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(54) METHOD FOR TEMPERATURE-COMPENSATING ZENER DIODES HAVING EITHER POSITIVE OR NEGATIVE TEMPERATURE COEFFICIENTS

VERFAHREN ZUR TEMPERATURKOMPENSATION VON ZENERDIODEN MIT ENTWEDER POSITIVEN ODER NEGATIVEN TEMPERATURKOEFFIZIENTEN

PROCEDE DE COMPENSATION DE LA TEMPERATURE DE DIODES ZENER PRESENTANT DES COEFFICIENTS DE TEMPERATURE SOIT POSITIFS SOIT NEGATIFS

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Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] This invention relates to temperature-compensated Zener-diode voltage references. More particularly, this invention relates to a so-called "auto-TC" voltage reference wherein trimming of a circuit resistance to give a predetermined output voltage will simultaneously optimize the temperature compensation for that output voltage.

2. Description of the Prior Art

[0002] One type of "auto-TC" voltage reference has been described in U.S. Patent 4,313,083. There a Zener diode voltage is applied to one input terminal of an operational amplifier and the other input terminal is supplied with a feedback voltage from a junction point in a series circuit comprising a pair of transistors with a pair of trimmable resistors. The bases of the two transistors are separately set to predetermined values by a three-resistor voltage divider between the output line and ground. The circuit disclosed can provide auto-TC compensation for Zener diodes having positive TC, but not for diodes having negative TC.

[0003] EP-A-0 220 789 shows a Zener-diode circuit for use with CMOS processes where parasitic bipolar transistors are produced as part of the CMOS process. Such bipolar-transistors are formed in such a fashion that the circuit designer cannot make independent connections to their collector. Thus, a special circuit arrangement is required.

[0004] The object of the present invention is to provide a temperature-compensated Zener-diode voltage reference and a corresponding method which automatically produces zero TC at the output voltage.

[0005] This object is achieved with the features of claims 1 and 9, respectively.

SUMMARY OF THE INVENTION

[0006] The present invention in one preferred embodiment provides an auto-TC voltage reference wherein an operational amplifier receives at one input the voltage of a Zener diode and at its other input receives a compensation signal from a feedback circuit comprising a transistor and resistor network. When one of the resistors of the network is trimmed to give a nominal output voltage for the reference, the TC of the reference voltage will have been reduced to zero, or nearly so. The circuitry is capable of compensating Zener diodes of either positive or negative TC.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007]

FIGURE 1 is a graph showing the temperature-response characteristics of Zener diodes made by the same process;

FIGURE 2 is a schematic to illustrate the functioning of a voltage reference in accordance with the invention;

FIGURE 3 shows a modified circuit based on Figure 2 but utilizing only a single transistor in the feedback network;

FIGURE 4 presents a generalized schematic diagram to illustrate further aspects of the invention;

FIGURE 5 is a circuit diagram showing a circuit design suitable for an integrated circuit; and

FIGURE 6 is a circuit diagram showing a modification to the circuit of Figure 5.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0008] The graph of Figure 1 depicts in an idealized manner the temperature response characteristics of the avalanche voltage (V_z) versus temperature of a group of Zener diodes produced by the same process. The slopes of upper and lower solid lines 10 and 12 illustrate extremes of positive and negative temperature coefficients (TC) respectively. Any one diode made by the process can have a TC which lies anywhere between these extremes. It will be assumed in the following discussion that the temperature response characteristic is linear, which is approximately correct as a practical matter.

[0009] With Zener diodes made by the same process, it will be found that the temperature-response characteristic lines for all diodes will (at least approximately) pass through the same voltage point V_m at a temperature of T_m, as shown in Figure 1. T_m is shown as being negative on the absolute or Kelvin scale, which is generally true in practice. Although such a negative T_m is not a realizable operating point, it is useful for analysis as an extrapolation of Zener behavior in a normal operating temperature range.

[0010] It will be seen from Figure 1 that the avalanche voltage of the Zener diodes can be described by:

$$V_z = V_m + \alpha_1 (T - T_m)$$

where:

- V_z is the avalanche voltage,
- V_m is a voltage parameter which is relatively insensitive to variations in a given process (and typically is in the range of 4.4V to 4.8V for a number of known processes),
- T_m is a temperature parameter which is relatively insensitive to variations in a given process, and
- α_1 is a parameter with a value associated with each fabricated device. Its variability from unit to unit encompasses most of the avalanche voltage variations which result from process variability.

[0011] Referring now to Figure 2, there is shown a circuit for illustrating aspects of the present invention. This circuit includes an operational amplifier 20 having its non-inverting input terminal 22 connected to the positive electrode of a Zener diode 24 producing a voltage V_z. The other Zener electrode is connected to a common line 26. The Zener voltage generally is temperature sensitive, as discussed above with reference to Figure 1.

[0012] The output terminal 28 of the amplifier 20 produces an output voltage V_o responsive to the applied Zener voltage. A negative feedback circuit generally indicated at 30 is connected between the output terminal 28 and the common line 26.

[0013] This feedback circuit 30 includes a number of series-connected elements comprising a first segment 32 with a resistor R1 and diode D1, a second segment 34 with a resistor R2 and a diode D2, and a resistor R3. The junction point 36 between the two segments 32, 34 is connected to the inverting input terminal 38 of the amplifier 20.

[0014] In considering the operation of this circuit, let it be assumed first that R1 = R2 , that R3 = 0, and that the diodes D1, D2 are matched. The voltage across the first segment 32 (i.e., at the amplifier input terminal 38) will be essentially V_z, due to feedback action. Since R1 and R2 are equal, and carry equal currents, the voltage V_x at the right-hand end of R2 (and at the output terminal 28) will be twice V_z. This relationship will hold true regardless of changes in temperature.

[0015] If the Zener diode 24 has a zero TC (rare, but possible), the output V_o will be temperature invariant. However, because there is a diode in each feedback segment 32, 34, and because the V_{BE} of a diode has a negative TC, the current in the feedback circuit nevertheless will vary with temperature.

[0016] With a Zener diode 24 having a negative TC ($\alpha_1 < 0$), the voltage V_z at the amplifier input terminals 22 and 38 will decrease with increasing temperature as will the output voltage V_o. Assuming that the V_{BE} of diode D1 has a TC which is more negative than the negative TC of V_z, the current through the feedback resistor R1 (and thus through R2) will have a positive TC. This is because the temperature-induced negative change in V_{BE} of diode D1 with increasing temperature will be greater than the negative change in Zener voltage V_z, so that the net voltage across R1 will increase with temperature, as will the current through R1 (and R2).

[0017] If R3 now is made greater than zero (R3 > 0), the output V_o will increase due to the added voltage drop across R3 resulting from the feedback current. This added increment to the output voltage will have a positive TC (since the feedback current will in the circumstances noted above have a positive TC). By adjusting the value of R3, the positive TC of the voltage across R3 can compensate for the negative TC of the Zener voltage V_z, so that the output V_o can be made (essentially) invariant with temperature.

[0018] The same circuit can be used to provide similar compensation for Zeners with a positive TC. In this case, rather than making R3 > 0, the value of R2 will be reduced. In effect, R3 will be made "negative" (although of course a negative resistance is not actually present in the circuit). The result will be that V_o is reduced (since the voltage drop across a reduced R2 is correspondingly reduced), and the TC of the voltage across "negative" R3 will be negative, thus compensating for the positive TC of the Zener.

[0019] The value of R3 thus can with advantage be viewed as an incremental deviation (± R) from the nominal value of R2 where R2 = R1 . To provide for a practical trimming sequence, the initial value of R2 can be set significantly less than R1 (R2 << R1), and R2 can be thought of as R2 "nominal" in series with an initially negative R3 of relatively large value. The circuit without any trimming should be capable of compensating for a limiting (maximum) positive TC in the Zener 24. Since the actual Zener normally will have a less positive TC than this limiting value, R2 can be trimmed up (increased in ohmic value) until the correct magnitude is reached to provide compensation for the actual Zener involved (including Zeners with negative TC).

