CA3091

Four-Quadrant Multiplier

Features:

- "Accuracy": ±4% (max.)
- "Linearity": 3.0% (max.)
- Feedthrough: 9 mV p-p (typ.)
- 3-db bandwidth: 4.4 MHz
- Low power operation capability: ±6.0 V, 4 mW drain
- Low power-supply sensitivity: 36 mV/V typ.
- Smooth overload characteristics – no foldback if full-scale input signal is exceeded
- Negligible warm-up drift
- Broadband operation capability (flat to 1 MHz) – both inputs have similar characteristics for reduced high-frequency phase shift between the inputs
- Low-level linearity correction circuitry minimizes low-level feedthrough for improved small-signal accuracy
- All multiplication is performed with wideband circuitry – this permits two signals of frequencies much higher than the –3 db frequency of the multiplier to produce a difference frequency that is within the multiplier's bandwidth
- High immunity to parasitic oscillation
- Essentially free from excess peaking – provides improved frequency response
- Requires no level shifting at the output – current-source operation at the output permits output signal to be referenced to ground or other levels within the output voltage swing capabilities of the multiplier
- Internal bias regulator

Applications:

- Multiplier ■ Divider ■ Squarer ■ Square Rooter
- Power-series approximator
- Full-wave rectifier
- Automatic level controller
- RMS converter
- Frequency discriminator
- Voltage-controlled filters and oscillators

RCA-CA3091D*, a monolithic silicon integrated circuit, is a four-quadrant multiplier that provides an output voltage that is the product of two input (x and y) voltages.

This device functions as a multiplier, divider, squarer, square rooter, and power-series approximator. In addition, this device is useful in applications such as ideal full-wave rectifiers, automatic level controllers, RMS converters, frequency discriminators, and voltage–controlled filters and oscillators.

The CA3091D comprises five basic circuits (See Fig. 1), including: a multiplier block, two linearity compensators, a current converter, a current source for biasing, and a regulator (reference voltage). A brief description of the operation, functions and typical applications is given in the section "Operating Considerations". In addition there is a separate section on "Symbols, Terms, and Definitions" that defines the terms and symbols used throughout the data bulletin.

The CA3091D is supplied in 14-lead dual-in-line ceramic package and operates over the full military temperature range of -55°C to +125°C.

* Formerly Developmental Type TA5855A.

File Number **534**

CA3091

MAXIMUM RATINGS, *Absolute-Maximum Values at $T_A = 25^oC$*

DC Supply Voltages:		
Between Terms. 12 and 1	+18	V
Between Terms. 4 and 1	−18	V
DC Supply Currents:		
At Term. 12 with DC Supply Voltage = +15 V	4	mA
At Term. 4 with DC Supply Voltage = −15 V	16	mA
Bias Current (At Term. 3)	1	mA
* Input Current	±1	mA
Output Short-Circuit Duration	No limitation	
Voltage Reference Current	10	mA
Linearity Correction Currents:		
At Terminals 7 and 8	10	mA
Device Dissipation (Up to 125°C)	200	mW
Ambient Temperature Range:		
Operating	−55 to +125	°C
Storage	−65 to +150	°C
Lead Temperature (during soldering):		
At distance not less than 1/32 inch (0.79 mm) from case for 10 seconds max.	+265	°C

* External resistance is required to limit the current to the indicated ±1 mA value.

ELECTRICAL CHARACTERISTICS, For Equipment Design

CHARACTERISTICS	SYMBOL	TEST CONDITIONS T_A = 25°C, I_{IB} = 0.5 mA, V^+ = 15 V, V^- = -15 V	TEST CONDITIONS Circuit and/or Char. Curve	LIMITS Min.	LIMITS Typ.	LIMITS Max.	UNITS
STATIC CHARACTERISTICS							
INPUT CIRCUIT							
Input Balance (Correction) Currents:							
At x Input	I_{IC}	x = 0	–	−20	−2.1	+20	µA
At y Input	I_{IC}	y = 0	–	−20	−8.7	+20	µA
Feedthrough Linearity Balance (Correction) Current	I_{OC}		–	−34	−2.9	+34	µA
OUTPUT CIRCUIT							
Output Offset Current	I_{OO}	x & y = 0,	–	−10	−0.23	+10	µA
Output Offset Voltage	V_{OO}	I_{OO} thru R_L = 33kΩ	–	−0.330	−0.0076	+0.330	V
Output Peak Current Swing	$\|I_O\|$	Thru R_L = 24kΩ	3	0.41	0.45	–	mA
Output Peak Voltage Swing	$\|V_O\|$	Across R_L = 33kΩ	4	12	12.9	–	V
DC SUPPLIES & BIASING							
Current Drain (Idling):							
At Term. 4		V^- = -15 V	–	–	2.9	4.5	mA
At Term. 12		V^+ = +15 V	–	–	2.0	3.0	mA
Reference Voltage	V_{ref}	Measured across Terms. 6 & 4 at I = 1mA	–	5.5	6.1	6.7	V
DYNAMIC CHARACTERISTICS							
Output Current	I_O	With I = 0.2mA at each input	–	–	0.21	0.32	mA
Normalized k Factor $\left(k_N = \frac{k}{k_r}\right)$			11	0.69	1.0	1.7	
Accuracy		Worst case at 25°C	–	–	2.6	4.0	% of 10 V
Linearity		Worst case at 25°C	–	–	1.7	3.0	% of 10 V
Feedthrough Voltage:							
At y = 20V p-p, x = 0			–	–	9	20	mV p-p
At x = 20V p-p, y = 0			–	–	9	20	mV p-p

NOTE: See page 7 for "Symbols, Terms and Definitions".

