Group 1 Low Voltage Bandgap Reference

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***Abstract*—A bandgap voltage reference is a circuit meant to provide a stable and accurate voltage reference regardless of variations in external factors like temperature and voltage supply variations. The bandgap voltage reference is essential in providing a precise voltage reference for many electronic applications. This paper provides insight about the different components, analysis, and results of our bandgap voltage reference.**

I. INTRODUCTION

Voltage references are a necessary component of many electronics. Thus, much research has been put into finding the best way to create a precise reference voltage, resulting in the bandgap voltage reference. Its ability to combat external factors such as temperature and voltage supply variations make it one of the most commonly used reference voltage generators. A bandgap reference is created utilizing the temperature dependence in semiconductor components [2]. Temperature independence is achieved by using two currents that are inversely dependent on temperature. Therefore, the increase of one current will cancel out the decrease of the other current.

We chose to follow Behzad Razavi's approach to the design of the low voltage bandgap as most of the course resources reference his work. We will explain his approach and our add ons in more detail in the following section.

II. CIRCUIT DESCRIPTION

As stated above, we chose to follow Behzad Razavi's approach. Our bandgap reference contains the following components: core, op amp, current reference, start-up circuit, and low-pass filter. It operates with a supply voltage of 1.2 V and supply current of 79 µA.

The core of the circuit, in Figure 1, is similar to the ones found on most of the papers on the topic. It is a complementary to absolute temperature (CTAT) voltage generator. This means as temperature increases, the current flowing through the PMOS transistors T0 and T1 increases as temperature increases. Then, the resistors R2 and R3 are added to make the currents in T0 and T1 constant currents [1].

However, similar to Razavi, the bandgap core used in Figure 1 did not meet specifications. Thus, we followed Razavi again by adding a second op amp. This second op amp suppresses error due to channel length modulation, adjusting the voltage at the gate of T3 to compensate.

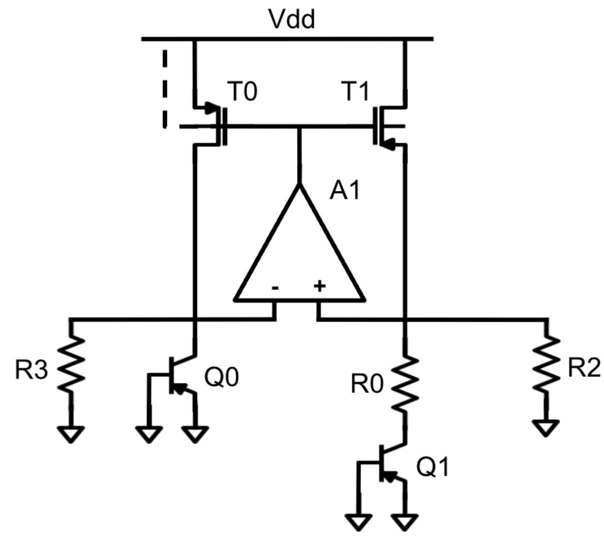

Fig. 1. Bandgap reference core

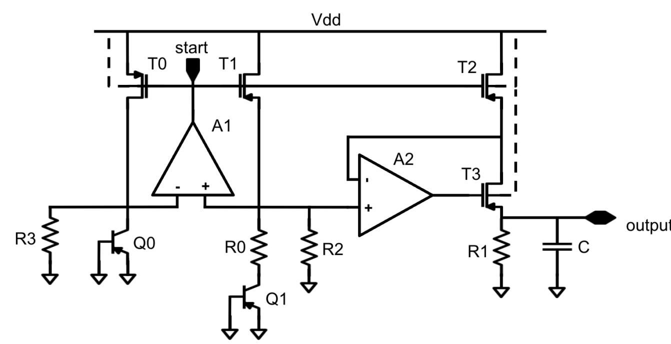

Fig. 2. Complete bandgap reference core

The op amp A1, shown in Figure 3, is a two-stage amplifier with a gain of 390 V/V. The first stage is a differential amplifier with a current source load. The second stage is a common drain amplifier. Both amplifiers have a current mirror on the bottom to supply the reference current, which will be discussed later. We needed a two-stage amplifier because of the needed gain. In addition, we used Miller compensation by adding resistor, R, and capacitor, C, to increase the stability of the amplifier.