[0020] The range of Zener TC which can be compensated is constrained by the relationship between the diode V_{BE} and the magnitude of the Zener voltage V_z which determines the maximum TC of the current in R1 and R2. To increase this range, more diodes can be added to both feedback segments 32, 34.

[0021] In determining the number of diodes in each feedback segment 32, 34, it may turn out that the desired number of diode drops in each may not be an integer. Fractional values of V_{BE} can be achieved and the circuit simplified (at least in the number of junctions required) by using a "V_{BE} multiplier" of known configuration, as shown at 40 in Figure 3 (and also as described in Brokaw Patent 4,622,512). The V_{BE} of transistor Q4 appears across resistor R6, and the accompanying current through R6, R5 and R4 produces a multiplied version of that V_{BE} across resistors R5 and R4.

[0022] The feedback voltage for input terminal 38 is tapped off an intermediate point 36A between R4 and R5. Thus the V_{BE} of one transistor can be "multiplied" to provide effective junction drops in both feedback segments 32A and 34A. Here the V_{BE} is effectively multiplied by $(1 + (R4 + R5)/R6)$, and this multiplied voltage is divided between the lower and upper segments in proportions determined by the resistance values.

[0023] One limitation of the Figure 2 arrangement is that the output voltage V_o will always be at or near $2V_z$. To accommodate a larger range of values for the output voltage, a modification as illustrated in general form in Figure 4 can be employed. This configuration uses a feedback circuit 30B where the elements in the second segment 34B have values "k" times the values of the corresponding elements in the lower segment 32B (with k being a preselected constant). Thus the diode drop in the upper segment is kV_c, and the series resistor $R2 = KR1$. The output voltage then will be $V_o = V_z \cdot (1 + k)$, for the nominal case where $\alpha_1 = 0$ and $V_z = V_m$. This Figure 4 relationship can be established in the Figure 3 feedback arrangement by appropriately-sized feedback resistors.

[0024] By selection of circuit values, V_o can be made a convenient value higher than V_m. In the case of an auto-TC design (referred to above in the section on prior art and as described in more detail below), the nominal value of V_o to which the output will be trimmed must be higher than the maximum anticipated Zener voltage by an amount which allows for the temperature compensation voltage.

[0025] It may particularly be noted that for negative values of α_1, trimming to increase the output TC will increase the output voltage V_o. Conversely, for positive α_1, trimming to decrease the output TC (by making $R2 < kR1$) will lower the output voltage V_o. Thus the direction of voltage change is correct for providing an auto-TC compensation. To achieve that result, it is necessary to establish correct proportions between the output voltage adjustment (change in V_o), and the induced TC.

[0026] Considering the auto-TC design further, the desired nominal output voltage V_o should first be chosen. This number can be somewhat arbitrary, but must be within practical constraints. It must for example be comfortably higher than the nominal Zener voltage V_m, and it must be within power supply voltage limitations. As an illustration, one might select V_o = 6 volts. To provide a practical example, and with reference to the V_{BE}-multiplier arrangement of Figure 3, the feedback resistors in one circuit were as follows:

R1 = 7K
R2 = 200 (initially)
R4 = 16.17K
R5 = 34.39K
R6 = 15K

[0027] Taking the case where the Zener diode produced a voltage V_m = 4.52V at a temperature T_m of -350°C (-78°K), and assuming that the Zener TC is a positive α_1 = 1 volt/°C, it was found that for the above simulated circuit a 6V output at 27°C (room temperature) occurred when R2 was trimmed up to 694Ω. A subsequent temperature sweep of 180° about room temperature (i.e., above and below room temperature) resulted in a change in "Zener voltage" of about 360mV. The output voltage V_o changed only about 4 millivolts peak-to-peak, in a convex curve centered roughly about 6 volts, with the output lower than 6V at both ends of the curve. For a simulated Zener with a negative TC of -1/°C, a V_o of 6 volts at room temperature was obtained when R2 was trimmed to 4.56K. The output changed by only about 5mV peak-to-peak over the same 180° temperature sweep, in a curve which was inverted relative to the positive TC Zener curve.

[0028] In both cases, the value of R2 which made $V_o = V_m (1 + k)$ also resulted in zero TC (or nearly so), thus providing the desired auto-TC feature. Moreover, the circuit provided auto-TC for Zener diodes with either positive or negative TC.

[0029] With regard to providing an auto-TC feature, it may be noted that R1 can be chosen to give any nominal current through the feedback network at a given temperature. Since V_c has a TC proportional to its value, the TC of the current can be adjusted by adjusting V_C. Thus it is possible to independently choose the current and the TC of the current, over some range. This is what makes it possible to find a single value of R3 which compensates both the TC of V_o to zero (or nearly so) and simultaneously sets the output voltage at $(1 + k)V_m$.

[0030] To see what value of V_c will achieve this condition, first consider the case where the Zener has a voltage V_m and zero TC. In this case, it will not be necessary to adjust R3 away from zero, the feedback ratio will be (1 + k) at all temperatures, and both V_x and V_o will equal $(1 + k)V_m$.

[0031] If a Zener with a negative TC now is substituted so that the output V_o at room-temperature is lower, it will be necessary to increase R3 to bring V_o up to the desired $(1 + k)V_m$ and to give it a zero TC, assuming that V_c has been chosen properly to give auto-TC. Then, at the trimming temperature, the feedback ratio from the amplifier output will differ from 1 + k. As temperature changes, the resulting change in proportions of resistor voltage to voltage source (diode drops) in the feedback network will adjust the feedback ratio to keep V_o constant in the face of changing V_z.

[0032] If it is imagined that the temperature is changed to T_m (even though physically it might not be possible to do so), the voltage of the Zener should change to V_m, since the characteristic temperature response lines of all Zeners pass through this point (Figure 1). If R3 has been properly adjusted in the feedback, V_o should be at $(1 + k)V_m$ at any temperature, including T_m. However, if R3 is not zero, the ratio of the resistive parts of the feedback would not be (1 + k), although the voltage source component ratio always is.

[0033] The only way that these conditions can be satisfied simultaneously is if the current in the feedback resistors is zero at the imagined condition where $T = T_m$, so that the resistors' contribution to the feedback voltage ratio is zero. This requirement will be satisfied if $V_c = V_m$ at T_m. This means that the temperature-response characteristic of V_c is a straight line (assuming linear relations) having a negative TC and passing through the voltage V_m at temperature T_m. This is illustrated by the interrupted line 42 in Figure 1.

[0034] It is possible to construct a voltage source the behavior of which at circuit temperatures extrapolates to this required behavior at T_m. First, it is noted that a transistor V_{BE} has a negative TC and its voltage extrapolates to go through the bandgap voltage (approximately 1.2V) at 0°K. Choosing V_c to be a multiple of V_{BE} makes it possible to develop such a voltage which extrapolates to V_m at T_m. Using k times this multiple of V_{BE} as the voltage source in the upper segment 34B of the feedback completes the compensation so that trimming R3 to bring V_o to $(1 + k)V_m$ should also cause the TC of V_o to be zero.

[0035] In the Figure 3 configuration, the magnitude of V_c is set by the values of the resistors in the feedback network. In the example given above, where V_m = 4.52V, it is necessary to select the resistors so that the value of V_c at room temperature will, when extrapolated back to T_m (assuming, as always in this analysis, linear relationships) be 4.52V. In the Figure 3 circuit, the value V_c = 4.52V will be represented by the voltage across R5 and R6 (it being noted that at the temperature T_m with $V_c = V_m$ there will be no current through any of the feedback resistors). The total voltage across all three feedback resistors R4, R5 and R6 similarly will be 6V, since that is the selected output voltage. Thus the resistance ratio (R5 +R6)/R4 will be as follows:

$$\frac{R5 + R6}{R4} = \frac{4.52}{6 - 4.52} \cong 3.04$$

It will be seen that the V_{BE} multiplier should produce a total of about 4 V_{BE}s, with one V_{BE} across R6, about two V_{BE}s across R5, and about one V_{BE} across R4.