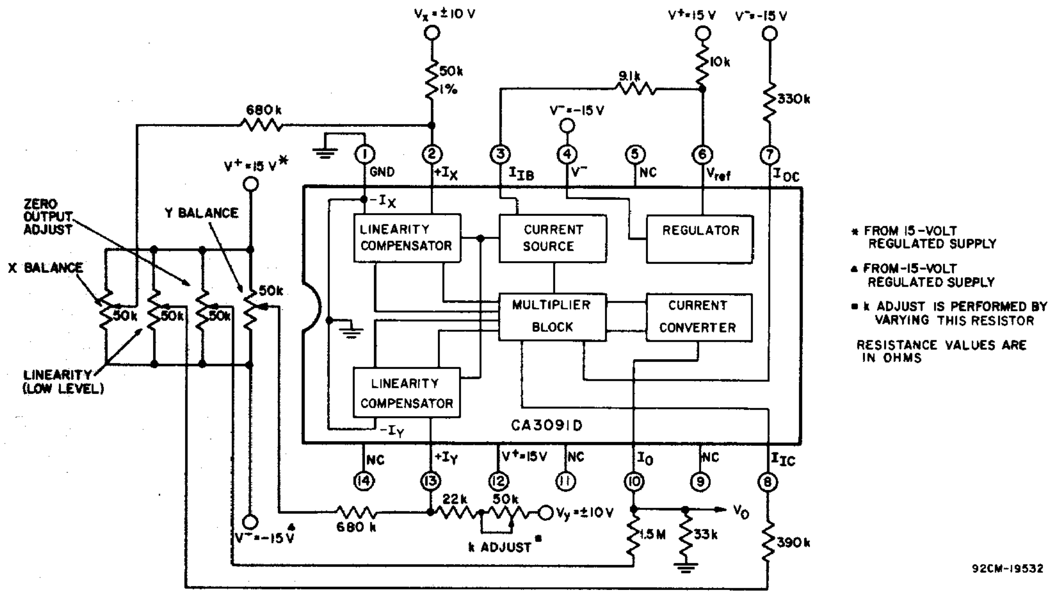


Fig.1—Functional block diagram of CA3091D with typical multiplier outboard (peripheral) circuitry.

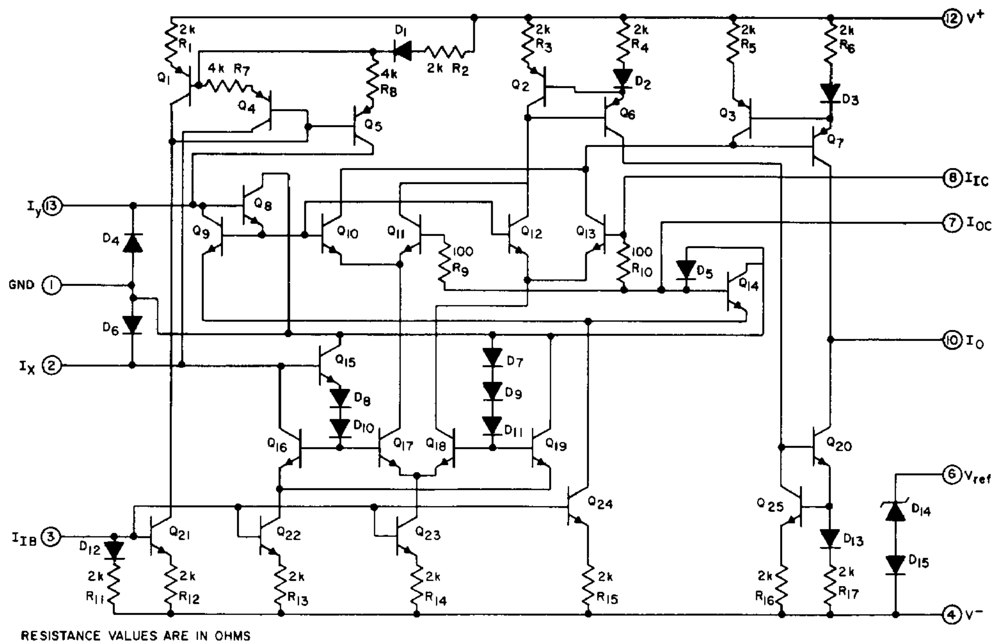


Fig.2—Schematic diagram of the CA3091D.

ELECTRICAL CHARACTERISTICS, Typical Values Intended Only for Design Guidance

CHARACTERISTICS	SYMBOL	TEST CONDITIONS $T_A = 25^oC$, $I_{IB} = 0.5$ mA, $V^+ = 15$ V, $V^- = -15$ V	TEST CONDITIONS Circuit and/or Char. Curve	TYPICAL VALUES	UNITS
STATIC CHARACTERISTICS					
INPUT CIRCUIT					
Input Resistance:					
At x Input	R_I	$\lvert I_x \rvert \leq 0.2$ mA	5	1.3	kΩ
At y Input		$\lvert I_y \rvert \leq 0.2$ mA		0.5	kΩ
Input Capacitance:					
At x Input	C_I	at 1 MHz	–	5.8	pF
At y Input				5.8	pF
OUTPUT CIRCUIT					
Output Resistance	R_O		6	1.0	MΩ
Output Capacitance:	C_O	at 1 MHz		4.0	pF
DC Supply Voltage Sensitivity:					
At Term. 4	$\frac{\Delta V_O}{\Delta V^-}$		11	26	mV/V
At Term. 12	$\frac{\Delta V_O}{\Delta V^+}$			36	mV/V
DYNAMIC CHARACTERISTICS					
Bandwidth (At -3dB point):					
Through x Input	BW		8, 10	4.8	MHz
Through y Input			8, 9	4.4	MHz
3° Error Frequency:					
Through x Input			–	360	kHz
Through y Input				310	kHz
Maximum Slew Rate	SR	7pF in parallel with 10 MΩ load	7	27	V/μs
Temperature Coefficients:					
Output Offset Current	$\Delta I_{OO}/\Delta T$	x & y = 0	–	–0.021	μA/°C
x-Input Balance Current	$\Delta I_{IC}/\Delta T$	x = 0	–	–0.063	μA/°C
y-Input Balance Current		y = 0	–	–0.063	μA/°C
Normalized k Factor $\left(k_N = \frac{k}{k_r}\right)$	k_N		–	–0.76	%/%/°C
Accuracy			–	0.11	%/°C
Linearity			–	0.06	%/°C
Feedthrough:					
At x = 0			–	5.6	mV/°C
At y = 0				5.7	mV/°C