[1]Manuscript received December 6, YEAR. This work was supported by the University of Michigan. Authors are in the class EECS 413: Monolith Amplifier Circuits.

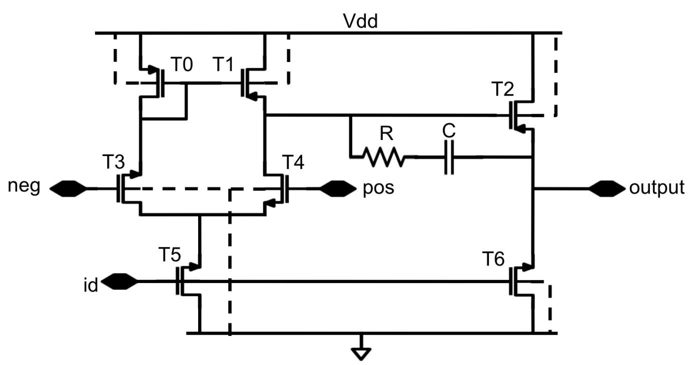

Fig. 3. Inside op amp A1

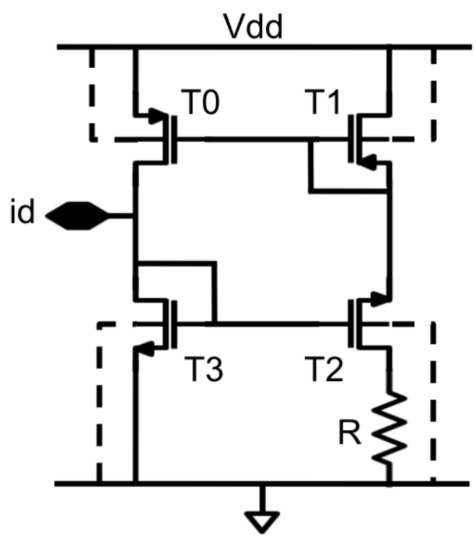

Fig. 4. Current reference circuit

The current reference circuit, shown in Figure 4, is a proportional to absolute temperature (PTAT) current reference. This means the current increases as temperature increases. We choose a PTAT current reference to combat the CTAT core mentioned earlier [3]. This means as temperature increases, the CTAT core current decreases, and the PTAT current reference current increases, resulting in a net zero change in current in an ideal world.

The start-up circuit, shown in Figure 5, consists of a resistor, capacitor, and NMOS transistor. It is based on Razavi's approach to a start-up circuit. The purpose of the start-up circuit is to reliably initiate the bandgap circuit from a powered off to the on state [1].

Finally, we added a low-pass filter to reduce the output noise. The low-pass filter is the capacitor C in Figure 2.

All in all, we followed Razavi's approach for the bandgap reference core and start-up circuit. For the op amps, we took inspiration from CAD 4 to obtain the necessary gain. We also added the Miller compensation capacitor and resistor to ensure stability within our amplifiers. The current reference and low-pass filter were our own doing.

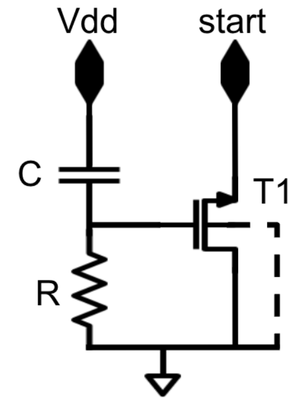

Fig. 5 Start-up circuit

III. CIRCUIT ANALYSIS

Although we used Razavi's approach as a guideline, we had to change much of the smaller details like the component sizes. In general, we had to increase the size of all the components as compared to Razavi's bandgap reference.

In the bandgap reference core, Razavi used a transistor ratio of $\frac{W}{L} = \frac{50\ \mu m}{120\ nm}$ [1]. However, we realized that this was too small for our needs, so we increased our transistor sizes making sure to maintain the same ratio. In Figure 2, T0 and T1 are identical with a length of 240 nm and width of 100 µm, comprised of twenty 5 µm fingers. Bipolar junction transistors Q0 and Q1 have an emitter area of 2.5 µm by 2 µm, but Q1 has a multiplicity of 16x as opposed to Q0's 1x multiplicity. Resistors R0, R2, R3 are 8 kΩ, 52 kΩ, and 52 kΩ respectively, which are 4x the resistance than Razavi's resistors. By increasing the component sizes, we are creating a more robust circuit; however, there are some downsides. Larger transistors result in a higher power consumption, and in the layout, we are forced to use a larger area for the circuit and have increased parasitic capacitance.

