LINEAR DIGITAL IC APPLICATIONS (LDIC)

UNIT – I

An integrated circuit (IC), sometimes called a chip or wafer on which thousands or millions of tiny resistors, capacitors are fabricated. An IC can function as a timer, counter, computer or microprocessor. A particular IC is categorized as either linear or digital depending on its intended application. A linear integrated circuit (linear IC) is a solid-state device characterized by a theoretically infinite number of possible operating states. It operates over a continuous range of input levels. In contrast, an IC has a finite number of discrete input and output states. Digital IC is expressed as a series of the digits 0 and 1, typically represented by values of a physical quantity such as voltage or magnetic polarization.

OPERATIONAL AMPLIFIER:

An operational amplifier is a direct coupled high gain amplifier consisting of one or more differential (OP-AMP) amplifiers and followed by a level translator and an output stage. An operational amplifier is available as a single integrated circuit package.

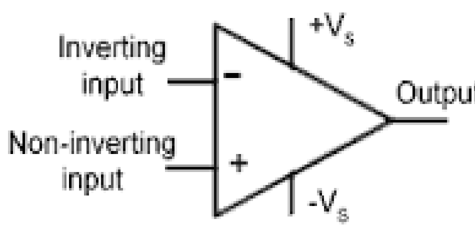

Fig 1.1 Op amp symbol

BLOCK DIAGRAM OF TYPICAL OP-AMP WITH VARIOUS STAGES:

The input stage is a dual input balanced output differential amplifier. This stage provides most of the voltage gain of the amplifier and also establishes the input resistance of the OPAMP. The intermediate stage of OPAMP is another differential amplifier which is driven by the output of the first stage. This is usually dual input unbalanced output. Because direct coupling is used, the dc voltage level at the output of intermediate stage is well above ground potential. Therefore level shifting circuit is used to shift the dc level at the output downward to zero with respect to ground. The output stage is generally a push pull complementary amplifier. The output stage increases the output voltage swing and raises the current supplying capability of the OPAMP. It also provides low output resistance.