[0036] Now considering the conditions at room temperature, with R2 adjusted to provide an output V_o with zero TC at an output V_o of 6V, just as it was when the temperature was imagined to be at T_m, except that now current will be flowing through the feedback resistors. Since the V_{BE} multiplier voltage ratio of the two segments 32A, 34A is to be the same at room temperature as when at temperature T_m, the ratios of resistors R1 and R2 must conform to the previously determined ratio of resistors R5 + R6 to R4 in order that the output be 6V. That is: R2/R1 = (6 - 4.52)/4.52 . If R1 is set at 7K for practical reasons, then R2 (nominal) will be about 2.3K, for the nominal case when the Zener TC = 0. (Of course, the initial value of R2 will be much less, say about 200Ω, in order that it can be trimmed in one direction to cover all of the possible Zener characteristics from positive to negative TCs.)

[0037] Having determined the conditions for two operating points ($T = T_m$; T = room temperature) for an output of 6V with zero TC, it will be seen that the output V_o must also be 6V, with zero TC, at all other operating points. This is because the characteristics of all of the elements in the circuit have been assumed to be linear, so that their summation or differencing must also be a linear relationship.

[0038] To provide a more detailed mathematical explanation of these relationships, the following is presented with reference to Figure 4:

$$V_o = V_x + V_3$$

$$V_o = (V_m + \alpha_1(T-T_m)(1 + k) + (R3/R1)(\alpha_1 - \alpha_2)(T-T_m)$$
$$= V_m (1+k) = \alpha_1(T-T_m)(1+k) + (R3/R1)(\alpha_1 - \alpha_2)(T-T_m)$$

(where α_2 is the temperature coefficient of V_c)

[0039] The first term of this expression is the same as the nominal value of V_o for which the circuit is intended. To get V_o to the nominal value, R3 must be adjusted to make the remaining terms zero.

$$\alpha_1(T-T_m)(1+k) + (R3/R1)(\alpha_1 - \alpha_2)(T-T_m) = 0$$

[0040] The temperature dependence can be divided out with the factor ($T-T_m$) to give:

$$\alpha_1(1+k) + (R3/R1)(\alpha_1 - \alpha_2) = 0$$

$$(R3/R1)(\alpha_2 - \alpha_1) = \alpha_1(1+k)$$

$$R3 = R1(1+k)\alpha_1/(\alpha_2-\alpha_1)$$

[0041] This value of R3 should cause $V_o = V_m(1+k) = V_o$ (nominal) at all temperatures.

[0042] There are practical constraints however. V_c is not a battery, but something constructed of forward-biased diode drops. Therefore, it must have some bias current to operate which implies that the voltage across R1 must be positive for all operating temperatures and bias conditions. Presumably $T-T_m$ will always be positive, since T_m is often less than 0° Kelvin. Therefore the constraint that $(\alpha_1 - \alpha_2)(T-T_m) > 0$ requires that $\alpha_1 - \alpha_2 > 0$ or $\alpha_1 > \alpha_2$. Since it is desired to accommodate a range of α_1 which may be positive or negative, α_2 must be made more negative than the most negative value of α_1. That is, the TC of the compensating voltage must be more negative than the most negative Zener TC expected from the process.

[0043] Another constraint arises from the nature of R3. In practice, R3 can be made large by trimming R2 well beyond its nominal value $R2 = kR1$. It cannot be made more negative than the value of R2, however, since negative values of R3 are realized in practice by leaving R2 trimmed below its nominal value. Therefore:

$$R3 > -R2$$

Substituting $R2/k = R1$ in the expression for R3 gives:

$$R2((1/k)+1)\alpha_1/(\alpha_2 - \alpha_1) > -R2$$

Since R2 is always positive it may be divided out, and multiplying through by -1 will reverse the inequality and change the denominator to give:

$$(\alpha_1/k + \alpha_1)/(\alpha_1 - \alpha_2) < 1$$

Since $\alpha_1 - \alpha_2 > 0$

$$\alpha_1/k + \alpha_1 < \alpha_1 - \alpha_2$$

$$\alpha_1/k < -\alpha_2$$

Since α_2 is negative, $-\alpha_2$ will be positive, and assuming k is always positive $k > \alpha_1/(-\alpha_2)$

Since the denominator of the right side is positive, k will be constrained when α_1 is positive. For example, if the largest anticipated Zener TC $\alpha_1(\max) = +2mV/°C$ and $\alpha_2 = -6mV/°C$, then $k > 1/3$.

[0044] With reference to Figure 3, the base emitter voltage of the transistor will fall more-or-less linearly with temperature according to the relation:

$$V_{BE} = V_{GO} - \frac{T}{To}(V_{GO} - V_{BEO}) + \frac{KT}{q}\ln\frac{I}{Io} + \frac{mkT}{q}\ln\frac{To}{T}$$

The largest component of this expression is the second term which is linear in T. The third term usually reduces the effect of the fourth term, although the circuit described here does not force a strictly PTAT collector current as is often done in bandgap circuits.

[0045] Common practice, in uncorrected bandgap circuits, is to extrapolate V_{BE} back towards zero using a tangent to the curve at the center of the temperature range. This results in a 0 Kelvin voltage slightly higher than V_{GO}, but the number is useful in a linearized approximation to behavior of V_{BE} vs. temperature.

[0046] In the auto-TC circuit disclosed herein, it is necessary to extrapolate the behavior of V_{BE} back to T_m, the Zener temperature parameter. Using the design temperature value of V_{BE} and the TC at this temperature (or the slope inferred from V_{BE} and the 0 Kelvin extrapolation as otherwise determined), an extrapolated voltage for V_{BE} at T_m can be calculated. Denoting this value V_E, the ratio of V_m to V_E will determine the "number" of V_{BE}s to be produced across R5 and R6. The value of R6 can be selected from biasing considerations by determining how much of the total current in R1 can be diverted to R4, R5 and R6. Then, $R5 = R6\ ((V_m/V_E)-1)$. This will cause the voltage across R5 and R6 to approximate the function $V_m + \alpha_2(T-T_m)$ where α_2 is a multiple of the design temperature TC of V_{BE}. An error will result from the base current of the transistor Q4, but this will generally be small. If low β is a problem, the error can be reduced by using an integral number of diode connected transistors less than V_m/V_E, and multiplying only one to get any fractional part (see Figure 6).

[0047] The proper upper segment compensating voltage kV_c can be produced by making $R4 = k(R5 + R6)$, for the value of k selected to fit the design goals and previous constraints. Again a mix of diodes and one multiplied V_{BE} can reduce base current error. Given the nominal V_{BE} and its multiplied value, the nominal voltage across R1 can be calculated based on expected Zener voltage. This voltage together with the selected operating current for the V_{BE} multiplier determines R1. The nominal value of R2 is kR1; however, the actual value to use will depend on the expected negative values calculated for R3. Its trim range will then depend on the positive values for R3.

[0048] The circuit also can be analyzed by holding R2 constant (R3 = 0). It will be found from such analysis that the circuit can be trimmed by adjusting R1.

[0049] Figure 5 presents a detailed circuit diagram of a voltage reference in accordance with this invention and suitable for adaptation to IC format. A dashed-line box 20 indicates the operational amplifier, as shown in the somewhat simplified diagrams previously discussed. The feedback circuit 30A is of the V_{BE}-multiplier type described with reference to Figure 3. A start-up circuit 46 is provided in the usual way.

[0050] Figure 6 presents a modified form of feedback circuit 30C for the voltage reference of Figure 5, to reduce errors due to base current in the V_{BE} multiplier transistor Q4. In this modification a pair of diode-connected transistors Q10 and Q11 have been connected in series with the transistor Q4 to produce the required integral number of V_{BE}s, with the fractional part for the lower feedback segment being supplied by the V_{BE} multiplier across R5. Similarly, an additional transistor-connected diode Q5 has been inserted between R4 and R2 with the fractional part of V_{BE} for the upper segment appearing across R4. The voltage between the network junction point 36C and the top of R1 will be about 3-1/3 V_{BE}s. With this circuit the required extrapolated value for V_{BE} can be obtained with a smaller total resistance in the multiplier portion of the circuitry (i.e., R4 and R5), so the base current of Q4 will flow through a smaller resistance (R4), and thus cause less voltage error due to base current.

