UNDERSTANDING AND USING 'OTA' OP-AMP ICs

Part 1

by Ray Marston

Take a look at Operational Transconductance Amplifier (OTA) op-amp principles and at practical CA3080 OTA circuits in this opening episode of a two-part mini-series.

Most popular op-amp (operational amplifier) ICs — such as the 741, CA3140, and LF351, etc. — give an output voltage that is proportional to the difference between the IC's two input pin voltages, and are thus known as voltage-differencing amplifiers or 'VDAs.' There are, however, two other basic types of op-amps that are in common use; one of these is the type that gives an output voltage that is proportional to the difference between the *currents* applied to its two input terminals, and is thus known as a current-differencing amplifier or 'CDA.' This type of op-amp was described in depth in the "Understanding and Using 'Norton' Op-Amp ICs" two-part mini-series published in this magazine. The third type of op-amp is known as an operational transconductance amplifier or 'OTA,' and acts as a variable-gain voltage-to-current amplifier.

One of the best known OTA ICs is the CA3080, which is of particular value in making voltage- or current-controlled amplifiers, or micro-power voltage comparators or oscillators, etc. OTAs have operating characteristics very different from conventional op-amps, and *Figure 1* illustrates the major differences between these two types of devices.

Figure 1(a) shows the basic symbol and formulas of the conventional op-amp, which is essentially a voltage amplifying device. It has differential input terminals and gives an output of A_O x (e_1 - e_2), where A_O is the open-loop voltage gain of the op-amp and e_1 and e_2 are the signal voltages at the non-inverting and inverting input terminals, respectively. Note that the open-loop voltage gain of this op-amp is fixed, and the device has a high input impedance and a low output impedance.

Figure 1(b) shows the basic symbol and formulas of an OTA, which is essentially a voltage-to-current amplifier. It has differential voltage input terminals (like a conventional op-amp) but — as indicated by the constant-current symbol on its output — these input voltages produce a high-impedance output in the form of a current with a value of gm x (e_1 - e_2), where gm is the transconductance or voltage-to-current gain of the device and can be controlled by (and is directly proportional to the value of) an external bias current fed into the I_{bias} terminal. In the CA3080, I_{bias} can be varied from 0.1μA to 1mA, giving a 10,000:1 gain-control range.

An OTA is a very versatile device. It can, for example, be made to act like a normal op-amp by simply wiring a suitable load resistance to its output terminal (to convert its output current into voltage). Again, since the magnitude of I_{bias} can easily be controlled by an external voltage and a series resistor, the OTA can easily be used as a voltage-controlled amplifier (VCA), oscillator (VCO), or filter (VCF), etc. Note that the total current consumption of the CA3080 OTA is only twice the I_{bias} value (which can be as low as 0.1μA), enabling the device to be used in true micro-power applications.

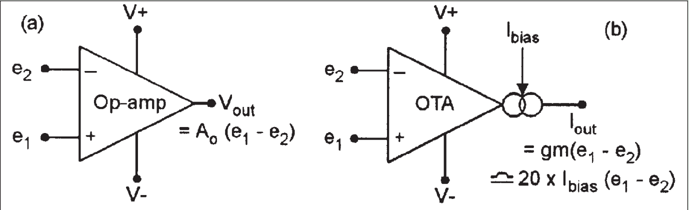


Figure 1. A conventional op-amp (a) is a fixed-gain voltage-amplifying device. An OTA (b) is a variable-gain voltage-to-current amplifier.

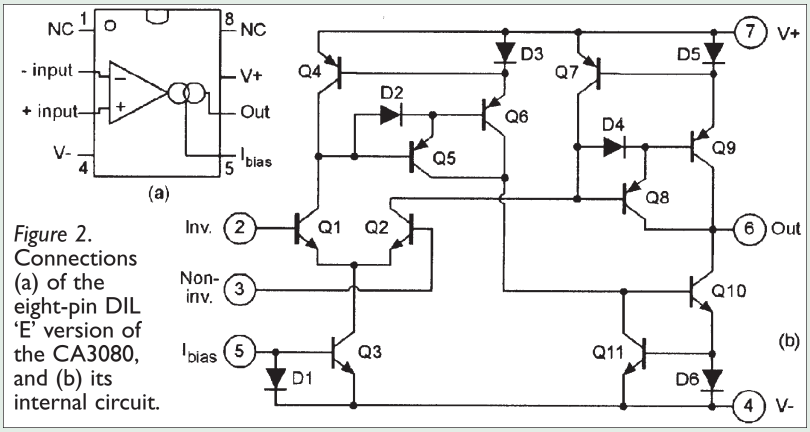


Figure 2. Connections (a) of the eight-pin DIL 'E' version of the CA3080, and (b) its internal circuit.

