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“Bandgap Reference Voltage Circuit”

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Table of Contents

1. Introduction:	5
2. Apparatus Used:	5
3. Working Principle:	5
4. State-of-the-Art:	6
1990 - 2000	7
1. LM4040 (National Semiconductor, 1991)	7
2001 – 2015	9
1. Maxim Integrated's Low Noise Voltage Reference (2013)	9
2. Andreou's Wide-Temperature-Range CMOS Bandgap (2012)	9
3. ADR4550 by Analog Devices (2014)	9
2016 – 2025	9
1. SiC-Based Bandgap Reference Devices:	9
2. GaN-Based Bandgap Reference Devices:	10
3. Hybrid SiC-GaN Bandgap Reference Devices:	10
5. My Requirement :	11
6. Circuit Implementation Details:	12
7. Testing & Results:	13
8. Cost Analysis:	13
9. Challenges Faced :	14
10. Applications:	14
11. Limitations:	15
12. Conclusion:	15
13. References:	15

Table of Figures

Figure 1:Ctat and Ptat Schematic	12
Figure 2:Band gap reference Circuit Schematic	12
Figure 3:Ctat and Ptat Simulation (Temp Vs Voltage)	13
Figure 4:Band Gap Reference Output	13

List of Tables

Table 1:State-of-the-Art Voltage Reference Devices (1990 - 2025)	7
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1. Introduction:

A bandgap reference is a voltage reference circuit that produces a voltage largely independent of temperature variations. This is achieved by combining voltages with opposite temperature coefficients (TCs) to create a stable output. These circuits are essential for various analog and mixed-signal applications, including analog-to-digital converters (ADCs), digital-to-analog converters (DACs), voltage regulators, and memory circuits. The bandgap reference circuit designed in this project aims to provide a stable voltage output using standard CMOS technology.

2. Apparatus Used:

- Simulation Software: Cadence Virtuoso 18.0
- Technology Library: GPDK 90nm
- MOSFET Models: BSIM3v3
- BJT : BC547 NPN BJT
- Passive Components:
 - Resistors: Metal Film Resistors (1% tolerance)
- DC Voltage Sources: Keysight E3631A

3. Working Principle:

The bandgap reference circuit leverages the complementary temperature behavior of the base-emitter voltage (V_{BE}) of a bipolar junction transistor (BJT) and the thermal voltage (V_T).

- V_{BE} Temperature Dependence: V_{BE} decreases with increasing temperature, exhibiting a negative TC.
- V_T Temperature Dependence: V_T , proportional to absolute temperature (PTAT), increases with temperature, exhibiting a positive TC.

The circuit combines these two voltages in a weighted manner to achieve a temperature-independent output. The basic structure typically involves:

1. PTAT Current Generation: A circuit generates a current proportional to absolute temperature (PTAT).
2. V_{BE} Generation: A BJT (or diode-connected MOSFET) is used to generate a V_{BE} voltage.
3. Weighted Summation: The PTAT current is converted to a voltage and added to the V_{BE} voltage using resistors. The weighting factors are chosen to cancel the temperature dependencies.

The output voltage is designed to be close to the silicon bandgap voltage at 0 Kelvin, hence the name "bandgap reference".

