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(54) VOLTAGE LEVEL SHIFT CIRCUITS

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 195 Broadway, New York City, New York State, United States of America, a Corporation organized and existing under the laws of the State of New York, 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 dc voltage level shift circuits. Such circuits may be used to provide a change in voltage level in order to match the output bias voltage level of one circuit with the input bias voltage level of another.

In many circuits it is desirable to change the average output voltage of one stage to a different level before applying it to the input of the succeeding stage. This is usually done to take advantage of the optimum bias conditions for each stage. However, sometimes it is done so that the outputs of various circuits will be the same, thereby allowing different combinations of the circuits to be used. This type of circuit is generally referred to as a voltage level shifter.

Prior art circuits for effecting dc level shifts include utilization of forward-biased diodes, Zener diodes, pi attenuators, and transistors having their collector-to-emitter voltage controlled directly by impedance ratios. The use of forward-biased diodes in level shifting is limited by the small fixed increments of voltage shift which can be achieved with a forward-biased diode and by its temperature dependence. The Zener diode is also limited to a fixed voltage shift and individual Zener diodes of a particular type may have relatively large variations in Zener voltage.

Resistive pi attenuators disclosed in the prior art provide level shift with little temperature or frequency dependence. The pi attenuator circuit also provides a continuously

variable level shift. However, it attenuates the transmitted signal in providing the level shift and requires the use of an amplifier to restore the signal. A level shifter using a pass transistor with resistors connected between the collector and base, and the base and emitter of the pass transistor is disclosed by the prior art. The base-to-emitter resistor is made much less than the dc base-to-emitter resistance of the transistor, thereby causing a fairly constant current to flow through the collector-to-base resistor. The constant current produces a relatively constant voltage from collector to emitter, assuming the base-to-emitter voltage of the transistor is relatively constant. Through changes in the values of the resistors the voltage shift is made continuously variable. However, the voltage shift produced by the circuit is very dependent on the base-emitter temperature characteristics of the transistor.

According to the invention a dc voltage level shifting circuit including a pass transistor having its collector-emitter path coupled between a signal input terminal and a signal output terminal and having its base coupled to a point of reference potential formed by the junction between a constant current source and a resistor the other end of which is connected to the input of the said collector-emitter path, so that, in operation, the base is controlled through said coupling to vary the conduction of the collector-emitter path of the pass transistor to maintain a constant voltage shift in signals passing therethrough from the input terminal to the output terminal and also so that temperature changes affecting the pass transistor do not substantially affect the said voltage shift.

In one illustrative embodiment of the invention a collector-to-base resistor of the pass transistor is connected to the collector of a first current regulator transistor. The emitter of this first current regulator transistor is connected to a voltage source and its base

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is connected through a regulator resistor to a reference terminal. The base and collector of a second current regulator transistor are connected to the base of the first current regulator transistor and its emitter is connected to the emitter of the first current regulator transistor. When all the transistors have the same characteristics the current through the regulator resistor is dependent on the supply voltage minus the V_{BE} of the second regulator transistor and is nearly equal to the current through the collector-to-base resistor. Variations in this current are dependent on the temperature variations of the V_{BE} of the second regulator transistor. If the temperature rises while the supply voltage stays fixed the base-to-emitter voltage of all the transistors decreases and the currents through the regulator resistor and the collector-to-base resistor increase. This increase in current to the collector-to-base resistor produces an increase in the collector-to-base voltage which compensates for the decrease in base-to-emitter voltage of the pass transistor, thereby keeping the level shift substantially constant with temperature.

In another embodiment of the invention, the impedance of the pass transistor, and thus of the magnitude of the voltage level shift is established by a reference voltage drop across the resistor energized by the constant current source. The transconductive paths of two differentially coupled transistors of identical characteristics couple the input terminal and the control electrode of the pass transistor to a second constant current source.

