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Abstract

An operational transconductance amplifier (OTA) has all of the characteristics of an operational voltage amplifier except that the output impedance ideally approaches infinity rather than zero. As a result, the forward gain characteristic is best described by transconductance rather than voltage gain. When operated into a suitable load resistor with feedback, however, the OTA is an "op amp" by all definitions.

Novel circuit techniques that eliminate all resistors have been employed to develop a linear monolithic IC chip containing 94 transistors and featuring four independent OTA's. The resistorless feature permits use over four decades of operating current levels. The design and characterization of the OTA's are discussed, as well as some interesting applications. The OTA can be used for two-quadrant multiplication, gated amplification, variable-gain amplification, amplitude modulation, gyrators, and diverse op-amp applications.

Introduction

The integrated operational transconductance amplifier (OTA) described is an outgrowth of an attempt to design a monolithic integrated micropower operational amplifier. During the early stages of design, it became apparent that bipolar transistors are inherently current output devices, and that a low output impedance could be obtained only by feedback techniques (emitter-followers being the method most commonly used). To obtain a low output impedance at a micropower level, it is generally necessary to provide a resistive value in the region of tens of megohms for feedback or for the driver-collector load; such a component is most difficult to integrate. If a high output impedance is acceptable, however, the load signal may be delivered from a bipolar collector without feedback, and the need for the very high resistive value is thereby circumvented.

Experiments with complementary bipolar transistors yielded circuits requiring a minimum number of resistors. After considerable analysis, it became apparent that the omission of all resistors in an IC design would permit functioning over decades of operating current. In addition, such a design would be relatively easy to produce.

Circuit Design

The basic circuit developed is shown in Fig. 1. An understanding of this circuit is best obtained by analysis of voltages and currents with almost complete disregard for voltage gain and impedance levels. The brief description below is followed later by a more detailed explanation.

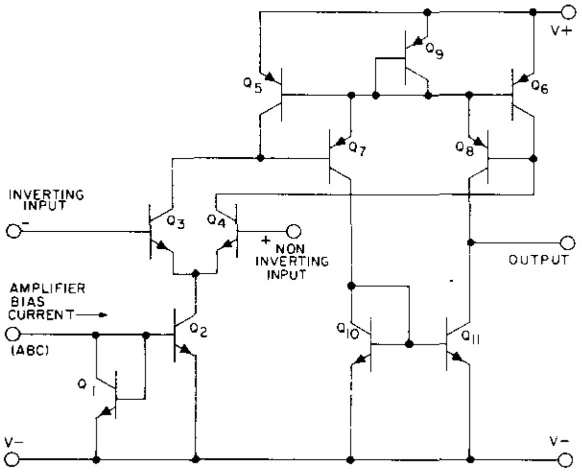


Fig.1 - Basic OTA circuit.

Transistors Q_1 through Q_4 in Fig. 1 perform conventional functions, serving as a current mirror, a constant-current source, and a differential pair. An amplifier bias current is externally developed and applied to the current mirror (Q_1, Q_2) to bias Q_3 and Q_4. The p-n-p transistors Q_5 through Q_9 form an interesting network. The differential signal currents of Q_3 and Q_4 are amplified by the beta of the differential pair Q_7 and Q_8. The current mirror Q_{10} and Q_{11} then transforms the double-ended output of the p-n-p network into a single-ended output. The entire circuit functions in a class A mode.

Ideally, there is no need for a signal ground because the input signal is differential and the output signal is a current. The input and output terminals may operate at most ac and dc potentials within the range of the supply voltages.

The amplifier bias current (ABC) level establishes bias for all transistors in the amplifier. As a result, the basic circuit functions as well for an ABC level of a picoampere or an ampere as it does when biased at one microampere. The circuit malfunctions only if it is biased at a level at which the transistors no longer have desirable characteristics. At high levels, malfunctions may be caused by either beta fall-off or parasitic ohmic effects. Low-current malfunctioning may occur as a result of beta fall-off, channeling, or leakage. Some samples of OTA's exhibited good performance for ABC levels from 10 nanoamperes to 1 milliampere, or over a range of five decades (100 dB). Time did not permit instrumentation for lower levels.

