THERMOMETER APPLICATIONS OF THE REF-02

Precision Monolithics Inc.

APPLICATION NOTE 18

INTRODUCTION

This application note describes electronic thermometer applications of the REF-02 +5V Voltage Reference where the voltage output is a direct measurement of temperature in °C or in °F. These applications use the predictable 2.1mV/°C TEMP output voltage temperature coefficient of the REF-02, a byproduct of a bandgap voltage reference design. Thermometer applications are described first followed by a discussion of bandgap voltage reference theory.

THERMOMETER ESSENTIALS

In addition to a highly linear temperature sensitive component, electronic thermometers should have the following characteristics:

1. Convenient scaling such as 10mV/°C, 100mV/°C, or 10mV/°F.
2. Direct voltage readings such as −0.55V at −55°C, 0V at 0°C, and +1.25V at +125°C.
3. Room temperature calibration.

BASIC CIRCUIT IMPLEMENTATION

The simplified schematic in Figure 1 shows the basic thermometer connections. An operational amplifier, three resistors, and the +5.000V output of the REF-02 function together to level shift and amplify V_{TEMP} allowing V_{OUT} to read in the desired manner. The expression for V_{OUT} is:

$$\text{EQ 1.}\quad V_{OUT} = \left(1 + \frac{R_c}{R_a \| R_b}\right) V_{TEMP} - \frac{R_c}{R_a}(V_{REF})$$

The first term is the gain of the circuit with V_{REF} equal to 0V; the second term is the gain of the circuit with V_{TEMP} equal to 0V. Differentiating Equation 1 with respect to temperature gives the slope, S, of the output-versus-temperature curve:

$$\text{EQ 2.}\quad \frac{dV_{OUT}}{dT} = S = m\left(1 + \frac{R_c}{R_a \| R_b}\right) = 2.1\text{mV/°C}\left(1 + \frac{R_c}{R_a \| R_b}\right)$$

where $m = TCV_{TEMP}$

Thus, the ratio of R_c to $R_a \| R_b$ sets the slope of V_{OUT}, and the ratio of R_c to R_a and V_{REF} set the initial output value at 25°C. Table 1 lists typical scaling ratios for different output scales.

Table 1. Temperature Scaling Ratios

V_{REF} = 5.000V, V_{TEMP} = 630mV @ 25°C, TCV_{TEMP} = 2.1mV/°C

V_{OUT}@25°C (77°F)	TCV_{OUT} (Slope)	$\frac{R_c}{R_a}$	$\frac{R_c}{R_a \| R_b}$
250mV	10mV/°C	0.55	3.76
2.5V	100mV/°C	5.50	46.6
770mV	10mV/°F	0.926	7.57

COMPLETE CIRCUIT

Two potentiometers, R_p and R_{bp}, have been added to the circuit for precise calibration and to allow for the ±1% resistor tolerances. V_{REF} is adjusted by R_p to set the V_{OUT} value at +25°C (77°F); the ratio of R_c to $R_a \| R_b$ is adjusted by R_{bp} to set the slope of V_{OUT} versus temperature. Resistor values for typical output scales are shown in Table 2.

