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Conducting Research on and Designing an Opamp-based Bandgap Reference Circuit

Pankaj Goel[1], Sagar Bansal[2], P. R. Narayana[3]

Student[1, 2], Assistant Professor[2]

Department of EEE

HVPM College of Engineering and Technology

Corresponding Author's Email id: *- goelpankaj24@gmail.com[1]*

Abstract

The current study is about a first order bandgap reference circuit (BGR) that makes use of a single stage differential amplifier and a BJT. An external start-up circuit (based on current mirror) is utilised to accelerate transistor switching and avoid non-stable BGR states. The opamp has been developed to provide optimal gain for the BGR. BGR temperature independence was accomplished by superimposing the effects of CTAT and PTAT. Constant voltage generation with temperature change (-40^{o}C to 125^{o}C) has been confirmed using an open source simulation tool (NGSPICE). According to simulation results, the temperature coefficient and starting time of the design were 78.8 ppm/^{o}C and 12s, respectively.

Keywords*: - PTAT, Bandgap, PTAT, CTAT, opamp.*

INTRODUCTION

Any integrated circuit (IC) requires a constant reference voltage, which may be provided by a simple circuit known as a bandgap reference (BGR), which gives a voltage that is independent of external influences such as temperature and supply voltage [4]. The bandgap refence voltage is calculated by combining two complimentary slopes (V/T) that fluctuate linearly with temperature. The slope that varies proportionally to temperature is known as PTAT (Proportional To Absolute Temperature voltage), whereas the slope that varies inversely proportionally to temperature is known as CTAT (Complementary To Absolute Temperature voltage). Combining these

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two circuits results in constant voltage [1] [4] [5].

There is a necessity of temperature independent voltage reference circuit in large ICs or even in System on Chip (SoC) and hence leads to numerous applications for BGR. These are mainly used in analog domain applications such as Low drop out (LDO) voltage regulators, domain conversion blocks such as ADC (Analog to Digital Converter), Voltage controlled Oscillators (VCO) etc. [5] [6]

CTAT AND PTAT

A. CTAT

The voltage VBE in a diode connected bipolar PNP as in fig. 1 act as CTAT circuit. The voltage VBE varies with temperature according to the equation 1 [2].

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} + (4+m)V_T - E_g/q}{T} \quad (1)$$

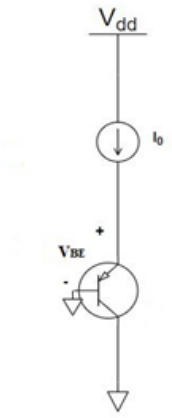


Fig. 1. Simple CTAT circuit with BJT

The equation 1 gives the temperature coefficient of V_{BE} at a given temperature. When calculated at T=300^{0}C and V_{BE}=750mV, we get [2].

$$\frac{\partial V_{BE}}{\partial T} \approx -1.5mV/K$$

PTAT

If the voltages V_1 and V_2 in the fig. 2 are made equal, then the voltage drop across the resistor R is given by [2]

$$V_R = V_T lnK$$

Where V_T is the thermal voltage given by KT/q. Thus making the voltage developed across the resistor as PTAT voltage. The resistor can be made using CMOS compatible process such as nwell resistors or poly resistors. [7]

Bandgap Reference

Ideally the summation of linear coefficients PTAT and CTAT gives a temperature independent reference voltage V_{REF}. This can be expressed by mathematical equation given in eq.2.

$$V_{REF} = \alpha V_{BE} + \beta V_T l(K) \quad (2)$$

where V_T is thermal equivalent voltage which is 26mV at 27^{0}C and α, β are proportionality coefficients. On calculating V_{REF} with conventional values, the obtained result is around 1.2V which is bandgap voltage of silicon at 0K [1].

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Hence the circuit is named as bandgap reference.

