The Differential Amplifier

By DONALD E. LANCASTER

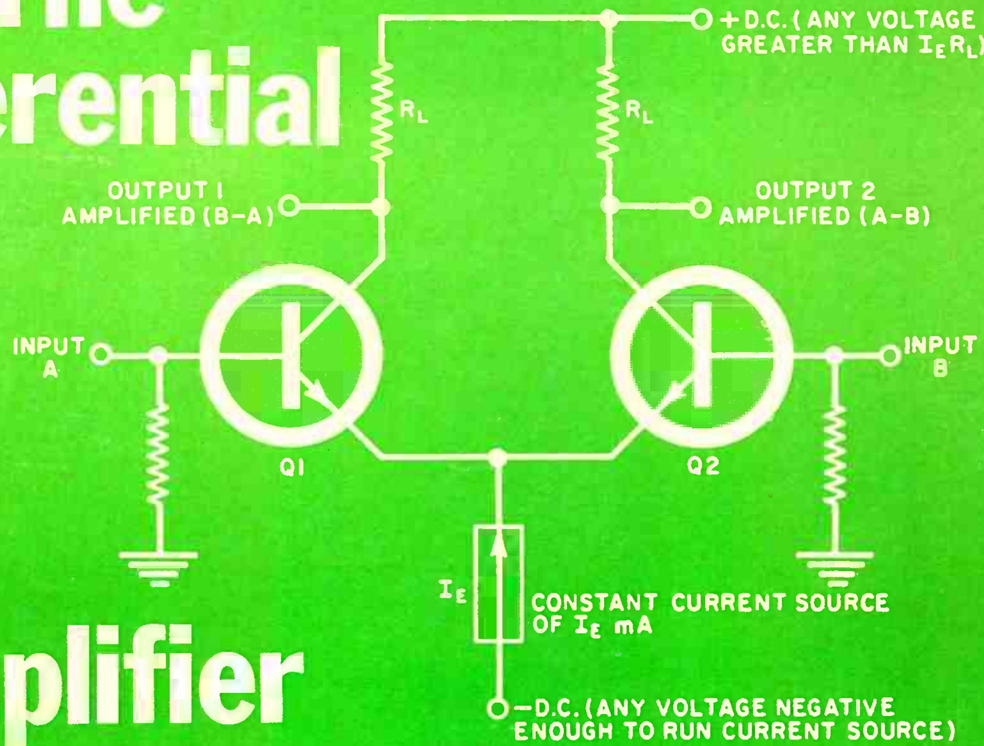


Fig. 1. Basic circuit diagram of the differential amplifier.

A stable, high-gain solid-state amplifier circuit that requires no large capacitors, ignores power-supply noise and ripple, is easy to gain control, limits readily, costs little, and is useful from d.c. up to about 500 MHz.

TODAY'S new accent on miniaturization and integrated circuitry has brought the differential amplifier into sharp focus as an important new cornerstone of future electronic systems. And, it is simple to understand and simpler yet to use.

The differential amplifier (or "diff amp") produces one or two output signals proportional to the *difference* of two input signals. If one input is grounded, it behaves as an ordinary amplifier. There are four ways you might use the diff-amp circuit; with one or two inputs or by using one or two outputs. The two available outputs are always exactly 180° out of phase with respect to each other.

Fig. 1 shows the basic circuit. Two transistors are used. Their emitters are tied together and are driven by a current source. An input signal at A goes through Q1 emitter-follower fashion and through Q2 as a grounded-base stage to arrive at output 2. Neither stage inverts the signal. Q2 provides the voltage gain and Q1 matches the input signal into Q2's low input impedance. An input signal at B goes through Q2 as a common-emitter amplifier to arrive at output 2, with voltage amplification and inversion being provided by a single transistor. Output 2 is an amplified version of the difference (A — B). Look at the circuit in a mirror and you will see that output 1 is an amplified version of the difference (B — A), this time with input A getting inverted by Q1 and B not.

Some handy features of this circuit should suggest themselves. Emitter followers and grounded-base stages can be made gain-stable independent of the common-emitter current gain (β) of the transistors used, so we might rightly suspect that a proper choice of components will make the circuit gain totally independent of the gain of the transistors used. The current source must somehow affect the stage gain, so we have a convenient method of electronically controlling or else setting the per-stage gain to any value we like. Since there are no large capacitors in the circuit, the diff amp can be made extremely small and manufactured as part of an integrated circuit.