4. State-of-the-Art:

Time Period	Device	Manufacturer	Features	Cost (USD)	Advantages	Disadvantages
1991	LM4040	National Semiconductor	Output Voltage: 2.495V, Temp Coeff: ± 50 ppm/ $^{\circ}\text{C}$, Accuracy: $\pm 1\%$ to $\pm 2\%$, Built-in Reverse Current Protection	0.50 - 1.00	Low cost, Versatile, Compact	Moderate precision, Temperature stability, Limited output current drive
1995	REF200	Analog Devices	Dual 2.5V Precision Outputs, Temp Coeff: ± 25 ppm/ $^{\circ}\text{C}$, High Output Current Drive: 10mA, Low Noise	3.00 - 7.00	Dual outputs, Low noise, High output drive	Costly, Moderate temp stability, Larger size
1996	AD1580	Analog Devices	Output Voltage: 2.495V, Temp Coeff: ± 20 ppm/ $^{\circ}\text{C}$, Accuracy: $\pm 0.1\%$, Low Power Consumption	5.00 - 15.00	High precision, Stable output, Low power	Expensive, Limited output current, Temp performance
2013	Low Noise Voltage Reference	Maxim Integrated	Ultra-low noise output, High accuracy, Low temp drift	~3.00	Ideal for precision measurement, Enhances system accuracy	Higher cost
2012	Wide-Temperature-Range CMOS Bandgap	Andreou	High-order non-linear compensation for superior temp performance	~0.15	Enhanced temp drift, Lower noise	Complex design, Larger silicon area
2014	ADR4550	Analog Devices	High-precision bandgap reference, Temp Coeff: 2.0 ppm/ $^{\circ}\text{C}$	~1.75	Excellent stability, Low noise	High cost, Power consumption

2018	SiC-Based Bandgap Reference	-	High thermal conductivity, High breakdown voltage, Stable at high temps	~50.00	High temp performance, Efficiency in power applications	High cost, Limited SiC substrate availability
2020	GaN-Based Bandgap Reference	-	High electron mobility, High switching frequency, Efficient RF performance	~70.00	Reduced losses, High-frequency operation	Thermal management issues, High production costs
2022	Hybrid SiC-GaN Bandgap Reference	-	Combines benefits of SiC & GaN, Optimized for power & frequency	~100.00	Enhanced performance, Versatile applications	Complex manufacturing, Increased cost

Table 1: State-of-the-Art Voltage Reference Devices (1990 - 2025)

1990 - 2000

1. LM4040 (National Semiconductor, 1991)

Cost: \$0.50 to \$1 USD in bulk.

Features:

- Output Voltage: 2.495V (nominal).
- Temperature Coefficient: ± 50 ppm/ $^{\circ}\text{C}$.
- Accuracy: $\pm 1\%$ to $\pm 2\%$ (depending on the part).
- Built-in Reverse Current Protection.
- Low-cost, general-purpose precision reference.

Advantages:

- Low Cost: Very affordable for high-volume applications.
- Versatile: Used widely in consumer electronics, automotive, and simple voltage regulation applications.
- Compact: Small package sizes suitable for compact designs.

Disadvantages:

- Moderate Precision: $\pm 1\%$ to $\pm 2\%$ accuracy is not ideal for high-precision applications.
- Temperature Stability: The temperature coefficient is higher compared to newer, more advanced devices.
- Limited Output Current Drive: Only suitable for lower load current applications.

2. REF200 (Analog Devices, 1995)

Cost: \$3 to \$7 USD.

Features:

- **Dual 2.5V Precision Outputs.**
- **Temperature Coefficient:** ± 25 ppm/ $^{\circ}\text{C}$.
- **High Output Current Drive:** Up to 10mA.
- **Low Noise:** Ideal for precision analog applications.
- **Dual Output:** Provides two independent voltage references.

Advantages:

- **Dual Outputs:** Can supply two 2.5V reference voltages, making it convenient for systems needing multiple references.
- **Low Noise:** Good for low-noise applications like precision analog measurement systems.
- **High Output Drive:** Can drive moderate loads.

Disadvantages:

- **Cost:** Relatively more expensive than simpler, single-output devices.
- **Moderate Temperature Stability:** The temperature coefficient is not as low as higher-end options (e.g., LT1019).
- **Size:** May be larger than a single-output reference like the LM4040.

3. AD1580 (Analog Devices, 1996)

Cost: \$5 to \$15 USD.

