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(54) OPERATIONAL AMPLIFIER

(71) We, RCA CORPORATION, formerly Radio Corporation of America, a corporation organized under the laws of the State of Delaware, United State of America, of 30 Rockefeller Plaza, City and State of New York, 10020, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to amplifier circuits and more particularly to amplifier circuits especially suited for integrated circuit techniques.

Integrated circuit amplifiers of the type referred to as operational amplifiers have been made using integrated circuit techniques. However, the ability to use these amplifiers in different circuit environments has been limited. The integrated circuit designer generally establishes the voltage gain versus frequency response to criteria determined by an expected application. Input and output impedances are a fixed part of the circuit design included on the integrated circuit semiconductor wafer. Therefore, many operational amplifiers have been designed for specific different applications which respectively require high or low input impedance, low or high voltage gain, high or low power output for various loads.

Feedback circuit design for operational amplifiers has provided some flexibility in application. However, the voltage gain, as well as the frequency response characteristic places strict limits on the adaptability to various applications due to the possibility of instability or self-oscillation.

Operational amplifiers as defined in textbooks have high input impedance, low output impedance and a characteristic voltage gain. Additionally, the voltage gain and phase shift as a function of frequency must be designated to permit the use of negative feedback circuits with stable operation. Operational amplifier performance with feedback circuits has traditionally been described in textbooks by

formulas in terms of the voltage gain characteristic. This characteristic has been relied upon because amplifiers usually have a load resistor integral to the amplifier which defined the available voltage gain.

For a high level of voltage gain, a large-value load resistor is conventionally used. However, this generally requires higher supply voltages which has the disadvantage of increasing device power consumption. For integrated circuits, large resistors in normally critical circuit areas such as collector loads also would require the "base-diffusion resistor". The physical size of this integrated resistor is directly proportional to its value. Thus, a large value resistor of this kind would use more area and increase the cost of the final integrated circuit.

It would be possible to use integrated circuit operational amplifiers for many more purposes of performance characteristics of the integrated amplifier could be adapted to the needs of an application by means external to the encapsulation.

A differential amplifier incorporating the principles of the present invention preferably uses an active load for input differential amplifier stages which can be used to develop the necessary voltage gain at low collector currents. This approach permits a design that will provide high voltage gain with low power consumption.

To accomplish this objective, an operational amplifier has been developed incorporating a novel differential amplifier as an input circuit. Input impedance may be varied over a very wide range by varying the input amplifier stage currents. Voltage gain is determined by an externally connected load resistor in addition to the control on transistor operating current. High common mode rejection is exhibited by the circuit.

According to the present invention there is provided an amplifier having a first differential amplifier comprising first and second transistors with their emitter electrodes coupled in common to a first source of direct current, their base electrodes coupled to out-

puts of respective input amplifier stages and their collector electrodes provided terminals for extraction of signal and application of operating potential; a third transistor connected as a common-emitter amplifier stage coupling said emitter electrode of said first transistor to its said base electrode; and a fourth transistor connected as a common-emitter amplifier stage coupling said emitter electrode of said second transistor to its said base electrode; there being means coupling the base electrodes of said third and fourth transistors together.

In the accompanying drawings:

FIGURE 1 is a schematic circuit diagram of a differential amplifier embodying the principles of the present invention;

FIGURE 2 is a schematic diagram of the differential amplifier of FIGURE 1 including a high gain input amplifier stage and biasing network; and

FIGURE 3 is a schematic diagram of an operational amplifier including the differential amplifier of FIGURE 1.

Referring to the drawings, and more particularly to FIGURE 1, all of the elements shown within the dashed rectangle 10 are formed as an integrated circuit on a single semiconductor wafer. The integrated circuit is a differential amplifier including a pair of transistors 11 and 12, a current source transistor 13, and an active load circuit comprising the five transistors 14, 15, 16 and 17 and diode 18. An external source of current, not shown, may be coupled between terminal 19 and common terminal 20 to establish a voltage across diode 21, the diode 21 being connected between the base and emitter electrodes of transistor 13.

