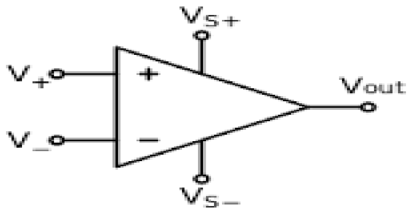
Linear ic applications: <u>UNIT-1</u>

<u>DIFFERENTIAL AMPLIFIER:</u>

A **differential amplifier** is a type of that amplifies the difference between two input but suppresses any voltage common to the two inputs. It is an with two inputs Vin(+) and Vin(-) and one output Vo in which the output is ideally proportional to the difference between the two voltages



Vo=A[Vin(+)-Vin(-)]

Where, A is the gain of the amplifier.

There are four different types of configuration in differential amplifier which are as follows:

i)Dual input and balanced output

ii)Dual input and unbalanced output

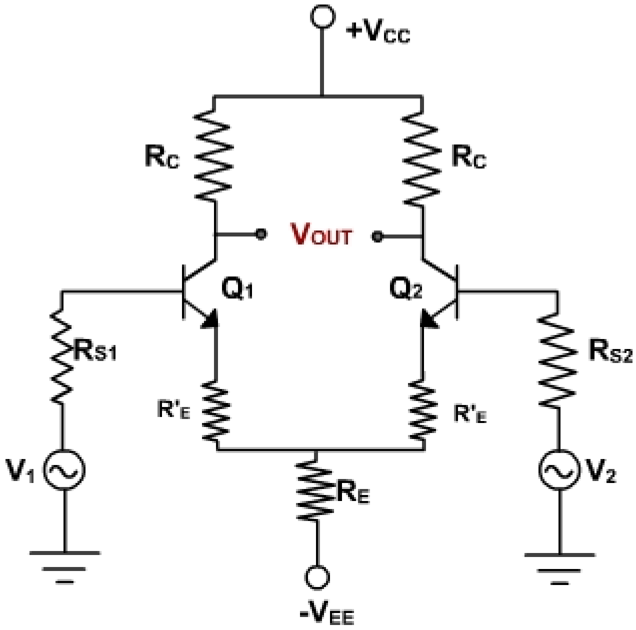
iii)Single input and balanced output

iv)Single input and unbalanced output

1) <u>DUAL INPUT, BALANCED OUTPUT DIFFERENTIAL AMPLIFIER</u>

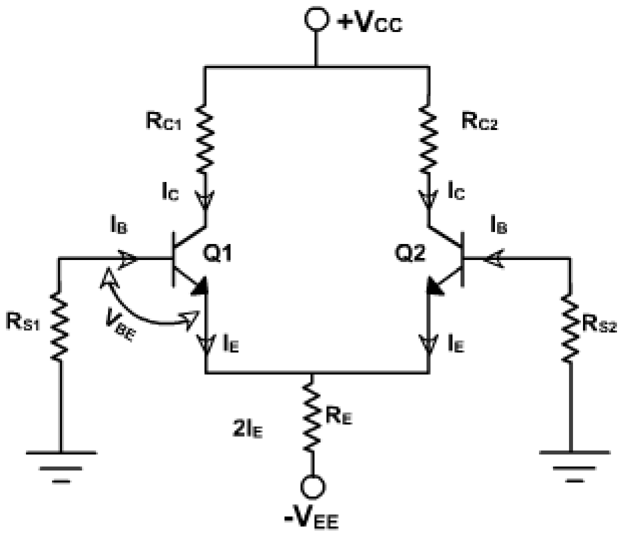
The circuit shown below is a dual-inputbalanced-output differential amplifier.Here in this circuit,the two input signals (dual input), v_{in1} and $v_{in2,}$ are applied to the bases B_1 and B_2 of transistors Q_1 and Q_2.The output v_o is measured between the two collectors C_1 and C_2 which are at the same dc potential.Because of the equal dc potential at the two collectors with respect to ground,the output is referred as a balanced output.

<u>Circuit Diagram</u> :-



DC Analysis :-

To determine the operating point values (I_{CQ} and V_{CEQ}) for the differential amplifier,we need to obtain a dc equivalent circuit.The dc equivalent circuit can be obtained simply by reducing the input signals v_{in1} and v_{in2} to zero.The dc equivalent circuit thus obtained is shown in fig below. Note that the internal resistances of the input signals are denoted by R_{in}because $R_{in1} = R_{in2}$.Since both emitter biased sections of the differential amplifier are symmetrical (matched in all respects), we need to determine the operating point collector current I_{CQ} and collector to emitter voltage V_{CEQ} for only one section.We shall determine the I_{CQ} and V_{CEQ} values for transistor Q_1 only.These I_{CQ} and V_{CEQ} values can then be used for transistor Q_2 also.



