Versuch 4: Transistor

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Contents

1 Introduction

In this experiment we examine the properties of a bipolar transistor as a class A amplifier. To observe the proporties we measured the characteristic curve of the transistor and tested different configurations of the emitter circuit.

2 Theoretical Considerations

2.1 Small Signal Model

For small deviations around the operating point one can use the small signal modell leading to the following equation.

$$\begin{pmatrix} dI_\mathrm{B} \\ dI_\mathrm{C} \end{pmatrix} = \begin{pmatrix} \frac{1}{r_\mathrm{BE}} & S_\mathrm{r} \\ S & \frac{1}{r_\mathrm{CE}} \end{pmatrix} \begin{pmatrix} dU_\mathrm{BE} \\ dU_\mathrm{CE} \end{pmatrix} \tag{1}$$

whereby r_BE, r_CE and the steepness S can be calculated with

$$\frac{1}{r_\mathrm{BE}} = \frac{\partial I_\mathrm{B}}{\partial U_\mathrm{BE}}|_{U_\mathrm{CE}} \tag{2}$$

$$\frac{1}{r_\mathrm{CE}} = \frac{\partial I_\mathrm{C}}{\partial U_\mathrm{CE}}|_{U_\mathrm{BE}} \tag{3}$$

$$S = \left.\frac{\partial I_\mathrm{C}}{\partial U_\mathrm{BE}}\right|_{U_\mathrm{CE}} = \frac{qI_\mathrm{C}}{k_\mathrm{B}T} \tag{4}$$

In addition to that I_B can be obtained by the following proportionality

$$I_\mathrm{B} \propto \exp\left(\frac{qU_\mathrm{BE}}{k_\mathrm{B}T}\right) \tag{5}$$

2.2 Emitter Circuit

An emitter circuit converts an input signal to an amplified output signal. The amplification of the output signal compared to the input signal is given by

$$A = \frac{dU_\mathrm{a}}{dU_\mathrm{e}} = -S \cdot (R_\mathrm{C} \,\| r_\mathrm{CE} \|\, R_\mathrm{L}) \tag{6}$$

and

$$A \approx -\frac{R_\mathrm{C}}{R_\mathrm{E}} \tag{7}$$

if the amplification is in the range of basevoltage drift.

3 Execution

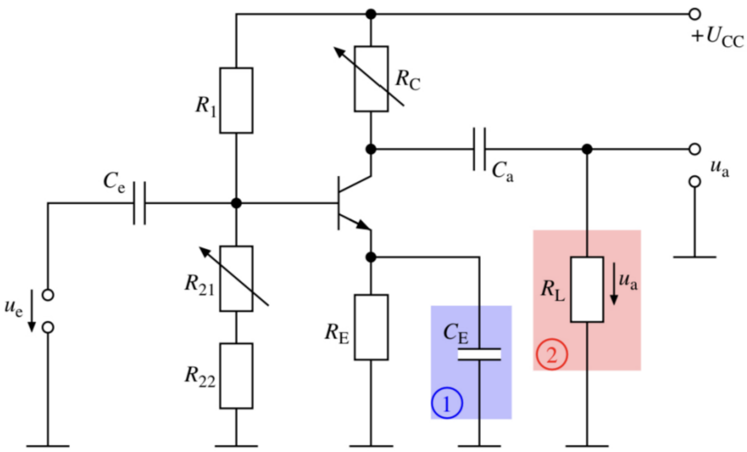

Figure 1: emittercircuit:
$R_1 = 47$ kΩ, $R_{22} = 100$ Ω,$R_E = 10$ kΩ, $C_e = 47$ µF,$C_a = 470$ µF, $U_{CC} = 9$ V R_{12}: potentiometer for the operating point, R_C: potentiometer 0 - 10 kΩ, u_e: inputvoltage, u_a: outputvoltage

3.1 Operating Point

A bipolar transistor has a specific base voltage range (the so called operating point) in which it behaves approximately linear. This operating point is tuned by setting the resistance at the potentiometer R_{12} (see circuit diagram 1) to a point whereby the output amplitude u_a is maximal and the signal is not distorted. To tune the operating point, the load resistor R_L was removed and a sinusoidal frequency of 5.5 kHz was applied. U_{BE}, U_{CE}, I_{C} where measured with varying R_{C} for further evaluation.