If we operate in a *balanced*, or "push-pull" output, mode any supply-voltage ripple or hum would indentically affect both outputs, but the *collector*-to-*collector* output signal would not see this variation. This means the balanced output signal would contain no hum nor ripple, a very definite advantage in low-level or low-noise applications.

The current source always provides a fixed amount of current. Although it can divide up any which way going through Q1 and Q2, the *total* current still must equal the value the current source is providing, and that identical current must be provided by the collector power supply. The supply current required by a diff amp is a constant value totally independent of the input or output signals. Because of this, there is no way that input or output signals can get

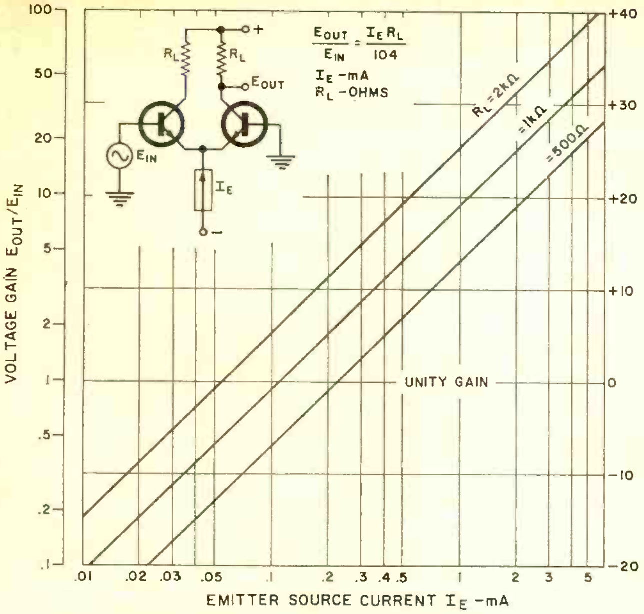


Fig. 2. Single-ended gain curves for the differential amplifier.

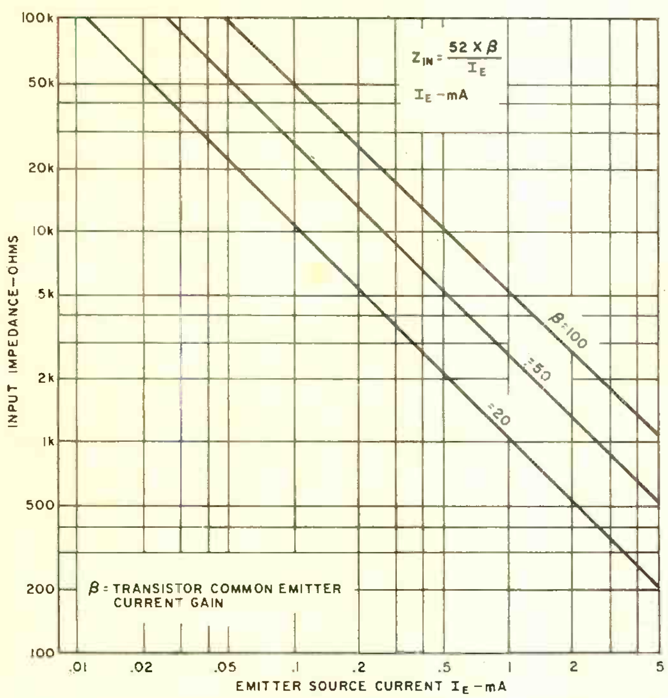


Fig. 3. Differential-amplifier input-impedance characteristics.

into the supply leads. Thus, very little supply filtering and decoupling is normally required due to the constant current drawn from the supply and the fact that the amplifier's output can be made largely independent of hum and ripple. In terms of an electronic system, we can eliminate or reduce the number of large electrolytic capacitors that the engineer often does not consider when circuit development costs are computed.