The control electrodes of the differentially coupled transistors are coupled to the resistor and to the output terminal, respectively. The ratio of the current transmitted to the second current source by the differentially coupled transistors is responsive to the magnitudes of the reference voltage drop and the voltage level shift at the output terminal, respectively. This current ratio controls the transconductive impedance of the pass transistor.

Due to the symmetry of the differential coupling the voltage level at the control electrodes of the differentially coupled transistors tends to equalize. Hence when the voltage level shift departs from the value established by the reference voltage drop, the current ratio adjusts to alter the transconductive impedance of the pass transistor to equalize the voltage level shift with the reference voltage drop.

This voltage level shifter accurately shifts voltage levels substantially independent of temperature variations and has the additional advantage of being adapted to be embodied in integrated circuit form with all the attendant advantages of this construction.

The invention will be better understood from the description of various embodiments

thereof when read in conjunction with the drawings in which:

Fig. 1 is a schematic of the a first embodiment of the invention;

Fig. 2 is a schematic of another embodiment of the invention useful for driving a transistor load;

Fig. 3 shows a further illustrative embodiment of a voltage level shifter according to the invention;

Fig. 4 shows a still further embodiment with auxiliary circuitry to permit a wide range of voltage level shifts without unbalancing the feedback control; and

Fig. 5 shows schematically a four-terminal balanced voltage level shifter in accordance with the invention.

The circuit of Fig. 1 is a dc voltage level shift network illustrating the present invention. The input to the circuit is applied to terminal 10, which is connected to the collector electrode 3 of a transistor 1 and the output of the circuit is derived from terminal 12, which is connected to the emitter electrode 4 of transistor 1. Resistor 21 is connected from terminal 10 to terminal 11, which is connected to the base electrode 5 of transistor 1. The collector electrode 6 of a second transistor 2 is also connected to terminal 11. The emitter electrodes 7 and 8 of transistor 2 and a third transistor 9 are connected to negative voltage source, V_S . The base electrodes 15 and 16 of transistors 2 and 9, respectively, and the collector electrode 17 of transistor 9 are connected to a terminal 13 which is connected to one end of resistance 22, the other end of which is connected to the reference or ground terminal 25.

The current through resistance 22 is equal to

$$\frac{V_S - V_{BE}}{R_{22}}$$

where V_{BE} is the base-to-emitter voltage of transistor 9.

If the transistors have high gain and their characteristics are similar, then the current through resistance 21 will be nearly the same as that through resistance 22. This occurs because the base-to-emitter voltage of transistors 2 and 9 are the same and therefore their emitter currents will be the same. This occurs because substantially equal current densities flow in emitter junctions placed in parallel, with only minor dependence on base-to-collector voltage. If the transistors have high gain, then the base currents can be ignored. Therefore, the current through resistance 22, which becomes the emitter current of transistor 9, and the current

through resistance 21, which becomes the emitter current of transistor 2, will be the same.

The voltage level shift is made up of the base-to-emitter voltage of transistor 1 and the voltage drop across resistance 21, which is equal to the current through resistance 21 multiplied by its resistance. This makes the voltage level shift equal to

$$V_{BE1} + \left[\frac{V_S - V_{BE9}}{R_{22}} \right] R_{21}$$

If R_{21} is the same as R_{22} and the V_{BE} 's are the same, the levels shift is equal to V_S . The transistors may be selected to have equal characteristics or they may be formed on the same substrate during a manufacturing process, such as an integrated circuit arrangement.

From the above analysis it is seen that the circuit can be made to provide a stable voltage level shift which is substantially independent of the temperature effect of V_{BE} . Also, the amount of the level shift can be continuously controlled by changing the supply voltage, V_S , and is independent of the input voltage.