3.2 Amplification of the Emittercircuit

To further examine the emitter circuit(see circuit diagram 1) the amplitude ratio u_a/u_e was measured for varying R_{C} in different circuit configurations:
1. with capacitor CE but without resistor R_{L}
2. without capacitor CE and without resistor R_{L}
3. with capacitor CE and resistor R_{L}

3.3 Frequency Response

In this experiment the input frequency was varied from 6 Hz - 250 kHz to measure the phase shift and the amplidude ratio u_a/u_e. Here circuit 1 with an collector resistor of R_{C} was used. In addition to that the oszilloscope was changed to x-y mode to observe lissajous curves.

3.4 Characteristic Curve

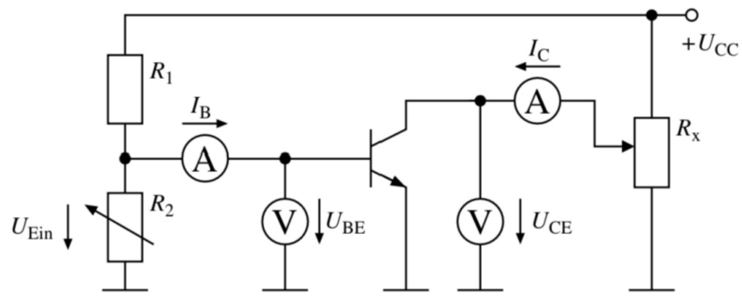

Figure 2: characteristic curve$R_1 = 1$ kΩ, $R_2 = 220$ Ω

To measure the characteristic curve of the transistor, the circuit was change as shown in the circuit diagram 2. First the entry curve $I_B = f(U_{BE})|_{U_{CE}}$ was taken by changing U_{BE} from 0 to 670 mV and measuring I_B, U_{BE} and U_{CE} with multimeters according to the schematic 2. Therby U_{CE} was dialed in to match the results from experiment 1 4.2 with $R_C = 5$ kΩ. Afterwards the output characteristic curve $I_C = f(U_{CE})|_{U_{BE}}$ was recorded with a varying U_{CE} from 1 - 10 V by measuring I_C, U_{BE} and U_{CE}. This curve was measured in both directions to observe the effect of heat on the transistor.

4 Evaluation and Results

4.1 Preliminary Considerations

4.1.1 Measuring of the characteristic Values

The characteristic values of a transistor are different for each operating point. Therefore the measurements have to be done with the voltages already applied. This could mess with the multimeter leadiging to wrong measurements, if it assumes free floating ends. This also means that the resistance of the power supply and the resistor have to be taken into account, as it is essentialy a second path for energy to flow parallel (same with the capacitance). Lastly the test voltage, which the multimeter uses to probe the resistance could be greater than the maximum of the small signal model, so that the multimeter measures outside the linear section. But if you either assume, that the flow of energy through the power supply is negligeble or that the transistor can be measured outside of the circuit, with three measurements each the resistances and capacitances can be calculated with formulas for a delta configuration. The arrangement can be seen in [1, figure 11].

4.1.2 Transformation of y to h parameters

The dependency of i_1, i_2, u_1 and u_2 in the small signal model 1 can also be written in h parameter form as

$$\begin{pmatrix} u_{BE} \\ i_c \end{pmatrix} = \begin{pmatrix} r_{BE} & 0 \\ S \cdot r_{BE} & \frac{1}{r_{CE}} \end{pmatrix} \begin{pmatrix} i_b \\ u_{CE} \end{pmatrix} . \tag{8}$$

With the formulas on the worksheet the small signal amplification β can be calculated

$$u_{BE} = i_b r_{BE} \text{see 8} \tag{9}$$
$$u_{re} = (1+\beta)\, i_b R_E \quad \text{see [1, figure 8 and formula (24)]} \tag{10}$$
$$u_e = i_b r_{BE} + (1+\beta)\, i_b R_e = i_b r_{BE} + u_{re} \quad \text{see [1, formula (28)]} \tag{11}$$
$$S\,(u_e - u_{re}) = \beta i_b = S\,(i_b r_{BE} + u_{re} - u_{re}) = S i_b r_{BE} \quad \text{see [1, formula (27)]} \tag{12}$$
$$\Rightarrow \quad \beta = S r_{BE} \,. \tag{13}$$

4.2 Characteristic Curve (Assignment 7)

As shown in table 4.2 some basevalues were recorded which were needed in following experiments. They seem to be in a reasonable range.

