Basics of Electronics

Design Project no 1^8 2a

Polish Japanese Institute of Technology 2006

Task 1. Transistor Investigation

Using Pspice simulator plot the static output and input characteristics of the *2n3904* transistor for the common emitter circuit with the emitter area increased *0.61* times. Plot the I_C and I_B currents as a funciton of the base-emitter voltage U_{BE} for large change of the currents. Draw all plots for the junction temperatures *32^{o}C* and *52^{o}C*. Discuss the influence of the temperature to the plots.

Assignment attachments: zad1.cir, zad1.out.

Zad1.cir holds the data for all the measurments in this task. The netlist contains two sources:

the **vce** voltage source that constitutes the difference of potentials between the collector and emitter nodes of the q1 transistor. It's value has been set at the Q-point collector-emitter voltage in task 2 for convenience.

the **ib** current source that constitutes the current flowing in the base node. It's value has been set by the Q-point value of the collector current in task 2 for convenience.

the **q1** is the investigated transistor.

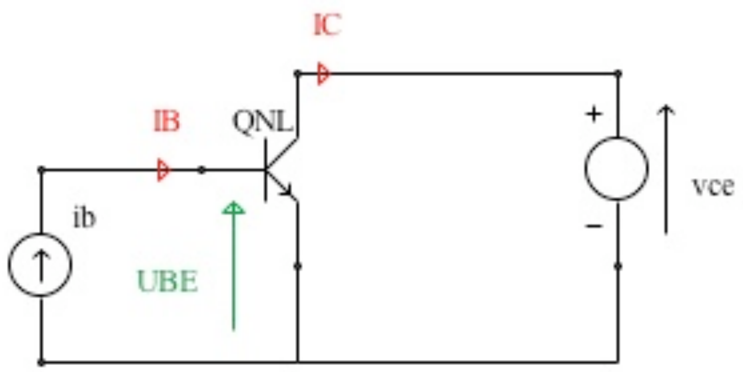


Diagram 1-1

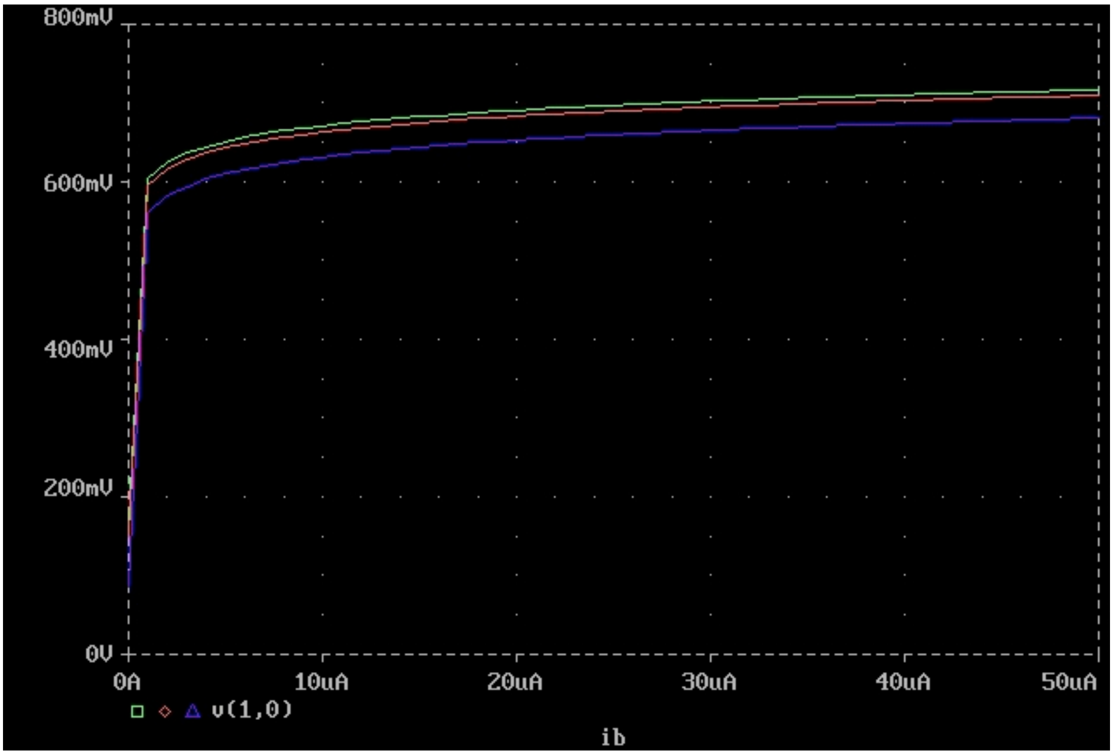
The zad1.cir contains two .dc declarations for the base current sweep and collector-emitter voltage sweep, each, depending on the nature of the analysis, has been subsequently commented out.

