VCAS INVESTIGATED

PART TWO

Continuing Ben Duncan's series, Part Two describes the approaches adopted by three designers and manufacturers of audio VCA ICs and modules

The first widely successful audio VCA using transistors was pioneered and patented between 1970 and 1973 by David Blackmer, co-founder of dbx. In the basic log-antilog VCA (**Fig 10**, Part One, *Studio Sound*, June 1989), operation is limited to one polarity of input signal. In an earlier patent for an audio VCA by Embley (1970), single-ended (unipolar) operation was made workable by suitable biasing. Eight years later, competing VCA pioneer Paul Buff, patented a scheme using full wave rectification at the input to facilitate the required four quadrant operation from a 2-transistor core. But dbx's model *202* was the first VCA to contain a core comprising symmetrical pairs of npn and pnp log-antilog transistors for bi-polar or 'balanced' operation (Fig 1).

dbx

The *202*'s biasing is Class A-B, meaning it's defined by the instantaneous signal level. As in power amplifiers, the minimum standing current is set by a V_{BE} multiplier. In the days when the conformity of npn IC fabricated transistors left a lot to be desired (fabricated pnps not even being mentionable in polite company!), the use of discrete devices in the dbx *202*'s core was a foregone conclusion for close matching. To this end, dbx developed ovens that could hold over 100 transistors under isothermal conditions, while simultaneously measuring and providing identification of those with matching V_{BE} voltages. On the other hand, isothermal conditions in the *202* were limited to improving thermal conductivity between the transistor cases through a thermally conductive ceramic block, interfaced with a silicone coating. If they occurred, 'vertical' temperature differentials between the npn and pnp core transistors (Q1, Q2 in Fig 1) would create an offset voltage (due to V_{BE}'s temperature dependence), leading to a thump when modulated by gain changes. In other words, the *202*'s feedthrough isolation might suffer if it were carelessly sited near parts radiating significant heat. At the same time, Class A-B operation means that feedthrough is inherently low, as the DC (bias) current in the cell, hence % changes created by V_{BE} mismatch, are both orders of magnitude smaller than in log-antilog VCAs operating in Class A.

Then again, with Class A-B operation, the core transistors' temperatures could be internally unbalanced horizontally (between Q1+3 and Q2+4, the loggers and antiloggers respectively) if the VCA's DC input blocking were leaky (leaving it open to DC offset) while being set to attenuate high level programme. Highly asymmetric, high level programme (eg percussion) could arguably have similar consequences: harmonic distortion. According to dbx, thermal inertia residing in the silicon substrate and the metal packaged transistors used in the core of the *202*, means distortion would only rise appreciably at the lowest audible frequencies. And while the distortion would be predominantly odd order, dbx consider that it's overshadowed in practice, by other error mechanisms.

Late in 1978, dbx introduced model *202C*, a refinement of the *202*. Additional circuitry was used to sense when any of the core transistors were approaching currents that would cause log errors, and generated a correction signal to compensate for the error[1]. This doubled the number of matched npn+pnp devices required, to eight. Further, the correction had to be adjusted to suit the transistors in individual cores, making the *202C* more expensive and difficult to manufacture. The benefits were a reduction in distortion of 10 dB or more for a given operating current and S/N ratio. Alternatively, the interplay between THD and S/N ratio meant that designers could choose to reduce the operating current, improving S/N ratio for a given THD. Either way, dbx claim the clean dynamic range is extended from around 110 dB (*202*) to 116 dB or more.

In 1980, dbx responded to demands by customers for a Class A VCA, with the ***2001***. The primary benefit of Class A operation is lower and more consistent distortion in comparison to Class A-B operation. dbx claim a typical midband THD of around 0.001% for the *2001*, contrast 0.03% for the *202* and 0.01% for the *202C*. The disadvantages cited include lower dynamic range, because the sum of V_n and I_n in the core increases in proportion to the square root of current. So in the Class A-B condition, an xdB increase in signal level causes an $x/2$ dB increase in noise. Bias in the Class A core needs to be set as large as the highest anticipated signal current. If this is 200 times higher (+46 dB), noise is then theoretically 22 dB higher under no-signal conditions. However, loss in dynamic range is mitigated by the necessarily high headroom of Class A operation, the *2001* returning a DNR that was only 10 and 16 dB short of the *202* and *202C* respectively. dbx also point out their Class A VCA has degraded feedthrough isolation (typically −66 dB) and greater susceptibility to thermal gradients (typically caused by adjacent hot components). The extent to which these specifications are inevitable consequences of Class A operation *per se* should become clearer later.

