Raytheon

Analog Multiplier RC4200

Features

- High accuracy
  Non-linearity — 0.1% maximum
  Temperature coefficient — 0.005%/°C maximum
- Multiple functions
  Multiply, divide square, square root, RMS-to-DC conversion, AGC, and modulate/demodulate
- Wide bandwidth — 4MHz
- Signal-to-noise ratio — 94dB

Description

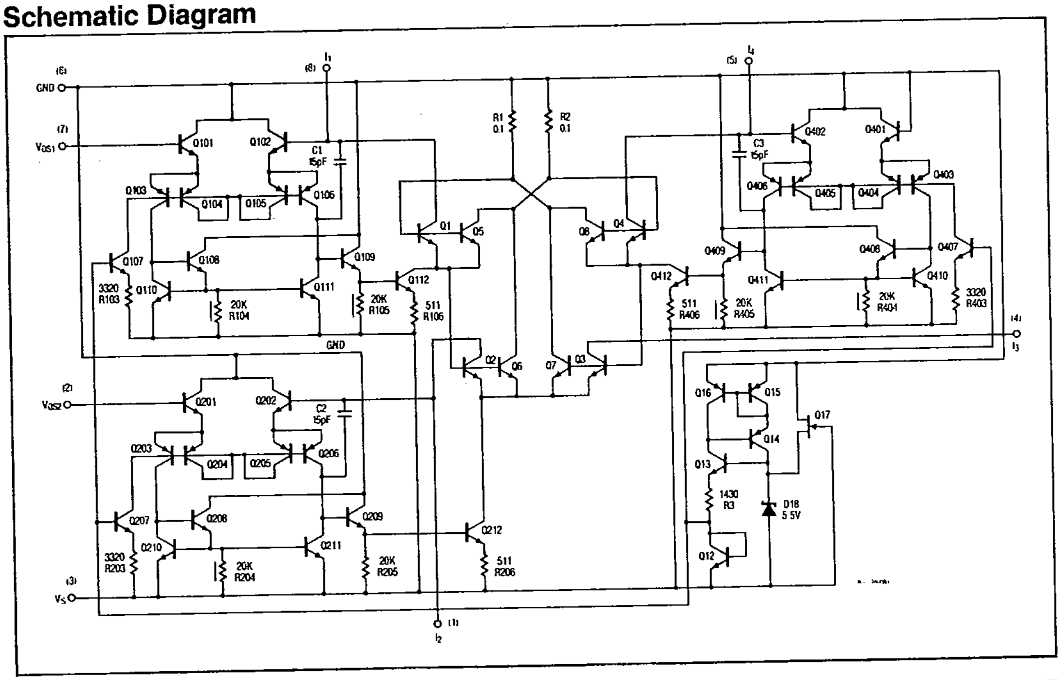
The Raytheon RC4200 is the industry's first integrated circuit multiplier to have complete compensation for nonlinearity, the primary source of error and distortion. This is also the first IC multiplier to have three on-board operational amplifiers designed specifically for use in multiplier logging circuits. These specially designed amplifiers are frequency compensated for optimum AC response in a logging circuit, the heart of a multiplier, and can therefore provide superior AC response in comparison to other analog multipliers.

Versatility is unprecedented; this is the first IC multiplier that can be used in a wide variety of applications without sacrificing accuracy. Four-quadrant multiplication, two-quadrant division, square-rooting, squaring and RMS conversion can all be easily implemented with predictable accuracy. The nonlinearity compensation is not just trimmed at a single temperature, it is designed to provide compensation over the full temperature range. This nonlinearity compensation combined with the low gain and offset drift inherent in a well designed monolithic chip provides a very low accuracy tempco.

The excellent linearity and versatility were achieved through circuit design rather than special grading or trimming, and therefore unit cost is very low. Analog multipliers can now be used in applications where price was previously an inhibiting factor.

The Raytheon RC4200 is ideal for use in low distortion audio modulation circuits, voltage-controlled active filters, and precision oscillators.

Schematic Diagram



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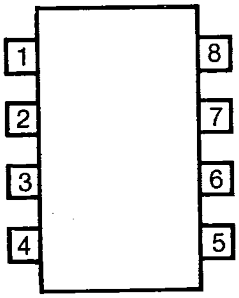
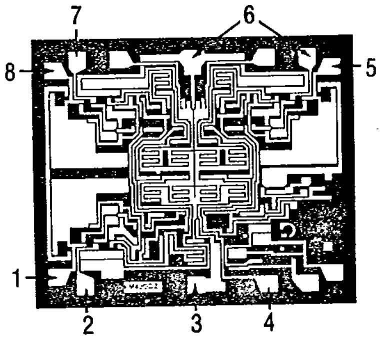
Connection Information

8-Lead
DE and NB Miniature
Dual In-Line Package
(Top View)



Pin	Function
1	I_2
2	V_{OS2}
3	$-V_S$
4	I_3 (Output)
5	I_4
6	GND
7	V_{OS1}
8	I_1

Mask Pattern



Die Size: 78 x 66 mils
Min. Pad Dimensions: 4 x 4 mils

Absolute Maximum Ratings

Supply Voltage	-22V
Internal Power Dissipation	500mW
Input Current	-5mA
Storage Temperature Range	
RM4200/4200A	-65°C to +150°C
RV4200/4200A	-55°C to +125°C
RC4200/4200A	-55°C to +125°C
Operating Temperature Range	
RM4200/4200A	-55°C to +125°C
RV4200/4200A	-40°C to +85°C
RC4200/4200A	0°C to +70°C

Thermal Characteristics

	8-Lead Plastic DIP	8-Lead Ceramic DIP
Max. Junction Temp.	125°C	175°C
Max. P_D $T_A < 50°C$	468mW	833mW
Therm. Res. θ_{JC}	—	45°C/W
Therm. Res. θ_{JA}	160°C/W	150°C/W
For $T_A > 50°C$ Derate at	6.25mW per °C	8.33mW per °C

Ordering Information

Part Number	Package	Operating Temperature Range
RC4200DE	Ceramic	0°C to +70°C
RC4200ADE	Ceramic	0°C to +70°C
RC4200NB	Plastic	0°C to +70°C
RC4200ANB	Plastic	0°C to +70°C
RV4200NB	Plastic	-40°C to +85°C
RV4200ANB	Plastic	-40°C to +85°C
RV4200DE	Ceramic	-40°C to +85°C
RV4200ADE	Ceramic	-40°C to +85°C
RM4200DE	Ceramic	-55°C to +125°C
RM4200ADE	Ceramic	-55°C to +125°C

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Electrical Characteristics (Over Operating Temperature Range, $V_S = -15V$ unless otherwise noted)

Parameters	Test Conditions	4200A			4200			Units
		Min	Typ	Max	Min	Typ	Max	
Input Current Range (I_1, I_2 and I_4)	(Note 1)	1.0		1000	1.0		1000	µA
Total Error as Multiplier Untrimmed	$T_A = +25°C$			±2.0			±3.0	%
With External Trim	(Note 2)			±0.2			±0.5	%
Versus Temperature			±0.005			±0.005		%/°C
Versus Supply (-9 to -18V)			±0.1			±0.1		%/V
Nonlinearity	$50\mu A \leq I_{1,2,4} \leq 250\mu A$, $T_A = +25°C$			±0.1			±0.3	%
Input Offset Voltage	$I_1 = I_2 = I_4 = 150\mu A$, $T_A = +25°C$			±5.0			±10	mV
Input Bias Current	$I_1 = I_2 = I_4 = 150\mu A$, $T_A = +25°C$			300			500	nA
Average Input Offset Voltage Drift	$I_1 = I_2 = I_4 = 150\mu A$			±50			±100	µV/°C
Output Current Range (I_3)	(Note 3)	1.0		1000	1.0		1000	µA
Frequency Response, -3dB point			4.0			4.0		MHz
Supply Voltage		-18	-15	-9.0	-18	-15	-9.0	V
Supply Current	$I_1 = I_2 = I_4 = 150\mu A$, $T_A = +25°C$			4.0			4.0	mA

Notes:
1. [1]The input circuits tend to become unstable at $I_1, I_2, I_4 < 50\mu A$ and linearity decreases when $I_1, I_2, I_4 > 250\mu A$ (eq. @ $I_1 = I_2 = 500\mu A$, non-linearity error ≈ 0.5%).
2. Refer to Figure 6 for example.
3. These specifications apply with output (I_3) connected to an op amp summing junction. If desired, the output (I_3) at pin 4 can be used to drive a resistive load directly. The resistive load should be less than 700Ω and must be pulled up to a positive supply such that the voltage on pin 4 stays within a range of 0 to +5V.

Functional Description

The RC4200 multiplier is designed to multiply two input currents (I_1 and I_2) and to divide by a third input current (I_4). The output is also in the form of a current (I_3). A simplified circuit diagram is shown in Figure 1. The nominal relationship between the three inputs and the output is:

$$I_3 = \frac{I_1 I_2}{I_4} \quad (1)$$

The three input currents must be positive and restricted to a range of 1µA to 1mA. These currents go into the multiplier chip at op-amp summing junctions which are nominally at zero volts. Therefore, an input voltage can be easily converted to an input current by a series resistor. Any number of currents may be summed at the inputs. Depending on the application, the output current can be converted to a voltage by an external op amp or used directly. This capability of combining input currents and voltages in various combinations provides great versatility in application.