I have copied the list of properties of the QNL transistor from the 2N3904 transistor model from the eval.lib file provided with Pspice Evaluation 6.1.

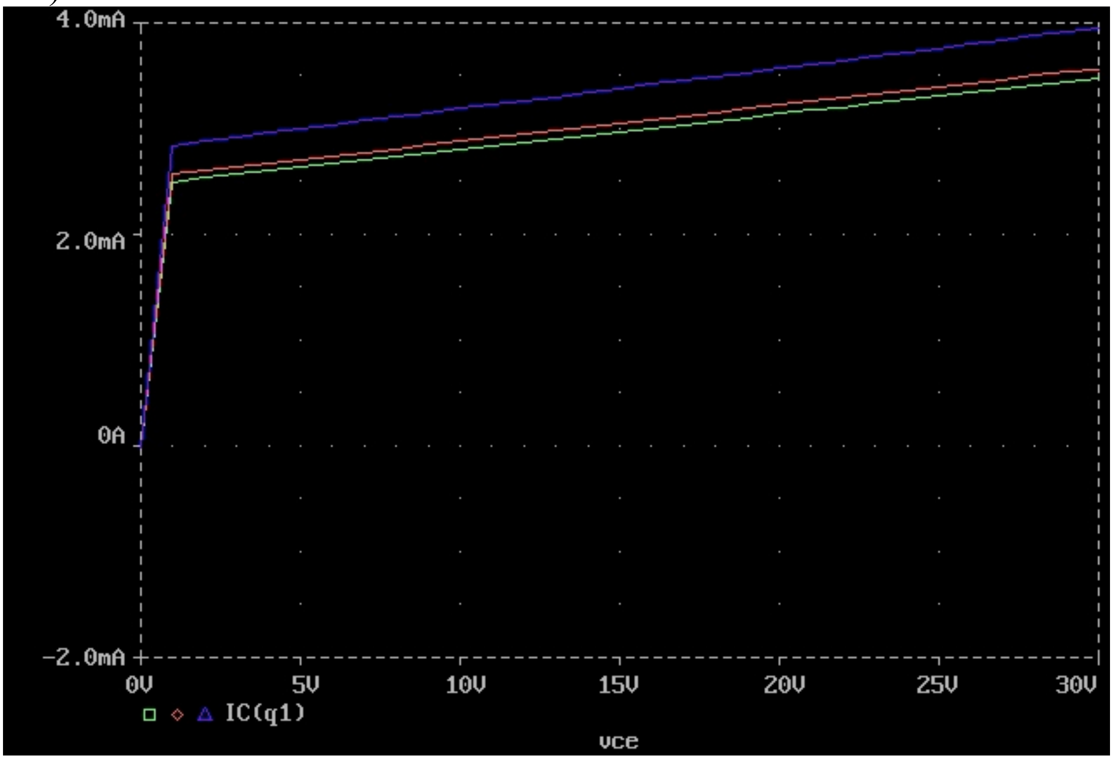
The measurements have been made for the temperatures 32 and 52 degrees as well as the temperature 27 degrees for further use.

The static input characteristic is the relation of the base-emitter voltage to the base current whilst the collector-emitter voltage is a constant, in our case – 6V. For the investigated transistor the dependency is as in the graph below.

The base-emitter voltage has been estimated as the difference of potentials between node 1 and 0.



The transistor's output characteristic is the relation of the collector current to the collector-emitter voltage whilst the base current is a constant (hereby at 15 uA).



Legend: – 27^{o}C, – 32^{o}C, – 52^{o}C.

Both the input and output characteristics are of the logarithmic rank and obviously depend on the junction temperature. That is to be anticipated, given the following dependency:

$$I_C = I_s(e^{\frac{V_{BE}}{(kT/q)}} - 1)$$

where *(kT/q)* is the voltage equivalent temperature, *q* is the electron charge, *k* is the Boltzmann constant, I_S is the saturation current and *T* is the transistor’s temperature, so the influence of the transistor‘s temperature on it’s output characteristic is apparent.