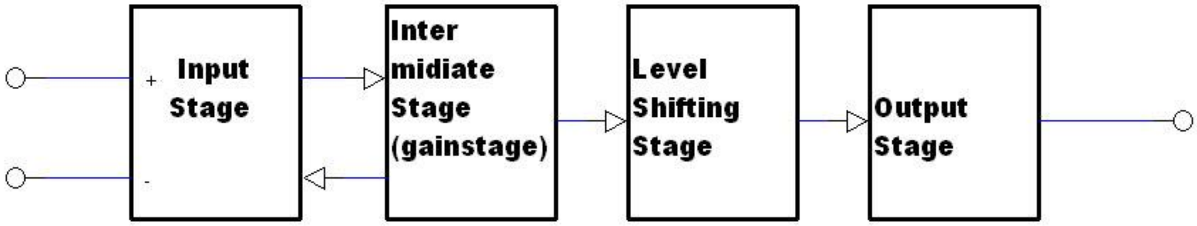

Fig 1.2 Block diagram of Op amp

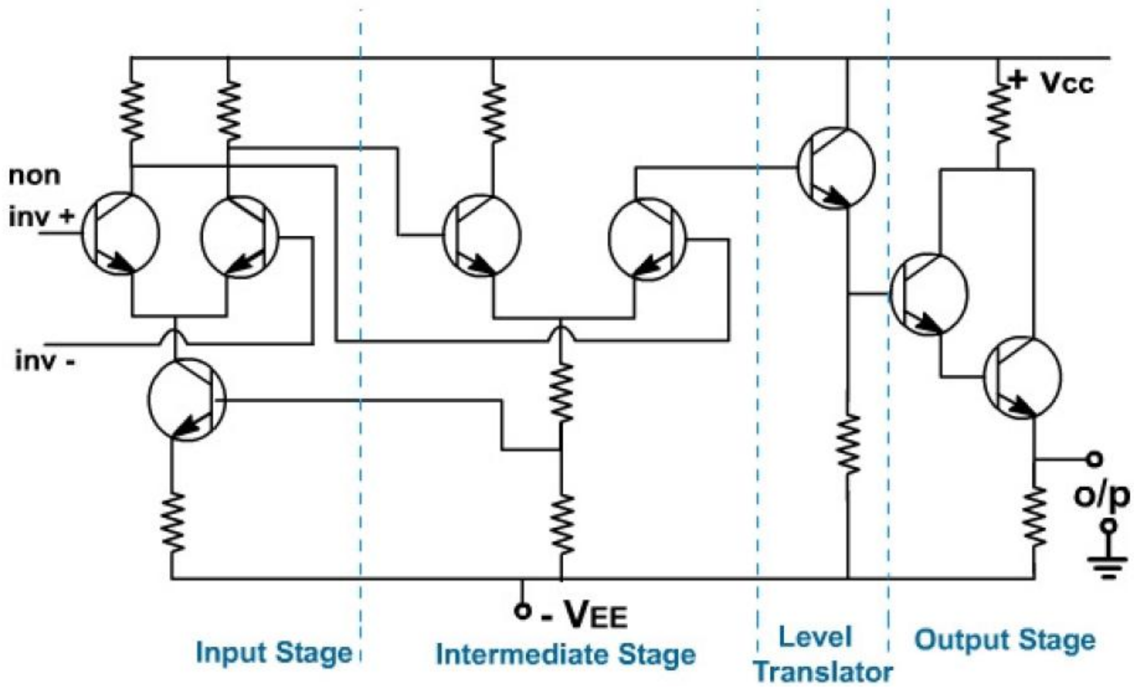

Fig 1.3 Circuit diagram of Op amp

DIFFERENTIAL AMPLIFIER:

A differential amplifier is an important building block of an op amp. It is a type of electronic amplifier that amplifies the difference between two input voltages but suppresses any voltage common to the two inputs. It is an analog circuit with two inputs and one output in which the output is ideally proportional to the difference between the two voltages.

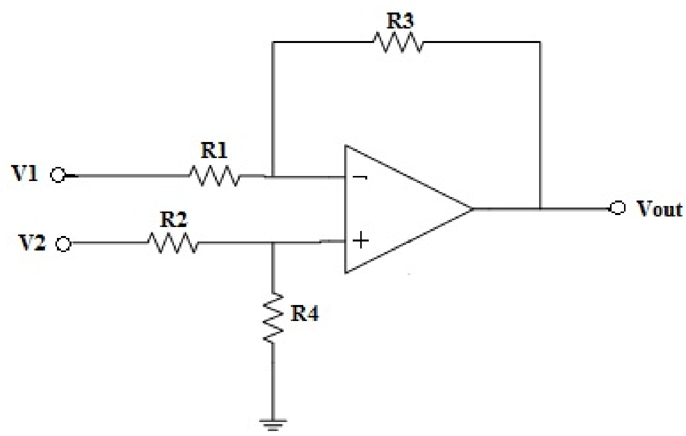

Fig 1.4 Differential amplifier circuit

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

i) Dual input balanced output

ii) Dual input unbalanced output

iii) Single input balanced output

iv) Single input unbalanced output

1) DUAL INPUT, BALANCED OUTPUT DIFFERENTIAL AMPLIFIER

The circuit shown below is a dual-input balanced-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.