The diode 21 comprises a transistor with its collector and base electrodes connected together. Since transistors 13 and diode 21 are formed on the same semiconductor wafer at the same time during fabrication, their electrical characteristics will be accurately matched. If the transistor 13 and diode 21 are equal area devices as fabricated on a single semiconductor wafer, the emitter current injections into the base regions will be equal.

The current flow which forward biases transistor 13 and diode 21 establishes equal base-emitter voltage drops and, therefore, equal emitter currents. The emitter current in transistor 13 is equal to the sum of its base and collector currents and most of the emitter current flows to its collector.

The current flow between terminal 19 and 20 is equal to the emitter current of diode 21, plus the small base current into transistor 13. Due to the high ratio between base and collector currents in transistor 13 and the equal areas of the transistor 13 and diode 21, the current flow between terminal 19 and 20 and the current in the collector of

transistor 13 are substantially equal. Therefore, the current supplied by the current source transistor 13 is easily and accurately determined by the parameters of an external source, not shown, which may be connected between terminal 19 and common reference terminal 20.

The combination of a diode connected transistor between the base and emitter electrodes of a second transistor will be referred to as a diode-transistor composite. The voltage drop developed between the base and emitter electrodes of a transistor when the transistor is subjected to a significant forward bias current will herein be referred to as V_{be} .

The collector current of transistor 13 is supplied to the emitter electrodes of transistors 11 and 12. The current will divide between the transistors 11 and 12, depending upon the difference of signal input voltages applied to the base electrodes of transistors 11 and 12 via input terminals 22 and 23, respectively. If the voltages applied to the input terminals 22 and 23 are equal, the current supplied by the transistor 13 will divide equally between the transistors 11 and 12. That is because the transistors 11 and 12 also have equal characteristics since they are fabricated in the same integrated circuit chip at the same time.

The active load circuit comprising transistors 14, 15, 16 and 17 connects the collector electrodes of transistors 11 and 12 to a source of operating potential (not shown) connected between terminal 24 and 20. Transistors 14, 15, 16 and 17 are opposite conductivity types compared to transistors 11 and 12.

The transistors 14 and 15 are connected in series with transistors 11 and 12 respectively. The transistors 16 and 17 which are connected in a differential configuration, have their emitter electrodes connected in common to the base electrodes of transistors 14 and 15, and through a diode connected transistor 18 to the operating potential supply terminal 24. The base electrodes of the transistors 16 and 17 are connected respectively to the collector electrodes of transistors 11 and 12.

The collector electrode of transistor 16 is connected through a diode connected transistor 25 to the reference terminal 20. The diode 25 is connected between the base and emitter electrodes of an output transistor 26. The transistor 26 and the transistor 17 which are opposite conductivity types are connected in series, and an output terminal 27 is connected to the collector electrodes of these transistors.

The connection of the transistors 14, 16, 15 and 17 provides a mechanism whereby the conductances of transistors 14 and 15 are automatically set to accommodate the current from transistor 13, which is established by

the external source connected between terminals 19 and 20. This is brought about because the base drive for transistors 14 and 15 is controlled by the transistors 16 and 17 as functions of the current through transistors 11 and 12. Even though the current through transistor 13 may be established at any point in a relatively wide range of currents, the voltage across the load transistors 14 and 15 does not change appreciably. The collector-to-emitter voltage of transistor 14 is $2V_{be}$, which is the sum of the voltage across the base-emitter junctions of transistors 14 and 16. Similarly, the collector-to-emitter voltage of transistor 15 is $2V_{be}$ due to the voltage across the base-emitter junctions of transistors 15 and 17. As a result, insignificant common mode signal voltage is developed across transistors 14 and 15. This degeneration is ineffective for differential mode signals, because the bases of transistors 14 and 15 are commoned, and thus cannot communicate the two opposite signals of a differential mode.

