A 1.5V P-Well Voltage Reference Circuit

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***Abstract*—A 1.5 V integrated bandgap voltage reference circuit with a temperature coefficient of $177\frac{ppm}{K}$ and a current draw of 39.81μA was designed in a low power WBAN system. The initial design was a discrete circuit operating with a $\pm$10V power supply, with parameters of 1.44V reference voltage, $6200\frac{ppm}{K}$ temperature coefficient, and current draw of 577μA. The transition of discrete to integrated included the replacement of an op-amp with a differential amplifier and replacement of BJTs with p-well transistors.**

***Key Words*—Bandgap, Voltage Reference, WBAN, P-Well, Discrete, Integrated**

I. Introduction

As the semiconductor industry continues to innovate, it has opened the doors for on-body monitoring systems such as the WBAN. Like any transceiver device, the system is comprised of multiple components and sub-circuits. The support circuit, being the keystone of the device, must contain a voltage reference sub-circuit, around which the rest of the device can be designed.

The purpose of this project is to design and implement a 1.5 V p-well voltage reference circuit as a sub-circuit of a more complex system. There are several topologies of voltage reference circuits such as bandgap, buried zener, and charged capacitor. For our design, we will be using the bandgap topology, which is the most common implementation of a voltage reference circuit for integrated circuits.

The bandgap circuit concept was first published by David Hilbiber in 1964 [2], which was soon developed by some others, notably, Paul Brokaw. The Brokaw circuit served as a starting point in our discrete voltage reference design. It allowed most design specifications to be met but was ultimately redesigned to implement p-well transistors for the purpose of converting the design into an integrated topology to meet all required specifications.

II. Background

A. Wireless Body Area Network

Rapid advancements in wireless communication and semiconductor technologies of sensor networks have paved the way to a wider range of applications of systems such as the Wireless Body Area Network (WBAN). A WBAN is a special network designed to operate autonomously as a receiver and transmitter in medical and non-medical applications while meeting IEEE 802.15.6 standards[4]. These wearable devices can be used in patient and health monitoring, cancer detection, real time streaming, entertainment, and many more applications[4]. The aim is to develop a device compliant with communication standards that allows longer performance while also consuming low power.

Frequency	Bandwidth
Human-Body Communication	
16 MHz	4 MHz
27 MHz	4 MHz
Narrowband Communication	
402-405 MHz	300 kHz
420-450 MHz	300 kHz
863-870 MHz	400 kHz
902-928 MHz	500 kHz
956-956 MHz	400 kHz
2360-2400 MHz	1 MHz
2400-2438.5 MHz	1 MHz
Ultra Wide Band Communication	
3.2-4.7 GHz	499 MHz
6.2-10.3 GHz	499 MHz

TABLE I. Frequency Bands and Bandwidth Standards of IEEE 802.15.6 [5]

B. IEEE 802.15.6 Standard

IEEE 802.15.6 is a standard for WBANs [5]. IEEE 802.15.6 pertains to short-range, wireless communications in the vicinity of, or inside, a human body (but not limited to only humans) as well as available Industrial Scientific Medical (ISM) frequency bands approved by national medical or regulatory authorities [5]. This standard is considered effective on portable antennas due to its consideration of various characteristics of the human body (weight, gender, shape). This standard also covers various frequency bands on which WBAN devices can operate, as shown in Table I. IEEE 802.15.6 also covers radiation patterns in concerns to specific absorption rates in the body, and low power data rates [5].

C. System Overview

The block level diagram in Fig.1 illustrates the overall design of a low power WBAN transceiver. It is composed of a transmitter, receiver, and support circuit.

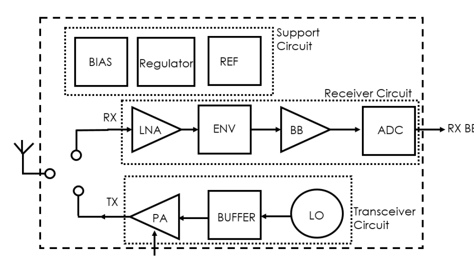


Fig. 1. Block level diagram of a WBAN system

Our contribution to the construction of the low power WBAN transceiver was by designing the bandgap voltage reference sub-circuit (abbreviated REF in Fig. 1) as part of the support circuit. As with any electronic devices with an analog to digital (or vice versa) converter, a reference voltage is necessary for its operation; moreover, the bandgap design is a common voltage reference circuit choice in integrated circuit designs.