Claims

1. A temperature-compensated voltage reference for use with a class of Zener diodes made by a single process, said voltage reference comprising:

an amplifier (20) having input means and an output circuit for producing a reference voltage;
a Zener diode (24) of said class connected to said amplifier input means;
a feedback network (30) coupled to said output circuit;
said feedback network comprising first and second serial segments (32, 34), wherein said second segment is connected to the output circuit of the amplifier,
said first and second segments (32, 34) respectively including first and second resistance means;
means connecting an intermediate point between said serial segments (32, 34) to said input means to furnish thereto a feedback signal representing the voltage across said first voltage segment (32), said feedback signal being made to correspond to the Zener diode voltage supplied to said input means;
means developing a temperature-responsive voltage having a negative temperature coefficient being associated with said first segment to develop a temperature-responsive current in said first segment having a positive temperature coefficient;
characterized by
said current flowing through said first segment (32) equally flowing through said resistance means of said second segment (34) to produce a corresponding voltage drop thereacross;
the magnitude of the voltage produced in said second segment (34) being predeterminedly proportional to the

magnitude of the voltage produced in said first segment (32);

the values of said first and second resistance means being set to effect temperature compensation of that reference voltage to compensate for either a positive or a negative temperature coefficient of the Zener diode voltage such that the current in said first segment resistance means is in accordance with said Zener diode voltage and the temperature-responsive voltage developed by said temperature responsive voltage means associated with said first segment (32).

2. A temperature-compensated Zener-diode voltage reference as claimed in Claim 1, wherein the temperature-responsive voltage means of said first segment (32) is sized to be equal to said particular voltage level when extrapolated to said particular temperature.

3. A temperature-compensated Zener-diode voltage reference as claimed in Claim 1 or 2, wherein the temperature-coefficient of said temperature-responsive means of said first segment (32) is more negative than the most negative temperature coefficient expected from said class of Zener diodes.

4. A temperature-compensated Zener-diode voltage reference as claimed in any of Claims 1 to 3, wherein said feedback network comprises a bipolar transistor (Q4) with a V_{BE} multiplier circuit (40) so arranged that a first part of the total V_{BE} voltage is effectively in said first segment (32) and a second part is effectively in said second segment (34).

5. A temperature-compensated Zener-diode voltage reference as claimed in Claim 4, including at least one series diode (Q10, Q11) connected in said first segment (32) to provide for reduced resistances in said V_{BE} multiplier circuit (40) so as to reduce errors due to the base current of said transistor (Q4).

6. A temperature-compensated Zener-diode voltage reference as claimed in any of Claims 1 to 5 wherein the resistive element in said second segment (34) is trimmable to adjust the reference voltage to a predetermined nominal level while optimizing the temperature compensation of said reference voltage.

7. A temperature-compensated voltage reference as claimed in any of Claims 1 to 6, wherein the nominal values of said second segment resistance and the voltage of the second segment voltage-producing means are sized to be (1 + k) times the first segment resistance and the voltage of the first segment voltage-producing means, where "k" is a preselected constant.

8. A temperature-compensated Zener-diode voltage reference as claimed in any of claims 1 to 7, wherein the values of said first and second resistance means being set to produce a predetermined nominal reference voltage.

9. The method of temperature-compensating the voltage of a Zener-diode comprising:

directing to the input means of an amplifier (20) a voltage derived from the Zener-diode voltage, said amplifier having an output circuit producing a reference voltage; wherein
a feedback network (30) being coupled to said output circuit;
said feedback network comprising first and second serial segments (32, 34) wherein said second segment is connected to the output circuit of the amplifier,
said first and second segments (32, 34) respectively including first and second resistance means;
furnishing a feedback signal representing the voltage across said first voltage segment (32) to said input means, wherein means connect an intermediate point between said serial segments (32, 34) to said input means, said feedback signal being made to correspond to the Zener-diode voltage supplied to said input means;
developing a temperature-responsive current in said first segment having a positive temperature coefficient, wherein means developing a temperature-responsive voltage having a negative temperature coefficient are associated with said first segment,
characterized by
producing a voltage drop corresponding to said current flowing through said first segment (32) equally flowing through said resistance means of said second segment (34),
setting the magnitude of the voltage produced in said second segment (34) to be predeterminedly proportional to the magnitude of the voltage produced in said first segment (32);
setting the values of said first and second resistance means to effect temperature compensation of that reference voltage to compensate for either a positive or a negative temperature coefficient of the Zener-diode volt-

age such that the current in said first segment resistance means is in accordance with said Zener-diode voltage and the temperature-responsive voltage developed by said temperature responsive voltage means associated with said first segment (32).

10. The method of temperature-compensating the voltage of a Zener diode as claimed in Claim 9, including the step of trimming one of said resistance means to fix said output voltage at a preselected level.

11. The method of temperature-compensating the voltage of a Zener diode as claimed in Claim 10, including the step of trimming said one resistance means to produce a predetermined output voltage level and simultaneously effect optimal temperature compensation of that output voltage.

12. The method of temperature-compensating the voltage of a Zener diode as claimed in Claim 10 or 11, wherein the resistance means in said second segment is trimmed to produce said predetermined output voltage level.

13. The method of temperature-compensating the voltage of a Zener diode as claimed in any of Claims 9 to 12, wherein said class of diodes have temperature-responsive voltage characteristics all of which pass through a specific voltage at a specific temperature;

sizing the magnitude of said temperature-responsive voltage means in said first segment (32) to a value which when extrapolated back to said specific temperature, will be equal to said specific voltage.

14. The method of any of Claims 9 to 13 wherein said feedback current of said one segment (32) is controlled to be proportional to the difference between said Zener diode voltage and said first temperature-responsive voltage.

15. The method of any of Claims 9 to 14 wherein said negative feedback current is derived at least substantially from said amplifier output circuit.

16. The method of any of claims 9 to 15 setting the values of said first and second resistance means to produce a predetermined nominal reference voltage.

Patentansprüche

1. Temperaturkompensierte Spannungsreferenz zur Verwendung mit einer Klasse von Z-Dioden, die in einem einzigen Prozeß hergestellt werden, wobei die Spannungsreferenz aufweist:

einen Verstärker (20) mit einer Eingangseinrichtung und einer Ausgangsschaltung zum Erzeugen einer Referenzspannung;
eine Z-Diode (24) der Klasse, die mit der Verstärkereingangseinrichtung verbunden ist;
eine Rückkopplungsschaltung (30), die mit der Ausgangsschaltung gekoppelt ist;
wobei die Rückkopplungsschaltung ein erstes und zweites serielles Segment (32, 34) aufweist, wobei das zweite Segment mit der Ausgangsschaltung des Verstärkers verbunden ist,
wobei das erste und zweite Segment (32, 34) eine erste bzw. zweite Widerstandseinrichtung aufweist;
eine Einrichtung, die einen dazwischen liegenden Punkt zwischen den seriellen Segmenten (32, 34) mit der Eingangseinrichtung verbindet, um an diese ein Rückkopplungssignal zu übergeben, das die Spannung über dem ersten Spannungssegment (32) darstellt, wobei bewirkt wird, daß das Rückkopplungssignal der Z-Diodenspannung entspricht, die an die Eingangseinrichtung übergeben wird;
eine Einrichtung, die eine temperaturabhängige Spannung mit einem negativen Temperaturkoeffizienten entwickelt und dem ersten Segment zugeordnet ist, um einen temperaturabhängigen Strom in dem ersten Segment mit einem positiven Temperaturkoeffizienten zu entwickeln;
dadurch gekennzeichnet, daß
der Strom, der durch das erste Segment (32) fließt, gleichermaßen durch die Widerstandseinrichtung des zweiten Segments (34) fließt, um einen entsprechenden Spannungsabfall über dieser zu erzeugen;
die Größe der Spannung, die im zweiten Segment (34) erzeugt wird, vorbestimmt proportional zur Größe der Spannung ist, die im ersten Segment (32) erzeugt wird;
die Werte der ersten und zweiten Widerstandseinrichtung eingestellt werden, um eine Temperaturkompensation dieser Referenzspannung zu bewirken, um entweder einen positiven oder einen negativen Temperaturkoeffizienten der Z-Diodenspannung zu kompensieren, so daß der Strom in der Widerstandseinrichtung des ersten Segments der Z-Diodenspannung und der temperaturabhängigen Spannung, die von der temperatur-

abhängigen Spannungseinrichtung entwickelt wird, die dem ersten Segment (32) zugeordnet ist, entspricht.