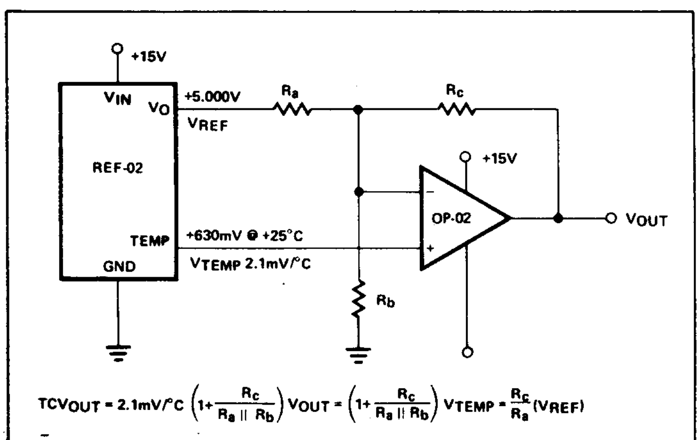

Figure 1. Simplified Schematic

Table 2. Resistor Values

TCV_{OUT} SLOPE(S)	10mV/°C	100mV/°C	10mV/°F
TEMPERATURE RANGE	−55° to +125°C	−55° to +125°C	−67°F to +257°F
OUTPUT VOLTAGE RANGE	−0.55V to +1.25V	−5.5V to +12.5V*	−0.67V to +2.57V
ZERO SCALE	0V@0°C	0V@0°C	0V@0°F
R_a (±1% resistor)	9.09kΩ	15kΩ	8.25kΩ
R_{b1} (±1% resistor)	1.5kΩ	1.82kΩ	1.0kΩ
R_{bp} (potentiometer)	200Ω	500Ω	200Ω
R_c (±1% resistor)	5.11kΩ	84.5kΩ	7.5kΩ

*For 125°C operation, the op amp output must be able to swing to +12.5V; increase V_{IN} to +18V from +15V if this is a problem.

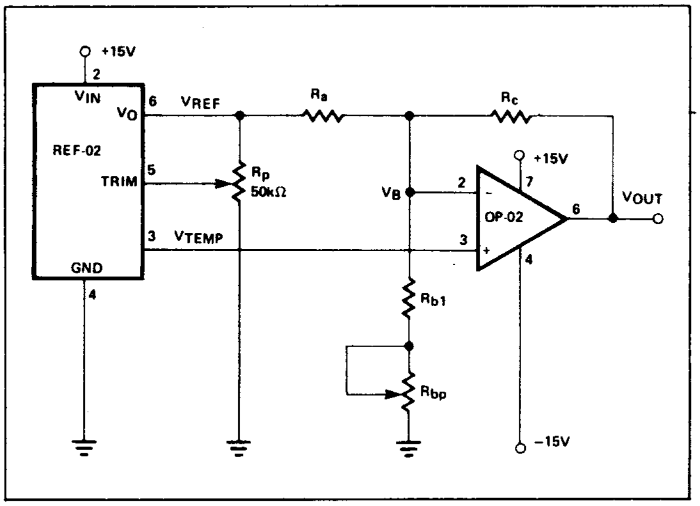

Figure 2. Complete Schematic

CALIBRATION CONDITIONS

All calibration is conducted in free air. Heatsinking of the REF-02 is unnecessary and is undesirable. The small (2°C) rise in chip temperature of the REF-02 above ambient temperature serves as an error-cancelling factor of some second order effects internal to the REF-02 design. The calibration procedure which follows assumes free air — no heatsinking — calibration.

CALIBRATION PROCEDURE

Calibration is performed at ambient temperature with two adjustments using the following procedure:

Step 1: Measure and record V_{TEMP} and T_A in °C.

Step 2: Calculate the calibration ratio "r" using Equation 3:

$$\text{EQ 3.}\quad r \equiv \frac{R_a \| R_b}{R_c + R_a \| R_b} = \frac{V_{TEMP}\text{ in mV}}{S(T_A + 273)}$$

Where S = TCV_{OUT}, T_A = ambient temperature in °C

Step 3: Turn power off, short V_{REF} terminal to ground, and apply a precise 100mV to the V_{OUT} terminal.

Step 4: Adjust R_{bp} so that $V_B = r(100mV)$; remove short.

Step 5: Turn power on; adjust R_p so that V_{OUT} equals the correct value at ambient temperature.

The system is now calibrated.

CALIBRATION EXAMPLE

Here is an example at $T_A = 25°C$, $S = 10mV/°C$, and $V_{TEMP} = 632mV$:

Step 1: $V_{TEMP} = 632mV$, $T_A = 25°C$.

Step 2: Using Equation 3:

$$r = \frac{V_{TEMP}}{S(T_A + 273)} = \frac{632}{10(25 + 273)} = \frac{632}{2980} = 0.2121$$

Step 3: Apply 100.00mV to V_{OUT} with power off and V_{REF} connected to ground.

Step 4: Adjust R_{bp} so that V_B = r(100mV) = 21.21mV.

