# Op amp stabilizes zener diode in reference-voltage source

The operational amplifier's isolation characteristics can be used to buffer a reference zener against the supply and load variations that would otherwise downgrade the diode's temperature and voltage stability

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☐ On its own, a reference zener diode can produce a reasonably stable voltage. But in conjunction with an operational amplifier, a reference diode of selected quality can be made to provide a voltage temperature stability as good as 1 part per million per degree celsius—precise enough for applications like data conversion and instrumentation.

To obtain a zener voltage and temperature coefficient as stable as this, the current through the zener must be kept constant and prevented from fluctuating with changes in power-supply voltage and in load conditions. The op amp does not cancel zener imperfections, but its excellent isolation characteristics can be used to create nearly ideal circuit conditions for the diode, buffering it against both supply and load variations.

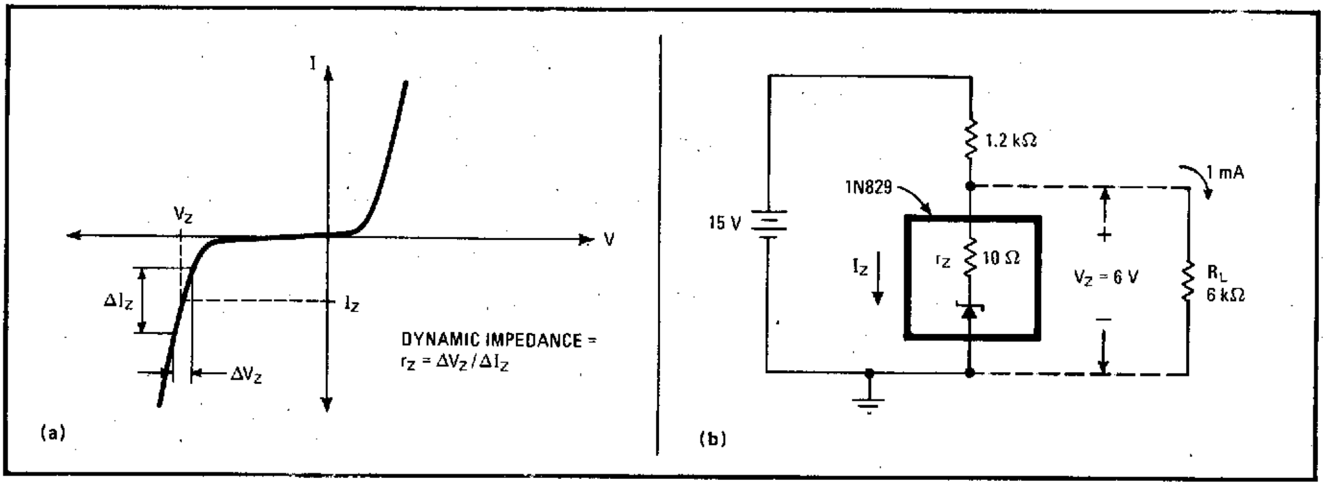
A third factor affecting zener current is operating temperature, and of course it also must be kept constant, by appropriate thermal management, which might even involve thermostatic control of the environment or a constant-temperature oil bath.