The best known current-production versions of the OTA are the CA3080 and the LM13700. The LM13700 is a dual second-generation OTA with built-in output-buffer stages, and will be fully described next month. The CA3080 is a first-generation OTA, and is the exclusive subject this month. *Figure 2(a)* shows the connections of the eight-pin DIL 'E' version of the CA3080. *Figure 2(b)* shows its internal circuit, and *Figure 3* lists its basic parameter values.

CA3080 BASICS

The CA3080 is a fairly simple device and consists of one differential amplifier and four current mirrors. *Figure 4* shows the basic circuit and formulas of its differential amplifier. Its emitter current (I_c) is equal to the sum of the two collector currents (I_a and I_b). When V_{in} is zero, I_a and I_b are equal and have a value of $I_c/2$. When V_{in} has a value other than zero (up to ±25mV maximum), the I_a and I_b currents differ and produce an I_b - I_a value of V_{in} x gm, where gm is the OTA's transconductance, is directly proportional to I_c, and has a typical mho value of about 20 x I_c.The *Figure 4* circuit is of little value on its own and, in the CA3080, it is turned to good use by using a simple current mirror to externally control its I_c value (and thus the gm of the OTA), and by using another three current mirrors to extract the difference between the I_a and I_b currents and make this difference current available to the outside world. A current mirror (CM) is a three-terminal circuit that, when provided with an external input bias current, produces an in-phase current of identical value at its output terminals, as shown in *Figure 5*. Some CMs act as current sinks, as shown in *Figure 5(a)* and others as current sources, as in *Figure 5(b)*. When a CM source and a CM sink are connected as shown in *Figure 6* and powered from split supply rails, they generate a differential (I_{source} - I_{sink}) current in any external load connected to the 0V rail. *Figure 7* shows the actual circuits of two sink-type current mirrors. In the simplest of these (*Figure 7(a)*), a diode-connected transistor (QA) is wired across the base-emitter junction of a second, closely matched, transistor that is integrated on the same chip. The input current is fed to the bases of both matched transistors and thus divides equally between them. Suppose these transistors have current gains of x100 and are each drawing base currents of 5µA. In this case, they each draw collector currents of 500µA. Note, however, that the QA collector current is drawn from the circuit's input current, which thus equals 500µA plus (2 x 5µA), or 510µA, and that the QB collector current is the output or mirror current of the circuit.

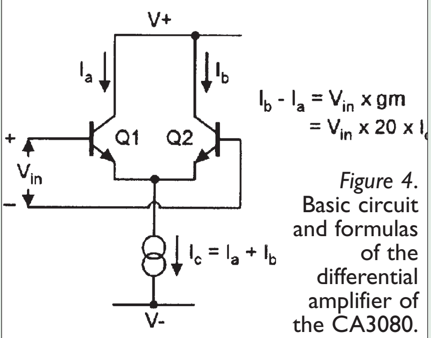


Figure 4. Basic circuit and formulas of the differential amplifier of the CA3080.

Characteristic	Limits
Supply voltage range	+4V to +30V DC or ±2V to ±15V
Max. differential input voltage	±5V
Power dissipation	125mW maximum
Input signal current	1mA maximum
Amplifier bias current	2mA maximum
Output short-circuit duration	Indefinite
Forward transconductance, gm	9600umho typical
Open loop bandwidth	2MHz
Unity-gain slew rate	50V/uS
Common-mode rejection ratio	100dB typical

Figure 3. Basic parameters/limits of the CA3080E.

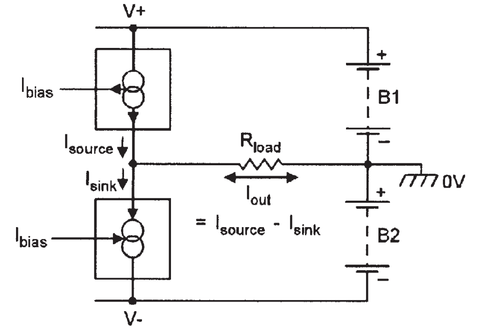


Figure 6. When two current mirrors are wired as shown, they generate a differential current in an external load.