For the op amp, shown in Figure 3, a single-stage amplifier is ideal, but, due to the needed gain of 390, we had to use a two-stage amplifier. We decided to stray away from Razavi's approach as we had already made an amplifier that could achieve this gain in the mini project. Thus, transistors T0 and T1 have a length of 600 nm and width of 18 µm, comprised of three 6 µm fingers. T3 and T4 have a length of 300 nm and width of 44 µm, comprised of eleven 4 µm fingers. T2 has a length of 600 nm and width of 20 µm, comprised of four 5 µm fingers. The miller compensation capacitor and resistor are 500 pF and 5 kΩ respectively. To obtain these values, we set R equal to 1/gm2 and used a reasonable capacitance. T5 and T6 are identical and have a length of 500 nm and width of 10 µm, comprised of two 5 µm fingers.

The Razavi approach had a single-stage amplifier for the second op amp A2 in Figure 2, but we were unable to successfully implement the single-stage amplifier. Thus, we made amplifier A2 the same as A1. However, the downside of this is an obvious increase in power consumption. This was something we unfortunately wanted to avoid but had to implement.

The current reference we created on our own with guidance from Professor Flynn. Instead of using a regular current mirror with a resistor, we settled on the PTAT current reference because the current output is inversely related to the bandgap reference core. This results in a smaller variation in output voltage with a change in temperature [3]. Even though there is more power consumption in the PTAT current reference, the opportunity cost of a smaller output voltage variation is worth it. At first, we had a reference current of 50 µA. However, we realized that our power consumption was too large. Thus, we increased the resistance of resistor R in Figure 4 to 10 kΩ and adjusted T3 width to 15 µm to get a final reference current of about 1 µA. Then our supply current is 78.6 µA, which is lower than the requested 100 µA.

All transistors in Figure 4 have the same length of 500 nm and finger width sizes of 5 µm. Transistors T0 and T1 have two fingers each (10 µm width), T3 has 3 (15 µm width), and T2 has 2 (10 µm width). For the resistor R, we choose a value of 10 kΩ.

The start-up circuit operates using a charging capacitor and a resistor to bias an NMOS transistor which generates a voltage at the start node in figure 2, activating the bandgap core. As the capacitor charges, the NMOS will eventually turn off, and the bandgap core will operate as intended. Initially, the capacitor was selected to be 500 pF, however, this meant that the capacitor would be larger than the rest of the circuit. Instead, we opted to use a 2 pF capacitor and combine four 100 kΩ resistors in series. This provides a sufficient time constant for our circuit to manage a ramped supply voltage.

The low-pass filter, which is C in Figure 2, is a capacitor with a value of 1 pF. We decided on a simple low-pass filter because the noise decreased a sufficient amount with just the single capacitor. This feature allowed us to output a signal with peak noise of 10 mV. However, this value is not a sufficient amount to declare the bandgap reference as low-noise.

IV. RESULTS

In the end, we were able to reach all requirements for the bandgap reference with a couple of improvements. Our bandgap reference showcases a low power supply, low-pass filter, and is LVS and DRC clean.

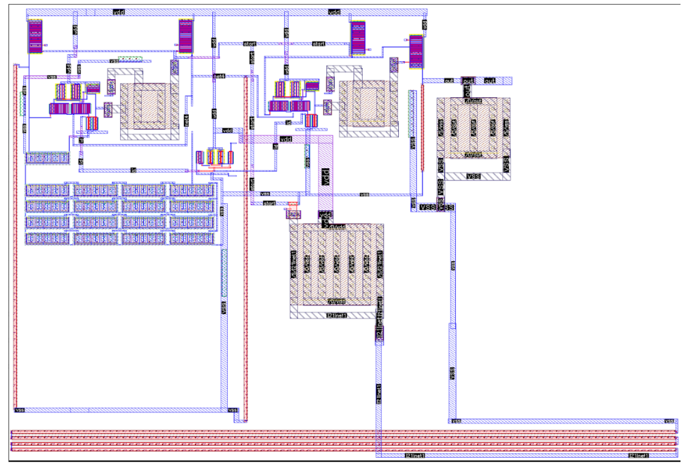

Fig. 6. Bandgap reference layout

Figure 6 shows the layout of the bandgap reference which passed all design checks. After generating and loading in the PEX file, our simulations were minimally affected.

