Study and Design of Opamp based Bandgap Reference Circuit

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Abstract

The present paper concerns about a first order bandgap reference circuit (BGR) employing a single-stage differential amplifier and BJT. An external start-up circuit (based on the current mirror) is used to expedite the transistor switching faster and to avoid the non-stable state of BGR. The opamp has been designed to offer optimum gain suitable for the BGR. Temperature independence of BGR was achieved by superposition of the effect of CTAT and PTAT. Generation of constant voltage with temperature variation (-40oC to 125oC) has been confirmed through an open-source simulation tool (NGSPICE). The simulation study reveals that the temperature coefficient and the start-up time of the design were 78.8 ppm/oC and 12µs, respectively.

Keywords— *Bandgap, PTAT, CTAT, opamp.*

INTRODUCTION

Any IC requires a constant reference voltage that can be achieved by a simple circuit, namely bandgap reference (BGR), which provides a voltage-independent of external factors such as temperature and supply voltage [4]. The bandgap reference voltage can be obtained by the addition of two complementary slopes (V/T) that vary linearly with temperature. The slope that varies in proportion to temperature is PTAT (Proportional To Absolute Temperature voltage), and the slope that varies inversely proportional to temperature is CTAT (Complementary To Absolute Temperature voltage). Superposing these two circuits leads to constant voltage [1] [4] [5].

There is a necessity for temperature-independent voltage reference circuits 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 is a diode-connected bipolar PNP as in fig. 1 act as a CTAT circuit. The voltage VBE varies with temperature according to equation 1 [2].

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

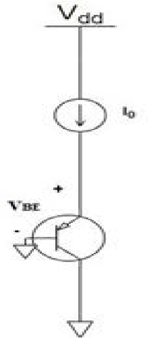

Fig. 1: Simple CTAT circuit with BJT

Equation 1 gives the temperature coefficient of V_{BE} at a given temperature. When calculated at $T=300^0C$ 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 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 processes such as well 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 the mathematical equation given in eq. 2.

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

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

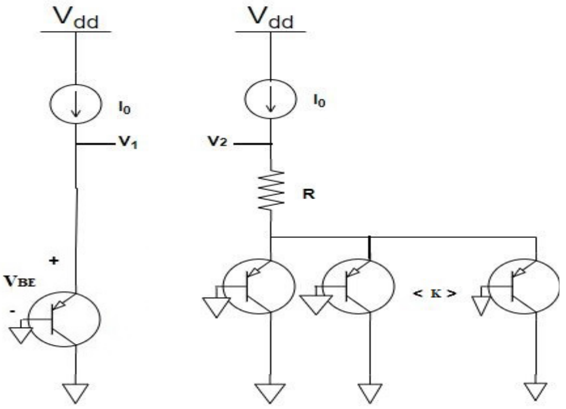

Fig. 2: Simple PTAT circuit with BJT

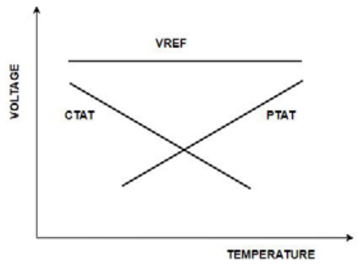

Fig. 3: Concept of BGR

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]