The collector impedance of transistors 14 and 15 is relatively low for common mode current in that the collector-to-emitter voltage of these transistors is substantially constant for a wide change in common mode current. For differential currents, the transistors 16 and 17 have equal and opposite changes in current so that the base drive to transistors 14 and 15 remains equal and unchanged. As a result, the collector impedance of transistors 14 and 15 to differential mode currents is very high, and substantially all of the differential mode current flows through the base-emitter paths of transistors 16 and 17.

The load circuit as described provides a modulated conductance in accordance with common mode current changes and provides a high load impedance for differential current flow. This load circuit provides common mode signal rejection over and above the common mode rejection normally provided by differential amplifier circuit configurations.

As mentioned above, transistors 16 and 17 are connected with their emitters in common and operate as a second differential amplifier. The amplitude of the collector currents of this differential amplifier is equal to beta times the difference signal current applied to its base electrodes. A transistor connected as a diode 18 is shown in FIGURE 1 connected in series with the emitter collector current path of transistors 16 and 17 and between the base and emitter electrodes of both transistor 14 and transistor 15.

Diode 18 is forward biased by the common mode emitter collector current of transistors 16 and 17 and forms in conjunction with transistor 14 and 15 a diode-transistor composite. When the junction area of diode 18 is made twice the junction area of transistor

14 and transistor 15, then a current flow of two microamperes in diode 18 will establish one microampere current flow in each of transistors 14 and 15.

By way of example, if a two microampere bias current is established in diode 21, one microampere will flow in each of the transistors 11 and 12, and one microampere will flow in each of transistors 14 and 15. Since the diode 18 junction area is twice the base-emitter junction area of transistor 14 and 15 and series connected with transistors 16 and 17, the current in diode 18 is two microamperes and equals the sum of one microampere in each of the transistors 16 and 17.

The transistor connected as a diode 25 and transistor 26 form a diode-transistor composite having a current gain of unity. Equal quiescent currents flowing from the collectors of transistors 16 and 17 establish a collector current in transistor 26 equal to the transistor 16 collector current. The output impedance of the collectors of transistors 17 and 26 may be very high dependent on the device fabrication. A load circuit for transistors 17 and 26 is then coupled to an output terminal 27 which is connected in common to the collectors of transistors 17 and 26.

As described above, wide ranges in operating current may be established in transistors 11, 12, 13, 14, 15, 16, 17, 18, 25 and 26. By way of example, the integrated circuit of FIGURE 1 has been operated in the range of emitter-to-collector current of 20 nanoamperes to 400 microamperes.

Since the output collector impedance of transistors 17 and 26 is high, the voltage gain of the operational amplifier is determined by the external load resistance used and may be determined by computation using the transconductance of the amplifier. The transconductance can be defined as the change in output current for a change in differential voltage across the input terminals 22 and 23.

The transconductance (g_m) of that portion of the differential amplifier including only transistors 11 and 12 is

$$g_m = \frac{39 \times I_e \text{ mho}}{2}$$

where I_e is the emitter current for one of the transistors 11 and 12 in amperes; and where the transconductance is defined as the change in one collector output current for a change in voltage between terminals 22 and 23.

Since the differential collector current flows through the base emitter paths of transistors 16 and 17, transistors 16 and 17 contribute a beta multiplier to the current gain of the differential amplifier. The output current of transistor 16 flows through the diode 25 to develop an equal and opposite phase output

from transistor 26. The output current from transistor 17 then combines with the output current from transistor 26 to drive a load coupled to them through terminal 27. The overall transconductance then is:

$$g_m = 39 \beta I_e \text{ mho}$$

where β is the beta of transistors 16 and 17, and I_e is the emitter current of one of transistors 11 and 12.

