Bandgap voltage reference pdf

Basics of electronic circuits Opamp principle operation Bipolar junction Transistor basics Many circuits, including voltage regulators, analog-digital and digital-analog converters, require voltage reference, which is as accurate as possible. Their accuracy depends on it. This means that the voltage reference value would ideally be independent of PVT: P: production process variants V: supply voltage T: bandgap reference circuits cancel out two opposite temperature deviations. This means that if we have two references, one producing voltage V_1 with temperature coefficient $$\frac{\partial V_1}{\partial T} = \alpha$$ and the other producing voltage V_2 with temperature coefficient $$\frac{\partial V_2}{\partial T} = -\alpha$$ Next operation $$V_{out} = V_1 V_out} = $V $V_{out} = $V $V <2> + V_2$$ creates a temperature-independent voltage: $$\frac{\partial V_{out}}{{partial T} = \frac{\partial V_1}{{partial T} + \frac{\partial V_2}{\partial T} = \alpha - \alpha = 0$$ Of course, for cancellation, temperature coefficients must have opposite characters, one negative (NTC) and one positive (PTC). Bipolar junction transistor (BJT) can provide both NTC and PTC voltage. So, let's review a little BJT. What you need to know about the BJT BJT stream collector is defined as: $$I_c = I_Se^{V_{be}/V_t}$$$$$ where V_{be}je the base voltage emitter. $V_t = kT/q$ is a thermal voltage that is practically insensitive to process changes and is defined by boltzmann constant k, electron charge q and temperature T. I_S parameter is process-dependent and temperature-dependent: $$I_S = I_0 e^{\frac{-V_{G0}}{V_t}}$$ $$I_0 = I_S I0 <1> <6> e^{\frac{V_{G0}}{V_t}}$$$, where I_0 is the device parameter and V_{G0}d reems the name of this reference circuit. It is the belt tension of silicon, the energy needed to release the electron from the outer shell of the silicon atom. Bandgap itself is temperature dependent, so V_{G0} is $V_G(T)$ extrapolated from 300ºK to 0ºK. The collector stream can also be expressed as follows: $$I_c = I_0e^{-\frac{V_{G0} - V_{be}}{Vt}}$$$,which makes it easier to relation to band voltage. Creating an NTC voltage A negative temperature coefficient is created by a PN junction. The basic emitter junction of the bipolar connecting transistor (BJT) is a common pn junction used in band references. Using the BJT collector current, the base emitter voltage is: $$V_{be} =V_{G0} - \frac{kT}{q} \log \frac{I_0}{I_c}$$ So how V_{be} depends on temperature? Assuming that $I_c$does not depend on temperature: $$\frac{\partial V_{be}}{partial T} = -\frac{k}{q}\log\frac{I_0}{I_c}$$ Because I_0 is much larger than I_c, the term $log\$ is not significantly affected by the current bjt. Normally, the temperature coefficient is around $-2mV$: $$\frac{\partial T} \approx. -2mV/ºC$$ Creating ptc voltage The positive temperature coefficient is generated by the thermal voltage V_t. Let's say we take the difference between two basic BJT emitter junctions: $$V_{be1} - V_{be2} = V_t \log \frac{I_{c1}}{I_{S1}} - V_t \log \frac{I_{c2}}{I_{s}{s2}}$$ $$\Delta V_{be} = V_t \log \frac{I_{c1} I_{S2}}{I_{c2} I_{S1}}$$ Simple enough ΔV_{be} gives us a voltage proportional to V_t, as well as a certain scale of this tension, if we want. But still... We want the tension to be referred to the ground, so we need to elaborate a little more. Find voltage across two resisters $$V_{R1} = V_B - V_{be2} - (V_B - V_{be1}) = V_{be1} - V_{be2} = \Delta V_{be}$$$$V_{R2} = R_2\cdot 2I_c = R_2 \cdot 2\frac{V_{R1}}{R_1} = 2\frac{R_2}{R_1}\Delta V_{be}$$ Voilá, V_{R2} is proportional to ΔV_{be} and refers to the ground! We can also replace V_{be}'s as: $$V_{R2} = 2\frac{R_2}{R_1}V_t \log \frac{I_{c}I_{S2}}{I_c I_{S1 }} = 2 \frac{R_2}{R_1}V_t \log \frac{I_{S2}}{I_{S1}} = KV_t$$ Because $$k and $$q are constants, the V_t is only proportional to the temperature, with temperature coefficient: $$\frac{\partial V_t}{\partial T} \approx. +0.085mV/ºC$$ The thing is that the terms I_S are proportional to the area of the transistor and very similar for nearby transistors (in terms of layout). Therefore, it is very accurate: $$\frac{I_{S2}}{I_{S1}}\cca\frac{A_2}{A_1}$$$$, where $$A represents the transistor area. Then: $$V_{R2}= 2\frac{R_2}{R_1}\log {frac{A_2}{A_1}V_t$$ Finally, it's interesting