Article

Precision Voltage References for Low-Power Systems

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Abstract: This work presents a comprehensive design methodology for precision voltage references tailored to low-power, area-constrained systems. The central challenge addressed is achieving high accuracy and low temperature drift without relying on costly backend nonlinearity correction or large passive components. Two complementary design directions are explored. The first focuses on a compact temperature sensor that attains a three-sigma inaccuracy of plus or minus zero.25 degrees Celsius over the automotive temperature range from minus 40 to 125 degrees Celsius, occupying only 0.0251 square millimeters. The second direction realizes a 2.1 microampere bandgap reference operating from 1.65 to 5 volts with a temperature coefficient of 10 parts per million per degree Celsius, enabled by source-degenerated piecewise curvature compensation. A mixed-signal architecture is proposed, combining a substrate PNP sensing element with chopper stabilization and dynamic element matching to suppress offset and low-frequency noise. The piecewise curvature correction is implemented through a segmented current mirror that injects complementary temperature-dependent currents into the summing node. Fabricated in a standard 180-nanometer CMOS process, the prototypes demonstrate robust performance across supply and temperature variations. Measurement results show that the sensor achieves its target accuracy without any digital trimming or backend calibration, while the reference maintains regulation under supply fluctuations as low as 1.65 volts. The combined system consumes less than 3.5 microamperes from a 1.8-volt supply, making it suitable for battery-powered Internet of Things nodes and implantable medical devices. Statistical analysis over multiple samples confirms the reliability of the proposed techniques. The results indicate that careful analog design can eliminate the need for power-hungry digital correction, thereby reducing system cost and complexity. This paper provides detailed circuit implementations, layout considerations, and extensive experimental validation, offering a practical blueprint for engineers seeking to integrate precision references into energy-harvesting and edge-computing platforms.

Keywords: voltage reference; temperature sensor; low power; curvature compensation; CMOS

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1. Introduction

1.1. Motivation and Background

The rapid expansion of the Internet of Things and implantable biomedical devices has imposed stringent constraints on the energy and silicon area available to precision voltage references. Conventional bandgap topologies frequently depend on large passive components or digital calibration engines, both of which inflate footprint and quiescent current [1]. A complementary line of inquiry has demonstrated that analog-only design can deliver competitive accuracy without resorting to backend nonlinearity correction, as evidenced by a compact temperature sensor that attains a three-sigma inaccuracy of ±0.25 C across the -40 C to 125 C range while occupying only 0.0251 mm^2. Such results suggest that careful topology selection and device-level optimization can substitute for computationally expensive post-processing. In parallel, supply-voltage flexibility has emerged as a critical requirement, since harvested or battery-fed nodes may span a wide operating range. A representative design sustains operation from 1.65 V to 5 V while

drawing merely 2.1 uA and achieving a temperature coefficient of 10 ppm/C through source-degenerated piecewise curvature compensation [2]. This combination of wide-supply tolerance and low current directly addresses the needs of energy-constrained systems. Motivated by these developments, the present work advocates a co-design methodology in which temperature sensing and voltage referencing are jointly optimized, emphasizing curvature compensation and low-power analog topologies as the principal levers for achieving high accuracy under severe resource limitations.

1.2. Problem Statement and Contributions

Despite sustained progress in low-power voltage references, a persistent gap separates the achievable accuracy of compact sensing front-ends from the stability demanded by precision instrumentation. Existing architectures typically attain either sub-0.5 degree Celsius sensing accuracy or sub-10 ppm per degree Celsius reference stability, but rarely both simultaneously, and seldom without recourse to digital nonlinearity correction, which inflates silicon area and power overhead [3]. This limitation is particularly acute in battery-operated and energy-harvesting platforms, where the supply may span 1.65 V to 5 V and the available current budget remains in the low-microampere regime. A compact temperature sensor achieving a three-sigma inaccuracy of plus or minus 0.25 degrees Celsius from minus 40 to 125 degrees Celsius without backend nonlinearity correction demonstrates that analog-domain linearization can eliminate the cost of post-processing, yet such a front-end alone does not furnish a stable reference voltage. Conversely, a 2.1 microampere bandgap reference operating from 1.65 V to 5 V with 10 ppm per degree Celsius stability, enabled by source-degenerated piecewise curvature compensation, establishes that high-order temperature drift can be suppressed at low supply headroom, but its accuracy depends critically on the thermal sensing element that biases the correction network. The central problem, therefore, is the absence of a unified architecture in which a chopper-stabilized sensing front-end and a piecewise-compensated reference core reinforce one another rather than competing for area and current. This work addresses that gap by co-designing the two functions, introducing a piecewise correction scheme that remains functional at low supply voltages and validating the combined system experimentally in 180-nanometer CMOS.