Step 5: Turn power on and adjust R_p so that V_{OUT} equals +0.25V.

The system is now calibrated.

TRANSDUCER ERROR FACTORS

Error terms are threefold:

1. Slope errors — Deviations from nominal slope. For example, if the slope is 10.04mV/°C instead of 10.00mV/°C, the accuracy due to the slope error is 0.4%.
2. Linearity errors — Deviations in V_{TEMP} versus temperature from straight line performance, a change in V_{TEMP} slope with temperature.
3. Offset error — V_{OUT} deviations due to changes in V_{REF} with temperature.

Since these errors are grade dependent, Table 3 is provided as an aid in specifying the correct combination of components for a given application. Offset error can be eliminated by using one REF-02 as a temperature sensor only and another REF-02 (operated at a constant temperature) as V_{REF}.

Table 3. Typical Transducer Performance vs Grade

GRADE / PARAMETER	REF-02A	REF-02	REF-02E	REF-02H	REF-02C
TEMPERATURE RANGE	−55° to +125°C	−55° to +125°C	0° to +70°C	0° to +70°C	0° to +70°C
SLOPE ERROR	±0.30%	±0.40%	±0.25%	±0.35%	±0.45%
TCV_{TEMP} ERROR	±0.10%	±0.12%	±0.08%	±0.10%	±0.15%
OFFSET ERROR	±0.15%	±0.40%	±0.10%	±0.30%	±0.60%
RMS ERROR SUM	±0.35%	±0.58%	±0.28%	±0.47%	±0.76%
TYPICAL ACCURACY	0.50%	0.75%	0.40%	0.60%	0.90%
OP-02 GRADE RECOMMENDED	OP-02A	OP-02	OP-02E	OP-02C	OP-02C

TRANSDUCER PERFORMANCE

Typical system accuracy is ±0.5% over the −55° to +125°C range of a REF-02A. For example, when calibrated at +25°C, the reading of V_{OUT} at +105°C may be 105.4°C, a deviation of 0.5% of the 80° temperature change (+25°C to +105°C).

Although the REF-02 is guaranteed to perform over the −55° to +125°C range only, operation beyond those limits is possible. A large number of devices were measured and found to be functioning satisfactorily over the −150°C to +170°C range, and there was only a slight degradation in accuracy.

REMOTE APPLICATIONS

In many applications, the sensor must be located some distance away from the measurement circuitry. One precaution must be taken with the REF-02: a 1.5kΩ resistor should be connected between Pin 3 (TEMP) and its associated cable conductor to isolate this pin from cable capacitances

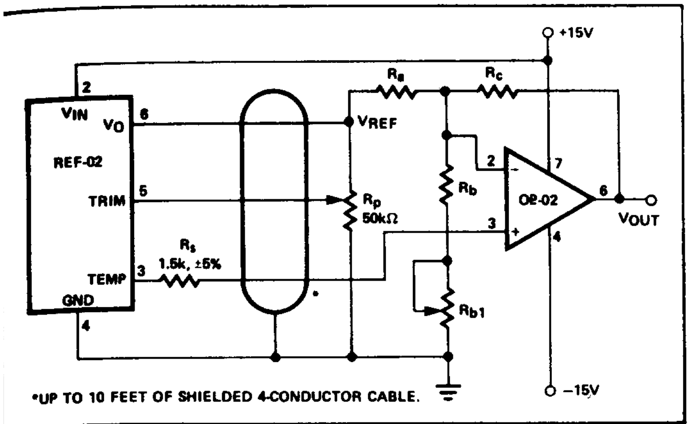

Figure 3. Precision Temperature Transducer with Remote Sensor

Remote application of the transducer is illustrated in Figure 3 with R_s, the isolation resistor.

TRANSDUCER SUMMARY

The accuracies indicated compare quite favorably to traditional temperature measurement methods such as thermocouples and thermistors. Ease-of-use, low cost, and high accuracy make this new bandgap method of temperature measurement attractive in a wide range of applications.

The following section describes the bandgap principle in theory and its use in the internal REF-02 design.