Fig. 2 shows an embodiment of the invention driving a transistor which is to operate at a voltage different from the input. It shows terminal 12 connected to the base 30 of a transistor 31. The emitter electrode of transistor 31 is connected to supply voltage, V_S , and the collector electrode 33 of transistor 31 is connected to the output terminal of the circuit 14. Resistor 23 is connected from base to emitter of transistor 31 and supplies a path for the emitter current of transistor 1. With this arrangement the driving voltage is fixed at

$$V_{in} = -V_S + 2V_{BE} + \left[\frac{V_S - V_{BE}}{R_{22}} \right] R_{21}$$

If $R_{21} = R_{22}$, then $V_{in} = V_{BE}$. Note that any variations of the supply voltage V_S are effectively masked from the driving point. If a diode is added in series with resistance 22, then the driving point bias voltage will be equal to zero. This current is useful where the driving source has a relatively small voltage swing. The invention may be used in an integrated circuit operational amplifier in which the following are typical values:

$V_{BE} = 0.7$ volt
 $V_S = 3.5$ volts
 $R_{21} = R_{22} = 2000$ ohms
 $R_{23} = 1500$ ohms

Thus the invention involves the use of a

base-emitter junction voltage of a transistor and a resistor with a constant current through it connected from collector to base of the transistor as a voltage level shifter. The output of the constant current source is a function of the base-emitter voltage of its transistors and can be made to cancel the effect of temperature changes in the level shifter.

The voltage level shifter disclosed schematically in Fig. 3 generates a constant voltage level shift between terminals 101 and 102 by controlling the series transconductive impedance of the pass transistor 130.

A floating reference voltage, which determines the magnitude of the voltage level shift is derived from the voltage drop across the resistor 141. This voltage drop is developed in response to a constant current flowing therein established by the collector-emitter current of the transistor 160. Transistor 160 is biased by the voltage drop across the diode-connected transistor 180, which in turn is biased by a current supplied by the voltage source 115 flowing through resistor 116. The resistor 141 is preferably constructed of material having temperature independent resistance characteristics, or if this is not possible it may be compensated by an electrical device having complementary temperature controlled resistance characteristics connected therewith and included in the generation of the reference voltage drop.

The differentially coupled transistors 110 and 120 compare the output voltage at terminal 102 with the reference voltage drop across the resistor 141. The voltage drop across resistor 141 is applied to the base electrode 111 of transistor 110. The voltage at the output terminal 102 is applied to the base electrode 121 of the transistor 120. The emitter electrodes 112 and 122 of transistors 110 and 120 are coupled to the collector electrode 173 of transistor 170. The transistor 170 biased by the constant voltage source 115 conducts a constant current. Inasmuch as the emitter electrodes 112 and 122 are both connected to the collector 173 of transistor 170, the sum of the currents traversing the two collector-emitter paths of transistors 110 and 120 is a constant.

It is readily apparent from the foregoing that as the voltage at the output terminal 102 varies with respect to the voltage drop across resistor 141, the relative conductivities of the transistors 110 and 120 are accordingly varied. If, for example, the voltage at the output terminal 102 rises above the voltage at the base 111, the collector-emitter path of the transistor 120 conducts a greater portion of the constant current drawn by transistor 170 than does transistor 110. This added current transmitted by transistor 120 diverts the current transmitted via the resistor 142 from the base 131 of transistor 130. This reduces the conductivity of transistor

130 and increases its transconductive impedance. The increased transconductive impedance of transistor 130 increases the voltage drop across the collector-emitter terminals and reduces the voltage at output terminal 102 until it equals the voltage at base 111. It is apparent from the foregoing description that the feedback arrangement will respond to a decrease in the output voltage at terminal 102 to cause a corresponding decrease in the transconductive impedance of transistor 130.

A capacitor 151 shunts the collector-emitter path of transistor 130. This capacitor 151 operates as a high frequency low impedance series path to bypass high frequency signals.

It is apparent from the foregoing description that since the voltage level shift is determined by the voltage drop across the resistor 141, the temperature responsive characteristics of the transistor will not significantly alter the voltage level shift. The voltage level shift additionally may be readily altered by simply altering the impedance of resistor 141, or by altering the current flow through transistor 160.