## Back to basics

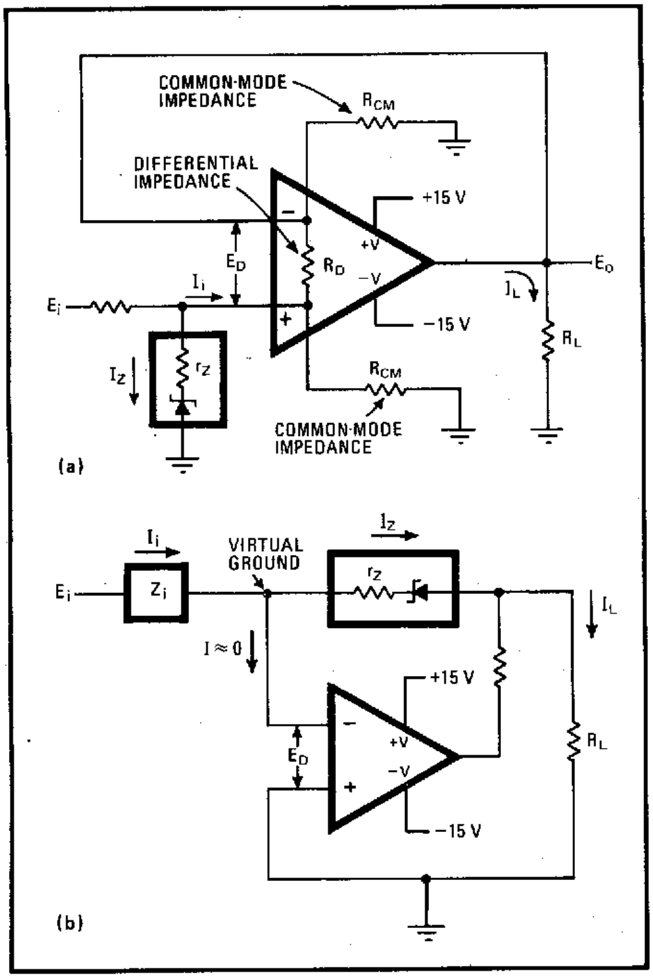
The transfer characteristic of a zener diode is shown in Fig. 1(a). Since the curve is not parallel to the current axis in the reverse breakdown region, where a zener is operated, the zener dynamic impedance ($r_Z$) is finite, usually on the order of 10 ohms. Because of this finite impedance, a zener cannot function as a perfect voltage source, supplying the same output voltage no matter what the size of the load. The intrinsic zener impedance and the load impedance always form a voltage divider that attenuates the zener output.

The zener current also influences the zener's voltage-temperature coefficient. Typically, this parameter rises or falls approximately 4 ppm/°C for each milliampere of increase or decrease in operating current. A zener diode, therefore, is most stable when operated at a constant current level. (In practice, the operating current that minimizes the temperature coefficient will vary slightly from device to device.)

The simple single-polarity reference source of Fig. 1(b) illustrates how load and supply variations affect zener current and, hence, zener voltage. Without the load connected, the zener current is 7.5 milliamperes, and the zener voltage is 6 volts. But when the load is put across the zener, it pulls 1 mA from the diode so that zener current drops to 6.5 mA and zener voltage is reduced by 10 millivolts. This output voltage change corresponds to a load regulation of 0.16%, which is too poor for many applications. Also, because the zener current has varied by 1 mA, the zener's voltage temperature coefficient will change by 4 ppm/°C.



**1. The problem.** Because of the finite slope of the zener diode's transfer characteristic (a) in the reverse breakdown region, zener current is affected by both supply and load variations. In circuit (b), for instance, without the load, the zener current is 7.5 mA, producing a zener voltage of 6 V. When the 1-mA load is connected, however, the zener voltage drops by 10 mV, corresponding to a load regulation of 0.16%.



**2. A helping hand.** If a zener is buffered by an op amp, it will be isolated from load fluctuations. For both circuits shown here, the zener current is independent of the load current, which is supplied by the op amp. In (a), the op amp acts as a high-impedance buffer for the zener. In (b), because of the virtual ground, the input current, however derived, determines the zener current. If the input current for either of these circuits is obtained from an op amp, then the zener will also be isolated from supply variations.

In contrast, quite a large change in the supply voltage, about 1.2 V, is needed to produce the same 10-mv output change. But the supply regulation becomes more important if the loading is lighter, say 10 microamperes instead of 1 mA. For example, a 10-μA change in the load will produce an approximate output change of only 0.1 mV. However, with a 10-μA load, a supply variation of just 12 mv will now cause a 0.1-mv output change.

An op amp, along with an appropriate feedback network, can isolate a zener from the adverse effects of both line and load variations. When a zener is properly buffered, its current will remain essentially constant so that changes in zener voltage and temperature coefficient can be held to a minimum.