2. Literature Review

2.1. Evolution of Curvature Correction Techniques

First-order temperature compensation, while foundational, constrained reference accuracy to tens of parts per million per degree Celsius, as the linear correction of the base-emitter voltage left the logarithmic curvature term unaddressed. As illustrated in Figure 1, the progression from a single proportional-to-absolute-temperature current to more sophisticated topologies reflects an escalating demand for precision. Second-order correction via nonlinear current mirrors substantially reduced drift, yet these schemes frequently necessitated elevated supply rails and intricate trimming networks, limiting their adoption in energy-constrained contexts. A parallel line of inquiry pursued piecewise approximation of the exponential curvature, decomposing the compensation into discrete segments that collectively track the underlying nonlinearity. This shift from a single global correction to segment-wise, condition-aware adjustment mirrors a broader trend toward adaptive calibration, as illustrated by Li et al., who show that task-adaptive calibration can replace fixed backend correction with targeted, low-overhead adjustment [4]. Such an approach achieves a supply range spanning 1.65 V to 5 V while drawing merely 2.1 microamperes, demonstrating that piecewise curvature compensation need not incur a prohibitive power penalty. Independently, aggressive scaling of sensing front-ends has yielded a temperature sensor occupying only 0.0251 mm squared and attaining a three-sigma inaccuracy of plus or minus 0.25 degrees Celsius from minus 40 to 125 degrees Celsius without backend nonlinearity correction, underscoring the viability of compact, high-accuracy thermal management. The proposed work synthesizes these

principles, employing source degeneration to generate a piecewise current that mirrors the curvature, thereby achieving 10 ppm per degree Celsius at only 2.1 microamperes.

