Precision Reference Uses Only Ten Microamperes

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Increasing interest in battery-operated analog and digital circuitry in recent years has created the need for a micro-power voltage reference. In particular, the reference should draw 10 μA or less and operate from a single 5V supply. These requirements eliminate zener diodes which tend to have unpredictable temperature drift and are noisy at low currents and low voltages. One possibility is the LM103 series of punch-through diodes which have break-down voltages of 1.8V to 5.6V and operate well at 10 μA. Unfortunately, these devices drift at -5 mV/°C and extra circuitry must be added to create a low-drift reference. Non-linearity in the drift characteristic limits usable drift compensation to about 50 ppm/°C. Variations in slope from device to device can be up to ± 0.5 mV/°C, so each reference must be individually corrected for temperature drift in an oven test.

The LM134 current source can provide an interesting solution to the low-power-drain reference problem. This device is a 3-terminal current source which has a compliance of 1V to 40V and is programmable over a current range of 1 μA to 10 mA. Current is determined by an external resistor. With a zero drift resistor, the LM134 current is directly proportional to absolute temperature (°K). Untrimmed accuracy of the current is $\pm 3\%$, but the key to the success of the LM134 is that initial errors are gain errors which are trimmed to zero when the external resistor is adjusted. Independent of initial current, if the current is adjusted to 298 μA at T = 25°C (298°K), all devices will have a current dependence of 1 ± 0.01 μA/°C.

A voltage reference can be made by combining the positive temperature coefficient of the LM134 with the negative TC of a forward-biased diode. The IC terminology for such a reference is "bandgap reference" because the total voltage of the reference is equal to the extrapolated (0°K) bandgap voltage of silicon. An important characteristic of bandgap references is that the zero TC voltage is independent of diode current even though the diode voltage and TC are not. This means that by adjusting the total voltage of the reference to a fixed value, T.C. will be adjusted to near zero at the same time. The zero TC voltage for most bandgap references falls between 1.20V and 1.28V.

The circuit in *Figure 1* is a micropower reference using the LM134 and an MPSA43 transistor connected as a diode with collector-base shorted. A transistor is used in place of a diode because the transistor characteristics as a double-diffused structure are more consistent than a diode. In particular, the emitter-biased voltage drift of wide-base high-voltage transistors connected as diodes is very linear with temperature.

In *Figure 1*, the LM134 controls the voltage between its R and V^- terminals to $\approx$ 64 mV. About 5.5% of the current out of the R terminal flows out of the V^- terminal. The total current flowing through R2 is then determined by 67.7 mV/R1. Output voltage is the sum of the diode voltage, plus the voltage across R2, plus 64 mV. The voltage TC across R2 and the 64 mV is positive and directly proportional to absolute temperature while the diode TC is negative. The overall TC of the output will be near zero (< 50 ppm/°C) when the output is adjusted to 1.253V by trimming R2. To obtain this level of performance, R1 and R2 must track well over temperature. 1% metal film resistors are suggested.

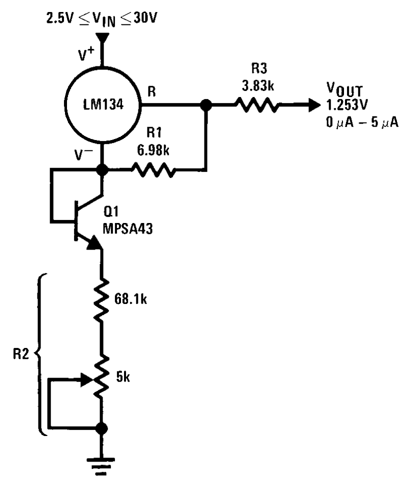

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FIGURE 1

For optimum results with a single point adjustment of voltage and temperature coefficient, an additional error term must be accounted for. Internal to the LM134 are low I_{dss} FETs used for starting the control loop. This FET current adds directly to the V^- pin current and therefore creates an additional output voltage equal to $(I_{dss})(R2)$. Typical I_{dss} is 200 nA, causing V_{OUT} to be 14 mV high. Temperature coefficient of I_{dss} is low, typically 0.1%/°C. For best results in a single point adjustment, V_{OUT} should be adjusted to 1.253V $+ I_{dss}$ (R2). I_{dss} can be easily measured by open circuiting R1 and measuring the drop across R2. The resulting voltage must be divided by 2 due to an internal action which causes 2 I_{dss} to flow when no current flows from the R pin. Example: with R1 open, 32 mV is measured across R2. Set V_{OUT} equal to 1.253V + 32 mV/2 = 1.269V. Even lower TC can be obtained by measuring the output at 2 temperatures and using the following formula to calculate the exact zero TC output voltage for each reference.

$$V_{OUT}\,(0\ \mathrm{TC}) = V1 - \frac{T1\,(V2 - V1)}{T2 - T1}$$

Where:

V1 = Output voltage at T1

V2 = Output voltage at T2

T = Absolute temperture (°K)

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The limitation on temperature drift after a 2 point calibration is non-linearity. This reference circuit has a non-reducible bow error of $\approx$ 10 ppm/°C over a temperature range of −25°C to +100°C and $\approx$5 ppm/°C from 0°C to +70°C. At 125°C, leakage creates significant error, causing the output voltage to droop about 5 mV.

Noise of the reference consists primarily of theoretical shot noise current from the LM134. At the 10 μA level, this is about 6 pA/$\sqrt{Hz}$ rms from 10 Hz to 10 kHz. Total output noise would be 0.4 μV/$\sqrt{Hz}$ rms over this frequency range, except that C1 bypasses most of the noise above 2 kHz. Measured output noise was 25 μVrms over a 10 Hz to 10 kHz bandwidth with C1 = 1000 pF. Larger values of C1 may be used if lower broadband noise is needed. Low frequency noise is about 25 μV peak-to-peak from 0.1 Hz to 10 Hz.

The LM134 has a negative output resistance at the R pin when resistance is inserted in series with the V^- pin. The value of this negative resistance is approximately $-R_X/19$, where R_X is the equivalent resistance from V^- to ground. In this reference circuit R_X is 72 kΩ, yielding a negative output resistance of 3.8 kΩ. Resistor R2 sums with this resistance to give the reference a net zero output resistance (±400Ω). Loading should be limited to about 5 μA. Line regulation for the reference is typically less than 0.5 mV with an input voltage of 5V ±2V. Minimum input voltage for a 2 mV drop in output voltage is 2.5V at −55°C, 2.4V at 25°C and 2.3V at 125°C.

Although this reference was designed for ultra-low operating current, there is no reason that it cannot be used at higher current levels as well. All resistor values are simply scaled downward. Higher operating current will give lower output resistance, more drive capability, less sensitivity to FET I_{dss}, lower noise, and less droop at 125°C.

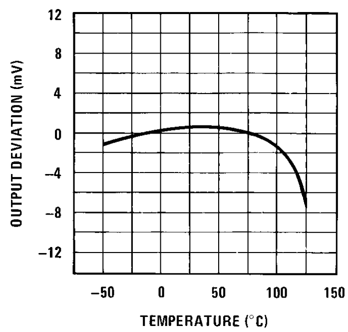

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FIGURE 2. Output Voltage Drift

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