## The op amp's advantages

Basically, an op amp is a differential amplifier that rejects equal in-phase signals if they are common to both its inputs. Since power-supply variations are such signals, they are rejected, and the op amp does not respond to them. Therefore, if the output of an op amp, which is inherently isolated from supply fluctuations, is used to drive a zener, that zener will also be isolated from line variations. The power-supply rejection of today's op amps is very good, frequently 80 decibels or greater.

Isolating a zener from load variations is another matter. To do this, some of the other characteristics of an op amp—such as high gain, low output impedance, and high input impedance—must be exploited. Figure 2 shows two circuit techniques that use these op-amp properties to make zener current independent of loading demands.

In the circuit of Fig. 2(a), the op amp simply acts as a high-impedance buffer for the zener. No matter what the load current is, very little current is drawn by the op amp, so that the zener current remains fairly constant. The current required by the op amp is:

$$I_i = E_D/R_D \qquad (1)$$

where $R_D$ is the op amp's differential input impedance, and $E_D$ is the voltage between the op amp's inverting and noninverting inputs. This voltage can be expressed as:

$$E_D = E_o/G \qquad (2)$$

where $E_o$ is the output voltage, and G is the gain of the op amp. Since G is usually very large, on the order of $10^4$ or more, differential voltage $E_D$ is approximately equal to zero, and the output voltage is essentially the zener voltage:

$$E_o = V_Z \qquad (3)$$

Substituting Eqs. 2 and 3 in Eq. 1 yields:

$$I_i = E_o/GR_D = V_Z/GR_D$$

which is a very small number. Effectively, differential impedance $R_D$ appears to be G times greater than its nominal value, so that it draws G times less current.

However, it should be noted that the common-mode impedance ($R_{CM}$) of the op amp is what actually limits the input impedance of this circuit. Since impedance $R_{CM}$ is grounded, it shunts the zener, as well as differential impedance $R_D$. Fortunately, for all op amps, $R_{CM}$ is much greater than $R_D$, so that $R_{CM}$ itself never unduly loads the zener. If zener loading must be kept to a minimum, then a FET-input op amp, because of its exceptionally high input-impedance levels, becomes a logical choice for the amplifier.

This circuit (Fig. 2a) offers a straightforward method of developing a single polarity reference source. However, the circuit of Fig. 2(b) makes possible even tighter control of zener current. Here, the zener diode is placed directly in the feedback loop of the op amp. Furthermore, this circuit (Fig. 2b) is useful for deriving both single-polarity and dual-polarity reference sources.

The high gain of the op amp and the feedback action combine to create a point that is very close to zero volt, or ground potential. This virtual ground permits the input current ($I_i$) to determine the feedback zener current ($I_Z$) precisely and independently of the load, regardless of how the input current is derived. Therefore, because of the virtual ground:

$$I_i = -I_Z$$

Furthermore, the input current is not affected by the level of the output voltage:

$$I_i = E_i/Z_i$$

where $E_i$ is the input voltage, and $Z_i$ is the input impedance. Again, as with the circuit of Fig. 2(a), the differential voltage, $E_D$, is about equal to zero, because:

$$E_D = E_o/G$$

where G, the op-amp gain, is very large.

### A single-polarity reference

One way to implement a single-polarity reference source, using the inverting circuit of Fig. 2(b), is shown in Fig. 3. In order to take advantage of the power-supply rejection of the op amp, the zener driving voltage is derived from the op amp by the addition of a small amount of positive feedback, through resistors $R_1$ and $R_2$. The destabilizing effect of this positive feedback is minimal since negative feedback predominates.