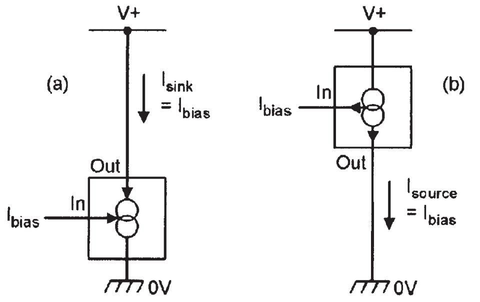


Figure 5. Symbols representing (a) a current-mirror sink and (b) a current-mirror source.

The input and output currents of this circuit are thus almost identical (within a few percent), irrespective of the input current magnitude. In practice, the input/output current ratio of the above circuit depends on the close gain matching of the two transistors, and this can actually vary by several percent. *Figure 7(b)* shows an improved current mirror circuit that is less sensitive to current gain variations and also gives an improved (greater) output impedance.

Figure 8 shows how the differential amplifier and four current mirrors are interconnected in the CA3080 to make a practical OTA. Bias current I_{bias} controls the emitter current, and thus the gm, of the Q1-Q2 differential amplifier via CMC. The collector currents of Q1 and Q2 are mirrored by CMA and CMB respectively, and then fed into the bias and sink terminals respectively of CMD, so that the externally available output current of the circuit is equal to I_B - I_A. Looking back to *Figure 2(b)*, which shows the actual internal circuit of the CA3080, the reader should now have little difficulty in working out the functions of individual circuit elements. Q1 and Q2 form the differential amplifier, with D1-Q3 making up CMC of *Figure 8*, and CMD comprising D6-Q10-Q11. Current mirrors CMA (Q4-Q5-Q6-D2-D3) and CMB (Q7-Q8-Q9-D4-D5) are slightly more complex, using Darlington pairs of transistors, plus speed-up diodes, to improve their performances.

SOME FINER POINTS

All the major operating parameters of the CA3080 are adjustable and depend on the value of I_{bias}. The maximum (short circuit) output current is equal to I_{bias}, the total operating current of the OTA is double the I_{bias} value, and the input bias currents drawn by pins 2 and 3 typically equal $I_{bias}/200$.

The transconductance (gm) and the input and output impedance values also vary with the I_{bias} value, as shown in the graphs in *Figure 9*, which show typical parameter values when the IC is driven from split 15V supplies at an ambient temperature of +25^0C. Thus, at a bias current of 10µA, gm is typically 200µmho, and input and output impedances are 800k and 700M, respectively. At 1mA bias, the values change to 20mmho, 15k, and 7M0, respectively.

The available output voltage swing of the IC depends on the values of I_{bias} and any external load resistor connected to the OTA output. If the load impedance is infinite, the output can swing to within 1V5 of the positive supply rail and to within 0V5 of the negative rail. If the impedance is finite, the peak output voltage swing is limited to I_{bias} x R_L. Thus, at 10µA bias with a 100k load, the available output voltage swing is a mere ±1V0.

The slew rate (and bandwidth) of the IC depend on the value of I_{bias} and any external loading capacitor connected to the output. The slew rate value, in volts per microsecond, equals I_{bias}/C_L, where C_L is the loading capacitance value in pF, and the I_{bias} value is in microamps. With no external loading capacitor connected, the maximum slew rate of the CA3080 is about 50V/µS.

BASIC CIRCUITS

The CA3080 is a very easy IC to use. Its pin 5 I_{bias} terminal is internally connected to the pin 4 negative supply rail via a base-emitter junction, so the biased voltage of the terminal is

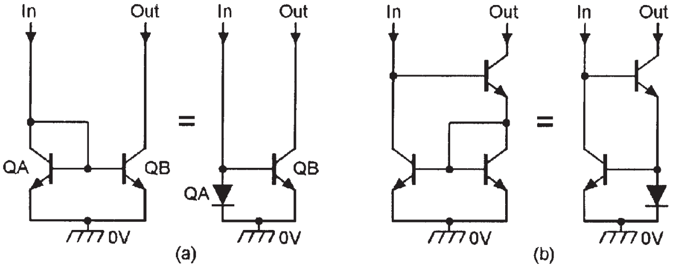


Figure 7. Examples of simple sink-type current mirrors.