DC EQUIVALENT CIRCUIT FOR DUAL-INPUT BALANCED OUTPUT DIFFERETIAL AMPLIFIER

Applying Kirchhoff’s voltage law to the base-emitter loop of the transistor Q_1,

$$R_{in}I_B - V_{BE} - R_E(2I_E) + V_{EE} = 0 \qquad (1)$$

But

$$I_B = I_E/B_{dc} \quad \text{since } I_C = I_E$$

Thus the emitter current through Q_1 is determined directly from eqn(1) as follows :

$$I_E = (V_{EE} - V_{BE})/(2R_E + R_{in}/B_{dc}) \qquad (2)$$

where $V_{BE} = 0.6V$ for silicon transistors

$V_{BE} = 0.2V$ for germanium transistors

Generally, $R_{in}/B_{dc} << 2R_E$.Therefore, eqn(2) can be rewritten as

$$ICQ=IE = (VEE - VBE)/2RE \qquad (3)$$

From eqn(3) we see that the value of R_E sets up the emitter current in transistors Q_1 and Q_2 for a given value of V_{EE}. In other words, by selecting a proper value of R_E, we can obtain a desired value of emitter current for a known value of $-V_{EE}$. Notice that the emitter current in transistors Q_1 and Q_2 is independent of collector resistance R_C.

Next we shall determine the collector to emitter voltage V_{CE}. The voltage at the emitter of transistor Q_1 is approximately equal to V_{BE} if we assume the voltage drop across R_{in} to be negligible. Knowing the value of emitter current $I_E(=I_C)$,we can obtain the voltage at the collector V_{CC} as follows:

$$V_C = V_{CC} - R_C I_C$$

Thus the collector to emitter voltage V_{CE} is

$$V_{CE} = V_C - V_E = (V_{CC} - R_C I_C) - (-V_{EE})$$

$$VCEQ=VCE = VCC+VBE - RCIC \qquad (4)$$

Thus for both transistors we can determine the operating point values by using the eqns (2)and(4), respectively, because at the operating point $I_E=I_{CQ}$ and $V_{CEQ}=V_{CE}$

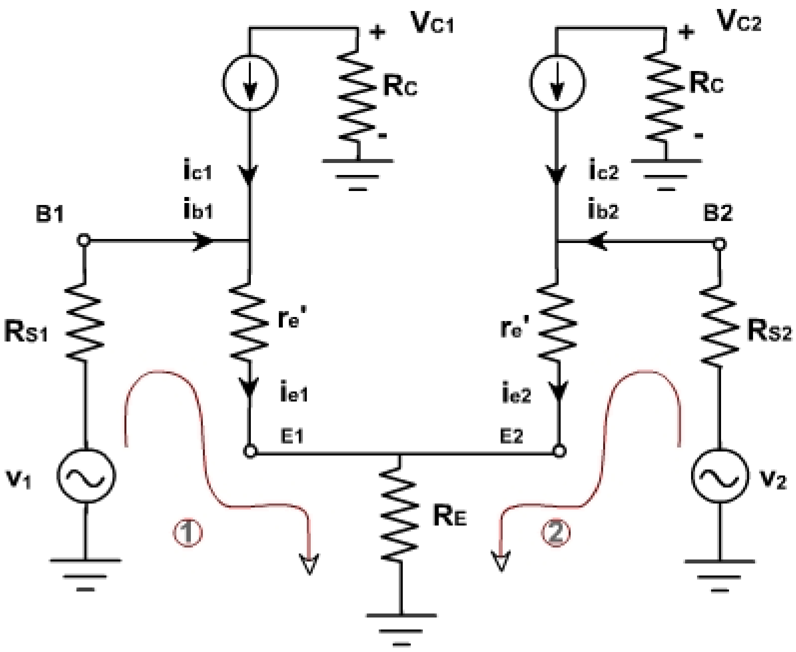
Remember that the dc analysis eqns (2) and (4) are applicable for all 4 differential amplifier configurations as long as we use the same biasing arrangement for each of them.

AC Analysis:-

To perform ac analysis to derive the expression for the voltage gain A_d and input resistance R_i of a differential amplifier:

1) Set the dc voltages $+V_{CC}$ and $-V_{EE}$ at 0
2) Substitute the small signal T equivalent models for the transistors

Figure below shows resulting ac equivalent circuit of the dual input balanced output differential amplifier



AC EQUIVALENTCIRCUIT FOR DUAL-INPUT BALANCED OUTPUT DIFFERETIAL AMPLIFIER

Voltage Gain :-

Before we proceed to derive the expression for the voltage gain A_d the following should be noted about the circuit in the figure above

1) $I_{e1}=I_{e2}$; therefore $r_{e1}=r_{e2}$. For this reason the ac emitter resistance of transistors Q_1 and Q_2 is simply denoted by r_e.
2) The voltage across each collector resistor is shown out of phase by 180^0 w.r.t the input voltages v_{in1} and v_{in2}.