The positive feedback factor can be written as:

$$\beta_P = R_2/(R_1+R_2)$$

which is less than 1. The negative feedback factor is:

$$\beta_N = R_3/(R_3+r_Z)$$

where $r_Z$ is the zener impedance. Since $r_Z$ is small compared to $R_3$, $\beta_N$ is approximately unity, so that:

$$\beta_N \textit{ is greater than } \beta_P$$

The op amp's differential input voltage is given by:

$$E_D = E_o\beta_P - (E_o - V_Z)\beta_N$$

Since:

$$E_D = E_o/G$$

then:

$$E_o = GE_D$$
$$E_o = G[E_o\beta_P - (E_o - V_Z)\beta_N]$$
$$E_o = GE_o(\beta_P - \beta_N) + GV_Z\beta_N$$
$$E_o = (\beta_N V_Z)/[(1/G) - (\beta_P - \beta_N)]$$

where G is the gain of the op amp. Since G is much greater than 1, $\beta_N$ approximately equals 1, and $\beta_N$ is greater than $\beta_P$, then:

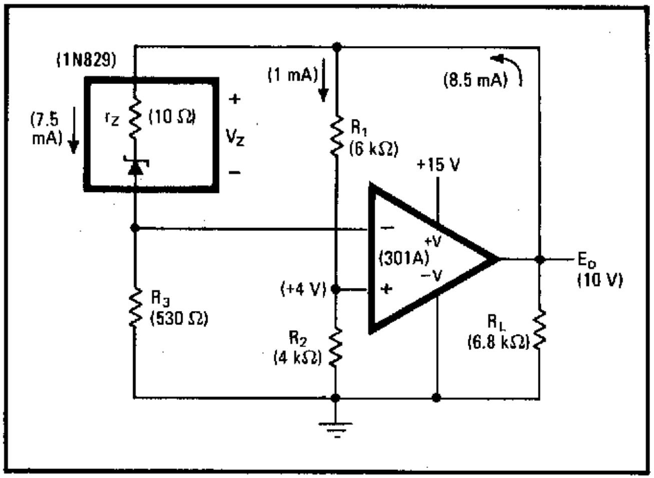
$$E_o = V_Z/(1 - \beta_P)$$
$$E_o = V_Z(R_1+R_2)/R_1$$
$$E_o = V_Z[1 + (R_2/R_1)]$$

The load regulation for the circuit can be expressed as:

$$\textit{regulation} = r_o/[R_L G(\beta_N - \beta_P)]$$

where $r_o$ is the output impedance of the op amp, and $R_L$ is the load resistance.

Since the output impedance of an op amp is quite low, ranging from milliohms to ohms, depending on the type of amplifier being used, the op amp acts much like an ideal voltage source, supplying a constant output voltage that is independent of the load. This means that the circuit's voltage regulation can be very good—anywhere between 0.001% and 0.01%, depending on the op amp and zener diode selected. Also, the voltage temperature coefficient of this circuit can be that of the zener itself, as long as the resistors used for the circuit are closely matched.



**3. Unipolar reference.** Here, the inverting circuit of Fig. 2(b) isolates the zener from load variations. A small amount of positive feedback permits the zener to derive its driving voltage from the op amp and thus take advantage of the op amp's power-supply rejection.

The op amp chosen must be able to supply all circuit operating currents, as well as the load current. In addition, since the noninverting op-amp input is above ground potential, the common-mode capability of the op amp must be adequate for desired circuit operation. Of course, the op amp's power-supply rejection and offset voltage drift are also important. Typical circuit values and device type numbers are indicated parenthetically in the diagram.

### Dual-polarity references

The requirements of a dual-polarity voltage reference can be even more demanding than those of a single-polarity source, especially if both the positive and negative voltages must be maintained symmetrically about ground. The inverting circuit of Fig. 2(b), because of its inherent virtual-ground point, is particularly adaptable for such an application.

In the dual-polarity source of Fig. 4, a single zener diode is made to generate precise ground-referenced bipolar output voltages. The zener voltage is the difference between the two outputs:

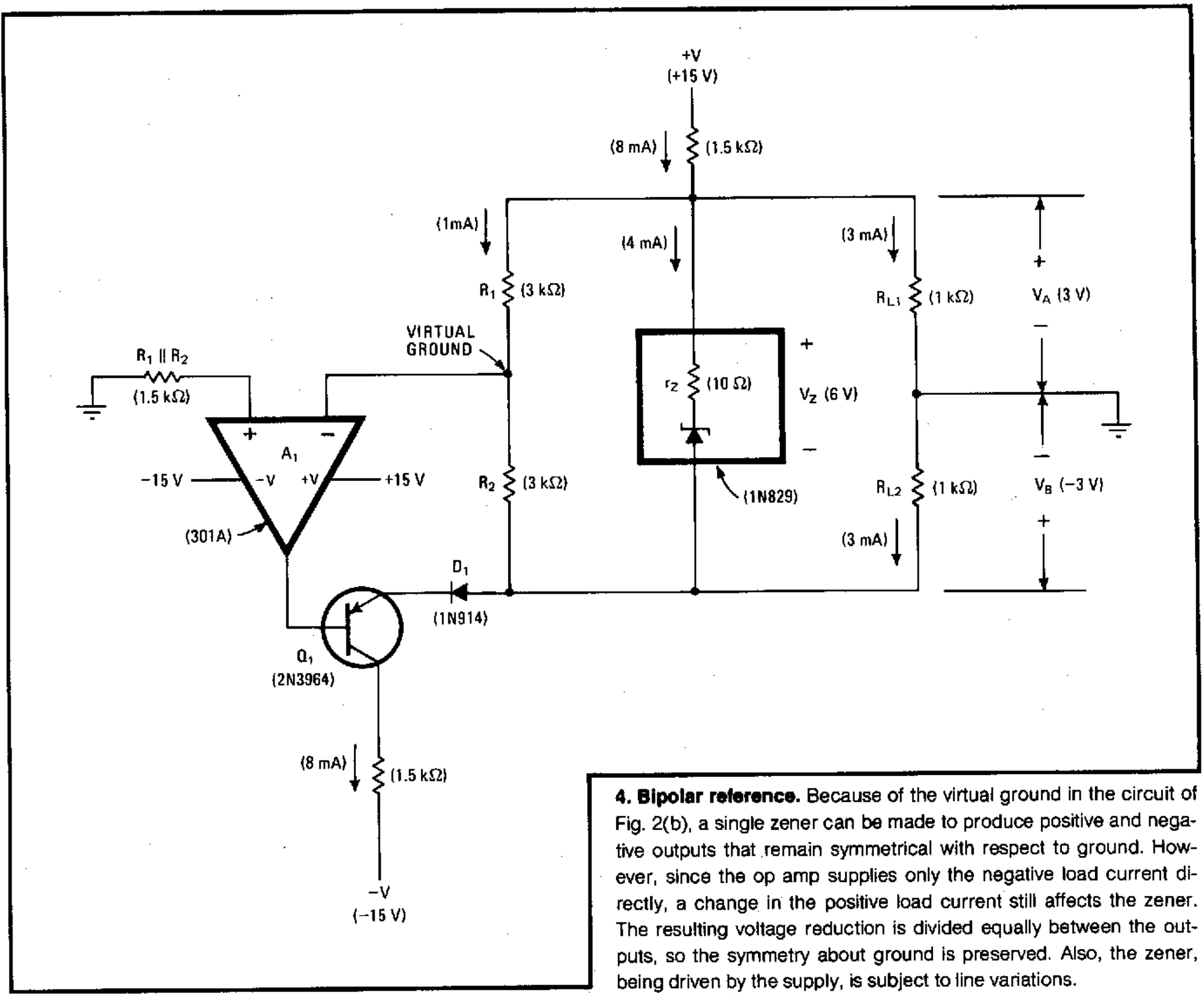
$$V_Z = V_A - V_B \qquad (4)$$

where $V_A$ is the positive output, and $V_B$ is the negative output. Since the virtual-ground point is the node to which all circuit voltages and currents are referred, the output voltages are merely scaled by resistors $R_1$ and $R_2$:

$$V_A/R_1 = -V_B/R_2$$

Rearranging the terms of this equation yields:

$$V_A = -(V_B R_1)/R_2 \qquad (5)$$



**4. Bipolar reference.** Because of the virtual ground in the circuit of Fig. 2(b), a single zener can be made to produce positive and negative outputs that remain symmetrical with respect to ground. However, since the op amp supplies only the negative load current directly, a change in the positive load current still affects the zener. The resulting voltage reduction is divided equally between the outputs, so the symmetry about ground is preserved. Also, the zener, being driven by the supply, is subject to line variations.