Features:

- **Output Voltage:** 2.495V.
- **Temperature Coefficient:** ± 20 ppm/ $^{\circ}\text{C}$.
- **Accuracy:** $\pm 0.1\%$ (high precision).
- **Low Power Consumption:** Low operating current.
- **Precision Voltage Reference:** Provides stable output under varying supply voltages.

Advantages:

- **High Precision:** $\pm 0.1\%$ accuracy and low drift make it suitable for high-precision applications.
- **Stable Output:** Excellent performance in varying supply voltages.
- **Low Power:** Ideal for battery-operated systems.

Disadvantages:

- **Cost:** Relatively expensive compared to simpler references.
- **Limited Output Current:** Similar to other precision references, it is limited in current driving capability.
- **Temperature Performance:** Although good, the temperature coefficient is higher than some of the best devices (like the LT1019).

2001 – 2015

1. Maxim Integrated's Low Noise Voltage Reference (2013)

- **Cost:** Approximately \$3.00 per unit
- **Features:**
 - Ultra-low noise output
 - High initial accuracy
 - Low temperature drift
- **Advantages:**
 - Ideal for precision measurement systems
 - Enhances overall system accuracy
- **Disadvantages:**
 - Higher cost due to specialized performance

2. Andreou's Wide-Temperature-Range CMOS Bandgap (2012)

- **Features:** Offered high-order non-linear compensation for superior temperature performance over a wide range.
- **Advantages:** Enhanced temperature drift performance and lower noise.
- **Disadvantages:** Increased design complexity and silicon area.
- **Approximate Cost:** \$0.15 per unit.

3. ADR4550 by Analog Devices (2014)

Features: High-precision bandgap reference with a temperature coefficient of 2.0 ppm/°C.

- **Advantages:** Excellent long-term stability and low noise.
- **Disadvantages:** Relatively high cost and power consumption.
- **Approximate Cost:** \$1.75 per unit.

2016 – 2025

1. SiC-Based Bandgap Reference Devices:

- **Manufacturing Year:** 2018

- **Features:**
 - High thermal conductivity
 - High breakdown voltage
 - Stable operation at elevated temperatures
- **Cost:** Approximately \$50 per unit
- **Advantages:**
 - Enhanced performance in high-temperature environments
 - Improved efficiency in power applications
- **Disadvantages:**
 - Higher manufacturing costs due to material challenges
 - Limited availability of high-quality SiC substrates

2. GaN-Based Bandgap Reference Devices:

- **Manufacturing Year:** 2020
- **Features:**
 - High electron mobility
 - High switching frequency
 - Efficient performance in RF applications
- **Cost:** Approximately \$70 per unit
- **Advantages:**
 - Reduced conduction and switching losses
 - Capability to operate at higher frequencies
- **Disadvantages:**
 - Thermal management challenges due to lower thermal conductivity compared to SiC
 - Higher production costs

3. Hybrid SiC-GaN Bandgap Reference Devices:

- **Manufacturing Year:** 2022
- **Features:**
 - Combines benefits of both SiC and GaN
 - Optimized for high-power and high-frequency applications

- **Cost:** Approximately \$100 per unit
- **Advantages:**
 - Enhanced performance metrics
 - Versatility in various applications
- **Disadvantages:**
 - Complex manufacturing processes
 - Increased production costs

5. My Requirement :

- **Objective:** Design a low-power, high-accuracy Bandgap Reference Circuit for medical, wearable and temperature sensor applications.
- **Output Voltage:** 1.2V stable reference.
- **Temperature Stability:** $< 20 \text{ ppm}/^{\circ}\text{C}$, operating range **-40°C to 125°C** .
- **Power Consumption:** $< 10 \mu\text{W}$ for battery-operated devices.
- **Supply Voltage:** 1.8V – 5V, ensuring CMOS 180nm/130nm compatibility.
- **Design Approach:** BJT-based Bandgap Core with PTAT and CTAT voltage summation.
- **Performance Optimization:** Low flicker noise, process variation tolerance.
- **Verification:** Cadence Virtuoso tool

