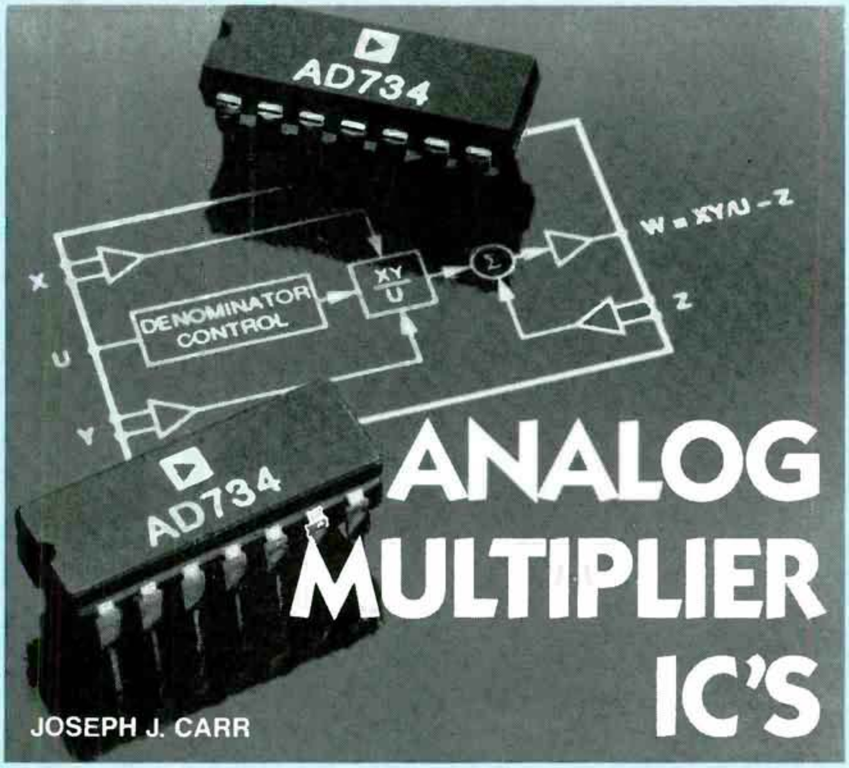
Learn how to multiply, divide, square, and get square roots of analog variables with an analog multiplier, and put that skill to work in your experiments and projects.



ANALOG MULTIPLIER IC'S

JOSEPH J. CARR

MONOLITHIC ANALOG MULTIPLIERS can multiply, divide, square, and extract the square root of analog inputs that represent various arithmetical values. Multiplier IC's can accept one or two inputs, and calculate analog outputs with few external components. These analog "math blocks" play important roles in data acquisition, automatic control, and instrumentation circuits. It's all a matter of how the input signals are connected to the multiplier.

Most popular IC multipliers perform what is called *variable-transconductance* multiplication in which the emitter currents of matched pairs of bipolar transistors are controlled. The calculations are represented by variations in gain. The results are then linearized and converted from differential to single-ended values.

Along about now you are probably saying to yourself: Who needs analog multipliers when there are so many low-cost digital computation techniques? The answer is that analog multipliers are appropriate where the factors needed for arithmetical calculations are analog signals representing "real-world" variables such as voltage, frequency, temperature, pressure, or flow rate.

The analog multiplier can perform the arithmetical calculations at or near the sensors or transducers that produced the variables. Moreover, the result will reflect instantaneous changes in the variables. If it is necessary to transmit the arithmetic solution to a remote computer, data logger, or display, only one channel will be needed, not the two or three that would be required if all variables were transmitted separately. Today that single analog result can easily and economically be converted to a binary code for more reliable transmission over long distances.

Analog multipliers are components in voltage-controlled amplifiers and video mixers. They are also found in radar receivers where they process radar returns, and they are in sonar receivers where they are located in automatic gain control circuits.

Specific applications for "math blocks" are:

- An *analog multiplier* can modulate or demodulate signals, make remote gain adjustments, measure power, or assist in curve fitting and linearizing.
- An *analog divider* can compute ratios of efficiency, attenuation, or gain, and then measure those ratios. It can also make remote gain adjustments.
- An *analog squarer* can double frequencies or measure the power of constant loads.
- An *analog square rooter* can compute vectors, root-mean squares (RMS), or linearize a flowmeter.

Don't be surprised if these "math blocks" are unfamiliar to you. Most readers of this magazine have studied such basic analog circuits as the operational amplifier and the linear circuits like active filters that include op-amps. But it's safe to assume that most have not studied analog "math blocks" unless they work in the analog instrumentation field.