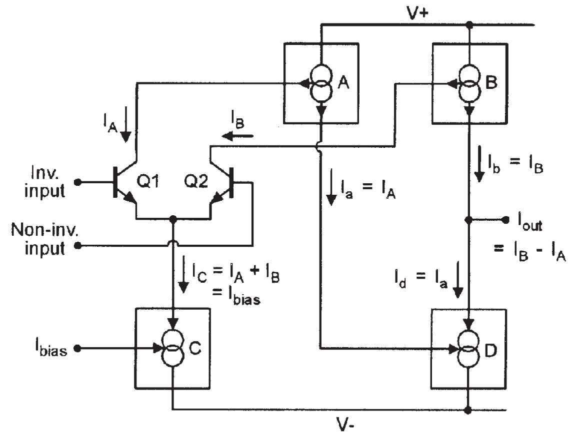


Figure 8. The CA3080 comprises one differential amplifier and four current mirrors.

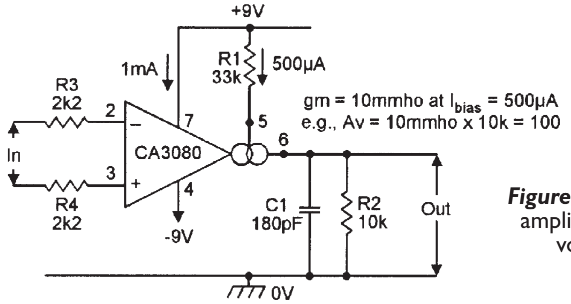


Figure 10. Differential amplifier with 40dB voltage gain.

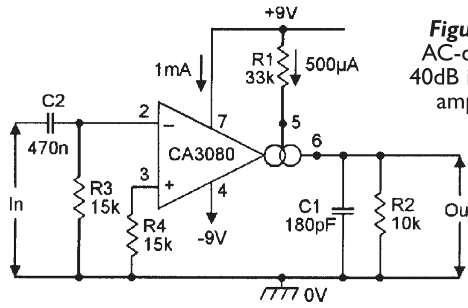


Figure 11. AC-coupled 40dB inverting amplifier.

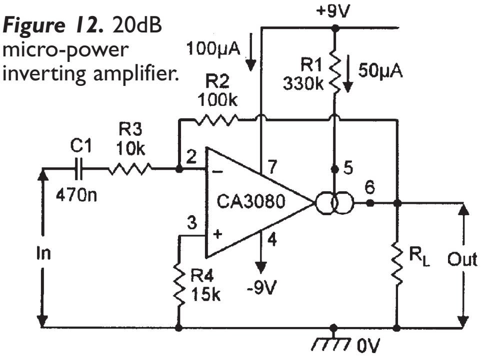


Figure 12. 20dB micro-power inverting amplifier.

about 600mV above the pin 4 value. I_{bias} can thus be obtained by connecting pin 5 to either the common rail or the positive supply rail via a suitable current limiting resistor.

Figures 10 and *11* show two simple ways of using the CA3080 as a linear amplifier with a voltage gain of about 40dB. The *Figure 10* circuit acts as a DC- differential amplifier, and *Figure 11* as an AC-coupled inverting amplifier. Both designs operate from split 9V supplies, so 17.4V is generated across bias resistor R1, which thus feeds an I_{bias} of 500µA into pin 5 and thus makes each IC consume another 1mA of supply current.

At an I_{bias} value of 500µA, the gm of the CA3080 is roughly 10mmho, so since the outputs of the *Figure 10* and *11* circuits are loaded by a 10k resistor (R2), they give an overall voltage gain of 10mmho x 10k = x100, or 40dB. The peak current that can flow into the 10k load is 500µA (I_{bias}), so the peak available output voltage is ±5V0. The output is also loaded by 180pF capacitor C1, giving the circuit a slew rate limit of 500µA/180pF, or 2.8V/µS. The output impedance of each circuit equals the R2 value of 10k.