A voltage level shifter permitting a wider range of adjustment in the voltage level shift is disclosed in Fig. 4. In the voltage level shifter disclosed in Fig. 3 and described above, the current flowing through the collector-emitter path of transistor 120 varies significantly with the magnitude of the voltage level shift. As the magnitude of the voltage level shift increases, the inequality of the currents flowing through transistors 110 and 120 increases to a point at which one of the differentially paired transistors may turn off.

The voltage level shifter disclosed in Fig. 4 includes a current bypass to transmit the increased current due to the increased voltage level shift directly to the output terminal 202 bypassing the differentially paired transistors 210 and 220. Hence the inequality of the respective current magnitudes flowing in the differentially paired transistors 210 and 220 at high voltage level shifts is reduced to prevent a turn-off of one of these transistors. The regulator transistors 230 and 235 are cascaded in a Darlington connection. The improved gain due to this connection reduces the dynamic impedance of the level shifter.

The level shifter of Fig. 4 is modified to permit a larger voltage level shift by including a current bypass transmission path including the transistor 250, and the resistor 291 to transmit excess current directly to the output terminal 202. A resistor 292 shunts the collector-base junction of the transistor 250 and connects the resistor 291 to the collector 231 of transistors 210. The magnitude of the current flow through the resistors 291 and 292 is controlled by the base-emitter junction voltages of the transistors 230, 235 and 250. The current flowing to the collector 231

of transistor 210, via resistor 292, is controlled by the collector-base voltage drop of transistor 250 and hence cannot change by large amounts. At high voltage level shifts, the resulting increased current traversing the resistor 291 is transmitted by the collector-emitter path of transistor 250 to the output terminal 202 of the level shifter. It is readily apparent that by bypassing this increased current to the output terminal 202 the currents traversing the differentially paired transistors 210 and 220 do not become significantly unbalanced causing one of the transistors to turn off.

The base electrodes 211 and 221 of the transistors 210 and 220 are coupled by a capacitor 262. This capacitor 262 is utilized to eliminate resonance between the impedance parameters of transistors 210 and 220 and the capacitor 261 which is used to bypass high frequency signals.

The capacitors 269 and 267 connected respectively to the base electrodes 211 and 221 of transistors 210 and 220, and shown in dotted form, represent parasitic capacitances to ground. The parasitic capacitance 269 draws a current through the resistor 241 to ground. This current increases the magnitude of the voltage level shift from terminal 201 to 202. However, the parasitic capacitance 267 draws a current which produces a voltage drop of opposite polarity across the resistor 282. This voltage drop developed across the resistor 282 neutralizes the increase in magnitude of the voltage level shift produced by the current drawn by parasitic capacitor 269. It is apparent from the foregoing that the range of voltage level shifts of the level shifter is greatly increased by the addition of the current bypass transmission path. Since the basic operation of the level shifter shown in Fig. 4 is identical to that of the level shifter disclosed in Fig. 3 it is not believed necessary to further describe its operation in detail.

The level shifting arrangement disclosed in Fig. 5 comprises two level shifting circuits as disclosed in Fig. 3 symmetrically connected in the two sides of a balanced four-terminal network arrangement. A balanced arrangement of this sort is desirable where it is necessary to protect the circuitry to which the level shift is applied from interference currents which may be generated in response to an unbalanced dc input voltage. The balanced voltage level shifter advantageously eliminates drift signals from the shifted output voltage derived from the input voltage. As is apparent from the examination of Fig. 5 the two voltage level shifters 375 and 385 connected in the two sides of the transmission network each operates in essentially the same manner as does the voltage level shifter disclosed in Fig. 3.

The two level shifters 375 and 385 share

a common constant current source 393 which supplies the constant current to derive the reference voltage drop across the resistors 341 and 381, respectively. The common constant current source comprises a differentially coupled pair of transistors 394 and 395 whose emitter electrodes 396 and 397 are coupled to a common current drain 391. The current flow through the collector-emitter path of transistor 395 is determined by the respective voltages at the base electrodes 386 and 387. The base 387 is coupled to the output voltage on terminals 302 and 307, via the equal value resistors 303 and 308. The dc voltage applied to the base 386 simultaneously controls the magnitude of the common voltage level shift in each of the level shifters 375 and 385 by controlling the current in resistors 341 and 381, respectively.