Inside the multiplier chip, the three op amps make the collector currents of transistors Q1, Q2, and Q4 equal to their respective input currents (I_1, I_2, and I_4). These op amps are designed with current-source outputs and are phase-compensated for optimum frequency response as a multiplier. Power drain of the op amps was minimized to prevent the introduction of undesired thermal gradients on the chip. The three op amps operate on a single supply voltage (nominally -15V) and total quiescent current drain is less than 4mA. These special op amps provide significantly improved performance in comparison to 741-type op amps.

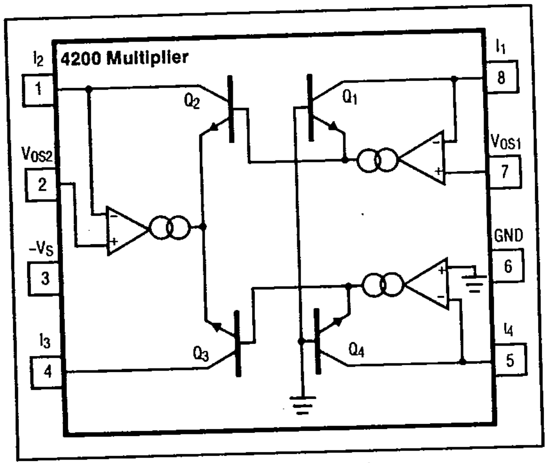

Figure 1. Functional Diagram

The actual multiplication is done within the log-antilog configuration of the Q1-Q4 transistor array. These four transistors, with associated proprietary circuitry, were specially designed to precisely implement the relationship

$$V_{BEN} = \frac{kT}{q} \ln \frac{I_{CN}}{I_{SN}} \quad (2)$$

Previous multiplier designs have suffered from an additional undesired linear term in the above equation; the collector current times the emitter resistance. This $I_C r_E$ term introduces a parabolic nonlinearity even with matched transistors. Raytheon has developed a unique and proprietary means of inherently compensating for this undesired $I_C r_E$ term. Furthermore, this Raytheon-developed circuit technique compensates linearity error over temperature changes. The nonlinearity versus temperature is significantly improved over earlier designs.

From equation (2) and by assuming equal transistor junction temperatures, summing base-to-emitter voltage drops around the transistor array yields:

$$\frac{kT}{q}\left[\ln \frac{I_1}{I_{S1}} = \ln \frac{I_2}{I_{S2}} - \ln \frac{I_3}{I_{S3}} - \ln \frac{I_4}{I_{S4}}\right] = 0 \quad (3)$$

This equation reduces to:

$$\frac{I_1 I_2}{I_3 I_4} = \frac{I_{S1} I_{S2}}{I_{S3} I_{S4}} \quad (4)$$

The ratio of reverse saturation currents, $I_{S1}I_{S2}/I_{S3}I_{S4}$, depends on the transistor matching. In a monolithic multiplier this matching is easily achieved and the ratio is very close to unity, typically 1.0 ±1%. The final result is the desired relationship:

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$$I_3 = \frac{I_1 I_1}{I_4} \qquad (5)$$

The inherent linearity and gain stability combined with low cost and versatility makes this new circuit ideal for a wide range of nonlinear functions.

Basic Circuits

Current Multiplier/Divider

The basic design criteria for all circuit configurations using the 4200 multiplier is contained in equation (1):

$$\text{i.e.} \qquad I_3 = \frac{I_1 I_2}{I_4}$$

The current-product-balance equation restates this as:

$$I_1 I_2 = I_3 I_4 \qquad (6)$$

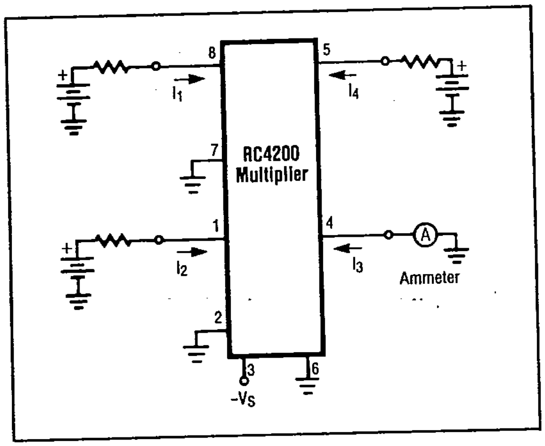
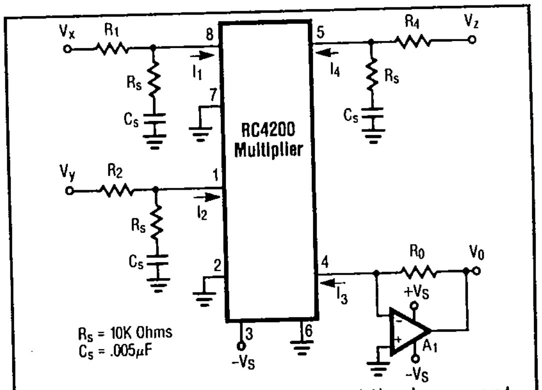


Figure 2

Dynamic Range and Stability

The precision dynamic range for the 4200 is from +50μA to +250μA inputs for I_1, I_2 and I_4. Stability and accuracy degrade if this range is exceeded.

To improve the stability for input currents less than 50μA, filter circuits ($R_S C_S$) are added to each input (see Figure 3).



Amplifier A_1 is used to convert the I_3 current to an output voltage.

Multiplier: V_z = constant $\neq 0$

Divider: V_y = constant $\neq 0$

Figure 3

Voltage Multiplier/Divider

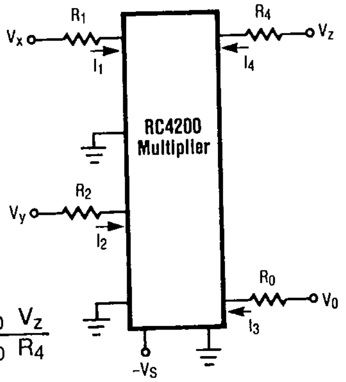
$$I_1 = \frac{V_x}{R_1}$$

$$I_2 = \frac{V_y}{R_2}$$

$$I_3 = \frac{V_0}{R_0}$$

$$I_4 = \frac{V_z}{R_4}$$

$$\frac{V_x}{R_1}\frac{V_y}{R_2} = \frac{V_0}{R_0}\frac{V_z}{R_4}$$



Solving for V_0: $V_0 = \frac{V_x V_y}{V_z} \frac{R_0 R_4}{R_1 R_2}$

For a multiplier circuit $V_z = V_R$ = constant

Therefore: $V_0 = \frac{V_x}{V_z} K$ where $K = \frac{V_R R_0 R_4}{R_1 R_2}$

For a divider circuit $V_y = V_{REF}$ = constant

Therefore: $V_0 = V_x V_y K$ where $K = \frac{R_0 R_4}{V_R R_1 R_2}$

Figure 4

Extended Range

The input and output voltage ranges can be extended to include 0 and negative voltage signals by adding bias currents. The R_SC_S filter circuits are eliminated when the input and biasing resistors are selected to limit the respective currents to 50µA min. and 250µA max.

Extended Range Multiplier

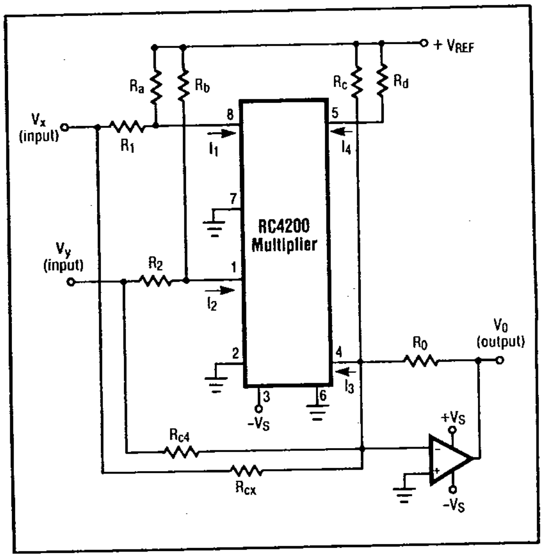


Figure 5

Resistors R_a and R_b extend the range of the V_x and V_y inputs by picking values such that:

$$I_1(\text{min.}) = \frac{V_x(\text{min.})}{R_1} + \frac{V_{REF}}{R_a} = 50\mu A,$$

$$\text{and } I_1(\text{max.}) = \frac{V_x(\text{max.})}{R_1} + \frac{V_{REF}}{R_a} = 250\mu A;$$

$$\text{also } I_2(\text{min.}) = \frac{V_y(\text{min.})}{R_2} + \frac{V_{REF}}{R_b} = 50\mu A,$$

$$\text{and } I_2(\text{max.}) = \frac{V_y(\text{max.})}{R_2} + \frac{V_{REF}}{R_b} = 250\mu A.$$

Resistor R_c supplies bias current for I_3 which allows the output to go negative.