Introductory electronics texts usually don't mention analog multipliers although they do describe the voltage multiplier, a different kind of circuit entirely. Moreover, most electronic engineering handbooks limit their coverage of analog multipliers to a paragraph or so. It turns out that IC manufacturers' data books and applications sheets and analog circuit design textbooks remain the best sources of information on those analog products.

Analog multipliers, like op-amps, had their origins back in the days when analog computation was the only game in town. Multipliers have evolved from discrete-component modules to hybrids since the 1960's—and they are now available as monolithic IC's with differing levels of complexity and on-chip support circuitry.

Figure 1 is a simplified block diagram of a single-ended multiplier that includes a gain-conditioning op-amp. The block, labeled "M," represents the multiplier "core," and the triangle represents the op-amp. The input signals are labeled X and Y. The circuit represented by this diagram can multiply, divide, square, or extract square roots if the proper external connections are made.

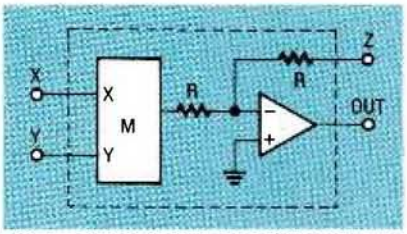


FIG. 1—FUNCTIONAL BLOCK DIAGRAM of a typical multiplier/divider.

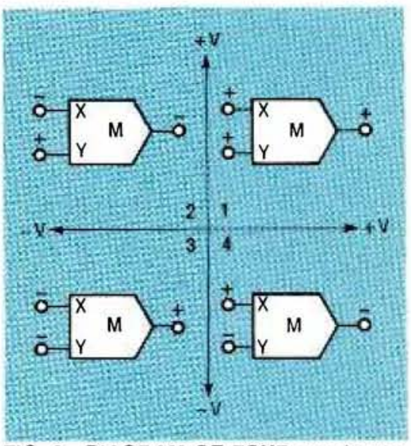


FIG. 2—DIAGRAM OF FOUR quadrants for multiplier shows how output polarity relates to input polarities.

Quadrants of operation

It will be useful to review the concept of quadrants before discussing multiplier circuitry: *single quadrant-*, *two-quadrant-* and *four-quadrant- operation*. Refer to Fig. 2 and notice the differences in the polarity symbols at the dual inputs and single output of each of the four five-sided symbols that represent a multiplier. The four quadrants are defined by Cartesian coodinates—right out of your old trigonometry book.

It can be seen that:

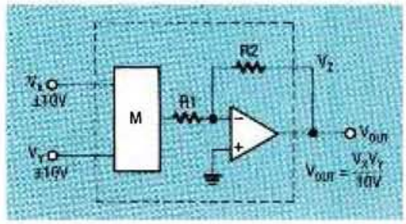


FIG. 3—MULTIPLIER IC CONNECTED as a multiplier.

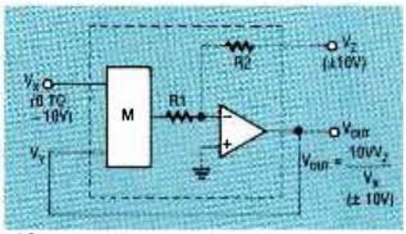


FIG. 4—MULTIPLIER IC CONNECTED as a divider.

- In Quadrant 1 both horizontal and vertical axes are positive, and that X and Y inputs to the multiplier are both positive, so its output is positive.
- In Quadrant 2 the horizontal axis is negative but the vertical axis is positive. The X input to the multiplier is negative and the Y input is positive, so its output is negative.
- In Quadrant 3, both the horizontal and vertical axes are negative. Because both X and Y multiplier inputs are negative, its output is positive.
- In Quadrant 4, the horizontal axis is positive but the vertical axis is negative. The X input to the multiplier is positive and the Y input is negative, so its output is going to be negative.

A one quadrant multiplier can handle either positive or negative inputs but not inputs that are either positive or negative. As a result, the output of a one-quadrant multiplier will always be positive.

