



# MAT02–SPECIFICATIONS

## ELECTRICAL CHARACTERISTICS (@ $V_{CB} = 15\text{ V}$ , $I_C = 10\text{ }\mu\text{A}$ , $T_A = 25^\circ\text{C}$ , unless otherwise noted.)

Parameter	Symbol	Conditions	MAT02A/E			MAT02F			Units
			Min	Typ	Max	Min	Typ	Max	
Current Gain	$h_{FE}$	$I_C = 1\text{ mA}^1$ $I_C = 100\text{ }\mu\text{A}$ $I_C = 10\text{ }\mu\text{A}$ $I_C = 1\text{ }\mu\text{A}$	500 500 400 300	605 590 550 485		400 400 300 200	605 590 550 485		
Current Gain Match	$\Delta h_{FE}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^2$		0.5	2		0.5	4	%
Offset Voltage	$V_{OS}$	$V_{CB} = 0$ , $1\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^3$		10	50		80	150	$\mu\text{V}$
Offset Voltage Change vs. $V_{CB}$	$\Delta V_{OS}/\Delta V_{CB}$	$0 \leq V_{CB} \leq V_{MAX}^4$ $1\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^3$		10	25		10	50	$\mu\text{V}$
Offset Voltage Change vs. Collector Current	$\Delta V_{OS}/\Delta I_C$	$V_{CB} = 0\text{ V}$ $1\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^3$		5	25		5	50	$\mu\text{V}$
Offset Current Change vs. $V_{CB}$	$\Delta I_{OS}/\Delta V_{CB}$	$0 \leq V_{CB} \leq V_{MAX}$		30	70		30	70	$\text{pA/V}$
Bulk Resistance	$r_{BE}$	$10\text{ }\mu\text{A} \leq I_C \leq 10\text{ mA}^5$		0.3	0.5		0.3	0.5	$\Omega$
Collector-Base Leakage Current	$I_{CBO}$	$V_{CB} = V_{MAX}$		25	200		25	400	$\text{pA}$
Collector-Collector Leakage Current	$I_{CC}$	$V_{CC} = V_{MAX}^{5,6}$ $V_{CE} = V_{MAX}^{5,6}$		35	200		35	400	$\text{pA}$
Collector-Emitter Leakage Current	$I_{CES}$	$V_{BE} = 0$		35	200		35	400	$\text{pA}$
Noise Voltage Density	$e_n$	$I_C = 1\text{ mA}$ , $V_{CB} = 0^7$ $f_O = 10\text{ Hz}$ $f_O = 100\text{ Hz}$ $f_O = 1\text{ kHz}$ $f_O = 10\text{ kHz}$		1.6 0.9 0.85 0.85	2 1 1 1		1.6 0.9 0.85 0.85	3 2 2 2	$\text{nV}/\sqrt{\text{Hz}}$ $\text{nV}/\sqrt{\text{Hz}}$ $\text{nV}/\sqrt{\text{Hz}}$ $\text{nV}/\sqrt{\text{Hz}}$
Collector Saturation Voltage	$V_{CE(SAT)}$	$I_C = 1\text{ mA}$ , $I_B = 100\text{ }\mu\text{A}$		0.05	0.1		0.05	0.2	$\text{V}$
Input Bias Current	$I_B$	$I_C = 10\text{ }\mu\text{A}$			25			34	$\text{nA}$
Input Offset Current	$I_{OS}$	$I_C = 10\text{ }\mu\text{A}$			0.6			1.3	$\text{nA}$
Breakdown Voltage	$BV_{CEO}$		40			40			$\text{V}$
Gain-Bandwidth Product	$f_T$	$I_C = 10\text{ mA}$ , $V_{CE} = 10\text{ V}$		200			200		$\text{MHz}$
Output Capacitance	$C_{OB}$	$V_{CB} = 15\text{ V}$ , $I_E = 0$		23			23		$\text{pF}$
Collector-Collector Capacitance	$C_{CC}$	$V_{CC} = 0$		35			35		$\text{pF}$

### NOTES

<sup>1</sup>Current gain is guaranteed with Collector-Base Voltage ( $V_{CB}$ ) swept from 0 to  $V_{MAX}$  at the indicated collector currents.

<sup>2</sup>Current gain match ( $\Delta h_{FE}$ ) is defined as:  $\Delta h_{FE} = \frac{100 (\Delta I_B) (h_{FE} \text{ min})}{I_C}$

<sup>3</sup>Measured at  $I_C = 10\text{ }\mu\text{A}$  and guaranteed by design over the specified range of  $I_C$ .

<sup>4</sup>This is the maximum change in  $V_{OS}$  as  $V_{CB}$  is swept from 0 V to 40 V.

<sup>5</sup>Guaranteed by design.

<sup>6</sup> $I_{CC}$  and  $I_{CES}$  are verified by measurement of  $I_{CBO}$ .

<sup>7</sup>Sample tested.

Specifications subject to change without notice.

# ELECTRICAL CHARACTERISTICS ( $V_{CB} = 15\text{ V}$ , $-25^{\circ}\text{C} \leq T_A \leq +85^{\circ}\text{C}$ , unless otherwise noted.)

Parameter	Symbol	Conditions	MAT02E			MAT02F			Units
			Min	Typ	Max	Min	Typ	Max	
Offset Voltage	$V_{OS}$	$V_{CB} = 0$ $1\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^1$			70			220	$\mu\text{V}$
Average Offset Voltage Drift	$TCV_{OS}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}$ , $0 \leq V_{CB} \leq V_{MAX}^2$ $V_{OS}$ Trimmed to Zero <sup>3</sup>		0.08	0.3		0.08	1	$\mu\text{V}/^{\circ}\text{C}$
Input Offset Current	$I_{OS}$	$I_C = 10\text{ }\mu\text{A}$			8			13	nA
Input Offset Current Drift	$TCI_{OS}$	$I_C = 10\text{ }\mu\text{A}^4$		40	90		40	150	$\text{pA}/^{\circ}\text{C}$
Input Bias Current	$I_B$	$I_C = 10\text{ }\mu\text{A}$			45			50	nA
Current Gain	$h_{FE}$	$I_C = 1\text{ mA}^5$ $I_C = 100\text{ }\mu\text{A}$ $I_C = 10\text{ }\mu\text{A}$ $I_C = 1\text{ }\mu\text{A}$	325 275 225 200			300 250 200 150			
Collector-Base Leakage Current	$I_{CBO}$	$V_{CB} = V_{MAX}$		2			3		nA
Collector-Emitter Leakage Current	$I_{CES}$	$V_{CE} = V_{MAX}$ , $V_{BE} = 0$		3			4		nA
Collector-Collector Leakage Current	$I_{CC}$	$V_{CC} = V_{MAX}$		3			4		nA

# ELECTRICAL CHARACTERISTICS ( $V_{CB} = 15\text{ V}$ , $-55^{\circ}\text{C} \leq T_A \leq +125^{\circ}\text{C}$ , unless otherwise noted.)

