

References Supplied on Request



Paul Brokaw's stamp on analog IC design

Paul Brokaw may be known to most IC designers as the inventor of the industry standard two-transistor bandgap voltage reference named after him, but Brokaw has made many

distinct contributions to circuit design and the culture of design, all of which have left a strong and lasting legacy. Among IC designers, Paul Brokaw is one of the greats.

Every mixed-signal IC uses a voltage reference. Except for a very few that use a buried Zener diode that requires special masks for fabrication, all of the rest are Brokaw's bandgap circuit [1] (cited ~600 times). Even voltage references in CMOS cannot be built without

two p-n junctions (usually parasitic bipolar transistors) biased at unequal current density and configured as a variant on Brokaw's circuit.

This came fast on the heels (within 1.5 years) of Kuijk's first description of the bandgap principle with a three-transistor circuit. But Brokaw's circuit (Figure 1) allowed the output to be defined by a resistor ratio, as a multiple (greater than one) of the

intrinsic 1.2 V at which the p-n junction forward voltage when added to a voltage proportional to ΔV_{BE} gives a nominally zero temperature coefficient. There were many other advantages to Brokaw's circuit, such as better immunity to "input" changes, that is, changes in the supply voltage. The first standalone product came in a three-terminal package: unregulated supply voltage, ground, and bandgap voltage output. The typical reference voltage accuracy was 0.5%, and the temperature coefficient was 50 ppm/°C. A particularly elegant touch is Brokaw's method to null the error caused by nonzero-base currents on display in his voltage-scaling bandgap voltage cell.

The circuit was internally compensated for feedback stability: Brokaw's analysis of the bandgap circuit's stability in [1] is as insightful as Solomon's for two-stage operation (op) amps [2], which appeared in the same issue of *IEEE Journal of Solid-State Circuits*. Although [2] has remained the standard teaching tool to date for the on-chip compensation of two-stage op amps, the Brokaw analysis is so polished (Figure 2) that only after development and widespread use of operational transconductance amplifiers for all-capacitor loaded CMOS circuits

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would it be recognized as the best way to model for stability with adequate phase margin.

The AD580 voltage reference has remained in production continuously since the mid-1970s, and from 1993 (when records are easily accessible, courtesy of Dave Robertson of Analog Devices) to the present, it has garnered a revenue of US\$30 million. This is the tip of the iceberg in terms of commercial impact: the AD580 is the oldest standalone Brokaw bandgap; Analog Devices has since developed a dozen variants, and every major catalog semiconductor company, such as Texas Instruments, Maxim, and others, offers equivalents and variants. All are based on the Brokaw circuit: its design has never been bettered.

The two-terminal electronic thermometer AD590 springing from this circuit has accumulated US\$200 million in revenue since 1993, and probably an equal amount in the

preceding 10 years. It created the industry for the digital thermometer that measures by heat conduction.

If we include the on-chip voltage references used on mixed-signal CMOS chips, it becomes impossible to ascribe a revenue to bandgaps since they are a small piece of a bigger chip, but the volume produced must run to billions per year. They, too, are based on the Brokaw circuit, modified to use substrate bipolar junction transistors (BJTs). Every experienced analog circuit designer has at one time or another designed this voltage reference.

But Brokaw is more than the man behind the standard bandgap reference. He is, for one, a consummate master of the use of on-chip feedback loops that exploit the unique benefits of monolithic realization. In 1971, Analog Devices introduced the monolithic instrumentation amplifier, which offers a very high input resistance, a fully balanced input with a very