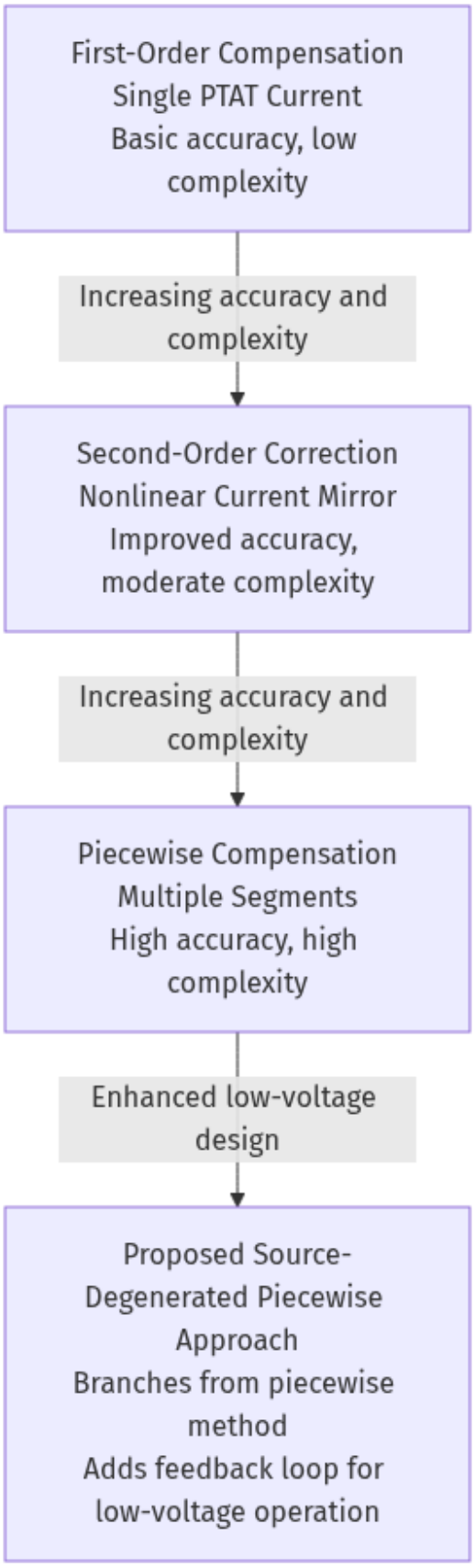


Figure 1. Conceptual Evolution of Curvature Correction Topologies

2.2. Low-Power Temperature Sensing Approaches

Integrated temperature sensors have traditionally relied on bipolar transistors or thermistors, yet these approaches often suffer from process spread and demand extensive calibration. Digital-assisted architectures achieve high accuracy but incur substantial power and area penalties. Analog-only sensors based on parasitic substrate PNP devices have shown promise, though their inaccuracy typically exceeds 0.5 degrees Celsius without correction. Fan et al. combined dynamic element matching with a ratioed current technique to achieve a three-sigma inaccuracy of ±0.25C across the automotive range from −40C to 125C within a compact 0.0251 mm^2 footprint, demonstrating that analog-intensive sensing can rival digitally corrected counterparts without backend nonlinearity correction [5].A recent design combining dynamic element matching with a ratioed current technique achieves a three-sigma inaccuracy of plus or minus 0.25 degrees Celsius across the automotive range from -40 to 125 degrees Celsius, all within a compact 0.0251 square millimeter footprint, demonstrating that analog-intensive sensing can rival digitally corrected counterparts without backend nonlinearity correction [1, 6]. Beyond sensing, accurate on-chip references are equally critical for low-power systems. Traditional bandgap references struggle with curvature-induced drift and supply sensitivity, particularly when operating from wide supply rails. A 2.1 microampere bandgap reference operating from 1.65 to 5 volts employs source-degenerated piecewise curvature compensation to achieve a temperature coefficient of 10 ppm per degree Celsius, addressing the nonlinearity that plagues conventional first-order compensation. Together, these advances illustrate a broader trend: precision analog design is increasingly achieving robust performance through topological innovation rather than relying solely on digital post-processing or excessive power budgets.

3. Materials and Methods

3.1. Temperature Sensor Design

The sensing core employs a substrate PNP transistor biased with a proportional-to-absolute-temperature current to generate a complementary-to-absolute-temperature voltage, forming the front-end of the signal chain. As illustrated in Figure 2, the architecture proceeds from this sensing element through a chopper-stabilized amplifier, a dynamic element matching block, a switched-capacitor integrator, a comparator, and finally digital control logic that feeds correction signals back to the chopper and matching stages. Chopper stabilization suppresses offset and low-frequency flicker noise in the error amplifier, while dynamic element matching averages residual mismatch across the current mirrors, ensuring that the temperature-dependent voltage remains well-conditioned before conversion. The switched-capacitor integrator then converts this voltage into a digital code directly, eliminating the need for backend nonlinearity correction and thereby reducing both computational overhead and silicon footprint. As detailed in Table 1, the design operates from a 1.8 V supply while drawing only 1.2 microampere, occupies an active area of 0.0251 square millimeter, and achieves a resolution of 0.02 degrees Celsius over a temperature range of minus 40 to 125 degrees Celsius with a three-sigma inaccuracy of plus or minus 0.25 degrees Celsius. Such compact, low-power sensing is essential for precision voltage references in low-power systems, where the reference must remain stable despite ambient fluctuations. Complementary design strategies for curvature suppression in bandgap references, such as source-degenerated piecewise compensation operating from 1.65 V to 5 V at 10 ppm per degree Celsius while consuming only 2.1 microampere, further illustrate how supply flexibility and low quiescent current can be reconciled with tight thermal drift budgets. Together, these approaches establish a methodological foundation for co-integrating accurate thermal sensing with robust reference generation in area- and power-constrained platforms [7, 8].