The next stage was monolithic construction. Packaged as an IC, temperature gradients across the core could be reduced by closing up the spacing between the core devices by two or more orders of magnitude and by layout that takes account of thermal isobars within the dice. Models *2151*, *2150A* and *2155* arrived in 1981—in the familiar SIL package. The series of numbers disguises a single, selected IC, *2151* being the number stamped on the cream of the batch, with *2155* being salable to the makers of budget audio systems; and *2150A* being the intermediate grade. After four years of development in conjunction with an IC manufacturer, dbx had arrived with a process capable of putting decent pnp transistors on a monolithic substrate in common with matched npns. The monolithic log-antilog core was finally born. The *2100* series ICs even included log conformance correction circuitry (as in the *202C*) to help the core devices along.

When operating in Class A-B, the dbx topology

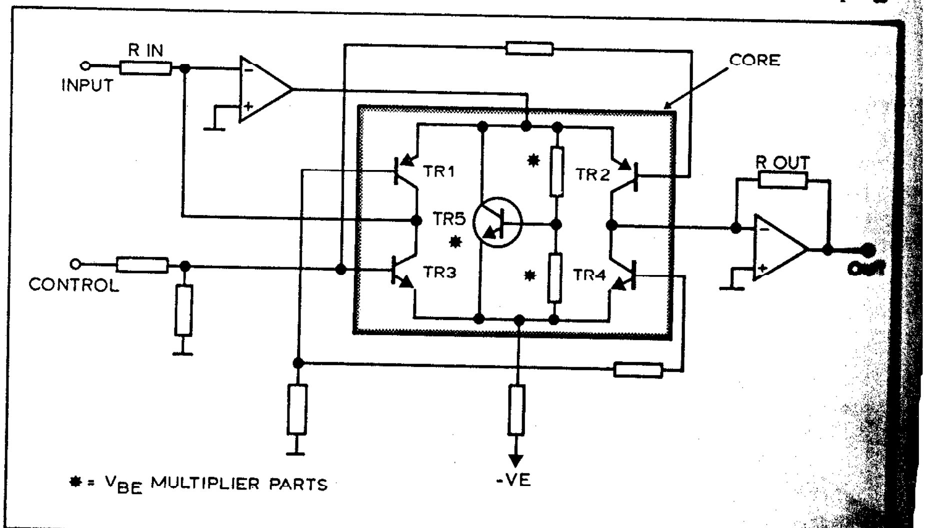


Fig 1: dbx Class A-B log-antilog VCA (excludes log conformance correction circuitry)

has a number of snags. First, at high signal levels, each half of the core is biased off with every polarity reversal. During this transition, the signal current approaches nil. With the remaining Class A-B bias current being as small as possible, the availability of current is restricted at the very point where transconductance is diminishing fast. Avoiding outright crossover distortion at high frequencies while keeping the bias current low relies on the core's input half being partnered with a wide-bandwidth, fast slewing op-amp. At the same time, the logging transistors' gain has to be degenerated, otherwise the poor phase margin and consequent risk of instability restricts the extent to which op-amp speed and open-loop gain can be used to 'kiss it better'.

SNR in Class A-B antilog VCAs is not quite what it seems. When signal levels are small, the standing bias current sets a respectably low noise floor. But then signal levels directly modulate the core current, so noise follows the signal. In real operating conditions, with programme near zero-level, dbx calculate the noise floor rises by 20 dB, though 30 dB has been measured[2] (our own measurements of modulation noise will be included next month). Generally, the noise should be masked by signal, but noise modulation is readily measurable (with suitable filtering or DC stimulation) and is held to be audible under suitable conditions by some sound engineers, as well as by other VCA makers. One explanation for the disparity may lie in the sensitivity of the control ports of dbx's VCAs. If the circuit and PCB designers are careless, excess noise present in the control path is liable to modulate and amplify the residual noise entering the VCA's audio input.

Valley International

Valley International's VCAs are an independent development of dbx's original, symmetrical log-antilog VCA. It began in 1980 with the *EGC-101* (Electronic Gain Control), made by Allison Research, Valley's predecessor. The *TA-101* and *TA-104* arrived in 1982. (Until 1987, Valley International were known as Valley People.)

Unlike other makers' VCAs, Valley's VCA modules contain just the core transistors needed to implement their patented design: *TA-104* and *101* are respectively no more than supermatched quad and octal Transistor Arrays (hence TA). It's not as penny-pinching as it sounds. Space saving, cost and manufacturing convenience aside, the core transistors are arguably the only element in log-antilog configuration that unreservedly benefits from some kind of integrated construction.

