# Bandgap voltage reference

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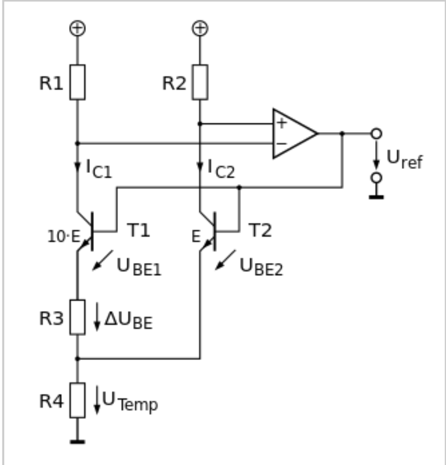
A **bandgap voltage reference** is a temperature independent voltage reference circuit widely used in integrated circuits. It produces a fixed (constant) voltage regardless of power supply variations, temperature changes and circuit loading from a device. It commonly has an output voltage around 1.25 V (close to the theoretical 1.22 eV bandgap of silicon at 0 K). This circuit concept was first published by David Hilbiber in 1964.[1] Bob Widlar,[2] Paul Brokaw[3] and others[4] followed up with other commercially successful versions.

## Contents



## Operation

The voltage difference between two p-n junctions (e.g. diodes), operated at different current densities, is used to generate a **p**roportional **t**o **a**bsolute **t**emperature (PTAT) current in a first resistor. This current is used to generate a voltage in a second resistor. This voltage in turn is added to the voltage of one of the junctions (or a third one, in some implementations). The voltage across a diode operated at constant current, or here with a PTAT current, is **c**omplementary **t**o **a**bsolute **t**emperature, with approximately −2 mV/K. If the ratio between the first and second resistor is chosen properly, the first order effects of the temperature dependency of the diode and the PTAT current will cancel out. The resulting voltage is about 1.2–1.3 V, depending on the particular technology and circuit design, and is close to the theoretical 1.22 eV bandgap of silicon at 0 K. The remaining voltage change over the operating temperature of typical integrated circuits is on the order of a few millivolts. This temperature dependency has a typical parabolic residual behavior since the linear (first order) effects are chosen to cancel.

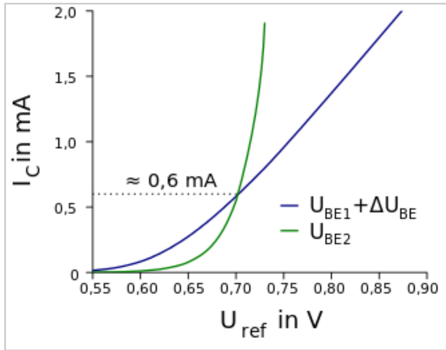


Circuit of a Brokaw bandgap reference

Because the output voltage is by definition fixed around 1.25 V for typical bandgap reference circuits, the minimum operating voltage is about 1.4 V, as in a CMOS circuit at least one drain-source voltage of a FET (field effect transistor) has to be added. Therefore, recent work concentrates on finding alternative solutions, in which for example currents are summed instead of voltages, resulting in a lower theoretical limit for the operating voltage (Banba, 1999).

Note that sometimes confusion arises when using the abbreviation CTAT, where the "C" is incorrectly taken to mean "**c**onstant" rather than "**c**omplementary". To avoid this confusion, although not in widespread use, the term **c**onstant **w**ith **t**emperature (CWT) is sometimes used.

When summing a PTAT (Proportional to Absolute Temperature) and a CTAT (Complementary to Absolute Temperature) current, only the linear terms of current are compensated, while the higher-order terms are limiting the TD (Temperature Drift) of the BGR at around 20ppm/°C, over a temperature range of 100 °C. For this reason, in 2001, Malcovati [5] designed a circuit topology that can compensate high-order non-linearities, thus achieving an improved TD. This design used an improved version of Banba [4] topology and an analysis of base-emitter temperature effects that was performed by Tsividis in 1980.[6] In 2012, Andreou [7] [8] has further improved the high-order non-linear compensation by using a second opamp along with an additional resistor leg at the point where the two currents are summed up. This method enhanced further the curvature correction and achieved superior TD performance over a wider temperature range. In addition it achieved improved line regulation and lower noise.