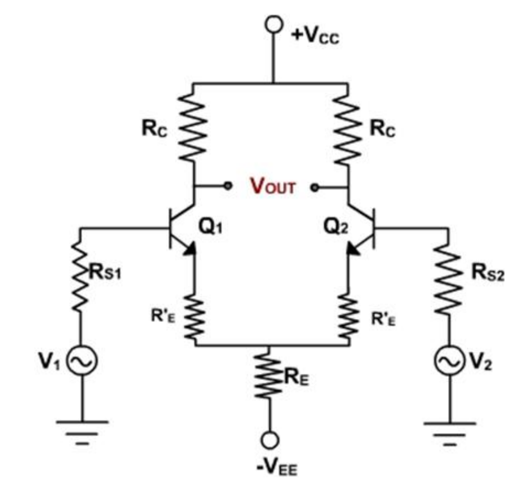

Fig 1.5 dual-input balanced-output differential amplifier circuit

Differential Amplifier with R_E DC Analysis:-

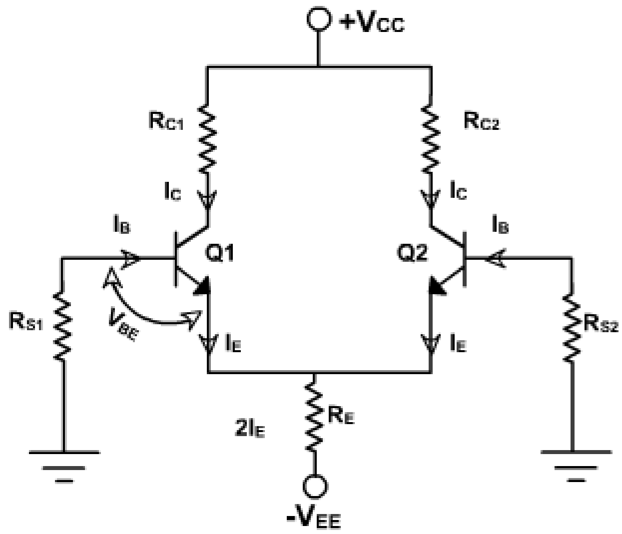

Fig 1.6 DC Equivalent Circuit For Dual-Input Balanced Output Differential Amplifier

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.

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

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

But, $I_B = I_E/\beta_{dc}$ since $I_C = I_E$. Thus the emitter current through Q_1 is determined directly from eqn (1) as follows :

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

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

$$\mathbf{I_{CQ} = I_E = (V_{EE} - V_{BE})/2R_E} \quad \mathbf{(3)}$$

From eqn(3), 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, a desired value of emitter current for a known value of

$-V_{EE}$ will be obtained. 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 $V_{CE} = V_C - V_E = (V_{CC} - R_C I_C) - (-V_{EE})$

$$\mathbf{V_{CEQ}=V_{CE} = V_{CC}+V_{BE} - R_C I_C} \qquad \textbf{(4)}$$

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.

<u>AC Analysis with r parameters</u> :-

To perform ac analyses 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

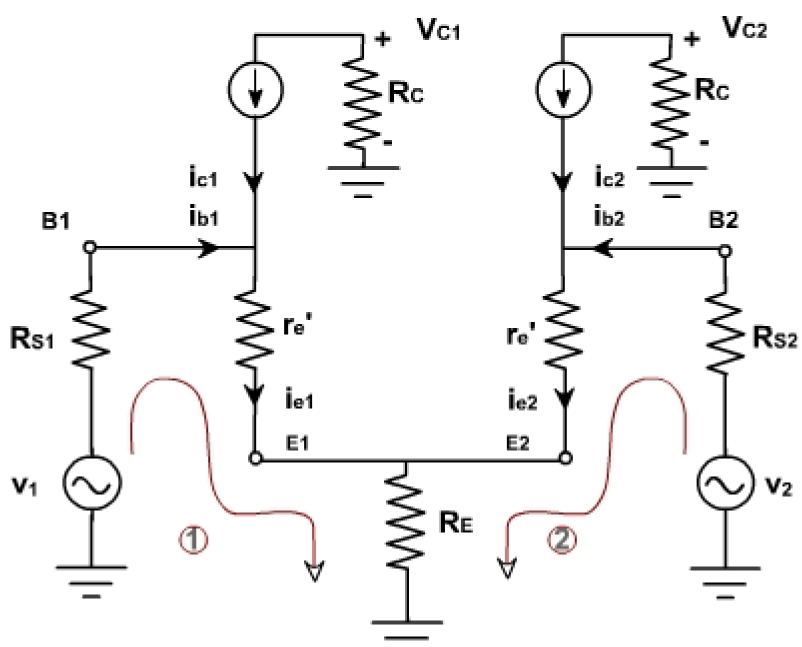

Fig 1.7 AC Equivalent circuit For Dual-Input Balanced Output Differential Amplifier

<u>Voltage Gain</u>:-

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

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

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

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:

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

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

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

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

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

Similarly

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

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

The output voltage is $v_o = v_{c2} - v_{c1}$

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

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

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

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

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

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

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

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

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)**

Differential Input Resistance:-

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 = β_{ac} r_e (2R_E)/R_E = 2$\beta_{ac}r_e$ **(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.

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.