that V_B is already the sum of the voltage proportional to $V_t $ (PTC) and V_{be} (NTC): $$V_B = V_{R2} + V_{be1} =2 \frac{R_2}{R_1}\log \frac{A_2}{A_1}V_t + V_{be1}$$ How V_B is biased and how we implement current resources there are questions that will be answered further... The sum of NTC and PTC voltages So our main idea is to produce two voltages, one PTC and another NTC, which cancel each other out in terms of temperature fluctuations. The diagram would look something like this: The sum of the two stresses would be: $$V_{be} + KV_t = V_{G0} - \frac{kT}{q} \log \frac{I_0}{I_c} + K\frac{kT}{q} = V_{G0} + \frac{kT}{q} \left(K - \log \frac{I_0}{I_c} \right)$$ As we saw when creating ptc voltage, K probably comes from the resistance ratio and/or transistors range. and with a value of $2/0.085\approx. $23.5. Before proceeding, note that after you cancel temperature-dependent terms, the bandgap reference remains V_{G0}. If you've ever seen a voltage link with a value close to 1.2 V, it comes from here! Another obvious question is: how to implement it with real circuits? There are several ways, but the main recipe is as follows: Generate two streams to the bias of two different BJTs Create a branch involving two BJTs and one resistance (or equivalent resistance) find a path that adds PTC and NTC voltages Tweak the sizes of the transistors and/or resistances to give the right K Add a startup circuit, or else the circuit may stabilize at zero current every time Examples Widlar bandgap The output is: $$ V_{out} = I_2 R_2 + V_{be3}$$ From the bottom branch: $$V_{be1} = V_{be2} + I_2R_3$$ $$I_2 = \frac{V_{be1} - V_{be2}}{R_3}$$ From the ΔV_{be} expression: $$I_2 = \frac{V_t}{R_3}\log\left(\frac{I_1I_{S1}}{I_2I_{S2}} \right)$$ Then: $$ V_{out} = \frac{R_2}{R_3} V_t\log\left(\frac{I_1I_{S1}}{I_2I_{S2}}\right) + V_{be3}$$ The circuit is sized such that $I_1=I_2$, resulting in : $$ V_{out} = \frac{R_2}{R_3} V_t\log\left(\frac{I_{S1}}{I_{S2}}\right) + V_ {be3}$$ Brokaw bandgap Output is: $$ V_{out} = V_{be1} + 2I_c R_1$$ Based on opamp feedback, both inputs are in the same voltage, therefore the upper resisters have the same voltage through them. Because they are the same, the same stream must flow through them and converge in $R_1 $. From the middle branch: $$V_{be1} = V_{be2} + I_cR_2$$ $$I_c = \frac{V_{be1} - V_{be2}}{R_2}$$ From the ΔV_{be} expression: $$I_c = \frac{V_t}{R_2}\log\left(\frac{I_cI_{S1}}{I_cI_{S2}} \right)$$ Then: $$V_{out} = 2\frac{R_1}{R_2} V_t\log\left(\frac{I_{S1}}{I_{S2}}\right) + V_{be1}$$ With PNP transistors The output is: $$V_{out} = V_{eb2} + V_{R2} + V_{R} $$ Since the opamp feedback is forcing both inputs to be equal, we have: $$V_{eb1} = V_{R2} + V_{eb2}$$ $$V_{R2} = V_{eb1} - V_{eb2}$$ and $$V_{R} = R \frac{V_{R2}}{R_2}$$ and $$I_1 = I_2$$ From the ΔV_{be} expression , which is exactly the same for ΔV_{eb}: $$V_{R2} = V_t\log\left(\frac{I_1I_{S1}}{I_2I_{S2}} \right) = V_t\log\left(\frac{I_{s1}}{I_{S2}} \right)$V$$$ lt;3>_{out} = V_{eb2} + \left(1+ \frac{R}{R_2}\right) V_t\log\left(\frac{I_{S1}}{I_{S2}}\right) $$ Some thoughts about other dependencies Process variants As noted, the voltage reference should also be insensitive to variant processing. This is usually balanced with the fact that the output depends on the ratio of values (pairs of resistances, pairs of BJTs, etc.). Special care should be exercised when unloading these devices, their value will be very similar in production and will depend very similarly on other parameters such as temperature. As you can see, the $K of $ is such a case in all bandgap links. Power If you need an accurate voltage link, that means you don't have one anymore, right? So the power supply for the link will not be accurate and the link should be insensitive to it. The way to solve this is differential circuitry. In the bandgap examples, if the power supply changed, the currents of both branches would be affected equally. Therefore, the assumption of the same currents would still be kept and the effects of changes to the power supply would be cancelled at the output voltage. Temperature Still, not every effect dependent on temperature can be For example: Temperature changes resistance values, resistance changes collector current, and collector current changes sensitivity V_{be} to temperature