

## FPM 17.5: A Low-Noise Wideband Variable-Gain Amplifier Using an Interpolated Ladder Attenuator

Barrie Gilbert  
Analog Devices, Beaverton, OR

A pervasive thread in implementing voltage-controlled amplifiers has been the use of nonlinear circuit elements directly in the signal path. For example, wide-band variable-gain amplifiers often invoke the exponential  $I_c$ - $V_{be}$  relationship in a bipolar junction transistor to implement a controlled current-fork or a translinear multiplier core. The nonlinear behavior of field-effect transistors has also been widely exploited in this field. All such circuits exhibit various types of residual signal-path nonlinearity (harmonic and intermodulation distortion) caused by non-ideal aspects of transistor behavior and the necessity for "open-loop" design. Furthermore, distortion and noise performance is often degraded by the use of  $V$ - $I$  stages at the input, and the AC and transient response may vary considerably with gain.

In the circuit described here, the signal passes only through elements which are essentially linear: a tapped attenuator and a fixed-gain amplifier which may advantageously employ closed-loop techniques (negative feedback) to enhance linearity. The key concept relates to the way in which the attenuator, a recursive ladder network made from fixed resistors, can be continuously interpolated. These techniques have been incorporated into a monolithic dual-channel amplifier for ultrasound applications. Figure 1 is a micrograph of this device. Each channel provides a gain of typically from 0 to 40dB and may be cascaded to provide 0 to 80dB of gain. The -3dB bandwidth is deliberately lowered to 20MHz to meet the specific requirements of the application; the same chip with alternative HF compensation can provide dc-100MHz operation. The noise-spectral-density referred to the input has been measured as  $1.3nV/\sqrt{Hz}$ , which, with the maximum input capability of 1V RMS, results in a dynamic range of 178dB in a 1Hz BW. The peak output is  $\pm 3V$  using  $\pm 5V$  supplies. The gain is voltage-controlled at a differential port with an accurate, temperature-stable scale of 32dB/V; the high input impedance ( $15M\Omega$ ) facilitates driving a large array of amplifiers from a common control source. The amplifier also includes a signal-gating ("channel OFF") feature, not discussed further here.

Electronic control of the gain of a signal channel requires that one or more parameters of the circuit be varied in response to the controlling input. In those cases where discrete steps of gain are permissible, various kinds of switching circuits can be used. For example, Figure 2 shows a method for controlling gain using a tapped attenuator and a series of switches, which might be MOS transistors, to select one tap at a time. Any resistor ratio can be used in the attenuator, but the  $R$ - $2R$  form found in binary-weighted applications might conveniently be used, providing an attenuation of 6.02dB per tap. (An  $R$ - $R$  network provides 8.36dB per section.) Since both the attenuator and the amplifier are essentially linear elements, distortion can be arbitrarily low. The amplifier can be optimized to provide ultra-low noise since it is never called upon to handle large input voltages. Other attributes of the amplifier, such as its amplitude and phase response, can be held under tight control, because of the fixed gain of open-loop block and the use of negative feedback. The distortion of such a system is a function primarily of the output amplitude, and does not fundamentally alter with the gain.

Importantly, this approach automatically results in a very precise decibel-scaled (exponential) gain law, arising directly from the recursive nature of the ladder network. This

is in contrast to previous methods, in which the provision of an exponential control law often depends on the bipolar  $I_c$ - $V_{be}$  relationship, and which may not be exact even for ideal devices (as in the voltage-controlled current-fork) nor accurate in practice (due to non-ideal device behavior). Furthermore, the practical need invariably arises for strong temperature-compensation in such cells ( $kT/q$  cancellation).