Resistors R_{cx} and R_{cy} permit equation (6) to balance, i.e.:

$$\left(\frac{V_x}{R_1} + \frac{V_{REF}}{R_a}\right)\left(\frac{V_y}{R_2} = \frac{V_{REF}}{R_b}\right) = \left(\frac{V_0}{R_0} + \frac{V_{REF}}{R_c} + \frac{V_x}{R_{cx}} + \frac{V_y}{R_{cy}}\right)\left(\frac{V_{REF}}{R_d}\right)$$

$$\frac{V_xV_y}{R_1R_2} + \frac{V_xV_{REF}}{R_1R_b} + \frac{V_yV_{REF}}{R_2R_a} + \frac{V_{REF}^2}{R_aR_b} =$$

$$\frac{V_0V_{REF}}{R_0R_d} + \frac{V_xV_{REF}}{R_{cx}R_d} + \frac{V_yV_{REF}}{R_{cy}R_d} + \frac{V_{REF}^2}{R_cR_d}$$

Cross-Product Cancellation

Cross-products are a result of the V_xV_{REF} and V_yV_{REF} terms. To the extent that:

$$R_1R_b = R_{cx}R_d \text{ and } R_2R_a = R_{cy}R_d,$$

cross-product cancellation will occur.

Arithmetic Offset Cancellation

The offset caused by the V_{REF}^2 term will cancel to the extent that: $R_aR_b = R_cR_d$, and the result is:

$$\frac{V_xV_y}{R_1R_2} = \frac{V_0V_{REF}}{R_0R_d} \quad \text{or } V_0 = V_xV_y\,K$$

$$\text{where } K = \frac{R_0R_d}{V_{REF}R_1R_2}$$

Resistor Values

Inputs:

$$V_x(\text{min.}) \leq V_x \leq V_x(\text{max.})$$

$$\Delta V_x = V_x(\text{max.}) - V_x(\text{min.})$$

$$V_y(\text{min.}) \leq V_y \leq V_y(\text{max.})$$

$$\Delta V_y = V_y(\text{max.}) - V_y(\text{min.})$$

$$V_{REF} = \text{Constant } (+7V \text{ to } +18V)$$

$$K = \frac{V_0}{V_xV_y} \text{ (Design Requirement)}$$

$$R_1 = \frac{\Delta V_x}{200\mu A},\ R_2 = \frac{\Delta V_y}{200\mu A},\ R_d = \frac{V_{REF}}{250\mu A}$$

$$R_a = \frac{\Delta V_xV_{REF}}{250\mu A\,\Delta V_x - 200\mu A\,V_x(\text{max.})}$$

$$R_b = \frac{\Delta V_yV_{REF}}{250\mu A\,\Delta V_y - 200\mu A\,V_y(\text{max.})}$$

$$R_c = \frac{R_aR_b}{R_d},\ R_{cx} = \frac{R_1R_b}{R_d},\ R_{cy} = \frac{R_2R_a}{R_d}$$

$$R_0 = \frac{\Delta V_x\,\Delta V_y\,K}{160\mu A}$$

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Multiplying Circuit Offset Adjust

$$10K \leq R_5 = R_9 = R_{16} \leq 50K$$

$$R_7 = R_{11} = R_{14} = 100\Omega$$

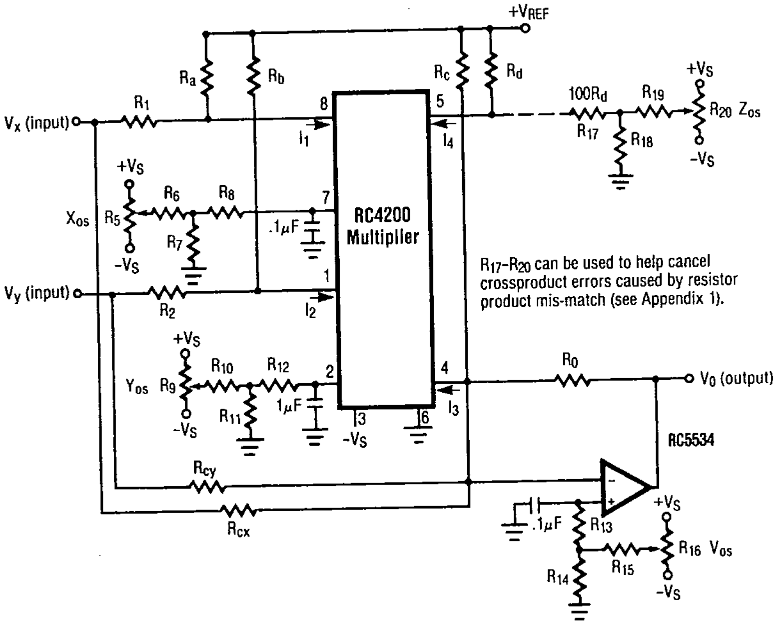
$$R_6 = R_{10} = 100\Omega\ \frac{V_S}{.05}$$

$$R_{14} = 100\Omega\ \frac{V_S}{.10}$$

$$R_8 = R_1 || R_a$$

$$R_{12} = R_2 || R_b$$

$$R_{13} = R_0 || R_c || R_{cx} || R_{cy}$$



R17-R20 can be used to help cancel crossproduct errors caused by resistor product mis-match (see Appendix 1).

Procedure:

1. Set all trimmer pots to 0V on the wiper.
2. Connect V_x input to ground. Put in a full scale square wave on V_y input. Adjust $X_{OS}(R_5)$ for no square wave on V_0 output (adjust for 0 feedthrough).
3. Connect V_y input to ground. Put in a full scale square wave on V_x input. Adjust $Y_{OS}(R_9)$ for no square wave on V_0 output (adjust for 0 feedthrough).
4. Connect V_x and V_y to ground. Adjust $V_{OS}(R_{16})$ for 0V on V_0 output.

Figure 6

Extended Range Divider

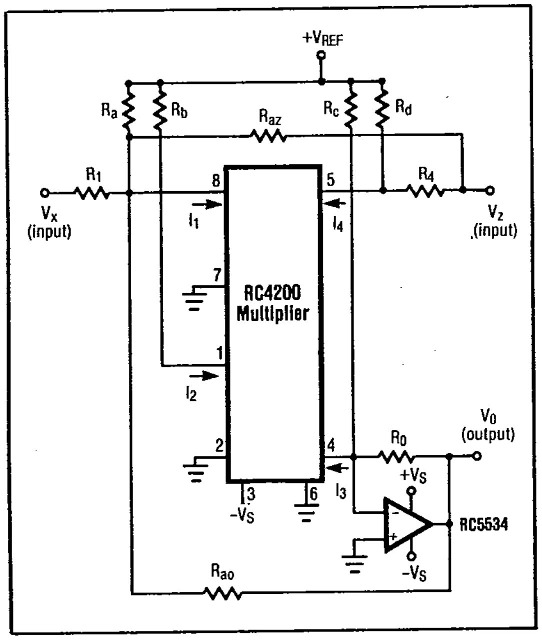


Figure 7

As with the extended range multiplier, resistors R_{az} and R_{ao} are added to cancel the cross-product error caused by the biasing resistors, i.e.,

$$\left(\frac{V_x}{R_1}+\frac{V_0}{R_{ao}}+\frac{V_z}{R_{az}}+\frac{V_{REF}}{R_a}\right)\left(\frac{V_{REF}}{R_b}\right)=\left(\frac{V_0}{R_0}+\frac{V_{REF}}{R_c}\right)\left(\frac{V_z}{R_4}+\frac{V_{REF}}{R_d}\right)$$

$$\frac{V_xV_{REF}}{R_1R_b}+\frac{V_0V_{REF}}{R_{ao}R_b}+\frac{V_zV_{REF}}{R_{az}R_b}+\frac{V_{REF}^2}{R_aR_b}=\frac{V_0V_z}{R_0R_4}+\frac{V_0V_{REF}}{R_0R_d}+\frac{V_zV_{REF}}{R_4R_c}+\frac{V_{REF}^2}{R_cR_d}$$

To cancel cross-product and arithmetic offset:

$R_{ao}R_b = R_0R_d$, $R_{az}R_b = R_4R_c$ and $R_aR_b = R_cR_d$

and the result is:

$$\frac{V_xV_{REF}}{R_1R_b}=\frac{V_0V_z}{R_0R_4} \quad \text{or } V_0 = V_x/V_y\, K$$

$$\text{where } K = \frac{V_{REF}R_0R_4}{R_1R_b}$$

NOTE: It is necessary to match the resistor cross-products above to within the amount of error tolerable in the output offset, i.e., with a 10V F.S. output, 0.1% resistor cross-product match will give 0.1% x 10V = 10mV untrimmable output offset voltage.