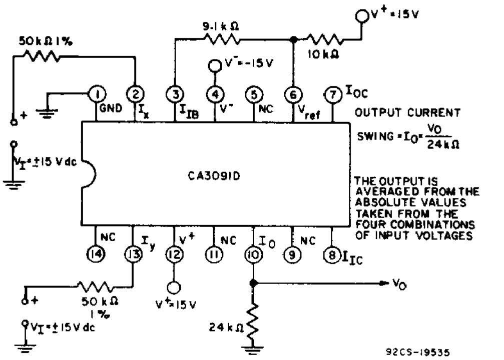


Fig.3—Test circuit for measurement of output current swing capability.

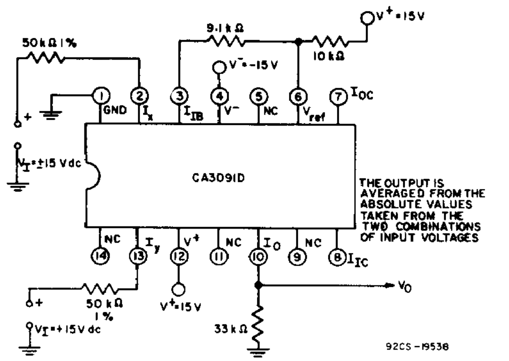


Fig.4—Test circuit for measurement of output voltage swing capability.

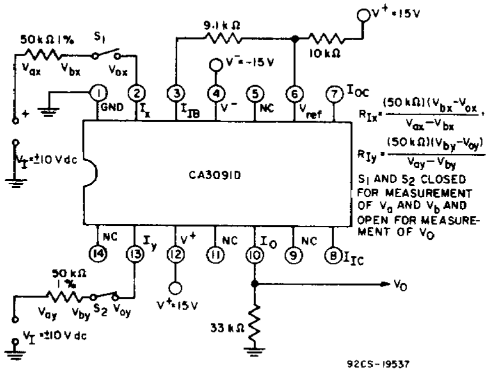


Fig.5—Test circuit for measurement of input resistance.

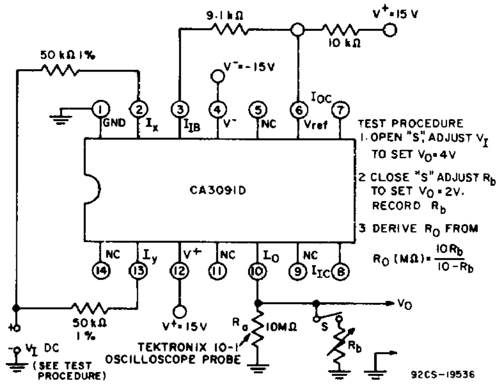


Fig.6—Test circuit for measurement of output resistance.

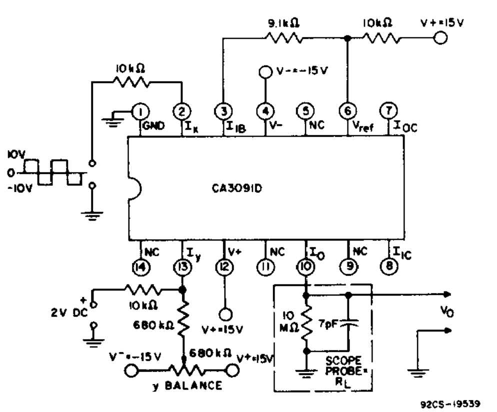


Fig.7—Test circuit for measurement of maximum slew rate.

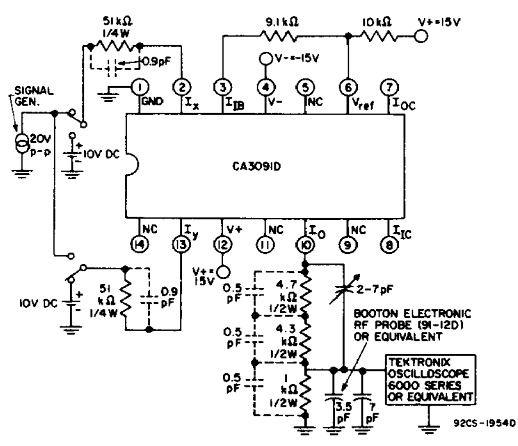


Fig.8—Test circuit for measurement of frequency response.