Note in these two circuits that the IC is used in the open-loop mode, and that if the slew rate of the IC is not externally limited via C1, the OTA will operate at its maximum bandwidth and slew rate. Under such a condition, the CA3080 may be excessively noisy, or may pick up unwanted RF signals. In the *Figure 10* circuit, the differential inputs are applied via series resistors R3 and R4, which help equalize the source impedances of the two signals and thus maintain the DC balance of the OTA. The *Figure 11* circuit is a simple variation of the above design, with both inputs tied to the common rail via 15k resistors and with the input signal applied to one terminal only. With the input fed to pin 2 as shown, the circuit acts as a 40dB inverting amplifier; alternatively, non-inverting action can be obtained by connecting the input signal to pin 3 via C2.

CLOSED-LOOP OPERATION

The *Figure 10* and *11* circuits are used in the open-loop mode and their voltage gains thus depend on the value of I_{bias} which, in turn, depends on the value of supply rail voltage. The voltage gain of the CA3080 can be made almost independent of the I_{bias} and supply voltage values by using conventional closed-loop op-amp techniques, as shown in the micro-power 20dB AC-coupled inverting amplifier in *Figure 12*.

Figure 12 is wired like a conventional op-amp inverting amplifier, with its voltage gain (A_V) determined primarily by the R2/R3 ratio (x10, or 20dB). This gain equation is, however, only valid when the value of an external load resistor (R_L) is infinite, since the output impedance of this design is equal to R2/A_V, or 10k, and any external load causes this impedance to give a potential divider action that reduces the output of the circuit.

In *Figure 12*, the main function of I_{bias} is to set the total operating current of the circuit and/or the maximum available output swing. With the component values shown, I_{bias} has a value of 50µA. When R_L is infinite, the output is loaded only by R2, which has a value of 100k, so the maximum available output voltage swing is ±5V0. If R_L has a value of 10k, on the other hand, the maximum output voltage swing is ±0.5V. This circuit can thus be designed to give any desired values of voltage gain and peak output voltage. Note that, since the IC is used in the closed loop mode, external slew rate limiting is not required.

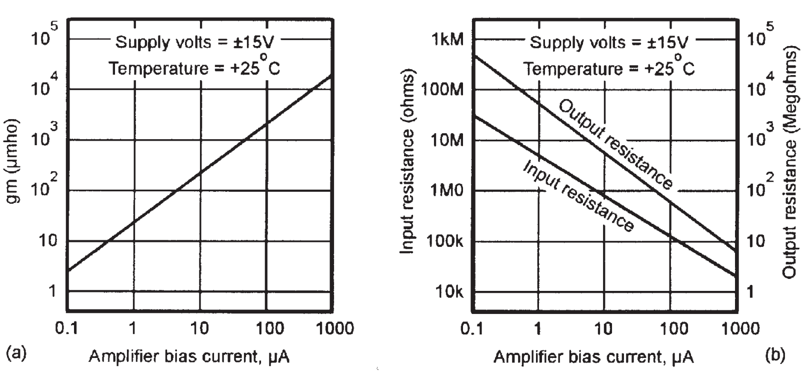
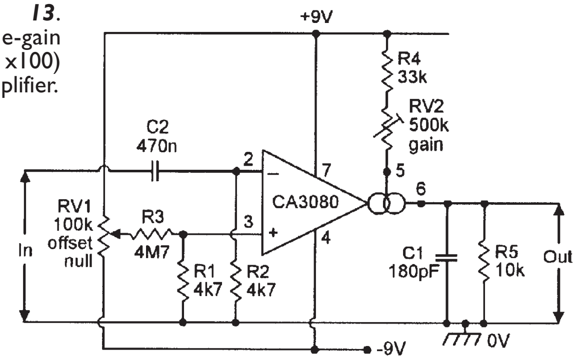


Figure 9. The transconductance (a) and the input and output resistances (b) of the CA3080 vary with the bias-current value.

Figure 13. Variable-gain (x5 to x100) AC amplifier.