The transistors 371 and 372 are included in the current path from the level shifters 375 and 385 to the common constant current source 393 to permit independent adjustments to the voltage level shift attained in each of the voltage level shifters 375 and 385. These adjustments are made in order to balance the output voltage at the output terminals 302 and 307. The adjustments to achieve the controlled differences between the voltage level shifts in the level shifters 375 and 385 are controlled by the respective voltages applied to the base electrodes 373 and 374. The trans-conductive impedance of transistors 371 and 372 adjusts the respective currents drawn through the resistors 341 and 381 and hence the voltage level shift of the level shifters 375 and 385.

It is apparent to those skilled in the art that variation in the above arrangement may be made to alter the polarities of the balanced output voltage by substituting semiconductor components of differing conductivity types. This balanced level shifting arrangement is useful in providing threshold voltages for applications to balanced networks.

It is also apparent from the foregoing description that the level shifting circuits may be readily constructed in the integrated circuit form so that the complete circuit may be contained on a single circuit chip.

WHAT WE CLAIM IS:—

1. A dc voltage level shifting circuit including a pass transistor having its collector-emitter path coupled between a signal input terminal and a signal output terminal and having its base coupled to a point of reference potential formed by the junction between a constant current source and a resistor the other end of which is connected to the input of the said collector-emitter path, so that, in operation, the base is controlled through said coupling to vary the conduction of the collector-emitter path of the pass transistor

to maintain a constant voltage shift in signals passing therethrough from the input terminal to the output terminal and also so that temperature changes affecting the pass transistor do not substantially affect the said voltage shift.

2. A circuit according to claim 1 wherein the constant current source includes a first transistor having its collector connected to the resistor and its emitter to a voltage source, a second transistor having its collector and base connected to the base of the first transistor and its emitter connected to the voltage source.

3. A circuit according to claim 2, wherein the base of the first transistor is connected to a further point of reference potential through a second resistor, the second resistor being substantially equal to the first resistor.

4. A circuit according to claim 2, wherein the coupling between the collector-emitter path of the pass transistor and the output terminal includes the base-collector path of a third transistor having its emitter connected to the voltage source, so that, in operation, variations of the voltage source are masked from the input terminal.

5. A circuit according to claim 2, wherein the connection from said junction to the base of the pass transistor comprises a feedback network including a fourth and fifth transistor having their main current paths interconnecting a constant current source and the base of the pass transistor and their control electrodes connected respectively to the said junction point and to the output terminal so that the conductivities of the fourth and fifth transistors are dependent upon the relative magnitudes of the voltages at the said junction and the output terminal whereby the voltage at the output terminal is made equal to that at the said junction.

6. A circuit according to claim 5, including a current path connected to the output terminal to effect a diversion of current in excess of a predetermined amount from one or both of the fourth and fifth transistors.

7. A circuit according to claim 5 or 6, including means for generating a voltage in response to current drawn by the capacitance of at least one of the control electrodes of the fourth and fifth transistors so as to compensate for variations in voltage level shift due to said capacitance.

8. A circuit according to claim 5 or 6, including a second pass transistor connected between a second input terminal and a second output terminal, a second feedback network including sixth and seventh transistors having their main current paths interconnecting a second constant current source and the base of the second pass transistor and their control electrodes connected respectively to the said junction point and to the second output terminal so that the conductivity of the sixth



a common constant current source 393 which supplies the constant current to derive the reference voltage drop across the resistors 341 and 381, respectively. The common constant current source comprises a differentially coupled pair of transistors 394 and 395 whose emitter electrodes 396 and 397 are coupled to a common current drain 391. The current flow through the collector-emitter path of transistor 395 is determined by the respective voltages at the base electrodes 386 and 387. The base 387 is coupled to the output voltage on terminals 302 and 307, via the equal value resistors 303 and 308. The dc voltage applied to the base 386 simultaneously controls the magnitude of the common voltage level shift in each of the level shifters 375 and 385 by controlling the current in resistors 341 and 381, respectively.

