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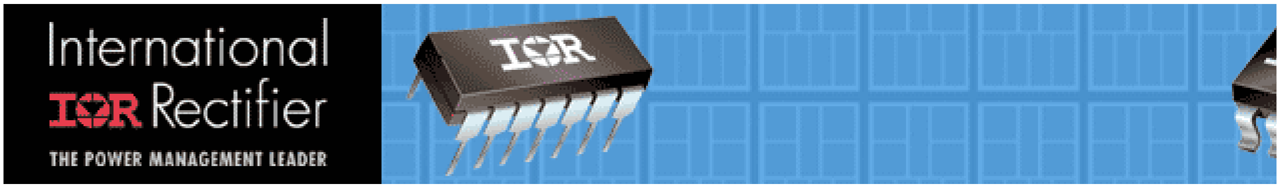

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Bandgaps in the crosshairs: What's the trim target?

How do you get the least temperature drift for your design? Read on for some pointers to get the optimal trim for your design.

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Emerson once said: "Never imitate...Every great man is unique," and unfortunately, so is every reference circuit, at least as far as its output voltage and process technology are concerned. Bandgap references may be relatively robust and accurate but not immune to process variations and mismatch offsets whose adverse effects on accuracy varies across devices, wafers, lots, and technology nodes, making each device unique. As a result, trimming (that is, tweaking) the output voltage is necessary to produce predictable reference values[1], [2]. Arbitrarily trimming a circuit to any voltage target, however, can be detrimental because the temperature drift at that level may be prohibitively large. Typically, only one voltage target produces the least temperature drift, and this target is specific to a circuit, its layout, and the processing technology with which it was fabricated (if circuit, layout, and/or process change, the optimal trim target also changes). This article discusses how this optimal trim target can be ascertained.

Temperature compensation

A reference circuit generates a predictable temperature-independent voltage by summing voltages and/or currents with opposite temperature-drift coefficients. In the case of a bandgap reference, thermal voltage V_t is the linearly dependent term that increases with temperature, in other words, proportional-to-absolute-temperature (PTAT), and base-emitter voltage V_{BE} the mostly linear component that decreases with temperature, complementary-to-absolute-temperature (CTAT)[3]. V_t is normally derived by extracting the voltage difference of two base-emitter voltages with dissimilar current densities (that is, two transistors with dissimilar emitter areas but equal currents flowing through them as shown in the inset of Figure 1), which is a manifestation of the well-known Gilbert principle[4].