CA3091

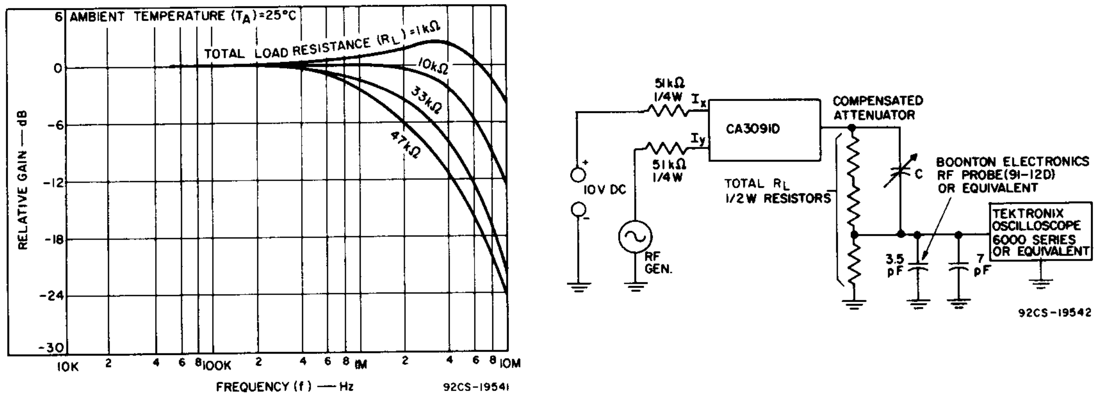


Fig.9- y–input frequency response characteristic curve with associated test circuit.

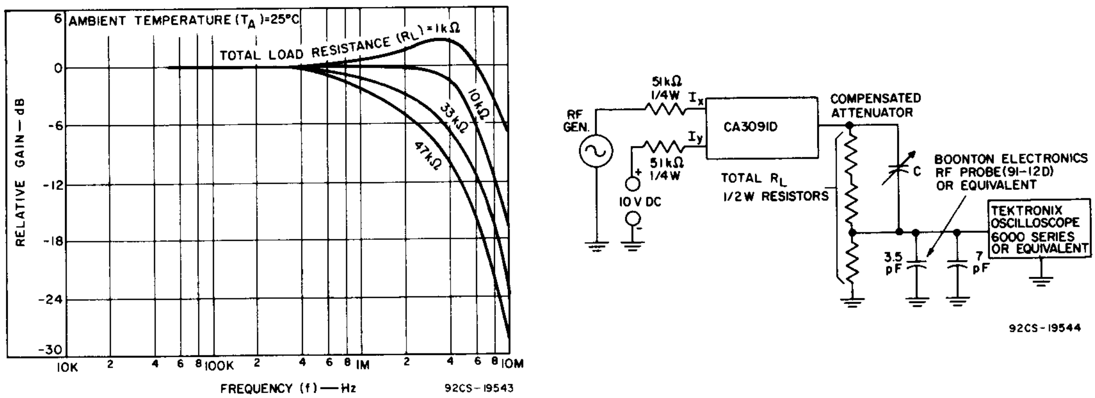


Fig.10- x–input frequency response characteristic curve with associated test circuit.

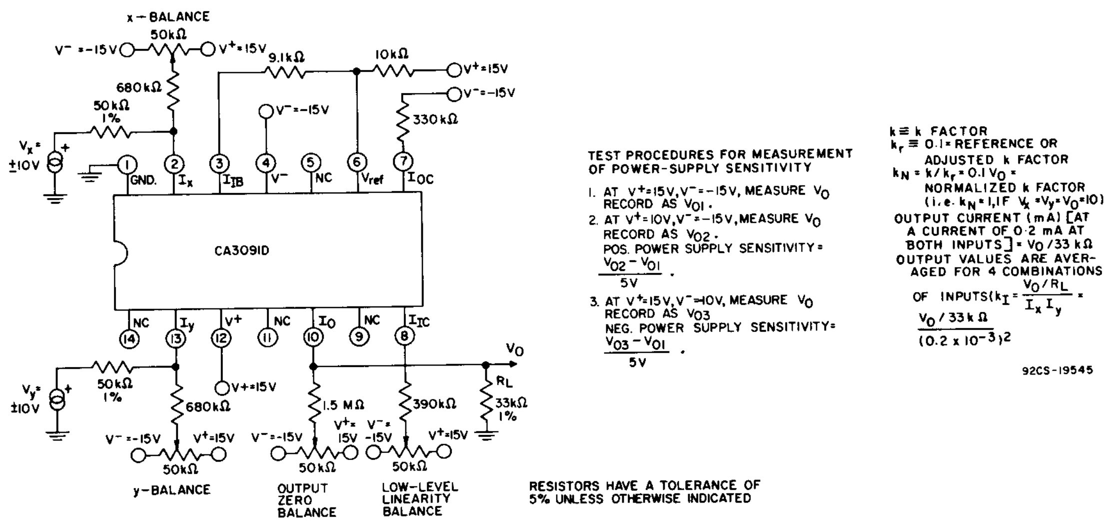
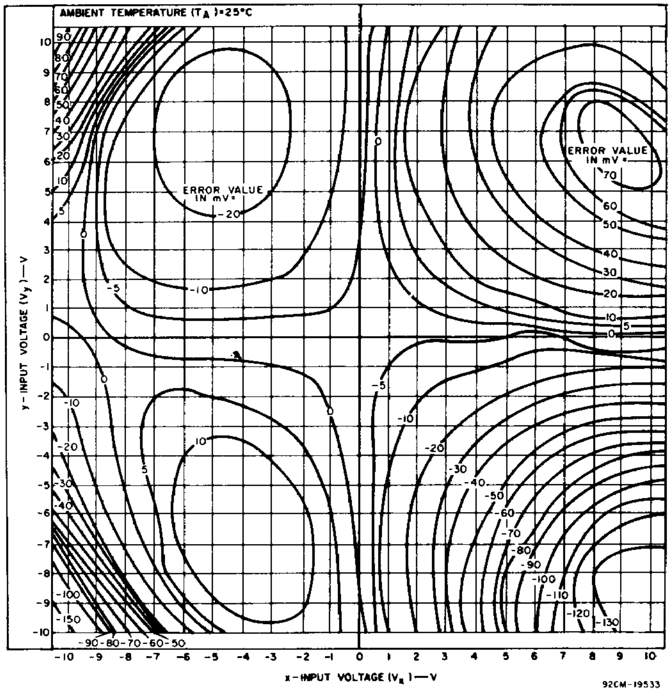


Fig.11–Test circuit for measurement of current gain and power-supply sensitivity.