Since $V_A = V_Z + V_B$ (from Eq. 4), Eq. 5 can be rewritten as:

$$V_Z + V_B = -(V_B R_1)/R_2$$

or:

$$V_B = -(V_Z R_2)/(R_1 + R_2)$$

Similarly, since $V_B = V_A - V_Z$ (from Eq. 4), Eq. 5 can again be rewritten as:

$$V_A = -[(V_A - V_Z)R_1]/R_2$$

or:

$$V_A = (V_Z R_1)/(R_1 + R_2)$$

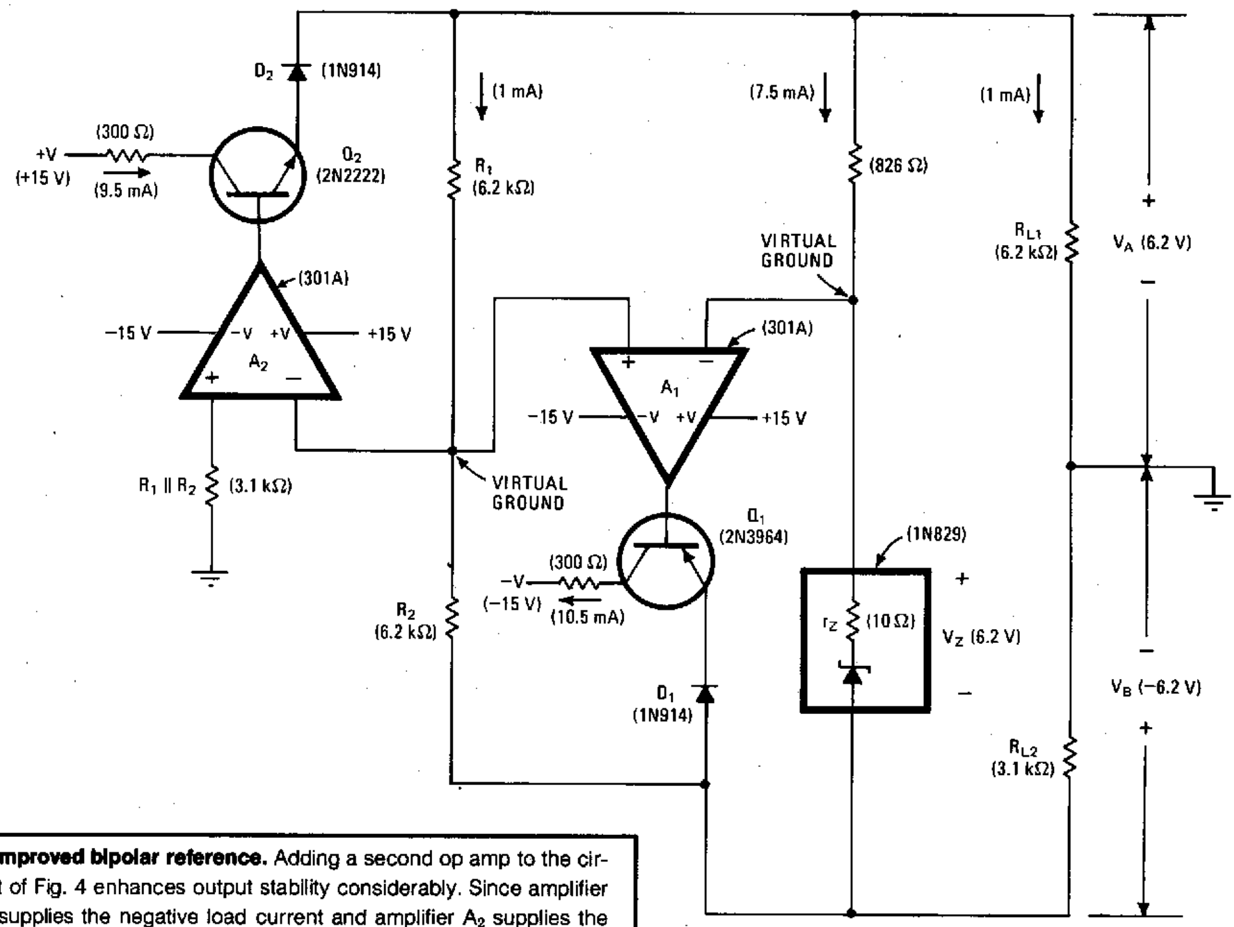
When resistors $R_1$ and $R_2$ are equal to each other, positive output $V_A$ becomes $+V_Z/2$, while negative output $V_B$ becomes $-V_Z/2$.

