibration and temperature compensation systems for analog circuit designs and production. The firm enables manufacturers to: cut scrap up to 50%; reduce in-line manufacturing process steps; eliminate binning, work-arounds, laser trimming, hand-sorting and trim-pots; decrease calibration costs by a factor of 10 without sacrificing performance; and return millions of dollars in production savings.

Microbridge's technology enables product designers to achieve one-step calibration and passive adjustment, is adaptive and adjustable in circuit, and it allows calibration in the analog domain to improve the design of current and future products.

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