Resistor Values

Inputs:

$$V_x(\text{min.}) \le V_x \le V_x(\text{max.})$$

$$\Delta V_x = V_x(\text{max.}) - V_x(\text{min.})$$

$$V_z(\text{min.}) \le V_z \le V_z(\text{max.})$$

$$\Delta V_z = V_z(\text{max.}) - V_z(\text{min.})$$

$$V_{REF} = \text{Constant } (+7V \text{ to } +18V)$$

Outputs:

$$V_0(\text{min.}) \le V_0 \le V_0(\text{max.})$$

$$\Delta V_0 = V_0(\text{max.}) - V_0(\text{min.})$$

$$K = \frac{V_0V_z}{V_x} \text{ (Design Requirement)}$$

$$R_0 = \frac{\Delta V_0}{750\mu A},\ R_b = \frac{V_{REF}}{250\mu A},\ R_4 = \frac{\Delta V_z}{200\mu A}$$

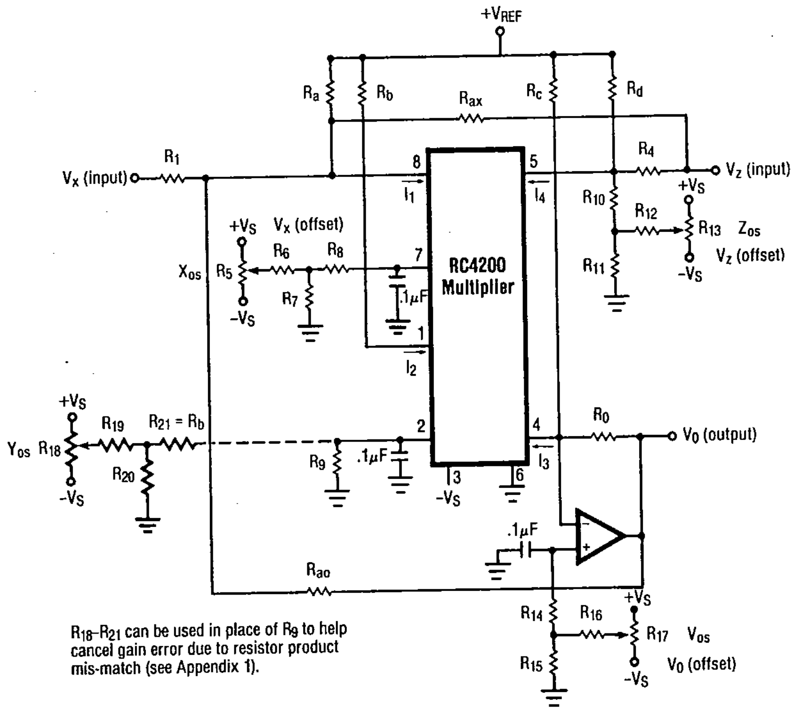
$$R_c = \frac{\Delta V_0 V_{REF}}{750\mu A\ \Delta V_0 - 700\mu A\ V_0(\text{max.})}$$

$$R_d = \frac{\Delta V_z V_{REF}}{250\mu A\ \Delta V_z - 200\mu A\ V_z(\text{max.})}$$

$$R_a = \frac{R_cR_d}{R_b},\ R_{az} = \frac{R_cR_4}{R_b},\ R_{ao} = \frac{R_0R_d}{R_b}$$

$$R_1 = \frac{\Delta V_0\ \Delta V_z}{600\mu AK}$$

Divider Circuit with Offset Adjustment



R_{18}–R_{21} can be used in place of R_9 to help cancel gain error due to resistor product mis-match (see Appendix 1).

General

$10K \le R_5 = R_{13} = R_{17} \le 50K$

$R_7 + R_8 \approx R_1 || R_a || R_{az} || R_{ao}$

$R_6 \approx \frac{V_S}{.05} R_7$

$R_9 = R_b$

$R_{10} \approx 100 \times R_4$

$R_{11} = 20K$

$R_{12} = 100K$

$R_{14} + R_{15} \approx R_o || R_c$

$R_{16} \approx \frac{V_S}{.10} R_{15}$

Example: Two-Quad Divider

$V_0 = K \frac{V_x}{V_z}$, $K = k$, $V_{REF} = +V_S = +15V$

$-10 \le V_x \le +10$, therefore $\Delta V_x = 20$
$0 \le V_z \le +10$, therefore $\Delta V_z = 10$
$-10 \le V_0 \le +10$, therefore $\Delta V_0 = 20$

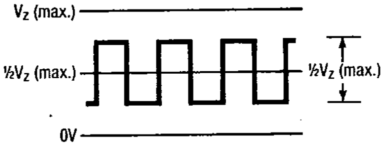
$R_0 = 26.7K$
$R_b = 60K$
$R_4 = 50K$
$R_c = 37.5K$
$R_d = 300K$
$R_a = 187.5K$
$R_{az} = 31.25K$
$R_{ao} = 133K$

$R_1 = 333K$
$R_5, R_{13}, R_{17} = 10K$
$R_7, R_{15} = 1K$
$R_8, R_{11} = 20K$
$R_6, R_9, R_{16} = 300K$
$R_{10} = 4.7M$
$R_{12} = 100K$

Figure 8

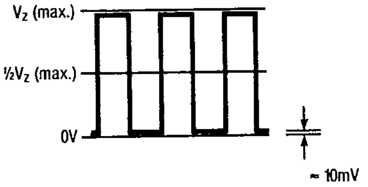
Divider Circuit Offset Adjustment Procedure

1. Set each trimmer pot to 0V on the wiper.
2. Connect V_X (input) to ground. Put a DC voltage of approximately ½V_Z (max.) DC on the V_Z (input) with an AC (squarewave is easiest) voltage of ½V_Z (max.) peak-to-peak superimposed on it. Adjust $X_{OS}(R_5)$ for zero feedthrough. (No AC at V_0)



3. Connect V_X (input to V_Z (input) and put in the ½V_Z (max.) DC with an AC of approximately 20mV less than V_Z (max.).

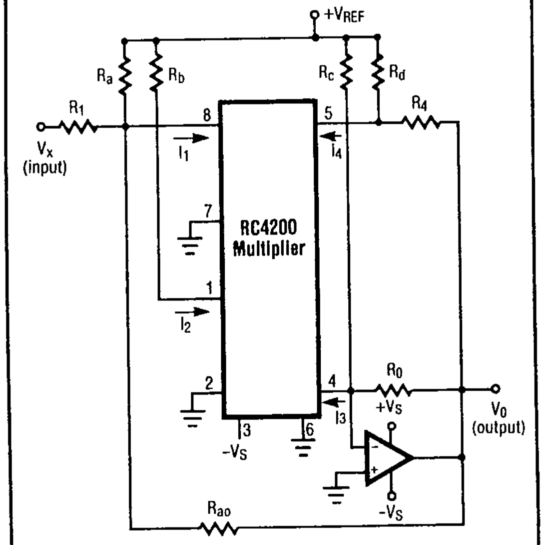
   Adjust $Z_{OS}(R_{13})$ for zero feedthrough.



4. Return V_X (input) to ground and connect V_Z (max.) DC on V_Z (input). Adjust output $V_{OS}(R_{17})$ for V_0 =
5. Connect V_X (input) to V_Z (input) and put in V_Z (max.) DC. (The output will equal K.) Decrease the input slowly until the output (V_0 = K) deviates beyond the desired accuracy. Adjust Z_{OS} to bring it back into tolerance and return to Step 4. Continue Steps 4 and 5 until V_Z reduces to the lowest value desired.

NOTE: As the input to V_X and V_Z gets closer to zero (an illegal state) the system noise will predominate so much that an integrating voltmeter will be very helpful.

Square Root Circuit $V_0 = N\sqrt{V_X}$



$$\frac{V_xV_{REF}}{R_1R_b} + \frac{V_{REF}^2}{R_aR_b} + \frac{V_0V_{REF}}{R_{ao}R_b} = \frac{V_0^2}{R_0R_4} + \frac{V_0V_{REF}}{R_cR_4} + \frac{V_0V_{REF}}{R_0R_d} + \frac{V_{REF}^2}{R_cR_d}$$

If $R_aR_b = R_cR_d$ and $R_{ao}R_bR_0R_d + R_{ao}R_bR_cR_4 = R_cR_dR_0R_4$

Then $\frac{V_0^2}{R_0R_4} = \frac{V_xV_{REF}}{R_1R_b}$ or $V_0 = V_xK$ where $K = \frac{V_{REF}R_0R_4}{R_1R_b}$

and $V_0 = N\sqrt{V_x}$ where $N = \sqrt{K}$

$0 \leq V_x \leq V_x$ (max) and V_0 (max) $= N\sqrt{V_x}$ (max)