Task 2. Amplifier Investigation – part 1

Design the amplifier using the *2n3904* transistor in the common emitter circuit with the divider in the base circuit and feedback in the emitter circuit. The frequency range of the amplifier: $f_L = 22\ Hz$, $f_H = 32\ kHz$ ($-3dB$). Calculate all resistors and capacitors, the current and voltage amplification factors k_i and k_u, input and output impedances and the maximum output amplitude. Use the source and load resistances $R_S = 22\ k\Omega$ and $R_L = 32\ k\Omega$ respectively. For all hand calculations use the simple transistor equivalent circuit $r_{bb'} = 0$ and $h_{22} = 0$. Please make all calculations for the junction temperature $t_{j1} = 27^oC$ and supply voltage $E_{CC} = 22\ V$. Calculate the change of the transistor operating point and the change of all dynamic data of the amplifier when the junction temperature changes to $tj2 = 52^oC$.

The prologue:

A BJT amplifier with a single transistor working in the common emitter arrangement is used to amplify signals with small amplitudes in the small frequency range. One of it's most common applications is acoustics (such as sound wave to electric signal conversion in microphones). Such a circuit reverses the input signal's phase, has good parameters, a simple construction and is easy to procure. It's active element is a BJT transistor, hence the name. All the passive elements of the circuit (resistors and capacitors) provide the neccesary conditions. The schematic for this project's BJT amplifier is to be found in Task 3.

Step-by-step guidelines:

1. Choice of the operating point and calculating R_C and R_E.
2. Calculating R_1, R_2 and R_B.
3. Calculating C_1, C_C and C_E.
4. Calculating the f_H, R_{IN}, R_{OUT}, k_v, k_i.
5. Performing any necessary circuit modifications before proceeding to task 3.

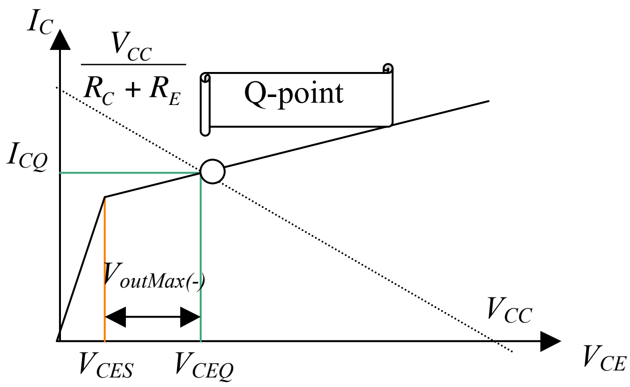
Calculations:

On the basis of the calculations done in Pspice in the course of the first task I will assume the operating point coordinates such that they, I estimate, should assure reasonable compromise for the best temperature behavior, maximum voltage gain and maximum output amplitude:

$$V_{CEQ} = \frac{3}{8}V_{CC}$$

$$V_{CEQ} = 8.25V$$

$$I_{CQ} = 2.7mA$$



An npn transistor's output characteristic.

Henceforth:

$V_{outMax(-)} = V_{CEQ} - V_{CES}$, where the saturation voltage V_{CES}=1V according to the Pspice readout from task 1, so:

$$V_{outMax(-)} = 8)25V - 1V = 7)25V$$

Given that for an undistorted output signal we need for $V_{outMax(+)} = V_{outMax(-)} = V_{outMax} = 7.25V$ and given that $V_{outMax} = I_{CQ}(R_C \| R_L)$

$$R_C = \frac{V_{outMax}R_L}{I_{CQ}R_L - V_{outMax}}, \text{ where } R_L = 32k\Omega$$

$$R_C = 2.931k\Omega$$

Given the equation:

$$E_C + E_E = \frac{V_{CC} - V_{CEQ}}{I_{CQ}}, \text{ so for the given operating point:}$$

$$R_E = \frac{V_{EE} - V_{EEQ}}{I_{EQ}} - R_E$$

$$R_E = \frac{33V - 7.35V}{3.6RA} - 3.932k\Omega$$

$$R_E = 3.263k\Omega$$

In order to ensure the stability of the transistor's work (meaning that the base potential's dependence on the base current should be close to none) the currents flowing through R_1 and R_2 should be adequately greater than the current of the transistor's base. Though, on the other hand, the resistance $R_B = R_1 \| R_2$ should be greater than $r_{b'e}$ (hereinafter computed) so that it's shunting influence will not cause a significant signal amplitude loss.