- 10 An example of the amplifier transconductance available at a transistor 11 current of 1 microampere, if the beta of transistor 16 equals 50 is:

$$g_m = 39 \times 50 \times 1 \times 10^{-6} \text{ mho} = 1950 \text{ micro mho.}$$

- 15 The voltage gain is then simply output voltage divided by input voltage or:

$$\frac{V_o}{V_i} = g_m R_L$$

where R_L is the output load resistance connected to terminal 27.

- 20 The maximum common mode input which upsets the operation of the differential amplifier input stage is determined by the sustaining voltage characteristics of the current source comprising transistor 13 and the required voltage drop across the load transistors 14 and 15 which both subtract from the available voltage of the supply. In the circuit shown in FIGURE 1, input common mode voltages at terminals 22 and 23 may swing to a negative limit equal to the negative source voltage at terminal 20 plus 0.8 Volt and to a positive signal limit of the positive source voltage at terminal 24 minus 1.4 Volts without upsetting differential amplifier operation.

- 35 Maximum common mode input is primarily determined by supply voltage reduced by very small magnitudes since both the source transistor 13 and the load transistors 14 and 15 require very small voltage drops for effective operation.

- 40 FIGURE 2 shows a differential amplifier including cascode connected pairs of transistors 28, 29 and 30, 31 which provide improved common mode rejection and improved low noise operation. Transistors 28 and 30 are special design input amplifier transistors coupled to input terminals 22' and 23'. Transistors 28 and 30 are high beta (super beta) transistors having beta values of the order of 1000 and very low collector to emitter breakdown voltages of the order of one volt. In conventional higher voltage transistors, the beta of the transistor is substantially constant as a function of collector voltage in the low voltage range of operation. However, at higher voltages in the range of values approaching $V_{ce0.9}$ collector current is both a function of

base current and also collector voltage. $V_{ce0.9}$ is defined as the collector-to-emitter breakdown voltage with the base electrode open circuit and unconnected.

Transistors in general are characterized by a collector-to-base leakage current proportional to the collector to base voltage for values less than 50 millivolt. This collector-to-base leakage characteristic contributes to poor noise performance for small signal inputs and has an undesirable temperature dependence characteristic.

Poor noise performance and temperature dependence is suppressed by a unique bias circuit which not only establishes a relatively fixed low collector voltage for operation of transistors 28 and 30 but establishes essentially zero collector to base voltage in transistors 28 and 30, such that the collector to base leakage current is also reduced to zero. Noise performance is greatly enhanced and use of the high beta transistor is, therefore, possible in the input stage of an operational amplifier.

Transistors 28, 29 and 30, 31 are cascode connected wherein 28 and 30 are operated common emitter deriving emitter current from source transistor 13' which may be similar to that described in FIGURE 1. Transistors 29 and 31 are operated common base wherein the base electrodes are returned to the emitters of transistors 28 and 30 through a bias supply comprising transistors 32 and 33 connected as diodes. The collector output of transistors 29 and 31 is coupled to a load circuit comprising transistors 14', 15', 16', 17', and 18' similar to that described in FIGURE 1.

Diodes 32 and 33 are forward biased and develop $2V_{be}$ of bias between the commonly connected base electrodes of transistors 29 and 31 and the emitters of transistors 28 and 30. The voltage drop across the base-emitter junction of transistors 29 and 31 is one V_{be} so that one V_{be} is developed between the collector and emitter electrodes of transistors 28 and 30. The transistors 28 and 30 are biased to conduct so that one V_{be} of forward bias voltage is developed between the base and emitter electrodes thereof. Negligible voltage then appears between the collector and base of transistors 28 and 30 resulting in very low leakage current as discussed above.

To minimize the voltage between the collector and base electrodes of transistors 28 and 30, the base-emitter junction areas of transistors 29, 31 and 33 are made equal and processed identically, and transistor 32 is a high beta and low breakdown device of equal area and processed identically to high beta transistors 28 and 30. The average currents passed through the two paths 28, 29 and 30, 31 are each made equal to the current through diodes 33, 32.