Writing Kirchhoff's voltage eqautions for loops 1 and 2 gives us

$$v_{in1} – R_{in1}i_{b1} – r_e i_{e1} – R_E(i_{e1}+i_{e2}) = 0 \qquad (5)$$

$$v_{in2} – R_{in2}i_{e2} – r_e i_{e2} – R_E(i_{e1}+i_{e2}) = 0 \qquad (6)$$

Substituting current relations $i_{b1} = i_{e1}/B_{ac}$ and $i_{b2} = i_{e2}/B_{ac}$ yields

$$v_{in1} – R_{in1}i_{e1}/B_{ac} – r_e i_{e1} – R_E(i_{e1}+i_{e2}) = 0$$

$$v_{in2} – R_{in2}i_{e2}/B_{ac} – r_e i_{e2} – R_E(i_{e1}+i_{e2}) = 0$$

Generally, R_{in1}/B_{ac} and R_{in2}/B_{ac} values are very small therefore we shall neglect them here for simplicity and rearrange these equations as follows:

$$(r_e+R_E)i_{e1} + R_{E2}i_{e2} = v_{in1} \qquad (7)$$

$$R_{E2}i_{e1} + (r_e+R_E)i_{e2} = v_{in2} \qquad (8)$$

Eqns (7) and (8) can be solved simultaneously for i_{e1} and i_{e2} by using Cramer's rule:

$$I_{e1} = |(v_{in1}/v_{in2})(R_E/r_e+R_E)|/|\{(r_e+R_E)/R_E\}\{R_E/(r_e+R_E)\}| \qquad (9a)$$

$$=\{(r_e+R_E)v_{in1} - R_E v_{in2}\}/\{(r_e+R_E)^2 - (R_E)^2\}$$

Similarly

$$I_{e2} = |(v_{in1}/v_{in2})\{(r_e+R_E)/R_E\}|/|\{(r_e+R_E)/R_E\}\{R_E/(r_e+R_E)\}| \qquad (9b)$$

$$=\{(r_e+R_E)v_{in2} - R_E v_{in2}\}/\{(r_e+R_E)^2 - (R_E)^2\}$$

The output voltage is

$$v_o = v_{c2} - v_{c1}$$

$$= -R_C i_{c2} - (-R_C i_{c1}) \qquad (10)$$

$$= R_C i_{c1} - R_C i_{c2}$$

$$=R_C(i_{e1} - i_{e2}) \qquad \text{since } i_c = i_e$$

Substituting current relations i_{e1} and i_{e2} in eqn(10), we get

$$v_o = R_C[\{(r_e+R_E)v_{in1} - R_E v_{in2}\}/\{(r_e+R_E)^2 - (R_E)^2\} - \{(r_e+R_E)v_{in2} - R_E v_{in1}\}/\{(r_e+R_E)^2 - (R_E)^2\}]$$

$$= R_C[\{(r_e+R_E)(v_{in1} - v_{in2})+(R_E)(v_{in1} - v_{in2})\}/\{(r_e+R_E)^2 - (R_E)^2\}]$$

$$=R_C[(r_e+2R_E)(v_{in1} - v_{in2})/r_e(r_e+2R_E)]$$

$$=(R_C/r_e)(v_{in1} - v_{in2}) \qquad (11)$$

Thus a differential amplifier amplifies the difference between two input signals as expected,the figure below shows the input and output waveforms of the dual-input balanced-output differential amplifier. By defining $v_{id} = v_{in1}$ as the difference in input voltages, we can write the voltage-gain equation of the dual-input balanced-output differential amplifier as follows:

Ad = vo/vid = RC/re

(12)

Notice that the voltage-gain equation of the differential amplifier is independent of R_E since R_E did not appear in the gain eqn(12). Another point of interest is that this equation is identical to the voltage-gain equation of the common emitter amplifier.

<u>Differential Input Resistance</u>:-

Differential input resistance is defined as the equivalent resistance that would be measured at either input terminal with the other terminal grounded.

$$R_{i1} = |v_{in1}/i_{b1}|_{Vin2=0}$$

$$=|v_{in}/(i_e/B_{ac})|_{Vin2=0}$$

Substituting the value of i_{e1} from eqn(9a), we get

$$R_{i1} = B_{ac}v_{in1}/[\{(r_e+R_E)v_{in1} - R_E(0)\}/\{(r_e+R_E)^2 - (R_E)^2\}] \qquad (13)$$

$=[B_{ac}(r_e^2+2r_eR_E)]/(r_e+R_E)$

$=[B_{ac}\, r_e(r_e+2R_E)]/(r_e+R_E)$

Generally,R_E>>r_e, which implies that $(r_e+2R_E) = 2R_E$ and $(r_e+R_E) = R_E$.

