A REVIEW ON BANDGAP VOLTAGE REFERENCE

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Abstract: The most common topology of CMOS Bandgap Voltage Reference (BGR) is the one with operational amplifier (op-amp), current source, two parasitic bipolar transistors and three resistors. This BGR offers simplicity, good performance and high-accuracy. Since the performance of BGR highly depends on the op-amp performance, the design of op-amp requires attention and its architecture must be carefully chosen. Thus, a comparative analysis is necessary to realize. This work evaluates the performance parameters achieved by different architectures of operational amplifiers that can be used to design BGR.

IndexTerms - **BGR, Voltage Reference, CTAT and PTAT currents.**

I. INTRODUCTION

A. Bandgap Voltage Reference

Bandgap Voltage Reference circuit produces a fixed constant voltage regardless of power supply variations, temperature changes and circuit loading from a device.

Voltage reference is an essential building block for a variety of analog and mixed signal electronic devices such as data converters viz. Analog to Digital Converters (ADCs) and Digital to Analog Converters (DACs), Pulse Width Modulator (PWMs), oscillators, controllers, linear regulators, Phase Locked Loops (PLLs), etc.

The working principle of a BGR can be illustrated by fig. 1.

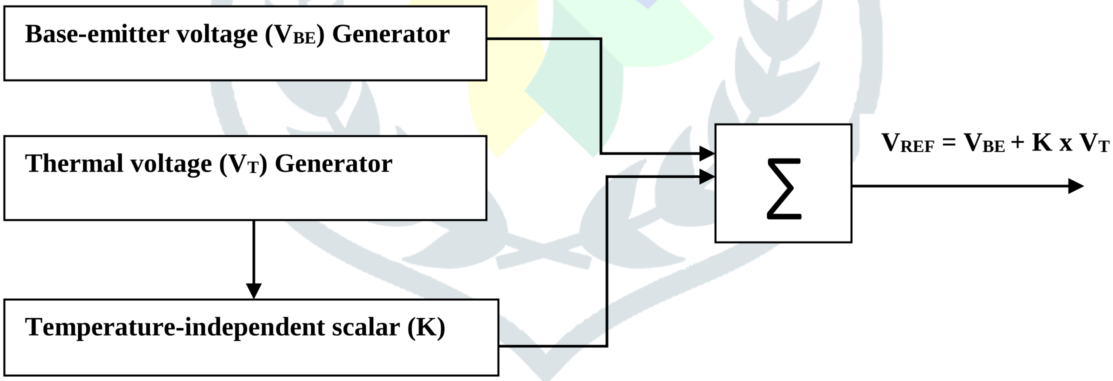


Fig 1. Bandgap Voltage Reference

The base-emitter voltage (V_{BE}) of BJT decreases approximately linear with temperature and the thermal voltage V_T increases linearly with temperature. Therefore, a reference voltage V_{REF} having low temperature dependence can be obtained by scaling up V_T and adding it with V_{BE} [6].

Conventional Bandgap Reference Circuit:

Various approaches have already been developed till now to implement voltage reference with low or even ultra low power consumption. One of the most popular voltage references in CMOS technology used for low voltage applications is shown in fig. 2.

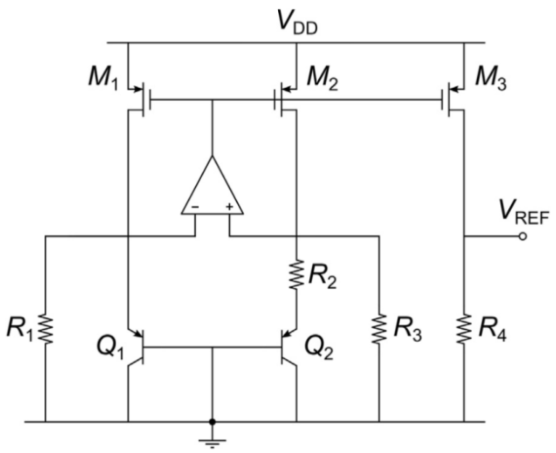


Fig. 2. Conventional Low-Voltage Bandgap Reference

The conventional BGR makes use of a linear combination of current which is proportional-to-absolute temperature (PTAT) and current which is complementary-to-absolute temperature (CTAT) in order to generate a reference voltage across resistor R_4. The circuit in fig. 1 uses parasitic bipolar PNP transistors that have a poor performance in respect of current gain β_F, and mainly endures the offset voltage due to op-amp which substantially effects accuracy [7].