The V_{be} voltage drops across collector-to-

emitter of transistors 28, 30 are equal to one V_{be} voltage drop as developed across ultra high beta transistor 32. Since the base-to-emitter voltage of transistors 28 and 30 is also equal to the V_{be} voltage as developed across diode 32, there is zero voltage drop between the collector and base electrodes of transistors 28 and 30.

The bias supply comprising diodes 32 and 33 is energized by current supplied by an additional transistor 34 which is forward biased by the voltage drop across diode 18'. The junction area ratio of diode 18' to the base emitter junction of transistor 34 establishes the current flowing through diodes 32 and 33 which must also flow into source transistor 13'. Therefore, the base-emitter junction of source transistor 13' is made 50 percent larger in area than transistor 13 as described in FIGURE 1 because it must supply 50 percent more current.

With 3 microamperes flowing in transistor 13', one microampere flows in each of the transistors 28 and 30 and in diode 32. The current in transistor 14' and 15' is one microampere each and transistors 16' and 17' each conduct one microampere. With transistors 16' and 17' each conducting one microampere, diode 18' conducts two microamperes.

The transistor 34 base-emitter junction area is half that of diode 18 and thus is caused to conduct one microampere which then flows through bias diodes 32, and 33. The magnitude of all these currents is controlled from the single input terminal 19' where bias current is supplied to diode 21' to control the current supplied by transistor 13'.

When a source voltage is applied to terminals 24' and 20' and an operating bias is applied to diode 21', transistor 13' will conduct current into transistors 28 and 30. However, upon the application of a source to terminals 24' and 20', no initial bias current will be supplied to the bias diodes 32 and 33 to cause conduction in transistors 29 and 31 and therefore, no conduction will occur in transistors 14, 15 and 18'.

In the absence of diode 18' conduction and therefore conduction in transistor 34, zero collector-to-emitter voltage will be developed across transistors 28 and 30. Therefore, in the absence of collector-to-emitter voltage, all current flow from transistor 13' will flow in the base emitter path of transistors 28 and 30 and into signal sources coupled to terminals 22' and 23'.

To provide initial conduction in diode 18', a small area transistor 41 is added having its base emitter input coupled across diode 21' and having its collector connected to diode 18'. Transistor 41 need only supply a very small start current to diode 18' to initiate the turn on cycle and its current contribution need only be so small that it need not inter-

fere with the area ratio specification of diode 18' and transistors 14, 15, 16 and 17.

Since the voltage drop across transistors 28 and 30 is low, peak-to-peak common mode input voltages at terminals 22' and 23' may be nearly as large as the power supply voltage used without affecting the operation of the amplifier as previously described.

With a high beta input transistor, input impedances are correspondingly higher such that higher emitter current may be developed in a given application and, therefore, higher transconductance may be established consistent with the high emitter current. Betas in the range of 1000 have been attained with satisfactory low noise performance. This practical performance depends on the two factors: (1) that of maintaining constant collector voltage to within a narrow range; and (2) that of establishing zero collector-to-base voltage for zero leakage currents.

High orders of common mode rejection are maintained because the use of integrated circuits results in easy achievement of balance between the two halves of the differential amplifier. The transistor construction used to fabricate the PNP transistors in integrated circuit form is a lateral construction along the surface of the semiconductor wafer. PNP laterals are characterized by low beta and by emitter-to-collector currents which are a function of emitter-to-collector voltage. Therefore, the gain of transistor 17' may be a function of output voltage signal swing upsetting the balance of equal gain in transistors 16' and 17'. However, for relatively low output voltage swings, which may be achieved using a relatively low output impedance load connected to terminal 27', the balance between the differential halves will be preserved.