Therefore eqn(13) can be rewritten as

$$R_{i1} = B_{ac}r_e(2R_E)/R_E = 2B_{ac}r_e \qquad (14)$$

Similarly, the input resistance R_{i2} seen from the input signal source v_{in2} is defined as

$$R_{i2} = |v_{in2}/i_{b2}|_{Vin1=0}$$

$$=|v_{in2}/(i_{e2}/B_{ac})|_{Vin1=0}$$

Substituting the value of i_{e2} from eqn(9b), we get

$$R_{i2} = B_{ac}v_{in2}/[\{(r_e+R_E)v_{in2} - R_E(0)\}/\{(r_e+R_E)^2 - (R_E)^2\}] \qquad (15)$$

$=[B_{ac}(r_e^2+2r_eR_E)]/(r_e+R_E)$

$=[B_{ac}\, r_e(r_e+2R_E)]/(r_e+R_E)$

However, (r_e+2R_E) and $(r_e+R_E) = R_E$ if $R_E>>r_e$. Therefore eqn(15) can be rewritten as

Ri2 = Bacre(2RE)/RE = 2Bacre (16)

Output Resistance:-

Output resistance is defined as the equivalent resistance that would be measured at either output terminal w.r.t ground.

Ro1 = Ro2 = RC (17)

The current gain of the differential amplifier is undefined; therefore, the current-gain equation will not be derived for any of the four differential amplifier configurations.

Common mode Gain:-

A common mode signal is one that drives both inputs of a differential amplifier equally. The common mode signal is interference, static and other kinds of undesirable pickup etc.

The connecting wires on the input bases act like small antennas. If a differential amplifier is operating in an environment with lot of electromagnetic interference, each base picks up an unwanted interference voltage. If both the transistors were matched in all respects then the balanced output would be theoretically zero. This is the important characteristic of a differential amplifier. It discriminates against common mode input signals. In other words, it refuses to amplify the common mode signals.

The practical effectiveness of rejecting the common signal depends on the degree of matching between the two CE stages forming the differential amplifier. In other words, more closely are the currents in the input transistors, the better is the common mode signal rejection e.g. If v_1 and v_2 are the two input signals, then the output of a practical op-amp cannot be described by simply

$v_0 = A_d\,(v_1-v_2)$

In practical differential amplifier, the output depends not only on difference signal but also upon the common mode signal (average).

$v_d = (v_1-v_2)$

andv_C = ½ (v_1 + v_2)

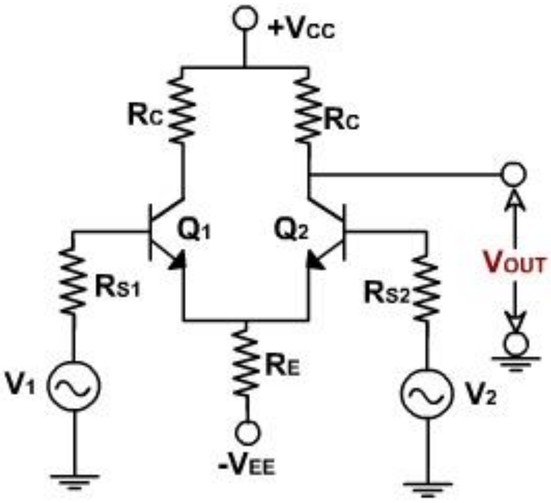
The output voltage, therefore can be expressed as

$v_O = A_1 v_1 + A_2 v_2$

Where A_1& A_2 are the voltage amplification from input 1(2) to output under the condition that input 2 (1) is grounded.

2)DUAL INPUT, UNBALANCED OUTPUT DIFFERENTIAL AMPLIFIER:

In this case, two input signals are given however the output is measured at only one of the two-collector w.r.t. ground as shown in fig. 1. The output is referred to as an unbalanced output because the collector at which the output voltage is measured is at some finite dc potential with respect to



ground. In other words, there is some dc voltage at the output terminal without any input signal applied. DC analysis is exactly same as that of first case.