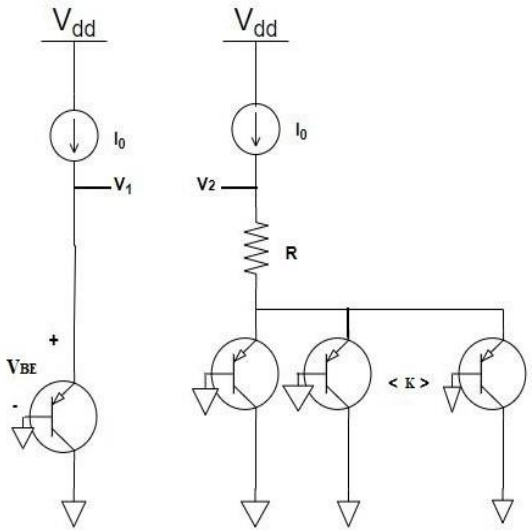


Fig. 2. Simple PTAT circuit with BJT

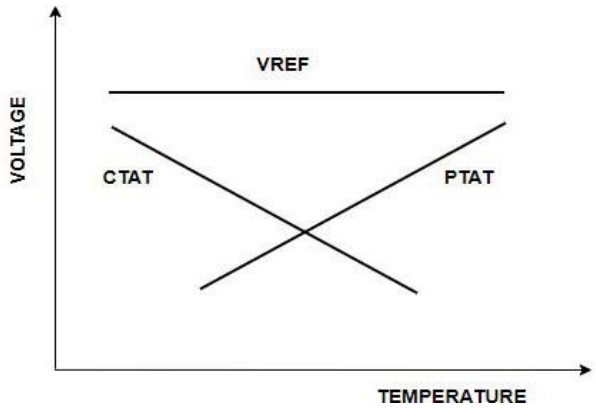


Fig. 3. Concept of BGR

In practice, the graph of reference voltage with respect to temperature have some curvature as shown in fig. 4 due to higher order residues that are not cancelled in linear addition.[2]

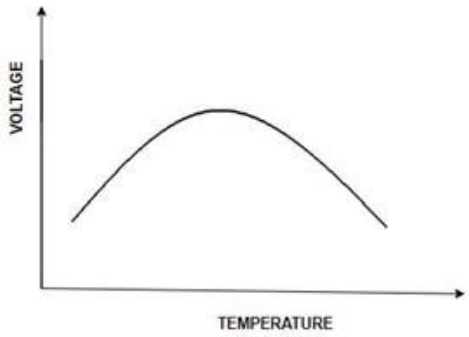


Figure 4 Curvature of Reference voltage

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CIRCUIT DIAGRAM

A. Bandgap Core

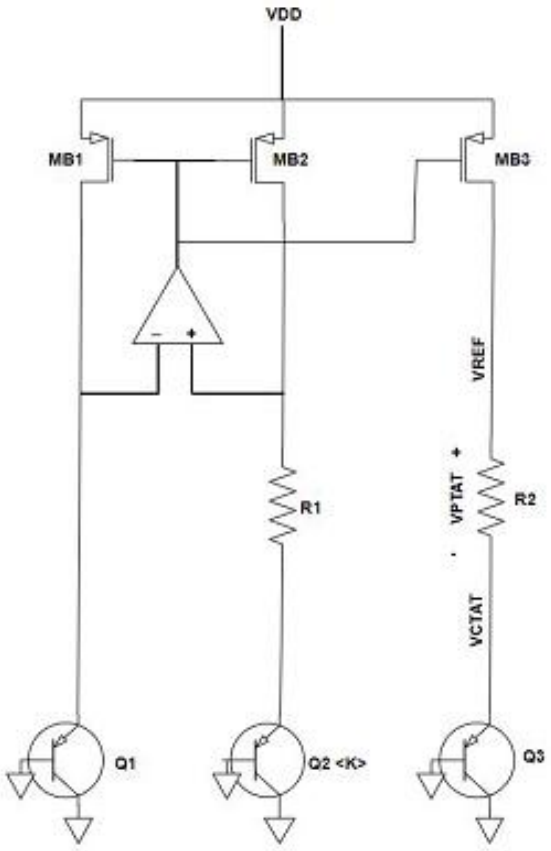


Fig. 5. Opamp based Bandgap

Reference

The voltage across resistor R1 in fig. 5 is $V_T ln(K)$ and hence the current flowing through it is given in eq. 3