Parameter	Symbol	Conditions	MAT02A			Units
			Min	Typ	Max	
Offset Voltage	$V_{OS}$	$V_{CB} = 0$ $1\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^1$			80	$\mu\text{V}$
Average Offset Voltage Drift	$TCV_{OS}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}$ , $0 \leq V_{CB} \leq V_{MAX}^2$ $V_{OS}$ Trimmed to Zero <sup>3</sup>		0.08	0.3	$\mu\text{V}/^{\circ}\text{C}$
Input Offset Current	$I_{OS}$	$I_C = 10\text{ }\mu\text{A}$			9	nA
Input Offset Current Drift	$TCI_{OS}$	$I_C = 10\text{ }\mu\text{A}^4$		40	90	$\text{pA}/^{\circ}\text{C}$
Input Bias Current	$I_B$	$I_C = 10\text{ }\mu\text{A}$			60	nA
Current Gain	$h_{FE}$	$I_C = 1\text{ mA}^5$ $I_C = 100\text{ }\mu\text{A}$ $I_C = 10\text{ }\mu\text{A}$ $I_C = 1\text{ }\mu\text{A}$	275 225 125 150			
Collector-Base Leakage Current	$I_{CBO}$	$V_{CB} = V_{MAX}$ $T_A = 125^{\circ}\text{C}$		15		nA
Collector-Emitter Leakage Current	$I_{CES}$	$V_{CE} = V_{MAX}$ , $V_{BE} = 0$ $T_A = 125^{\circ}\text{C}$		50		nA
Collector-Collector Leakage Current	$I_{CC}$	$V_{CC} = V_{MAX}$ $T_A = 125^{\circ}\text{C}$		30		nA

## NOTES

<sup>1</sup>Measured at  $I_C = 10\text{ }\mu\text{A}$  and guaranteed by design over the specified range of  $I_C$ .

<sup>2</sup>Guaranteed by  $V_{OS}$  test ( $TCV_{OS} \equiv \frac{V_{OS}}{T}$  for  $V_{OS} \ll V_{BE}$ )  $T = 298^{\circ}\text{K}$  for  $T_A = 25^{\circ}\text{C}$ .

<sup>3</sup>The initial zero offset voltage is established by adjusting the ratio of IC1 to IC2 at  $T_A = 25^{\circ}\text{C}$ . This ratio must be held to 0.003% over the entire temperature range. Measurements are taken at the temperature extremes and  $25^{\circ}\text{C}$ .

<sup>4</sup>Guaranteed by design.

<sup>5</sup>Current gain is guaranteed with Collector-Base Voltage ( $V_{CB}$ ) swept from 0 to  $V_{MAX}$  at the indicated collector current.

Specifications subject to change without notice.

# MAT02

## WAFER TEST LIMITS (@ 25°C for $V_{CB} = 15\text{ V}$ and $I_C = 10\text{ }\mu\text{A}$ , unless otherwise noted.)

Parameter	Symbol	Conditions	MAT02N Limits	Units
Breakdown Voltage	$BV_{CEO}$		40	V min
Offset Voltage	$V_{OS}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^1$	150	$\mu\text{V}$ max
Input Offset Current	$I_{OS}$		1.2	nA max
Input Bias Current	$I_B$	$V_{CB} = 0\text{ V}$	34	nA max
Current Gain	$h_{FE}$	$I_C = 1\text{ mA}$ , $V_{CB} = 0\text{ V}$	400	min
		$I_C = 10\text{ }\mu\text{A}$ , $V_{CB} = 0\text{ V}$	300	
Current Gain Match	$\Delta h_{FE}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}$ , $V_{CB} = 0\text{ V}$	4	% max
Offset Voltage Change vs. $V_{CB}$	$\Delta V_{OS}/\Delta V_{CB}$	$0\text{ V} \leq V_{CB} \leq 40\text{ V}$	50	$\mu\text{V}$ max
Offset Voltage Change vs. Collector Current	$\Delta V_{OS}/\Delta I_C$	$V_{CB} = 0$	50	$\mu\text{V}$ max
Bulk Resistance	$r_{BE}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}^1$		
Collector Saturation Voltage	$V_{CE(SAT)}$	$100\text{ }\mu\text{A} \leq I_C \leq 10\text{ mA}$	0.5	$\Omega$ max
		$I_C = 1\text{ mA}$	0.2	V max
		$I_B = 100\text{ }\mu\text{A}$		

### NOTES

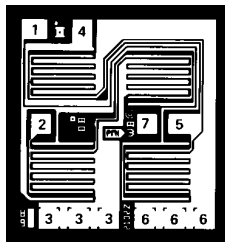
<sup>1</sup>Measured at  $I_C = 10\text{ }\mu\text{A}$  and guaranteed by design over the specified range of  $I_C$ .

Electrical tests are performed at wafer probe to the limits shown. Due to variations in assembly methods and normal yield loss, yield after packaging is not guaranteed for standard product dice. Consult factory to negotiate specifications based on dice lot qualification through sample lot assembly and testing.

## TYPICAL ELECTRICAL CHARACTERISTICS ( $V_{CB} = 15\text{ V}$ , $I_C = 10\text{ }\mu\text{A}$ , $T_A = +25^\circ\text{C}$ , unless otherwise noted.)

Parameter	Symbol	Conditions	MAT02N Limits	Units
Average Offset Voltage Drift	$TCV_{OS}$	$10\text{ }\mu\text{A} \leq I_C \leq 1\text{ mA}$	0.08	$\mu\text{V}/^\circ\text{C}$
Average Offset Current Drift	$TCI_{OS}$	$0 \leq V_{CB} \leq V_{MAX}$	40	$\text{pA}/^\circ\text{C}$
Gain-Bandwidth Product	$f_T$	$V_{CE} = 10\text{ V}$ , $I_C = 10\text{ mA}$	200	MHz
Offset Current Change vs. $V_{CB}$	$\Delta I_{OS}/\Delta V_{CB}$	$0 \leq V_{CB} \leq 40\text{ V}$	70	$\text{pA}/\text{V}$

### DICE CHARACTERISTICS



1. COLLECTOR (1)
2. BASE (1)
3. EMITTER (1)
4. COLLECTOR (2)
5. BASE (2)
6. EMITTER (2)
7. SUBSTRATE

Die Size  $0.061 \times 0.057\text{ inch}$ , 3,477 sq. mils  
( $1.549 \times 1.448\text{ mm}$ , 224 sq. mm)

### CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the MAT02 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.