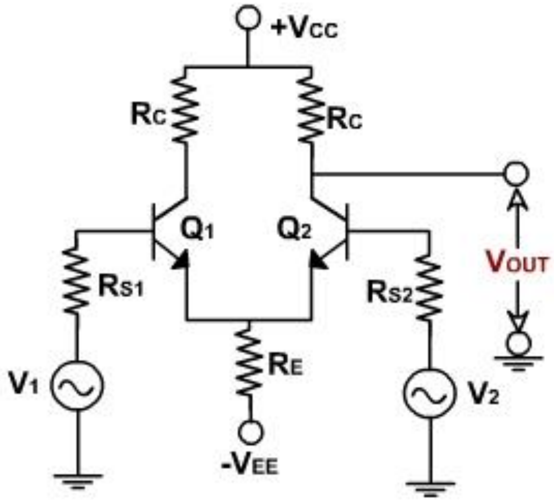

Fig 1.8 dual-input unbalanced-output differential amplifier circuit

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.

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

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

AC Analysis:

The output voltage gain in this case is given by

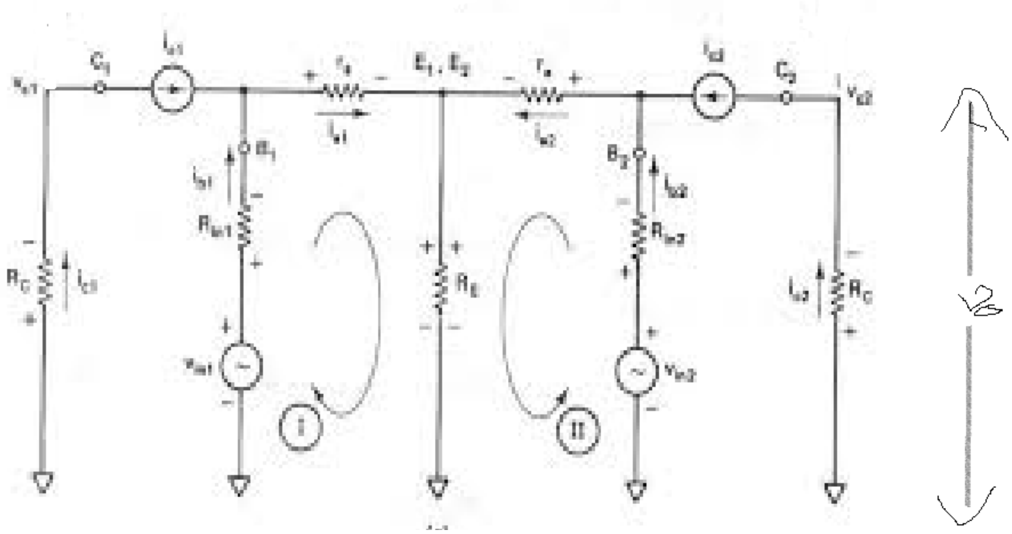

Fig 1.9 AC Equivalent circuit For Dual-Input Un-Balanced Output Differential Amplifier

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

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

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

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

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

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

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

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 Resistance:

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 Resistance:

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:

Figure illustrates a differential amplifier where the input to Q_2 is grounded and the output is taken as v_{o1}. As discussed in the previous section, a constant current source is used in place of R_{EE}. This configuration is known as a **single-ended input and output amplifier with phase reversal**. To analyze this amplifier, all we have to do is set $v_2=0$ in the earlier equations. If we assume that the equivalent resistance of the current source is very large, the common-mode gain is approximately equal to zero. This means the single-ended differential-mode gain of the amplifier will determine the output, which will be

$$v_{out} = A_d v_{di} = \frac{-R_C v_1}{2r_e}$$

The negative sign indicates that there is a 180^o phase shift between the input (v_1) and the output (v_{o1}).

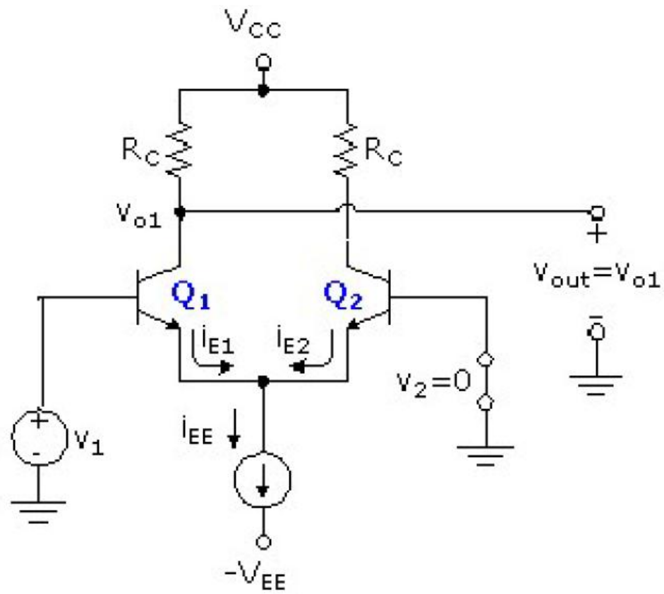

Fig 1.10 Single input and output differential amplifier

CONSTANT CURRENT SOURCE

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.