2. Temperaturkompensierte Z-Diodenspannungsreferenz nach Anspruch 1, wobei die temperaturabhängige Spannungseinrichtung des ersten Segments (32) so bemessen ist, daß sie dem bestimmten Spannungspegel entspricht, wenn dieser bis zu der bestimmten Temperatur extrapoliert worden ist.

3. Temperaturkompensierte Z-Diodenspannungsreferenz nach Anspruch 1 oder 2, wobei der Temperaturkoeffizient der temperaturabhängigen Einrichtung des ersten Segments (32) negativer ist als der von der Klasse von Z-Dioden erwartete negativste Temperaturkoeffizient.

4. Temperaturkompensierte Z-Diodenspannungsreferenz nach einem der Ansprüche 1 bis 3, wobei die Rückkopplungsschaltung einen bipolaren Transistor (Q4) mit einer V_{BE}-Multipliziererschaltung (40) aufweist, die so angeordnet ist, daß ein erster Teil der V_{BE}-Gesamtspannung effektiv in dem ersten Segment (32) und ein zweiter Teil effektiv in dem zweiten Segment (34) ist.

5. Temperaturkompensierte Z-Diodenspannungsreferenz nach Anspruch 4, mit mindestens einer reihengeschalteten Diode (Q10, Q11), die in dem ersten Segment (32) so verbunden ist, daß für reduzierte Widerstände in der V_{BE}-Multipliziererschaltung (40) gesorgt wird, um Fehler aufgrund des Basisstroms des Transistors (Q4) zu reduzieren.

6. Temperaturkompensierte Z-Diodenspannungsreferenz nach einem der Ansprüche 1 bis 5, wobei das Widerstandselement in dem zweiten Segment (34) abstimmbar ist, um die Referenzspannung auf einen vorbestimmten Nennpegel einzustellen, wobei die Temperaturkompensation der Referenzspannung optimiert wird.

7. Temperaturkompensierte Spannungsreferenz nach einem der Ansprüche 1 bis 6, wobei die Nennwerte des Widerstands des zweiten Segments und der Spannung der Spannungserzeugungseinrichtung des zweiten Segments so bemessen sind, daß sie das (1 + k)-fache des Widerstands des ersten Segments und der Spannung der Spannungserzeugungseinrichtung des ersten Segments betragen, wobei "k" eine vorgewählte Konstante ist.

8. Temperaturkompensierte Z-Diodenspannungsreferenz nach einem der Ansprüche 1 bis 7, wobei die Werte der ersten und zweiten Widerstandseinrichtung eingestellt werden, um eine vorbestimmte Nennreferenzspannung zu erzeugen.

9. Verfahren zur Temperaturkompensation der Spannung einer Z-Diode mit den Schritten:

Leiten einer Spannung, die von der Z-Diodenspannung abgeleitet ist, zur Eingangseinrichtung des Verstärkers (20), wobei der Verstärker eine Ausgangsschaltung aufweist, die eine Referenzspannüng erzeugt; wobei eine Rückkopplungsschaltung (30), die mit der Ausgangsschaltung gekoppelt ist;
wobei die Rückkopplungsschaltung ein erstes und zweites serielles Segment (32, 34) aufweist, wobei das zweite Segment mit der Ausgangsschaltung des Verstärkers verbunden ist,
wobei das erste und zweite Segment (32, 34) eine erste bzw. zweite Widerstandseinrichtung aufweisen;
Liefern eines Rückkopplungssignals, das die Spannung über dem ersten Spannungssegment (32) darstellt, an die Eingangseinrichtung, wobei die Einrichtung einen dazwischen liegenden Punkt zwischen den seriellen Segmenten (32, 34) mit der Eingangseinrichtung verbindet, wobei bewirkt wird, daß das Rückkopplungssignal der Z-Diodenspannung entspricht, die an die Eingangseinrichtung übergeben wird;
Entwickeln eines temperaturabhängigen Stroms in dem ersten Segment mit einem positiven Temperaturkoeffizienten, wobei die Einrichtung, die eine temperaturabhängige Spannung mit einem negativen Temperaturkoeffizienten entwickelt, dem ersten Segment zugeordnet ist,
gekennzeichnet durch
Erzeugen eines Spannungsabfalis, der dem Strom entspricht, der durch das erste Segment (32) fließt und der gleichermaßen durch die Widerstandseinrichtung des zweiten Segments (34) fließt,
Einstellen der Größe der Spannung, die in dem zweiten Segment (34) erzeugt wird, so daß sie vorbestimmt proportional der Größe der Spannung ist, die in dem ersten Segment (32) erzeugt wird;
Einstellen des Wertes der ersten und zweiten Widerstandseinrichtung, um eine Temperaturkompensation dieser Referenzspannung zu bewirken, um entweder einen positiven oder negativen Temperaturkoeffizienten der Z-Diodenspannung zu kompensieren, so daß der Strom in der Widerstandseinrichtung des ersten Segments der Z-Diodenspannung und der temperaturabhängigen Spannung, die von der temperaturabhängigen Spannungseinrichtung entwickelt wird, die dem ersten Segment (32) zugeordnet ist, entspricht.

10. Verfahren zur Temperaturkompensation der Spannung einer Z-Diode nach Anspruch 9, mit dem Schritt des Abstimmens einer der Widerstandseinrichtungen, um die Ausgangsspannung auf einen vorgewählten Pegel festzulegen.

11. Verfahren zur Temperaturkompensation der Spannung einer Z-Diode nach Anspruch 10, mit dem Schritt des Abstimmens einer der Widerstandseinrichtungen, um einen vorbestimmten Ausgangsspannungspegel zu erzeugen und gleichzeitig eine optimale Temperaturkompensation dieser Ausgangsspannung zu bewirken.

12. Verfahren zur Temperaturkompensation der Spannung einer Z-Diode nach Anspruch 10 oder 11, wobei die Widerstandseinrichtung in dem zweiten Segment abgestimmt wird, um den vorbestimmten Ausgangsspannungspegel zu erzeugen.

13. Verfahren zur Temperaturkompensation der Spannung einer Z-Diode nach einem der Ansprüche 9 bis 12, wobei die Diodenklasse temueraturabhängige Spannungskurven hat, die alle bei einer spezifischen Temperatur durch eine spezifische Spannung laufen;

Bemessen der Größe der temperaturabhängigen Spannungseinrichtung in dem ersten Segment (32) auf einen Wert, der, wenn er bis zu der spezifischen Temperatur zurückextrapoliert wird, der spezifischen Spannung entspricht.

14. Verfahren nach einem der Ansprüche 9 bis 13, wobei der Rückkopplungsstrom des einen Segments (32) so gesteuert wird, daß er proportional der Differenz zwischen der Z-Diodenspannung und der ersten temperaturabhängigen Spannung ist.

15. Verfahren nach einem der Ansprüche 9 bis 14, wobei der negative Rückkopplungsstrom zumindest wesentlich von der Verstärkerausgangsschaltung abgeleitet wird.

16. Verfahren nach einem der Ansprüche 9 bis 15, wobei die Werte der ersten und der zweiten Widerstandseinrichtung eingestellt werden, um eine vorbestimmte Nennreferenzspannung zu erzeugen.