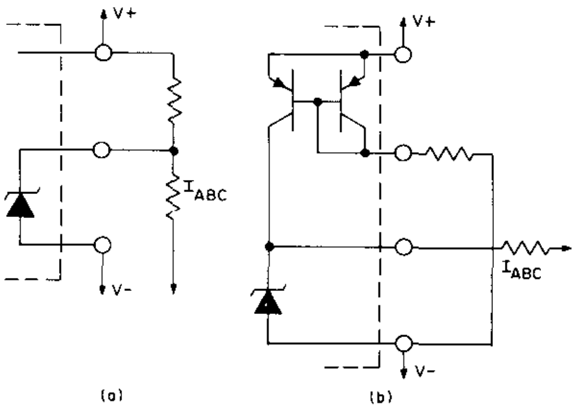
Chip Design

The final chip design selected features four OTA's and two zener diodes, or a total of 94 transistors, on a 65-by-65-mil chip fabricated with conventional non-critical processing. The p-n-p transistors are lateral. Although Fig. 1 shows only 11 transistors, the actual circuit for each OTA employs 23 transistors; the additional 12 transistors add a degree of sophistication to enhance the performance without altering the basic functioning.

Two metalizing alternatives have been investigated. One features an array of four OTA's with a zener diode, and the other an array of three OTA's, a zener diode, and a p-n-p current mirror. Both designs have been fabricated in 16-terminal dual-in-line ceramic packages.

In the quad-array, the ABC terminals of all OTA's are connected to a common pin because of the limited number of terminals. As a result, all amplifiers of the quad must be biased at the same ABC level. (This requirement does not affect cross talk between amplifiers.) The remaining terminal of the quad is used for the zener diode, which is referenced to the negative supply. This arrangement permits a simple voltage regulator, as shown in Fig. 2(a), and thereby maintains the excellent power-supply rejection offered by the OTA.

The ABC terminals of the tri-array are brought out separately to permit independent biasing. The two remaining terminals are used for a zener diode that regulates the ABC level and a p-n-p current mirror that permits regulation at lower supply voltages than that allowed by the simple zener circuit. This regulator circuit is shown in Fig. 2(b). The p-n-p current mirror in the tri-array configuration is metalized from the unused OTA on the basic chip.



(a) (b)

Fig.2 - Voltage-regulator circuits in (a) quad-array, and (b) tri-array.

Bipolar Performance

Operation of transistors in the sub-microampere region appears to be less uncertain than previously supposed. Some conventionally processed transistors similar to those used in the OTA were measured for current gain as a function of collector current. Figs. 3 and 4 show the beta characteristics of an n-p-n transistor and of a lateral p-n-p transistor, and Fig. 5 shows the voltage-current characteristic of a zener diode (n$^+$ into B and R diffusions). Although the performance shown may not be achieved by some devices, a great many others will have such characteristics.

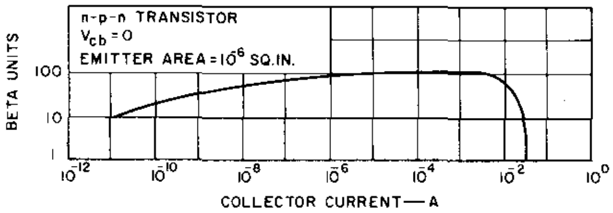


Fig.3 - Beta characteristics of n-p-n transistor.

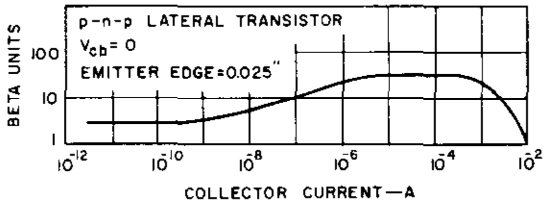


Fig.4 - Beta characteristics of p-n-p transistor.

The betas of p-n-p transistors appear to be well matched and quite independent of temperature. Although the output impedance of these lateral transistors is lower than might be desired, this shortcoming can by corrected by circuit design.