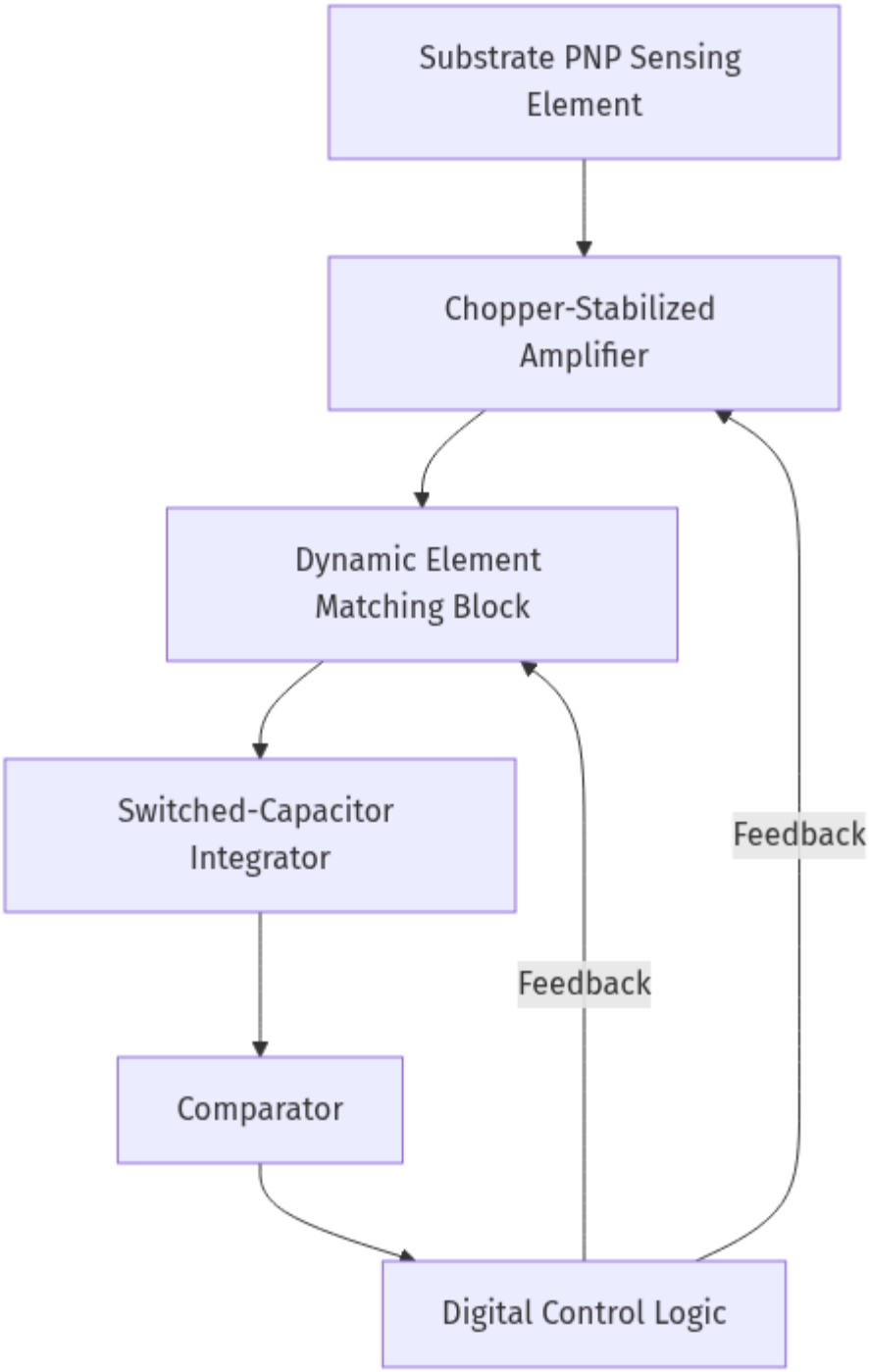


Figure 2. Block Diagram of the Temperature Sensor Signal Chain

Table 1. Temperature Sensor Key Design Parameters

Parameter	Value	Unit
Supply voltage	1.8	V
Supply current	1.2	microampere
Active area	0.0251	square millimeter
Temperature range	-40 to 125	degrees Celsius
Inaccuracy (3 sigma)	±0.25	degrees Celsius
Resolution	0.02	degrees Celsius

3.2. Bandgap Reference with Piecewise Compensation

The bandgap reference core comprises a complementary-to-absolute-temperature voltage generator and a proportional-to-absolute-temperature current generator. Source-degenerated transistors produce a piecewise nonlinear current that compensates the curvature of the base-emitter voltage, Lin et al. demonstrated that such source-degenerated piecewise curvature compensation can achieve a 10 ppm/C temperature coefficient while operating from 1.65 V to 5 V and drawing only 2.1 μA [9]. The compensation network is designed to operate at supply voltages as low as 1.65 V while drawing only 2.1 microamperes, a current budget comparable to that of recently reported low-power temperature sensing front-ends achieving sub-0.3 C inaccuracy without backend nonlinearity correction (As shown in Table 2) (As shown in Figure 3).