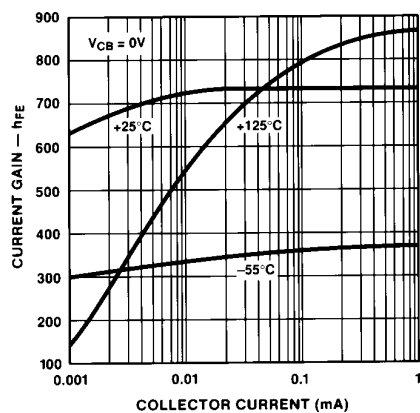


Figure 1. Current Gain vs. Collector Current

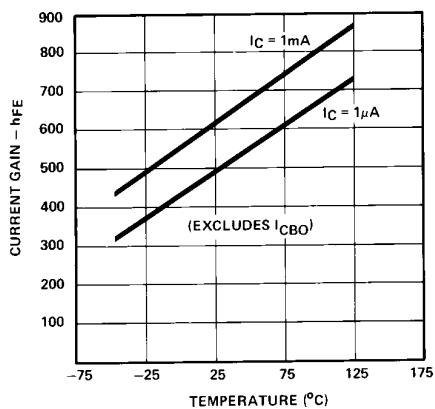


Figure 2. Current Gain vs. Temperature

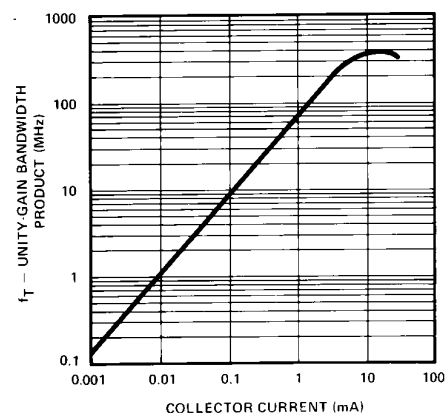


Figure 3. Gain Bandwidth vs. Collector Current

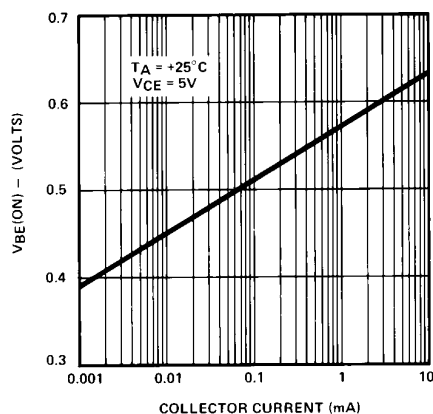


Figure 4. Base-Emitter-On Voltage vs. Collector Current

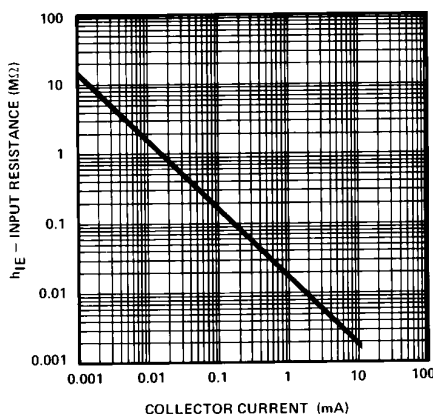


Figure 5. Small Signal Input Resistance vs. Collector Current

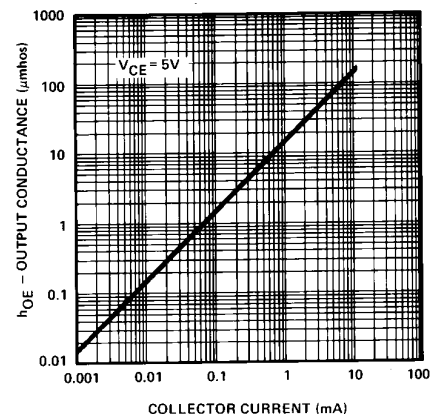


Figure 6. Small-Signal Output Conductance vs. Collector Current

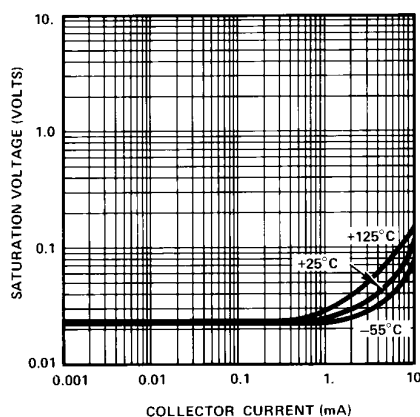


Figure 7. Saturation Voltage vs. Collector Current

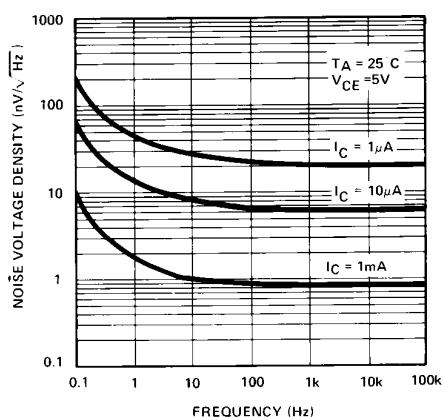


Figure 8. Noise Voltage Density vs. Frequency

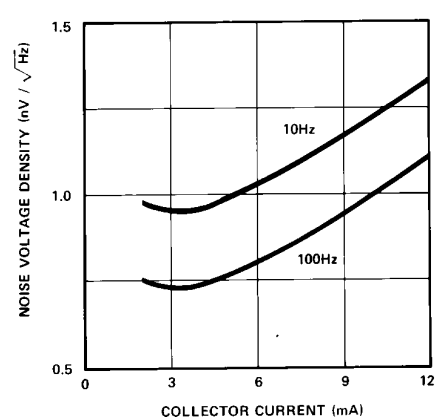


Figure 9. Noise Voltage Density vs. Collector Current

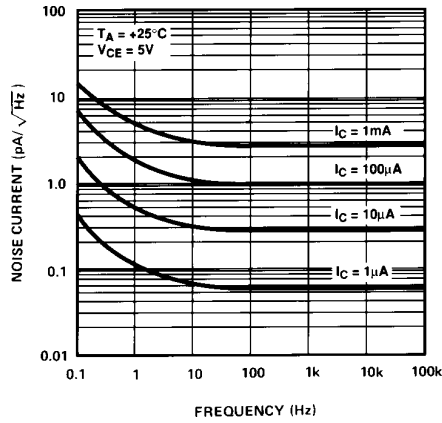


Figure 10. Noise Current Density vs. Frequency

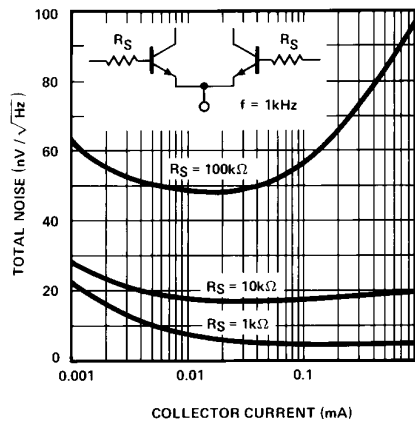


Figure 11. Total Noise vs. Collective Current

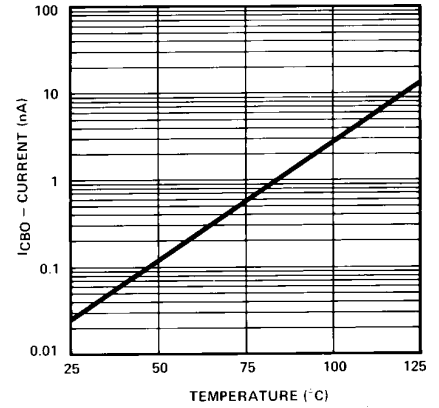


Figure 12. Collector-to-Base Leakage vs. Temperature

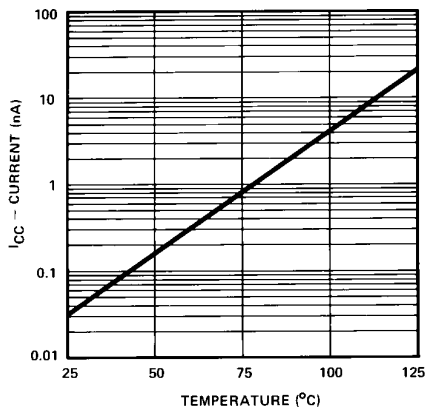


Figure 13. Collector-to-Collector Leakage vs. Temperature

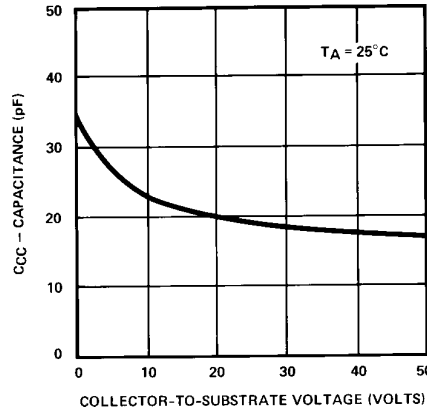