The higher noise level of the B and R zener diode is not a disadvantage in the ABC supply because the noise is approximately 80 dB down. In addition, the ABC noise is further suppressed because the signal is common-mode. An n$^+$, p$^+$ zener diode would have a lower noise, but the voltage-current characteristic would be poorer at low current. In addition, fabrication would require the addition of a p$^+$ diffusion.

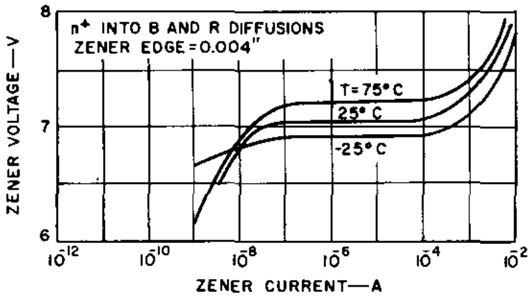


Fig.5 - Voltage-current characteristics of zener diode.

Detailed Circuit Operation

The conventional circuit shown in Fig. 6 is well known. Simply stated, Q_1 operates with 100-per-cent feedback, forcing the base-to-emitter potential V_{be} to assume a value that causes the collector current i_{c_1} to approximate the bias current I_{ABC}. As a result, Q_2 is a "slave" to Q_1.

All four transistors are assumed to be identical. Therefore, because the base-to-emitter bias voltages of Q_1 and Q_2 are identical, and because the collector voltages of these transistors are above the saturation potential (about 0.2 volt), the collector currents must be equal for a first-order approximation. Because the diode-connected transistor Q_1 is operated with 100-per-cent collector-to-base feedback and a zero collector-to-base potential, the base current i_b is given by

$$i_b = \frac{i_{c_1}}{\beta} + \frac{i_{c_2}}{\beta} \tag{1}$$

The collector current i_{c_2} is then given by

$$i_{c_2} = I_{ABC}\left(\frac{\beta}{\beta + 2}\right) \tag{2}$$

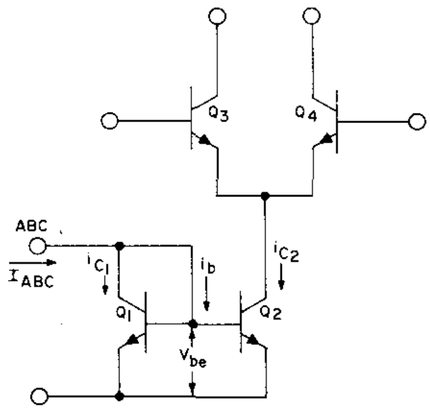


Fig.6 - Conventional op-amp circuit.

If Q_2 is made up of n_1 parallel transistors identical to Q_1 (n_1 may be fractional), Eq.(2) becomes

$$i_{c_2} = n_1 I_{ABC} \left(\frac{\beta}{\beta+n_1+1}\right) \tag{3}$$

Exceptions to Eq.(3) may exist for any of the following conditions:

1. An unintentional geometry mismatch between Q_1 and Q_2 produces a current error approximately equal to the area error.

2. Non-compensating ohmic drops produce a maximum error of 4 per cent per millivolt of drop.

3. Thermal gradients along the chip that cause Q_1 and Q_2 to operate at different temperatures produce an error which is variable but approximates 7 per cent per degree C.

4. Local thermal mismatch caused by Q_2 dissipation produces an error which may be sufficiently severe to cause thermal regeneration.[1]

5. Loading effects produce an error that can be severe if additional transistors are biased from Q_1 and if the collector voltages of these transistors are allowed to reach saturation or breakdown.

6. Different collector voltages on Q_2 and Q_1 produce an error which is small but normally affects the common-mode rejection ratio if the current mirror drives a differential amplifier such as Q_3 and Q_4.

The differential amplifier Q_3 and Q_4 provides a class A double-ended output (push-pull) for signals appearing between the bases of Q_1 and Q_2 (differential signal). Signals mutually common to the bases (common-mode signals) are suppressed by the constant-collector-current characteristic of Q_2, Q_3, and Q_4. The amplifier functions linearly for differential signals approaching 100 millivolts peak to peak, and for any common-mode signals provided the common-mode signal voltage does not drive Q_2, Q_3, or Q_4 into saturation or breakdown.