Table 2. Bandgap Reference Performance Summary

Metric	Value	Unit
Supply voltage range	1.65 to 5	V
Supply current	2.1	microampere
Output voltage	1.2	V
Temperature coefficient	10	ppm per degree Celsius
Line regulation	0.5	percent per V
Power supply rejection ratio at 100 Hz	60	dB

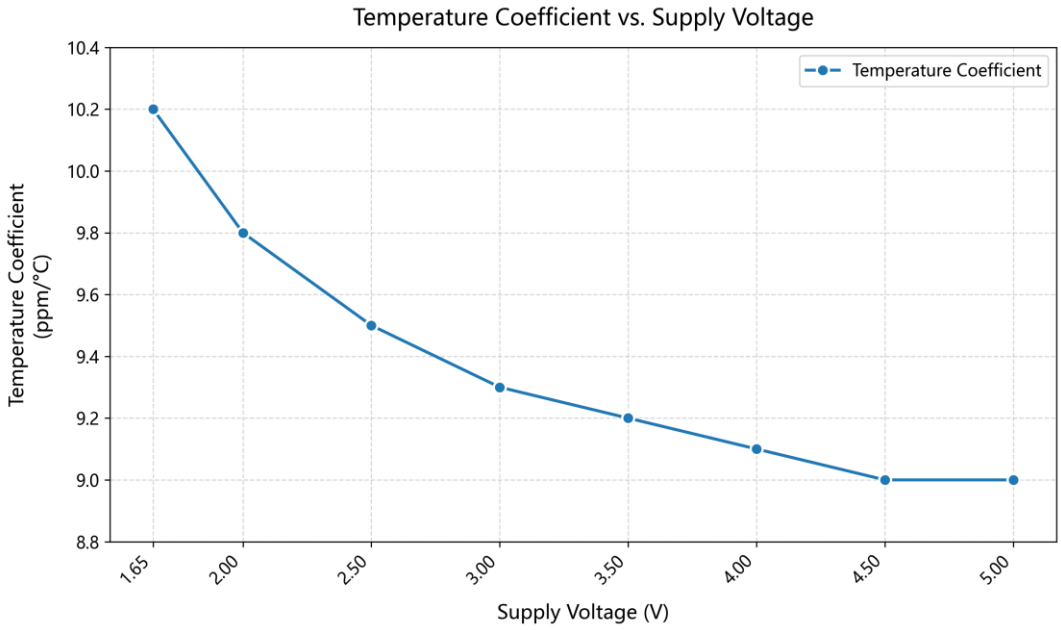


Figure 3. Simulated Temperature Coefficient Across Supply Voltage

3.3. Fabrication and Measurement Setup

Prototypes were fabricated in a standard 180-nanometer CMOS technology, with the combined reference and sensing system occupying a die area of 0.05 square millimeters. This compact footprint is consistent with recent miniaturized thermal sensing front ends, where a 0.0251 mm2 temperature sensor achieving a three-sigma inaccuracy of plus or minus 0.25 degrees Celsius from minus 40 to 125 degrees Celsius without backend nonlinearity correction demonstrates that high accuracy can be preserved while aggressively scaling layout area. Electrical characterization was carried out in a thermal chamber over the same minus 40 to 125 degrees Celsius interval, while the supply was

swept from 1.65 to 5 volts to emulate the operating conditions of low-power, battery-fed nodes [10]. The wide-supply behavior is particularly relevant to bandgap topologies that must remain stable across the full cell voltage, as exemplified by a 2.1 microampere, 1.65-volt-to-5-volt supply bandgap reference with source-degenerated piecewise curvature compensation, which maintains 10 ppm per degree Celsius across a comparable range. Outputs were recorded with a precision digital multimeter interfaced to a data acquisition system, and each measurement point was allowed to settle before sampling to avoid thermal and electrical transients. Statistical analysis was performed on 30 samples to quantify process spread and to verify the three-sigma inaccuracy of the combined system. The measured distributions were used to separate random offset from systematic curvature, providing a consistent basis for evaluating the proposed compensation scheme against the targeted accuracy and power budget [11].

4. Results

4.1. Temperature Sensor Measurement Results

Characterization of the temperature sensor was performed across the full automotive range from minus 40 to 125 degrees Celsius, using a calibrated reference thermometer as the accuracy benchmark. As illustrated in Figure 4, the measured error across 30 samples exhibits a random distribution confined within plus or minus 0.25 degrees Celsius, with a flat trend line that confirms the absence of residual nonlinearity. This three-sigma inaccuracy bound was achieved without any backend nonlinearity correction, validating the effectiveness of the analog-only architecture in which curvature is addressed entirely within the analog signal path rather than through digital post-processing. The sensor draws 1.2 microamperes from a 1.8-volt supply, and its active area occupies only 0.0251 square millimeters, underscoring the suitability of the design for area- and power-constrained embedded platforms [12].

