Differential Amplifier

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Intro

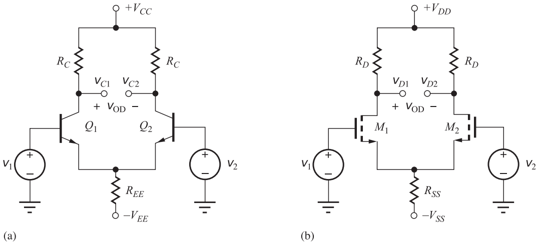
Differential Amplifier

Direct Coupled Amplifier

- Coupling capacitors limit the low-frequency of the amps and reduce its applications as dc amps
- For an amp to deliver gain at dc, capacitors connected in series must be removed
- Using a direct coupled design eliminates additional resistors that are needed to bias individual stages in an ac coupled amp
- dc-coupled differential amps are the most important basic buildings blocks for analog design
- Differential amp are like soja, it appear in every analog integrated circuit
- These circuits are key for operational amp as well as of most dc coupled analog circuits
- A differntial amp has 2 BJT in symmetrical configuration, it usually is a single stage amp

Direct Coupled Amplifier

- Figure shows a BJT & MOS version of a differential amp
- Each circuit has 2 input v_1 & v_2 and a differential output mode v_{OD}
- Ground reference outputs are focused between collector and drain v_{C1}, v_{C2}, v_{D1}, or v_{D2} and ground
- The symmetrical nature of the amp gives useful dc and ac properties
- The diff. amp. behaves as an inverting or non-inverting amp for diff. input signals but tend to reject signals common to both inputs

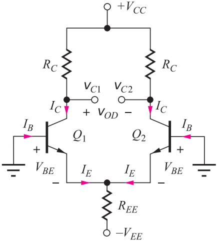


Direct Coupled Amplifier

- Ideal performance is obtained from the differential amplifier only when it is perfectly symmetrical
- Best versions are built using IC technology in which the transistor characteristics can be closely matched
- Two transistors are said to be matched if they have identical characteristics and parameter values
- The parameter sets ($I_S, \beta_{FO}, V_A) or (K_n, V_{TN}$ and λ), Q-points, and temperatures of the two transistors are identical

dc Analysis of the BJT Diff. Amp.

- We, as always, start by finding the transistor operating point
- the quiescent operation points can be found by setting both input signals to zero as shown in fig.
- Both bases are grounded and the two emitters are connected together, ergo $V_{BE1} = V_{BE2} = V_{BE}$
- If Q_1 & Q_2 match, the symmetry forces $V_{C1} = V_{C2} = V_C$ and Is at both transistors are identical $I_{C1} = I_{C2} = I_C$, $I_{E1} = I_{E2} = I_E$



$$I_C = \alpha_F \frac{V_{EE} - V_{BE}}{2R_{EE}} \cong \frac{V_{EE} - V_{BE}}{2R_{EE}}$$

$$V_{CE} = V_{CC} + V_{BE} - I_C R_C$$

dc Analysis of the BJT Diff. Amp.

- Emitter current according to Q_1 is

$$V_{BE} + 2I_E R_{EE} - V_{EE} = 0$$

and

$$I_C = \alpha_F I_E = \alpha_F \frac{V_{EE} - V_{BE}}{2R_{EE}}$$

by considering

$$I_B = I_C/\beta_F$$

colector voltages are defined as: $V_{C1} = V_{C2} = V_{CC} - I_C R_C$ and $V_{CE!} = V_{CE2} = V_{CC} + V_{BE} - I_C R_C$ For the symmetrical amplifier, the dc output is zero

$$V_{OD} = V_{C1} - V_{C2} = 0V$$

Example 1

- Determine que Q-point for the emitter coupled pair by considering $V_{CC} = V_{EE} = 15V$, $R_{EE} = R_C = 75k\Omega$, β_F=100

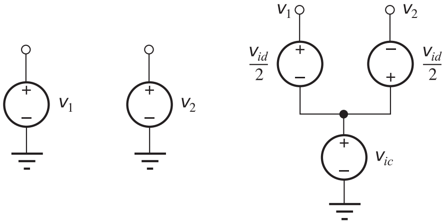
$$I_E = \frac{V_{EE} - V_{BE}}{2R_{EE}} = \frac{17 - 0.7}{2 \cdot 75} \approx 9.53 \times 10^{-2} mA$$

$$I_C = \alpha I_E = \frac{100}{100 + 1} \cdot 9.53 \times 10^{-2} = 9.44 \times 10^{-2} mA$$

$$V_{CE} = V_{CC} - I_C R_C + V_{BE} = 15 - 9.44 \times 10^{-2} \cdot 75 + 0.7 = 8.62V$$

ac Analysis of the BJT Diff. Amp.

- Once we've got the Q-point info, we continue to small signal analysis to characterize the gain voltage as well as input and output resistance
- ac Analysis of the diff. amp. is simplified by breaking the input sources v_1 & v_2 into the equivalent differential-mode input (v_{id}) and common-mode input (v_{ic}), $v_{id} = v_1 - v_2$ and $v_{ic} = \frac{v_1 - v_2}{2}$
- The input voltage can be written in terms of v_{ic} and v_{id}, ergo $v_1 = v_{ic} + \frac{v_{id}}{2}$ and $v_2 = v_{ic} - \frac{v_{id}}{2}$



ac Analysis of the BJT Diff. Amp.