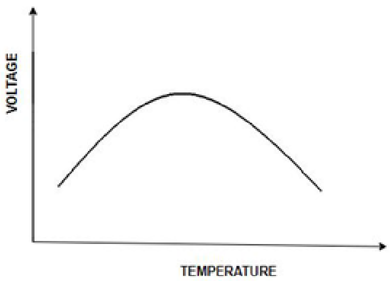

Fig. 4: Curvature of Reference voltage

CIRCUIT DIAGRAM

A. Bandgap Core

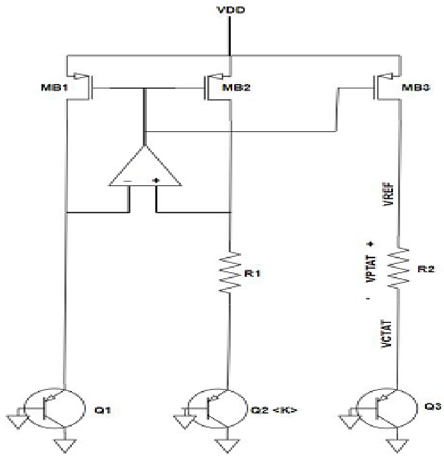

Fig. 5: Opamp based Bandgap Reference

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

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

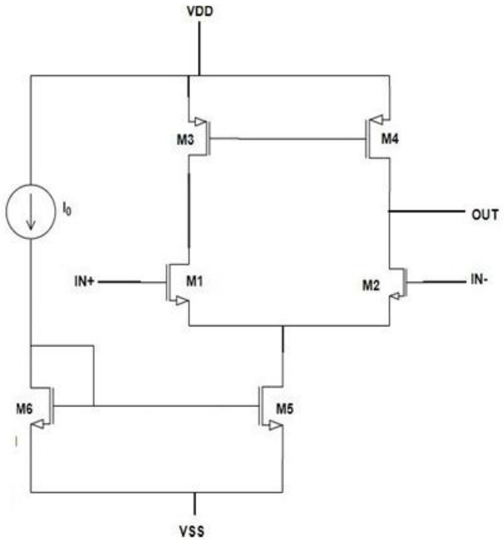

Fig. 6: Internal Structure of Opamp

Opamp Design

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

The configuration is based on a 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 the 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.

Start up Circuit

When the supply voltage is changed from 0 to VDD, it takes some time for the circuit to switch on completely due to internal parasitic capacitance. Also, the non-ideal behaviour of voltage supply might result in a non-stable state of bandgap reference. In order to overcome this problem and to turn transistors into an 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 a sufficiently high voltage across its gate terminal [4].

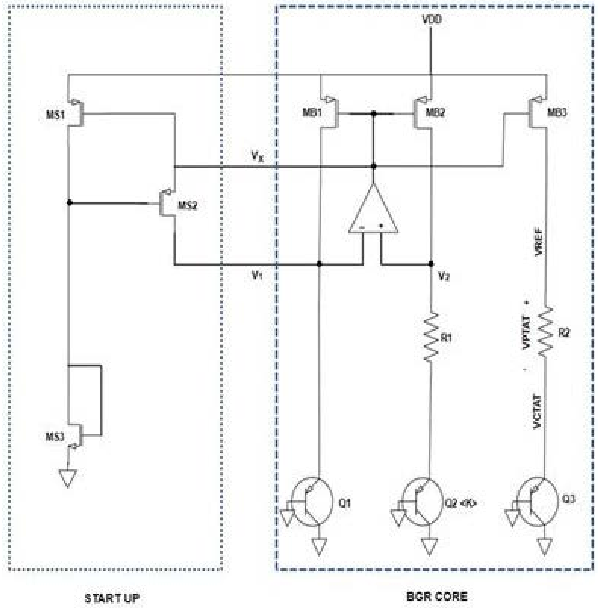

Fig. 7: BGR design with startup circuit

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.