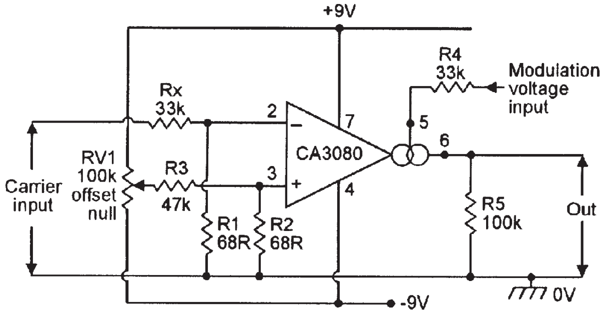
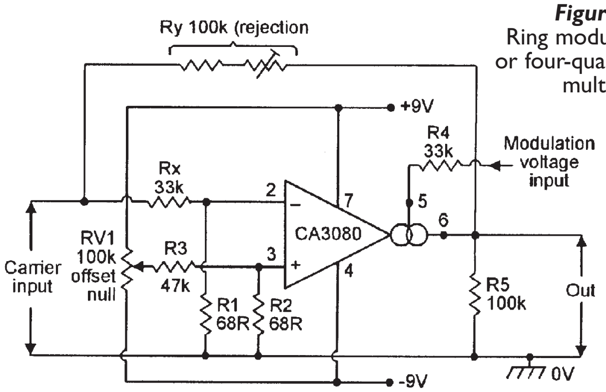


Figure 14. Amplitude modulator or two-quadrant multiplier.

Figure 15. Ring modulator or four-quadrant multiplier.



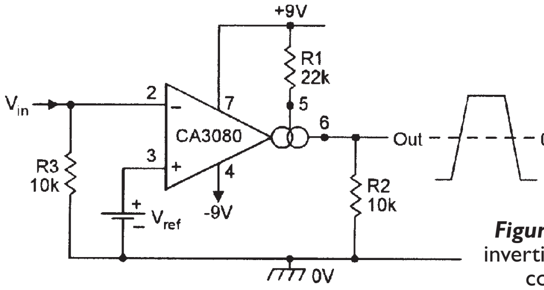


Figure 16. Fast inverting voltage comparator.

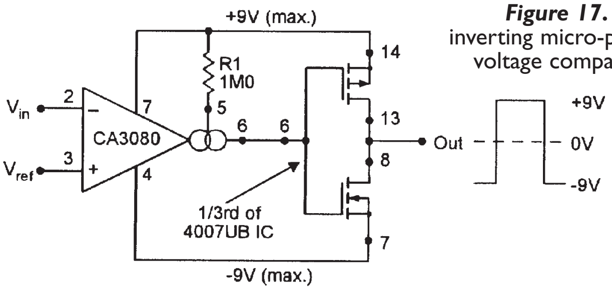


Figure 17. Non-inverting micro-power voltage comparator.

OFFSET BALANCING

If the CA3080 is to be used as a high-gain DC amplifier, or as a wide-range variable-gain amplifier, input bias levels must be balanced to ensure that the output correctly tracks the input signals at all prevailing I_{bias} values. *Figure 13* shows how suitable bias can be applied to an inverting AC amplifier in which the voltage gain is variable from roughly x5 to x100 via RV2, and the offset balance is pre-set via RV1. The circuit is set up by adjusting RV2 to its minimum (maximum gain) value and then trimming RV1 to give zero DC output with no AC input signal applied.

VOLTAGE-CONTROLLED GAIN

The most important uses of the CA3080 are in true micro-power amplifier and oscillator applications, and in applications in which important parameters are variable via an external voltage. In the latter category, one important application is as a voltage-controlled amplifier (VCA) or amplitude modulator, in which a carrier signal is fed to an amplifier's input, and its output amplitude is controlled or modulated by another signal fed to the I_{bias} terminal. *Figure 14* shows a practical version of such a circuit.

The *Figure 14* circuit acts as a variable-gain inverting amplifier. Input bias resistors R1 and R2 have low values, to minimize the noise levels of the IC and eliminate the need for external slew-rate limiting, and offset biasing is applied to the non-inverting pin of the IC via R3-RV1. The carrier input signal is applied to the inverting pin of the CA3080 via potential divider Rx-R1. When Rx has the value shown, the circuit gives roughly unity gain when the modulation input terminal is tied to the zero volts rail. The gain is x2 when the modulation terminal is at +9V, and the circuit gives roughly 80dB of signal rejection when the modulation terminal is tied to the -9V rail. Note that the instantaneous polarity of the output signal in the *Figure 14* circuit is determined entirely by the instantaneous polarity of the input signal, which has only two possible 'states'. This type of circuit is thus known as a two-quadrant multiplier. The amplitude of the output signal is determined by the product of the input and gain-control values.