Disadvantages

The basic circuit requires two transistors which must be a matched pair and must be held at the same temperature. The current source might involve a zener diode and a third transistor, bringing the total semiconductor count to four per stage in some circuits. Because of this, the circuit has not seen too much use in the past for ordinary amplification. Today, the four semiconductors can cost less than the associated components required in a single-transistor amplifier, and they certainly take up far less space. In an integrated circuit, an entire diff-amp stage might be easily put down on a 30-mil square of silicon.

Low-cost matched pairs of transistors are now readily available, and a good match can often be obtained for moderate-performance circuits simply by selecting any two newer semiconductors from a single manufacturer's stock and clipping them together. Matching is no problem at all in integrated circuits; the close spacing and identical geometry automatically provide excellent matched transistors that are always at the same temperature.

Gain Curves

The exact expression for the voltage gain you can expect from a differential amplifier is peppered with all sorts of complicated terms. If we make a few reasonable assumptions, the gain expression can become quite simple. Let's assume that both transistors have a common-emitter current gain (β) of at least 20, that both inputs come from low-impedance sources, and that the current source will provide a few milliamperes at most. The voltage gain is then given by $(R_L \times I_E)$ 104, where R_L is the load resistance in *ohms* and I_E is the total emitter current in *milliamperes*. To get the voltage gain in decibels, we take 20 times the log of the numerical gain, just as in any decibel problem.

We see that only two things affect the gain: the collector load resistors and the source current I_E, making the stage performance nicely independent of transistor parameters.

Fig. 2 shows how you can find the gain of any low-level diff amp. For instance, if you need a 10:1 voltage gain (20 dB) and you must use a 1000-ohm collector load resistor, you would choose an emitter source current I_E of 1.04 milliamperes, or roughly 1 mA. Or, if you were analyzing another circuit with an R_L of 500 ohms and an I_E of 5 mA, you would conclude that the stage gain would be 24:1 or 27.6 decibels.

Now, supposing we reduce the emitter current from 5 mA to 50 microamperes (0.050 mA). What happens? The "gain" drops to 0.24 or −12.4 decibels. We no longer have an amplifier, but an "unamplifier", more properly called an attenuator. We get less signal out than we put in. Simply by varying the emitter current, we can electronically vary the stage gain, and linearly too. This makes the diff amp particularly attractive for a.g.c. and a.v.c. stages and anywhere else it is desirable to electronically control the gain of an amplifier. By careful control of the networks between diff amps, the a.g.c. and a.v.c. action can be obtained without affecting the bandwidth of the amplifier, a very attractive feature for r.f. work.

Our gain curves are for the output voltage you would get from one collector to ground. This is called the *single-ended voltage gain*. The balanced, or *double-ended voltage gain* is the collector-to-collector output voltage, and is twice (or +6 decibels) the single-ended gain. To obtain the double-ended voltage gain from the curves, just double your results or add 6 decibels to get the new figure.

Input Impedance

If we stick to the lower frequencies and the assumptions we made for the gain curves, the input impedance will be given by $(52 \times \beta)/I_E$ where β is the common-emitter current gain of the transistor and I_E is the source current in milliamperes. We have plotted this in Fig. 3, where we see that higher gain transistors and lower values of I_E result in the higher input impedances. For instance, a 1 mA I_E and a pair of $\beta = 50$ transistors will give an input impedance of 2600 ohms.

For our gain equations to be accurate, and for minimum interaction between system gain and bandwidth, the signal source impedance should be considerably less than the amplifier input impedance. A 500-ohm source would work well driving a 5000-ohm input-impedance amplifier. If we wanted, we could cascade several diff amps by using 500-ohm collector resistors and biasing that would keep the input impedance of the next stage 5000 ohms or above. For a.c. systems, we could capacitor- or transformer-couple from stage to stage. However, d.c. coupling is a bit more elaborate as level-shifting techniques and feedback are often required.

Where exceptionally high input impedances are required, emitter followers or field-effect transistors may be added to raise the input impedance to a desired value. Electronic voltmeters (transistor v.t.v.m.'s) are one important example of this particular technique.