R_{C} in kΩ	U_{BE} in V	U_{CE} in V	I_{C} in mA	S in 1/Ω
1	0,57	7,86	0,58	0.025
5	0,57	5,53	0,58	0.025
10	0,57	3,22	0,58	0.025

Table 1: Base values

The characteristic input curve is plotted in figure 3. With the slope of the tangent one can calculate the base resistance $r_{\mathrm{BE}} = 3.92$ kΩ with equation 2. The operating temperature $T = 272{,}2$ K can be obtained by using the fitparameters from the exponetial fit and equation 5. Although the operating temperature has the correct magnitude it should be at least 30 K higher. With this operating temperature and equation 4 the steepness S can be calculated as shown in figure 4.2.

The characteristic output curve is plotted in figure 4. By utilizing equation 3 one can calculate the collector - emitter resistance $r_{\mathrm{CE}} = 532$ kΩ with the slope of the tangent. The high resistance was anticipated because no current should flow from collector to emitter in the closed transistor state.

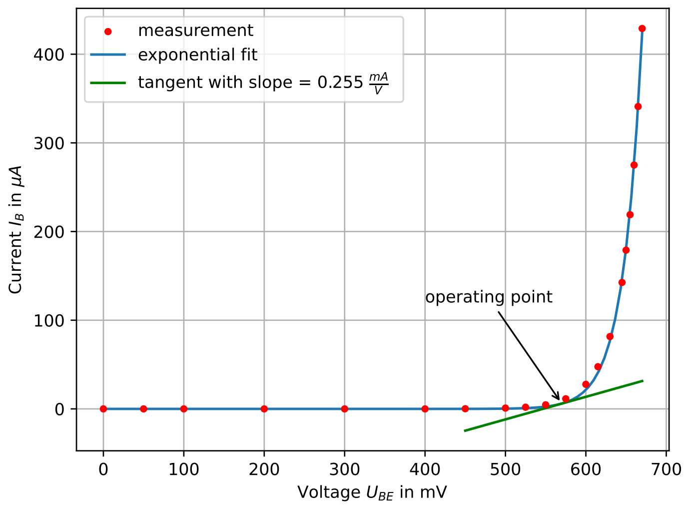

Figure 3: Characteristic curve from the input

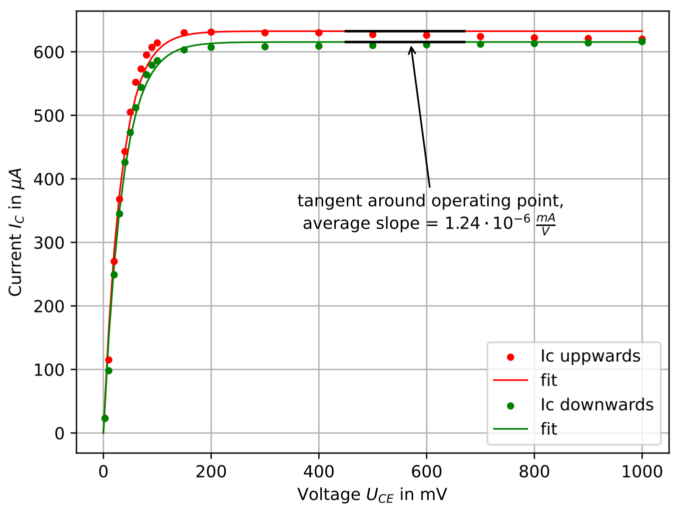

Figure 4: Characteristic curve from the output

4.3 Amplification (Assignment 8)

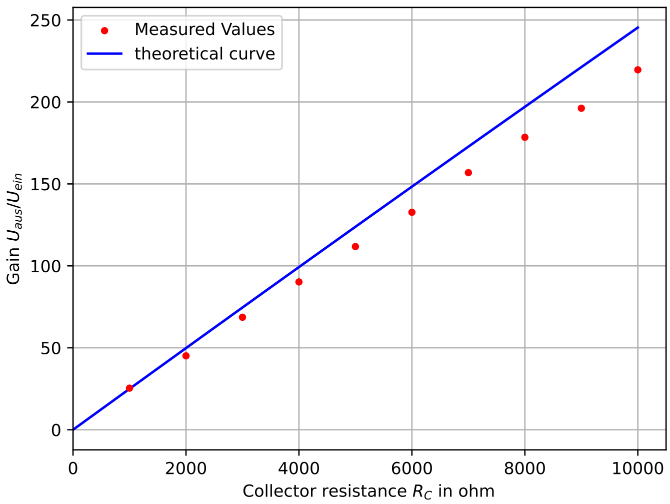