Let $I_{R1} = 30 I_B$ and $I_B + I_{R1} + I_{R2} = 0$

$$R_1 = \frac{V_{CC} - V_B}{30 \cdot I_{BQ}},$$

$$R_2 = \frac{V_B}{31 \cdot I_{BQ}}$$

The 2N3904 model's the β_0 factor amounts to 178 at T=300°K, so:

$$I_{BQ} = \frac{I_{CQ}}{\beta_0} = \frac{2.7mA}{178} = 0.015mA,$$

so:

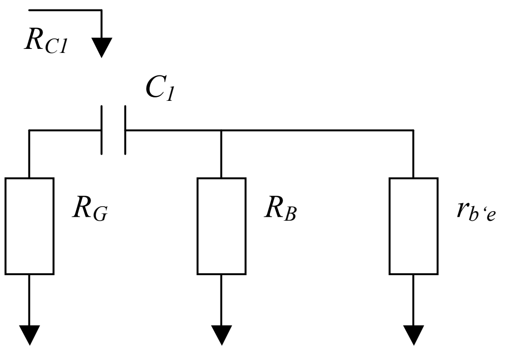
$$R_1 = 37.436k\Omega,$$
$$R_2 = 11.084k\Omega$$

Now we might as well calculate the base resistance R_B. We are going to find it useful further on.

$$R_B = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2},$$
$$R_B = 8.552k\Omega$$

Having now calculated the resistor values of the BJT amplifier we are going to compute it's variable constituents.

To find the capacities C_1, C_C and C_E we have to calculate the equivalent resistances seen from their ports.



The f_{LC1} high-pass frequency is related to the C_1 capacitance.

$$R_{C1} = R_S + \frac{R_B r_{b'e}}{R_B + r_{b'e}}$$

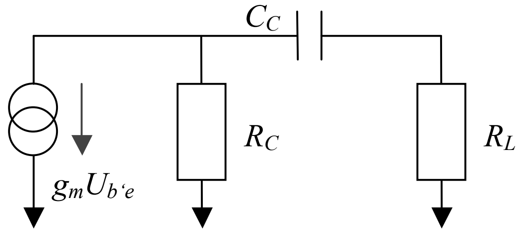
where: $r_{b'e} = \frac{\beta_0 \varphi_T}{I_{CQ}}$, $\varphi_T = \frac{kT}{q}$, k – the Boltzmann constant, T – temperature absolulte scale and q – the charge of an electron.

So $\varphi_T = 0.026$ and $r_{b'e} = 1.714k\Omega$:

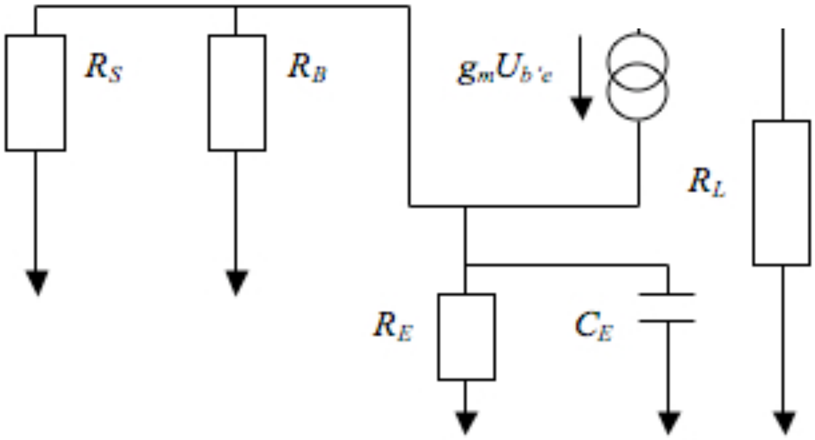
$$R_{C1} = 23.428k\Omega$$

The f_{LCC} high-pass frequency is related to the C_C capacitance.

$$R_{CC} = R_C + R_L$$
$$R_{CC} = 34.931k\Omega$$



The f_{LCE} high-pass frequency is related to the C_E capacitance.



$$R_{CE} = R_E \parallel \left(\frac{r_{b'e} + R_S \parallel R_B}{\beta_0 + 1} \right)$$
$$R_{CE} = 0.043k\Omega$$