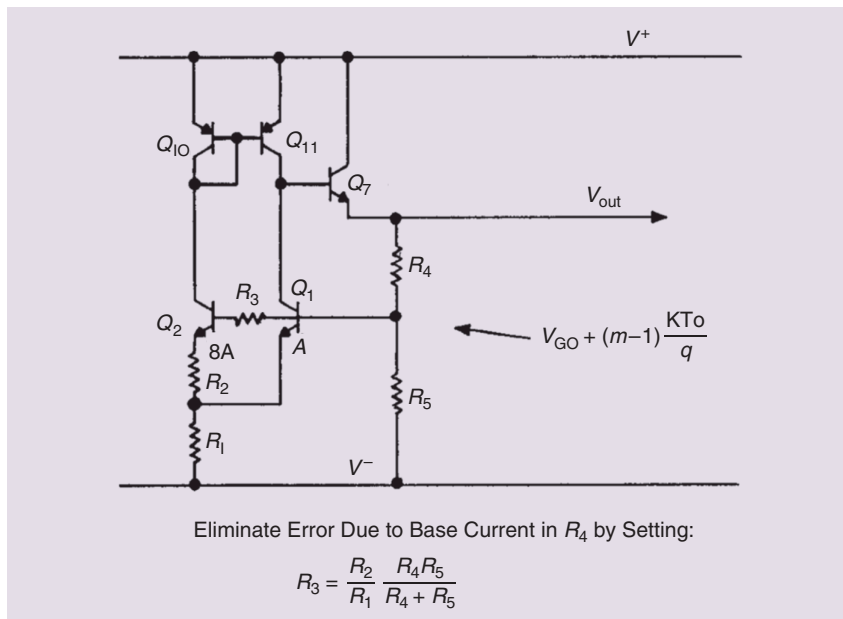


FIGURE 1: Brokaw's original bandgap voltage reference. Image from [1].

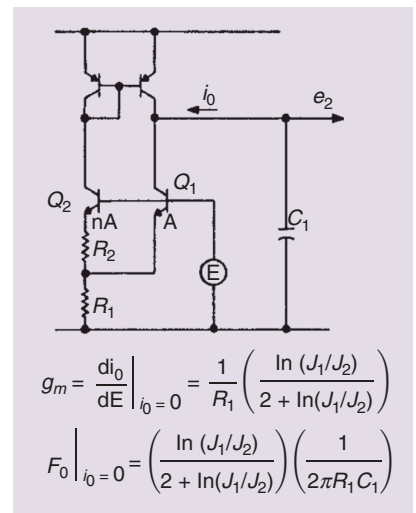


FIGURE 2: A model of the bandgap reference to frequency compensates it for stable feedback. g_m is the effective transconductance, and F_0 is the unity gain frequency. Image from [1].

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high common-mode rejection, and a well-defined gain to a single-ended output with a user-defined common voltage. This is the cornerstone of most sensor interfaces. The first instrumentation amplifier employed a nested feedback loop that is hard to compensate for stability (Figure 3).

Although monolithic, to a certain degree, its topology reflects a discrete op amp legacy. In 1975, Brokaw advanced it [3] by breaking the nested feedback into two independent feedback loops (Figure 4) that are much easier to stabilize individually. In the presence of large

differential input voltages, the input stage transistors carry a constant current, transferring the input voltage accurately to a degeneration resistor. This method would be reinvented in the 1980s for linear CMOS transconductors used in continuous-time Gm-C analog filters. The input stage is specially designed to reject common-mode stimuli very effectively, reaching a common-mode rejection ratio of 120 dB.

Perhaps Brokaw's least well-known contribution to the community—although it may well be his second most important—is the development in 1977 of a 10-b analog-to-digital converter (the AD571), followed shortly by a 12-b converter (the AD574) that uses a successive approximation algorithm and in which the digital-to-analog converter, successive approximation and control logic, comparator, clock, and, of course, voltage reference are, for the first time, all integrated on a single chip [4]. Previous products were multichip modules. The AD574 has been called the “741 of data converters,” referring to the part number of the most famous IC of all time, the 741 op amp. To this day, this converter and its derivatives remain listed in the Analog Devices, Texas Instruments, and Maxim catalogs. There are numerous uses for such a converter, especially when it is priced as a commodity item.