FIGURE 3 shows an additional pair of cascode connections of transistors 16'' and 17'' with transistors 35 and 36 to establish constant collector-to-emitter voltage in transistors 16'' and 17'' to maintain equal gain in each half of the differential amplifier. A bias circuit comprising diodes 37, 38 and 39 provides base bias for transistors 35 and 36 when a current flows in the diodes derived from a second current source transistor 40.

The magnitude of bias current through the diodes 37, 38 and 39 is not critical for providing base voltage to transistors 35 and 36. However, by biasing transistor 40 from diode 21'' as is the case of transistor 13'' in FIGURE 2, the current in diodes 37, 38 and 39 can be made to track the currents in all the other transistors.

A start circuit including transistor 41' is included to provide start current as described in reference to FIGURE 2. A low bias current can be set for low dissipation operation when all the other transistors are so operated and

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conversely a high current for high current operation.

Transistors 35 and 36 are coupled to the output terminal 27'' by means of a diode 25''-transistor 26'' composite as described with respect to FIGURE 1 to drive a load in an unbalanced manner, when connected between terminal 27'' and a potential reference. The amplifier is characterized as having a transconductance gain factor since the voltage gain is determined by the external load used. Such operation establishes an additional degree of freedom for the user greatly increasing the range of applicability to diverse function problems.

WHAT WE CLAIM IS:—

1. An amplifier having a first differential amplifier comprising first and second transistors with their emitter electrodes coupled in common to a first source of direct current, their base electrodes coupled to outputs of respective input amplifier stages and their collector electrodes provided terminals for extraction of signal and application of operating potential; a third transistor connected as a common-emitter amplifier stage coupling said emitter electrode of said first transistor to its said base electrode; and a fourth transistor connected as a common-emitter amplifier stage coupling said emitter electrode of said second transistor to its said base electrode; there being means coupling the base electrodes of said third and fourth transistors together.

2. An amplifier as claimed in claim 1, wherein said first source of direct current comprises a semiconductor rectifier connected in parallel with the emitter to base junctions of said third and fourth transistors between a source of operating potential and said coupling to said emitter electrodes of said first and second transistors.

3. An amplifier as claimed in claim 1 or 2, wherein said first and second signal sources comprise fifth and sixth transistors each in an amplifier configuration with signal input across its base-emitter junction and signal output provided from its collector electrode, said third and fifth transistors being opposite conductivity types and having their collector-to-emitter current paths connected in series, and said fourth and sixth transistors being opposite conductivity types having their collector-to-emitter paths connected in series.

4. An amplifier as claimed in claim 3, wherein said fifth and sixth transistors have their emitter electrodes coupled to each other and to a current source and have signal input across their base electrodes.

5. An amplifier as claimed in claim 3, wherein seventh and eighth transistors of same conductivity type as said fifth and sixth transistors have their emitter electrodes coupled to each other and to a junction point

coupling to a current source, have signal input across their base electrodes, and have their respective collector electrodes coupled to separate emitter electrodes of said fifth and sixth transistors; and having a voltage regulator coupling the base electrodes of said fifth and sixth transistors to said junction point, said voltage regulator providing potential offset proportional to and approximately twice that of a forward biased semiconductor junction.

6. An amplifier as claimed in claim 5, wherein each of said seventh and eighth transistors is a high-beta transistor having a breakdown on the order of 1 volt.

7. An amplifier as claimed in claim 5 or 6, wherein said voltage regulator comprises two semiconductor rectifiers in series.

8. An amplifier as claimed in any of the previous claims, wherein said collector electrode of said second transistor is coupled through a first common-base transistor amplifier to its load.

9. An amplifier as claimed in any of the previous claims, wherein said collector electrode of said first transistor is coupled through a second common-base transistor amplifier to its load, said first and second common-base amplifier transistors having their base electrodes connected to a single bias potential source.

10. An amplifier as claimed in any of the prior claims, having a current amplifier having a signal transfer factor substantially equal to -1 , having input coupled from the collector electrode of said first transistor, and delivering output coupled to an output terminal to which said collector electrode of said second transistor is also coupled.