Figure 3 is a functional block diagram of a four-quadrant multiplier connected for multiplication. The V_Z terminal is connected to the V_{OUT} terminal. The values of V_X and V_Y can be either positive or negative. The transfer function for the multiplier is:

$V_{OUT} = (V_X V_Y)/V_{ref}$

Where V_{ref} is a dimensional constant, usually 10 volts

Replacing V_{ref} with 10V:

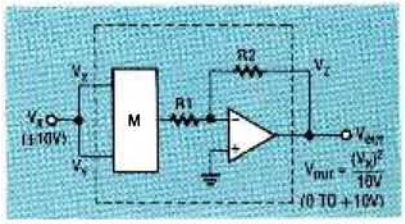


FIG. 5—MULTIPLIER IC CONNECTED as a squarer.

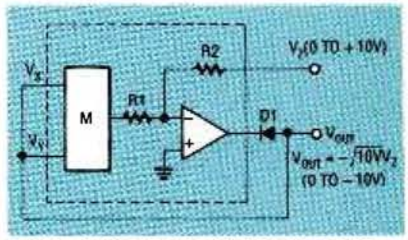


FIG. 6—MULTIPLIER IC CONNECTED as a square rooter.

$V_{OUT} = (V_X V_Y)/10V$

Where V_X and V_Y are limited to $\pm$ 10 volts.

If V_X and V_Y = 10 volts, V_{OUT} = 10 volts

Figure 4 shows the same four-quadrant multiplier connected as a *divider*. The V_Y input is connected to the V_{OUT} terminal, V_X is limited to 0 to -10 volts, and V_Z can be ± 10 volts. For a numerator input V_Z, a denominator input V_X, and a constant of 10V, the equation for division with a multiplier is:

$V_{OUT} = 10V V_Z/V_X$

V_{OUT} will be 10 volts or less for V_Z equal to or less than V_X.

V_X has a single polarity and will not provide a meaningful result if it is close to zero. If V_X can be either positive or negative, the device is a *two-quadrant divider*, and the output will reflect the polarity of V_X.

Figure 5 shows the four-quadrant multiplier connected as a *squarer*. V_X and V_Y are tied together to form a new V_X, which is limited to ± 10 volts. The V_Z terminal is again tied to V_{OUT}. The equation for a squarer is:

$V_{OUT} = (V_X)^2/10V$

A four-quadrant multiplier, used as a squarer, will have an output that is positive whether V_X is positive or negative.

Figure 6 shows the four-quadrant multiplier organized as a *square rooter*. Terminals V_X and V_Y are tied together and connected to the anode of diode D1 at the V_{OUT} terminal. The value

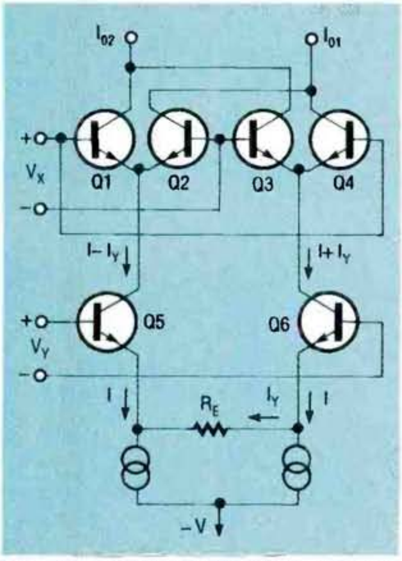


FIG. 7—FOUR-QUADRANT MONOLITHIC modulator is basically two two-quadrant transconductance multipliers.

to be squared (within a range of 0 to +10 volts) is connected to terminal V_Z. If the constant is 10V, the equation for determining the square root is:

$$V_{OUT} = -\sqrt{10VV_Z}$$

V_{OUT} will be in the range of 0 to 10 volts.

A square rooter works in one quadrant: Figure 6 shows an external diode that prevents latchup if the input polarity changes, even momentarily.

Commercial multiplier IC's

Commercial IC multipliers are typically four-quadrant extensions of the basic two-quadrant concept. A simplified four-quadrant monolithic multiplier circuit is shown in Fig. 7. The circuit can be viewed as a pair of cross-connected differential

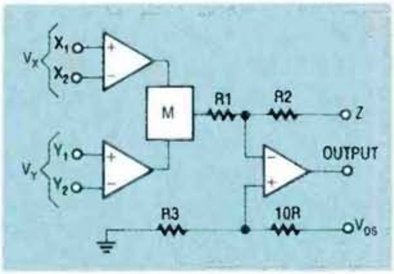


FIG. 8—FUNCTIONAL BLOCK DIAGRAM of an Analog Devices AD532 showing its differential inputs. Note the single Z input and the V_{OS} input.

pairs (Q1 and Q2 with Q3 and Q4) fed by controlled emitter current (from Q5 and Q6). Each half is single differential pair, the basis for the two-quadrant multiplier.