Figure 5: Amplification curve of the emitter circuit with capacitor C_E and without load resistor R_L. Theoretical values: $S = 0.025\ 1/\Omega$, $r_\mathrm{CE} = 532\ \mathrm{k}\Omega$

The voltage amplification with and without load resistor is shown in figure 5 and 6. To calculate the amplification, equation 6 was used due to the non conductive properties of C_E in low frequency ranges. By removing the emitter capacitor C_E one can observe a many times lower amplification. We used equation 7 and 6 to calculate the theoretical values. Figure 5 and 7 display a linear behavior. The measured values match the theoretical curves pretty closely, but the do diverge slightly at higher values. Presumably because the assumed values, with which the theoretical curves were calculated, are a little bit off.

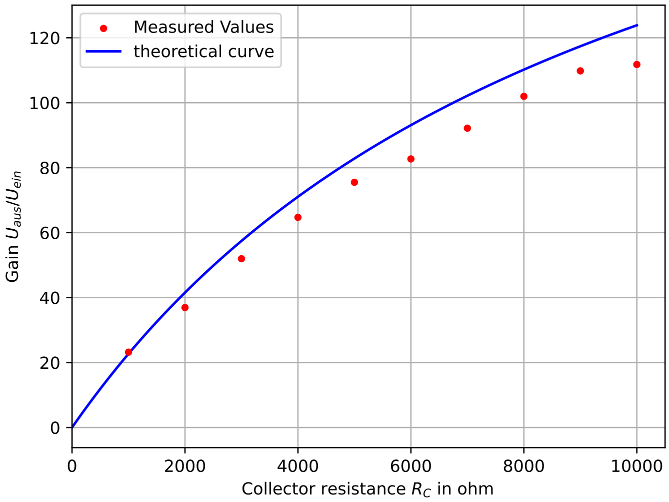

Figure 6: Amplification curve of the emitter circuit with capacitor C_E and load resistor R_L. Theoretical values: $S = 0.025\ 1/\Omega$, $r_\mathrm{CE} = 9815\ \Omega$

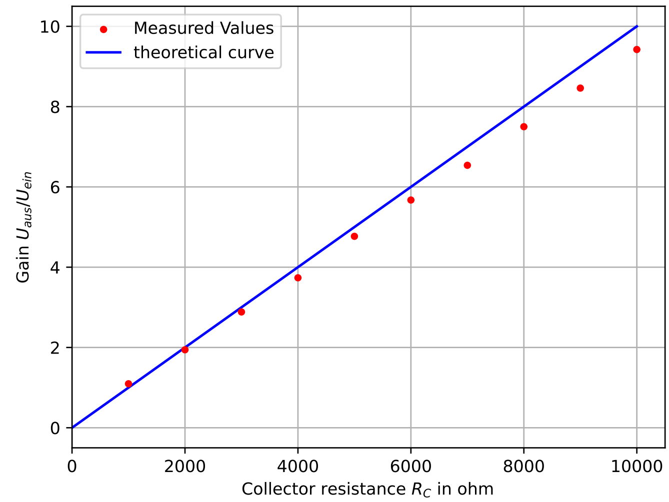

Figure 7: Amplification curve of the emitter circuit without capacitor C_E and load resistor R_L.. Theoretical value $R_\mathrm{E} = 1\ \mathrm{k}\Omega$