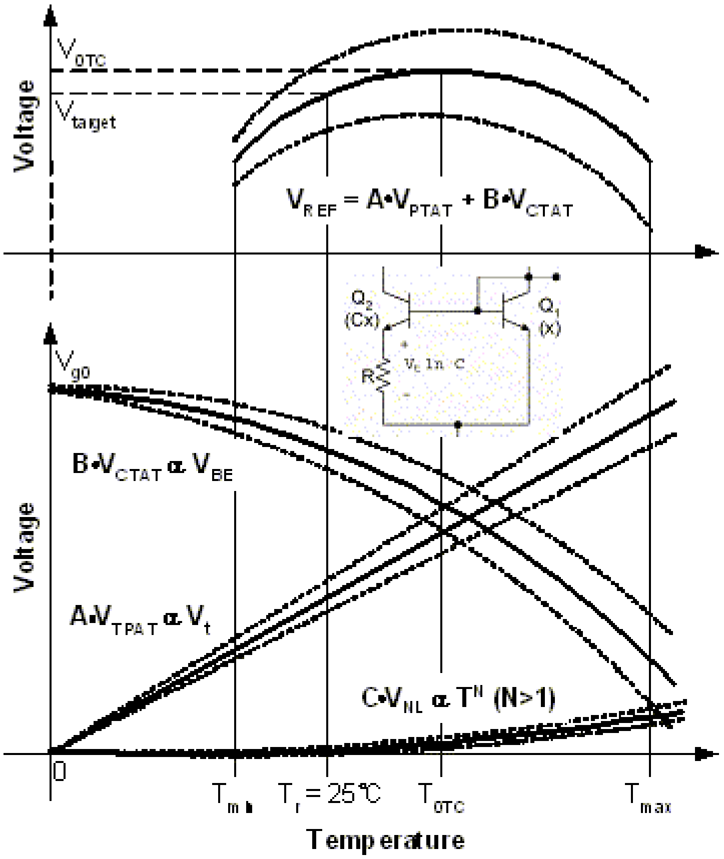

Figure: 1. Formulation of a temperature-independent bandgap reference voltage

Trimming

In reality, V_{BE} is an exponential term with a strong first-order (linear) dependence, which is why the first-order compensated circuit has a parabolic shape with respect to temperature (Figure 1). To reduce this total variation and achieve better than first-order cancellation, a higher-order correcting term is added, as depicted by nonlinear voltage V_{NL} in Figure 1, but this level of compensation is only warranted when all offset-causing mechanisms like package-shift effects are well understood and accounted for in the design and trimming process. If only first-order compensation is desired, which is more often than not the case, since V_{PTAT} is in theory perfectly linear, reducing to 0V at 0°K, any process-induced variation is compensated by trimming at a single temperature point, that is, V_{PTAT} falls back to its intended slope when trimmed at any one temperature (dotted line of V_{PTAT} shifts back to its solid counterpart in Figure 1). The same applies to V_{CTAT} when neglecting all nonlinear terms because V_{BE} is bandgap voltage constant V_{g0} at 0° K, which is why trimming need only be performed at one temperature, of which the most practical is room temperature.

Since V_t (V_{PTAT}) and V_{BE} (V_{CTAT}) extend to 0V and bandgap voltage V_{g0} (roughly 1.2V) at 0°K, respectively, their temperature-independent sum, which is the ideal reference voltage, is approximately 1.2V. However, since the actual relation is parabolic, as mentioned earlier and shown in Figure 1, the optimum reference point varies slightly with operating temperature range. In other words, the lowest drift variation is achieved when the reference voltage at both temperature extremes T_{min} and T_{max} are equal (solid V_{REF} trace in Figure 1), and extending one temperature extreme and not the other negates this condition, necessarily changing the V_{PTAT}-to-V_{CTAT} recipe for the best drift performance. This variation constitutes a systematic shift in trim target voltage V_{target}, which can therefore be observed to be dependant on temperature range and the nonlinearities of V_{BE}. It is worth noting that zero temperature coefficient (TC) point V_{0TC}, where there is virtually no change in V_{REF} when subjected to a small variation in temperature, is normally halfway between T_{min} and T_{max} (for example, 42.5°C for a 0 to 85°C operating range), not room temperature T_r necessarily; as a result, V_{target} is related to V_{0TC} but not always equal to it.

The nonlinearities of V_{BE} are strongly dependent on the process technology (for example, doping profile concentrations, etc.) and the circuit (for example, current-density variations resulting from Early voltage effects, mismatches, etc.). Consequently, V_{target}, which is the room temperature target voltage for which the least temperature-drift variation is achieved within a specified temperature range, is unique to each circuit-process combination. Some but not all process- and circuit-dependent effects are modeled by simulators with the precision required to design a reliable reference, which is why "magic voltage" V_{target} is ultimately determined empirically, through experimental characterization of a specific circuit fabricated in a particular process node.

Trim target

Thermal voltage V_t is fortunately free of second and higher order terms for a wide range of temperatures and is therefore a suitable trimming medium. A V_t-derived (PTAT) trimming voltage is consequently linearly proportional to temperature,

$$V_{REF} = V_{PTAT} + V_{CTAT} + V_{PTAT\_Trim} \quad \textbf{(1)}$$

that is to say, the highest trim code systematically produces the highest TC in V_{REF} and the lowest trim code the lowest TC, as shown in Figures 2 and 3. V_{target} is therefore determined statistically by measuring and averaging the TCs of a relatively large sample of circuits (over several wafers) halfway across the temperature range (for example, 42.5°C for a -20-to-125°C operating range) at the maximum and minimum trim codes (Figure 3) and linearly interpolating zero TC point V_{0TC} from the resulting minimum-to-maximum relationship:

$$V_{0TC} = V_{REF\_min\_avg} + \left(\frac{V_{REF\_max\_avg} - V_{REF\_min\_avg}}{TC_{maxavg} - TC_{minavg}}\right)(0 - TC_{minavg}) \quad \textbf{(2)}$$