$$I_{R1} = \frac{V_T ln(K)}{R1} \qquad (3)$$

A copy circuit is designed which consists of MB3, R2 and Q3. Since same current is flowing in this branch, the voltage drop across resistor R2 is PTAT voltage given in eq. 4 [6]

$$V_{PTAT} = \frac{R2 V_T ln(K)}{R1} \qquad (4)$$

The voltage across diode Q3 acts as CTAT and therefore summation of PTAT and CTAT voltages gives bandgap reference voltage VREF and can be written as eq.5

$$V_{REF} = \frac{R2}{R1} V_T ln(K) + V_{BE} \qquad (5)$$

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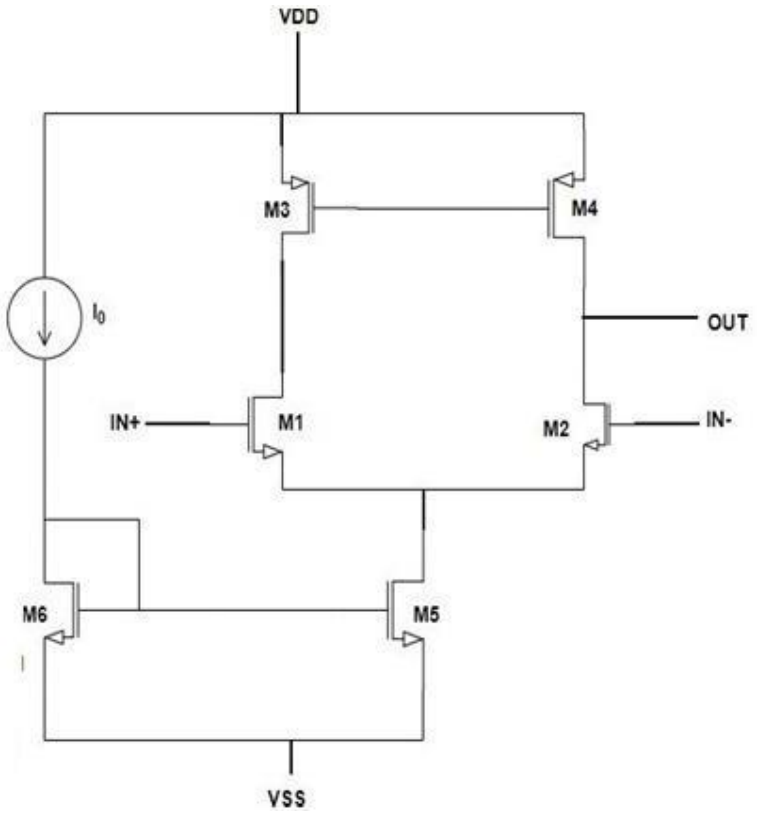


Fig. 6. Internal Structure of Opamp

Opamp Design

A single stage opamp is designed with a bias current I_0.

The configuration is based on simple differential amplifier for which the tail is biased using a current mirror configuration formed by M5-M6 as shown in fig. 6. The aspect ratios of each transistor are designed in such a way that it gives sufficient gain to get efficient performance of BGR. Here opamp is used in BGR for equating terminal voltages V1 and V2 given in fig. 7 which plays a major role in BGR design.

Startup Circuit

When supply voltage is changed from 0 to VDD, it takes some time for circuit to switch on completely due to internal parasitic capacitance. Also non ideal behaviour of voltage supply might result in non-stable state of bandgap reference. In order to overcome this problem and to turn transistors into ON state, a start-up circuit is needed. The MS2 transistor makes sure the current mirror of the BGR core switches ON. Once the current starts flowing through the current mirror, MS3 turns off MS2 by providing sufficiently high voltage across its gate terminal [4].