$N = \frac{V_0}{\sqrt{V_x}}$ (Design Requirement)

$$R_1 = \frac{V_0(\text{max})^2}{75\mu A\ N^2}$$

$$R_a = R_d = \frac{V_{REF}}{50\mu A}$$

$$R_b = R_c = \frac{V_{REF}}{150\mu A}$$

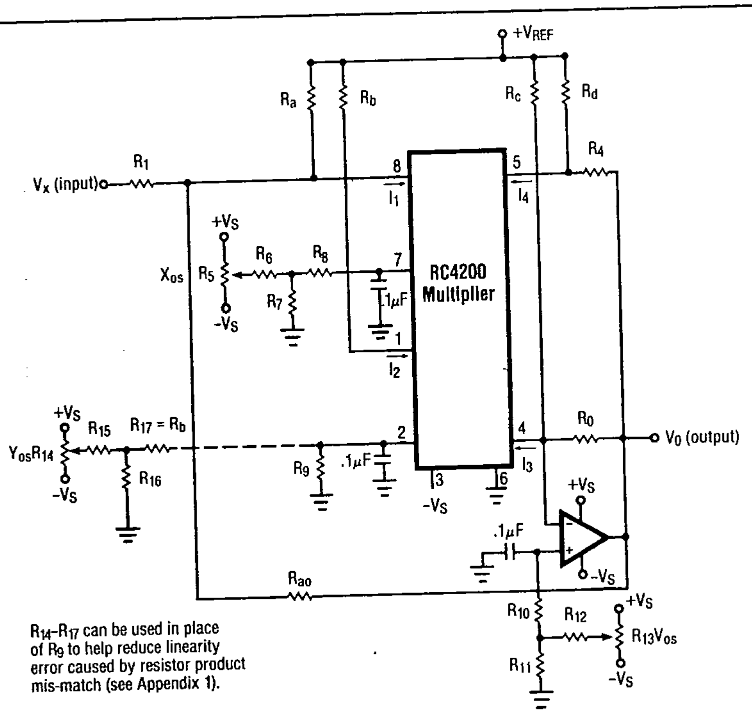
$$R_4 = \frac{V_0(\text{max})}{50\mu A}$$

$$R_{ao} = \frac{V_0(\text{max})}{125\mu A}$$

$$R_0 = \frac{V_0(\text{max})}{225\mu A}$$

Figure 9

Square Root Circuit Offset Adjust



R_{14}-R_{17} can be used in place of R_9 to help reduce linearity error caused by resistor product mis-match (see Appendix 1).

$$10K \leq R_5 = R_{13} \leq 50K$$

$$R_7 = 100\Omega$$

$$R_6 = R_7 \frac{V_S}{.05}$$

$$R_8 = R_1 || R_a || R_{ao}$$

$$R_9 = R_b$$

$$R_{10} = R_0 || R_c$$

$$R_{11} = 100\Omega$$

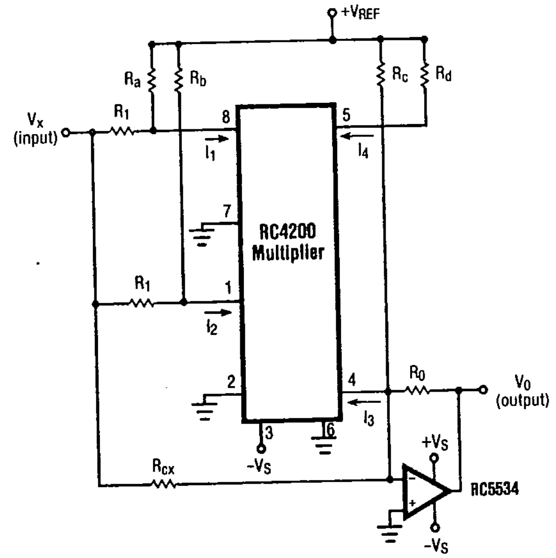
$$R_{12} = R_{11} \frac{V_S}{.1}$$

Procedure

1. Set both trimmer pots to 0V on the wiper.
2. Put in a full scale (0 to V_x(max.)) squarewave on V_x input. Adjust $X_{ox}(R_5)$ for proper peak-to-peak amplitude on V_0 output. (Scaling adjust)
3. Connect V_x input to ground. Adjust $V_{os}(R_{13})$ for 0V on V_0 output.

Figure 10

Squaring Circuits $V_0 = K\,V_x^2$



$$\frac{V_x^2}{R_1^2} + \frac{2V_xV_{REF}}{R_1R_a} + \frac{V_{REF}^2}{R_a^2} = \frac{V_0V_{REF}}{R_0R_d} + \frac{V_{REF}^2}{R_cR_d} + \frac{V_xV_{REF}}{R_{cx}R_d}$$

if $R_a^2 = R_cR_d$ and $R_1R_a = 2R_{cx}R_d$

then $\frac{V_0V_{REF}}{R_0R_d} = \frac{V_x^2}{R_1^2}$ or $V_0 = KV_x^2$ where $K = \frac{R_0R_d}{V_{REF}R_1^2}$

$V_x(\text{min.}) \leq V_x \leq V_x(\text{max.})$ $\Delta V_x = V_x(\text{max.}) - V_x(\text{min.})$

$K = \frac{V_0}{V_x^2}$ (Design Requirement)

$$R_1 = \frac{\Delta V_x}{200\mu A}$$

$$R_a = \frac{\Delta V_x V_{REF}}{250\mu A\,\Delta V_x - 200\mu A\,V_x(\text{max.})}$$

$$R_d = \frac{V_{REF}}{250\mu A}$$

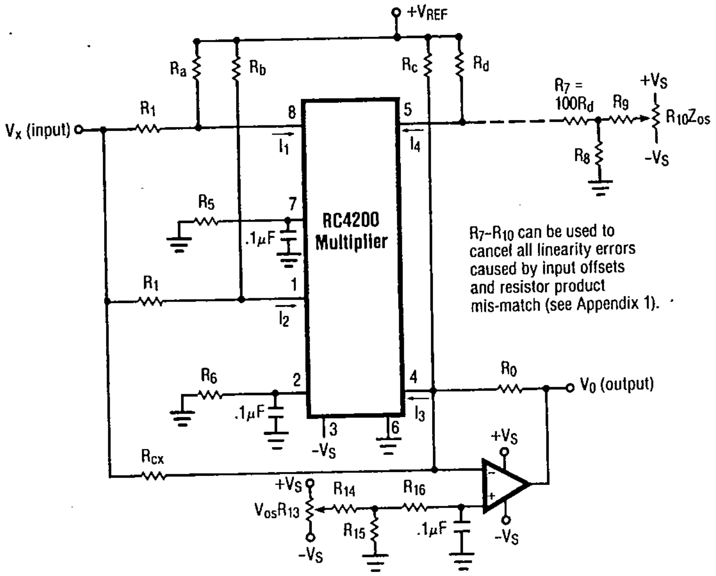
$$R_c = \frac{R_a^2}{R_d}$$

$$R_{cx} = \frac{R_1R_a}{2R_d}$$

$$R_0 = \frac{\Delta V_x^2 K}{160\mu A}$$

Figure 11

Squaring Circuits Offset Adjust



R7–R10 can be used to cancel all linearity errors caused by input offsets and resistor product mis-match (see Appendix 1).

$$10K \leq R_{10}, R_{11} \leq 50K$$

$$R_8, R_{15} = 100\Omega$$

$$R_9, R_{14} = 100\Omega \frac{V_S}{.1}$$

$$R_5, R_6 = R_1 || R_a$$

$$R_{16} = R_0 || R_c || R_{cx}$$

Procedure

1. Set both trimmer pots to 0V on the wiper.
2. Put in a full scale ($\pm V_x$) squarewave on V_x input. Adjust $Z_{os}(R_{10})$ for uniform output.
3. Connect V_x input to ground. Adjust $V_{os}(R_{11})$ for 0V on V_0 output.

Figure 12

Appendix 1 — System Errors

There are four types of accuracy errors which effect overall system performance. They are:

1. Nonlinearity — Incremental deviation from absolute accuracy.(1)
2. Scaling Error — Linear deviation from absolute accuracy.
3. Output Offset — Constant deviation from absolute accuracy.
4. Feedthrough(2) — Crossproduct errors caused by input offsets and external circuit limitations.