Transistors Q_3 and Q_4 are normally well matched to one another, and thus provide only a very small dc offset voltage for identical collector currents with excellent dc stability as a function of temperature. The offset voltage is often caused by second-stage effects. Typical offset voltages are below one millivolt with a theoretical thermal coefficient equal to the offset voltage divided by the Kelvin temperature (first stage only).

If the collector currents are balanced, the input bias to each base is given by

$$I_{BIAS} = \frac{i_{c_2}}{2\beta} \tag{4}$$

Because the two transistors typically have a beta mismatch of 5 per cent, the offset current is equal to

$$I_{OFFSET} = \frac{i_{c_2}}{40\beta} \tag{5}$$

The current gain of n-p-n transistors typically has a temperature coefficient of 0.7 per cent per degree C; therefore, the anticipated offset-current temperature coefficient is given by

$$\text{Offset-current temp. coeff.} = \frac{i_{c_2}}{5000\beta} \tag{6}$$

The input impedance R_{IN} is equal to

$$R_{IN} = \frac{2KT}{qI_{BIAS}} = \frac{\beta}{10\, i_{c_2}} \tag{7}$$

The transconductance g_m for each collector is then given by

$$g_m = 10\, i_{c_2} \tag{8}$$

The p-n-p Network

Fig. 7 shows the network of five p-n-p transistors used in each OTA. For an analysis of this network, the following assumptions are made:

1. All p-n-p betas are equal.

2. Q_5 and Q_6 are identical.

3. Q_9 is equivalent to n_2 parallel transistors identical to Q_5.

4. All transistors are at the same temperature.

5. All current gains are independent of collector voltage.

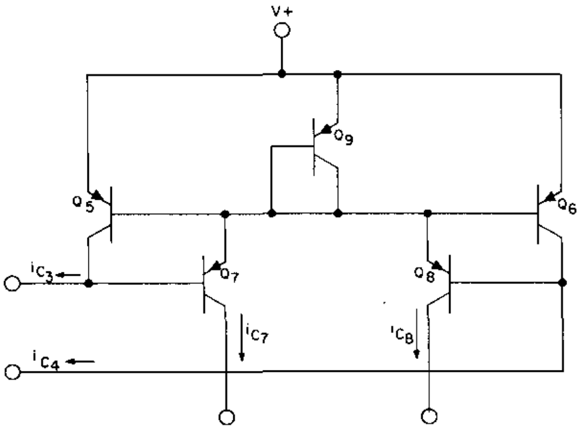


Fig.7 - Network of p-n-p transistors used in OTA.

An exact analysis, which is simple but lengthy, produces the following results:

$$(i_{c_7} + i_{c_8}) = (i_{c_3} + i_{c_4}) \frac{\beta_p\,(n_2 + 2 + n_2\beta_p)}{(n_2 + 2)(1 + \beta_p) + 2\beta_p^{\,2}} \tag{9}$$

$$(i_{c_7} - i_{c_8}) = \beta_p\,(i_{c_3} - i_{c_4}) \tag{10}$$

Eq.(9) implies a dc bias of the network which is independent of the p-n-p beta, the differential signal, and the common-mode signal. Eq.(10) shows that the differential output signal depends only on the p-n-p beta and the differential input-current signal; as a result, common-mode rejection is high. Fig. 8 shows the ratio of $(i_{c_7} + i_{c_8})$ to $(i_{c_3} + i_{c_4})$ for various values of n_2.

If the collector of Q_7 is fed to a current mirror which, in turn, is connected to the collector of Q_8, the resulting output current is approximately equal to

$$i_{out} = (i_{c_8} - i_{c_7}) \tag{11}$$

The peak-to-peak output-current swing then limits at the following value:

$$i_{p\text{-}p} = 2\,(i_{c_7} + i_{c_8}) \tag{12}$$

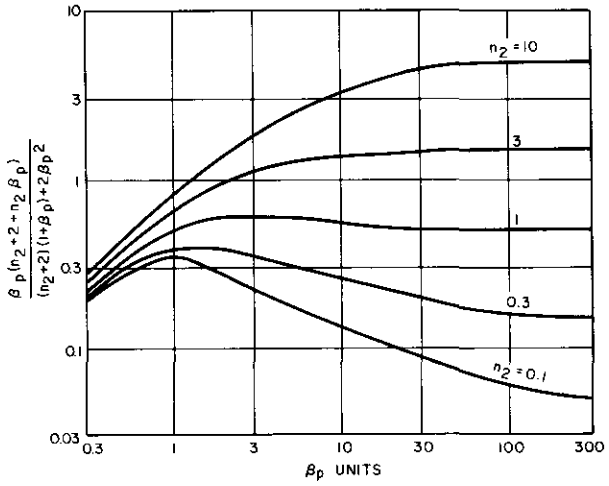


Fig.8 - Current ratios in OTA.

Total Circuit Performance

The total circuit current drain I_T is given by

$$I_T = (I_{ABC})\,(1 + n_1 + n_1 n_2/2) \tag{13}$$

The transconductance g_m is as follows:

$$g_m = (\beta_p)\,(20\,n_1)\,(I_{ABC}) \tag{14}$$

The input bias current is given by

$$I_{BIAS} = \frac{n_1\,I_{ABC}}{2\beta_n} \tag{15}$$

The offset current is given by

$$I_{OFFSET} = \frac{n_1\,I_{ABC}}{40\beta_n} \tag{16}$$

The offset-current temperature coefficient is equal to

$$\text{Offset-current temp. coef.} = \frac{n_1\,I_{ABC}}{5000\beta_n} \tag{17}$$

The input impedance R_{IN} is given by

$$R_{IN} = \frac{\beta_n}{10\,n_1\,I_{ABC}} \tag{18}$$

The peak-to-peak output-current capability is then

$$I_{p\text{-}p} = n_1 n_2\,I_{ABC} \tag{19}$$

Measured Performance

The curves in Fig. 9 show both predicted circuit performance and the measured performance for some typical samples.

The curves of predicted performance include deviations from the above equations caused by the additional 12 transistors mentioned previously.

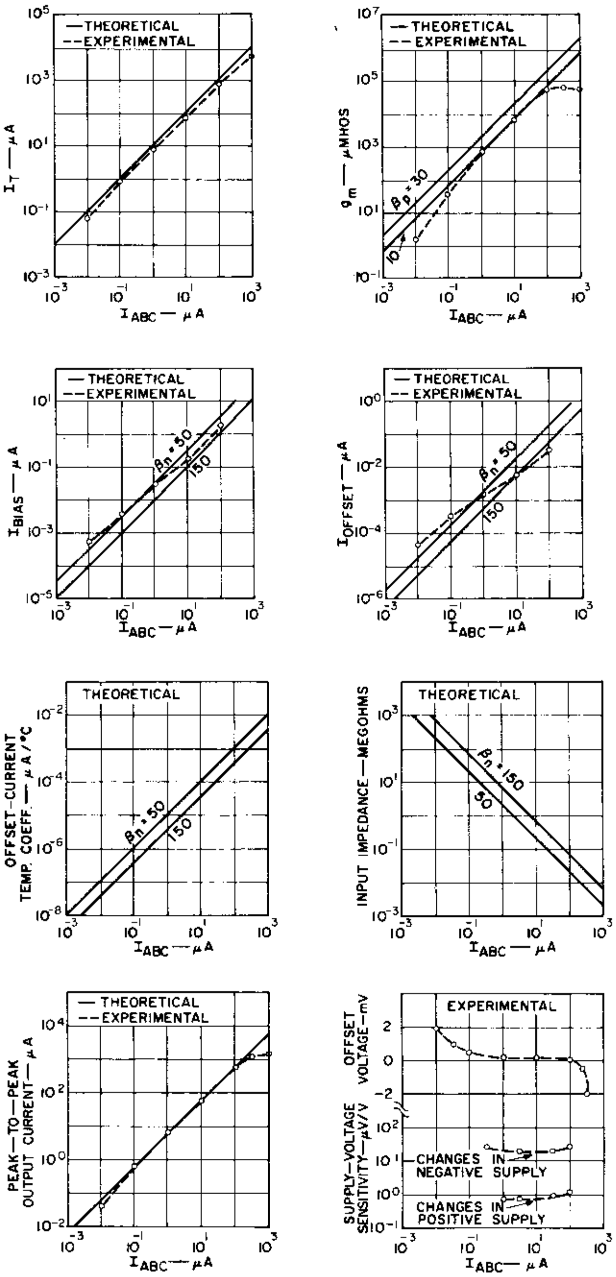


Fig.9 - Performance curves for OTA.

