Exercise 5.

Testing basic transistor circuits

Required knowledge

- DC and AC models of transistors (Linear DC model of the bipolar transistor in active region, G-parameter model, H-parameter model, Hybrid Pi model)
- Input and output characteristics of the bipolar transistor
- Transistors in switching mode.

Introduction

In the field of analogue electronics, the basic transistor amplifiers represent a typical example of such electrical engineering knowledge where both the theory and the practical experiences are important.

Aim of the measurement

The students get acquainted with the basic calculations and measurements on bipolar transistor amplifiers (calculation of the operation point data, parameters of the equivalent circuit, calibrating measurements etc.).

Keywords

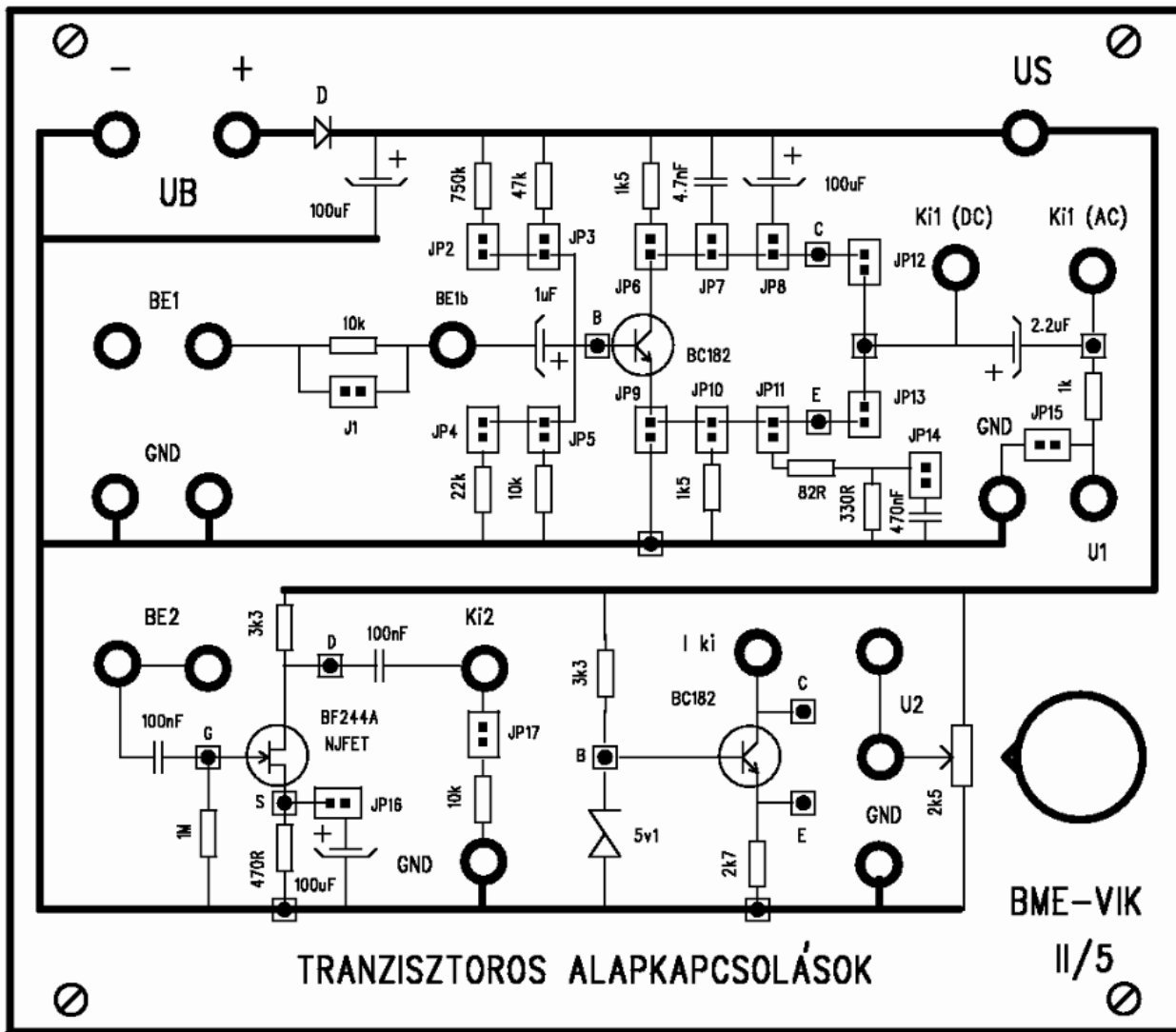Common emitter amplifier, emitter feedback, phase splitter, emitter follower, BJT