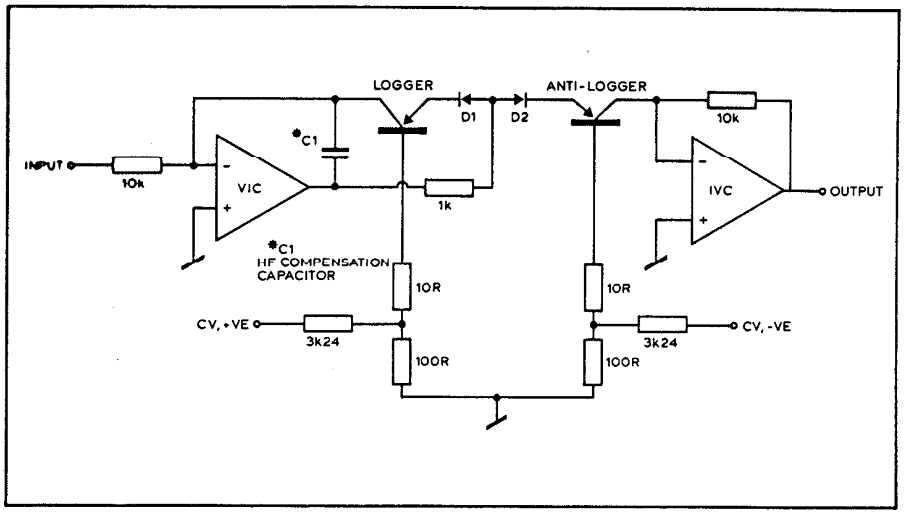


Fig 2: Valley Class A log-antilog VCA core. Simplified half-circuit showing pnp log and antilog transistors only

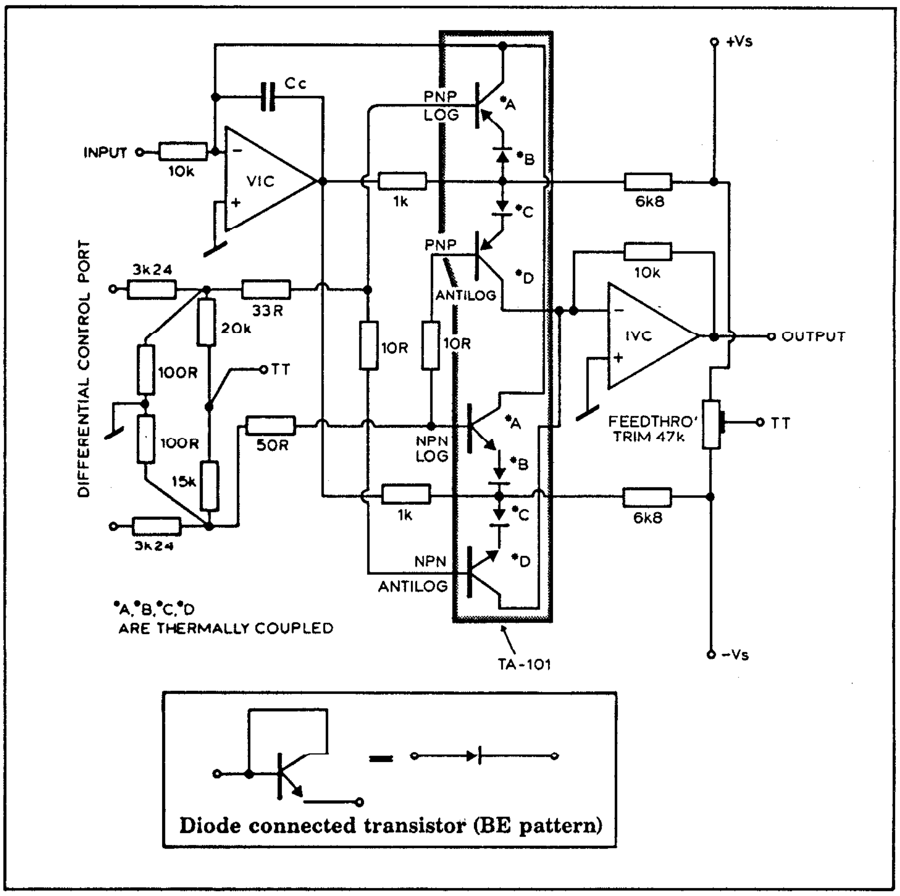


Fig 3: Valley Class A log-antilog VCA—the full circuit

Looking at Fig 3, the shaded area outlines the contents of Valley's prime VCA array, the *TA-101*, surrounded by the recommended support circuitry. Initial comprehension should come a little easier by studying the 'half circuit' in Fig 2, which has been simplified by surgically removing the negative half of the core—meaning it can only pass a unidirectional signal.