The operation of this transconductance analog multiplier IC will not be explained in detail here because of space limitations. You don't need to know exactly how the circuitry works if you just want to make practical use multipliers. However, there are many excellent references available on the core circuitry of this multiplier, known as the Gilbert "gain cell." (as shown in Fig. 7) in manufacturers' applications notes and analog circuit design texts.

However, notice that the output signals at I_{O2} and I_{O1} are differentially multiplied *currents*. A differential current-to-voltage converter is required to convert the current back to a voltage.

Now, to move this discussion from theory to practice, consider the Analog Devices' AD532, a ready-to-use complete multiplier IC. It multiplies in four quadrants, divides in two quadrants, and square roots in one quadrant. In addition to these basic functions, its differential X and Y inputs provide a lot of operating flexibility for both algebraic computation and transducer output conditioning.

The functional block diagram of the AD532 is shown in Fig. 8, and the complete schematic diagram is shown in Fig. 9. The AD532 IC has 28 transistors, a big increase from the six transistors in the basic Gilbert "gain cell" shown in Fig. 7. The

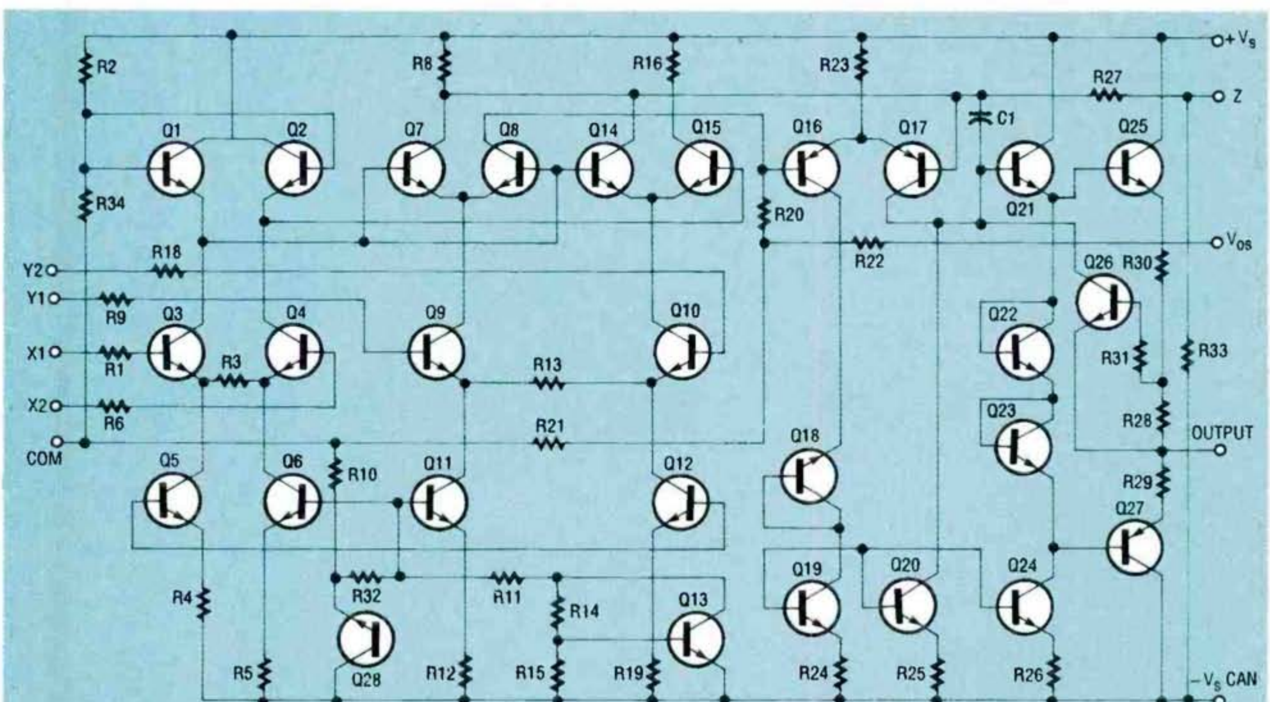


FIG. 9—SCHEMATIC DIAGRAM for a monolithic AD 532 multiplier.