Limiting

Without an input signal, each transistor uses half the source current I_E. As one input swings positive, its transistor will draw more current and less current will be left for the other transistor. The *sum* of both transistor currents must always equal I_E. Now, suppose one transistor takes all the available current because of a very positive input. All of I_E will flow through its load resistor, while zero current will be left for the opposite transistor and load resistor. We can have no more output current than I_E, and no less output current than zero. The maximum possible *change* we could get in output voltage must equal the maximum peak-to-peak output signal we could ever hope to obtain. This maximum possible output signal swing is equal to $I_E R_L$ by Ohm's law. We say the differential amplifier *limits* with a peak-to-peak output of $I_E R_L$, independent of how much larger than necessary the input is. Fig. 4 is a plot that lets you determine the limiting output level of any diff amp. We see that the maximum possible output signal we could ever get out of a diff amp with a 1 mA I_E and a 1000-ohm collector load is 1 volt peak-to-peak.

If we want a linear amplifier, we must never allow the output signal to get as big as the limiting output value, or distortion will result. A factor of three makes a good safety margin. On the other hand, if we want the circuit to limit, we simply overdrive the input with a signal strong enough to force the diff amp stage into the limiting mode.

We can make any diff amp limit at a higher level by increasing either I_E or R_L and *vice versa*.

There is hidden beauty in the diff amp as a limiter. *Neither transistor ever saturates*, so we do not have to contend with storage times, d.c. offsets, and other gremlins common to limiters that often interfere with fast, smooth limiting action. Further, the limiting action is equal for positive and negative input excursions. We call this *symmetric* limiting. Symmetric limiting is very much necessary for quality self-limiting FM i.f. amplifiers, forming an important application for diff amps. When used in this manner, the diff amp is often called an *emitter-coupled limiter*. Comparators, squaring circuits, and zero-crossing detectors are other circuit examples which take advantage of these symmetric limiting properties.

Why Matched Pairs?

The base and emitter of any conducting transistor are separated by an internal voltage V_{BE}. Although this is around 0.6 volt for a silicon transistor, the *exact* value of this voltage varies with the particular transistor and changes with temperature. If one transistor had a V_{BE} of 0.60 volt and the other had a V_{BE} of 0.65 volt, it would be just the same as adding an extra 0.05 volt to one input. This would certainly unbalance the amplifier and send much more current through one load resistor than the other. It would also change the gain balance between both sides of the circuit.

To obtain a good balanced circuit, V_{BE} matched pairs of transistors should be used and, if the transistors are not already in the same case, they should be heatsunk or clipped together to allow the circuit to track over a wide temperature range without unbalancing.