Applications

Circuit design with the OTA is no more complex than design with a conventional operational amplifier. However, the OTA affords an additional degree of design freedom that must be considered.

The OTA, unlike most operational amplifiers, is capable of operation over a wide range of current. This current range is established by application of an external current to the amplifier bias terminal, which then establishes the transconductance and the maximum output current of the amplifier. For example, if the OTA is operated at an amplifier bias current of 100 microamperes, the transconductance is 100 millimhos and the maximum positive and negative output current is 300 microamperes. Amplifier supply current is then 1 milliampere, and the input bias current is 3 microamperes. If the amplifier bias current (ABC level) is reduced by an order of magnitude (from 100 to 10 microamperes), a corresponding decade change results in all other parameters, i.e., the transconductance is 10 millimhos, the output current is 30 microamperes, the amplifier supply current is 100 microamperes, and the input bias current (input base current) is 300 nanoamperes.

For example, the typical 40-dB inverting amplifier shown in Fig. 10 is operated at an ABC level of 10 microamperes (terminal 15). The open-loop voltage gain of the amplifier is then equal to g_m R_L, or $10 \times 10^{-3} \times 1 \times 10^{6}$, or 10^{4} (the feedback network and any other loads reflect directly in the open-loop voltage gain). The standard design equations for operational amplifiers may be used to calculate the amplifier closed-loop characteristics, with the load resistance on the amplifier again being substituted for the output resistance in the operational-amplifier equations. The calculated closed-loop gain is 39.9 dB.

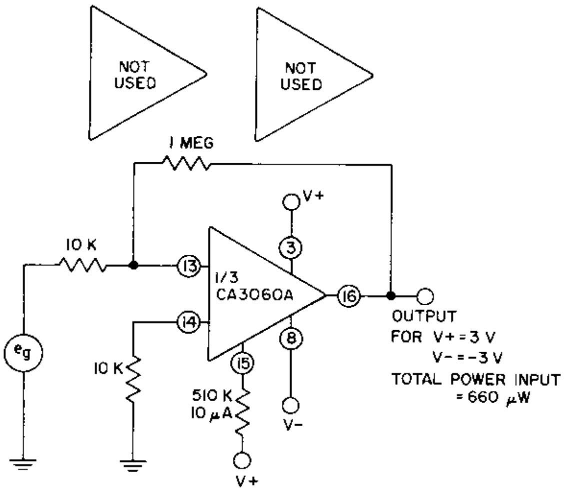


Fig.10 - Typical 40-dB inverting amplifier.

The OTA is especially suitable for use in gyrators because the high output impedance satisfies one of the basic requirements for this application. Inductances in excess of 10 kilohenries have been realized by use of only two OTA's. Fig. 11 shows a gyrator circuit that produces such a high synthetic inductance with only a 3-microfarad capacitor. There is no reference to ground in this circuit; the "inductor" may float within the common-mode restraints of the OTA. Effectively, the inductor is isolated from the supplies by the high-impedance input and output of the amplifier. An attenuation network around the input of both amplifiers extends the differential operating range of each OTA about 100 times. In addition, this network reduces the transconductance by the same factor and thus further increases the gyration resistance. The provision for adjustable bias current to the OTA permits direct control of transconductance and, therefore, varies gyration resistance inversely.

The variable-transconductance characteristic of the OTA is also useful in an agc amplifier. When the OTA operates in the open-loop condition, the transconductance, and thus the amplifier gain, can be varied directly by adjustment of the ABC level. Therefore, an excellent agc amplifier is obtained by rectifying and storing the amplifier output and applying this signal to the bias terminal. Fig. 12 shows a functional diagram of such a system. Low-frequency feedback is provided around the gain-controlled stage to balance the amplifier. As the input signal increases, the amplifier bias current decreases and reduces the transconductance and therefore the system gain.