The nonlinearity error in the transfer function of the 4200 is ±0.1% max. (±0.03% max. for 4200A).

$$\text{i.e., } I_3 = \frac{I_1 I_2}{I_4} \pm 0.1\% \text{ F.S.}^{(4)}$$

The other system errors are caused by voltage offsets on the inputs of the 4200 and can be as high as ±3.0% (±2.0% for 4200A).

$$\text{i.e., } V_0 = \frac{V_x V_y}{V_z}\,\frac{R_0 R_4}{R_1 R_2} \pm 3.0\% \text{ F.S.}^{(3)(4)}$$

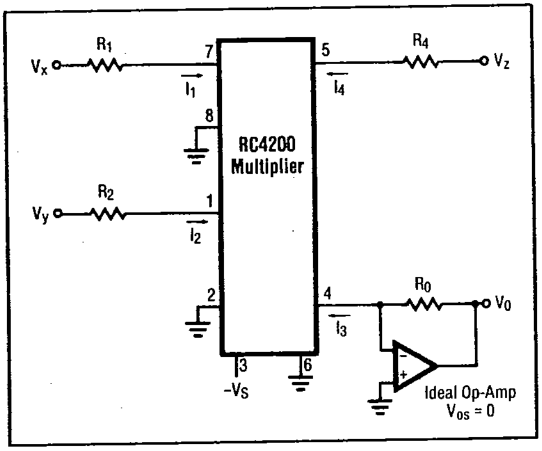
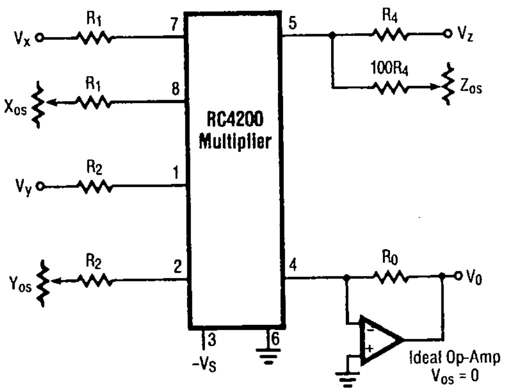


Figure 13

Errors caused by input offsets.

$$V_0 = \frac{R_0 R_4}{R_1 R_2}\left[\frac{V_x V_y}{V_z} \pm \frac{1}{V_z} \underbrace{V_y V_{osx}}_{V_y\text{ Feedthrough}} \pm \underbrace{V_x V_{osy}}_{V_x\text{ Feedthrough}} \pm \underbrace{V_0 V_{osz}}_{\text{Scaling Error}} \pm \underbrace{V_{osx} V_{osy}}_{\text{Output Offset Error}})\right]$$

Systems errors can be greatly reduced by externally trimming the input offset voltages of the 4200. (±0.3% F.S. for 4200 and ±0.1% F.S. for 4200A.)



if; $X_{os} = V_{osx}$, $Y_{os} = V_{osy}$, $Z_{os} = -V_{osz}$,

$$\text{then } V_0 = \frac{V_x V_y}{V_z}\,\frac{R_0 R_4}{R_1 R_2} \pm 0.3\% \text{ F.S.}^{(3)}$$

Figure 14. 4200 With Input Offset Adjustment

Notes:
1. The input circuits tend to become unstable at $I_1, I_2, I_4 < 50\mu A$ and linearity decreases when $I_1, I_2, I_4 > 250\mu A$ (e.g., @ $I_1 = I_2 = 500\mu A$ nonlinearity error ≈ 0.5%).
2. This section will not deal with feedthrough which is proportional to frequency of operation and caused by stray capacitance and/or bandwidth limitations. (Refer to Figure 21.)
3. Not including resistor tolerance or output offset on the op amp.
4. For $50\mu A \le I_1, I_2, I_4 \le 250\mu A$.

Extended Range Circuit Errors

The extended range configurations have a disadvantage in that additional accuracy errors may be introduced by resistor product mis-matching.

Multiplier (Figure 6)

An error in resistor product matching will cause an equivalent feedthrough or output offset error:

1. $R_1R_b = R_{cx}R_d \pm\alpha$,
   V_x feedthrough ($V_y = 0$) = $\pm\alpha V_x$
2. $R_2R_a = R_{cy}R_d \pm\beta$,
   V_y feedthrough ($V_x = 0$) = $\pm\beta V_y$
3. $R_aR_b = R_cR_d \pm \gamma$,
   V_0 offset ($V_x = V_y = 0$) = $\pm\gamma V_{REF}$*

*Output offset errors can always be trimmed out with the output op amp offset adjust, $V_{os}(R_{16})$.

Reducing Mis-Match Errors

You need not run out and buy .01% resistors to reduce resistor product mis-match errors. Here are a couple of ways to squeeze maximum accuracy out of the extended range multiplier (Figure 6) using 1% resistors.

Method #1

V_x feedthrough, for example, occurs when $V_y = 0$ and $V_{osy} \neq 0$. This V_x feedthrough will equal $\pm V_xV_{osy}$. Also, if $V_{osz} \neq 0$, there is a V_x feedthrough equal to $\pm V_xV_{osz}$. A resistor-product error of α will cause a V_x feedthrough of $\pm \alpha V_x$. Likewise, V_y feedthrough errors are: $\pm V_yV_{osx}$, $\pm V_yV_{osz}$ and $\pm \beta V_y$.

Total feedthrough =
$\pm V_xV_{osy} \pm V_yV_{osx} \pm \alpha V_x \pm \beta V_y \pm (V_x + V_y)\, V_{osz}$

By carefully adjusting $X_{os}(R_5)$, $Y_{os}(R9)$ and $Z_{os}(R_{20})$ this equation can be made to very nearly equal zero and the feedthrough error will practically disappear.

A residual offset will probably remain which can be trimmed out with $V_{os}(R_{16})$ at the output op amp.

Method #2

Notice that the ratios of $R_1R_b : R_{cx}R_d$ and $R_2R_a : R_{cy}R_d$ are both dependent on R_d, also that R_1, R_2, R_a and R_b are all functions of the maximum input requirements. By designing a multiplier for the same input ranges on both V_x and V_y then $R_1 = R_2$, $R_{cx} = R_{cy}$ and $R_a = R_b$. (Note: It is acceptable to design a four quadrant multiplier and use only two quadrants of it.)

Select R_d to be 1% or 2% below (or above) the calculated value. This will cause α and β to both be positive (or negative) by nearly the same amount. Now the effective value of R_d can be trimmed with an offset adjustment $Z_{os}(R_{20})$ on pin 5.

This technique will cause: 1) a slight gain error which can be compensated for with the R_0 value, and 2) an output offset error that can be trimmed out with $V_{os}(R_{16})$ on the output op amp.

Extended Range Divider (Figure 8)

The only crossproduct error of interest is the V_z feedthrough ($V_x = 0$ and $V_{osx} \neq 0$) which is easily adjusted with $X_{os}(R_5)$.

Resistor product mis-match will cause scaling errors (gain) that could be a problem for very low values of V_z. Adjustments to $Y_{os}(R_{18})$ can be made to improve the high gain accuracy.

Square Root and Squaring (Figures 10 and 12)

These circuits are functions of single variables so feedthrough, as such, is not a consideration. Crossproduct errors will effect incremental accuracy that can be corrected with $Y_{os}(R_{14})$ or $Z_{os}(R_{10})$.

Appendix 2 — Applications

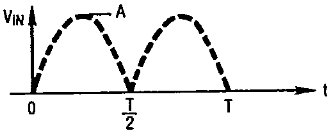
Design Considerations for RMS-to-DC Circuits

Average Value

Consider $V_{in} = A\sin\omega t$. By definition,

$$V_{AVG} \equiv \frac{2}{T}\int_0^{\frac{T}{2}} V_{in}dt$$

Where T = Period
$\omega = 2\pi f$
$= \frac{2\pi}{T}$



$$\begin{aligned} V_{AVG} &\equiv \frac{2}{T}\int_0^{\frac{T}{2}} A\sin\omega t\ dt \\ &= \frac{2A}{T}\left[-\frac{1}{\omega}\cos\omega t\right]_0^{\frac{T}{2}} \\ &= \frac{2A}{2\pi}\left[-\cos(\pi) + \cos(0)\right] \\ &= \frac{2}{\pi}A \end{aligned}$$

Avg. Value of $A\sin\omega t$ is $\frac{2}{\pi}A$

RMS Value

Again consider $V_{in} = A\sin\omega t$

$$V_{rms} = \sqrt{V_{AVG}} = \sqrt{\frac{1}{T}\int_0^T [V_{in}]^2\,dt}$$

V_{rms} for $A\sin\omega t$:

$$\begin{aligned} V_{rms} &= \sqrt{\frac{1}{T}\int_0^T A^2\sin^2\omega t\ dt} \\ &= \sqrt{\frac{A^2}{T}\int_0^T\left(\frac{1}{2} - \frac{1}{2}\cos 2\,\omega t\right)dt} \\ &= \sqrt{\frac{A^2}{2}\left(\frac{T}{2} - \frac{1}{4\omega}\sin 2\,\omega t\right)_0^T} \\ &= \sqrt{\frac{A^2}{T}\left(\frac{T}{2}\right)} \\ &= \sqrt{\frac{A^2}{2}} \end{aligned}$$

therefore the rms value of $A\sin\omega t$ becomes:

$$V_{rms} = \frac{A}{\sqrt{2}}$$

RMS Value for Rectified Sine Wave

Consider $V_{in} = |A\sin\omega t|$, a rectified wave. To solve, integrate over each half cycle.