Note: See "Contour Map" in "Symbols, Terms and Definitions" Section.

Fig.12—Contour mapping of multiplier accuracy (plotted on isomers) and linearity.

SYMBOLS, TERMS AND DEFINITIONS

Output Offset Current
The multiplier output current produced when both of the multiplier input signals are in the zero state.

Output Zero
Sets the output at the zero level when the x and y inputs are in the zero state. (It is implied that all other zeroing adjustments have been effected.)

R_I
Input Resistance – Converts the input voltage to an input current.

R_L
Output (Load) Resistance – Converts the output current to a voltage.

R_O
Output Resistance – See V_O and I_O for the equations associated with these properties.

Regulator Diode
A temperature compensated Zener diode, included in the multiplier circuit, to provide a stable I_{IB}.

Scale Factor or k factor (k)
Represents the basic gain of the multiplier as expressed in the equation $V_O = kV_xV_y$

The equation indicates the ideal transfer function for the multiplier. The normalized k factor is expressed by $k_N = k/k_{ref}$ where k_{ref} is the ideal or reference k factor. The ideal factor, k_{ref} is the value at which the k factor is set when the k-factor adjust control is trimmed. Optimum operation of the CA3091D is achieved when the k-factor is 0.1.

V_{IM}
The maximum ac sine-wave voltage to be applied to the multiplier; a 20-volt p-p sine wave is the nominal maximum swing voltage recommended for use with 50-kilohm input resistors.

V_{MID}
An ac or dc voltage that approximately satisfies the equation

$$V_{MID} = V_{IM}/\sqrt{2}.$$

V_O
The output product voltage derived from the expression

$$(kV_xV_y = V_o)$$

$V_{ref.}$
Temperature compensated zener connected to the –15 volt supply to provide a reference voltage as an aid in setting up a stable I_{IB}.

V_x, V_y
The input voltages to be multiplied.

x-Balance Circuit
Sets the output to the zero level when the x-input is in the zero state.

y-Balance Circuit
Sets the output to the zero level when the y-input is in the zero state.

SYMBOLS, TERMS AND DEFINITIONS – continued

Accuracy
Accuracy defines the degree of error encountered in the operation of the multiplier. It is portrayed on a contour map by isomers (contour lines). Isomers with the highest values indicate "less-accurate" operation of the multiplier. (See illustrative Contour Map in Fig. 12.)

Contour Map
The contour map, shown in Fig. 12, is a graphical portrayal of the multiplier errors in the x, y input plane. Each contour line, termed "isomer", connects those points whose error values (in millivolts) are equal in magnitude. For example, a −20 mV contour line with points at $V_x = 5V$ and $V_y = -3V$ indicates that the output voltage is 20 mV less than the theoretical output product (kV_xV_y). This error voltage, presented in percent of full-scale input (±10 V), defines the "accuracy" of the device. Thus, a 20-mV error voltage represents an "accuracy" of 0.2% as derived from the equation:

$$\text{Accuracy} = 20\ \text{mV}/10 \times 100\% = 0.2\%.$$

A contour map provides a true indication of multiplier performance in each of the four quadrants. Each CA3091D is comprehensively tested and must provide the specified accuracy in the four quadrants.

Current Converter
This portion of the IC combines the multiplier's differential-amplifier output currents and converts them to a single-ended output current.

Current Sources
These circuits provide the biasing currents for the various circuits in the IC. The I_{IB} terminal provides the control current for the current-source circuit.

Feedthrough
Feedthrough occurs when an output signal is produced even though one of the input signals is zero. Consequently, feedthrough signal characteristics constitute a source of error in the operation of a multiplier. In the CA3091D, for example, the feedthrough signal output is specified to be less than 20 mV p-p when either terminal is set at 20 V p-p and the other terminal is set to zero.

I_{IB}
Circuit biasing control current.

I_{IC}
See I_{OC}.

I_O
Output product current ($k_I I_x I_y = I_O$), where $k_I = kR_I^2/R_L$

I_{OC}, I_{IC}
Compensatory input and output currents required to correct unlinearity along the x axis. (Optional for low-level signal use.)

I_x, I_y
Input currents to be multiplied.

k
Voltage Scale Factor (determines the gain of the multiplier).

k_I
Current Scale Factor (k_I) = (R_I^2 / R_L)k.

k adjust
Scale-Factor Adjustment.

Linearity
"Linearity" indicates the degree of multiplier error (i.e. deviation from "straight-line" characteristics) along each of the four boundaries of the input x, y field. These boundaries are formed when one input is held at one of the two maximum values (10 volts or −10 volts) and the other input is swept through the voltage range. (See Contour Map for additional information.)

Linearity Adjust
An external circuit to provide vernier adjustment for optimum linearity. This control should be adjusted before adjusting the y-balance control.

Linearity Balance Circuit (Low-Level)
This circuit makes the multiplier's transfer function linear for low-level x-input signals.

Linearity Compensator
Internal circuitry that converts input current into a non-linear voltage, a requisite for producing a linear output in the differential amplifiers of the multiplier circuit.

Multiplier Circuitry
Provides the product of the two input voltages.