Figure 15 shows how the above circuit can be modified so that it acts as a ring-modulator or four-quadrant multiplier, in which the output signal polarity depends on the polarities of both the input signal and the modulation voltage. The *Figure 15* circuit is identical to that of *Figure 14*, except that resistor network Ry is connected between the input and output terminals. The action here is such that, when the modulator input is tied to the zero volts rail, the inverted signal currents feeding into R5 from the output of the OTA are exactly balanced by the non-inverting signal currents flowing into R5 from the input signal via Ry, so that zero output is generated across R5. If the modulation input goes positive, the output of the OTA exceeds the current of the Ry network, and an inverted gain-controlled output is obtained. If the modulation input is negative, on the other hand, the output current of Ry exceeds that of the OTA, and the non-inverted gain-controlled output is obtained.

Thus, both the phase and the amplitude of the output signal of this four-quadrant multiplier are controlled by the modulation signal. The circuit can be used as a ring modulator by feeding independent AC signals to the two inputs, or as a frequency doubler by feeding identical sinewaves to the two inputs. Note that, with the Rx and Ry values shown, the *Figure 15* circuit gives a voltage gain of x0.5 when the modulation terminal is tied to the positive or negative supply rail; the gain doubles if the values of Rx and Ry are halved. Also note that the *Figure 14* and *15* circuits each have a high-output impedance, and

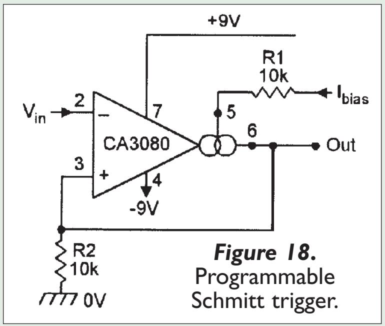


Figure 18. Programmable Schmitt trigger.

that, in practice, a voltage following buffer stage must be interposed between the output terminal and the outside world.

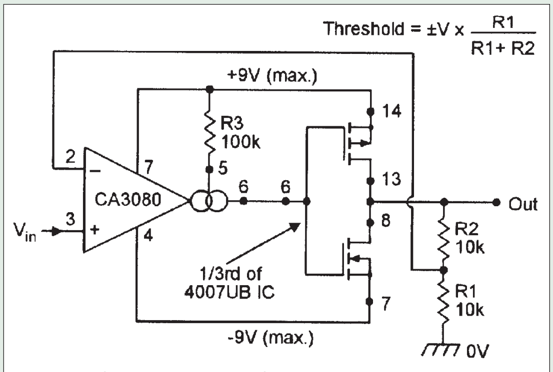


Figure 19. Micro-power Schmitt trigger.

COMPARATOR CIRCUITS

The CA3080 can easily be used as a programmable or micro-power voltage comparator. *Figure 16* shows the basic circuit of a fast, programmable, inverting comparator, in which a reference voltage is applied to the non-inverting input terminal, and the test input is applied to the inverting terminal. The circuit action is such that the output is driven high when the test input is below V_{ref}, and is driven low when test is above V_{ref} (the circuit can be made to give a non-inverting comparator action by transposing the input connections of the IC). With the component values shown, the I_{bias} current in the *Figure 16* circuit is several hundred microamps and under this condition, the CA3080 has a slew rate of about 20V/µS and thus acts as a 'fast' comparator. When the test and V_{ref} voltages are almost identical, the IC acts as a linear amplifier with a voltage gain of gm x R2 (about x200 in this case). When the two input voltages are significantly different, the output voltage limits at values determined by the I_{bias} and R2 values. In *Figure 16*, the output limits at about ±7V0 when R2 has a value of 10k, or at ±0.7V when R2 has a value of 1k0.

Figure 17 shows how the above circuit can be modified so that it acts as an ultra-sensitive micro-power comparator which typically consumes a quiescent current of only 50µA, but gives an output voltage that swings fully between the two supply rails and can supply drive currents of several milliamps. Here, the CA3080 is biased at about 18µA via R1, but has its output fed to the near-infinite input impedance of a CMOS inverter stage made from one section of a 4007UB IC. The CA3080-plus-4007UB combination gives the circuit an overall voltage gain of about 130dB, so input voltage shifts of only a few microvolts are sufficient to switch the output from one supply rail to the other.