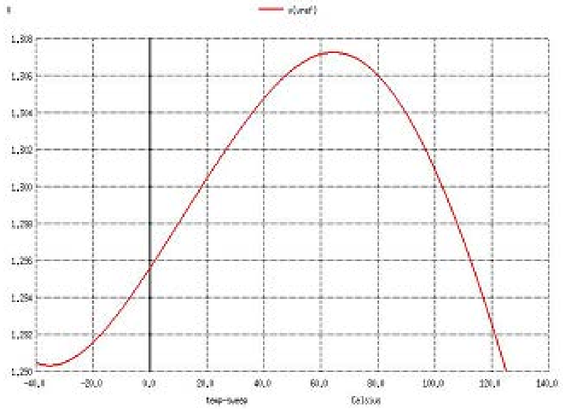

Fig. 8: Temperature Sweep Analysis of VREF

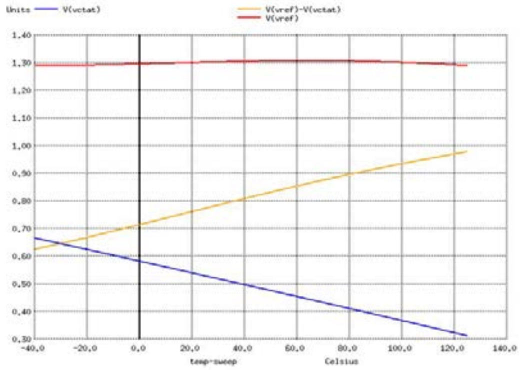

Fig. 9: CTAT, PTAT and VREF variation with respect to temperature

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

The calculated value for startup time is around 12μs.

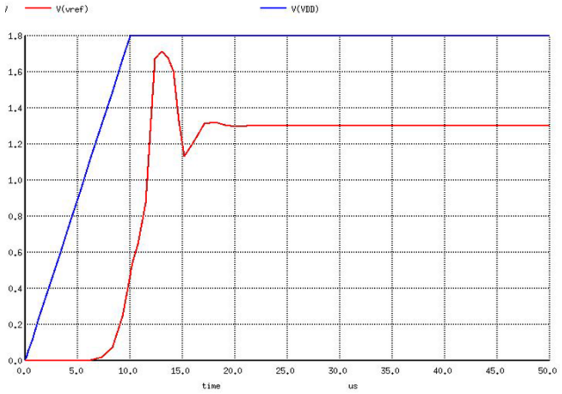

Fig. 10: Startup Voltage Variation

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

An opamp based bandgap reference circuit is designed and explained. The simulations of BGR are shown in detail, and the reference voltage obtained is around 1.3V in the temperature range of -4000C to 1250C. The startup time achieved is 12µs. This BGR circuit can be a useful guideline to the designer for designing various systems such as LDO, ADC, and VCO.

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REFERENCES

1. Paul R. Gray, Paul J. Hurst, Stephen H. Lewis, Robert G. Meyer, ”Analysis and Design of Analog Integrated Circuits Fifth ed”, Wiley, pp. 313-320.
2. Behzad Razavi, ”Design of Analog CMOS Integrated Circuits”, McGraw Hill Education, [2,pp. 382 Eq 11.13], [2,pp. 383], [2,pp. 390], [2,pp. 382], [2,pp. 383-384].
3. Paul Horowitz and Winfield Hill (1989). The Art of Electronics. Cambridge University Press. pp. 343–349. ISBN 978-0-521-37095-0.
4. S. Sarangi, D. Tripathy, S. S. Mohapatraand S. Rout, “A Power and Area Efficient CMOS Bandgap Reference Circuit with an Integrated Voltage-Reference Branch”, 08-Aug-2019.
5. Design of A CMOS Bandgap Voltage Reference Circuit with High PSRR and Low Temperature Coefficient using 180nm Technology”, International Journal of Emerging Technologies and Innovative Research (www.jetir.org — UGC and issn Approved), ISSN:2349-5162, Vol.5, Issue 11, page no. pp261-272, November-2018.
6. R. Akshaya and S. Y. Siva, ”Design of an improved bandgap reference in 180nm CMOS process technology,” 2017 2nd IEEE International Conference on Recent Trends in Electronics, Information Communication Technology (RTEICT), Bangalore, 2017, pp. 521-524, doi:10.1109/RTEICT.2017.8256651.
7. Tiancheng, Zhu Suying, Yao Binqiao, Li. (2009). A high precision programmable bandgap voltage reference design for high resolution ADC. Journal of Semiconductors. 30. 075005. 10.1088/1674-4926/30/7/07