Web links

http://en.wikipedia.org/wiki/Transistor

Measurement instruments

Digital oscilloscope   AGILENT 54622A

Function generator   AGILENT 33220A

Digital multimeter (6½ digit)   AGILENT 33401A

Power Supply   AGILENT E3630

Test panel

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Test boards

Schematic diagram of the Test board

Theoretical background

1. Bipolar transistor (recall from Laboratory I.)

Two types of bipolar transistors are defined according to the doping of the different layers of the transistor: type npn and type pnp transistors (the first letter gives the doping type of the collector, the second gives that of the base and the third letter is that of the emitter layer).

The polarities of a bipolar transistor in the so-called normal active region:

Type: npn
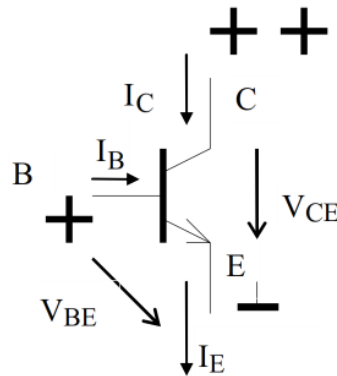
With respect to the emitter as the reference electrode, the voltage of the base must be more positive (by about 0.6 – 0.7V) and the voltage of the collector must be more positive than that of the base.

Transistor-effect

Because of the thin base layer, the transistor cannot be considered as a simple combination of two diodes. Due to the forward biased base-emitter junction, electrons enter the base layer from the emitter. There, as minority charge carriers, they will be attracted by the positive collector voltage and flow against this reverse biasing voltage mainly towards the collector. Only a small part of the electrons flows to the base electrode. The ratio of the collector current and the base current is called the current gain of the transistor in common emitter connection. The current gain is nearly independent of the amount of these currents. Its notation is B:

$$B = \frac{I_C}{I_B}$$

The typical order of magnitude is: B = 100. The constant current gain makes it possible to control the relatively large collector current (and the related emitter current) by the much smaller base current.

Summary of the transistor-effect: although the collector-base pn-junction is reverse biased, a current flows through this pn-junction, and the amount of the greater collector (and emitter) current can be controlled by the much smaller base current.

Output characteristics of a transistor

Parameter of the characteristics: I_B. $I_{B3} > I_{B2} > I_{B1} > I_{B0}$

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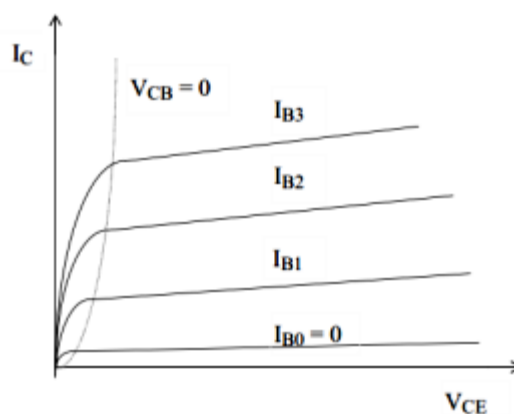
The greater is I_B, the higher runs the corresponding characteristic line. The area between the limit lines with the parameters $V_{CB} = 0$ and $I_{B0} = 0$ is called normal active region. Transistors in amplifiers are operated in this region.

The input characteristic of a transistor is like the characteristic of a diode, giving the relationship of I_B and V_{BE}. In the normal active region with the usual current values in small signal transistors:

$$I_E \approx I_C = 0.1\ mA\ ...\ 10\ mA$$

The voltage between the base and the emitter is (just like in case of the diode junctions):

$$V_{BE} = 0.6\ V$$

This means that the *DC equivalent circuit* of the transistor is:
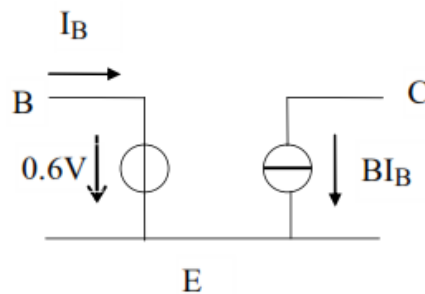
By means of this DC equivalent circuit, the operation point of the transistor can be determined. The operation point data comprises I_C, V_{CE} and sometimes also I_B (if it is not negligible).