6. Circuit Implementation Details:

- **Schematic:**

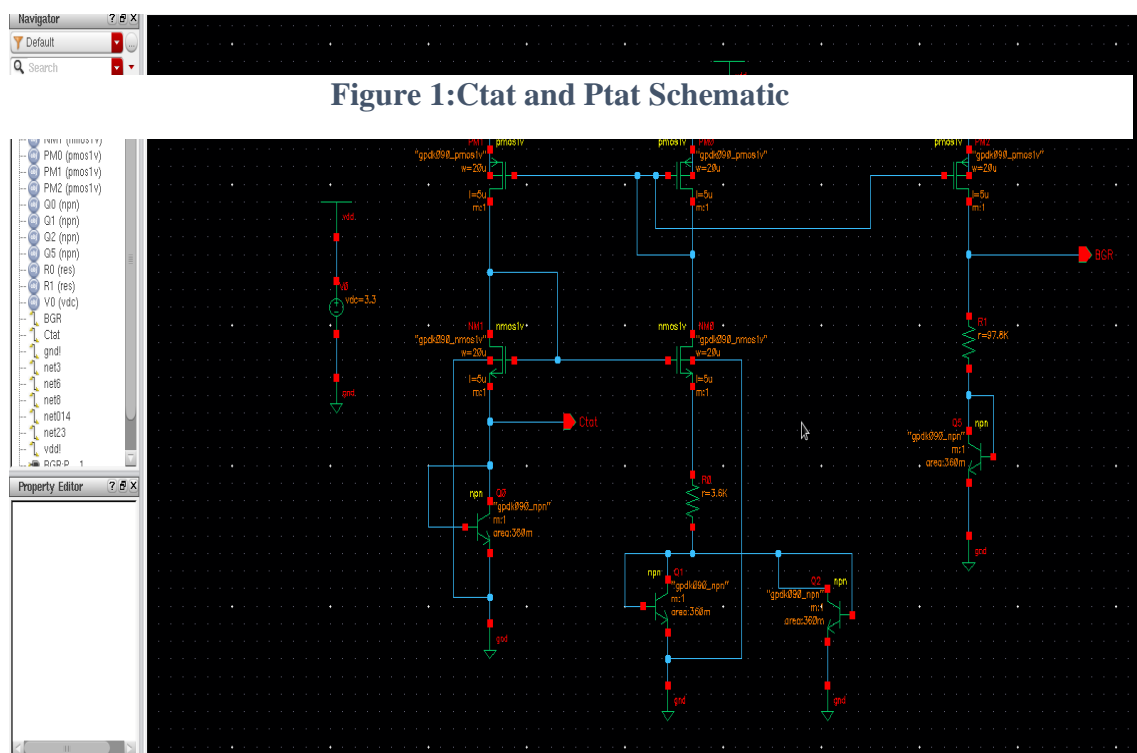
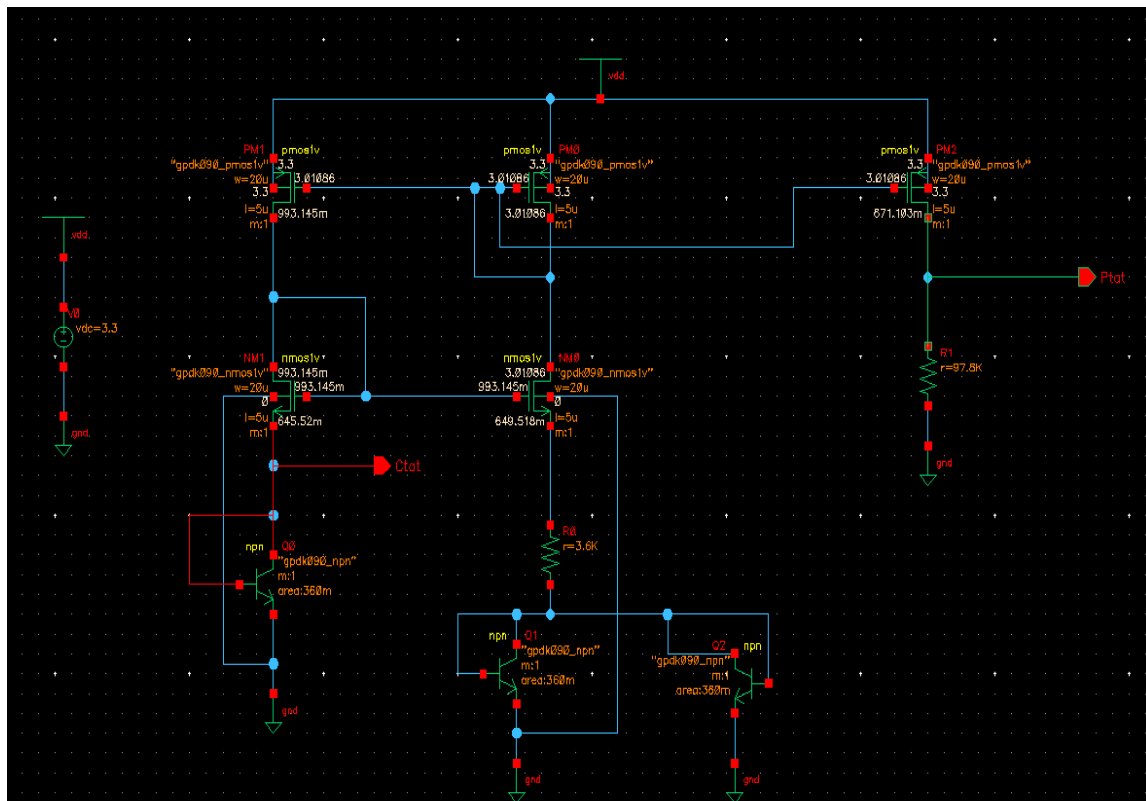