Figure 14. Collector-to-Collector Capacitance vs. Collector-to-Substrate Voltage

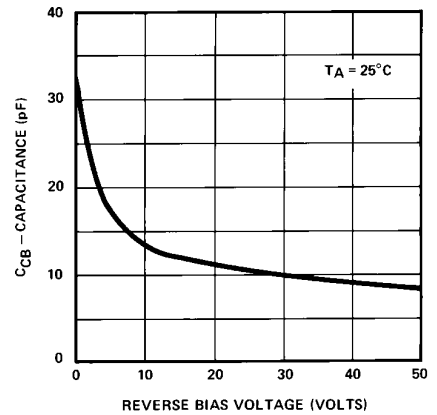


Figure 15. Collector-Base Capacitance vs. Reverse Bias Voltage

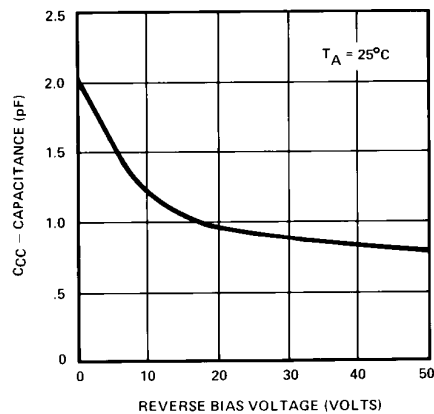


Figure 16. Collector-to-Collector Capacitance vs. Reverse Bias Voltage

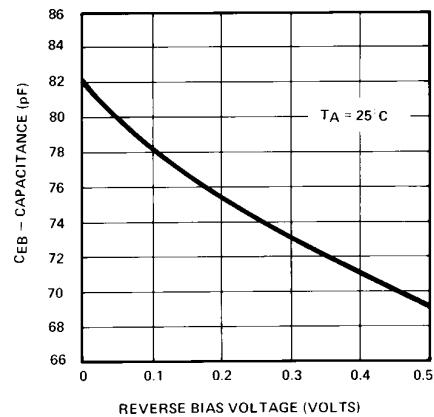


Figure 17. Emitter-Base Capacitance vs. Reverse Bias Voltage

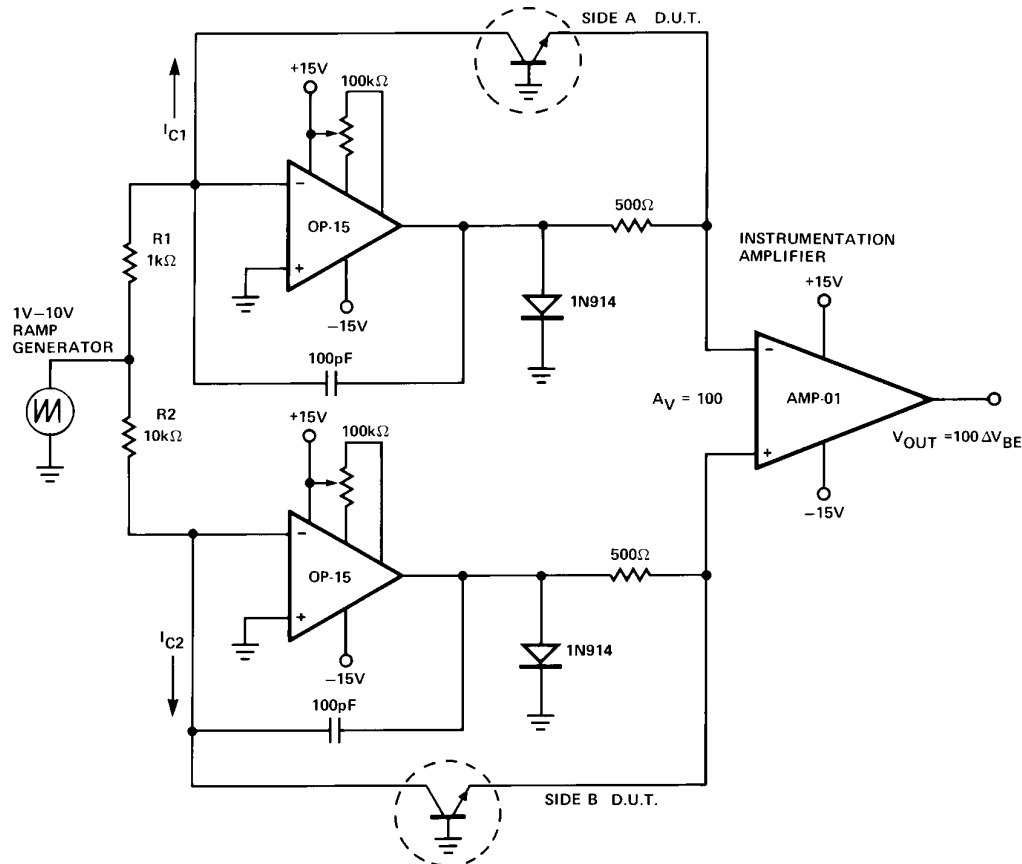


Figure 18. Log Conformance Test Circuit

### LOG CONFORMANCE TESTING

The log conformance of the MAT02 is tested using the circuit shown above. The circuit employs a dual transdiode logarithmic converter operating at a fixed ratio of collector currents that are swept over a 10:1 range. The output of each transdiode converter is the  $V_{BE}$  of the transistor plus an error term which is the product of the collector current and  $r_{BE}$ , the bulk emitter resistance. The difference of the  $V_{BE}$  is amplified at a gain of  $\times 100$  by the AMP01 instrumentation amplifier. The differential emitter-base voltage ( $\Delta V_{BE}$ ) consists of a temperature-dependent dc level plus an ac error voltage which is the deviation from true log conformity as the collector currents vary.