General method of the operation point calculation of a transistor

The following circuit is given.

DC equivalent circuit:

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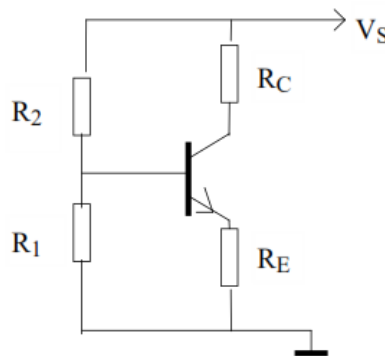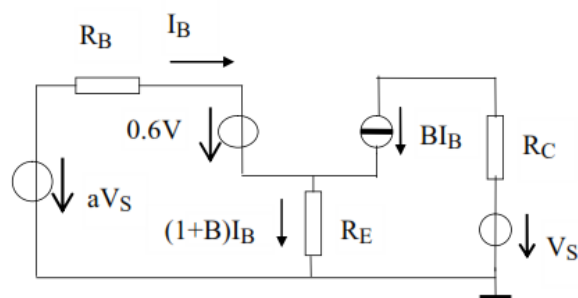
In the equivalent circuit:

- R_B is the internal resistance of the base-divider: $R_B = R_1 \times R_2$

- $a = \dfrac{R_1}{R_1 + R_2}$

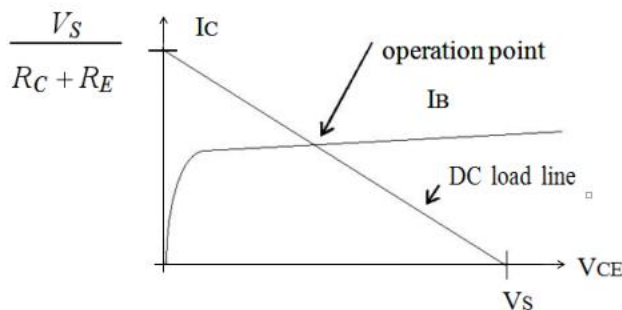By means of the equivalent circuit: $I_B = \dfrac{aV_s - 0.6}{R_B + (1+B)R_E}$

$I_C = BI_B$

$V_{CE} \approx V_S - (R_E + R_C)I_C$

supposing that: $I_C \approx I_E$

Graphically:

Practical method of the operation point calculation of a transistor

Approximation: $I_B \approx 0$ (verified by whether $[1+B]R_E \gg R_B$ is fulfilled)
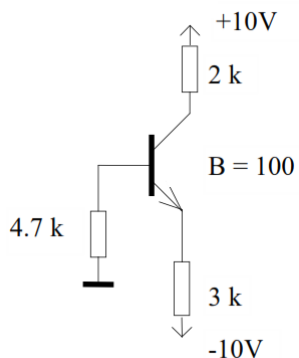
With this: $V_B = aV_S$

$V_E = V_B - 0.6V$

$I_C \approx I_E$

$I_C \approx I_E = \dfrac{V_E}{R_E}$

$V_{CE} \approx V_S - (R_E + R_C)I_C$

Example:

$I_B = 0$ $\rightarrow$ $V_B = 0$ $\rightarrow$ $V_E = -0.6$ V
Thus:

$I_C \approx I_E = (-0.6 - [-10])/3 = \underline{3.1 \text{ mA}}$
$V_{CE} = 20 - 3.1*(3 + 2) = \underline{4.5 \text{ V}}$

Check:

$(1 + 100) \, 3 \gg 4.7$ ✓   O.K.

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The significance of the resistance R_E: stabilisation of the operation point by negative DC feedback. If the temperature changes, a different base-emitter voltage belongs to the same emitter current. The relations can be described by the following temperature coefficient:

$$\frac{dV_{BE}}{dT} = -2... - 2.2 \frac{mV}{{}^\circ C}.$$

For example the rise of the temperature results a smaller V_{BE} maintaining the same current. If the base voltage, in spite of the temperature change, remains constant, and the connection

has no R_E, the current of the transistor will increase. The greater current means greater power on the transistor heating it and thereby resulting a still higher temperature, etc. This process may destroy the transistor at the end. But if there is a resistance R_E, the greater current develops a greater voltage drop across it, making the voltage V_{BE} almost automatically smaller and with a proper value of R_E, the catastrophic overheating of the transistor will be hindered.