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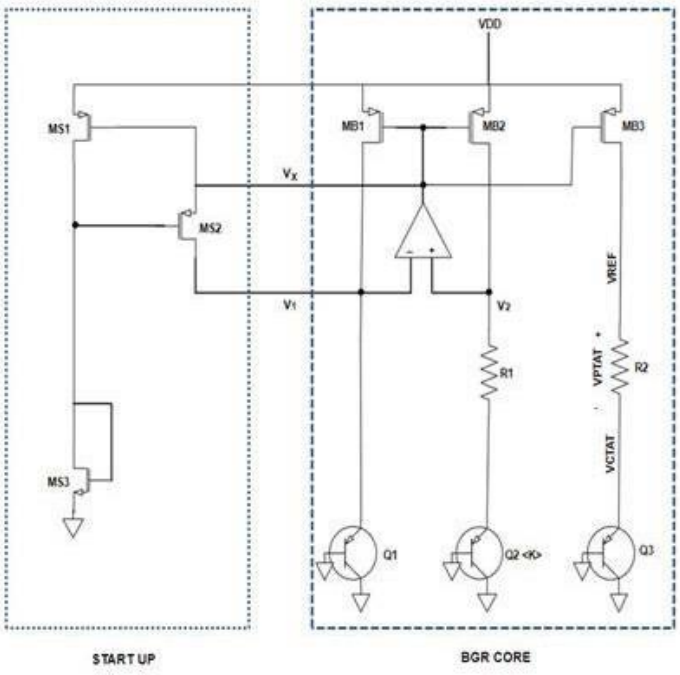


Fig. 7. BGR design with startup circuit

RESULTS AND DISCUSSION

The designed bandgap reference has a constant voltage around 1.3V. Fig. 8 is the temperature analysis of reference voltage resulting in a bell shaped curve when temperature is varied from -40^{0}C to 125^{0}C and fig. 9 gives the PTAT and CTAT variations with respect to temperature.

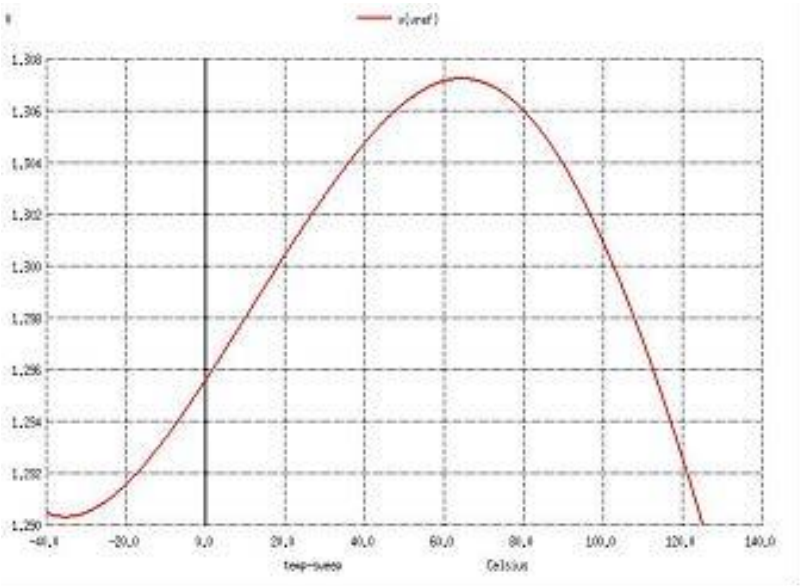


Fig. 8. Temperature Sweep Analysis of V_{REF}

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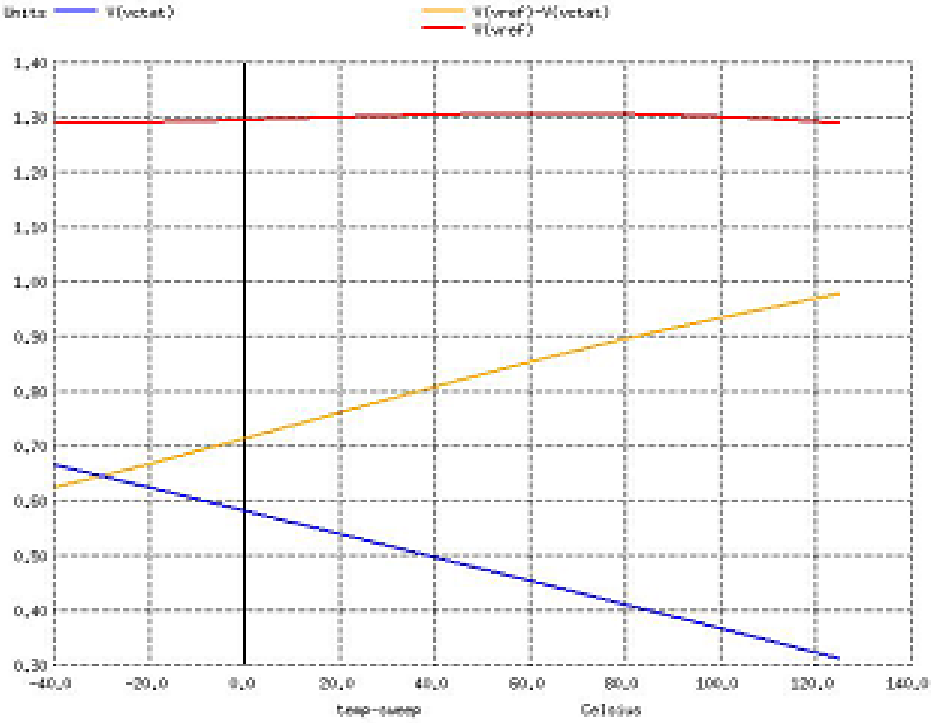