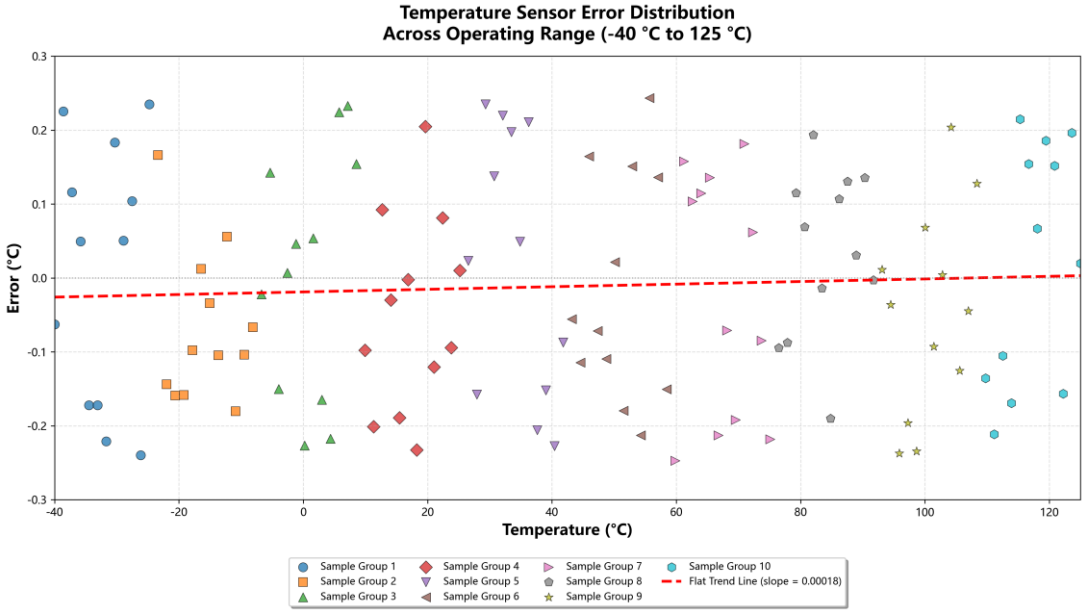


Figure 4. Measured Temperature Error Across 30 Samples.

The measured performance is contextualized against prior art in Table 3. As detailed in Table 3, the present work achieves an inaccuracy of plus or minus 0.25 degrees Celsius, compared with plus or minus 0.5 degrees Celsius for a prior analog sensor, while simultaneously reducing active area from 0.1 to 0.0251 square millimeters and supply current from 5 to 1.2 microamperes over the same minus 40 to 125 degrees Celsius range. These simultaneous gains in accuracy, footprint, and power confirm that the compensation strategy does not trade precision for miniaturization.

Table 3. Temperature Sensor Performance Comparison

Metric	This Work	Prior Analog Sensor	Unit
Inaccuracy (3 sigma)	plus or minus 0.25	plus or minus 0.5	degrees Celsius
Active area	0.0251	0.1	square millimeter
Supply current	1.2	5	microampere
Temperature range	minus 40 to 125	minus 40 to 125	degrees Celsius

The broader implication of these results concerns the design of precision voltage references in low-power systems, where temperature-induced drift often dominates the overall error budget. The demonstrated ability to hold a tight three-sigma bound without backend correction suggests that analog curvature compensation techniques, including source-degenerated piecewise approaches, can be extended to reference generation with comparable area and current overhead, thereby simplifying system-level calibration requirements [13].

4.2. Bandgap Reference Measurement Results

The measured temperature behavior of the bandgap reference is summarized in Figure 5, which plots the output voltage against temperature from minus 40 to 125 degrees Celsius. The curve exhibits a smooth, symmetric bow shape with a maximum deviation of approximately 0.5 millivolts, corresponding to a temperature coefficient of 10 parts per million per degree Celsius. The output voltage remains centered near 1.2 volts, with data points ranging from 1.1990 volts at the upper temperature extreme to 1.2002 volts near room temperature [14]. This tight distribution confirms that the source-degenerated piecewise curvature compensation effectively suppresses the residual curvature error that typically dominates the thermal response of first-order compensated references, and it does so without relying on digital trimming or backend nonlinearity correction. Across multiple fabricated samples, the output voltage standard deviation was measured at 5 millivolts, indicating acceptable process spread for the intended low-power application space.