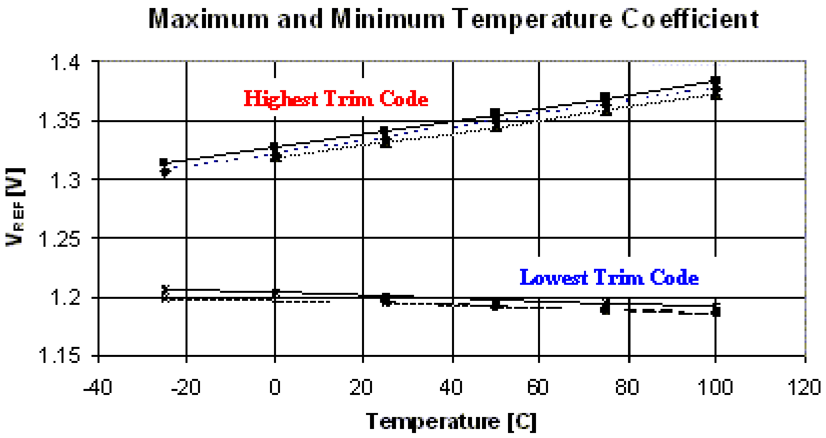

Figure 2: Six samples of V_{REF} at trim-code extremes

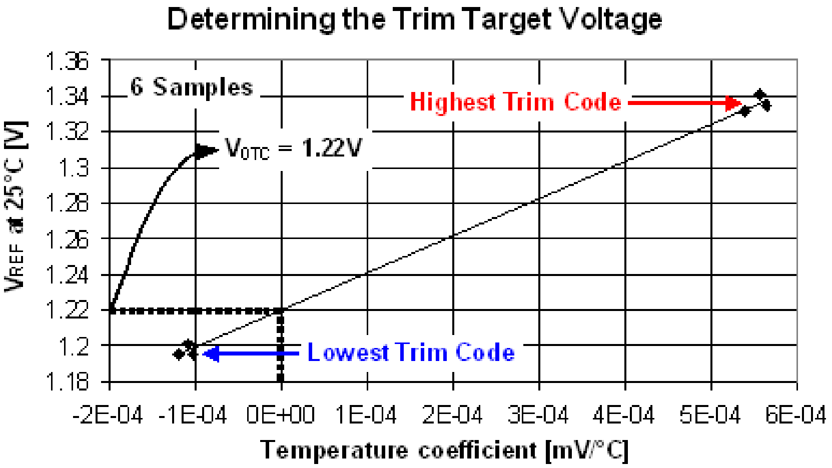

Figure 3: Temperature coefficients (TCs) of 6 samples halfway across the temperature range at trim-code extremes and their linear correlation

As mentioned earlier, target voltage V_{target} is not necessarily equal to zero-TC voltage V_{0TC}. Consequently, to ascertain V_{target}, the sample set is trimmed to V_{0TC} (for example, 1.22V) at mid-temperature T_{mid} (for example, 42.5°C). Similar to the V_{0TC} procedure, a linear interpolation is performed to determine V_{target} from V_{0TC} to the average of V_{REF} at temperature extreme T_{min} (V_{REF_avg} (T_{min})):

$$V_{target} = V_{REF\_avg}(T_{min}) + \left(\frac{V_{0TC} - V_{REF\_avg}(T_{min})}{T_{mid} - T_{min}}\right)(T_r - T_{min}) \quad \textbf{(3)}$$

The temperature curves that these optimally trimmed devices produce are not all parabolic in nature, as one would hope, because the process-induced mismatch effects differ from one device to the next. Averaging the measurements, however, mitigates their effects on extrapolating V_{target}. Note that this interpolation assumes V_{REF} changes linearly with temperature from T_{min} to T_{mid}, which is not true in practice but, given the total measured variation of trimmed V_{REF} across temperature is approximately 5-10 mV for a first-order bandgap circuit, is close enough to produce reliable results.