Characteristic and balance point of T1 and T2

The other critical issue in design of bandgap references is power efficiency and size of circuit. As a bandgap reference is generally based on BJT devices and resistors, the total size of circuit could be large and therefore expensive for IC design. Moreover, this type of circuit might consume a lot of power to reach to the desired noise and precision specification.[9]

Despite these limitations, the bandgap voltage reference is widely used in voltage regulators, covering the majority of 78xx, 79xx devices along with the LM317, LM337 and TL431 devices. Temperature coefficients as low as 1.5 - 2.0 PPM/°C can be obtained with bandgap references (LT6657 from Linear Technology and ADR4550 from Analog Devices). Bandgaps are also suited for low-power applications (1 µA cathode current with the Maxim Integrated MAX6009 shunt voltage reference).

## Patents

- 1966, US Patent 3271660, *Reference voltage source*, David Hilbiber.[10]
- 1971, US Patent 3617859, *Electrical regulator apparatus including a zero temperature coefficient voltage reference circuit*, Robert Dobkin and Robert Widlar.[11]
- 1981, US Patent 4249122, *Temperature compensated bandgap IC voltage references*, Robert Widlar.[12]
- 1984, US Patent 4447784, *Temperature compensated bandgap voltage reference circuit*, Robert Dobkin.[13]

## See also

- Brokaw bandgap reference
- LM317
- Silicon bandgap temperature sensor

## References

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2. Widlar, Robert J. (February 1971), "New Developments in IC Voltage Regulators", *IEEE Journal of Solid-State
3. Brokaw, Paul (December 1974), "A simple three-terminal IC bandgap reference", *IEEE Journal of Solid-State Circuits*, **9** (6): 388–393, doi:10.1109/JSSC.1974.1050532

4. Banba, H.; Shiga, H.; Umezawa, A.; Miyaba, T.; Tanzawa, T.; Atsumi, S.; Sakui, K. (May 1999), "A CMOS bandgap reference circuit with sub-1-V operation", *IEEE Journal of Solid-State Circuits*, **34** (5): 670–674, doi:10.1109/4.760378
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6. 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, pp. 1076 – 1084, Dec. 1980.
7. C. M. Andreou, S. Koudounas, and J. Georgiou, "A Novel Wide-Temperature-Range, 3.9ppm/$^o$C CMOS Bandgap Reference Circuit," IEEE Journal of Solid-State Circuits, vol.47, no. 2, pp. 574–581, Jan. 2012, doi:10.1109/JSSC.2011.2173267 (http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6078439&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6078439)
8. S. Koudounas, C. M. Andreou and J. Georgiou, "A Novel CMOS Bandgap Reference Circuit with Improved High-Order Temperature Compensation," IEEE International Symposium on Circuits and Systems (ISCAS), Paris, France,2010 pp. 4073-4076, doi:10.1109/ISCAS.2010.5537621 (http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=5537621&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D5537621)
9. A. Tajalli, et al. ,"Design and optimization of a high PSRR CMOS bandgap voltage reference," IEEE ISCAS 2004 DOI: 10.1109/ISCAS.2004.1328127 [1] (http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=1328127&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D1328127)
10. US Patent 3271660 - *Reference voltage source*, David F Hilbiber; United States Patent and Trademark Office; September 6, 1966. (https://www.google.com/patents/US3271660)
11. US Patent 3617859 - *Electrical regulator apparatus including a zero temperature coefficient voltage reference circuit*; Robert C Dobkin and Robert J Widlar; United States Patent and Trademark Office; November 2, 1971. (https://www.google.com/patents/US3617859)
12. US Patent 4249122 - *Temperature compensated bandgap IC voltage references*; Robert J Widlar; United States Patent and Trademark Office; February 3, 1981. (https://www.google.com/patents/US4249122)
13. US Patent 4447784 - *Temperature compensated bandgap voltage reference circuit*; Robert C Dobkin; United States Patent and Trademark Office; May 8, 1984. (https://www.google.com/patents/US4447784)


# External links

- The Design of Band-Gap Reference Circuits: Trials and Tribulations (http://www.ti.com/ww/en/bobpease/assets/www-national-com_rap.pdf) p.286 – Robert Pease, National Semiconductor
- Features and Limitations of CMOS Voltage References (http://ecad.tu-sofia.bg/et/1999/Statii%20ET99-I/Features%20and%20Limitations%20of%20CMOS%20Voltage%20References.pdf)
- ECE 327: LM317 Bandgap Voltage Reference Example (http://www.tedpavlic.com/teaching/osu/ece327/lab3_vreg/lab3_vreg_lm317_example.pdf) – Brief explanation of the temperature-independent bandgap reference circuit within the LM317.

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- This page was last modified on 30 December 2016, at 02:48.