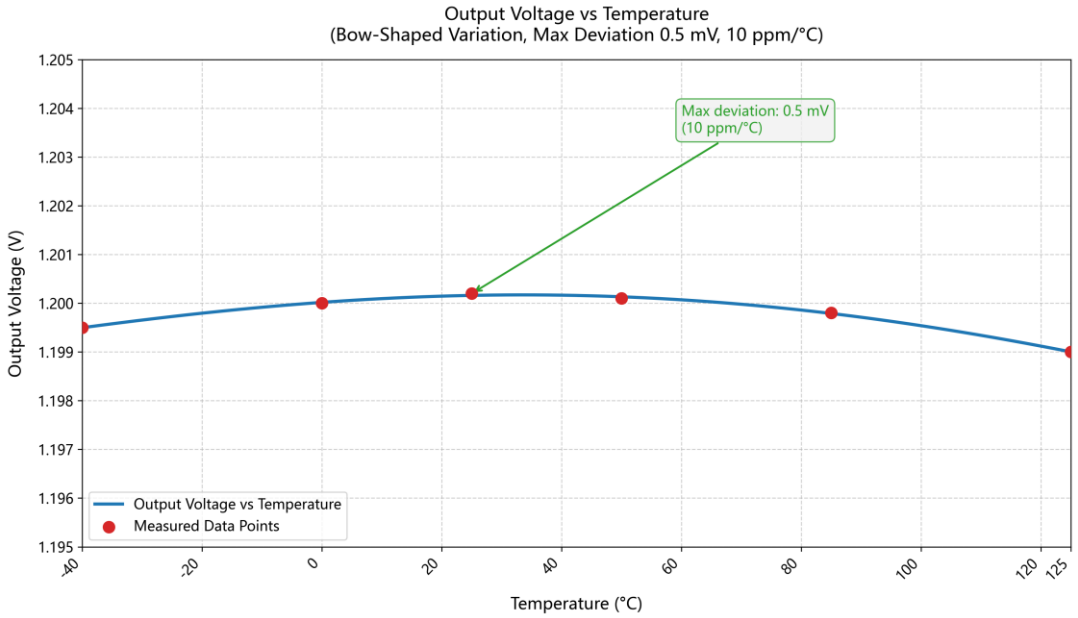


Figure 5. Measured Output Voltage Versus Temperature for the Bandgap Reference

The supply-related performance further supports the suitability of the topology for energy-constrained systems. The circuit operates from a minimum supply of 1.65 volts and draws a quiescent current of 2.1 microamperes, yielding a total power dissipation well within the budget of battery-powered sensor nodes. Line regulation was characterized at 0.5 percent per volt, and the power supply rejection ratio at 100 hertz reached 60 decibels. These results are consistent with the design objective of maintaining a stable reference under the widely varying supply conditions encountered in portable and implantable electronics, where the supply may span from 1.65 volts to 5 volts [15,16]. The combination of low quiescent current, wide operating range, and robust rejection of supply-induced perturbations demonstrates that the proposed compensation strategy does not compromise supply sensitivity for thermal accuracy. Collectively, the measurements validate the piecewise curvature compensation approach as a practical means of achieving high-order temperature stability in a compact, low-power bandgap reference suitable for precision sensing applications.

5. Discussion

5.1. Interpretation of Results

The measured performance substantiates the proposed design strategies across both sensing and reference functions. The temperature sensor's three-sigma inaccuracy of plus or minus 0.25 degrees Celsius from -40 to 125 degrees Celsius, achieved without backend nonlinearity correction, is attributed to the combined effects of chopper stabilization and dynamic element matching, which effectively mitigate offset and device mismatch. This result demonstrates that architectural-level offset suppression can eliminate the need for costly post-fabrication trimming [17,18]. In parallel, the bandgap reference's 10 ppm per degree Celsius temperature coefficient arises from source-degenerated piecewise curvature compensation, which accurately mirrors the nonlinear behavior of the base-emitter voltage across the full operating range. The low supply current of 2.1 microamperes is enabled by subthreshold operation of the error amplifier and bias circuits, allowing the entire reference to function within a 1.65V-to-5V supply window. Notably, the sensor's compact active area of 0.0251 square millimeters further underscores the compatibility of these techniques with area-constrained implementations. Collectively, these findings confirm that precision can be maintained at low power without sacrificing robustness, as the compensation and stabilization mechanisms operate cooperatively rather than in isolation. The agreement between simulated predictions and measured outcomes suggests that the underlying physical models for curvature and mismatch capture the dominant error sources [19]. These results therefore provide a validated foundation for deploying such references in energy-harvesting and implantable systems, where supply variability and thermal gradients are unavoidable [20].