Multiplier Transfer Function
This function mathematically describes the interaction of the two inputs and the resulting output signal. The basic transfer function for a multiplier is

$$k(V_x + V_{xe})(V_y + V_{ye}) = V_o + V_{oe}$$

where: k = k factor and represents the basic gain of the multiplier

V_x, V_y = the external inputs to be multiplied

V_o = the desired value of the product output signal

V_{xe}, V_{ye} = the "effective" errors that occur at the inputs of the multiplier and cause an output signal when either input is in a zero state.

V_{oe} = the error voltage that develops at the output of the multiplier

DC correction factors are added to the multiplier inputs and output to compensate for the errors and offset variations. A complex linearity error term appears in the transfer function; however, this term is not included in the above equation for the purpose of clarity.

OPERATING CONSIDERATIONS

Operation of a Multiplier

A multiplier is, essentially, a gain-controlled amplifier (See Fig. 13) that multiplies the input signal (V_x) with the external gain controlling signal (V_y) to produce the resultant output (V_o). The gain is externally adjustable by a coefficient (k). Stated simply, a multiplier produces an output voltage that is the linear product of two input voltages.

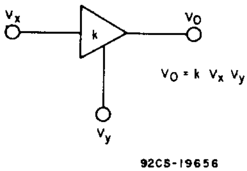
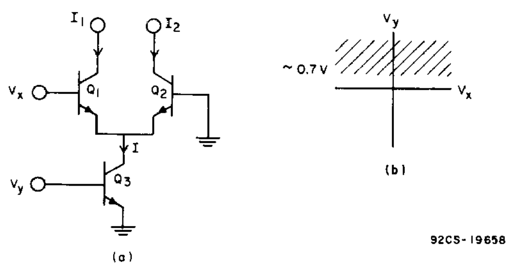


Fig. 13—Gain-controlled amplifier.

The basic multiplier, shown in Fig. 14a, is a two-quadrant multiplier. The input signal (V_x) may have either a positive or negative polarity whereas, the external gain-controlling signal (V_y) must be positive and greater than the base-to-emitter voltage (Fig. 14b). The output current ($I_1 - I_2$) of the differential amplifier, comprised of transistors Q1 and Q2, is related to both the input signal (V_x) and the current source (I). Since the current source (I) is related to the gain controlling signal (V_y) the output current ($I_1 - I_2$), therefore, is related to both V_x and V_y.



a) Basic circuit. *b) Multiplier functional only in shaded region.*

Fig. 14—Two-quadrant multiplier.

This relationship is essentially non-linear; thus an appropriate linearization circuit must be provided in the input stage to achieve the following linear relationship:

$$I_1 - I_2 = k' V_x V_y \qquad \text{(Eq. 1)}$$

where k' is a constant

Figure 15 shows a typical arrangement of three differential amplifiers to form a four-quadrant multiplier. This arrangement incorporates the operating principles of the two-quadrant multiplier, but, in addition, it permits both of the input signals (V_x and V_y) to have positive or negative polarities (or zero). When either input is zero, the output current ($I_1 - I_2$) must, theoretically, be zero as is shown by the following:

1. Assume $V_x = 0$,
   then $i_1 = i_2$ and $i_3 = i_4$
   therefore $i_1 + i_4 = i_2 + i_3$.
   Since $I_1 = i_1 + i_4$ and $I_2 = i_2 + i_3$,
   then $I_1 = I_2$.
   This equality is independent of V_y
2. Now assume $V_y = 0$,
   then $i_5 = i_6$.
   Sine $i_5 = i_1 + i_2$ and $i_6 = i_3 + i_4$,
   then $i_1 + i_2 = i_3 + i_4$.
   Since $i_1 = i_3$ and $i_2 = i_4$
   then $i_1 + i_4 = i_3 + i_2$.
   Therefore $I_1 = I_2$.
   This equality is independent of V_x.

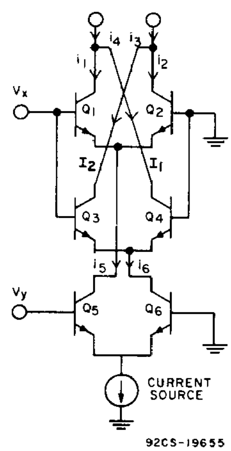


Fig. 15—Basic four-quadrant multiplier.

The multiplying operation discussed in the previous section applies when neither V_x nor V_y is zero. The output current ($I_1 - I_2$) then satisfies Equation 1,

$$I_1 - I_2 = k' V_x V_y.$$

The multiplying action of the four-quadrant multiplier is dependent on current unbalance in the three differential amplifiers. Ideally, the multiplying operation should not occur if either V_x or V_y is O. However, in practical applications slight current unbalances do exist. It is necessary, therefore, to null out such unbalances with external potentiometers prior to operation.

TYPICAL OPERATING CONSIDERATIONS

The RCA-CA3091D, shown in Fig. 2, is a four-quadrant multiplier that incorporates the basic multiplier principle, previously discussed in "Operation of a Multiplier". Because the design of this multiplier is based on the multiplication of two input currents to produce an output current it is necessary to convert the input voltages to input currents and the output current to an output voltage by inserting resistors at both input and output terminals. Fig. 1 shows the four-quadrant multiplier with its peripheral circuitry for nulling current unbalances.

The Bias Current (I_{IB}) at Term. 3 sets the operating current level for the entire multiplier circuit by means of a current-source circuit. Therefore, it is essential that this bias current level remain constant under all operating conditions. To maintain this steady state, a temperature compensated zener diode is provided on the chip and connected to the Reference Voltage (Term.6).

Linearity of the differential amplifier transconductance function is accomplished by linearity compensators as shown in Fig. 1. To correct low-level signal unbalances that may occur between Differential Amplifiers A and B, an external potentiometer is connected to Terminals 7 and 8 (See Fig. 1). The Current Converter circuit, which consists of a set of current mirrors, supplies the output current ($I_1 - I_2$). It is important that circuit unbalances be corrected prior to operation. Table I describes the alignment procedures for correcting these unbalances.