DC Analysis:

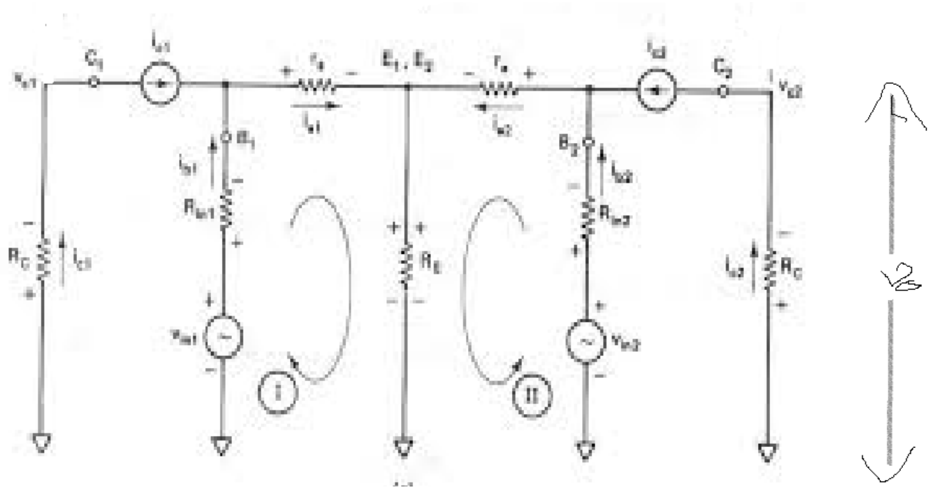
The dc analysis procedure for the dual input unbalanced output is identical to that dual input balanced output because both configuration use the same biasing arrangement. Therefore the emitter current and emitter to collector voltage for the dual input unbalanced output differential amplifier are determined from equations.

$I_{E=}I_{CQ}$= (V_{EE}.V_{BE}) / (2R_E+β_{dc})

V_{CE}=V_{CEQ}=V_{CC}+V_{BE}-$R_C I_{CQ}$

AC Analysis:

The output voltage gain in this case is given by



VOLTAGE GAIN:

Writing Kirchhoff's voltage equations of loops I and II is given as

$$V_{in1}-R_{in1}i_{b1}-r_e i_{e1}-R_E\ (i_{e1}+i_{e2})=0$$

$$V_{in2}-R_{in2}i_{b2}-r_e i_{e2}-R_E\ (i_{e1}+i_{e2})=0$$

Since these equations are the same as equations the expressions for i_{e1} and i_{e2} will be the same equations respectively.

$$i_{e1}=((r_e+R_E)\ v_{in1}-R_E v_{in2})/\ ((r_e+R_E)^2-R_E^2)$$

$$i_{e2}=((r_e+R_E)v_{in2}-R_E v_{in1})/\ ((r_e+R_E)^2-R_E^2)$$

The output voltage is

$$Vo=v_{c2}=-R_C i_{c2}=-R_C i_{e2} \quad \text{since } i_c=i_e$$

Substituting the value of i_{e2}

$$Vo=-Rc\ ((r_e+R_E)v_{in1}-R_E v_{in2})/((r_e+R_E)^2-R_E^2)$$

$$=Rc\ ((R_E v_{in2}-\ r_e+R_E)v_{in1}/((r_e+R_E)^2-R_E^2)$$

Generally $R_E>>r_e$ hence $(r_e+R_E)=R_E$ &$(re+R_E)=2R_E$ Therefore

$Vo=R_C(\ (R_E v_{in1}-\ R_E v_{in2})/2r_e R_E)$

$=R_C(\ (R_E(v_{in1}-v_{in2})/2r_e R_E)$

$$=R_C(v_{in1}-v_{in2})/2r_e)$$

$$A_d=v_o/v_{id}=R_C/2R_E$$

The voltage gain is half the gain of the dual input, balanced output differential amplifier. Since at the output there is a dc error voltage, therefore, to reduce the voltage to zero, this configuration is normally followed by a level translator circuit.

INPUT RESISTENCE:

The only difference between the circuits is the way output voltage is measured. The input resistance seen from either input source does not depend on the way the output voltage is measured.

$$R_{i1}=R_{I2}=2\beta_{ac}r_e$$

OUTPUT RESISTENCE:

The output resistance R_0 measured at collector C_2 with respect to ground is equal to the collector resistor R_C.

$$R_0=R_C$$

3)SINGLE INPUT, BALANCED OUTPUT DIFFERENTIAL AMPLIFIER:

From the figure of single input balanced output differential amplifier, input is applied to the base of transistor Q1 and the output is measured between 2 collectors which are at the same dc potential. Therefore ,the output is said to be a balanced output

DC Analysis:

The dc analysis procedure and bias equations for the single input balanced output differential amplifier are identical to those of the 2 previous configurations is the same.Thus the bias equations are

$$I_{E=}I_{CQ=(}V_{EE-}V_{BE)/(}2R_E + R_{in}\beta_{dc)}$$

$$V_{CE=}V_{CEQ=}V_{CC}+V_{BE-}R_CI_{CQ}$$

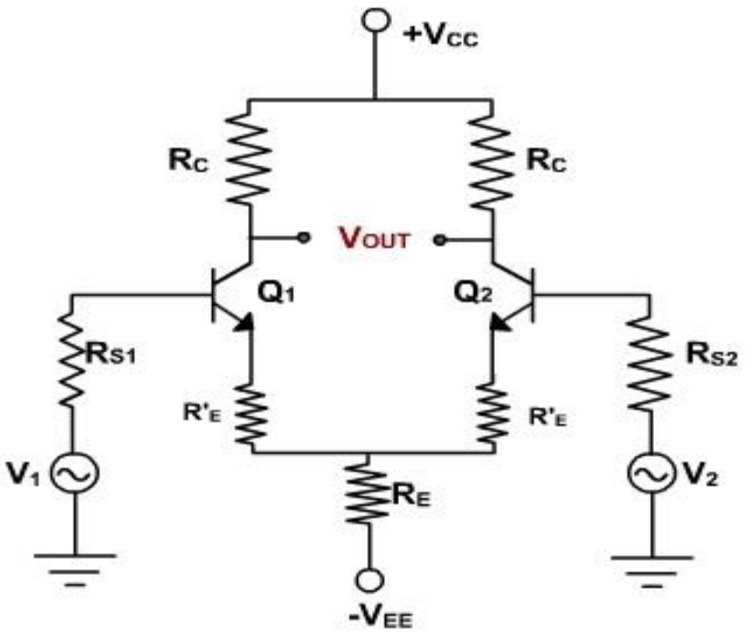
AC Analysis:

The ac equivalent circuit of this differential amplifier with a small input T-equivalent model substituted for transistors

From input and output waveforms,

During the positive half cycle of the input signal, the base-emitter voltage of the transistor Q1 is positive and that of transistor Q2 is negative. This means that the collector current in Q1 increases and that in transistor Q2 decreases from the operating point value I_{CQ}. This change in collector currents during the positive half cycle of the input signal is indicated in figure in which the currents of both the sources i_{c1} and i_{c2} are shown to be in the same direction. In fact, during the negative half cycle of the input signal, the opposite action takes place that is; the collector current of transistor Q1 decreases and that in transistor Q2 increases.

DIFFERENTIAL AMPLIFIER WITH SWAMPING RESISTORS



By using external resistors R'E in series with each emitter, the dependence of voltage gain on variations of r'e can be reduced. It also increases the linearity range of the differential amplifier shows the differential amplifier with swamping resistor R'E. The value of R'_E is usually large enough to swamp the effect of $r'_{E.}$

$$R_1 \; I_B + V_{BE} + R'_E I_E + 2 R_E I_E = V_{EE}$$

$$R_1 \, I_E / \beta_{dc} + V_{BE} + R'_E I_E + 2 R_E I_E = V_{EE}$$

From the equation, I_E can be obtained as

$$I_E = \frac{V_{EE} - V_{BE}}{R'_E + 2R_E + R_1 / \beta_{dc}}$$

$$V_{CEQ} = V_{CC} + V_{BE} - I_{CQ} R_C$$

The new voltage gain is given by $A_d = \dfrac{R_C}{r_e + R_E}$

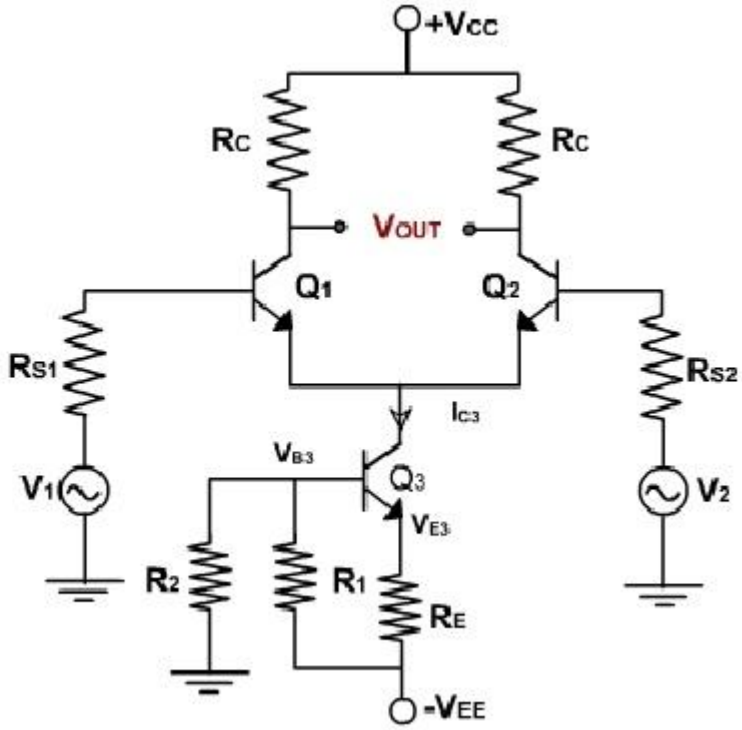
The input resistance is given by $R_{i1} = R_{i2} = 2\beta \, (r'_e + R'_E)$