Like dbx, Valley's patented Class A VCA scheme is built around a symmetrical core, composed of pairs of pnp and npn transistors. Designer Paul Buff enumerates the residual base-emitter resistance of the core transistors as a source of non-linearity. The resulting THD is proportional to signal current. The symmetry of the pnp-npn core acts to cancel the majority of the 2nd harmonic. While yielding low THD figures, cancellation leaves the 3rd and higher odd-order harmonics produced by Class A-B operation to dominate, together with associated intermodulation products. Nasty. Because Valley's VCAs operate in Class A, distortion is almost exclusively even order, which can be largely nulled by balancing the core transistors. Significant odd order distortion products don't arise until the signal current tries to exceed the bias current, at clip. For the *TA-101*'s recommended bias current of 2 mA, current clipping implies peak input levels beyond 50 VRMS (+36 dBu), so the conditions for producing substantial odd-order distortion are rather hypothetical.

Previous attempts at operating log-antilog cells in Class A had come unstuck. The logging transistor in the classic transdiode configuration (Fig 8, Part One, *Studio Sound*, June 1989) exhibits current gain, which is a nuisance. For a start, it makes the transdiode circuit, an otherwise excellent log amplifier topology, notoriously difficult to stabilise. With 30 to 40 dB of current gain present inside the feedback loop of the associated op-amp, VHF instability is likely even with a tame UGS chip like LF351. Second, the unwanted gain magnifies voltage and current noise (V_n and I_n). This has a direct effect on audio S/N ratio, since current fluctuations in the core are recovered as signal voltage. Third, the gain in the core can magnify the bias current.

Valley's VCA patent specifies the use of diodes in series with the core devices, to reduce the excess gain. As a result, VHF stability can be guaranteed with a simple lead compensation capacitor (C1 in **Fig 2**), which can be kept small in value, thereby preserving the op-amp's bandwidth and slewing capabilities. Precise electrical and thermal matching between each transistor and its associated diode is achieved by doubling the number of core transistors, then connecting the extra ones as diodes (**Fig 3a**). With the diode degeneration in place, the intrinsic scale factor of the Valley VCA's control port doubles, to 120 mV per decade I_c, or 120/20=6 mV per dB. Bias current is only apportioned equally between the two halves of the core (pnp+npn) when the control signal is 0 V and gain is unity. With increasing attenuation, the bias current is progressively channelled through the logging transistors, and for gain, bias current is directed likewise into the anti-logging transistors. In this way, the ratio of bias and signal currents in each transistor remains constant, as does the total bias current, irrespective of VCA gain.

V_n is kept at bay by setting the bias current high and making the core devices' geometry as big as is feasible. I_n is minimised by employing low impedances at the core transistors' bases and emitter terminals. Designing for minimum noise at the outset is important, because with Class A operation, the noise voltage at the output is invariant, meaning that S/N ratio falls in proportion to increasing attenuation. At the same time, the Valley scheme should have none of the noise modulation effects that characterise log-antilog VCAs working in Class A-B.

One other trade-off potentially arising from Class A operation is excessive control feedthrough. It doesn't matter whether the VCA is a log-antilog or transconductance type. The same vertical and horizontal temperature gradients that can cause DC offsets and LF distortion in Class A-B VCAs result in a shifting DC residual at a Class A VCA's output. If DC blocking isn't a problem, and assuming the DC offset is small enough not to result in loss of headroom, it need only be considered a source of distortion if it's actually audible. So much depends in turn on the rate of change of the control signal. With the original *ECG-101*, use as a fast acting muting element (one of the toughest tests of control feedthrough rejection) could result in a discernible 'thump'. In the *TA* series, improved thermal coupling reduces control-feedthrough by at least 20 dB. Again, the bottom line rests with the designer and how carefully the control circuitry is configured.

David Blackmer's patent 'Multiplier circuits' is not limited to a specific bias level (hence operating class), so it covers the schemes promoted by Valley. Although Valley, have argued quite reasonably that the *TA* series are not VCAs in themselves (they are just precision-matched transistor arrays), Valley cite Blackmer's patent alongside their own and pay royalties to dbx. At the time of writing, Valley are the only pro-audio VCA manufacturers licensed by dbx.