12-b linearity in a monolithic realization is hard to achieve at the best of times: that Brokaw obtained it is due largely to a brilliant innovation, which enables the realization of a binary-weighted array of bipolar current sources using a thin-film, laser-trimmed R-2R ladder. This requires equal emitter voltages across 12 BJTs biased at the same base voltage and degenerated by the resistor ladder, where the currents through adjacent transistors change by a ratio of 2:1. To maintain equal current density, the emitter area would have to be scaled at 2:1 as well, which means that the largest emitter area would be 4,000 times the smallest. This was completely impractical at the

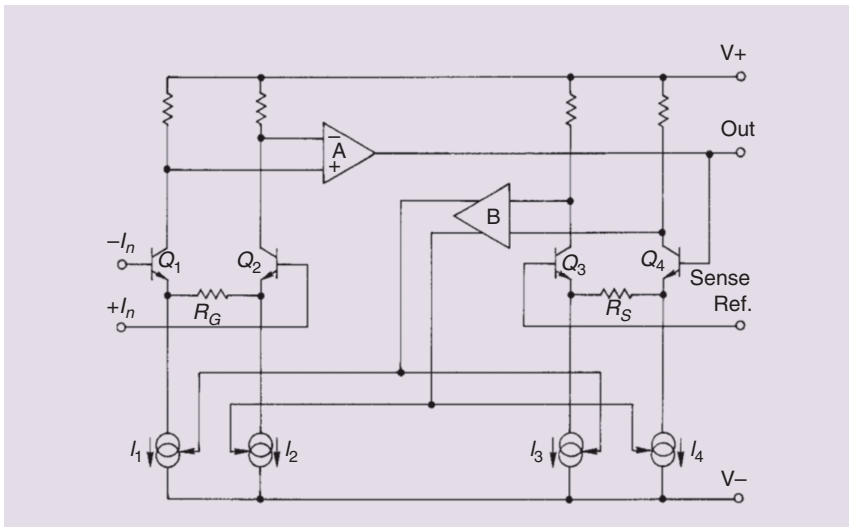


FIGURE 3: A pre-Brokaw Analog Devices instrumentation amplifier, which requires two pairs of well-matched, differentially controlled current sources. Image from [3].

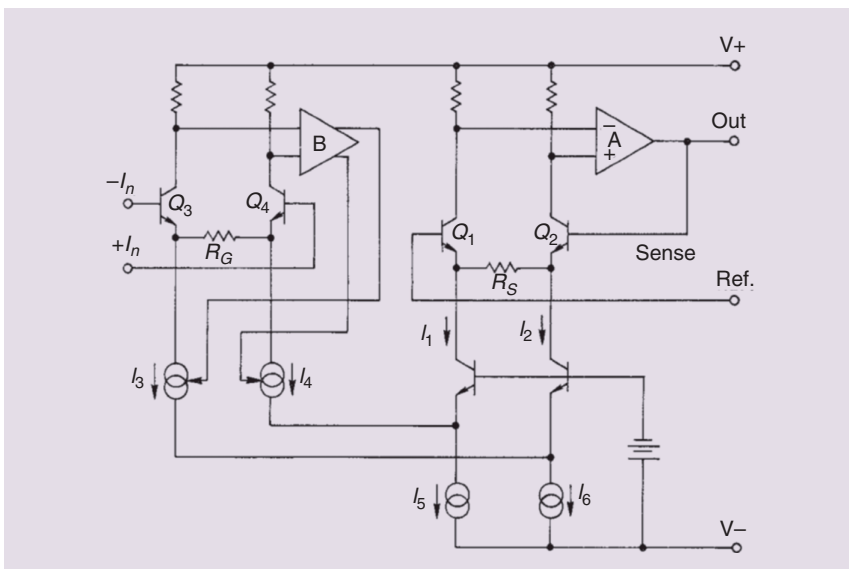


FIGURE 4: Brokaw's instrumentation amplifier. This provides fully differential signal processing up to the output. The topology anticipates the folded cascode.

time. Instead, Brokaw biased the bases off a resistor ladder carrying a proportional-to-absolute-temperature current (Figure 5), with each tap being apart in voltage by $V_T \log_e(2)$. All of the transistors can now be of the same emitter area, making the layout compact and regular, and the doubling of current density is exactly compensated for by the gradually rising bias voltage at the base. The patent describing this innovation [5] has been called “the most referenced data converter patent ever issued” [6, p. 10]. One sees here the insights from the bandgap circuit proportional-to-temperature current applied in an ingenious way to a binary-weighted current array. Since 1993, the AD571 has earned US\$20 million in revenue and the AD574 US\$130 million.