Thumb-rule for the required value of the emitter resistance:

$$\mathbf{R_E \, I_E \geq 1V.}$$

It is also possible to stabilise the operation point by means of a parallel voltage feedback. An example for this:
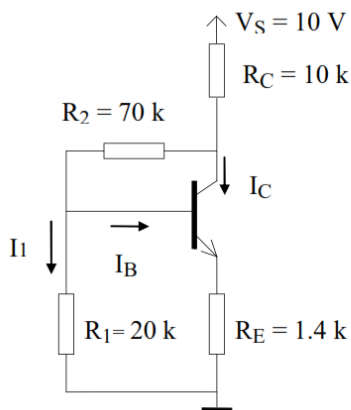
Calculation of the op. point data:
Suppose: $I_B \approx 0$.
The following equations can be written:

1. $V_C = V_S - (I_C + I_1)R_C =$
          $= I_1(R_1 + R_2)$

2. $V_B = \dfrac{V_C R_1}{R_1 + R_2} = I_1 R_1$

3. $V_E = V_B - 0{,}6 \text{ V}$

4. $I_C = I_E = \dfrac{V_E}{R_E}$

With numbers:
From equation No.1.: $I_1 = (V_S - R_C I_C)/(R_1 + R_2 + R_C) = ... = 0.1 - 0.1 I_C$

From equations Nos. 4, 3 and 2: $I_C = (I_1 R_1 - 0.6)/R_E =$
          $= ([0.1 - 0.1 I_C] \, 20 - 0.6)/1.4$

From this the current I_C can be calculated: $\underline{I_C = ... = 0.412 \text{ mA}}$
Substituting this result into the equation of I_1: $I_1 = 0.1 - 0.1*0.412 = 0.059 \text{ mA}$
The corresponding collector-emitter voltage: $\underline{V_{CE} = 10 - 10(0.412 + 0.059) - 0.412*1.4 =}$
          $\underline{= 4.74 \text{ V}}$

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The above calculation if I_B is not negligible ($I_B \neq 0$, suppose that $B = 100$):
The equations in this case:

1. $V_C = V_S - (I_C + I_1 + I_B)R_C = I_1 R_1 + (I_1 + I_B) R_2$
2.- $V_B = I_1 R_1$
3. $V_E = V_B - 0{,}6 \text{ V}$
4. $I_C + I_B = I_E = \dfrac{V_E}{R_E}$

Writing everywhere $I_B = \dfrac{I_C}{B}$, we get

from equation 1:

$$I_1 = \frac{V_S - I_C\left[\left(1 + \dfrac{1}{B}\right)R_C + \dfrac{R_2}{B} + \dfrac{R_2}{B}\right]}{R_1 + R_2 + R_C}$$

and from equations 4, 3 and 2:

$$I_1 = \frac{I_C\left(\left(1 + \dfrac{1}{B}\right)R_E + 0.6\right)}{R_1}.$$
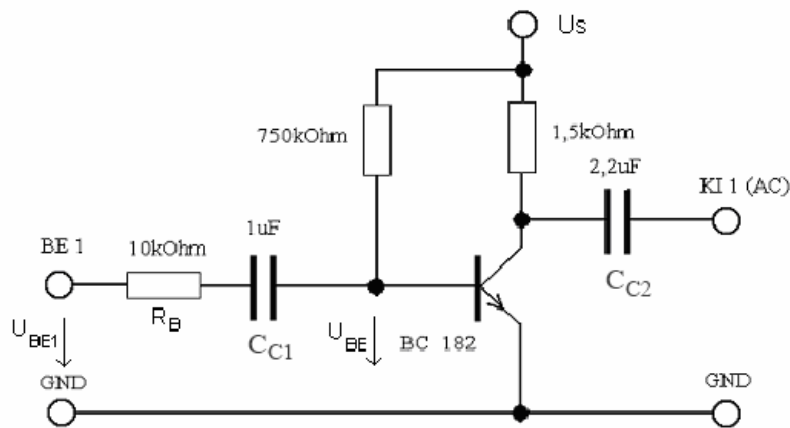
From the equality of the two right sides I_C can be calculated: $I_C = \ldots = 0.41 \text{ mA}$.