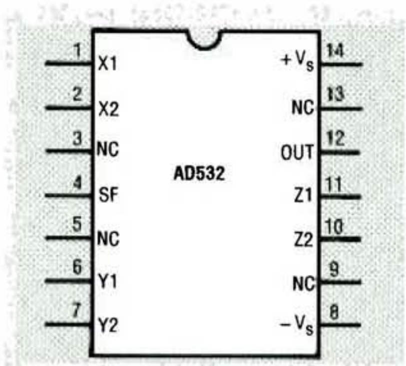


FIG. 10—PINOUT DIAGRAM for an AD532 in a 14-pin DIP.

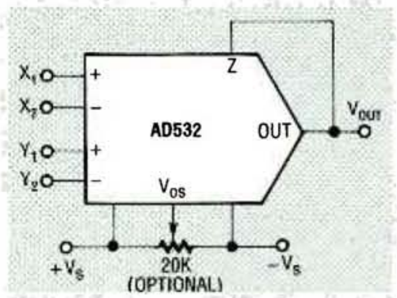


FIG. 11—SCHEMATIC DIAGRAM of the AD532 organized as a multiplier.

AD532 has pretrimmed adjustments for scale factor and offset. The product of the two inputs is resolved in a "gain cell." In the multiplying and squaring modes, the Z terminal is connected to the output to close the feedback around the output op-amp. (In the divide mode, the terminal is used as an input terminal.)

The X and Y inputs are fed to high-impedance differential amplifiers with low distortion and good common-mode rejection. The input voltages are converted to current, and the currents are multiplied together and then divided by a reference. The output current, $I_X \times I_Y/I_{ref}$ is converted to voltage by feedback around the output multiplier. The AD532 has a stated maximum multiplying error of ±1.0%, and offers a 10-volt output. It is powered by a ±15-volt power supply.

The built-in op-amp provides low output impedance and makes self-contained operation possible. The residual output voltage offset can be zeroed as V_{OS} in critical applications. (The V_{OS} terminal should be grounded when not used.)

Figure 10 is the pinout diagram for an AD532 packaged in a TO-116 14-pin DIP. However, it is also available in a hermetically-sealed TO-100 metal can and in a leadless chip-carrier package.

Multiplier

Figure 11 shows the AD532 multiplier organized as a multiplier. Its differential inputs change its transfer function from that given in Fig. 3 to:

$V_{OUT} = (V_{X1} - V_{X2})(V_{Y1} - V_{X2})/10V$

The inputs can be fed differentially to the X and Y inputs, or single-ended by grounding the unused input. Connect the inputs according to the desired polarity in the output. The Z terminal is tied to the output to close the feedback loop. The offset adjust V_{OS} is optional, and it

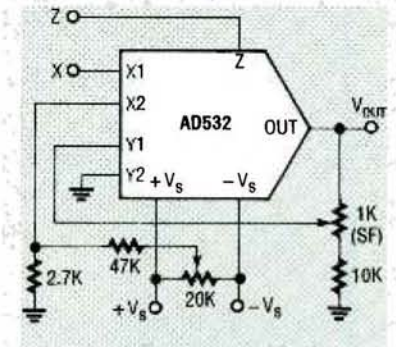


FIG. 12—SCHEMATIC DIAGRAM of the AD532 organized as a divider.

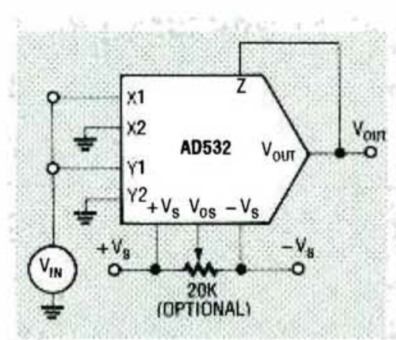


FIG. 13—SCHEMATIC DIAGRAM of the AD532 organized as a squarer.

is adjusted when both inputs are zero volts to obtain zero out, or to cancel the other system offsets.

Divider

The AD532 can be configured as a two-quadrant divider by

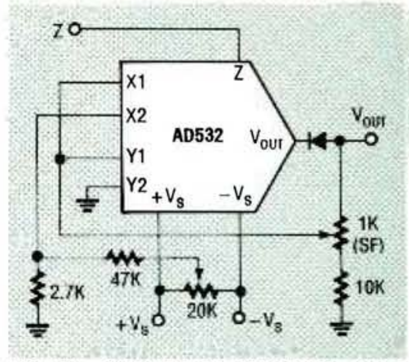


FIG. 14—SCHEMATIC DIAGRAM of the AD532 organized as a square rooter.

connecting the multiplier cell in the feedback loop of the op-amp and using the Z terminal as a signal input, as shown in Fig. 12. The transfer function when X1 is greater than X2 is:

$V_{OUT} = 10V V_Z/(V_{X1} - V_{X2})$

To avoid positive feedback, Analog Devices recommends that the X input be restricted to negative values. Thus for single-ended negative inputs (0 volts to −10 volts), connect the input to X1 and the offset null to X2; for single-ended positive inputs (0 volts to +10 volts), connect the input to X2 and the offset null to X1.