slightly Changes offset opamp voltage, which in turn changes the voltage between transistors/resistors and balances the collector current of both transistors. References If I helped you in some way, please help me back by liking this website at the bottom of the page or by clicking on the link below. It would mean everything to me! Temperature-independent reference voltage The reference band voltage is a temperature-independent reference circuit widely used in integrated circuits. Creates a fixed (constant) voltage regardless of power changes, temperature changes, and circuit load from the device. It usually has an output voltage of around 1.25 V (close to the theoretical 1.22 eV (0.195 aJ) silicon band gap at 0 K). This concept of the circuit was first published by David Hilbiber in 1964. [1] Paul Brokaw[2] and others[4] followed up with other commercially successful versions. Operating circuit of the reference belt Brokaw Characteristics and balance point T1 and T2 The voltage difference between two p-n junctions (e.g. diodes) controlled at different current densities is used to generate a current that is proportional to the absolute temperature (PTAT) in the resistor. This current is used to generate voltage in the second resistor. This voltage, in turn, is added to the stress of one of the junctions (or the third, in some implementations). The voltage across the diode operated at constant current is supplemented by an absolute temperature (CTAT) with a temperature coefficient of approximately −2 mV/K. If the ratio between the first and second resistor is correctly selected, the effects of the temperature dependence of the diode and the PTAT current shall be ed out in the first order. The resulting voltage is about 1.2-1.3 V, depending on the specific technology and design of the circuit, and is close to the theoretical 1.22 eV band of silicon at 0 K. The remaining voltage change above the operating temperature of typical integrated circuits is of the order of several millivolts. This temperature dependency has typical parabolic residual behavior because linear effects (first order) are selected for cancellation. Since the output voltage is by definition set at around 1,25 V for typical belt reference circuits, the minimum operating voltage is about 1,4 V, since at least one field-effect drain source (FET) stress must be added in the CMOS circuit. Therefore, recent work focuses on finding alternative solutions in which, for example, currents are added instead of voltage, resulting in lower theoretical limits of operating voltage. [4] The first letter of the abbreviation CTAT is sometimes misinterpreted in such a way that constant rather than complementary. The term, constant with temperature (CWT), exists to address this confusion, but is not in widespread use. When adding ptat and ctat current, only linear current conditions are compensated, while conditions of higher order limit the temperature shift (TD) of the band reference at a temperature of around 20 ppm /°C, in the temperature range of 100 °C. For this reason, in 2001, Malcovati [5] proposed a circuit topology that can compensate for high-order non-linearity and thus achieve better TD. This design used an improved version of the Banba topology [4] and an analysis of the temperature effects of the base emitter by Tsividis in 1980. [6] In 2012, Andreou[7][8] further improved the high nonlinear compensation with a second operating amplifier along with another resistor foot at the point where both currents are summarized. This method further improved curvature correction and achieved excellent TD performance over a wider temperature range. In addition, it achieved better regulation of wiring and lower noise. Another critical issue in the design of bandgap links is energy efficiency and circuit size. Since the reference to bandgap is generally based on BJT devices and resistors, the total size of the circuit could be large and therefore costly for the IC design. In addition, this type of circuit can consume a lot of energy to achieve the required noise specification and accuracy. [9] Despite these limitations, bandgap reference voltage is widely used in voltage regulators that cover most 78xx, 79xx, along with LM317, LM337 and TL431. Temperature coefficients up to 1.5-2.0 ppm/°C can be