A trimmed first-order reference

Figure 4 illustrates the temperature-drift performance across 20 samples of a first-order bandgap reference trimmed with four bits of resolution at room temperature T_r. The full-scale trim range was 60mV and its voltage resolution 4mV. For ease and expediency, at the possible cost of degraded performance, V_{0TC} was measured at T_r instead of T_{mid} so that V_{target} is V_{0TC}. Using the "box method" to ascertain the overall TC performance of the circuit, which amounts to dividing the voltage extremes of V_{REF} across the entire temperature range for all measured samples by the temperature range and the nominal value of V_{REF} at T_r,

$$TC = \frac{1}{V_{REF\_avg}(T_r)}\left(\frac{V_{REFmax} - V_{REFmin}}{T_{max} - T_{min}}\right) \quad \textbf{(4)}$$

the resulting combined effective TC of the reference was 34.7ppm/°C with a mean of 13.9ppm/°C and a 1-sigma variation of 6.9ppm/°C.

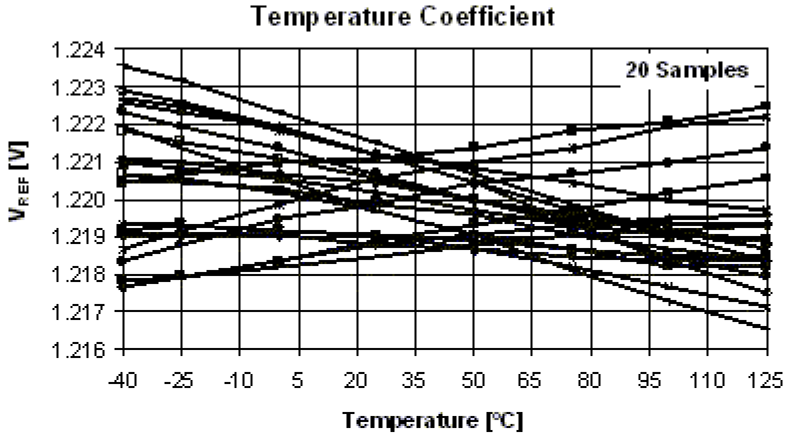

Figure 4: Measured temperature-drift performance of 20 trimmed samples for which V_{0TC} was extracted at T_r (not T_{mid}): $V_{0TC} = V_{target}$

Extracting V_{0TC} at T_r instead of T_{mid} and defining V_{target} to be V_{0TC} produce a slightly larger variation than otherwise possible. V_{0TC} at T_r should be the target voltage for a reference whose mid-range temperature is at 25°C, not 42.5°C, and using it for a -40 to 125°C range amounts to extending the upper range, the net result of which is a negative TC, that is, V_{REF} at 125°C is lower than at -40°C. In Figure 4, as expected, average V_{REF} at T_{min} is slightly higher than at T_{max}. This net shift, however, for the case shown, is only 1.5mV, which was not sufficiently significant to cause concern. This is not to say, however, it will always be insignificant, which is why it should always be checked. The more rigorous and accurate approach to extracting V_{target} is recommended because the accuracy requirements of portable, battery-powered applications are increasingly stringent while the extracting procedure is non-recurring, which means its associated costs are relatively low in high volume markets.

Trimming a higher order reference

Including a nonlinear term in V_{REF} (for example, V_{NL} as shown in Figure 1) to correct the nonlinearities of V_{BE} complicates the circuit and the V_{target}-extraction process. For one thing, no longer will trimming at a single temperature setting properly compensate for process variations because the target resolution range of V_{REF} is sensitive to the combined nonlinear variations of V_{BE} and V_{NL}, which affect V_{REF} more at higher temperatures than at lower temperatures. In practice, the trimming voltage remains PTAT (that is, completely independent of V_{NL}) because relative TC variations in V_{NL} ($\Delta V_{NL}/V_{NL}$) are proportionally larger than in V_{PTAT} and therefore less predictable. Determining the statistically optimal V_{NL} value is a more involved process, and trimming it normally requires at least two trimming temperatures, which tends to be prohibitively expensive in volume-driven markets where test time is a significant production cost. V_{NL} is consequently left untrimmed and set to its nominal point, which requires second- and higher-order polynomial curve-fitting functions to extract.

For additional details, questions, and/or comments on this article, please contact us, the Georgia Tech Analog and Power IC Laboratory, at gtap@ece.gatech.edu. More information about our research can be found at http://www.rincon-mora.com/research.

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