11. An amplifier as claimed in claim 10, using a current-amplifier transistor having a semiconductor rectifier coupled in parallel with its base-emitter junction, the emitter electrode of said current amplifier transistor being connected to a reference potential, the base electrode of said current-amplifier transistor being coupled to receive input current signals from the collector electrode of said first transistor, the collector electrodes of said current-amplifier and second transistors being coupled to a terminal from which output signals may be taken.

12. An amplifier as claimed in any of the prior claims, wherein of said couplings not specified as being otherwise at least one comprises a direct connection.

13. An amplifier comprising first and second transistors of a first conductivity type and connected as an emitter-coupled differential amplifier; third and fourth transistors of a second conductivity type and each connected as a common-emitter amplifier, the collector electrodes of said first and said third transistors being direct current conductively coupled together, the collector elec-



conversely a high current for high current operation.

- Transistors 35 and 36 are coupled to the output terminal 27'' by means of a diode 25''-transistor 26'' composite as described with respect to FIGURE 1 to drive a load in an unbalanced manner, when connected between terminal 27'' and a potential reference. The amplifier is characterized as having a transconductance gain factor since the voltage gain is determined by the external load used. Such operation establishes an additional degree of freedom for the user greatly increasing the range of applicability to diverse function problems.

WHAT WE CLAIM IS:—

1. An amplifier having a first differential amplifier comprising first and second transistors with their emitter electrodes coupled in common to a first source of direct current, their base electrodes coupled to outputs of respective input amplifier stages and their collector electrodes provided terminals for extraction of signal and application of operating potential; a third transistor connected as a common-emitter amplifier stage coupling said emitter electrode of said first transistor to its said base electrode; and a fourth transistor connected as a common-emitter amplifier stage coupling said emitter electrode of said second transistor to its said base electrode; there being means coupling the base electrodes of said third and fourth transistors together.
2. An amplifier as claimed in claim 1, wherein said first source of direct current comprises a semiconductor rectifier connected in parallel with the emitter to base junctions of said third and fourth transistors between a source of operating potential and said coupling to said emitter electrodes of said first and second transistors.
3. An amplifier as claimed in claim 1 or 2, wherein said first and second signal sources comprise fifth and sixth transistors each in an amplifier configuration with signal input across its base-emitter junction and signal output provided from its collector electrode, said third and fifth transistors being opposite conductivity types and having their collector-to-emitter current paths connected in series, and said fourth and sixth transistors being opposite conductivity types having their collector-to-emitter paths connected in series.
4. An amplifier as claimed in claim 3, wherein said fifth and sixth transistors have their emitter electrodes coupled to each other and to a current source and have signal input across their base electrodes.
5. An amplifier as claimed in claim 3, wherein seventh and eighth transistors of same conductivity type as said fifth and sixth transistors have their emitter electrodes coupled to each other and to a junction point

coupling to a current source, have signal input across their base electrodes, and have their respective collector electrodes coupled to separate emitter electrodes of said fifth and sixth transistors; and having a voltage regulator coupling the base electrodes of said fifth and sixth transistors to said junction point, said voltage regulator providing potential offset proportional to and approximately twice that of a forward biased semiconductor junction.

6. An amplifier as claimed in claim 5, wherein each of said seventh and eighth transistors is a high-beta transistor having a breakdown on the order of 1 volt.

7. An amplifier as claimed in claim 5 or 6, wherein said voltage regulator comprises two semiconductor rectifiers in series.

8. An amplifier as claimed in any of the previous claims, wherein said collector electrode of said second transistor is coupled through a first common-base transistor amplifier to its load.

9. An amplifier as claimed in any of the previous claims, wherein said collector electrode of said first transistor is coupled through a second common-base transistor amplifier to its load, said first and second common-base amplifier transistors having their base electrodes connected to a single bias potential source.