SSM (Solid State Microtechnology)

SSM was founded in 1975. More than any of the other audio VCA manufacturers, SSM are exclusively into OEM monofab, in manufacturing a variety of audio 'function' chips for inclusion into electronic music and, more recently, pro-audio equipment. In recent years, former and long-serving President Dan Parks realised that amalgamation with a major semiconductor maker was the only way to go to satisfy the company's technological ambitions. In 1988, SSM was acquired by PMI (Precision Monolithics Inc), a major manufacturer of innovative, precision ICs. It's brought the benefit of advanced processes beyond the reach of a small company (in IC manufacture, anything under $100 million is small).

Fig 4 displays the contents of SSM's *2014* (presently their most highly specified VCA chip) together with the main external parts needed to produce a standard VCA. Although substantially integrated, external op-amps (A1, A2) are desirable for decent drive capabilities. The

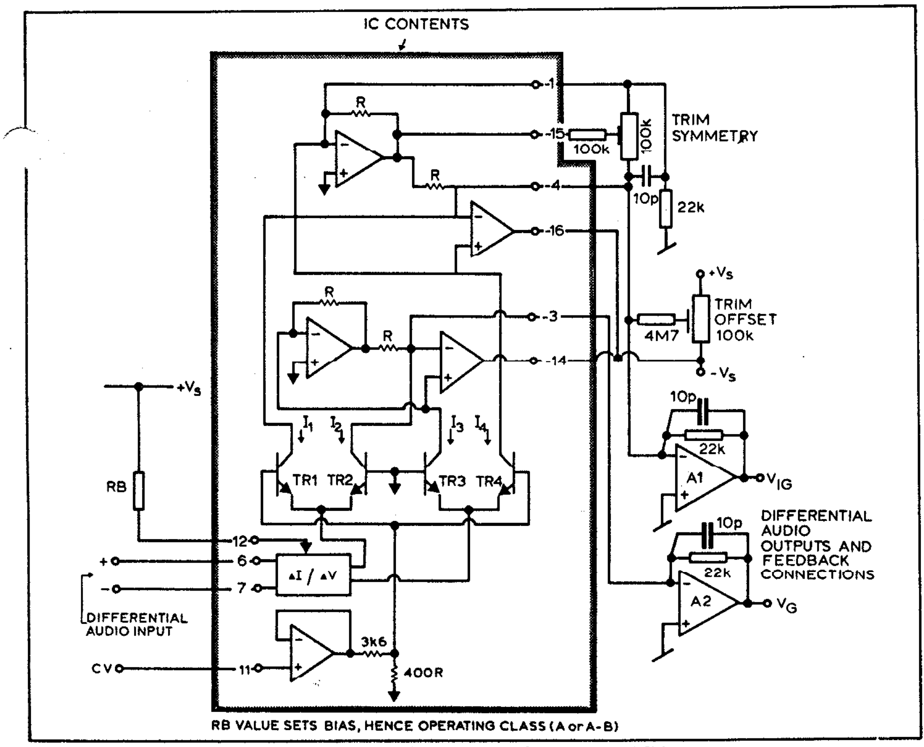
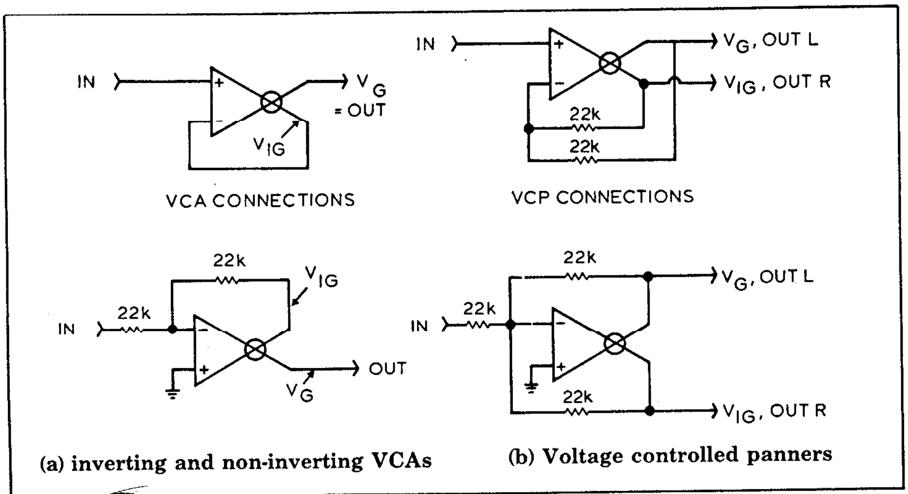