Fig. 9. CTAT, PTAT and VREF variation with respect to temperature

The startup time variation of VREF can be seen in fig. 10.

The calculated value for startup time is around 12µs.

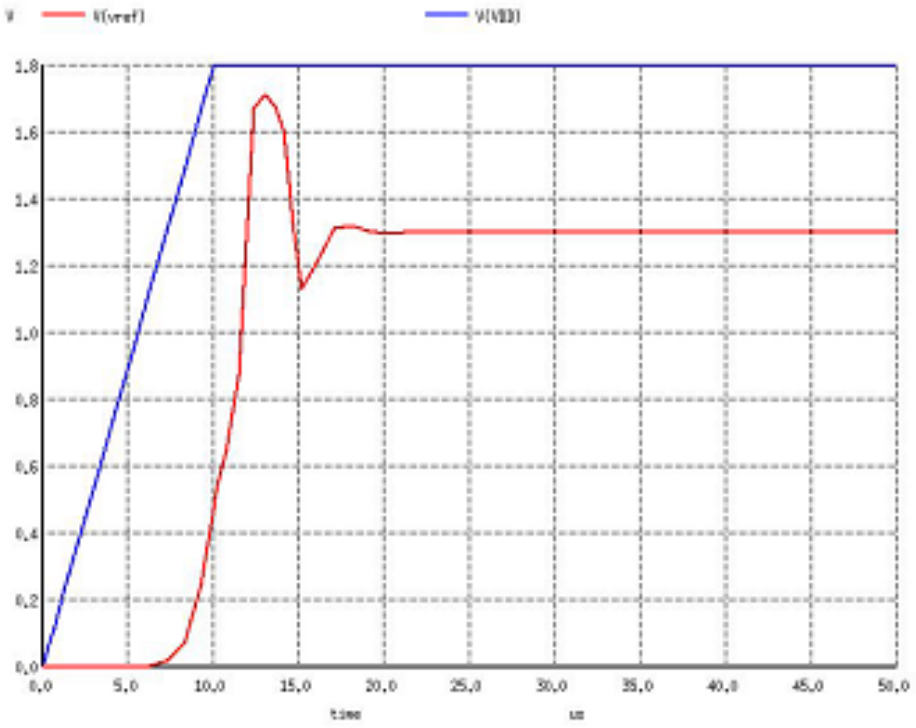


Fig. 10. Startup Voltage Variation

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The brief details are explained in a tabular form in Table I.

Table I Performance Parameters of Designed BGR

Performance parameter of temperature	Simulated values
Temperature range (^{0}C)	-40 to 125
ΔT	180^{0}C
V_{REF} Max	1.307V
V_{REF} Min	1.290V
Start up Time	12µs
Temperature coefficient (TC)	78.8ppm/^{0}C

CONCLUSION

A bandgap reference circuit based on opamps is developed and discussed. The BGR simulations are detailed, and the reference voltage achieved in the temperature range of -4000C to 1250C is roughly 1.3V. The startup time obtained is 12s. This BGR circuit may be used as a design guideline for numerous systems such as LDO, ADC, and VCO.

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