A large part of Brokaw’s career has been spent as a teacher, a mentor, and an ambassador of the culture of circuit design within various divisions of Analog Devices. When I stumbled across his 1990 application note AN-202, “An IC Amplifier Users’ Guide to Decoupling, Grounding, and Making Things Go Right for a Change” (the title is writ large with Brokaw’s wit), I found it to be the first scientific treatment of problems that every engineer who has designed a circuit board had struggled with (Figure 6). This application note and subsequent writings from Analog Devices inspired me to develop an entire course on the circuit theory of decoupling and grounding. Two IC designers tell me that, of all the literature they have referred to over 30-odd years of practice, this application note is perhaps the most useful.

Those who know Brokaw’s philosophy of design reviews (see the end of this paragraph) yet are courageous enough to seek out his advice will experience first hand his deep engagement with IC designers, which is legendary at Analog Devices [7], [8]. His insistence on not accepting any circuit idea until he understands it fully from first principles is what sets him apart as the great teacher

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and deep thinker: nothing is taken at face value, or just because it sounds right, or especially because Spice says that it is so. His internal memo of 1974 on the philosophy of design reviews has recently been reprinted [9, p. 24], with the following extracts highlighted:

Brokaw believed that a design review should be an adversarial procedure, just as in a court of law. “The reviewers take on the role of prosecutor and the designer takes on the role of defending attorney.”

Design reviews should be a game of wits, where the designer prepares ... an impenetrable defense and the reviewers make a tactical attack prepared to expose any weaknesses.

Recently, I revisited a publication of which Brokaw is coauthor [10] that

bears on some of my recent research on a long-standing problem in radio frequency circuits: What is the mechanism that upconverts flicker noise in the transistors of an oscillator? Over the years, numerous causes have been hypothesized, but none of them has yet led to a cure by design. In this article, an oscillator phase noise spectrum is shown that is free of flicker noise at offsets as low as 1 kHz, with a passing mention that the cross-coupled differential pair was emitter-degenerated with resistors. To have realized this in 1997 when no theory was available—indeed, none is today that convinces—shows an impressively deep insight, which I venture was contributed by Brokaw among its authors.

Paul Brokaw is an innovator, a circuit designer par excellence, a teacher, the invisible hand behind numerous

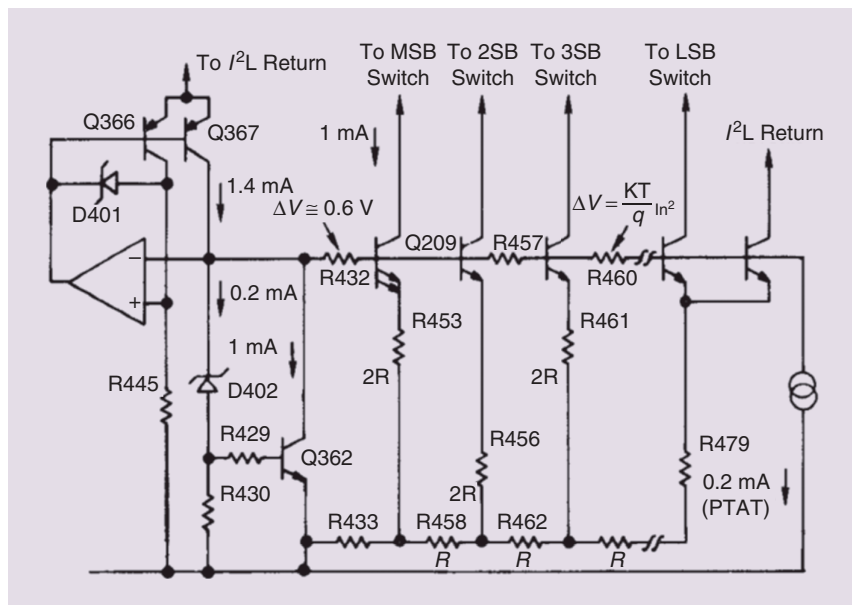


FIGURE 5: A 10- to 12-bit binary-weighted current source array using transistors of an equal emitter area. The 4,000:1 spread in current density is compensated for by a synthesized gradient in base voltages. Image from [4].