Our bandgap reference varies about 1.1 mV from 0 to 70 ºC. As shown in Figure 7, at 0 ºC, we output about 515.9 mV, and, at 70 ºC, we output about 514.8 mV. At 27 ºC, we output 515.6 mV. This equates to a temperature coefficient of 30.4 ppm/ºC, which is below the requested amount of 50 ppm/ºC. This analysis was done by varying the temperature in DC analysis, and using (1).

$$\frac{Vout(0C)-Vout(70C)}{Vout(27C)} * \frac{1000000}{70} \quad (1)$$

Figure 8 showcases the output voltage of the bandgap reference in regards to a ± 10% variation in input voltage (Vdd). Our output voltage ranged from 515.7 mV at 1.08 V Vdd to 515.5 mV at 1.32 V Vdd, resulting in a 0.2 mV change. This analysis was done by sweeping Vdd from 1.08 to 1.32 V in DC.

The total power consumption of the bandgap reference is 94.3 µW, which is lower than the requested 330 µW. This was calculated by checking the current flowing through the circuit and multiplying it by Vdd.

The transient response in Figure 9 showcases a 1 ms ramp of the Vdd. The bandgap reference is able to settle at the output voltage in 0.7 ms and maintain its value, showing that the bandgap reference is functional and stable.

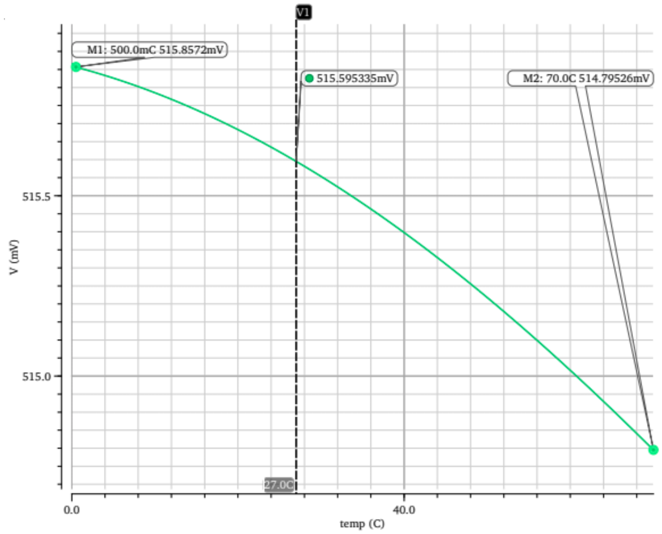

Fig. 7 Output voltage over temperature variation (0-70C)

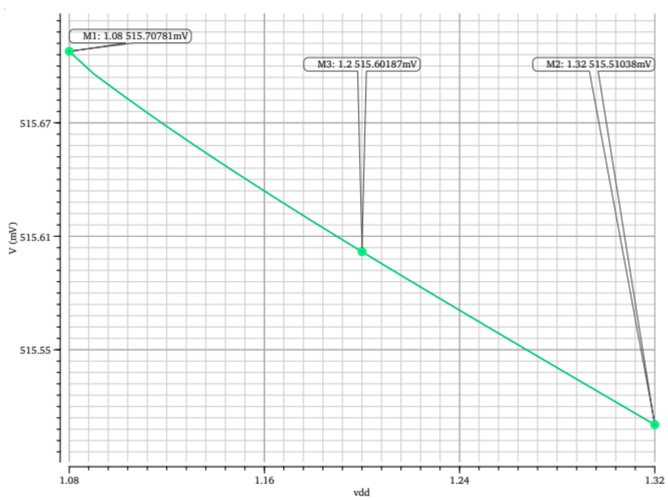

Fig. 8 Output voltage over input voltage variation (± 10%)