I_1 can be calculated now from either of the above expressions: $I_1 = \ldots = 0.055 \text{ mA}$

From eqations 1 and 2 V_C and V_E can be calculated and with them: $V_{CE} = \ldots = 4.74 \text{ V}$.

(End of practice)

2. Common emitter stage

The role of capacitances C_{C1} and C_{C2}: DC separation of the generator and the load, so that they will not disturb the operation point. But on AC these coupling capacitances are practically short circuits:
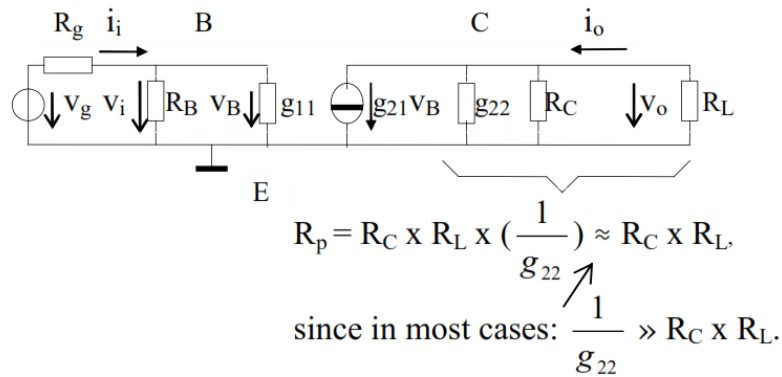
$$\frac{1}{\omega C_{Ci}} \approx 0 \quad (i = 1, 2).$$

The behavior of the stage on AC can be analyzed by means of the AC equivalent circuit.
Principles of drawing the AC equivalent circuit:
• The transistor is drawn with its own equivalent circuit.

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- DC voltage sources are replaced by short circuits (e.g. the supply lines are considered as AC grounds)
- Large capacitances are replaced by short circuit and small ones by open circuit.

The AC equivalent circuit of the common emitter stage:

$$R_p = R_C \times R_L \times (\frac{1}{g_{22}}) \approx R_C \times R_L,$$

$$\text{since in most cases: } \frac{1}{g_{22}} \gg R_C \times R_L.$$

The voltage gain:
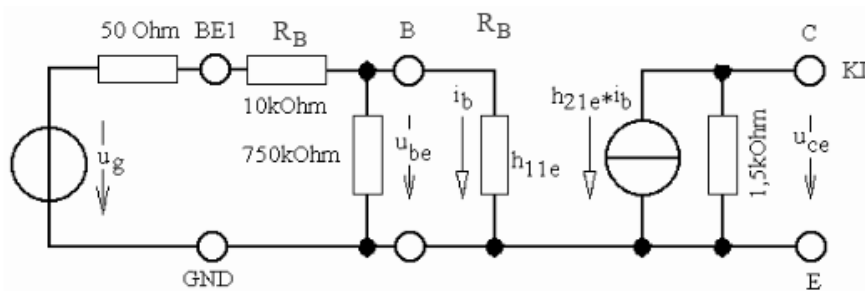
$$A_v = \frac{v_0}{v_i} = - g_{21}v_B R_p / v_B = - g_{21}R_p$$

The input resistance:

$$R_{in} = v_i / i_i = R_B \times (\frac{1}{g_{11}})$$

The output resistance:

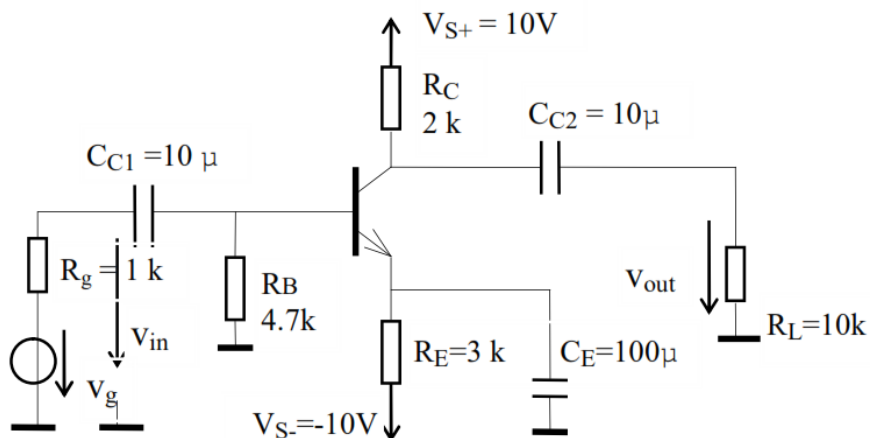$$R_{out} = R_C \times (\frac{1}{g_{22}}) \approx R_C$$