This idea can be extended to provide continuous control of gain as shown in Figure 3. The gm-stage associated with the input of the operational amplifier in Figure 2 has been replaced by  $N$  such stages. If the tail currents  $I_j$  of these gm-stages were simply a single source  $I_e$ , switched discretely from  $j=1$  to  $j=N$ , the situation would be similar to that in Figure 2. However, if the current  $I_e$  could somehow be steered smoothly from one gm-stage to another, and the transconductances varied (not necessarily in proportion) with  $I_e$ , the effect would be to interpolate between attenuator taps. This is achieved through the use of a special circuit shown in Figure 4; bipolar transistors are shown for the gm stages, but MOS devices can also be used. The lower rank of transistors generates a partially-overlapping series of Gaussian-shaped current pulses, each of slightly less than  $I_e$  in amplitude, in response to a linear voltage change at the ends of the base network. Figure 5 shows the typical form of these current pulses. It can be shown that a voltage of  $8 \cdot I_b R_b$  is required to move the current  $I_e$  from one gm-stage to the next, that is, to change the gain by 6.02dB. The voltage  $I_b R_b$  can be very precisely introduced into the network, and thus gain scaling can be accurately traced to an on-chip voltage reference, in this case, a band-gap circuit. The emitter current pulses are thus applied to each gm stage in turn, with some overlap between them. Although  $I_e$  controls the magnitude of transconductance of each pair, and thus bandwidth of the feedback amplifier, it does not materially affect the gain accuracy, which is defined primarily by the feedback attenuator. Its value is chosen as 1.8mA to meet shot noise requirements, and it is made proportional to absolute temperature to further stabilize gain and bandwidth.

Figure 6 shows typical AC response results. The -3dB bandwidth is 20MHz and essentially independent of the gain, which was plotted for gain-control input voltages of 0 through 1.25V resulting in gains of 0 through 40dB. There is a subtle new source of distortion, which can be reduced to arbitrarily low levels, arising from the fact that more than one (nonlinear) gm stage is simultaneously contributing to the output.

#### Acknowledgments:

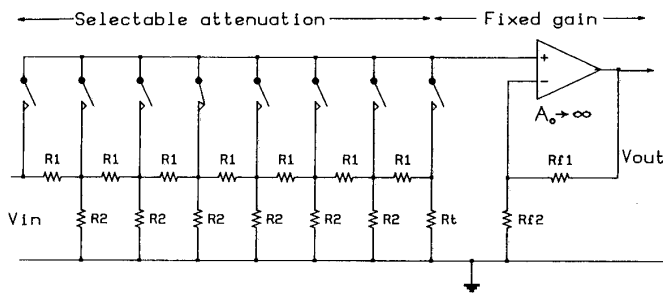
This development owes much to F. den Brejeen for market research, T. Freitas layout, B. Beucler, F. Holden, and T. Kelly for product engineering.

#### Reference

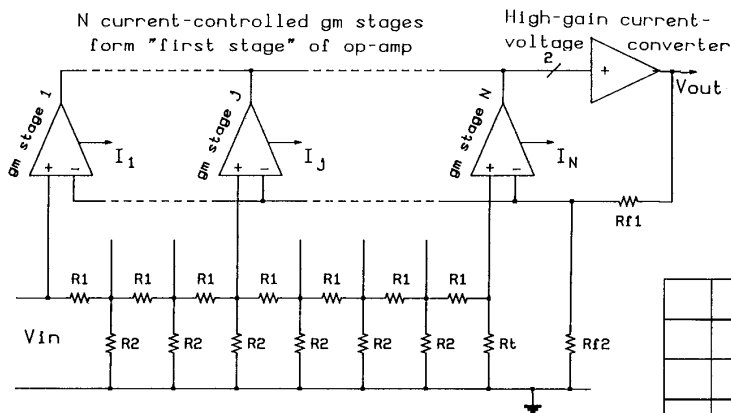
<sup>1</sup>A Monolithic Microsystem for Analog Synthesis of Trigonometric Functions and Their Inverses", JSSC Vol. SC-17, No. 6, December 1982

See also US patent 4,475,169 "High-accuracy Sine-Function Generator", issued October 2, 1984, Other patents pending

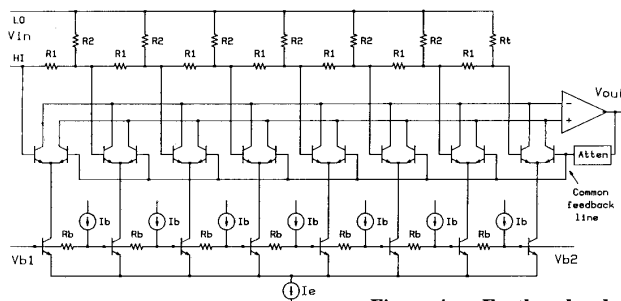
FIGURE 1 — See page 330



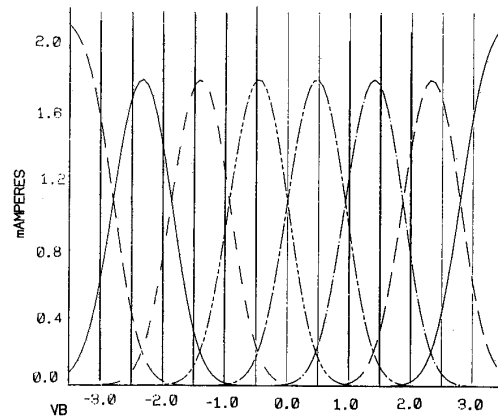
**Figure 2:** Discrete-step scheme: each section of ladder network attenuates input by a constant decibel amount