The output resistance with or without R'_E is the same i.e.

$$R_{01} = R_{01} = R_C$$

CONSTANT CURRENT BIAS METHOD

In the differential amplifiers discussed so far the combination of R_E and V_{EE} is used to step up the dc emitter current. We can also use constant current bias circuit to set up the dc emitter current if desired. In fact, the constant bias current circuit is better because it provides current stabilization and in turn assures a stable operating point for the differential amplifier. The figure shows the dual input, balanced-output differential amplifier using a resistive constant current bias. Note that the resistor R_E is replaced by a constant current transistor Q_3circuit. The dc collector current in transistor Q_3 is established by resistors $R_{1,}R_2$ and R_3 and can be determined as follows. Applying the voltage-divider rule. The voltage at the base of transistor Q_3 is



4)DUAL INPUT, BALANCED OUTPUT DIFFERENTIAL AMPLIFIER USING CONSTANT CURRENT BIAS

$$I_{E1} = I_{E2} = \frac{I_{C3}}{2} = \frac{V_{EE} - \left[\frac{R_2}{R_1+R_2} V_{EE}\right] - V_{BE3}}{2R_E}$$

$$V_{B3} = \frac{R_2}{R_1+R_2}(-V_{EE})$$

$$V_{E3} = V_{B3} - V_{BE3}$$

$$= -\frac{R_2}{R_1+R_2} V_{EE} - V_{BE3}$$

$$I_{BE3} = I_{C3} = \frac{V_{E3} - (-V_{EE})}{R_E}$$

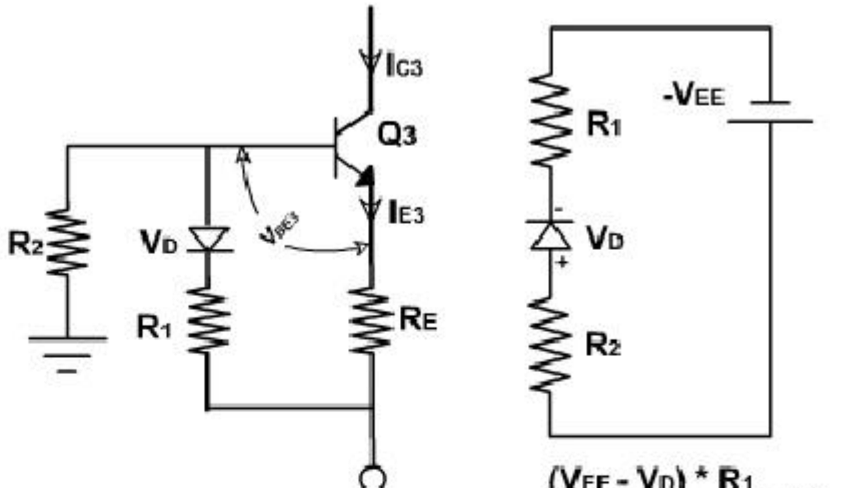
$$= \frac{V_{EE} - \left(\frac{R_2}{R_1+R_2}\right) V_{EE} - V_{BE3}}{R_E}$$

The collector current I_{C3} in transistor Q3 is fixed and must be invariant signal is injected into either the emitter or the base of Q3.thus the transistor Q3 is a source of constant emitter current for transistor Q1 and Q2 of the differential amplifier.

Recall that in the analysis of differential amplifier circuit with emitter bias we required that R_b>>I_C.Besides supplying constant emitter current the constant current bias also provides a very high source resistance since the ac equivalent of the dc current source is ideally a open circuit.therefore the performance equations obtained for the differential amplifier configuration using emitter base are also applicable to differential amplifier using constant current bias.

To improve the thermal stability of constant bias replace R1 by diodes D1 and D2. Note that high to flows to the node at the base of Q3 and then divides paths I_{B3} if the temperature Q3 increases the emitter voltage V_{BE}.