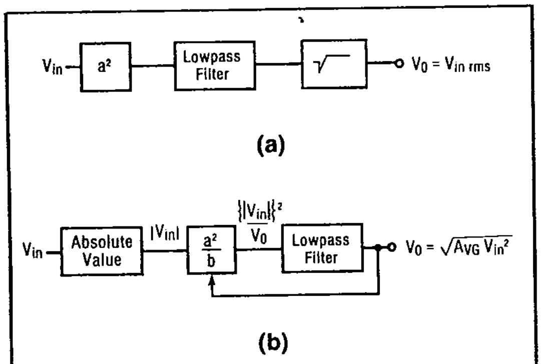
$$\text{i.e. } \frac{1}{T}\int_0^T V_{in}^2\,dt =$$

$$\frac{1}{T}\left[\int_0^{\frac{T}{2}} A^2\sin^2\omega t\ dt + \int_{\frac{T}{2}}^T (-A\sin\omega t)^2dt\right]$$

This is the same as $\frac{1}{1}\int_0^T A^2\sin^2\omega t\ dt$

so, $|A\sin\omega t|_{rms} = A\sin\omega t_{rms}$

Practical Consideration: $|A\sin\omega t|$ has high-order harmonies; $A\sin\omega t$ does not. Therefore, non-ideal integrator may cause different errors for two approaches:



(a)

(b)

$$\text{Avg}\left\{\frac{V_{in}^2}{V_0}\right\} = V_0$$

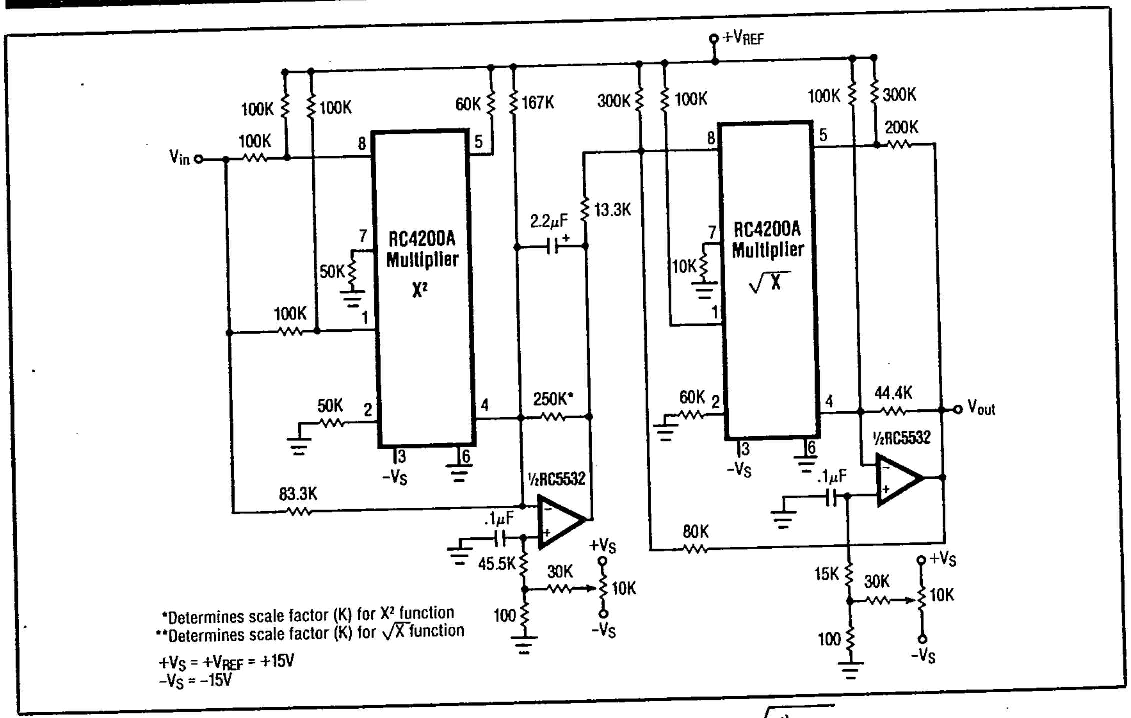
$$\text{implies } V_0 = \sqrt{\text{Avg }\{|V_{in}|^2\}}$$

$$V_0 = \sqrt{\text{Avg } V_{in}^2}$$

Figure 15

Analog Multiplier

RC4200



*Determines scale factor (K) for X^2 function
**Determines scale factor (K) for $\sqrt{X}$ function
$+V_S = +V_{REF} = +15V$
$-V_S = -15V$

Figure 16. RMS to DC Converter $V_{out} = \sqrt{\int V_{in}^2}$

Amplitude Modulator with A.G.C. (Figure 17)

In many AC modulator applications unwanted output modulation is caused by variations in carrier input amplitude. The versatility of the RC4200 multiplier can be utilized to eliminate this undesired fluctuation. The extended range multiplier circuit (Figure 5) shows an output amplitude inversely proportional to the reference voltage V_{REF}.

$$\text{i.e., } V_0 = \frac{V_x V_y}{V_{REF}} \frac{R_0 R_d}{R_1 R_2}$$

By making V_{REF} proportional to V_y (where V_y is the carrier input) such that:

$$V_{REF} = V_H = f(|V_y|),$$

Then the denominator becomes a variable value that automatically provides constant gain, such that the modulating input (V_x) modulates the carrier (V_y) with a fixed scale factor even though the carrier varies in amplitude.

If V_H is made proportional to the average value of $A\sin\omega t$ (i.e., $2A/\pi$) and scaled by a value of $\pi/2$ then:

$$V_H = A$$

and if: V_x = Modulating input (V_M)
and: V_y = Carrier input ($A\sin\omega t$)
then: $V_0 = K\, V_M \sin\omega t$ where $K = \frac{R_0 R_d}{R_1 R_2}$

The resistor scaling is determined by the dynamic range of the carrier variation and modulating input.

The resistor values are solved, as with the other extended range circuits, in terms of the input voltages.

Input voltages:
- Modulation Voltage (V_M): $0 \leq V_M \leq V_x(\text{max.})$
- Carrier (V_y: $V_y = A\sin\omega t$
- Carrier amplitude fluctuation (ΔA):
  - $A(\text{min.}) \sin\omega t \leq V_y \leq A(\text{max.}) \sin\Omega\omega t$
- Dynamic Range (N): A(max.)/A(min.)
  - $A(\text{max.}) = V_H(\text{max.})$ and $A(\text{min.}) = V_H(\text{min.})$

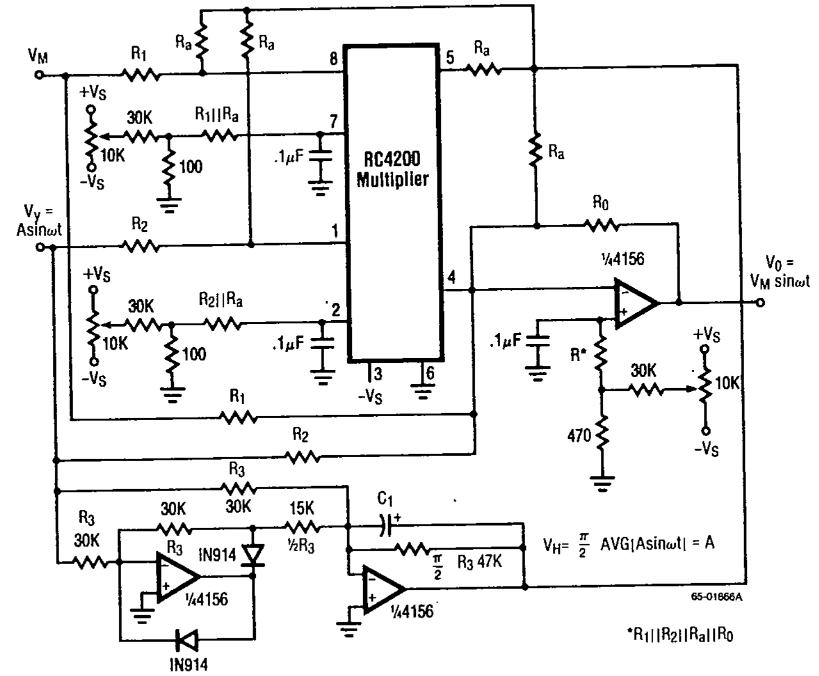


Figure 17. Amplitude Modulator with A.G.C.

The maximum and minimum values for I_1 and I_2 lead to:

$$I_1(\text{max.}) = \frac{V_x(\text{max.})}{R_1} + \frac{V_H(\text{max.})}{R_a} = 250\mu A$$

$$I_1(\text{min.}) = \frac{V_H(\text{min.})}{R_a} = 50\mu A \quad V_M(\text{min.}) = 0$$

$$I_2(\text{max.}) = \frac{A(\text{max.})}{R_2} + \frac{V_H(\text{max.})}{R_a} = 250\mu A$$

$$I_2(\text{min.}) = \frac{V_H(\text{min.})}{R_a} = 50\mu A$$

For a dynamic range of N, where

$$N = \frac{A(\text{max.})}{A(\text{min.})} < 5,$$

These equations combine to yield:

$$R_1 = \frac{V_x(\text{max.})}{(5-N)50\mu A}, R_2 \frac{A(\text{max.})}{(5-N)50\mu A},$$

$$R_a = \frac{A(\text{min.})}{50\mu A} \text{ and } R_0 = K\frac{R_1R_2}{R_a}$$

Example #1

$V_y = A\sin\omega t$ $2.5V \leq A \leq 10V$, therefore N = 4
$0V \leq V_M \leq 10V$, therefore $V_x(\text{max.}) = 10V$
K = 1, therefore $V_0 = V_M \sin\omega t$

$$R_1 = \frac{V_x(\text{max.})}{50\mu A} = \frac{10V}{50\mu A} = 200K$$

$$R_2 = \frac{A(\text{max.})}{50\mu A} = \frac{10V}{50\mu A} = 200K$$

$$R_a = \frac{A(\text{min.})}{50\mu A} = \frac{2.5V}{50\mu A} = 50K$$

$$R_0 = K\frac{R_1R_2}{R_a} = 1\,\frac{200K \times 200K}{50K} = 800K$$

Example #2

$V_y = A\sin\omega t$ $3 \leq A \leq 6$, therefore N = 2
$0V \leq V_M \leq 8V$, therefore $V_x(\text{max.}) = 8V$
K = .2, therefore $V_0 = .2V_M\sin\omega t$
so:
$R_1 = 53.3K$, $R_2 = 40K$
$R_a = 60K$ and $R_0 = 7.11K$