obtained using belt links. [a] However, the parabolic characteristic of stress versus temperature means that one digit in ppm/°C does not adequately describe the behaviour of the circuit. The data of the manufacturers show that the temperature at which the peak (or trough) of the stress curve occurs is subject to normal changes in the production of samples. Bandgaps are also suitable for low power applications. [b] Patents 1966, US Patent 3271660, Reference Voltage Source, by David Hilbiber. [10] 1971, U.S. Patent 3617859, Electrical controller of the device including a reference circuit with zero temperature coefficient voltage, Robert Dobkin and Robert Widlar. [11] 1981, U.S. Patent 4249122, Temperature-compensated references to jet ic voltage, by Robert Widlar. [12] 1984, U.S. Patent 4447784, Temperature-compensated Band Voltage Reference Circuit, by Robert Dobkin. [13] Notes ^ For example, LT6657 from linear technology and ADR4550 from analog devices. ^ For example, a cathode current of 1 μA with a reference short-circuit voltage of Maxim 6009. See also Brokaw bandgap reference LM317 Silicon bandgap temperature sensor References

^ Hilbiber, D.F. (1964), New Standard semiconductor voltage, 1964 Conference on solid circuits: Overview of technical documents, 2: 32-33, doi:10.1109/ISSCC.1964.1157541 ^ Widlar, Robert J. (February 1971), New developments in IC voltage regulators, IEEE Journal of Solid-State Circuits, 6 (1): 2-7, Bibcode:1971IJSSCSC ... 6....2W, doi:10.1109/JSSC.1971.1050151, S2CID 14461709 ^ Brokaw, Paul (December 1974), Simple Three-Terminal IC Bandgap Reference, IEEE Journal of Solid-State Circuits, 9 (6): 388-393, Bibcode:1974IJSSC ... 9..388B, doi:10.1109/JSSC.1974.1050532, S2CID 12673906 ^ a b c Banba, H.; Shiga, H.; Umezawa, A.; Miyaba, T.; Tanzawa, T.; Atsumi, S.; Sakui, K. (May 1999), CMOS bandgap reference circuit with sub-1-V operation, IEEE Journal of Solid-State Circuits, 34 (5): 670-674, Bibcode:1999IJSSC.. 34..670B, doi:10.1109/4.760378, S2CID 10495180 ^ Malcovati, P.; Maloberti, F.; Fiocchi, C.; Pruzzi, M. (2001). Bandgap BiCMOS compensated by curvature with a voltage of 1-V power supply. IEEE Journal of Solid-State Circuits. 36 (7): 1076–1081. Bibcode:2001IJSSC.. 36.1076M. doi:10.1109/4.933463. S2CID 7504312. ↑ Y. P. Tsividis, Accurate analysis of temperature effects in Ic-Vbe characteristics with application to bandgap reference sources, IEEE J. Solid-State Circuits, vol. 15, No. 6, p. 1076 – 1084, December 1980. ↑ Andreou, Charalambos M.; Koudounas, Savvas; Georgiou, Julius (2012). The new wide temperature range, 3.9 PPM/$^{\circ}, $C the CMOS Bandgap reference circuit. IEEE Journal of Solid-State Circuits. 47 (2): 574-581. doi:10.1109/JSSC.2011.2173267. S2CID 34901947. ↑ Koudounas, Savvas; Andreou, Charalambos M.; Georgiou, Julius (2010). New CMOS Bandgap reference circuit with improved high-order temperature compensation. Proceedings of the 2010 IEEE International Symposium on Circuits and Systems. p. 4073-4076. doi:10.1109/ISCAS.2010.5537621. ISBN 978-1-4244-5308-5. S2CID 30644500. ↑ Tajalli, A.; Atarodi, M.; Khodaverdi, A.; Sahandi Esfanjani, F. (2004). Design and optimization of high psrr CMOS bandgap voltage reference. 2004 IEEE International Symposium on Circuits and Systems (IEEE Cat. No. 04CH37512). p. I-45-I-48. doi:10.1109/ISCAS.2004.1328127. ISBN 0-7803-8251-X. S2CID 9650641. ↑ US Patent 3271660 - Reference voltage source, David F Hilbiber; U.S. Patent and Trademark Office; September 6, 1966. ↑ US Patent 3617859 - Electrical controller of equipment including reference circuit with zero temperature coefficient of voltage; Robert C. Dobkin and Robert J. Widlar; U.S. Patent and Trademark Office; November 2, 1971. ↑ US Patent 4249122 - Temperature-compensated references to IC band voltage; Robert J. Widlar; U.S. Patent and Trademark Office; February 3, 1981. ↑ US Patent 4447784 - Temperature-compensated band voltage reference circuit; Robert C. Dobkin; U.S. Patent and Trademark Office; May 8, 1984. External links Design a band space reference Tests and Tribulations p. 286 - Robert Pease, National Semiconductor Function and CMOS Voltage Limitation References ECE 327: LM317 Bandgap Voltage Reference Example - A brief explanation of the temperature-independent bandgap reference circuit within LM317. Obtained from