Squaring

The squaring circuit of Fig. 13 is a variation of the multiplier circuit. The transfer function for squaring is:

$V_{OUT} = (V_{X1} - V_{X2})^2/10V$

The differential input capability of the AD532 can be used, however, to obtain positive or negative output response to the input.

Square rooting

The connections for square rooting are shown in Fig. 14. Similar to the divide mode, the multiplier cell is connected in the feedback of the op-amp by connecting the output back to both the X and Y inputs. The diode D1 is connected as shown to prevent latchup as Z_{in} approaches 0 volts. The square rooting transfer function is:

$V_{OUT} = -\sqrt{10V V_Z}$

Here the V_{OS} adjustment is made with Z= 0.1 volts DC, adjusting V_{OS} to obtain −1.0 volts DC in the output, $V_{OUT} = -\sqrt{10V_Z}$.

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VIDEO NEWS

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ment be of the "viewable" diagonal, or the diagonal of the picture itself, rather than the tube. No other country followed our lead. Thus, in the U.S., smaller tubes lost an inch in diagonal measurement, while larger ones lost two inches (representing the thickness of the tube walls).

The new 16:9 TV's are measured the same way—diagonally, the viewable portion in U.S. and overall elsewhere. But because of the different dimensions, they're not directly comparable with standard 4:3 tubes. For example, the biggest widescreen CRT tube size is 34 inches in the U.S. and 36 inches elsewhere. In height, however, it would be the equivalent of a 28-inch standard 4:3 tube (U.S. measurement). A 30-incher is similar to a 25-inch standard tube stretched horizontally, and a 26-inch widescreen is a 21-inch tube with "ears." Ω

WHAT'S NEWS

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imately 60 watts were used to meet the electrical requirements of the heating system, which produced 7.2 kW or 25,000 BTU/hour of heat (about one-quarter the output of a typical home heating system). The "leftover" 100 watts of auxiliary power could have been used to run a sump pump, or even a TV set.

GE's generator is based on the effects of thermoelectricity explored more than 150 years ago by Thomas Seebeck. The Seebeck Effect refers to the electromotive force produced in a circuit formed by two wires of different metals, one of whose junctions is kept at a higher temperature than the other. The GE design includes several thermocouples, each of which has circuitry of dissimilar semiconducting alloys. Electricity is generated by the unequal heating of the two different alloys at their junctions. Ω

ANALOG MULTIPLIER IC'S

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This article is intended as an introduction to the multiplier IC. Any readers interested in performing experiments with the AD532 (or any other Analog Devices analog multipliers/dividers) are advised to request copies of the device's data sheets from:
Analog Devices, Literature Center, 70 Shawmut Road, Canton MA 02021, fax 617-821-4273

Analog Devices multipliers are available in single quantities from Allied Electronics (800-433-5700) or Newark Electronics (312-784 5100) for about $35 each.

Other sources

A comparison of analog multipliers will reveal variations in speed, linearity, signal bandwidth, operating quadrants, and internal circuitry.

Motorola offers two monolithic four-quadrant multipliers that also operate on the variable transconductance principle, the MC1494L/1595L and the MC1495L/1595L.

With associated peripheral circuitry, the MC1494/1594 can multiply, divide, square root, and determine mean squares. It can also function as a phase detector, frequency doubler, balanced modulator/demodulator, and an electronic gain control. It is powered from a ±15-volt supply.

Harris Semiconductor offers two wideband, two-quadrant analog multipliers, the HA-2546 and the HA-2547. The HA-2546, for example, is a two-quadrant device that has a voltage output with a 30-MHz signal bandwidth, 300 volt-per-microsecond slew rate, and a 17-MHz control input bandwidth.

Harris says that the HA-2546 is well suited for AGC circuits as well as mixer applications for sonar, radar and medical imaging equipment. The voltage output of the HA-2546 eliminates the current-to-voltage conversion stage required for current-output multipliers. Ω