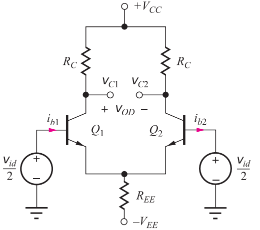
- The differential-mode and common-mode output voltages, v_{od} and v_{oc} , are defined as $v_{od} = v_{c1} - v_{c2}$ and $v_{oc} = \frac{v_{c1} - v_{c2}}{2}$
- For the general case, v_{od} & v_{od} are function of v_{id} and v_{ic} can be written as

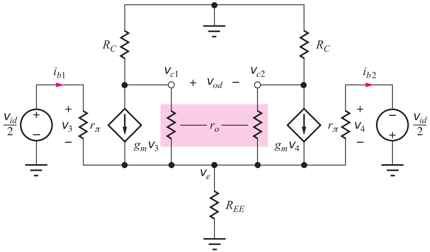
$$M = \begin{bmatrix} v_{od} \\ v_{oc} \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{cd} \\ A_{dc} & A_{cc} \end{bmatrix} = \begin{bmatrix} v_{id} \\ v_{ic} \end{bmatrix}$$

where:
A_{dd} = differential-mode gain
A_{cd} =common-mode(todifferential-mode)conversiongain
A_{cc} = common-mode gain
A_{dc} = differential-mode (to common-mode) conversion gain

Differential mode gain and input resistance

- Purely differential-mode input signals are applied to the differential amplifier
- 2 transistors are replaced with their small-signal models





$$\frac{V_{be1}}{r_\pi} + gmV_{ve1} + g_m v_{be2} + \frac{v_{be2}}{r_\pi} = \frac{v_e}{r_{EE}}$$

$$\frac{1}{r_\pi} + g_m(v_{be1} + v_{be2}) = \frac{v_e}{R_{EE}}$$

$$v_{be1} = \frac{v_{id}}{2} - v_e;\ v_{be2} = -\frac{v_{id}}{2} - v_e;\ v_{be1} + v_{be2} = -2v_e$$

$$(I/r_\pi + g_m)(-2v_e) = \frac{v_e}{R_{EE}}\quad v_e\left(\frac{1}{R_{EE}} + \frac{2}{r_\pi} + 2g_m\right) = 0 \rightarrow v_e = 0$$

Differential mode gain and input resistance

- For a purely differential-mode input voltage, the voltage at the emitter node is identically zero
- The "virtual ground" at the emitter node causes the differential amplifier to behave as a common-emitter (or common-source) amplifier $v_{be1} = \frac{v_{id}}{2}$; $v_{be2} = -\frac{v_{id}}{2}$

$$v_{c1} = -(g_m v_{be1})R_C$$

$$v_{c2} = -(g_m v_{be2})R_C$$

$$v_{od} = -gmR_C v_{id}$$

- The differential mode gain (A_{dd}) for a balanced output, $v_{od} = v_{c1} - v_{c2}$ is defined as

$$A_{dd} = \frac{v_{od}}{v_{id}} \mid_{v_{ic}=0} = -g_m R_C$$

Differential mode gain and input resistance

- If either v_{c1} or v_{c2} alone is used as the output, referred to as a single-ended (or ground-referenced) outputs

$$A_{dd1} = \frac{v_{c1}}{v_{id}} \Big|_{v_{ic}} = \frac{-g_m v_{be1} R_C}{2 v_{be1}} = -\frac{g_m R_C}{2} = \frac{A_{dd}}{2}$$

$$A_{dd2} = \frac{v_{c2}}{v_{id}} \Big|_{v_{ic}} = \frac{g_m v_{be2} R_C}{2 v_{be2}} = \frac{g_m R_C}{2} = -\frac{A_{dd}}{2}$$

- The differential mode input resistance

$$R_{id} = \frac{v_{id}}{i_{b1}} = 2 r_\pi$$

- The differential-mode output resistance

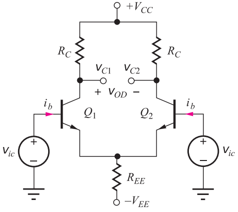
$$R_{od} = 2 R_C$$

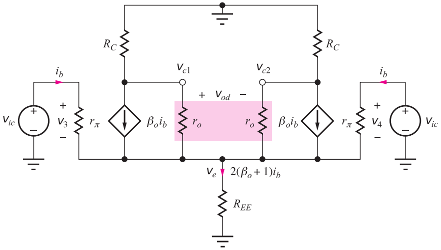
- For single-ended outputs

$$R_{out} = R_C$$

Common mode gain and input resistance

- Both sides of the amplifier are completely symmetrical
- The two base, the emitter, the collector currents and the two collector voltages must be equal
- According to Figure, the small-signal model we've got
  $v_{ic} = i_b r_\pi + 2(\beta_0 + 1) i_b R_{EE}$ $i_b = \frac{v_{ic}}{r_\pi + 2(\beta_0 + 1) R_{EE}}$
  $v_{cl} = v_{c2} = -(\beta_0 i_b) R_C$