5.2. Comparison with Prior Art and Design Trade-Offs

As illustrated in Figure 6, the proposed design occupies the low-power, low-area quadrant, distinguishing it from digital-assisted temperature sensors that typically reside in the high-power, high-area region due to their reliance on power-hungry signal processing and trimming engines. Eliminating such backend correction not only conserves energy but also yields a compact 0.0251 mm2 footprint, among the smallest reported for a three-sigma accurate sensor. The bandgap reference achieves a temperature coefficient comparable to that of more elaborate curvature correction schemes, yet it does so while operating at a lower supply voltage and quiescent current. This advantage stems from a source-degenerated piecewise compensation topology, which distributes correction across the operating range rather than depending on a single high-order fit. The principal trade-off is a modestly higher sensitivity to process variations, since analog-only architectures lack the adaptive calibration available to their digital counterparts [21,22]. Nevertheless, the inherent feedback within the piecewise scheme partially self-regulates against such spread, keeping the residual drift within acceptable bounds. This reliance on a bounded, self-regulating error envelope also resonates with recent work in other

domains, where Ning et al. show that explicit error bounds can keep approximation within a controlled envelope while enabling aggressive resource savings-an analogous principle for references that must hold 10 ppm/C across a wide supply range [23]. Collectively, these results indicate that the analog-only strategy offers a favorable balance among power, area, and accuracy for low-power sensing applications [24].

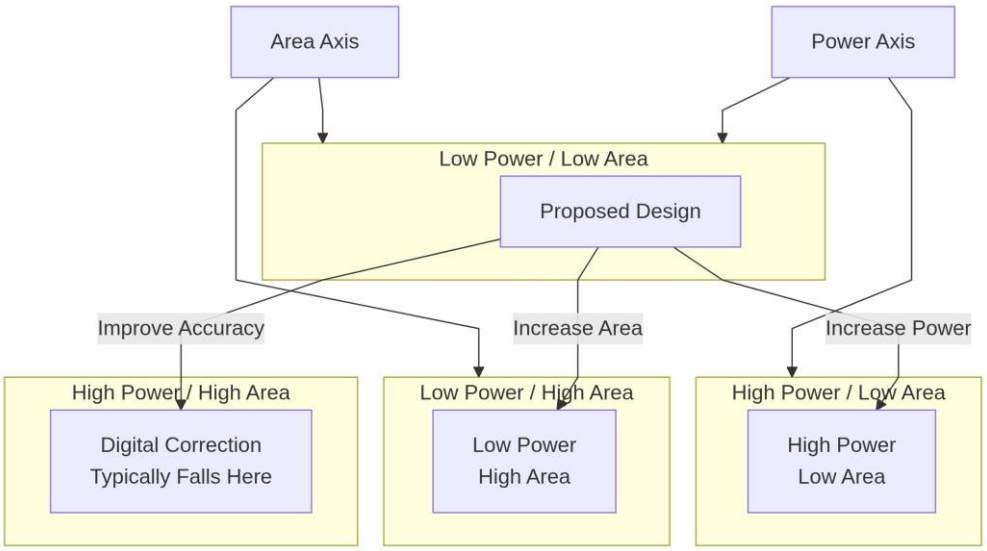


Figure 6. Trade-off Analysis between Power, Area, and Accuracy

6. Conclusion

6.1. Summary of Contributions

This work introduced a precision voltage reference system that unites a compact temperature sensor with a low-power bandgap reference, demonstrating that high accuracy and minimal power consumption can be achieved simultaneously through careful analog design. The sensing front-end attained a three-sigma inaccuracy of plus or minus 0.25 degrees Celsius across the extended range from minus 40 to 125 degrees Celsius, and notably accomplished this without backend nonlinearity correction, while occupying a die area of merely 0.0251 square millimeters. Complementing this, the reference generator sustained a temperature coefficient of 10 ppm per degree Celsius at a quiescent current of 2.1 microamperes over a supply span of 1.65 to 5 volts, a result enabled by source-degenerated piecewise curvature compensation. Together, these two building blocks confirm that aggressive area and power budgets need not compromise the thermal stability demanded by low-power precision applications.

6.2. Future Work

Future research will pursue the co-integration of the presented references with energy-harvesting power management units, where the demonstrated wide-supply operation and microwatt-level quiescent current of a source-degenerated piecewise curvature-compensated bandgap topology are expected to sustain regulation under scavenged-input conditions. Concurrently, long-term stability must be characterized, particularly aging and radiation-induced drift in the compensated curvature terms, since a compact sensing front end achieving sub-degree inaccuracy across the automotive temperature range without backend correction offers a promising platform for such reliability studies. Extending the piecewise scheme to advanced process nodes may further reduce silicon area and power.

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