In the work [7], the proposed BGR circuit uses PTAT and CTAT self-biased current generators, derived from CMOS transistors M_1 and M_2 which are operating in subthreshold region, and resistances R_{PTAT} and R_{CTAT} , respectively. The PTAT and CTAT currents are fed into resistance R_{out} and results out in the generation of reference voltage, V_{REF}.

The main objective of this proposed design is to achieve low voltage capability, low line sensitivity, and low small-signal Power Supply Response (PSR), providing operation in a wide range of supply voltages.

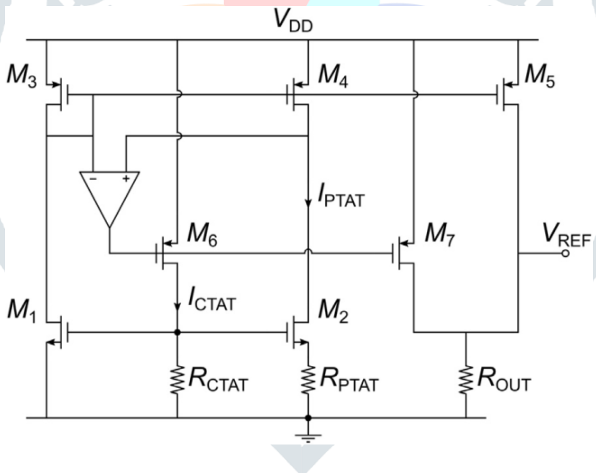


Fig. 3. Schematic of the Threshold Voltage Reference proposed in work [7].

In this circuit, subthreshold-biased MOS transistors and a transconductance operational amplifier are used. The use of CMOS transistors in weak inversion instead of bipolar transistors, used in conventional BGR, has various advantages such as low gate-source voltage which reduces the minimum bias voltage. Apart from this, the use of subthreshold-biased MOS transistors in CTAT current generator provides a negative temperature coefficient just similar to the bipolar transistors. Nevertheless, CMOS transistors prevent inaccuracy due to the contribution of base currents, which is not prevented in the other case since bipolar transistors of standard CMOS technologies abide low β_F.

$$I_{PTAT} = \frac{V_{PTAT}}{R_{PTAT}} = \frac{V_{GS1} - V_{GS2}}{R_{PTAT}} = \frac{mV_T lnN}{R_{PTAT}}$$

Where m and N are subthreshold slope parameters and the ratio of the form factor of M_2 to the form factor of M_1, respectively, and V_T is the thermal voltage.

$$I_{CTAT} = \frac{V_{GS1}}{R_{CTAT}} = \frac{V_{th,0} + k_{t1}\left(\frac{T}{T_0} - 1\right) + mV_T ln \frac{I_D}{\mu_n C_{ox} {V_T}^2 (\frac{W}{L})}}{R_{CTAT}}$$

Where $V_{th,0}$ is threshold voltage at the nominal temperature T_0, k_{t1} is a temperature parameter of threshold voltage, I_D is the drain current of M_1.