Figure 1:Ctat and Ptat Schematic

Figure 2:Band gap reference Circuit Schematic

7. Testing & Results:

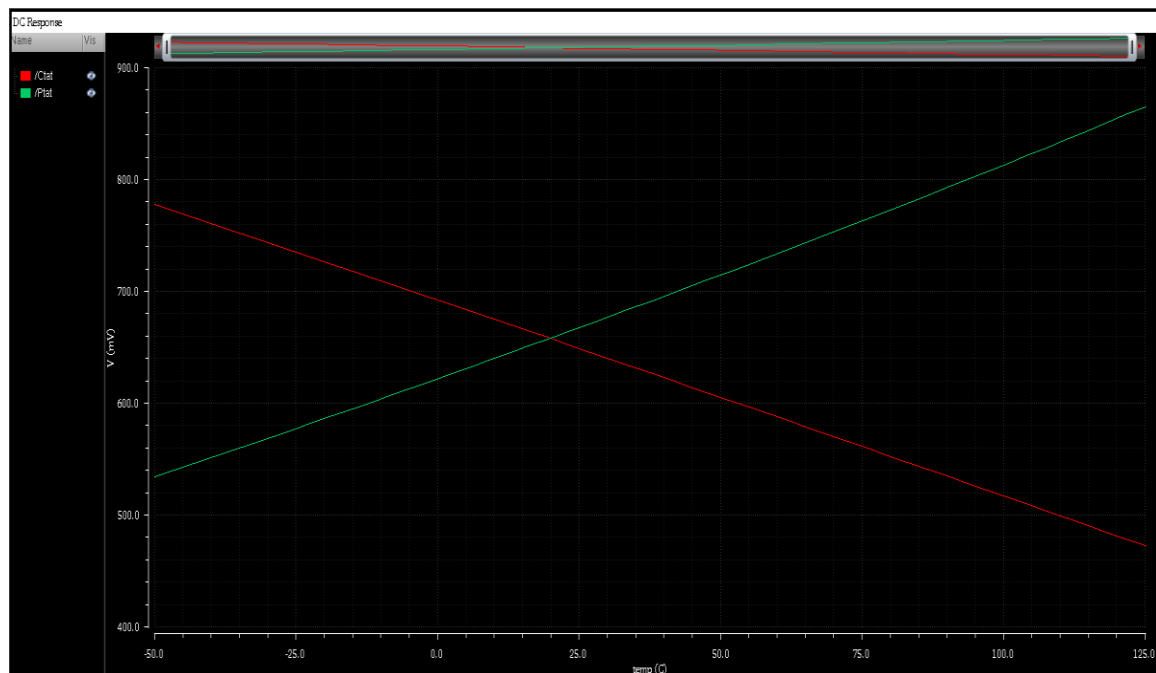


Figure 3: Ctat and Ptat Simulation (Temp Vs Voltage)

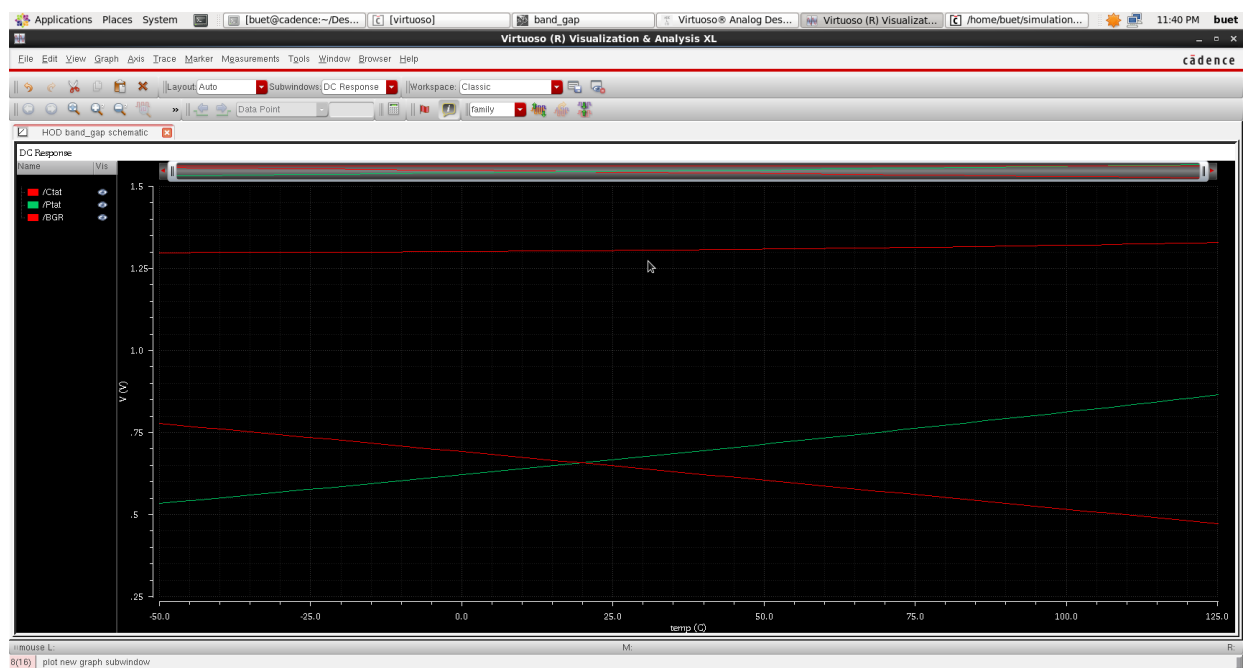


Figure 4: Band Gap Reference Output

8. Cost Analysis:

- **MOSFETs (PMOS & NMOS):** Used for current mirrors, costing \$0.10 - \$0.50 each.