4.4 Frequency Response (Assignment 9)

Another important characteristic of a transistor is the frequency response. Therefore the amplitude and phase response is plotted in figure 8 and 9. Therby the amplidude response behaves like a high pass filter from 0 - 10^3 Hz and like a low pass filter from 10^3 - 10^6 Hz. The section of frequencies, where $|A| \geq \frac{1}{\sqrt{2}} \cdot |A_{max}|$ is also shown in figure 8. The phase reponse is calculated with the measured data on page 5 of the appended pdf with measurement data. If t is the time shift between input and output in microseconds and f is the frequency the phase shift is calculated with

$$\phi = t \cdot 10^{-6} \cdot f \cdot 360\,. \tag{14}$$

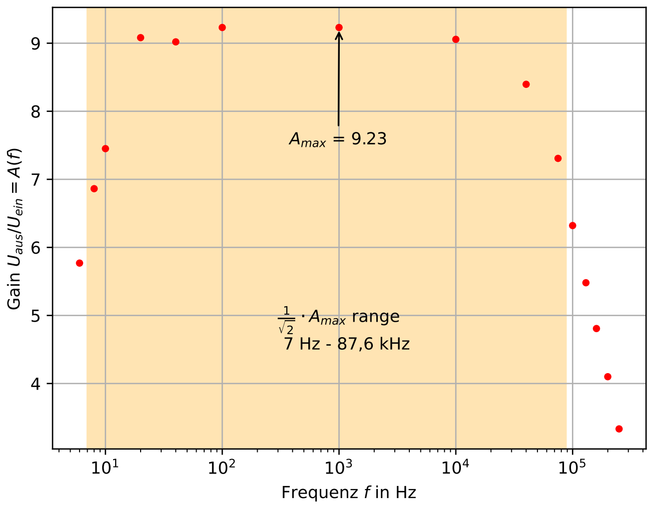

Figure 8: Amplitude response for different frequencies

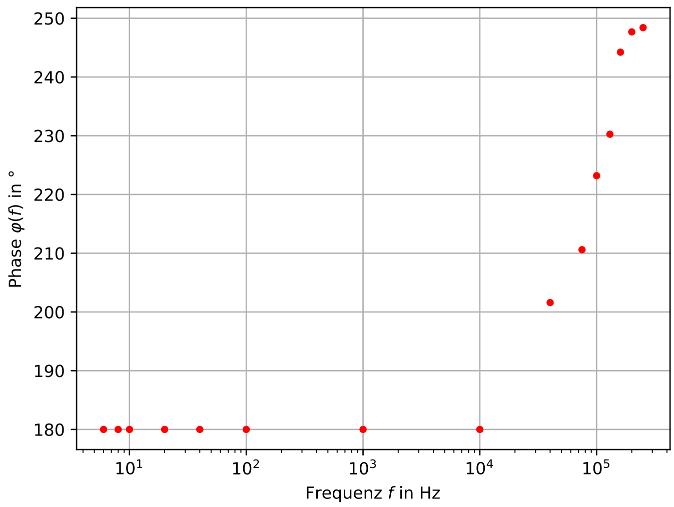

Figure 9: Phase response for different frequencies

4.5 Transfer Function

The transfer function H of the schematic in [1, figure 5], two complex resistors in serial, can be calculate with Kirchhoff's laws

$$H\left(Z_1, Z_2\right) = \frac{U_A}{U_E} = \frac{Z_2}{Z_1 + Z_2}\,. \tag{15}$$

It is assumed that $I_A = 0$. If $Z_1 = \frac{1}{i\omega C}$ is a capacitor and $Z_2 = R$ is a resistor, the function can be simplified to

$$H\left(\omega\right) = \frac{R}{R + \frac{1}{i\omega C}}\,. \tag{16}$$

This is a high pass filter, because if ω gets bigger, the denominator gets smaller and H gets bigger. So high frequencies are attenuated less than low frequencies

If $Z_1 = R$ is a resistor and $Z_2 = \frac{1}{i\omega C}$ is a capacitor, the function can be simplified to

$$H\left(\omega\right) = \frac{\frac{1}{i\omega C}}{R + \frac{1}{i\omega C}} = \frac{1}{1 + i\omega CR}\,. \tag{17}$$

This circuit is a low pass filter, because if ω gets bigger, H gets smaller. Low frequencies can pass with less loss than high frequencies.

References

[1] Technische Universität München. Aufgabenstellung Transistor (TRA). https://www.ph.tum.de/academics/org/labs/ap/ap2/TRA.pdf, Februar 2021.