Revendications

1. Référence de tension compensée en température à utiliser avec une classe de diodes Zener fabriquée par un seul processus, ladite référence de tension comprenant:

un amplificateur (20) ayant des moyens d'entrée et un circuit de sortie permettant de produire une tension de référence;
une diode Zener (24) de ladite classe connectée auxdits moyens d'entrée de l'amplificateur;
un réseau de contre-réaction (30) couplé audit circuit de sortie;
ledit réseau de contre-réaction comprenant des premier et deuxième segments série (32, 34), dans lequel ledit deuxième segment est connecté au circuit de sortie de l'amplificateur;
lesdits premier et deuxième segments (32, 34) incluant respectivement des premier et deuxième moyens de résistance;
des moyens connectant un point intermédiaire entre lesdits segments série (32, 34) auxdits moyens d'entrée afin de fournir à ceux-ci un signal de contre-réaction représentant la tension à travers ledit premier segment de tension (32), ledit signal de contre-réaction étant fait pour correspondre à la tension de diode Zener fournie auxdits moyens d'entrée;
des moyens développant une tension sensible à la température ayant un coefficient de température négatif associé audit premier segment afin de développer un courant sensible à la température dans ledit premier segment ayant un coefficient de température positif;
caractérisée par
ledit courant circulant à travers ledit premier segment (32) circulant également à travers lesdits moyens de résistance dudit deuxième segment (34) afin de produire une chute de tension correspondante à travers ceux-ci;
l'amplitude de la tension produite dans ledit deuxième segment (34) étant proportionnelle de façon prédéterminée à l'amplitude de la tension produite dans ledit premier segment (32);
les valeurs desdits premier et deuxième moyens de résistance étant fixées afin d'effectuer une compensation en température de cette tension de référence afin de compenser un coefficient de température soit positif soit

négatif de la tension de diode Zener de telle manière que le courant dans ledit moyen de résistance du premier segment soit en accord avec ladite tension de diode Zener et la tension sensible à la température développée par lesdits moyens de tension sensibles à la température associés audit premier segment (32).

2. Référence de tension de diode Zener compensée en température selon la revendication 1, dans laquelle les moyens de tension sensibles à la température dudit premier segment (32) sont calibrés pour être égaux audit niveau de tension particulier lorsqu'ils sont extrapolés à ladite température particulière.

3. Référence de tension de diode Zener compensée en température selon la revendication 1 ou 2, dans laquelle le coefficient de température desdits moyens sensibles à la température dudit premier segment (32) est plus négatif que le coefficient de température le plus négatif prévu par ladite classe de diodes Zener.

4. Référence de tension de diode Zener compensée en température selon l'une quelconque des revendications 1 à 3, dans laquelle ledit réseau de contre-réaction comprend un transistor bipolaire (Q4) avec un circuit multiplieur de V_{BE} (40) monté de telle manière qu'une première partie de la tension V_{BE} totale soit effectivement dans ledit premier segment (32) et qu'une deuxième partie soit effectivement dans ledit deuxième segment (34).

5. Référence de tension de diode Zener compensée en température selon la revendication 4, incluant au moins une diode série (Q10, Q11) montée dans ledit premier segment (32) afin d'assurer des résistances réduites dans ledit circuit multiplieur de V_{BE} (40) de manière à réduire les erreurs dues au courant de base dudit transistor (Q4).

6. Référence de tension de diode Zener compensée en température selon l'une quelconque des revendications 1 à 5, dans laquelle l'élément résistif dans ledit deuxième segment (34) est ajustable afin de régler la tension de référence à un niveau nominal prédéterminé tout en optimisant la compensation en température de ladite tension de référence.

7. Référence de tension compensée en température selon l'une quelconque des revendications 1 à 6, dans laquelle les valeurs nominales de ladite résistance de deuxième segment et de la tension des moyens produisant la tension du deuxième segment sont calibrées pour être (1 + k) fois la résistance du premier segment et de la tension des moyens produisant la tension du premier segment, où "k" est une constante présélectionnée.

8. Référence de tension de diode Zener compensée en température selon l'une quelconque des revendications 1 à 7, dans laquelle les valeurs desdits premier et deuxième moyens de résistance sont fixées afin de produire une tension de référence nominale prédéterminée.

9. Procédé de compensation en température de la tension d'une diode Zener comprenant:

l'orientation vers les moyens d'entrée d'un amplificateur (20) d'une tension dérivée de la tension de diode Zener, ledit amplificateur ayant un circuit de sortie produisant une tension de référence; dans lequel
un réseau de contre-réaction (30) étant relié audit circuit de sortie;
ledit réseau de contre-réaction comprenant des premier et deuxième segments série (32, 34) dans lequel ledit deuxième segment est connecté au circuit de sortie de l'amplificateur,
lesdits premier et deuxième segments (32, 34) incluant respectivement des premier et deuxième moyens de résistance;
la fourniture d'un signal de contre-réaction représentant la tension à travers ledit premier segment de tension (32) auxdits moyens d'entrée, dans lequel des moyens connectent un point intermédiaire entre lesdits segments série (32, 34) auxdits moyens d'entrée, ledit signal de contre-réaction étant fait pour correspondre à la tension de diode Zener fournie auxdits moyens d'entrée;
le développement d'un courant sensible à la température dans ledit premier segment ayant un coefficient de température positif, dans lequel des moyens développant une tension sensible à la température ayant un coefficient de température négatif sont associés audit premier segment,
caractérisé par
la production d'une chute de tension correspondant audit courant circulant à travers ledit premier segment (32) circulant également à travers ledit moyen de résistance dudit deuxième segment (34),
la sélection de l'amplitude de la tension produite dans ledit deuxième segment (34) pour qu'elle soit proportionnelle de manière prédéterminée à l'amplitude de la tension produite dans ledit premier segment (32);
la détermination des valeurs desdits premier et deuxième moyens de résistance afin d'effectuer la compensation en température de cette tension de référence afin de compenser un coefficient de température soit positif

soit négatif de la tension de diode Zener de telle manière que le courant dans lesdits moyens de résistance du premier segment soit en accord avec ladite tension de diode Zener et la tension sensible à la température développée par lesdits moyens de tension sensibles à la température associés audit premier segment (32).

10. Procédé de compensation en température de la tension d'une diode Zener selon la revendication 9, incluant l'étape consistant à ajuster un desdits moyens de résistance afin de fixer ladite tension de sortie à un niveau présélectionné.

11. Procédé de compensation en température de la tension d'une diode Zener selon la revendication 10, incluant l'étape consistant à ajuster ce moyen de résistance afin de produire un seuil de tension de sortie prédéterminé et d'effectuer simultanément une compensation en température optimale de cette tension de sortie.

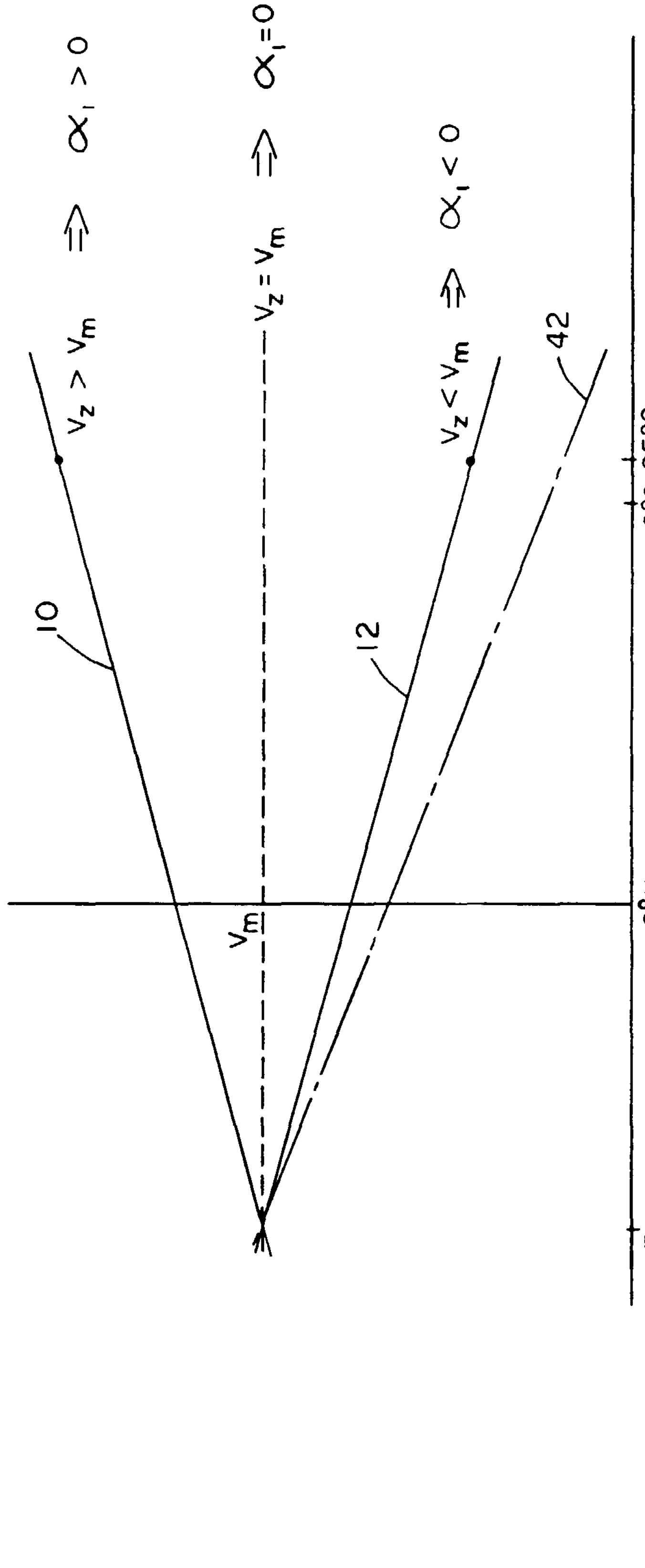
12. Procédé de compensation en température de la tension d'une diode Zener selon la revendication 10 ou 11, dans lequel le moyen de résistance dans ledit deuxième segment est ajusté afin de produire ledit niveau de tension de sortie prédéterminé.