D. Bandgap Voltage Reference Circuits

The purpose of a bandgap voltage reference is to generate a known and constant voltage [1],[6]. The reference signal is a fixed voltage, independent of temperature, power supply variations, and circuit loading [6]. It is used as a reference, which can be measured and compared within a system to improve precision and maintain the system in operating range [1],[6].

E. Survey of Commercial Bandgap circuits

Table II provides a list of available products in the market for bandgap devices that have a relatively low bias current and low temperature coefficient.

Product	$V_{out}(V)$	Temp. Coefficient(ppm)	Bias Current (μA)
REF2925	2.5	100	50
ISL21080CIH	1.5	50	1.5
ADR1500BKS	1.29	170	50
LM4121	1.25	50	160
TLVH431BQ1	1.24	161	70
AD1580	1.2	150	50
LM185	1.2	150	10
ADR130	1	15	85

TABLE II. COMMERCIALLY AVAILABLE VOLTAGE REFERENCES.

III. THEORY

The bandgap circuit provides a temperature independent output voltage by summing a complementary to absolute temperature (CTAT) voltage with a proportional to absolute temperature (PTAT) voltage to cancel the temperature coefficients of the voltages [6]. A visual representation is shown in Fig. 2.

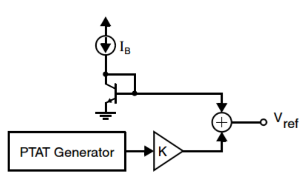


Fig. 2. Model of a bandgap Voltage Reference [6].

The CTAT voltage can be generated through a base to emitter voltage (V_{BE}) and is given by

$$V_{BE} = V_{G0}(1-\frac{T}{T_0})+V_{BE0}\frac{T}{T_0}+\frac{mkt}{q}ln(\frac{T_0}{T})+\frac{kt}{q}ln(\frac{J_c}{J_{C0}}) \quad (1)$$

where T is the transistor temperature and V_{BE0} is the bandgap voltage of the transistor at temperature T_0 [6]. V_{G0} is the bandgap voltage of silicon extrapolated to 0 Kelvin, k is Boltzmann's constant, and m is a constant of 2.3 for a typical BJT. J_c is the collector current density at T while J_{c0} is the collector current density at T_0.

At a constant collector current, the CTAT coefficient of V_{BE} is $-2\frac{mV}{^\circ K}$ at room temperature. A PTAT voltage equation can be derived from Eqn. 1 to be inversely proportional to the CTAT coefficient. The PTAT voltage is generated through the difference of two base to emitter voltages (ΔV_{BE}) from two transistors with varying current densities of J_1 and J_2, as shown in Eqn. 2.

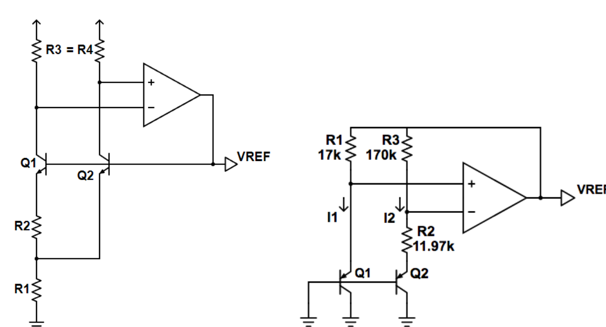
$$\Delta V_{BE} = V_1 - V_2 = \frac{kt}{q}ln(\frac{J_2}{J_1}) \quad (2)$$

$$V_{ref} = \Delta V_{BE} + V_{BE} \quad (3)$$

The PTAT voltage (ΔV_{BE}) can be generated with two forward biased transistors with their base tied to their emitter junctions [6]. When configured in this way the transistor becomes the equivalent of a diode. Since ΔV_{BE} may not be be as dependent to temperature as the transistor voltage, it is a requirement to amplify the PTAT voltage. The goal is to amplify it to the point where the magnitudes of the dependencies of temperature match and cancel when added together [6]. Doing so creates a reference voltage that is constant through varying temperatures.

Brokaw's reference circuit, shown in Fig. 3a, was used as a starting schematic to add a PTAT and CTAT voltage together. In the Brokaw reference circuit, R_3 is equal to R_4, and the voltages across them are equal due to the virtual ground created from the negative feedback of the Op-Amp to the positive and negative input terminals [1],[6]. The currents flowing through the transistors are equal, however the voltages (V_{BE}) across the transistors Q_1 and Q_2 are not equal due to differing transistor current densities. Choosing the current density of Q_2 to be eight times larger than that of Q_1 will create a difference in transistors' V_{BE} and creates a PTAT voltage across R_2 [1]. The V_{ref} can be written as a function of two voltages as seen in Eqn. 4 [6].

$$V_{ref} = V_{BE2} + \frac{2R_1}{R_2}\Delta V_{BE} \quad (4)$$



(a) (b)

Fig. 3. (a) Schematic of Brokaw's bipolar bandgap voltage reference [1],[6]. (b) Brokaw's bandgap voltage reference with p-well CMOS transistors [6].