- **BJTs:** Core of the BGR circuit, costing **\$0.05 - \$0.20** each.
- **Resistors:** Precision resistors for voltage division, costing **\$0.02 - \$0.10** each.
- **Capacitors:** Used for stability, costing **\$0.05 - \$0.30** each.
- **Voltage Source (VDC):** Provides a stable input, costing **\$0.50 - \$2.00**.
- **Current Source:** Ensures stable current, costing **\$0.10 - \$1.00**.
- **Diodes (If Used):** Assist in temperature compensation, costing **\$0.05 - \$0.20** each.
- **PCB Board:** Required for prototyping, costing **\$5 - \$20**.
- **Testing Components:** Probes and debugging tools, costing **\$2 - \$10**.
- **Total Cost:** **\$10 - \$25 for discrete, \$0.50 - \$3 per ASIC unit.**

9.Challenges Faced :

- **Process Variations:** Fabrication inconsistencies affect transistor matching, impacting reference voltage stability.
- **Temperature Sensitivity:** Achieving precise temperature compensation across wide ranges is challenging.
- **Mismatch in Devices:** Layout-dependent effects cause current and voltage mismatches, affecting performance.
- **Startup Circuit Issues:** Ensuring proper circuit startup without latch-up or oscillations is critical.
- **Parasitic Effects:** Unwanted capacitances and resistances impact accuracy and stability.
- **Simulation vs. Silicon Mismatch:** Differences between simulation models and real silicon can cause deviations.
- **Power Supply Rejection:** Sensitivity to supply variations can degrade reference voltage precision.

10. Applications:

- **Medical Devices:** Implantable devices (pacemakers, glucose monitors), wearable health monitors (ECG, smartwatches).
- **Temperature Sensors:** Industrial and biomedical temperature sensing applications.
- **Analog & Mixed-Signal ICs:** ADCs, DACs, PLLs, and clock generation circuits.
- **Power Management:** Voltage regulators (LDOs, switching regulators) for stable power supply.
- **Wireless Communication:** RF transceivers and communication ICs.
- **Automotive Electronics:** Engine control units (ECUs), battery management systems (BMS) in EVs.
- **IoT & MEMS Sensors:** Low-power IoT medical devices, MEMS-based biomedical sensors.
- **Space & Defense:** Radiation-hardened circuits for aerospace and defense applications.

11. Limitations:

- **Accuracy:**
 - Factors: Process variations, mismatch, resistor tolerances, and temperature effects.
- **Power Consumption:**
 - Trade-offs: Higher accuracy often requires higher power consumption.
- **Temperature Range:**
 - Performance: Bandgap references have a limited temperature range over which they maintain high accuracy.
- **Start-up Circuit:**
 - Necessity: Bandgap reference circuits often require a start-up circuit to ensure they operate correctly.

12. Conclusion:

This report presented the design, analysis, and implementation of a bandgap reference circuit. The simulation results demonstrate the circuit's ability to provide a stable voltage reference over a wide temperature range. The cost analysis provides a rough estimate of the component and fabrication costs. The state-of-the-art discussion highlights the ongoing research and development in bandgap reference design. The applications and limitations discussed provide a comprehensive overview of the circuit's potential and challenges.

13. References:

- <https://circuitcellar.com/resources/quickbits/bandgap-voltage-reference>
- <https://www.analog.com/en/resources/design-notes/2022/07/16/11/10/bandgap-reference-calculator-tutorial.html>
- https://en.wikipedia.org/wiki/Bandgap_voltage_reference
- <https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1087&context=eleguht>
- https://en.wikipedia.org/wiki/Brokaw_bandgap_reference
- https://youtu.be/aM6-7KfKJo0?si=sg6Rc8H_8Z46BySD
- <https://youtu.be/zzmgG6WugUo?si=7HlB24TDclclgH8f>