Fig 4: Inside the SSM 2014 advanced transconductance VCA



(a) inverting and non-inverting VCAs

(b) Voltage controlled panners

Fig 5: SSM 2014 circuit permutations

external parts count can be reduced by omitting A1+2 but then the on-board output amps (shown disabled in **Fig 4** by tying their outputs 14 and 16, to −Vs) have limited output current. The problem is an intrinsic one, concerned with the management of heat, rather than a process limitation: the +20 dBu into 600 Ω line driving capability that is demanded by pro-audio designers has to be turned down for their own good! That's because any such output stage in the close confines of a monolithic VCA will almost certainly produce thermal gradients across the cell, unbalancing it. If such a VCA existed, there would be difficulties in deciding at which point to trim THD and feedthrough, as the device warmed up. At best, such a VCA might gain a reputation for only sounding its best after reaching thermal equilibrium, several hours after the console or processor has been switched on. Worse still, a 'heat-saving' Class A-B output stage would thermally modulate the cell to produce a THD rising steeply below 200 Hz.

Returning to SSM's *2014*, the overall circuit is more complicated than any of the previous VCAs, because overall NFB is employed. This gives rise to several permutations: a choice of inverting and non-inverting VCAs (**Fig 5a**) and even VCPs (**Fig 5b**).

All SSM's VCAs are based on a marriage between the current-ratioing transconductance cell and log-antilog core. In his patents of 1981 and 1984, co-designer Douglas Frey has developed a topology that is suited to low cost monolithic production, meaning it has to beget good yields. To begin with, the cell can be implemented with just npn or pnp devices—or both. Restricting the cell to npn devices alone (as in *2014*) saves the cost and design headaches involved in developing a usable pnp process that doesn't infringe existing patents. Second, when operating in Class A-B mode, matching between the cell's four devices is less critical than usual, for good results. In particular, Frey cites improvements in control feedthrough rejection over a previous transconductance type of VCA, where rejection depended on 'extreme matching'—something that is difficult for even the best IC makers to accomplish with high yields and hence low cost. Another perennial problem area, the need for isothermal conditions, is readily accomplished in the *2014*, being a full-scale monofab.

The unique features of SSM's patented VCA technique extend to programmable operation: biasing can be Class A, A-B, or even Sliding-Bias Class A[3,4]. And in Class A-B mode, distortion cancellation circuitry comes into play, yielding a THD residual that's close to Class A. For class selection, only one resistor value need be changed. In fact, for demanding applications, SSM recommend that level detection (an application circuit is supplied with their evaluation PCB) is arranged to switch from Class A-B over to A, at high signal levels. Class switching promises to overcome all the associated tradeoffs—with the caveat that attack and release time constants need careful attention[4], depending on the nature of the programme. According to Ron Dow, SSM's founder and chief designer, provided the class change has a time constant above 10 ms, the main sonic effect of the changeover is a 16 dB change in the noise floor, which shouldn't be audible at the high programme levels where the class change occurs. SSM's model *2018* (due later this year) is scheduled to yield further process refinements leading to reductions in THD, noise and feedthrough.☐

(Part Three will appear next month).

Technical definitions and abbreviations

Cell: Active heart of a variable transconductance VCA
Core: Active heart of a log-antilog VCA
DNR: Dynamic range
H_{FE}: Current gain in a bipolar transistor
I_C: Collector current (in a bipolar transistor)
I_N: Current noise
Isothermal: Areas of equal temperature
Monofab: Monolithic fabrication, a true (not hybrid) IC
NFB: Negative feedback
S/N ratio: Signal to noise ratio
UGS: Unity gain stable
V_{BE}: Base-emitter voltage of a bipolar transistor
VCP: Voltage controlled panner
V_N: Voltage noise
ZOL: Zero operating level, eg +4 dBu
I_c, H_{fe}, V_{be}: The lower case letters indicate incremental (or 'small signal') changes in these quantities

References

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2 P Buff, 'Specsmanship and the new generation of VCA', *RE/P*, pp.138-49, Oct 1982
3 B Duncan, 'Which Amplifier Technology?', *Studio Sound,* Dec 1988
4 R Bransbury, 'Automation and the VCA', *Studio Sound,* Aug 1985