The bandgap circuit illustrated in Fig. 3b is a variant based around Brokaw's circuit with p-well transistors. Changing the circuit to incorporate p-well transistors caused the PTAT voltage to no longer be proportional to the ratio of current densities. The PTAT became proportional to the current ratio $\frac{I_2}{I_1}$, and the currents are directly related to the resistors R_1 and R_3 [6]. This causes the PTAT voltage to be proportional to the ratio $\frac{R_3}{R_1}$. The V_{ref} voltage function is then represented by Eqn. 5 [6].

$$V_{ref} = V_{BE1} + \frac{R_3}{R_2}\frac{kT}{q}ln(\frac{R_3}{R_1}) \quad (5)$$

The PTAT voltage being a function of the three resistors allows for greater control over the temperature dependency [6], which enables more control over the value of V_{ref}. This is advantageous to Brokaw's circuit since transistor current densities are difficult to control and the design uses one less resistor.

IV. Proof of Concept

A. Design of a Discrete Bandgap Circuit

In order to design the bandgap circuit, resistor values for the circuit in Fig. 3b were calculated according to the following criteria: I_1 = 50 μA, I_2 = 5 μA, V_{ref} = 1.5 V, while assuming V_{BE} of Q_1 at T= 300 K is 0.65 V. R_1 was found to be 17 kΩ by using Kirchoff's voltage law (KVL). With V_+ and V_- being equal due to the op-amp's negative feedback loop, R_3 was found to be 170 kΩ by using KVL. R_2 was calculated to be 11.97 kΩ through Ohm's law and ΔV_{BE} was $0.06V$. These calculated values were used with Eqn. 5 and found the calculated V_{ref} was $1.5V$.

The calculated resistance values were not standard and unavailable as discrete components. They were replaced by the closest standard values which were 16kΩ, 12kΩ and 160kΩ for R_1, R_2 and R_3, respectively, from Fig.3b. The standard resistor values were used in Eqn. 5 and gave a calculated V_{ref} of 1.44V. The bandgap circuit was simulated in Cadence Virtuoso. The simulated results closely matched the calculated results with V_{ref} of the simulation being 1.443 V versus the calculated value of 1.44 V.

B. Discrete Bandgap Circuit Results

Using the temperature sweep function, the circuit was simulated through the standard commercial temperature range from 0°C to 80°C. The results showed that V_{ref} was linearly proportional to temperature with V_{ref}, rising approximately 0.93 $\frac{mV}{°C}$ as seen as slope in Fig. 4. The slope was divided by the actual V_{ref} value to find the temperature coefficient of 6200 $\frac{ppm}{K}$.

In order to test the sensitivity of V_{ref}, two separate experiments were conducted. In the first experiment, the Op Amp was switched with similar 741c devices as shown in Fig. 5b. The varying Op-Amps affected V_{ref}, but remained within ±50 mV from the expected value.

In the second experiment, the transistors were swapped with new sets of the same device (CPN2907A). The switching of transistors had a large effect on the sensitivity of V_{ref}, varying the original value by up to 0.16 V, as shown in Fig. 5.

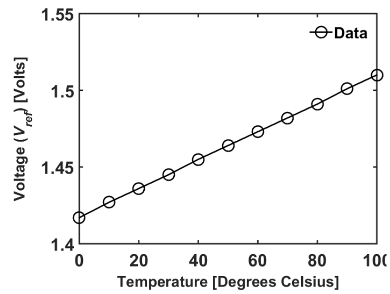


Fig. 4. Discrete Circuit V_{ref} vs Temperature

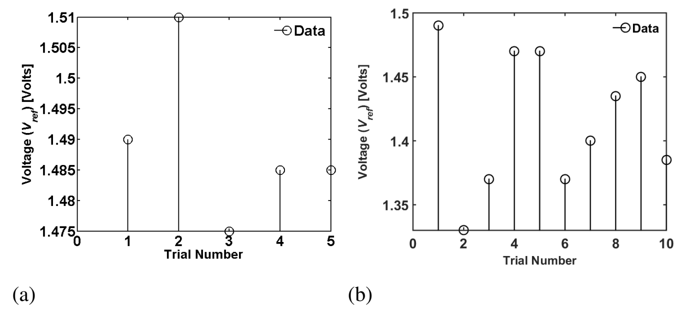


Fig. 5. (a) V_{ref} variance from switching the circuit's Op-Amp. (b) V_{ref} variance from switching the circuit's bjt