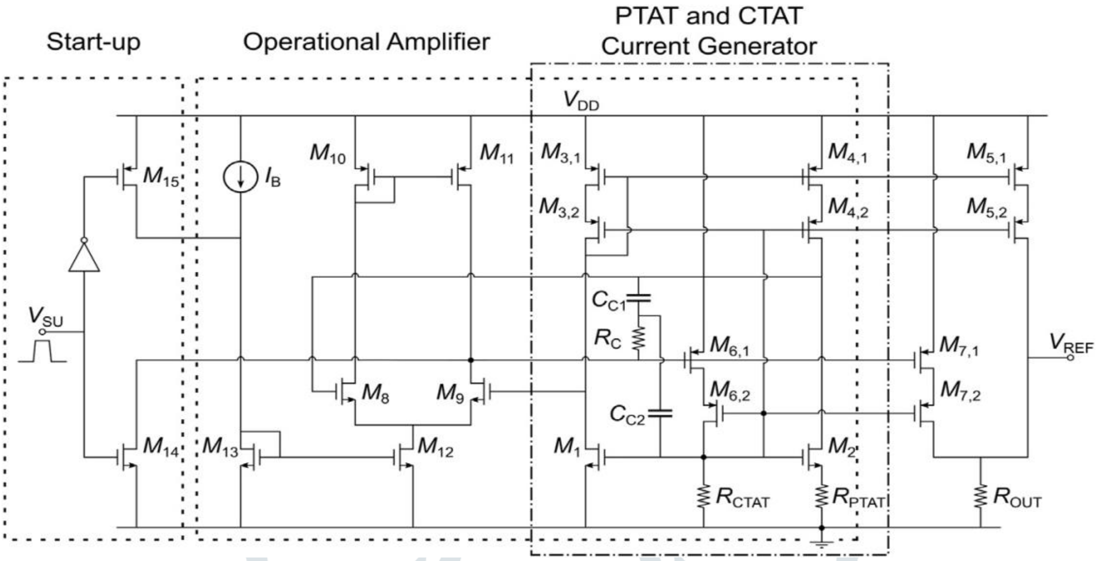


Fig. 4. Schematic of the Threshold Voltage Reference proposed in the work[7]

I_{PTAT} and I_{CTAT} currents are mirrored into R_{OUT} with the use of current mirrors M_{3-5} and M_{6-7} ,respectively and results out in the generation of reference voltage V_{REF} given by

$$V_{REF} = R_{OUT}(I_{PTAT} + I_{CTAT}) = \alpha V_T + \beta V_{GS1}$$

Where,

$\alpha = \frac{mR_{OUT}lnN}{R_{PTAT}}$ and $\beta = \frac{R_{OUT}}{R_{CTAT}}$

In fig.4, the differential stage includes MOS transistors M_{8-13}. They drive the gain stage which is implemented by the cascode stage, $M_{6,1}$, $M_{6,2}$, loaded by R_{CTAT}. The transistors $M_{3-4,2}$ and resistance R_{PTAT} make up a self-biased PTAT current generator. Here, operational transconductance amplifier (OTA) is used.

B. Operational Amplifier

Operational amplifier plays a very critical role in the performance of BGR, in respect of DC errors and output noise voltage. Since, various types of op-amps are available, the op-amp module in fig.4 can be replaced by any one of the following mentioned op-amp architecture, depending on the specifications to be achieved.

1. **Telescopic OTA:**
   The single stage OTA has lower gain because of its output impedance. The impedance can be increased by adding some transistors at the output side using an active load such as parasitic capacitances. When the transistors are cascaded, the output impedance is increased and hence, gain is increased.
   The Telescopic operational amplifier is shown in fig. 5 and all the transistors should operate in saturation region. Transistors M_1- M_2, M_7-M_8, and tail current source M_9 must have at least V_{dsat} to provide good common-mode rejection, better frequency response and gain.
   When large supply voltage is applied, telescopic architecture is the better choice for the systems demanding moderate gain for the op-amp. Nonetheless, when the supply voltage is reduced, folded cascode design is preferable.
   While a telescopic op-amp without the tail current source fig. 5(b) improves the differential swing by $2V_{dsat}$+$2V_{margin}$. The common-mode rejection and power-supply rejection of this circuit is greatly compromised. Moreover, the

performance parameters (such as unity gain frequency) of the op-amp with no tail or with a tail transistors in the linear region is sensitive to input common-mode and supply voltage variation which is undesired in most analog cases [8].