13. Procédé de compensation en température de la tension d'une diode Zener selon l'une quelconque des revendications 9 à 12, dans lequel ladite classe de diodes a des caractéristiques de tension sensibles à la température qui passent toutes par une tension spécifique à une température spécifique; le calibrage de l'amplitude desdits moyens de tension sensibles à la température dans ledit premier segment (32) à une valeur qui, quand elle est extrapolée en arrière vers ladite température spécifique, sera égale à ladite tension spécifique.

14. Procédé selon l'une quelconque des revendications 9 à 13, dans lequel ledit courant de contre-réaction dudit premier segment (32) est commandé pour être proportionnel à la différence entre ladite tension de diode Zener et ladite première tension sensible à la température.

15. Procédé selon l'une quelconque des revendications 9 à 14, dans lequel ledit courant de contre-réaction négatif est dérivé au moins notablement dudit circuit de sortie de l'amplificateur.

16. Procédé selon l'une quelconque des revendications 9 à 15 fixant les valeurs desdits premier et deuxième moyens de résistance afin de produire une tension de référence nominale prédéterminée.



$V_z > V_m$ ⇒ $\alpha_1 > 0$
$V_z = V_m$ ⇒ $\alpha_1 = 0$
$V_z < V_m$ ⇒ $\alpha_1 < 0$
10
12
42
V_m
0°K
0°C 25°C
T_m