The current of the operational amplifier (Op-Amp) was measured and found to be 515 μA with a supply voltage of ±10 V. The current was large compared to the measured current of 62 μA, and was over the specification current of 100 μA total. The Op-Amp needs to be replaced with a differential amplifier specifically designed to meet the current specifications of the bandgap reference circuit. The bandgap circuit met the specifications to be implemented into the transceiver system. However, the discrete circuit consumed too much space and power, specifically through the Op Amp. In order to improve the circuit, it was redesigned into an integrated circuit (IC) by replacing the Op-Amp with a low current differential amplifier.

C. Design of an Integrated Bandgap Circuit

The differential active loaded amplifier needed to consume less current while still providing the specified voltage. To make this possible, a differential pair loaded with a current mirror was chosen as the preferred topology as illustrated in Fig. 6. In order to bring the currents and voltages within the desired ranges, the current mirror ratio needed to be taken into account, and custom CMOS transistors needed to be characterized. Table III shows the theoretical relationships between the characteristics of CMOS transistors. Knowing the relationship between transistor width and current, a transfer ratio of 17 in the current mirror was chosen in order to lower current consumption while providing sufficient power to the bandgap sub circuit to operate properly.

The integrated differential amplifier was designed to allow 25 μA to be drawn in order to supply the feedback loop to

	Unit	NMOS	PMOS
W/L	μm/μm	10/1	20/1
$V_{DS,SAT}$	mV	130	100
$\lvert V_{GS}\rvert$	mV	500	600
g_m	μS	250	170
$\lvert I_{DS}\rvert$	μA	20	20
g_m/I_D	S/A	12.5	8.5
g_m/g_{ds}	S/S	38	44
V_{th}	mV	400	-400
μC_{ox}	μA / V^2	400	50
λ	1/V	0.3	0.2

TABLE III. TABLE OF CMOS CHARACTERISTICS[6]

the bandgap circuit. Since the current design of the bandgap circuit requires 55 μA of current to be powered, the resistor values of the bandgap circuit also needed to be redesigned in order to draw less current.

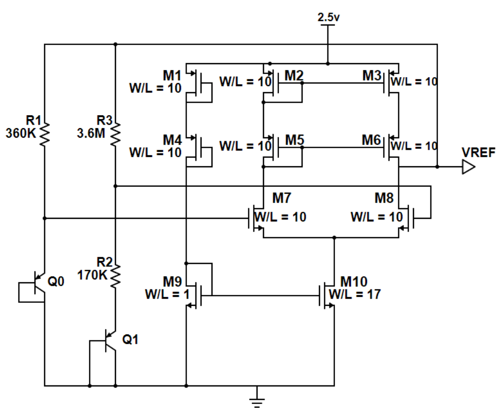


Fig. 6. Schematic of Integrated Voltage Reference Circuit.

The topology for the bandgap sub-circuit used in Fig. 3 was kept for the integrated circuit, but with the resistor values changed as seen in Fig. 6. The differential amplifier and the redesigned bandgap circuit were combined and simulated.

D. Integrated Bandgap Circuit Results

The simulation of the integrated circuit consumed a current of 39.81 μA while maintaining an average output of 1.492 V for V_{ref}. It had a high voltage of 1.51 V and a low of 1.476 V through the commercial temperature range of $0-80^oC$.The simulated temperature coefficient was calculated to be 177 $\frac{ppm}{K}$. The integrated circuit design used $475\mu A$ less current and had over 6000 $\frac{ppm}{K}$ decrease from the discrete design, thus demonstrating that the integrated circuit consumed less power and was more temperature independent.

V_{ref} of the circuit was plotted through a temperature sweep with varying currents by means of differing resistance values of R_2. The results are plotted in Fig. 7. The plot shows that V_{ref} is proportional to the current of the circuit. Therefore the current can be lowered at the expense of having larger resistors and a lower V_{ref}. For the desired average V_{ref} (1.5 V) and low current (39.81 μA) at normal operating temperatures, the value of R_2 is 170 kΩ.