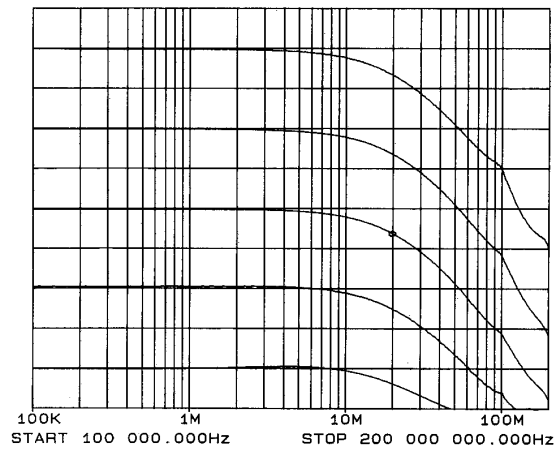
**Figure 3:** N current-controlled gm-stages at input of op-amp allow attenuation taps to be smoothly interpolated



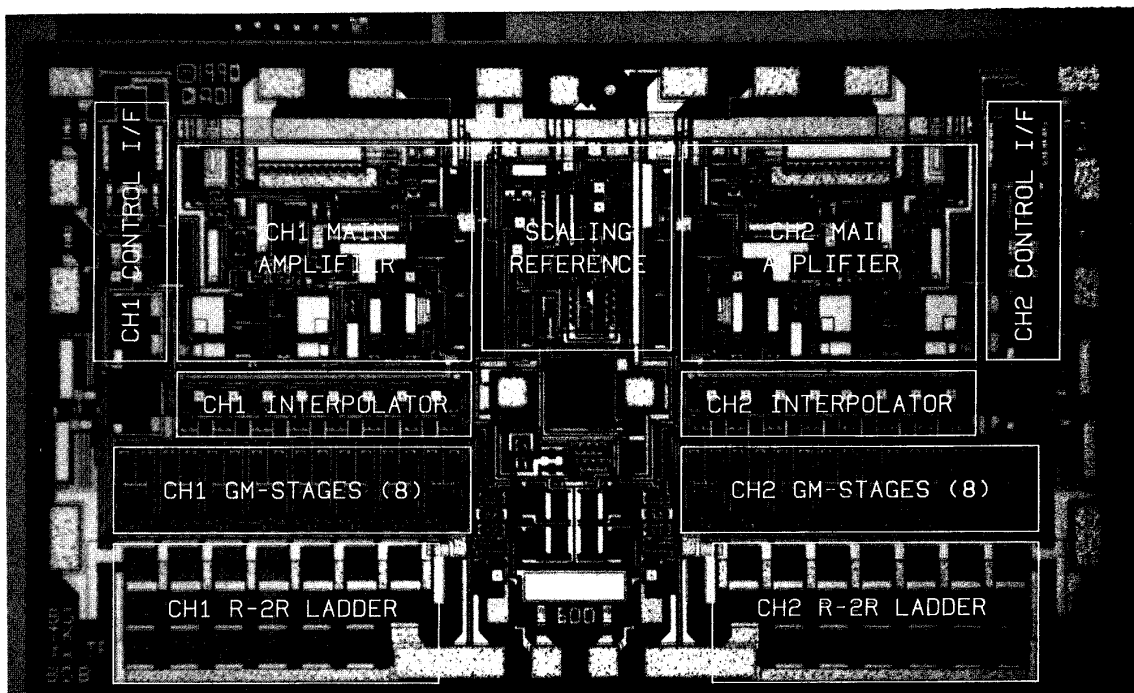
**Figure 4:** Further development shows the bipolar gm-stages and the basic Gaussian interpolation circuit



**Figure 5:** Typical form of the emitter control currents at  $T=300K$ ;  $V_B$  is the difference voltage  $V_{b1}-V_{b2}$  (Figure 4)



**Figure 6:** AC response for gains of 0dB to 40dB. Vertical scale is 5dB/div; -3dB bandwidth is 20MHz



**Figure 1:** Micrograph of the low-noise dual-channel variable-gain amplifier