A multifunctional circuit board (Figs. 16 and 17) is available for performing the four basic applications, such as, multiplying, dividing, squaring and taking the square root.

When the CA3091D is used as a multiplier (Fig. 18) or as a squarer (Fig. 18) only the basic pheripheral circuitry on the multifunctional circuit board is utilized and the general-purpose operational amplifier (CA3741T) is disabled from operation. Follow the ac alignment procedures for these two applications before operating the circuit.

When the CA3091D is used as a divider (Fig. 20), the operational amplifier is required in order to provide the proper negative feedback. The limitations for operation as a divider are that $0 < V_y \leqslant 10V$ and $-10V \leqslant V_z \leqslant 10V$. Note, the range of V_y is limited to the positive polarity; if V_y was permitted to go negative, the feedback loop would go positive and, thereby, create an unstable operating condition.

Alignment of the divider (Fig. 19) differs from multiplier and squarer alignment because of the additional variances introduced by the operational amplifier. A coupling capacitor is

Table I

AC Alignment Procedures For CA3091D, Four-Quadrant Multiplier

(Refer to Fig. 16, for circuit pertaining to following alignment procedures.)

Step No.	Voltage Setting		Control Adjust	Test Equipment Used	Measure	Notes
	V_x	V_y				
1	–	–	–	–	–	Set all potentiometers to center of range.
2	O	V_{IM}	x Balance	AC VM	V_O	Adjust for a minimum reading.
3	O	V_{IM}	Linearity	AC VM	V_O	Adjust for a minimum reading.
4	–	–	–	–	–	Repeat Steps 1 and 2 until no further improvement is noted.
5	V_{IM}	O	y Balance	AC VM	V_O	Adjust for a minimum reading.
6	O	O	Zero Output	DC VM	V_O	Adjust for zero output.
7	V_{MID}	V_{MID}	R_k	AC/DC VM	V_O	Adjust for $V_{MID}^2/10$ at the output.
8	–	–	–	–	–	Check multiplier for alignment in all four quadrants.

V_{IM} – Is the maximum AC swing of the sine wave that will be applied to the multiplier. A 20-volt p-p value is the nominal maximum swing of the AC sine wave with input resistors of 50 kilohms.

V_{MID} – An AC or DC voltage that approximately satisfies the equation $V_{MID} = V_{IM}/\sqrt{2}$. For example, if a 50-kilohm resistor is used with a 7-volt input, then R_k should be adjusted for a 4.9-volt output.

provided at the output of the divider alignment circuit in order to separate the ac signal from the dc signal and, thus, avoid interaction between the calibrating potentiometers.

The alignment procedure for the square-rooter function (Fig. 21) is identical to the alignment procedure for the divider function. The input voltage range is limited to $0 < V_I \leq 10V$. This limitation is necessary in order to prevent the output voltage (V_O) from latching to the negative output saturation voltage of the operational amplifier. Table II describes the divider alignment procedure.

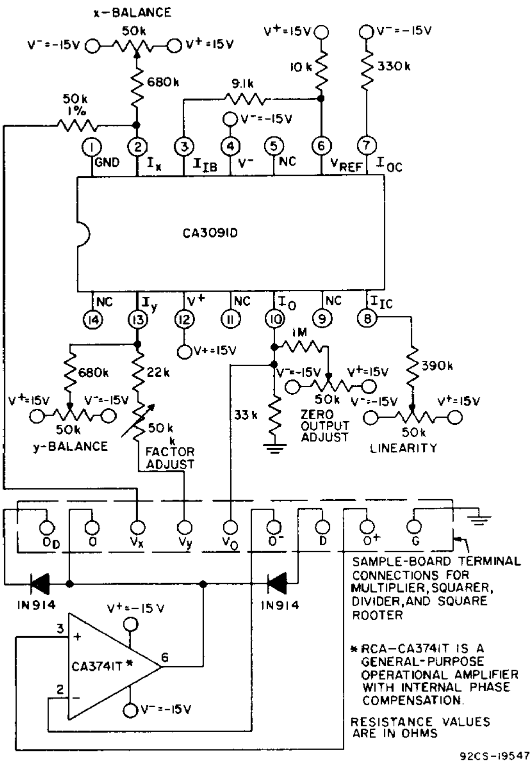
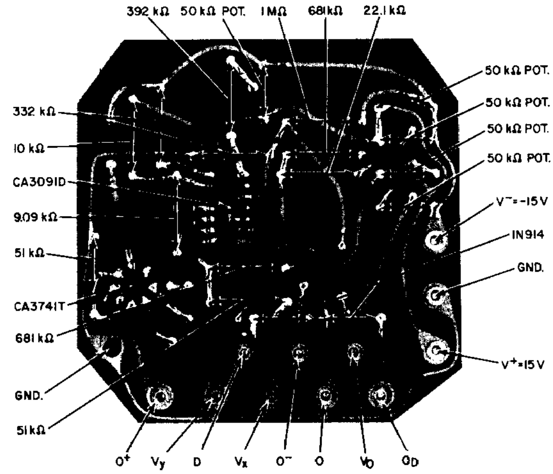
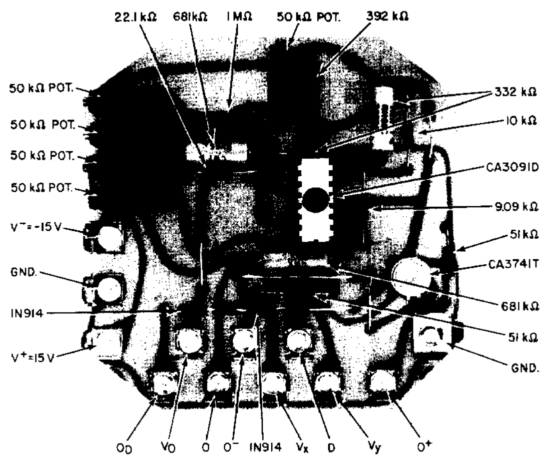


Fig. 16—Typical multifunction circuit arrangement utilizing the CA3091D and CA3741T.



a) Foil side.



b) Component side.