The output of the transdiode logarithmic converter comes from the idealized intrinsic transistor equation (for silicon):

$$V_{BE} = \frac{kT}{q} \ln \frac{I_C}{I_S} \text{ where} \quad (1)$$

$k$  = Boltzmann's Constant ( $1.38062 \times 10^{-23} \text{ J/}^\circ\text{K}$ )

$q$  = Unit Electron Charge ( $1.60219 \times 10^{-19} \text{ }^\circ\text{C}$ )

$T$  = Absolute Temperature,  $^\circ\text{K}$  ( $= ^\circ\text{C} + 273.2$ )

$I_S$  = Extrapolated Current for  $V_{BE} \rightarrow 0$

$I_C$  = Collector Current

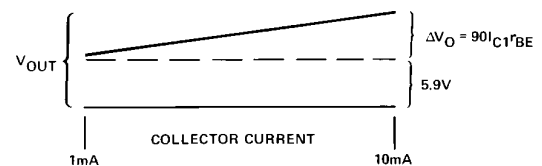
An error term must be added to this equation to allow for the bulk resistance ( $r_{BE}$ ) of the transistor. Error due to the op amp input current is limited by use of the OP15 BiFET-input op amp. The resulting AMP01 input is:

$$\Delta V_{BE} = \frac{kT}{q} \ln \frac{I_{C1}}{I_{C2}} + I_{C1} r_{BE1} - I_{C2} r_{BE2} \quad (2)$$

A ramp function which sweeps from 1 V to 10 V is converted by the op amps to a collector current ramp through each transistor. Because  $I_{C1}$  is made equal to 10  $I_{C2}$ , and assuming  $T_A = 25^\circ\text{C}$ , the previous equation becomes:

$$\Delta V_{BE} = 59 \text{ mV} + 0.9 I_{C1} r_{BE} (\Delta r_{BE} \sim 0)$$

As viewed on an oscilloscope, the change in  $\Delta V_{BE}$  for a 10:1 change in  $I_C$  is then displayed as shown below:



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With the oscilloscope ac coupled, the temperature dependent term becomes a dc offset and the trace represents the deviation from true log conformity. The bulk resistance can be calculated from the voltage deviation  $\Delta V_O$  and the change in collector current (9 mA):

$$r_{BE} = \frac{\Delta V_O}{9 \text{ mA}} \times \frac{1}{100} \quad (3)$$

This procedure finds  $r_{BE}$  for Side A. Switching  $R_1$  and  $R_2$  will provide the  $r_{BE}$  for Side B. Differential  $r_{BE}$  is found by making  $R_1 = R_2$ .

## APPLICATIONS: NONLINEAR FUNCTIONS MULTIPLIER/DIVIDER CIRCUIT

The excellent log conformity of the MAT02 over a very wide range of collector current makes it ideal for use in log-antilog circuits. Such nonlinear functions as multiplying, dividing, squaring, and square-rooting are accurately and easily implemented with a log-antilog circuit using two MAT02 pairs (see Figure 19). The transistor circuit accepts three input currents ( $I_1$ ,  $I_2$ , and  $I_3$ ) and provides an output current  $I_O$  according to  $I_O = I_1 I_2 / I_3$ . All four currents must be positive in the log-antilog circuit, but negative input voltages can be easily accommodated

by various offsetting techniques. Protective diodes across each base-to-emitter junction would normally be needed, but these diodes are built into the MAT02. External protection diodes are therefore not needed.

For the circuit shown in Figure 19, the operational amplifiers make  $I_1 = V_X / R_1$ ,  $I_2 = V_Y / R_2$ ,  $I_3 = V_Z / R_3$ , and  $I_O = V_O / R_O$ . The output voltage for this one-quadrant, log-antilog multiplier/divider is ideally:

$$V_O = \frac{R_3 R_O}{R_1 R_2} \frac{V_X V_Y}{V_Z} \quad (V_X, V_Y, V_Z > 0) \quad (4)$$

If all the resistors ( $R_O$ ,  $R_1$ ,  $R_2$ ,  $R_3$ ) are made equal, then  $V_O = V_X V_Y / V_Z$ . Resistor values of 50 k $\Omega$  to 100 k $\Omega$  are recommended assuming an input range of 0.1 V to +10 V.

## ERROR ANALYSIS

The base-to-emitter voltage of the MAT02 in its forward active operation is:

$$V_{BE} = \frac{kT}{q} \ln \frac{I_C}{I_S} + r_{BE} I_C, \quad V_{CB} \sim 0 \quad (5)$$

The first term comes from the idealized intrinsic transistor equation previously discussed (see equation (1)).

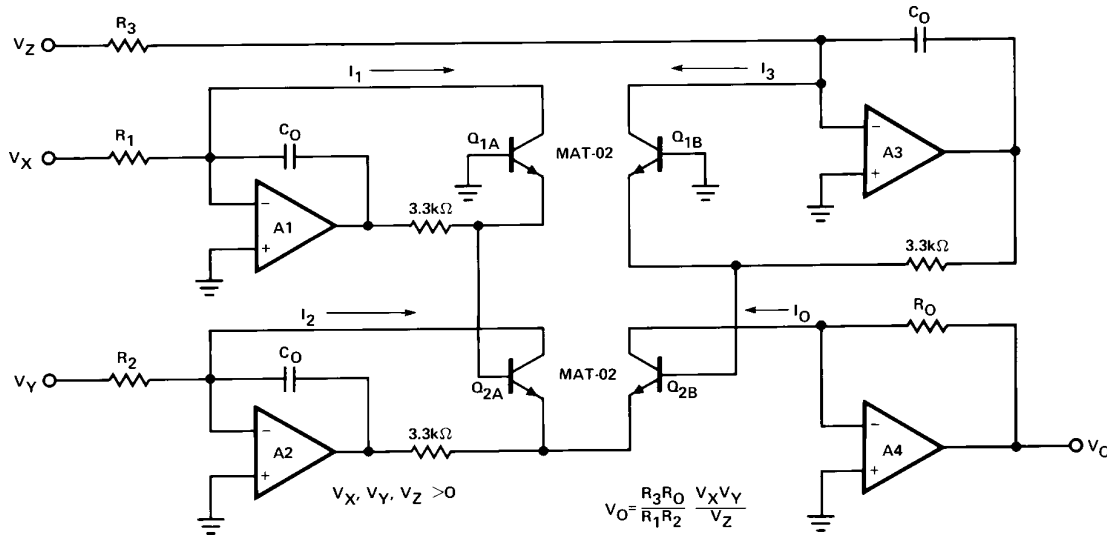


Figure 19. One-Quadrant Multiplier/Divider



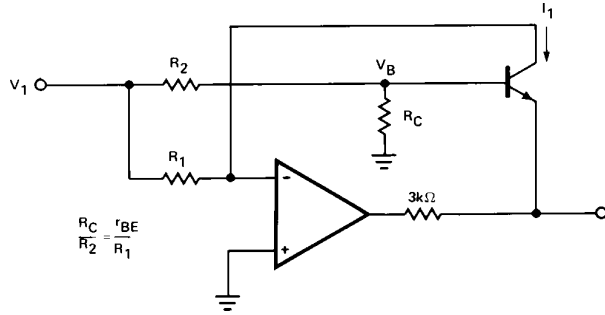


Figure 20. Compensation of Bulk Resistance Error

Extrinsic resistive terms and the early effect cause departure from the ideal logarithmic relationship. For small  $V_{CB}$ , all of these effects can be lumped together as a total effective bulk resistance  $r_{BE}$ . The  $r_{BE}I_C$  term causes departure from the desired logarithmic relationship. The  $r_{BE}$  term for the MAT02 is less than  $0.5 \Omega$  and  $\Delta r_{BE}$  between the two sides is negligible.