V. FUTURE WORK

The integrated bandgap circuit, from Section IV, uses large resistors, which take a large amount of space and is area ineffi-

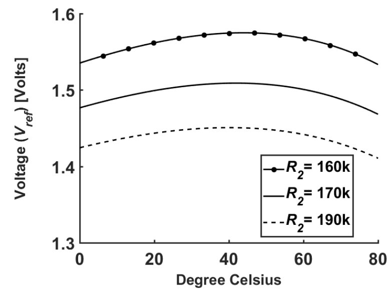


Fig. 7. Simulated output voltage V_{ref} of integrated circuit as a function of temperature with varying R_2 resistances.

cient. The circuit also lacked a low temperature independence when compared to reference circuits found through market analysis as shown in Table II. A possible solution for these limitations is to redesign the circuit using the topology shown in Fig. 8.

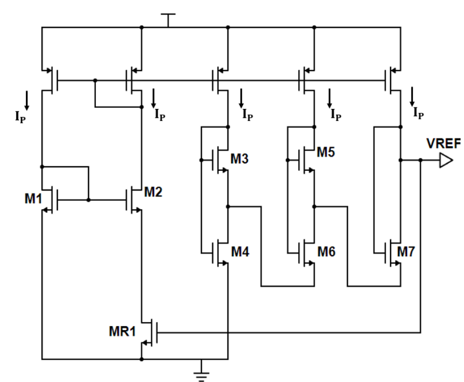


Fig. 8. Schematic of a 300 nW, 15 ppm/K, voltage reference circuit [3]

The circuit consists of a reference sub-circuit powered by a current mirror. Transistors M_1, M_2, and M_{R1} make the current source sub-circuit [3]. The transistors M_3, M_4, M_5, M_6, and M_7 make the reference sub-circuit [3]. Transistors M_6 and M_4 have currents of $2I_P$ and $3I_P$ respectively. The transistors M_3 through M_7 form a closed loop by negative feedback to the gate node of M_{R1} which acts as a potentiometer that controls the magnitude of I_P. An increase in V_{REF} causes an increase in I_P which decreases V_{REF}. This cycle continues until V_{REF} reaches a steady state voltage.

The circuit in Fig. 8 generates a reference voltage by summing all the gate to source voltages of the transistors in the reference sub-circuit, as seen in Eqn. 6 [3]. where n is the sub-threshold slope factor, V_T is thermal voltage ($\frac{kT}{q}$), and K is the aspect ratio ($\frac{W}{L}$) of the transistor. V_{GS4} is a CTAT voltage and V_T is a PTAT voltage. The temperature coefficients of the voltages cancel out when summed and produce a reference voltage that is temperature independent and equal to the threshold voltage (V_{TH}) of the M_4 transistor [3].

$$\begin{aligned} V_{ref} &= V_{GS4} - V_{GS3} + V_{GS6} - V_{GS5} + V_{GS7} \\ &= V_{GS4} + nV_T ln(\frac{2K_3K_5}{K_6K_7}) \end{aligned} \quad (6)$$

The MOSFETs in the circuit, with the exception of M_{R1}, are operated in the subthreshold region [3]. M_{R1} is operated in the triode region to control the current source sub-circuit. A MOSFET in subthreshold region means the voltage between the gate node and source node of the transistor is less than the threshold voltage of the transistor. MOSFETs in subthreshold region operate as gate controlled BJTs and have current linearly proportional to the gate voltage [3]. This minimizes the current flowing through the transistors, which requires a lower supply voltage and effectively reduces power consumption.

VI. CONCLUSION

The bandgap voltage reference presented utilized PTAT technology in order to operate at a steady voltage regardless of temperature. The chosen circuit topology made the PTAT voltage of the discrete and integrated designs a function of resistors which improved our control of V_{ref} throughout temperature. Our initial discrete prototype had a V_{ref} of 1.44 V, a total current of 577μA, and a temperature coefficient of 6200 $\frac{ppm}{K}$. This discrete circuit consumed too much current for low power WBAN applications. In addition, the temperature coefficient was too high when compared to commercial competitors. To resolve these issues, the circuit was redesigned into an integrated typology.

Our integrated bandgap circuit replaced the OP-Amp with a differential amplifier and was designed with custom CMOS transistors. The replacement of the Op-Amp and redesign of the circuit into an IC lowered the current significantly to 39.81μA, improved V_{ref} to 1.492 V, and also allowed the temperature coefficient to be lowered to 177 $\frac{ppm}{K}$.

The integrated bandgap design met the given specifications but still falls short in temperature independence and space consumption when compared to commercially available devices. A possible solution is to redesign the circuit to implement MOSFETs operated in the threshold region to replace our circuit's bipolar junction transistors and resistors. Doing so has the potential to decrease power consumption and physical size while increasing the reference voltage temperature independence.

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