Ordinary transistors may occasionally be used if balanc-

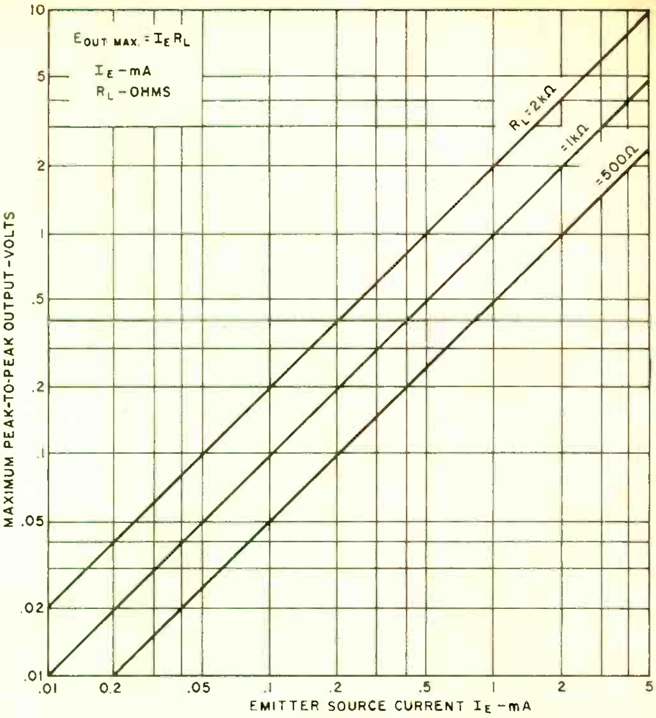
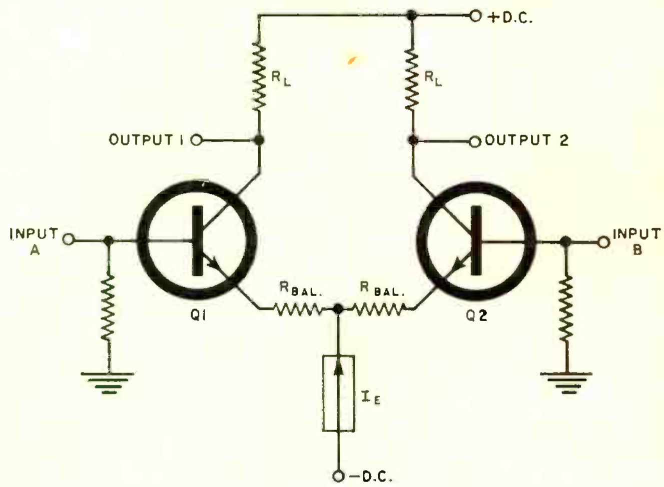
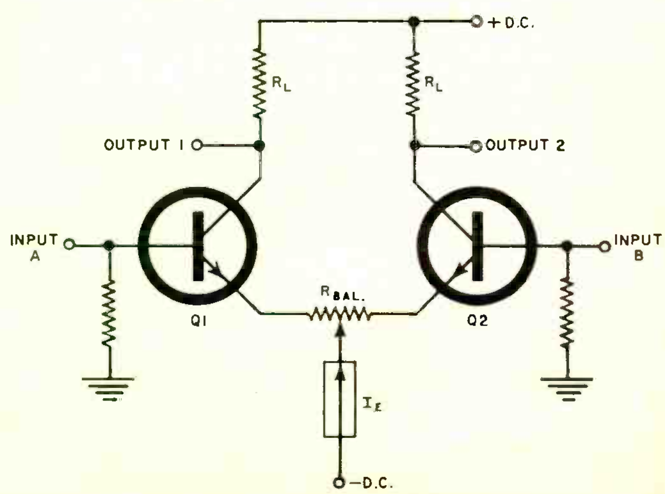


Fig. 4. This family of three curves illustrates the performance of the differential amplifier when employed as limiter. Operation for typical values of load resistance is shown.

Fig. 5. Showing use of balancing resistors or potentiometer to compensate for differing characteristics of transistors.



(A) RESISTORS ARE CAREFULLY CHOSEN TO COMPENSATE ANY V_{BE} DIFFERENCE IN Q1 AND Q2



(B) USING A BALANCING POTENTIOMETER

ing resistors are added to the emitters as in Fig. 5A. The resistors are chosen such that an extra V_{BE} drop in one transistor is made up by an equal extra voltage drop in the opposite emitter resistor so that the voltage drops cancel out each other's effects. A pot (Fig. 5B) is usually used instead of the two resistors to allow a control range that will compensate for different transistors. These usually run from 10 to 500 ohms and are adjusted to make both collector voltages identical under no-signal conditions. The balancing resistors will also lower the gain and raise the input impedance, so some performance trade-offs are involved in using ordinary transistors.

Why a Current Source?

Since we have a difference amplifier, we would not want any signal that appeared simultaneously at *both* inputs to appear in the output. We call such a signal a *common-mode signal,* and the ability to minimize its effect is called the *common-mode rejection* of the amplifier. A perfect current source will have infinite common-mode rejection, since no combination of transistor voltage could possibly change the current out of an ideal current source. The *degree* to which a current source approaches the ideal determines how good the common-mode rejection will be.

If the common-mode rejection is poor, the gain and d.c. bias points will shift with a common-mode input. Power-supply noise and hum also become common-mode signals when two or more balanced amplifiers are cascaded, and could not be properly rejected in a poor amplifier design.

An example can show the effects of a common-mode signal. In Fig. 6A, we have *approximated* the current source by a 5000-ohm resistor and a −5.6-volt supply. We can see that a common-mode signal will change the voltage across the emitter resistor. This will change I_E which, in turn, will change the gain and d.c. operating points of each collector. If we check the gain curves, we will find the amplifier will have a gain of 9.4 or 19.5 decibels without a common-mode input signal, while the collectors will be d.c.-biased at 2.5 volts, determined by Ohm's law as applied to the collector resistors.