FIG. 1

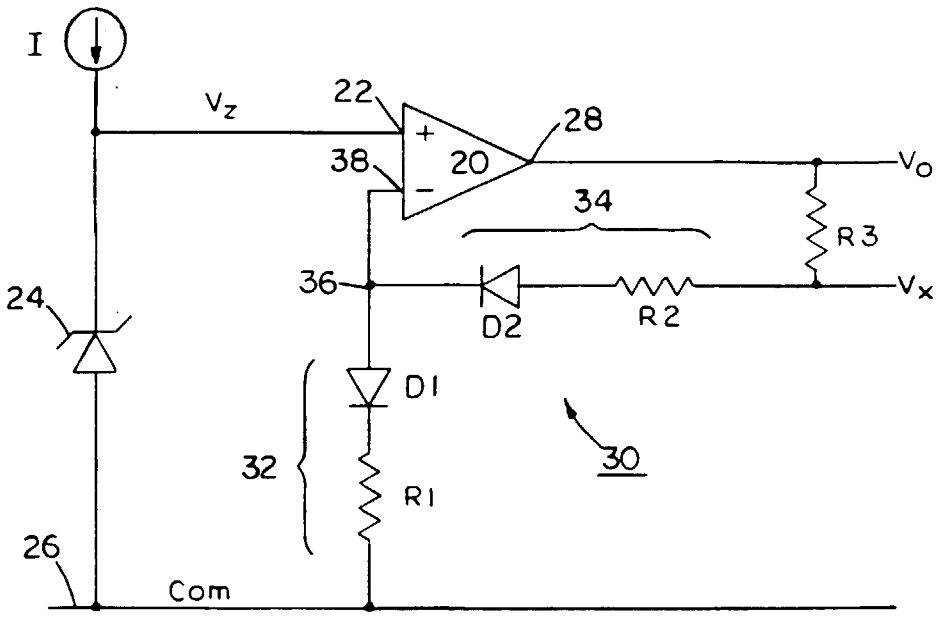

I
Vz
22
28
38
20
Vo
34
R3
36
Vx
24
D2
R2
D1
32
R1
30
26
Com

FIG. 2

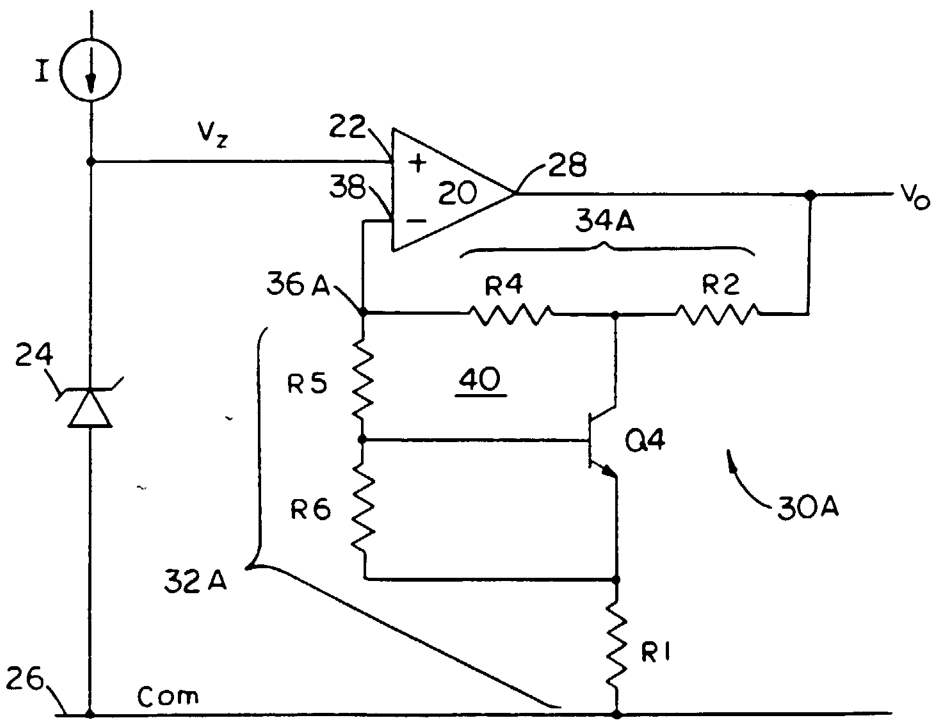

I
Vz
22
28
38
20
Vo
34A
36 A
R4
R2
24
R5
40
Q4
30A
R6
32 A
R1
26
Com

FIG. 3

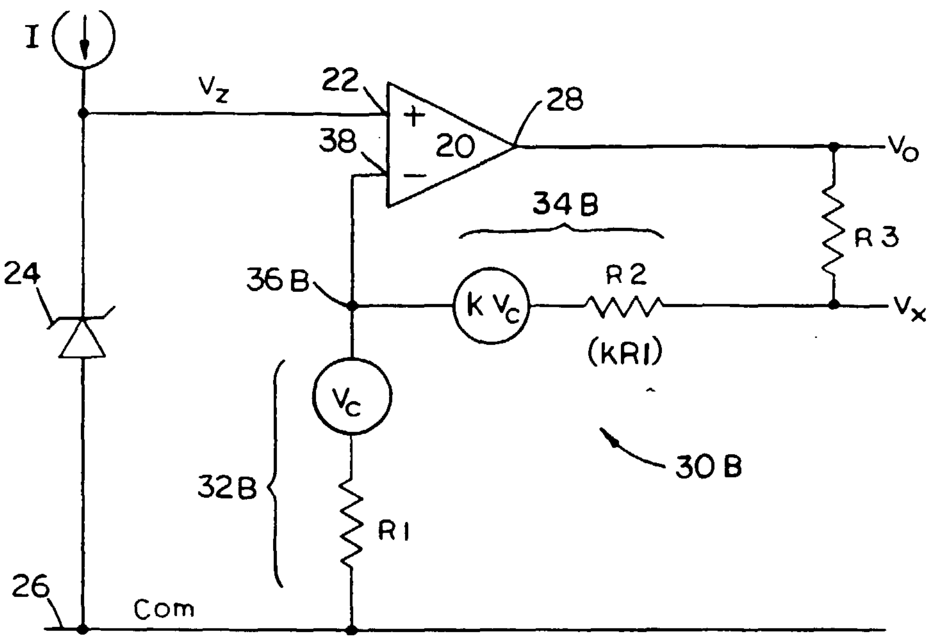

I
Vz
22
28
+
20
38
−
Vo
34 B
R 3
24
36 B
K Vc
R 2
Vx
(KR1)
Vc
30 B
32B
R1
26
Com

FIG. 4

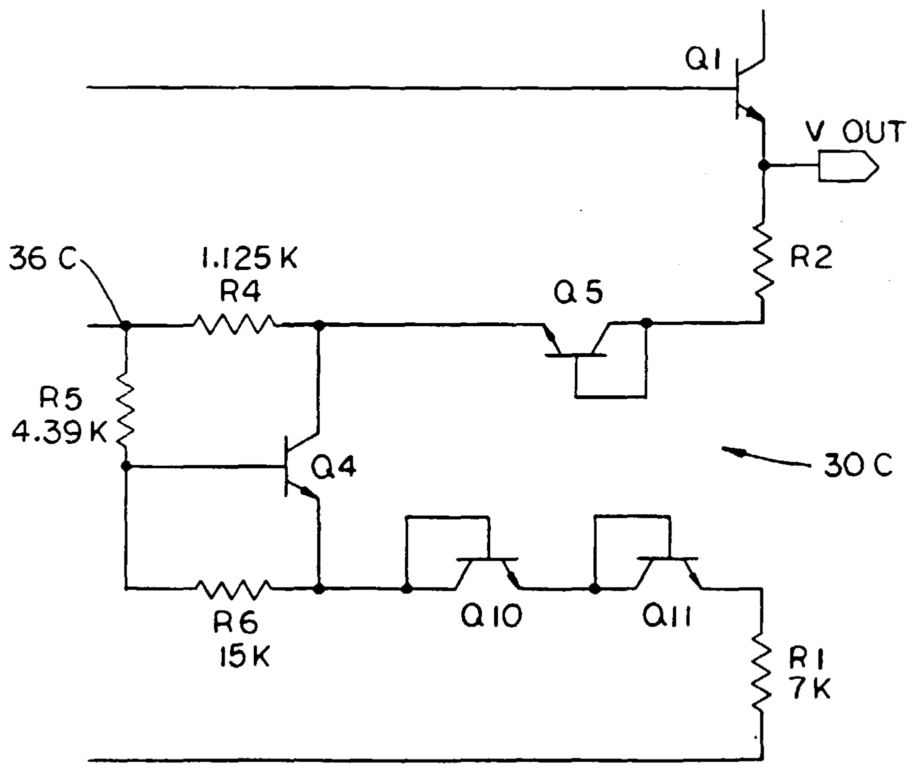

Q1
V OUT
R2
36 C
1.125 K
R4
Q 5
R5
4.39 K
Q4
30 C
R6
15K
Q10
Q11
R1
7K

FIG. 6

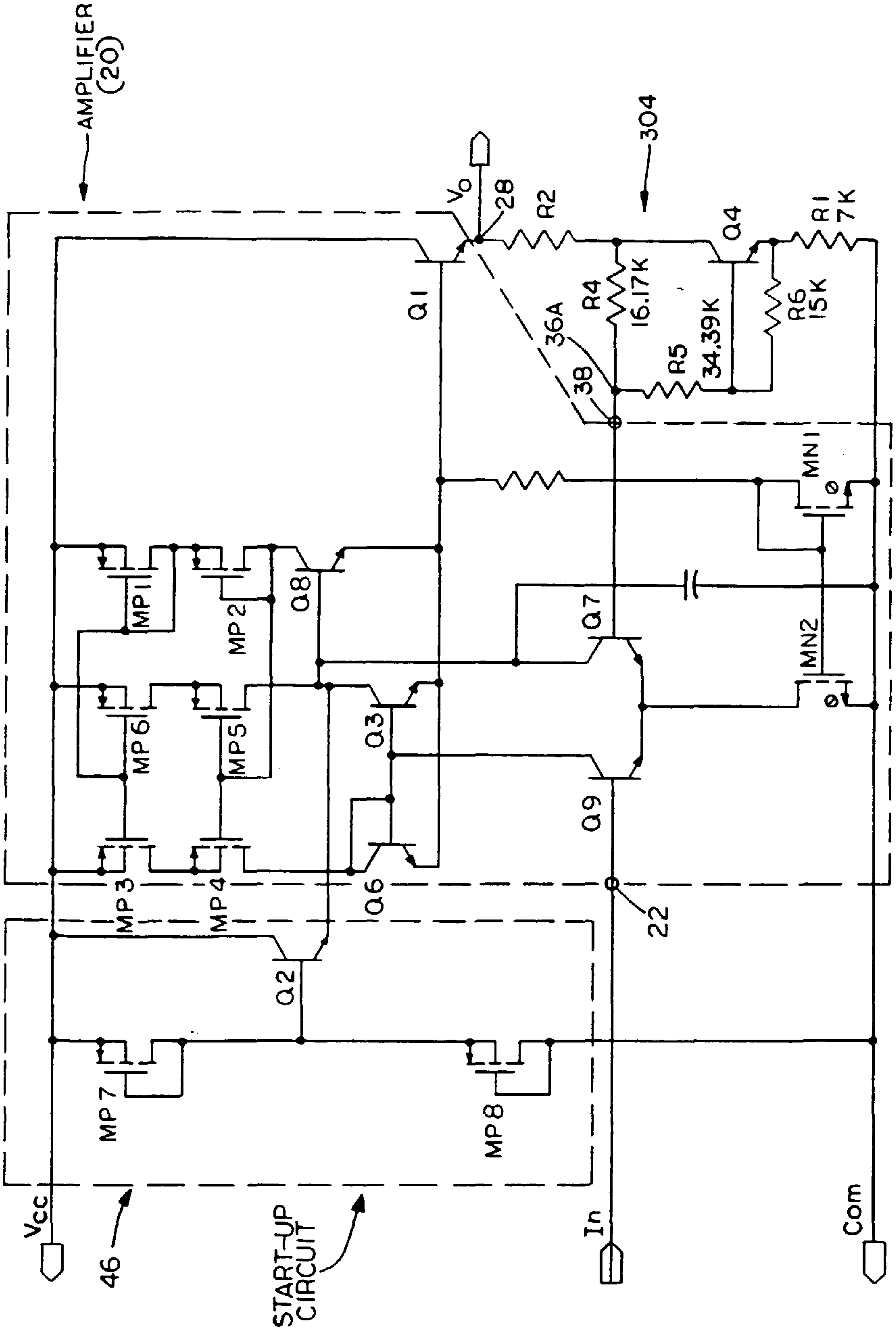

AMPLIFIER
(20)
304
Vo
28
R2
Q1
Q4
R1
7K
R4
16.17K
R6
15K
36A
38
R5
34.39K
MN1
Q8
MP1
MP2
Q7
MN2
MP6
MP5
Q3
Q9
MP3
MP4
Q6
22
Q2
MP7
MP8
Vcc
46
START-UP
CIRCUIT
In
Com

FIG. 5