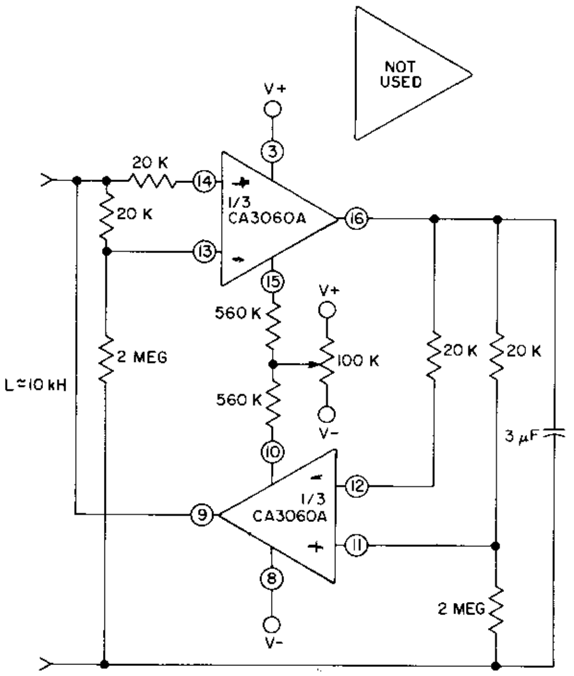


Fig.11 - Gyrator circuit using OTA.

This gain-control characteristic can also be used to provide modulation from dc to the upper cutoff frequency of the system with a single OTA. In this application, a carrier signal is applied to the differential input and a modulating signal to the amplifier bias terminals. Fig. 13 shows a modulator with carrier and modulating frequency capability greater than 20 kHz. Fig. 14 shows the waveforms obtained when the modulator operates at a carrier frequency of 10 kHz and a modulation frequency of 500 Hz. For two-quadrant multiplication, the circuit should also be able to handle a 500-Hz carrier and a 10-kHz modulating signal; waveforms obtained under these conditions are shown in Fig. 15.

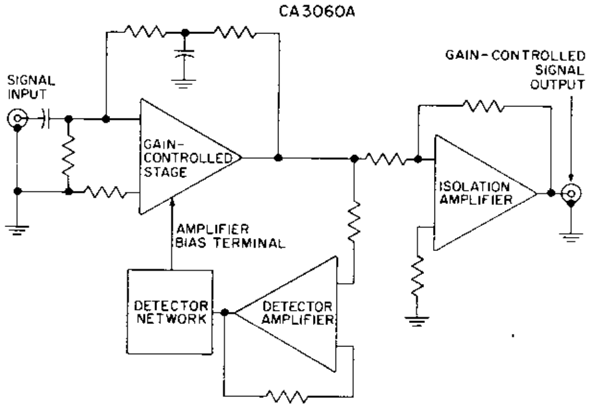


Fig.12 - Gain-controlled amplifier.

Fig. 16 shows a three-channel gated amplifier in which each amplifier or channel may be sequentially activated to display its input with gain of about 20 dB. Because the output impedance is extremely high when the OTA is biased "off", all amplifier outputs are connected in parallel and a common feedback network is used to apply the signal to each amplifier in the voltage-follower mode. Position control of each channel is accomplished with little interaction by applying bias to the inverting input of each amplifier.

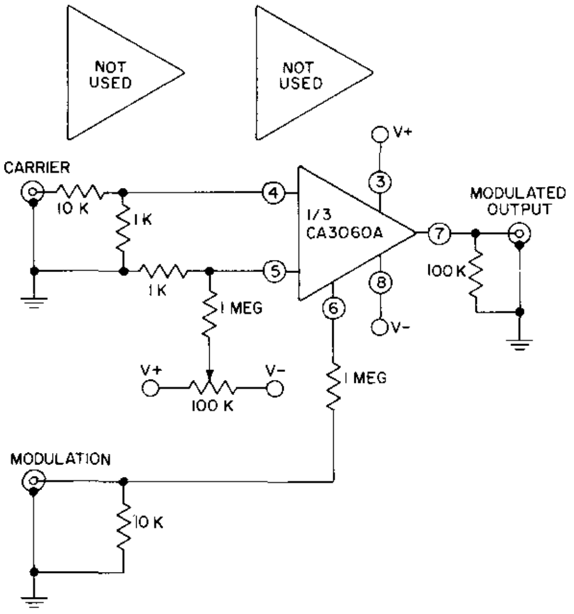


Fig.13 - Modulator circuit using OTA.