The h parameters of the transistor can be measured based on the following equivalent circuit:

The value of h_{11e}:

$$\left(\Delta i_{BE1} = \frac{v_{BE1} - v_{BE}}{R_B} \quad , \quad h_{11e} = \frac{\Delta v_{BE}}{\Delta i_{BE1}} \bigg|_{U_{KI1=0}} \right)$$

Numeric example for the common emitter stage (Practice):

Data of the transistor:

    $r_{BB'}$ is negligible

    $B \approx \beta = 100$

    $g_{22} = 10 \mu S$

The operation point:

    $I_B \approx 0$

    $I_C \approx I_E = \underline{3.1mA}$

    $V_{CE} = \underline{4.5V}$

Calculated transistor parameter:

$$r_E = V_T/I_E = 26/3,1 = 8.4\Omega$$

thus: $h_{11} = r_{BB'} + (1+\beta)r_E \approx (1+100)8.4 = 847\Omega$

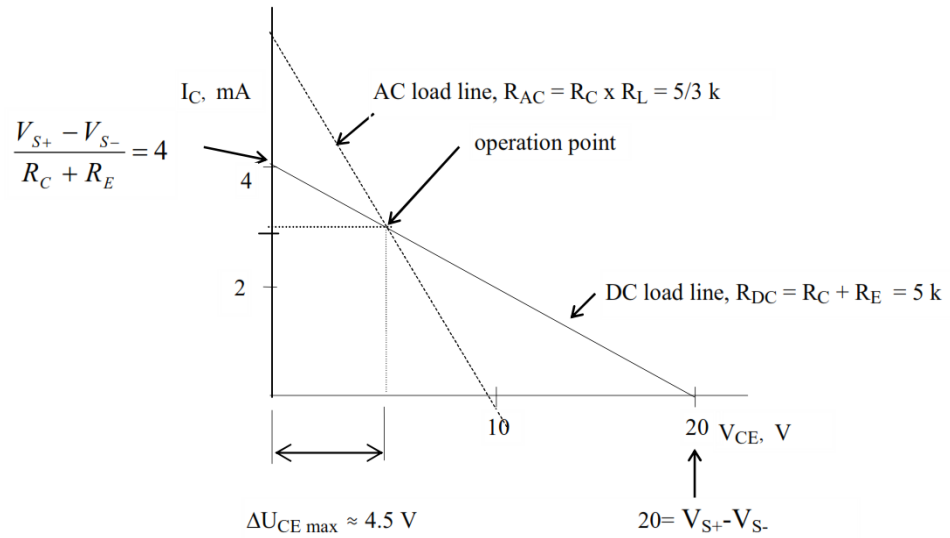and: $g_{21} = h_{21}/h_{11} = \beta/h_{11} = 100/0.847 = 118mS$

The voltage gain:

    $A_V = - g_{21}/R_p = -118/(2 \times 10 \times 100) = -197$ ($R_p = 1.67k\ \Omega$)

The input resistance:

$$R_{in} = R_B \times \left(\frac{1}{g_{11}}\right) = R_B \times (h_{11}) = 4.7 \times 0.847 = \underline{0.72\,k\Omega}$$

$$R_{out} \approx R_C \times \left(\frac{1}{g_{22}}\right) = 2 \times 100\ k \approx \underline{2\ k\Omega}$$

The maximum output voltage swing:

$\dfrac{V_{S+} - V_{S-}}{R_C + R_E} = 4$

I_C, mA

AC load line, $R_{AC} = R_C \times R_L = 5/3$ k

operation point

DC load line, $R_{DC} = R_C + R_E = 5$ k

$\Delta U_{CE\ max} \approx 4.5$ V

$20 = V_{S+} - V_{S-}$

V_{CE}, V

To the right, the operation point could have greater amplitude (about $3.1\text{mA} \cdot 5/3\text{k}\Omega = 5.17\text{V}$), but the maximum output swing is determined always by the nearer limit, since a symmetrical driving signal is supposed. Thus:

$$V_{out\ p\ max} = \Delta V_{CE\ max} \approx 4.5\ \text{V}$$

$\uparrow$
(p = 'peak')

Common emitter stage with feedback in the emitter circuit:
The C_E is removed from the above circuit and a resistor is connected to the emitter. If the base voltage and thereby the emitter current changes, a voltage drop develops across R_E, which makes the B-E voltage smaller, thus it makes the emitter current also smaller (this phenomenon, the so-called emitter feedback, did not occur in the presence of the emitter capacitance C_E since this worked as an AC short circuit).