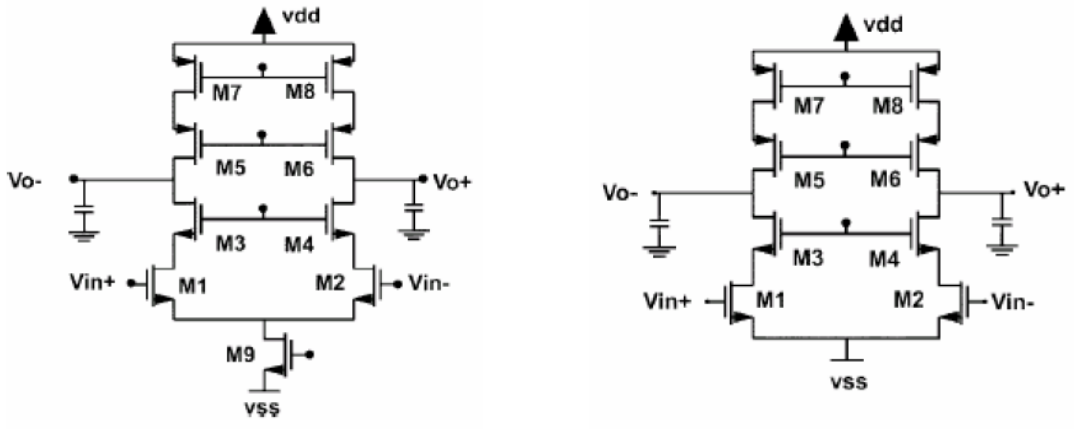


Fig.5 (a) Telescopic Amplifier (b) No-Tail Telescopic Amplifier

2. Balanced OTA:

It is also called symmetric or three current-mirror OTA because of the use of self-biased loads. In symmetric OTA, two input transistors have the same load (a diode-connected transistor), so the difference of V_{DS} between input transistors is the smallest among all differential OTAs. Thus, this OTA has the least offset. It has larger slew rate, CMRR, power dissipation level and unity gain bandwidth (GBW) because of increase in current mirror factor.

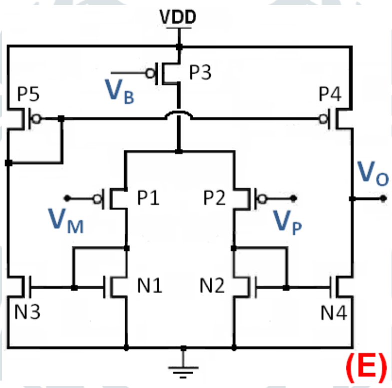


Fig. 6. Symmetrical OTA

Table:1- Comparison between Telescopic OTA and Balanced OTA [3].

Parameters	Simulation results- Telescopic OTA	Simulation results- Balanced OTA
Gain	75dB	65dB
Phase Margin	55 degree	63.04 degree
Unity Gain BW	60MHz	55.11MHz

3. Two Stage Op-Amp:

The use of two-stage op-amp would be suitable to guarantee accuracy and low voltage capability. The differential stage comprising of M_1,M_2,M_3 and M_4 form the first stage of op-amp. The transistors M_1 and M_2 are standard NMOS which form the basic input stage of the differential amplifier. The resistance of the active load transistors and the output resistance of the active load transistors (M_3 and M_4) contribute to the output resistance. The gain of two stage op-amp is the product of transconductance of M_2 and the total output resistance at drain of M_2.

The second gain stage comprises of M_5 and M_6, to provide additional gain to the amplifier. Just like differential gain stage, this stage utilizes an active device M_6, to serve as the resistance of M_5. The gain of this stage is the product of transconductance of M_5 and the effective load resistance which comprises of the output resistance of M_5 and M_6[1].