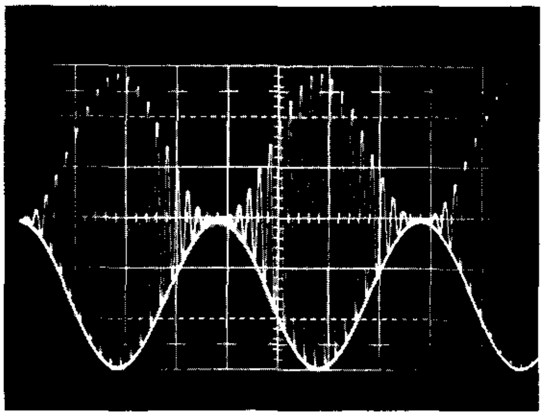


Fig.14 - Waveforms showing modulating signal (lower trace) and modulated carrier (f_c = 10 kHz, f_m = 500 Hz).

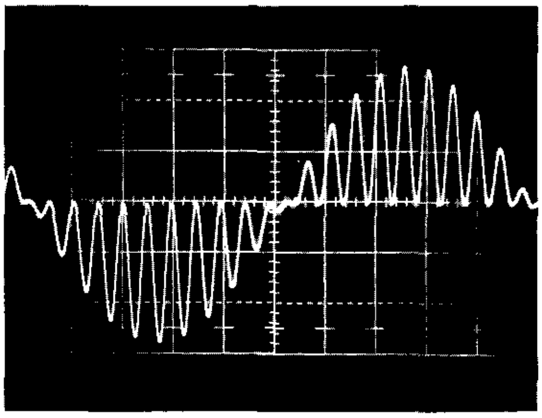


Fig.15 - Waveforms showing modulated carrier with frequencies of Fig.14 interchanged (f_c = 500 Hz, f_m = 10 kHz).

Activation of each channel is accomplished by cutting off the normally saturated transistors that shunt the amplifier bias-current terminals. Drive to the transistor switches may be applied from a ring-counter-type circuit that is either triggered by an external source or "free run" to chop the signals.

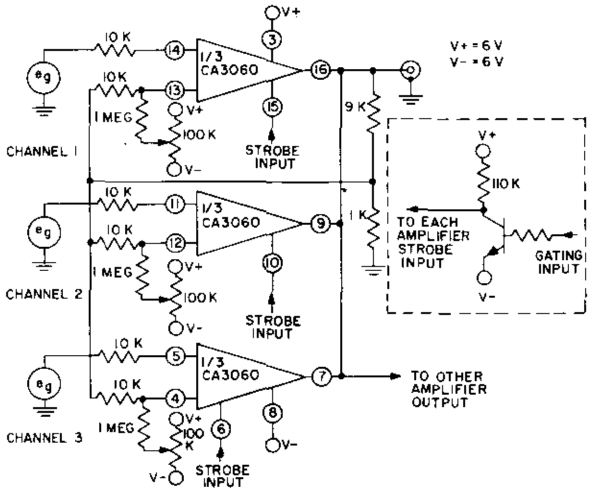


Fig.16 - Three-channel gated amplifier.

Conclusion

The OTA concept described features two-quadrant operation with virtually no dc offset. In addition, isolation of the input and output from each other and from the power supplies permits four-terminal operation of circuits at frequencies down to dc. This four-terminal operation (at ac only) previously was a circuit luxury available only from a transformer. The controlled characteristics of OTA's over many decades of bias offer an additional control means. These desirable characteristics will probably result in circuit design techniques employing OTA's in a manner parallel to present usage of discrete transistors. The ultra-low-current bipolar operation demonstrated and implied should also stimulate a re-evaluation of bipolar, unipolar, and hybrid monolithic integrated circuits.

References

1. C. F. Wheatley, "Thermal Regeneration in Power-Dissipating Elements", THE ELECTRONIC ENGINEER, January 1967.

Acknowledgement

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