3. Phase splitter circuit
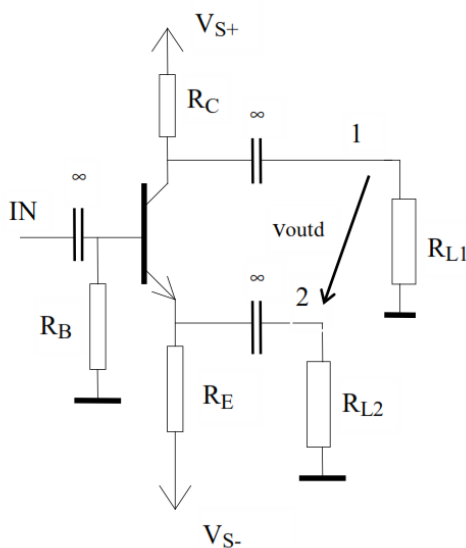
The voltage gain can be calculated towards output 1 as in case of the CE, towards output 2 as in case of the CC stage:

$$A_{v1} = -\frac{g_{21}(R_C \times R_{L1})}{1 + g_{21}(R_E \times R_{L2})}$$

$$A_{v2} = \frac{g_{21}(R_C \times R_{L2})}{1 + g_{21}(R_E \times R_{L2})}$$

If $R_C \times R_{L1} = R_E \times R_{L2}$, then $A_{v1} = -A$, thus signals with same amplitudes but opposite phases can be taken from the two outputs.
It is also possible to use the voltage between the two output points as output voltage, e.g. for the drive of a differential input amplifier with pure differential mode input voltage. The voltage gain to this

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differential mode output is: $A_{vd} = -2$.

4. Common emitter stage (emitter follower)
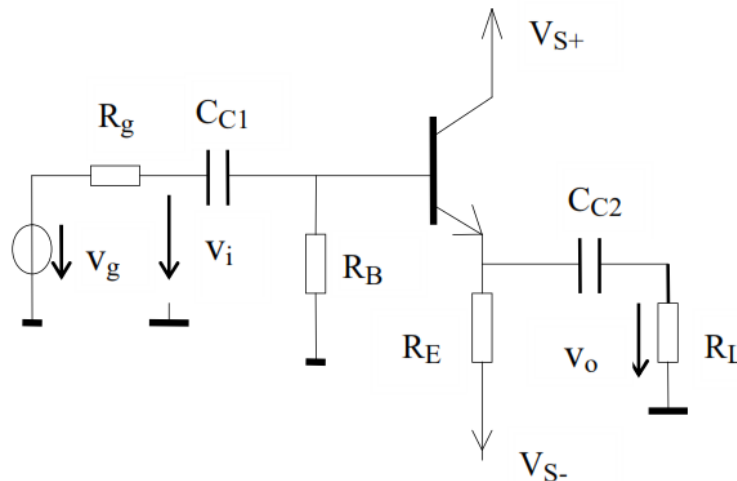
For the coupling capacitances:

$$\frac{1}{\omega C_{C1}}, \quad \frac{1}{\omega C_{C2}} \approx 0.$$

The change V_{BE} is the difference of the input and output voltages. Since V_{BE} is almost constant, the output voltage is nearly equal to the input voltage.

Test questions:

1. How to calculate the input and the output time-constants of a common emitter amplifier stage?

2. How do we define the rise time and the fall time?

3. What is the cause of the voltage droop?

4. What is the relation between the rise time and the high limit frequency?

5. What is the relation between the low limit frequency and the voltage droop?

6. How can be determined the operation point of the transistor in a common emitter / collector / base configuration in case of a single supply or a double supply?

7. What does it mean „physical parameter"?

8. What is the effect of the emitter resistance on the high frequency time constants?

9. Draw the Bode plot of a common emitter stage at low frequency.

10. What is the effect of the emitter capacitance on the Bode plot of the common emitter amplifier?