Common mode gain and input resistance

$$A_{cc} = \frac{v_{oc}}{v_{ic}} \Big|_{v_{id}=0} = -\frac{\beta_0 R_C}{r_\pi + 2(\beta_0+1)R_{EE}} \approx -\frac{R_C}{2R_{EE}}$$

$$A_{cc} = -\frac{R_C}{2R_{EE}} = -\frac{C_{CC}}{2(V_{EE}-V_{BE})} \approx \frac{V_{CC}}{2V_{EE}}$$

the differential output voltage v_{od} is zero: $v_{od} = v_{c1} - v_{c2} = 0$

$$A_{cd} = \frac{v_{od}}{v_{ic}} \Big|_{v_{id}=0} = 0$$

A more accurate expression for the common-mode gain is

$$A_{cc} = R_C \left(\frac{1}{\beta_0 r_0} - \frac{1}{2R_{EE}} \right)$$

For an infinite R_{EE}, A_{cc} is limited to $R_C/\beta_0 r_0 \approx V_{CC}/2\beta_0 V_A$
It is determined by the total signal current (2_{ib}) being supplied from the common-mode source

$$R_{ic} = \frac{v_{ic}}{2_{ib}} = \frac{r_\pi + 2(\beta_0+1)R_{EE}}{2} = \frac{r_\pi}{2} + (\beta_0+1)R_{EE}$$

Common mode rejection ratio (CMRR)

- CMRR, characterizes the ability of an amplifier to amplify the desired differential-mode input signal and reject the undesired common- mode input signal
- It is defined as

$$CMRR = \left| \frac{A_{dm}}{A_{cm}} \right|$$

  where A_{dm} and A_{cm} are the overall differential-mode and common-mode gains
- For a differential output v_{od} , the common-mode gain of the balanced amplifier is zero, and the CMRR is infinite and the output is taken from each collector as
  $v_{c1} = v_{oc} + \frac{v_{od}}{2} = A_{cc}v_{ic} + \frac{A_{dd}}{2}v_{id}$ and
  $v_{c2} = v_{oc} + \frac{v_{od}}{2} = A_{cc}v_{ic} + \frac{A_{dd}}{2}v_{id}$

Common mode rejection ratio (CMRR)

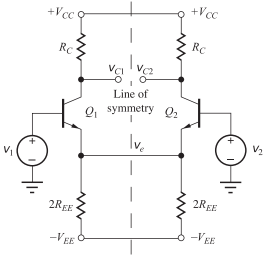
- CMRR is based as

$$\frac{A_{dm}}{a_{cm}} = \frac{\frac{A_{dd}}{2}}{A_{cc}} = \frac{\frac{g_m R_C}{2}}{R_C\left(\frac{1}{\beta_0 r_0} - \frac{1}{2R_{EE}}\right)} = \frac{1}{2\left(\frac{1}{\beta_0 r_0} - \frac{1}{2g_m R_{EE}}\right)}$$

- For infinite R_{EE}, $CMRR \approx \frac{\beta_0 \mu_f}{2}$
- If the term containing R_{EE} is dominant $CMRR \approx g_m R_{EE} = 40 I_C R_{EE} = 20(2 I_E R_{EE}) = 20(V_{EE} - V_{BE}) \approx 20 V_{EE}$

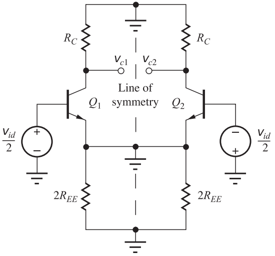
Rules to design differential half-circuits

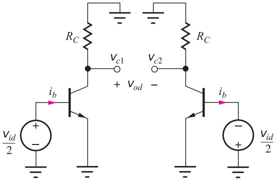
- We noted that the differential amplifier behaves much as the single-transistor common-emitter amplifier
- Differential-mode signals, Points on the line of symmetry represent virtual grounds and can be connected to ground for ac analysis
- Common-mode signals, Points on the line of symmetry can be replaced by open circuits



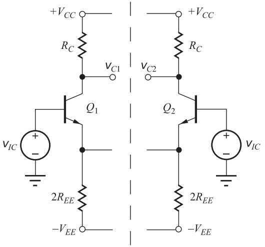
Common-mode half circuits

- Emitters are in short





- we've got



Common-mode half circuits

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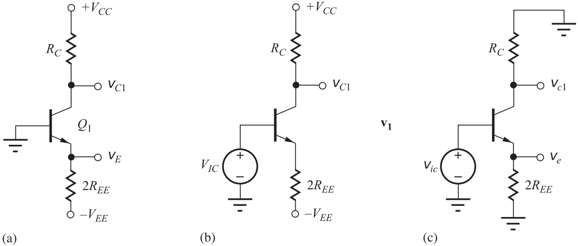

- To be continue···