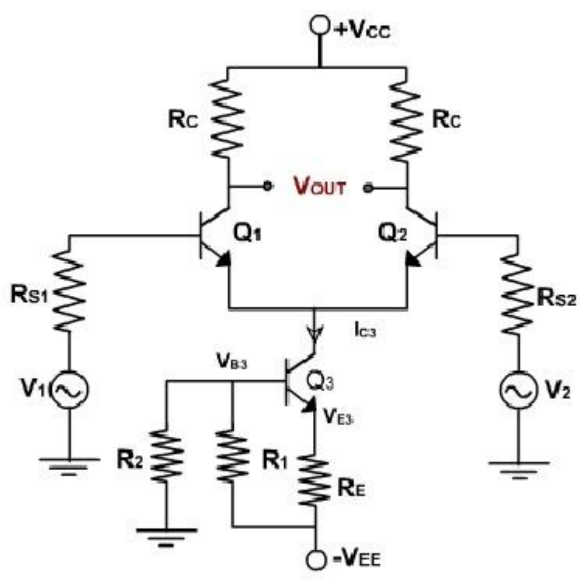

Fig 1.11 Constant Current Source

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

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

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

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

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

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

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

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.

CURRENT MIRROR CIRCUIT:

The circuit in which the output current is forced to equal the input current is said to be a current mirror circuit. Thus in a current mirror circuit, the output current is a mirror image of the input current.

Once the current I2 is set up, the current IC3 is automatically established to be nearly equal to I2. The current mirror is a special case of constant current bias and the current mirror bias requires of constant current bias and therefore can be used to set up currents in differential amplifier stages. The current mirror bias requires fewer components than constant current bias circuits. Since Q3 and Q4 are identical transistors the current and voltage are approximately same.

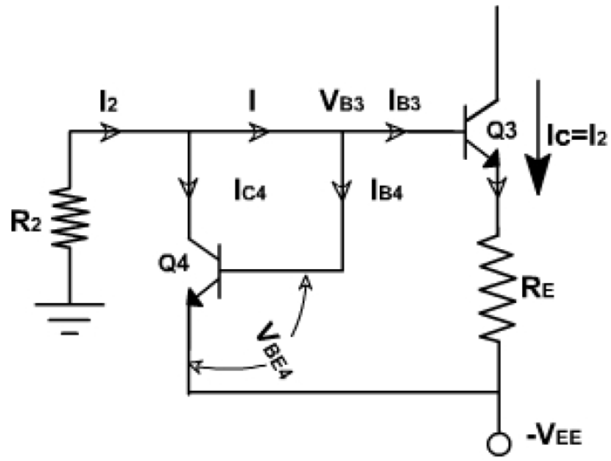

Fig 1.12 current mirror circuit

$$V_{BE3} = V_{BE4}$$

$$I_{B3} = I_{B4}$$

$$I_{C3} = I_{C4}$$

Summing currents at node V_{B3}

$$I_2 = I_{C4} + I$$

$$= I_{C4} + 2I_{B4} = I_{C3} + 2I_{B3}$$

$$= I_{C3} + 2\left(\frac{I_{C3}}{\beta_{dc}}\right)$$

$$= I_{C3}\left(1 + \frac{2}{\beta_{dc}}\right)$$

Generally β_{dc} is large enough, therefore $2/\beta_{dc}$ is small.

$$\therefore I_2 \approx I_{C3}$$

$$I_2 = \frac{V_{EE} + V_{BE3}}{R_2}$$

LEVEL TRANSLATOR:

Level shifting circuit is used to shift the dc level at the output downward to zero with respect to ground. An emitter follower with voltage divider is the simplest form of level translator. Instead of voltage divider emitter follower either with diode current bias or current mirror bias may be used to get better results. In this case, level shifter, which is common collector amplifier, shifts the level by 0.7V. If this shift is not sufficient, the output may be taken at the junction of two resistors in the emitter leg.