10. An amplifier as claimed in any of the prior claims, having a current amplifier having a signal transfer factor substantially equal to -1 , having input coupled from the collector electrode of said first transistor, and delivering output coupled to an output terminal to which said collector electrode of said second transistor is also coupled.

11. An amplifier as claimed in claim 10, using a current-amplifier transistor having a semiconductor rectifier coupled in parallel with its base-emitter junction, the emitter electrode of said current amplifier transistor being connected to a reference potential, the base electrode of said current-amplifier transistor being coupled to receive input current signals from the collector electrode of said first transistor, the collector electrodes of said current-amplifier and second transistors being coupled to a terminal from which output signals may be taken.

12. An amplifier as claimed in any of the prior claims, wherein of said couplings not specified as being otherwise at least one comprises a direct connection.

13. An amplifier comprising first and second transistors of a first conductivity type and connected as an emitter-coupled differential amplifier; third and fourth transistors of a second conductivity type and each connected as a common-emitter amplifier, the collector electrodes of said first and said third transistors being direct current conductively coupled together, the collector elec-

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trodes of said second and said fourth transistors being direct current conductively coupled together, the base electrodes of said third and said fourth transistors each being
 5 direct-current conductively coupled from their respective own collector electrodes; fifth and sixth transistors of said second conductivity type and each connected as a common-emitter amplifier, the base electrodes
 10 of said fifth and said sixth transistors each being direct current conductively coupled to separate ones of the collector electrodes of said first and said second transistors; and seventh and eighth transistors of said first conductivity type each connected as a common-emitter transistor amplifier, the collector electrodes of said fifth and said seventh transistors being direct current conductively coupled together, the collector electrodes of
 15 said sixth and said eighth transistors each being direct current conductively coupled to a first terminal to provide output signals in response to input signals applied between the base electrodes of said first and said second transistors, the base electrodes of said seventh and said eighth transistors each being direct current conductively coupled to the collector electrode of said seventh transistor, the emitter electrodes of said transistors of first conductivity type direct current conductively coupled to a second terminal suitable for application of a first operating potential, the emitter electrodes of said transistors of said second conductivity type direct current conductively coupled to a third terminal suitable for application second operating potential.
 14. An amplifier as claimed in claim 13, wherein said coupling of said base electrode of said third transistor from its said collector electrode is via the base-emitter junction of said fifth transistor and said coupling of said base electrode of said fourth transistor from its said collector electrode is via the base-emitter junction of said sixth transistor.
 15. An amplifier as claimed in claim 14, wherein a semiconductor rectifier poled for forward conduction connects the interconnection of the emitter electrodes of said fifth and

said sixth transistors to said second terminal.

16. An amplifier as claimed in any of claims 13—15, wherein said direct current conductive coupling of said collector electrode of said sixth transistor to said first terminal is via a common-base amplifier.

17. An amplifier as claimed in any of claims 13—16, wherein said direct current conductive coupling of said collector electrode of said fifth transistor is via a common-base amplifier to said collector electrode of said seventh transistor.

18. An amplifier comprising a first differential amplifier having two emitter-coupled transistors of one conductivity type, and a second, input differential amplifier having two emitter-coupled transistors of the opposite conductivity type and constituting input amplifier stages, the outputs of the latter being individually coupled to the base inputs of the former transistors, and a load transistor of the one conductivity type for each of the latter transistors, connected thereto collector-towards-collector, the emitters and the bases of the two load transistors being commoned, both emitters being connected to a reference potential for common emitter operation, and both bases being connected to the coupled together emitters of the first differential amplifier, for degeneration of common mode signals but not of differential mode signals.

19. An amplifier as claimed in claim 18 wherein the two outputs of the first differential amplifier are commoned, by subjection of one of them to a (-1) times buffer amplification.

20. A differential amplifier including current regulating means for the differential input stage, substantially as hereinbefore described in conjunction with Figure 1 or Figure 2 or Figure 3 of the accompanying drawing.

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* C L M S *