Now, suppose we add a common-mode signal of −1 volt

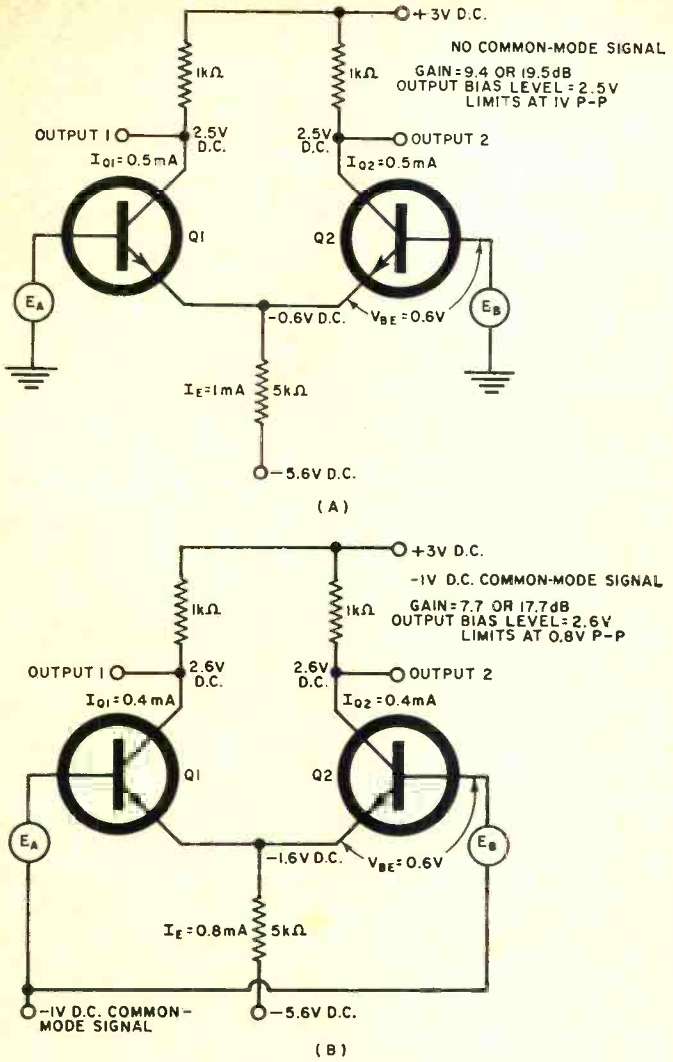
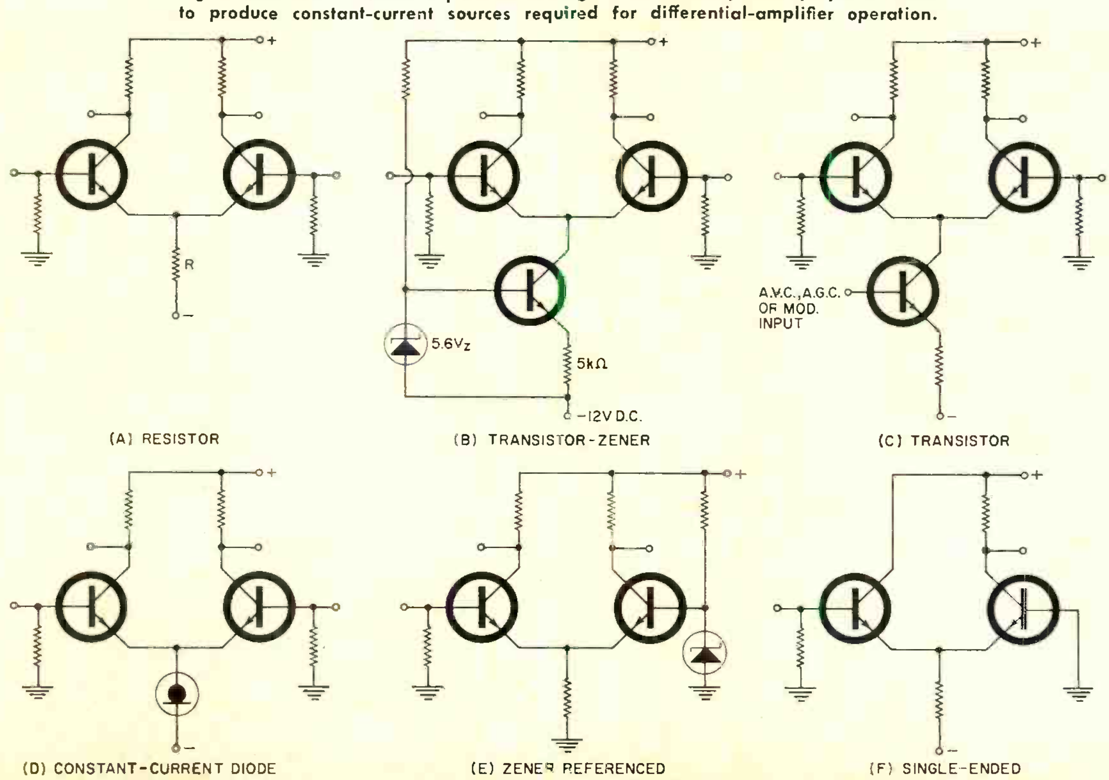