Returning to the multiplier/divider circuit of Figure 1 and using Equation (4):

$$V_{BE1A} + V_{BE2A} - V_{BE2B} - V_{BE1B} + (I_1 + I_2 - I_O - I_3) r_{BE} = 0$$

If the transistor pairs are held to the same temperature, then:

$$\frac{kT}{q} \ln \frac{I_1 I_2}{I_3 I_O} = \frac{kT}{q} \ln \frac{I_{SA} I_{S2A}}{I_{SB} I_{S2B}} + (I_1 + I_2 - I_O - I_3) r_{BE} \quad (6)$$

If all the terms on the right-hand side were zero, then we would have  $\ln(I_1 I_2 / I_3 I_O)$  equal to zero which would lead directly to the desired result:

$$I_O = \frac{I_1 I_2}{I_3}, \text{ where } I_1, I_2, I_3, I_O > 0 \quad (7)$$

Note that this relationship is temperature independent. The right-hand side of Equation (6) is near zero and the output current  $I_O$  will be approximately  $I_1 I_2 / I_3$ . To estimate error, define  $\phi$  as the right-hand side terms of Equation (6):

$$\phi = \ln \frac{I_{SA} I_{S2A}}{I_{SB} I_{S2B}} + \frac{q}{kT} (I_1 + I_2 - I_O - I_3) r_{BE} \quad (8)$$

For the MAT02,  $\ln(I_{SA}/I_{SB})$  and  $I_C r_{BE}$  are very small. For small  $\phi$ ,  $e^\phi \sim 1 + \phi$  and therefore:

$$\frac{I_1 I_2}{I_3 I_O} = 1 + \phi \quad (9)$$

$$I_O \sim \frac{I_1 I_2}{I_3} (1 - \phi)$$

The  $\ln(I_{SA}/I_{SB})$  terms in  $\phi$  cause a fixed gain error of less than  $\pm 0.6\%$  from each pair when using the MAT02, and this gain error is easily trimmed out by varying  $R_O$ . The  $I_C r_{BE}$  terms are more troublesome because they vary with signal levels and are multiplied by absolute temperature. At  $25^\circ\text{C}$ ,  $kT/q$  is

approximately 26 mV and the error due to an  $r_{BE}I_C$  term will be  $r_{BE}I_C/26$  mV. Using an  $r_{BE}$  of  $0.4 \Omega$  for the MAT02 and assuming a collector current range of up to  $200 \mu\text{A}$ , then a peak error of  $0.3\%$  could be expected for an  $r_{BE}I_C$  error term when using the MAT02. Total error is dependent on the specific application configuration (multiply, divide, square, etc.) and the required dynamic range. An obvious way to reduce  $I_C r_{BE}$  error is to reduce the maximum collector current, but then op amp offsets and leakage currents become a limiting factor at low input levels. A design range of no greater than  $10 \mu\text{A}$  to  $1 \text{ mA}$  is generally recommended for most nonlinear function circuits.

A powerful technique for reducing error due to  $I_C r_{BE}$  is shown in Figure 20. A small voltage equal to  $I_C r_{BE}$  is applied to the transistor base. For this circuit:

$$V_B = \frac{R_C}{R_2} V_1 \text{ and } I_C r_{BE} = \frac{r_{BE}}{R_1} V_1 \quad (10)$$

The error from  $r_{BE}I_C$  is cancelled if  $R_C/R_2$  is made equal to  $r_{BE}/R_1$ . Since the MAT02 bulk resistance is approximately  $0.39 \Omega$ , an  $R_C$  of  $3.9 \Omega$  and  $R_2$  of  $10 R_1$  will give good error cancellation.

In more complex circuits, such as the circuit in Figure 19, it may be inconvenient to apply a compensation voltage to each individual base. A better approach is to sum all compensation to the bases of Q1. The "A" side needs a base voltage of  $(V_O/R_O + V_Z/R_3) r_{BE}$  and the "B" side needs a base voltage of  $(V_X/R_1 + V_Y/R_2) r_{BE}$ . Linearity of better than  $\pm 0.1\%$  is readily achievable with this compensation technique.

Operational amplifier offsets are another source of error. In Figure 20, the input offset voltage and input bias current will cause an error in collector current of  $(V_{OS}/R_1) + I_B$ . A low offset op amp, such as the OP07 with less than  $75 \mu\text{V}$  of  $V_{OS}$  and  $I_B$  of less than  $\pm 3 \text{ nA}$ , is recommended. The OP22/OP32, a programmable micropower op amp, should be considered if low power consumption or single-supply operation is needed. The value of frequency-compensating capacitor ( $C_O$ ) is dependent on the op amp frequency response and peak collector current. Typical values for  $C_O$  range from  $30 \text{ pF}$  to  $300 \text{ pF}$ .

#### FOUR-QUADRANT MULTIPLIER

A simplified schematic for a four-quadrant log/antilog multiplier is shown in Figure 21. As with the previously discussed one-quadrant multiplier, the circuit makes  $I_O = I_1 I_2 / I_3$ . The two input currents,  $I_1$  and  $I_2$ , are each offset in the positive direction. This positive offset is then subtracted out at the output stage. Assuming ideal op amps, the currents are:

$$I_1 = \frac{V_X}{R_1} + \frac{V_R}{R_2}, I_2 = \frac{V_Y}{R_1} + \frac{V_R}{R_2} \quad (11)$$

$$I_O = \frac{V_X}{R_1} + \frac{V_Y}{R_1} + \frac{V_R}{R_2} + \frac{V_O}{R_O}, I_3 = \frac{V_R}{R_2}$$

From  $I_O = I_1 I_2 / I_3$ , the output voltage will be:

$$V_O = \frac{R_O R_2}{R_1^2} \frac{V_X V_Y}{V_R} \quad (12)$$

## MAT02

Collector-current range is the key design decision. The inherently low  $r_{BE}$  of the MAT02 allows the use of a relatively high collector current. For input scaling of  $\pm 10$  V full-scale and using a 10 V reference, we have a collector-current range for  $I_1$  and  $I_2$  of:

$$\left( \frac{-10}{R_1} + \frac{10}{R_2} \right) \leq I_C \leq \left( \frac{10}{R_1} + \frac{10}{R_2} \right) \quad (13)$$

Practical values for  $R_1$  and  $R_2$  would range from 50 k $\Omega$  to 100 k $\Omega$ . Choosing an  $R_1$  of 82 k $\Omega$  and  $R_2$  of 62 k $\Omega$  provides a collector-current range of approximately 39  $\mu$ A to 283  $\mu$ A. An  $R_O$  of 108 k $\Omega$  will then make the output scale factor 1/10 and  $V_O = V_X V_Y / 10$ . The output, as well as both inputs, are scaled for  $\pm 10$  V full scale.

Linear error for this circuit is substantially improved by the small correction voltage applied to the base of Q1 as shown in Figure 21. Assuming an equal bulk emitter resistance for each MAT02 transistor, then the error is nulled if:

$$(I_1 + I_2 - I_3 - I_O) r_{BE} + \rho V_O = 0$$

The currents are known from the previous discussion, and the relationship needed is simply:

$$V_O = \frac{r_{BE}}{R_O} V_O \quad (14)$$

The output voltage is attenuated by a factor of  $r_{BE}/R_O$  and applied to the base of Q1 to cancel the summation of voltage drops due to  $r_{BE}I_C$  terms. This will make  $\ln(I_1 I_2 / I_3 I_O)$  more nearly zero which will thereby make  $I_O = I_1 I_2 / I_3$  a more accurate relationship. Linearity of better than 0.1% is readily achievable with this circuit if the MAT02 pairs are carefully kept at the same temperature.