In silicon units V_{BE}decreases 2mv/c and in germanium units V_{BE} decreases 1.6mv/c.this decreased V_{BE} tends to raisethe voltage drop across R2and in turn current I_E.for better performance of transistor CA3086 have been used a constant current bias.



$$\frac{(V_{EE} - V_D) * R_1}{R_1 + R_2} + V_D$$

$$(V_{EE} - V_D)\ \frac{R_1}{R_1 + R_2} + V_D = V_{BE3} + I_{E3} R_E$$

where V_D is the diode voltage. Thus,

$$I_{E3} = \frac{1}{R_E} \left\{ V_{EE}\ \frac{R_1}{R_1 + R_2} + V_D\ \frac{R_1}{R_1 + R_2} - V_{BE3} \right\}$$

If R_1 and R_2 are so chosen that

$$\frac{R_2}{R_1 + R_2}\ V_D = V_{BE3}$$

then,

$$I_{E3} = \frac{1}{R_3} \cdot \frac{V_{EE} R_1}{R_1 + R_2}$$

$$R2 = \underline{(V_{EE} - 1.4V)}/I_{E3}$$

$$V_{E3} = -V_{EE} + V_Z – V_{BE3}$$

$$I_{E3} = (V_{E3} – (-V_{EE}))/R_E$$

$$I_{E3} = (V_Z – V_{BE3})/R_E$$

$$R2 = (V_{EE} – V_Z)/I2$$

SWAMPING RESISTORS:

In differential amplifier we use many biasing techniques to improve the CMRR ratio (common mode rejection ratio). One of the technique is using active loads to improve CMRR. As we use this method the differential gain(Ad) increases ,thereby increases the collector resistance but there are some limitations for the increase in collector resistance denoted with Rc.

The limitations are

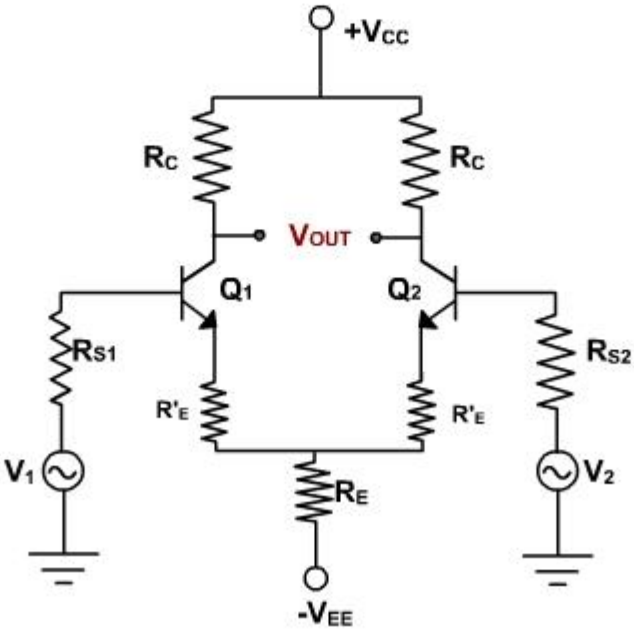
- The chip area increases
- Shows the effect on temperature
- There will be a shift in the Qpoint

Various methods are applied to reduce the high input resistance produced due to the active load techniques

- Use of darlington pair
- Use of fet
- Use of swamping resistors

Swamping resistors:

Resistors which are connected in series with the emitter resistance to reduce the input resistance .the circuit is shown below



We can observe the dual input balanced output differential operational amplifier circuit .Two inputs Rs1 and Rs2 are connected across the base of the transistors Q1 and Q2 respectively.Q1 and Q2 are the npn transistors connected .V1 and V2 are the inputs given to the circuit. Rc is the collector resistance connected to collector of the transistors .supply Vcc is given to the collector resistances connected Vcc is the dc supply given to the circuit. The external resistances Re' and Re' are connected in series with each emitter. The dependence of the voltage gain of the differential amplifier or variations in Re can be reduced. Re also increases the linearity range of the differential amplifier. Generally value of Re'is large enough to swamp the effect of Re.for this reason the Re' is referred to as the swamping resistance.Vee the supply at the emitter resistance

$$R_1 \; I_B + V_{BE} + R'_E I_E + 2 R_E I_E = V_{EE}$$

$$R_1 I_E / \beta_{dc} + V_{BE} + R'_E I_E + 2 R_E I_E = V_{EE}$$

From the equation, I_E can be obtained as

$$I_E = \frac{V_{EE} - V_{BE}}{R'_E + 2R_E + R_1 / \beta_{dc}}$$

$$V_{CEQ} = V_{CC} + V_{BE} - I_{CQ} R_C$$

The new voltage gain is given by $A_d = \frac{R_C}{r_e + R_E}$

The input resistance is given by $R_{i1} = R_{i2} = 2\beta \; (r'_e + R'_E)$

The output resistance with or without R'_E is the same i.e.

$$R_{01} = R_{01} = R_C$$

Advantages of the sawmpling resistors is:

- Input resistance is high
- Increase the linearity range of the differential amplifier
- Minimization of the changes in the transistor parameters due to the temperature