BANDGAP REFERENCE THEORY

Bandgap voltage references (1), (2), (3), use predictable relationships from semiconductor physics to generate a constant voltage. The base-emitter voltage of a transistor (V_{BE}) has a processing and current density dependent **negative** temperature coefficient of about −2.1mV/°C. Another well-known relationship with a **positive** temperature coefficient is the difference between base-emitter voltages of two transistors operated at different current densities:

EQ 4. $\Delta V_{BE} = \frac{kT}{q} \log_e \left(\frac{J2}{J1}\right)$, where

k = Boltzmann's constant = 1.38×10^{-23} joules/°K

T = absolute temperature, °K

q = charge of an electron = 1.6×10^{-19} coulomb

J = current density

When ΔV_{BE} is amplified and added to V_{BE}, a voltage reference with zero temperature coefficient results if the sum (V_Z) of these two terms equals the linearly-extrapolated bandgap voltage of silicon (V_{go}) at 0°K or −273°C, V_{go} = 1.205V. A more exact calculation, see reference 2, will show that V_Z will have zero temperature coefficient if:

EQ 5. $V_Z = V_{go} + \frac{kT}{q} = 1.230V @ +25°C$

The circuit in Figure 4 generates a ΔV_{BE} of 72mV at 25°C by making the current density of Q2 16 times greater than Q1. Q2 has four times the current of Q1, and Q1 has four times the emitter area of Q2. A ΔV_{BE} of 72mV appears across R1

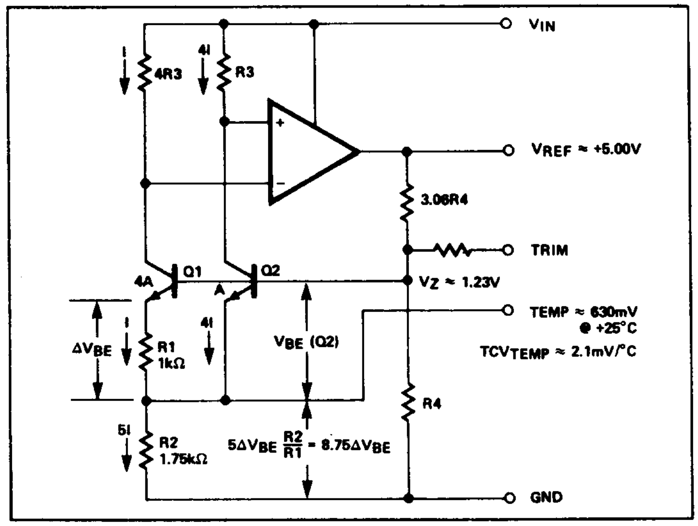

Figure 4. REF-02 Simplified Schematic

Table 4. REF-02 Typical Nodal Voltages

VOLTAGE \ TEMPERATURE	$T_A = -75°C$ ($T_J = 200°K$)	$T_A = +25°C$ ($T_J = 300°K$)	$T_A = +125°C$ ($T_J = 400°K$)
$\Delta V_{BE} = \frac{kT}{q} \log_e 16$	48mV	72mV	96mV
$V_{TEMP} = 8.75\ \Delta V_{BE}$	420mV	630mV	840mV
V_{BE}(Q2)	810mV	600mV	390mV
$V_{REF} \approx V_{BE} + V_{TEMP}$	1.23V	1.23V	1.23V
$V_{REF} \approx 1 + \frac{3.06R4}{R4} \approx 4.06V_Z$	5.00V	5.00V	5.00V

and is amplified by 8.75 (becoming the TEMP output) and is added to V_{BE} (Q2) to produce a nearly constant V_Z of 1.23V. The −2.1mV/°C of TCV_{BE} is cancelled by the +2.1mV/°C of TCV_{TEMP}; and V_Z is amplified by 4.06 to produce an output of V_{REF} of 5.000V.

CONCLUSION

The REF-02, by using a bandgap design, provides both a stable +5V reference voltage output and an additional output voltage directly proportional to temperature. Accurate electronic thermometers reading in °C or in °F can be constructed at low cost for a wide variety of temperature monitoring and controlling applications.

REFERENCES

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