### MULTIFUNCTION CONVERTER

The multifunction converter circuit provides an accurate means of squaring, square rooting, and of raising ratios to arbitrary powers. The excellent log conformity of the MAT02 allows a wide range of exponents. The general transfer function is:

$$V_O = V_Y \left( \frac{V_Z}{V_X} \right)^m \quad (15)$$

$V_X$ ,  $V_Y$ , and  $V_Z$  are input voltages and the exponent "m" has a practical range of approximately 0.2 to 5. Inputs  $V_X$  and  $V_Y$  are often taken from a fixed reference voltage. With a REF01 providing a precision +10 V to both  $V_X$  and  $V_Y$ , the transfer function would simplify to:

$$V_O = 10 \left( \frac{V_Z}{10} \right)^m \quad (16)$$

As with the multiplier/divider circuits, assume that the transistor pairs have excellent matching and are at the same temperature. The  $\ln I_{SA}/I_{SB}$  will then be zero. In the circuit of Figure 22, the voltage drops across the base-emitter junctions of Q1 provide:

$$\frac{R_B}{R_B + KR_A} V_A = \frac{kT}{q} \ln \frac{I_Z}{I_X} \quad (17)$$

$I_Z$  is  $V_Z/R_1$  and  $I_X$  is  $V_X/R_1$ . Similarly, the relationship for Q2 is:

$$\frac{R_B}{R_B + (1-K)R_A} V_A = \frac{kT}{q} \ln \frac{I_O}{I_Y} \quad (18)$$

$I_O$  is  $V_O/R_O$  and  $I_Y$  is  $V_Y/R_1$ . These equations for Q1 and Q2 can then be combined.

$$\frac{R_B + KR_A}{R_B + (1-K)R_A} \ln \frac{I_Z}{I_X} = \ln \frac{I_O}{I_Y} \quad (19)$$

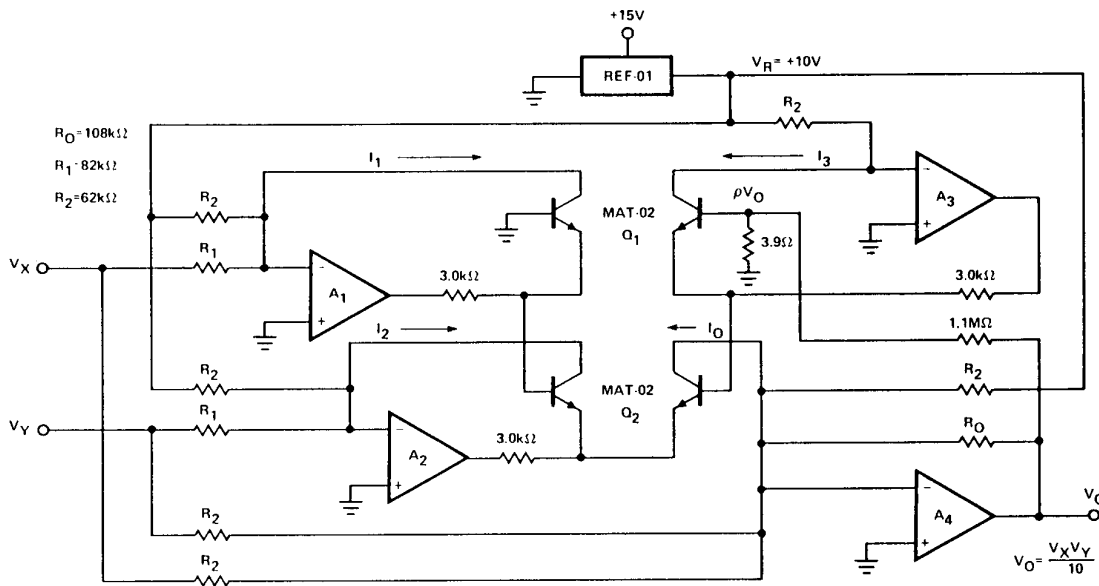


Figure 21. Four-Quadrant Multiplier

Substituting in the voltage relationships and simplifying leads to:

$$V_O = \frac{R_O}{R_1} V_Y \left( \frac{V_Z}{V_X} \right)^m, \text{ where} \quad (20)$$

$$m = \frac{R_B + KR_A}{R_B + (1-K)R_A}$$

The factor “K” is a potentiometer position and varies from zero to 1.0, so “m” ranges from  $R_B/(R_A + R_B)$  to  $(R_B + R_A)/R_B$ . Practical values are 125  $\Omega$  for  $R_B$  and 500  $\Omega$  for  $R_A$ ; these values will provide an adjustment range of 0.2 to 5.0. A value of 100 k $\Omega$  is recommended for the  $R_1$  resistors assuming a full-scale input range of 10 V. As with the one-quadrant multiplier/divider circuit previously discussed, the  $V_X$ ,  $V_Y$ , and  $V_Z$  inputs must all be positive.

The op amps should have the lowest possible input offsets. The OP07 is recommended for most applications, although such programmable micropower op amps as the OP22 or OP32 offer advantages in low-power or single-supply circuits. The micropower op amps also have very low input bias-current drift, an important advantage in log/antilog circuits. External offset nulling may be needed, particularly for applications requiring a wide dynamic range. Frequency compensating capacitors, on the order of 50 pF, may be required for  $A_2$  and  $A_3$ . Amplifier  $A_1$  is likely to need a larger capacitor, typically 0.0047  $\mu$ F, to assure stability.

Accuracy is limited at the higher input levels by bulk emitter resistance, but this is much lower for the MAT02 than for other transistor pairs. Accuracy at the lower signal levels primarily depends on the op amp offsets. Accuracies of better than 1% are readily achievable with this circuit configuration and can be better than  $\pm 0.1\%$  over a limited operating range.

#### FAST LOGARITHMIC AMPLIFIER

The circuit of Figure 23 is a modification of a standard logarithmic amplifier configuration. Running the MAT02 at 2.5 mA per side (full-scale) allows a fast response with wide dynamic range. The circuit has a 7 decade current range, a 5 decade voltage range, and is capable of 2.5  $\mu$ s settling time to 1% with a 1 V to 10 V step.

The output follows the equation:

$$V_O = \frac{R_3 + R_2}{R_2} \frac{kT}{q} \ln \frac{V_{REF}}{V_{IN}} \quad (21)$$

The output is inverted with respect to the input, and is nominally  $-1$  V/decade using the component values indicated.

#### LOW-NOISE $\times 1000$ AMPLIFIER

The MAT02 noise voltage is exceptionally low, only 1 nV/ $\sqrt{\text{Hz}}$  at 10 Hz when operated over a collector-current range of 1 mA to 4 mA. A single-ended  $\times 1000$  amplifier that takes advantage of this low MAT02 noise level is shown in Figure 24. In addition to low noise, the amplifier has very low drift and high CMRR. An OP32 programmable low-power op amp is used for the second stage to obtain good speed with minimal power consumption. Small-signal bandwidth is 1 MHz, slew rate is 2.4 V/ $\mu$ s, and total supply current is approximately 2.8 mA.