The load current for the negative output is supplied directly by the op amp. Therefore, any variations in the negative load current will not affect the zener's current or voltage. A load variation on the positive output, however, will directly reduce zener current, thereby changing the zener voltage. But, because of the virtual ground created by the op amp, this change in zener voltage is divided equally between the two outputs, so that both positive and negative outputs remain symmetrical with respect to ground.

With this circuit, however, the zener, being driven directly by the supply and not by the op amp, is not isolated from supply fluctuations. As a rule, though, a supply having adequate regulation for an op amp will pose no problems for the zener.

A current-booster transistor, $Q_1$, is included here to permit the use of an op amp having only a moderate output capability. The op amp must be able to sink all of the circuit's operating currents, except for the positive load current, and this can add up to a heavy demand and a costly amplifier. The transistor is an inexpensive way to save money on the op amp. Diode $D_1$ is included to assure that the amplifier turns on properly. Typical circuit values and device type numbers are noted parenthetically in the figure.

To build a dual-polarity reference that is immune to line fluctuations, as well as load variations on both the positive and negative outputs, requires a second op amp. In the circuit of Fig. 5, amplifier $A_1$ supplies the negative load current, while amplifier $A_2$ supplies the positive load current. The zener current then will not be



**5. Improved bipolar reference.** Adding a second op amp to the circuit of Fig. 4 enhances output stability considerably. Since amplifier $A_1$ supplies the negative load current and amplifier $A_2$ supplies the positive load current, the zener is immune to load variations on either output. The zener is now also isolated from line variations because its driving voltage is obtained through the op amps.

affected by a change in the load for either output. Moreover, since the driving voltage for the zener is derived from the op amps, the zener is isolated from supply variations by the power-supply rejection of the op amps.

Both outputs are maintained symmetrically about ground because each amplifier creates its own virtual-ground point. The negative output voltage is simply an inverted version of the zener voltage:

$$V_B = -V_Z$$

The positive output voltage, on the other hand, is scaled by resistors $R_1$ and $R_2$, permitting it to be an amplified or attenuated version of the zener voltage:

$$V_A = (V_Z R_1)/R_2$$

If resistors $R_1$ and $R_2$ are equal, then $V_A$ is simply $+V_Z$. As with the dual-polarity reference of Fig. 4, the two output voltages are related to each other by:

$$V_A/R_1 = -V_B/R_2$$

Transistors $Q_1$ and $Q_2$ act as economical current boosters, while diodes $D_1$ and $D_2$ provide the gating action necessary for turning the amplifiers on properly. If chopper-stabilized op amps are chosen for amplifiers $A_1$ and $A_2$, the circuit's thermal and long-term stability will be quite good. Typical device type numbers and circuit values are shown parenthetically in Fig. 5.

Both of the dual-polarity references described here permit a line and load regulation of 0.001% to 0.01% to be achieved. And the temperature stability of both circuits can be as good as that of the zener diode being used. For example, the temperature coefficient of the popular type 1N829 reference diode can be as low as 4 ppm/°C.

Naturally, any reference source must operate in an appropriate thermal environment if circuit stability is to be maximized. Remember that the circuitry associated with the zener diode can dissipate significant amounts of power. An obvious way to minimize the unwanted heat this generates is to choose a low-current reference diode and low-power op amps. ☐

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