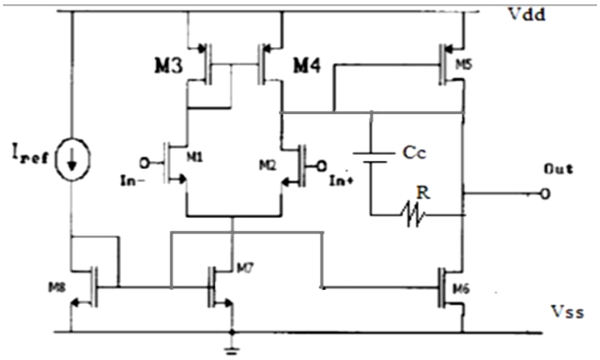


Fig. 7.Circuit Diagram of Two-Stage Op-Amp

Advantages:

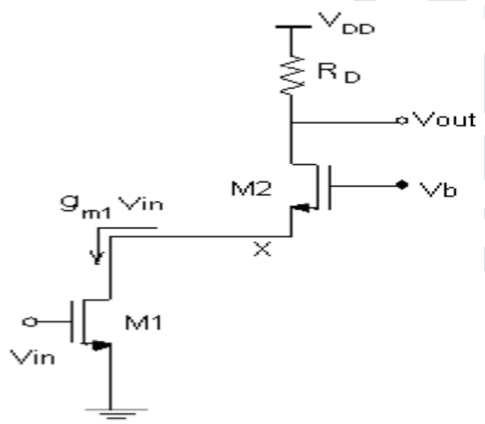
- It has high output swing.

Disadvantages:

- It has compromised frequency response.
- High power consumption due to two stages in the design.
- It has poor negative supply PSRR at higher frequency [8].

4. Folded Cascode Op-Amp:

The two stage op-amp is basically used in the designs where high gain and high output impedance are required. But, the performance can be made better if folded cascade op-amp is used.



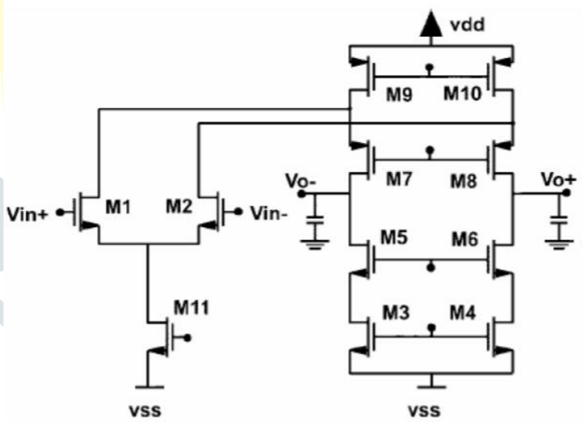


Fig.8(a). Schematic of Cascode Stage

Fig.8(b). Folded Cascode Amplifier

In fig.8(a), transistor M1 produces small signal drain current proportional to V_{in} and transistor M2 enroutes this current to resistance R_D.

The folded cascode op-amp employs cascading at the output stage combined with differential amplifier which results in improved ICMR. The folded cascode op-amp is more widely used than the telescopic op-amp. Apart from this, the folded cascode op-amp allows the input common-mode level nearer to the supply voltage. Also, it is more suitable for negative feedback. The overall power consumption is nearly same as that of two stage structure [8].

Advantages:

- The structure provides much better frequency response than two stage op-amp.
- It provides decent PSRR at high frequency.

II. COMPARISON

Table 2. Comparison between different Operational Amplifiers [3]

Topology	Gain	Output-Swing	Speed	Power
Two Stage	High	High	Low	Medium
Telescopic Cascode	Medium	Medium	High	Low
Gain Boosted	High	Medium	Medium	High
Folded Cascode	Medium	Medium	High	Medium

III. CONCLUSION

The design methodologies of bandgap voltage reference circuit have been discussed. The focus of this review paper is mainly on the op-amp module of the BGR circuit which plays a crucial role in the performance of the circuit. Since, different types of op-amps are available, so the operational transconductance amplifier used in conventional BGR design can be replaced with any of the other op-amps viz. two-stage op-amp, telescopic op-amp, balanced op-amp, folded cascade op-amp in accordance to the design specifications.

From the analysis given in this paper, it is possible to verify the suitable op-amp architecture which is adequate for the bandgap specification to be designed. For example, BGR using OTA is less susceptible to the fabrication process effects.

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