Fig. 17—Photographs of a printed-circuit board for multi-function applications (multiplier, squarer, divider, square rooter) utilizing the CA3091D and CA3741T.

Table II — Divider Alignment Procedure

Step No.	Set V_z V	Set V_y V	Measure	Output Coupling	Test Equipment Used	Adjust	Notes
1	–	–	–	–	–	–	Set all potentiometers to center of range.
2	0	V_S	V_O	ac	ac – VM	O_{zero}	Adjust for minimum reading.
3	0	10V dc	V_O	dc	dc – VM	$x_{balance}$	Adjust for OV dc output.
4	V_S	V_S	V_O	ac	ac – VM	$y_{balance}$	Adjust for minimum reading.
5	5V dc	5V dc	V_O	dc	dc – VM	k_{adjust}	Adjust for 10V dc output.

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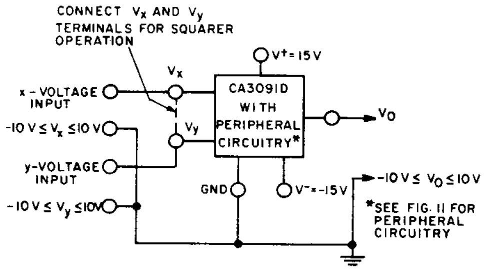
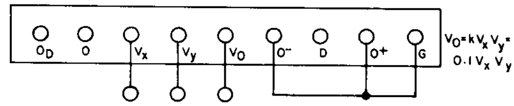
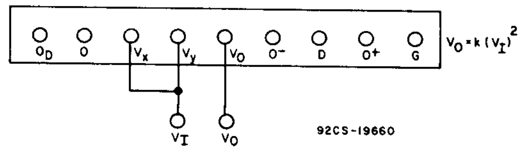


a) Circuit arrangement for multiplier or squarer operation.



b) Terminal connections for multiplying operation.



c) Terminal connections for squarer operation.

Fig.18—Multifunction circuit-board arrangement with terminal connections for multiplier and squarer operation.

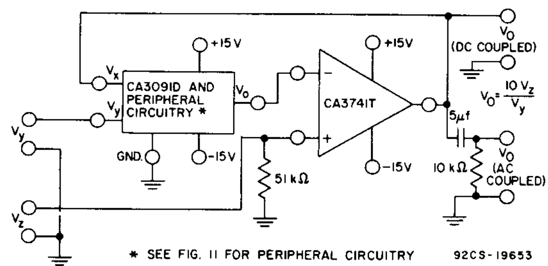


Fig.19—(a) Divider alignment circuit.

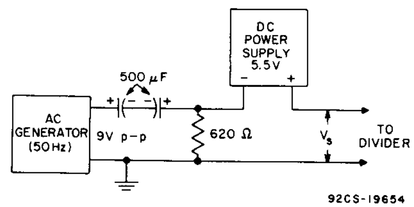
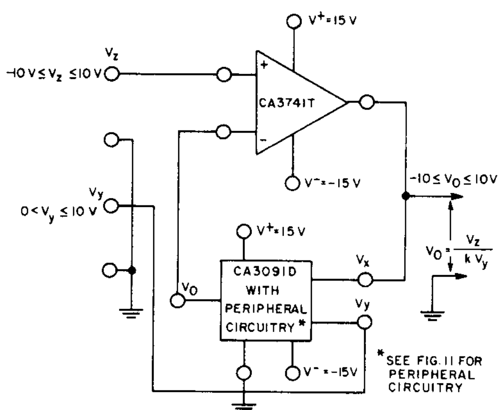
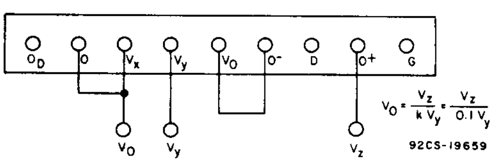


Fig.19—(b) Circuit to provide offset ac signal for use in divider alignment procedure.

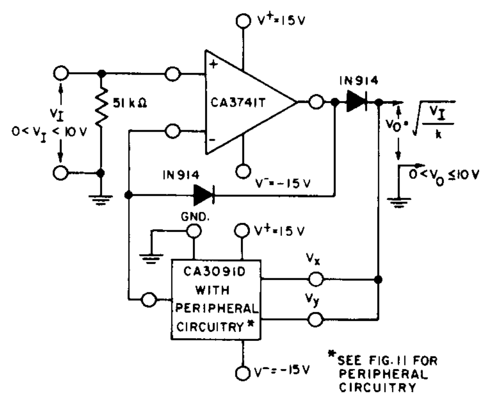


a) Circuit arrangement for divider operation.

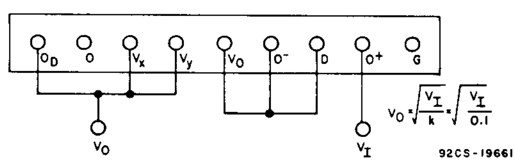


b) Terminal connections for divider operation.

Fig.20—Multifunction circuit-board arrangement with terminal connections for divider operation.



a) Circuit arrangement for square-rooter operation.



b) Terminal connections for square-rooter operation.

Fig.21—Multifunction circuit-board arrangement with terminal connections for square-rooter operation.