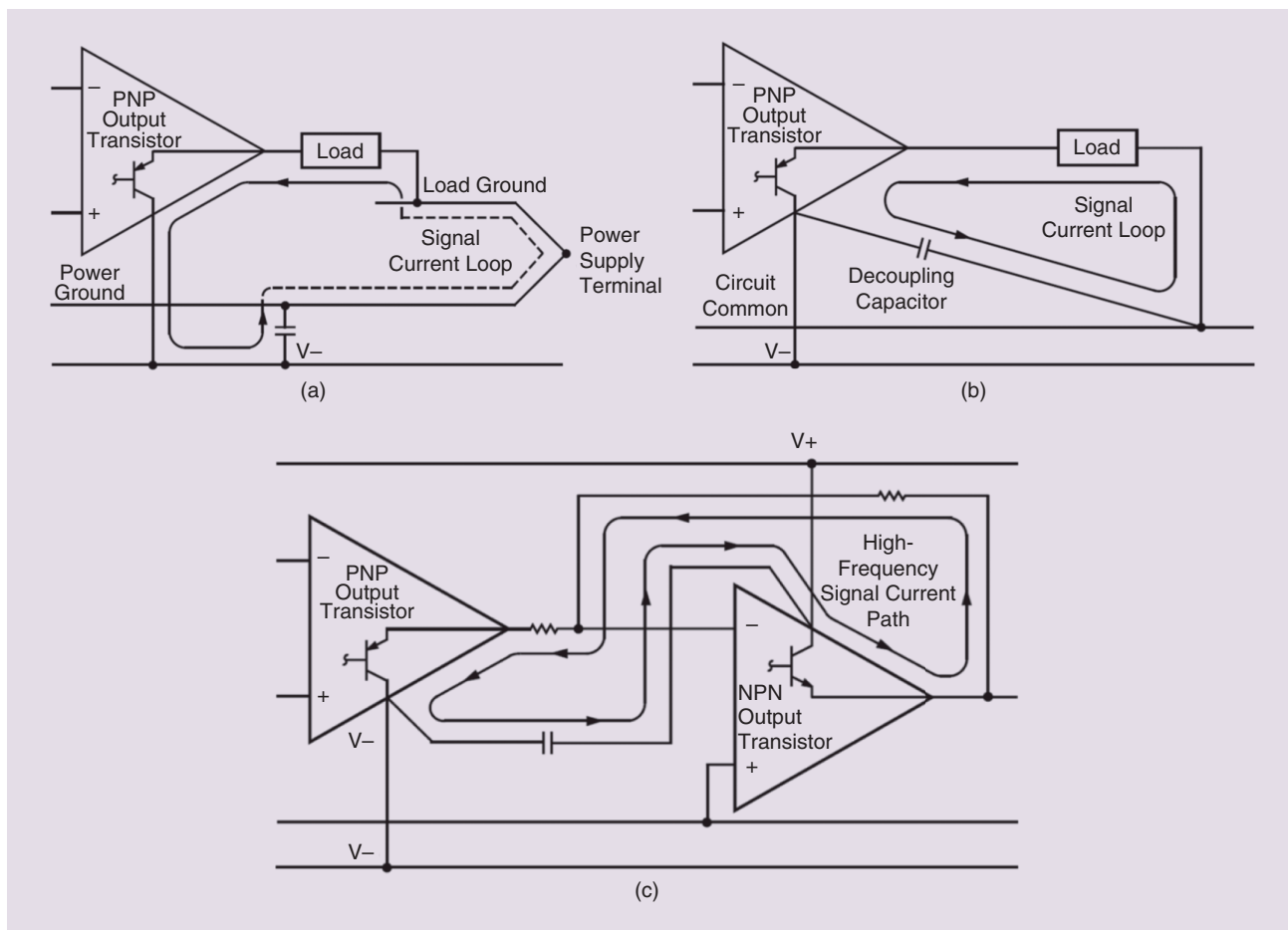


FIGURE 6: The knowledgeable placement of a decoupling capacitor. (a) This connection forces the current to flow into the power supply connector; (b) this returns the load current to the driving transistor over the shortest path; and (c) this returns the signal current in the inverting amplifier over the short path to the driver. Image from Analog Devices Application Note AN-202.

successful products, and a proponent and exemplar of the culture of circuit design. His original contributions span numerous analog circuits, most recently in power electronics.

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