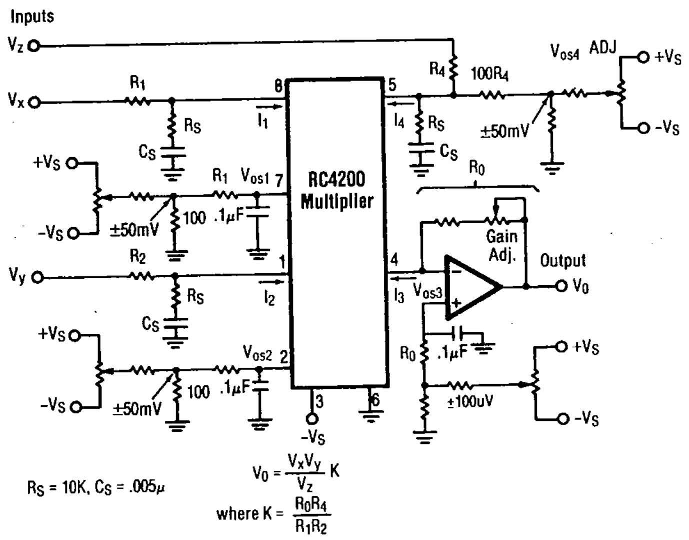


Figure 18. First Quadrant Multiplier/Divider

Limited Range, First Quadrant Applications

The following circuit has the advantage that cross-product errors are due only to input offsets and nonlinearity error is slightly less for lower input currents.

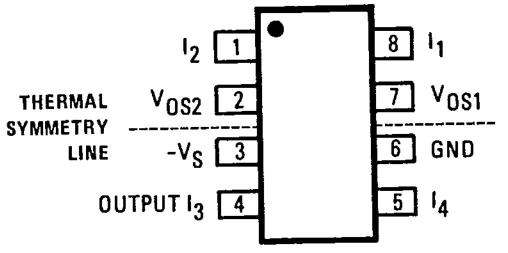
The circuit also has no standby current to add to the noise content although the signal-to-noise ratio worsens at very low input currents (1-5µA) due to the noise current of the input stages.

The $R_S C_S$ filter circuits are added to each input to improve the stability for input currents below 50µA.

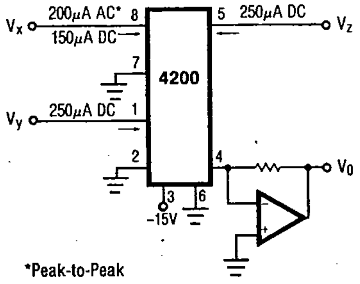
Caution

The bandpass drops off significantly for lower currents (<50µA) and non-symmetrical rise and fall times can cause second harmonic distortion.

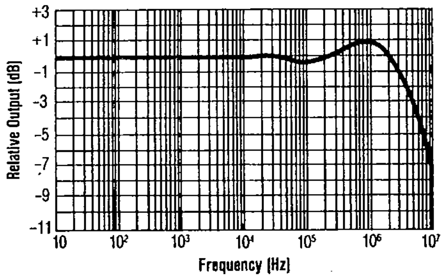
Thermal Symmetry

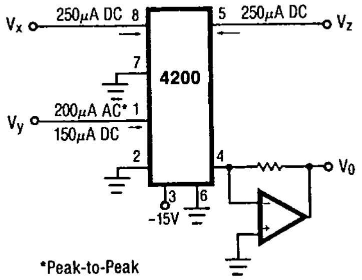


The scale factor is sensitive to temperature gradients across the chip in the lateral direction. Where possible, the package should be oriented such that sources generating temperature gradients are located physically on the line of thermal symmetry. This will minimize scale-factor error due to thermal gradients.

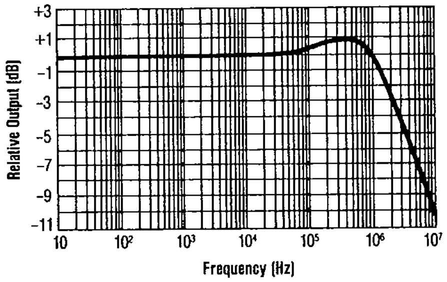


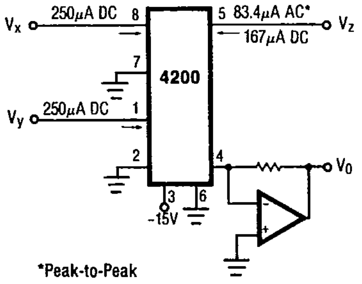
*Peak-to-Peak



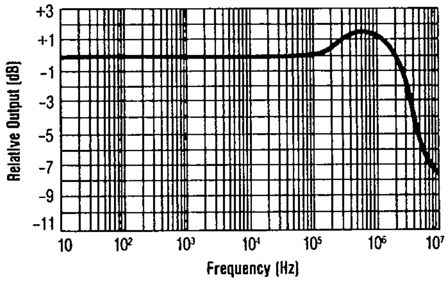


*Peak-to-Peak





*Peak-to-Peak



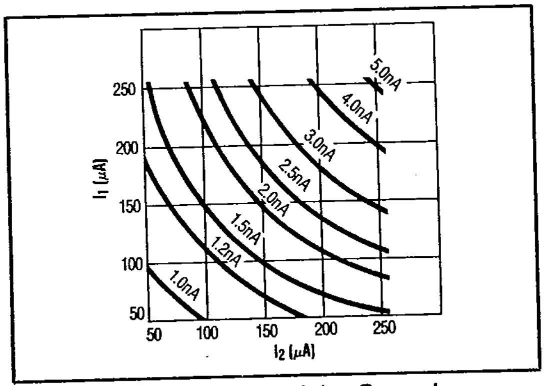


Figure 20a. Output Noise Current vs. Input Current (I_4 = 250µA)

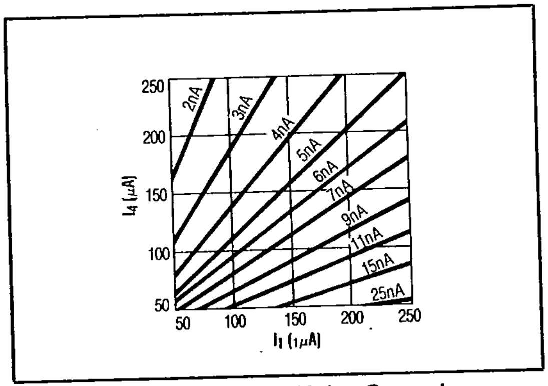


Figure 20b. Output Noise Current vs. Input Current (I_2 = 250µA)

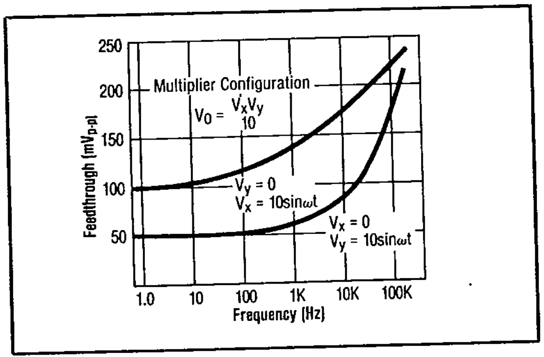


Figure 21. AC Feedthrough vs. Frequency

High Reliability Options

Part Type	Added Screening	Order Part No.
RM4200DE RM4200ADE	With MIL-STD-883 Class C processing	RM4200DE/883C RM4200ADE/883C
RV4200DE RC4200DE RV4200ADE RC4200ADE	With A + 3 processing* including burn-in and tightened AQL	RV4200DE3 RC4200DE3 RV4200ADE3 RC4200ADE3
RV4200NB RC4200NB RV4200ANB RC4200ANB	With A + 2 processing* including "Hot Rail" testing, burn-in, temp cycle and tightened AQL	RV4200NB2 RC4200NB2 RV4200ANB2 RC4200ANB2
RV4200NB RC4200NB RV4200ANB RC4200ANB	With A + 1 processing* including "Hot Rail" testing, temp cycle and tightened AQL	RV4200NB1 RC4200NB1 RV4200ANB1 RC4200ANB1

*Full descriptions of the process steps involved are contained in the Raytheon A + Bulletin available at your local Raytheon Sales Office