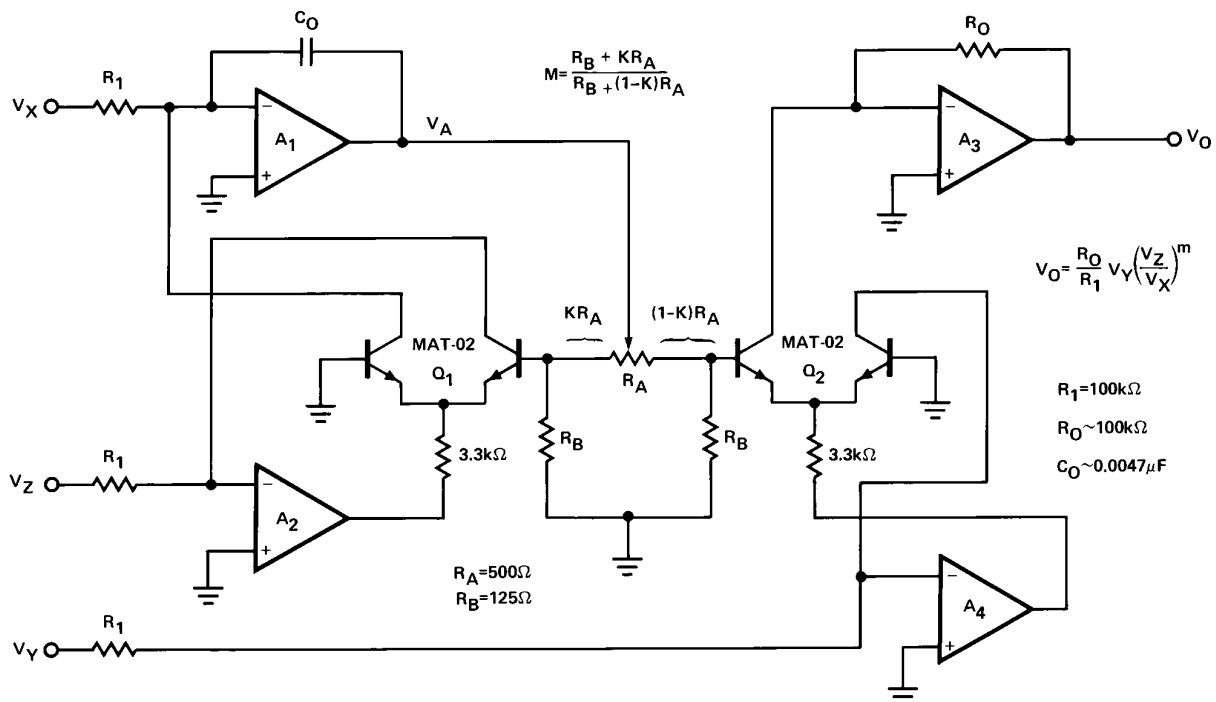


Figure 22. Multifunction Converter

# MAT02

Transistors Q2 and Q3 form a 2 mA current source (0.65 V/330 Ω ~ 2 mA). Each collector of Q1 operates at 1 mA. The OP32 inputs are 3 V below the positive supply voltage ( $R_L I_C \sim 3$  V). The OP32's low input offset current, typically less than 1 nA, and low offset voltage of 1 mV cause negligible error when referred to the amplifier input. Input stage gain is  $g_m R_L$ , which is approximately 100 when operating at  $I_C$  of 1 mA with  $R_L$  of 3 kΩ. Since the OP32 has a minimum open-loop gain of 500,000, total open-loop gain for the composite amplifier is over 50 million. Even at closed-loop gain of 1000, the gain error due to finite open-loop gain will be negligible. The OP32 features excellent symmetry of slew-rate and very linear gain. Signal distortion is minimal.

Frequency compensation is very easy with this circuit; just vary the set-resistor  $R_S$  for the desired frequency response. Gain-bandwidth of the OP32 varies directly with the supply

current. A set resistor of 549 kΩ was found to provide the best step response for this circuit. The resultant supply current is found from:

$$R_{SET} = \frac{(V_+) - (V_-) - (2 V_{BE})}{I_{SET}}, I_{SY} = 15 I_{SET} \quad (22)$$

The  $I_{SET}$ , using  $\pm 15$  V supplies and an  $R_{SET}$  of 549 kΩ, is approximately 52 μA which will result in supply current of 784 μA.

Dynamic range of this amplifier is excellent; the OP32 has an output voltage swing of  $\pm 14$  V with a  $\pm 15$  V supply.

Input characteristics are outstanding. The MAT02F has offset voltage of less than 150 μV at 25°C and a maximum offset drift of 1 μV/°C. Nulling the offset will further reduce offset drift. This can be accomplished by slightly unbalancing the collector load resistors. This adjustment will reduce the drift to less than 0.1 μV/°C.

Input bias current is relatively low due to the high current gain of the MAT02. The minimum  $\beta$  of 400 at 1 mA for the MAT02F implies an input bias current of approximately 2.5 μA. This circuit should be used with signals having relatively low source impedance. A high source impedance will degrade offset and noise performance.

This circuit configuration provides exceptionally low input noise voltage and low drift. Noise can be reduced even further by raising the collector currents from 1 mA to 3 mA, but power consumption is then increased.

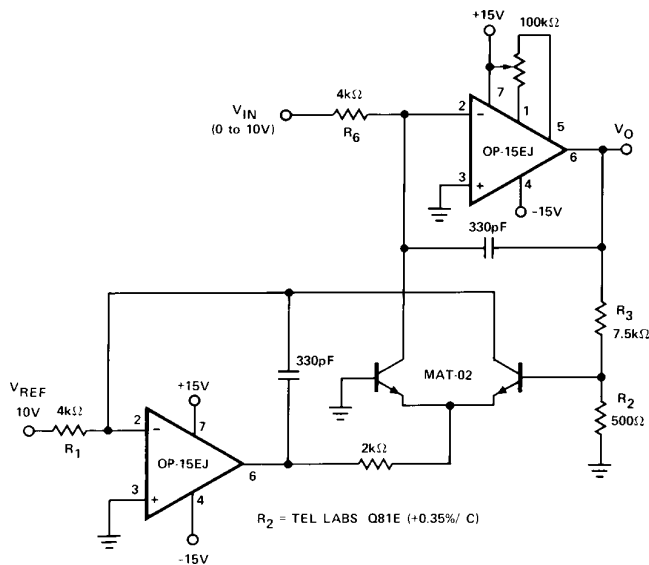


Figure 23. Fast Logarithmic Amplifier

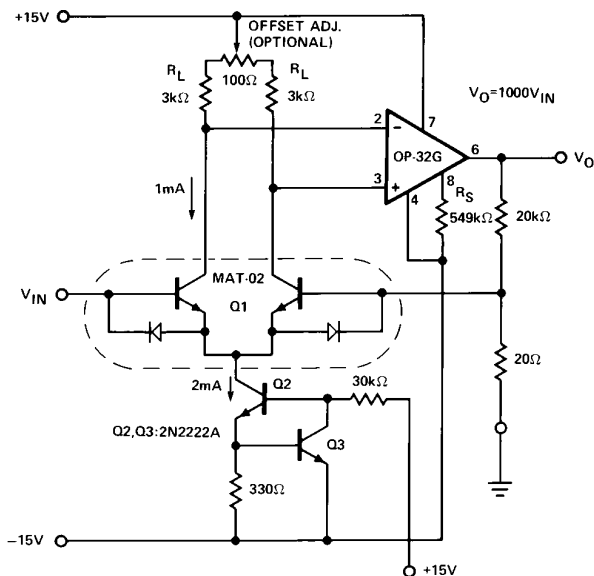


Figure 24. Low-Noise, Single-Ended X1000 Amplifier

## OUTLINE DIMENSION

Dimensions shown in inches and (mm).

### 6-Lead Metal Can (TO-78)