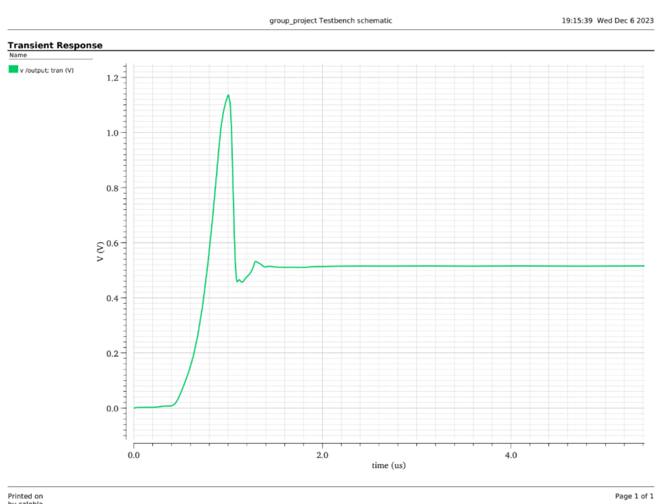

Fig. 9. Transient response of the bandgap reference

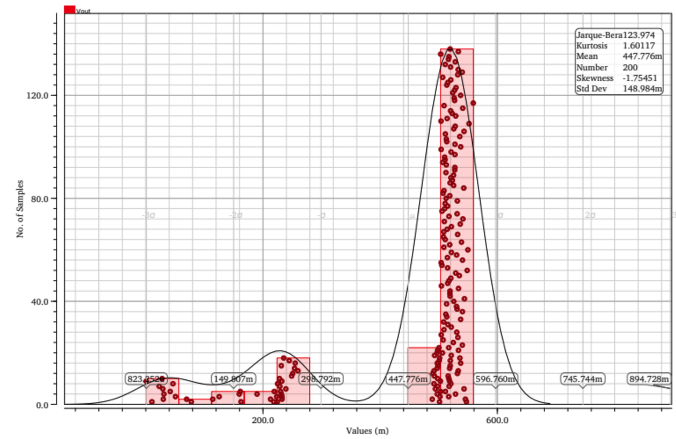

Fig. 10. Monte Carlo simulation with PEX

Figures 10 show the Monte Carlo simulation with PEX. The Monte Carlo with PEX has a yield of about 80%. This is below the requested yield of 95%, showing that we need improvement in our start-up circuit.

TABLE 1

SUMMARY OF BANDGAP REFERENCE RESULTS

Power Consumption (at 27 C)	Temperature Coefficient	Area/Die Area	Supply Current (at 27 C)
94.3 µW	30.4 ppm/ºC	55,000 μm^2	78.6 µA
Supply Voltage Sensitivity	Noise	Start-up Yield	Reference Voltage (at 27 C)
0.20 mV	10 µV	≈ 80%	515.6 mV

V. CONCLUSION

Overall, we fulfilled the basic requirements of the bandgap reference. As a group, we are satisfied with the results. We were able to generate a reference voltage of 515.6 mV with a 30.4 ppm/ºC temperature coefficient. The required supply current was 78.6 µA and our sensitivity to supply variation was only 200 µV. All the results are summarized in Table 1.

In comparison to other state of the art bandgap references, many of the bandgap references use a supply voltage of 3.3 - 5 V. Compared to Analog Devices' ADR280, which supplies a 1.2 V reference voltage, we find that our temperature coefficient is actually better than the 40 ppm/ºC listed in the data sheet. However, the ADR280 does consume less power than our design at a maximum of 16 µA. Furthermore, the ADR280 has an output noise of 12.5 nV/√HZ [4]. Ultimately, our device needs a bit more work before it could be truly compared to existing bandgap references on the market.

There are a couple of improvements we could make. First, we can improve our start-up circuit. As shown by Figure 10, there are many instances where we are unable to turn on the circuit. Furthermore, the start-up circuit in the layout is large. There are many resistors in series, so it would be better to implement a different start-up circuit that will not consume as much area in the layout. Third, we can make our second op amp A2 in Figure 2 a single-stage amplifier. This was done in the Razavi approach, but we were unable to implement it effectively. Changing the two-stage amplifier to a single-stage amplifier will decrease power consumption. Furthermore, it will decrease the area needed for the layout. Another improvement we could have implemented is curvature correction. This can be done by increasing the temperature dependence of the PTAT current reference.

VI. REFERENCES

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