Fig. 6. The effects of a common-mode signal is shown here.

Fig. 7. Here are a number of practical arrangements that may be employed in order to produce constant-current sources required for differential-amplifier operation.



(Fig. 6B). The emitter voltage now drops to −1.6 volts and the current through the 5000-ohm resistor drops to 0.8 mA. The gain drops to 7.7 or 17.7 decibels, a 20% reduction, while the collector operating point goes up to 2.6 volts, and the stage now limits with a 20-percent smaller output swing.

A positive common-mode signal would do the opposite—the gain would increase as would the limiting output level. How bad these effects are depends entirely upon the electronic system. In d.c.-coupled circuits, any shift in operating point at all is bad and must somehow be corrected by feedback. Low-level signals also make the common-mode design problem more severe, as do circuits where a large d.c. offset may accompany a small a.c. signal.

Practical Current Sources

A negative voltage and a resistor is the simplest current source (Fig. 7A). In the previous common-mode example, we saw that a 5000-ohm resistor and a −5.6-volt source would give a 20% gain variation for a 1-volt common-mode signal. A 50,000-ohm resistor and a −50.6-volt source would do ten times better, allowing only a 2% variation, while a 500,000-ohm resistor and a −500.6-volt source would hold the variation to only 0.2%.

There are better ways that employ more reasonable supply voltages. A transistor connected as an emitter follower will provide a constant collector current, independent of supply variations. In Fig. 7B we have used a zener diode and transistor to provide a constant 1-mA source. A different emitter resistor or base voltage will result in a different constant collector current. In Fig. 7C, the source transistor is driven by a control signal. This input allows us to electronically vary the gain, either slowly to provide a.g.c. or a.v.c., or rapidly to provide a modulator or electronic multiplier.

In Fig. 7D, we use a *current-limiting field-effect diode*, a new device that automatically provides a constant current just like a zener diode provides a constant voltage.

Another approach is to eliminate the possibility of a common-mode signal. In 7E, one input is returned to a zener diode. A common-mode signal cannot exist different from that of the zener itself, so a single resistor serves as the current source. This circuit is often used in regulated power supplies, as the slightest difference between the zener voltage and the input voltage produces a strong collector current unbalance which, in turn, is used to correct the input signal, returning it to a value equal to that of the zener, thus providing regulation.

Grounding one input (Fig. 7F) also eliminates the common-mode problem, and once again a single resistor serves as a current source. The same circuit shows another twist—if we only make use of one output, the opposite load resistor is not needed and may be eliminated from the circuit with no change in performance.

The loss of one input does eliminate a lot of circuit possibilities but we still have a gain-stable, low-cost, capacitor-free amplifier or limiter useful for practically any simple low-level application. ▲

(Editor's Note: The careful reader will note that we have shown all the current sources in the various diagrams in this article with arrows indicating the direction of electron-current flow rather than conventional current flow. On the other hand, arrows in standard transistor and diode symbols point in the direction of conventional current. This method of indicating external current flow is entirely consistent with our own practice and with the practice that is followed in most military manuals and in most basic texts.

This method of indicating current flow should not cause any confusion providing the reader keeps in mind that we are usually concerned with the flow of electrons, and that these flow from minus to plus in the external circuit.)

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