SCHMITT TRIGGER CIRCUITS

The simple voltage comparator circuit in *Figure 16* can be made to act as a programmable Schmitt trigger by connecting the non-inverting reference terminal directly to the output of the CA3080, as shown in *Figure 18*. In this case, when the input is high, a positive reference value of I_{bias} x R2 is generated. When V_{in} exceeds this value, the output regeneratively switches low and generates a negative reference voltage of I_{bias} x R2.

When V_{in} falls below this new value, the output switches high again and once more generates a positive reference voltage of I_{bias} x R2. Thus, the trigger thresholds (and also the peak output voltages) of this Schmitt circuit can be precisely controlled or programmed via either I_{bias} or R2. *Figure 19* shows an alternate type of Schmitt, in which the output transitions fully between the supply rail values, and the switching threshold values are determined by the R1 and R2 ratios and the values of supply voltage, V, and equal ±V x R1/(R1 + R2).

ASTABLE CIRCUITS

The *Figure 19* Schmitt trigger circuit can be made to act as an astable multivibrator or squarewave generator by connecting its output back to the non-inverting input terminal via an R-C time-constant network, as shown in *Figure 20*. The output of this circuit switches fully between the supply rail values, is approximately symmetrical, and has a frequency that is determined by the values of R3 and C1, and by the ratios of R1 and R2. The circuit action is such that, when the output is high, C1 charges via R3 until the C1 voltage reaches the positive reference voltage value determined by the R1-R2 ratio, at which point, the output switches low. C1 then discharges via R3 until the C1 voltage reaches the negative reference voltage value determined by the R1-R2 ratio, at which point, the output switches high again, and the whole process then repeats *ad infinitum*.

Finally, to complete this look at the CA3080 OTA, *Figure 21* shows how the above circuit can be modified to give an output waveform with a variable mark-space ratio. In this case, C1 alternately charges via D1-R3 and the left half of RV1, and discharges via D2-R3 and the right half of RV1, to give a mark-space ratio that is fully variable from 10:1 to 1:10 via RV1.

Note in the above two astable circuits that the CA3080 is biased at only a few microamps and that the total current consumption of each design is determined primarily by the series values of R1 and R2 and by the value of R3. In practice, total current consumption figures of only a few tens of microamps can easily be obtained. **NV**

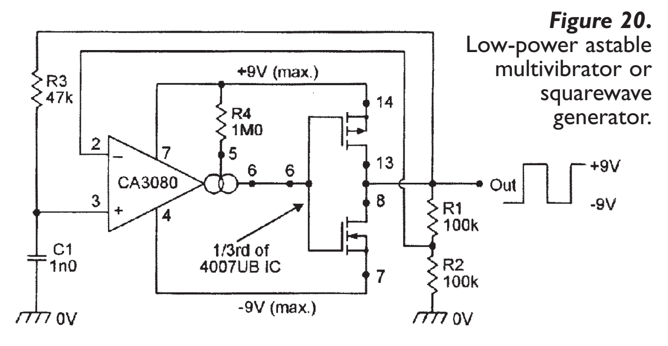


Figure 20. Low-power astable multivibrator or squarewave generator.

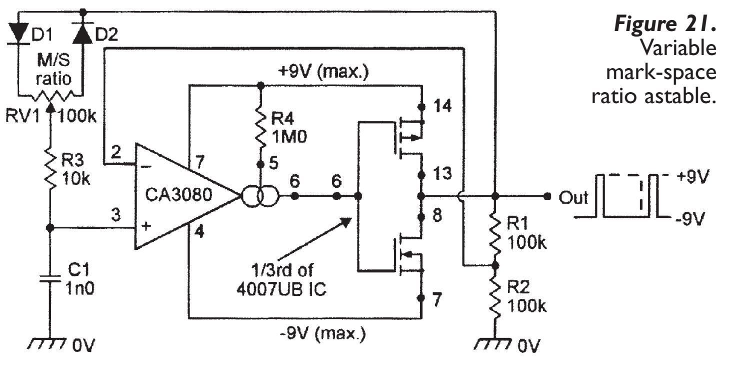


Figure 21. Variable mark-space ratio astable.