The transistors 371 and 372 are included in the current path from the level shifters 375 and 385 to the common constant current source 393 to permit independent adjustments to the voltage level shift attained in each of the voltage level shifters 375 and 385. These adjustments are made in order to balance the output voltage at the output terminals 302 and 307. The adjustments to achieve the controlled differences between the voltage level shifts in the level shifters 375 and 385 are controlled by the respective voltages applied to the base electrodes 373 and 374. The trans-conductive impedance of transistors 371 and 372 adjusts the respective currents drawn through the resistors 341 and 381 and hence the voltage level shift of the level shifters 375 and 385.

It is apparent to those skilled in the art that variation in the above arrangement may be made to alter the polarities of the balanced output voltage by substituting semiconductor components of differing conductivity types. This balanced level shifting arrangement is useful in providing threshold voltages for applications to balanced networks.

It is also apparent from the foregoing description that the level shifting circuits may be readily constructed in the integrated circuit form so that the complete circuit may be contained on a single circuit chip.

WHAT WE CLAIM IS:—

1. A dc voltage level shifting circuit including a pass transistor having its collector-emitter path coupled between a signal input terminal and a signal output terminal and having its base coupled to a point of reference potential formed by the junction between a constant current source and a resistor the other end of which is connected to the input of the said collector-emitter path, so that, in operation, the base is controlled through said coupling to vary the conduction of the collector-emitter path of the pass transistor

to maintain a constant voltage shift in signals passing therethrough from the input terminal to the output terminal and also so that temperature changes affecting the pass transistor do not substantially affect the said voltage shift.

2. A circuit according to claim 1 wherein the constant current source includes a first transistor having its collector connected to the resistor and its emitter to a voltage source, a second transistor having its collector and base connected to the base of the first transistor and its emitter connected to the voltage source.

3. A circuit according to claim 2, wherein the base of the first transistor is connected to a further point of reference potential through a second resistor, the second resistor being substantially equal to the first resistor.

4. A circuit according to claim 2, wherein the coupling between the collector-emitter path of the pass transistor and the output terminal includes the base-collector path of a third transistor having its emitter connected to the voltage source, so that, in operation, variations of the voltage source are masked from the input terminal.

5. A circuit according to claim 2, wherein the connection from said junction to the base of the pass transistor comprises a feedback network including a fourth and fifth transistor having their main current paths interconnecting a constant current source and the base of the pass transistor and their control electrodes connected respectively to the said junction point and to the output terminal so that the conductivities of the fourth and fifth transistors are dependent upon the relative magnitudes of the voltages at the said junction and the output terminal whereby the voltage at the output terminal is made equal to that at the said junction.

6. A circuit according to claim 5, including a current path connected to the output terminal to effect a diversion of current in excess of a predetermined amount from one or both of the fourth and fifth transistors.

7. A circuit according to claim 5 or 6, including means for generating a voltage in response to current drawn by the capacitance of at least one of the control electrodes of the fourth and fifth transistors so as to compensate for variations in voltage level shift due to said capacitance.

8. A circuit according to claim 5 or 6, including a second pass transistor connected between a second input terminal and a second output terminal, a second feedback network including sixth and seventh transistors having their main current paths interconnecting a second constant current source and the base of the second pass transistor and their control electrodes connected respectively to the said junction point and to the second output terminal so that the conductivity of the sixth

and seventh transistors are dependent upon the relative magnitudes of the voltages at the said junction and the second output terminal whereby the voltage at the second output terminal is made equal to that at the said junction.

5 9. A dc voltage level shifting circuit arranged and adapted to operate substantially as hereinbefore described with reference to

Fig. 1 or Fig. 2 or Fig. 3 or Fig. 4 or Fig. 10
5 of the drawings.

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