Since $f_L = \sqrt{f_{LC1}{}^2 + f_{LCC}{}^2 + f_{LCE}{}^2} = \sqrt{\left(\frac{1}{2\pi C_1 R_{C1}}\right)^2 + \left(\frac{1}{2\pi C_C R_{CC}}\right)^2 + \left(\frac{1}{2\pi C_E R_{CE}}\right)^2}$

and R_{CE} is the smallest of all the above calculated resistances let it be the dominating pole of the lower cut-off frequency. I.e.:

$$C_E = \frac{1}{2\pi R_{CE} f_L},$$
$$C_E = 168\mu F$$

Now let f_{LC1} and f_{LCC} be tolerable aberrations of f_L and let them amount to the value 1kHz. So:

$$C_1 = \frac{1}{2\pi R_{C1} f_{LC1}} = 6.8\mu F,$$
$$C_C = \frac{1}{2\pi R_{CC} f_{LCC}} = 4.5\mu F$$

The input and output impedances:

$$R_{IN} = R_B \parallel r_{b'e} = 1.427k\Omega$$
$$R_{OUT} = R_C \parallel h_{22} = 2.931k\Omega$$

The voltage and current amplifications:

$$k_v = \frac{V_{OUT}}{V_{IN}} = \frac{R_{IN} g_m R_L}{R_{IN} + R_S} = 202.717$$

$$k_i = k_v \frac{R_S}{R_L} = 139.368$$

The high frequency cut-off:

$$f_H = \frac{1}{2\pi (R_{IN} \parallel R_S)(C_{je} + C_{jc} + C_{jc} g_m R_L)},$$

where the C_{jc} and C_{je} can be found in the zad1.out bias point calculations, their values for junction temperature $27^o C$ $1.96pF$ and $65.8pF$ respectively.

$$f_H = 193.1kHz$$

Obviously this value is way beyond the desired high cut-off frequency. Because the calculated f_H is disproportionately higher than the specified one we have to solve the matter somehow.

Adding a capacitor C_L parallelly to the R_L resistor is one option, because the additional capacity will serve us as a low-pass filter thus limiting the high cut-off frequency.

The resistance as seen from the ports of C_L:

$$R_{CL} = R_C \parallel R_L = 2.685k\Omega$$

So:

$$C_L = \frac{1}{2\pi R_{CL} f_H} = 1.411nF$$

Summary:

Obtained values:

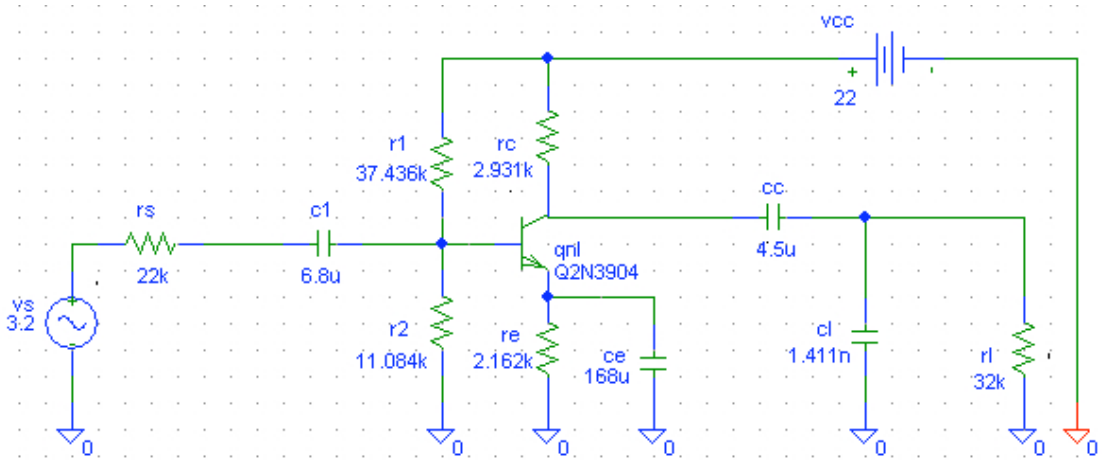
V_{CEQ}	8.25V
I_{CQ}	2.7mA
V_{outMax}	7.25V
R_C	2.931kΩ
R_E	2.162kΩ
R_1	37.436kΩ
R_2	11.084kΩ
I_{BQ}	0.015mA
R_B	8.552kΩ
C_1	6.8uF
C_C	4.5uF
C_E	168uF
$r_{b'e}$	1.714kΩ

R_{IN}	1.427kΩ
R_{OUT}	2.931kΩ
k_v	202.717
k_i	139.368

Task 3. Amplifier Investigation - part 2

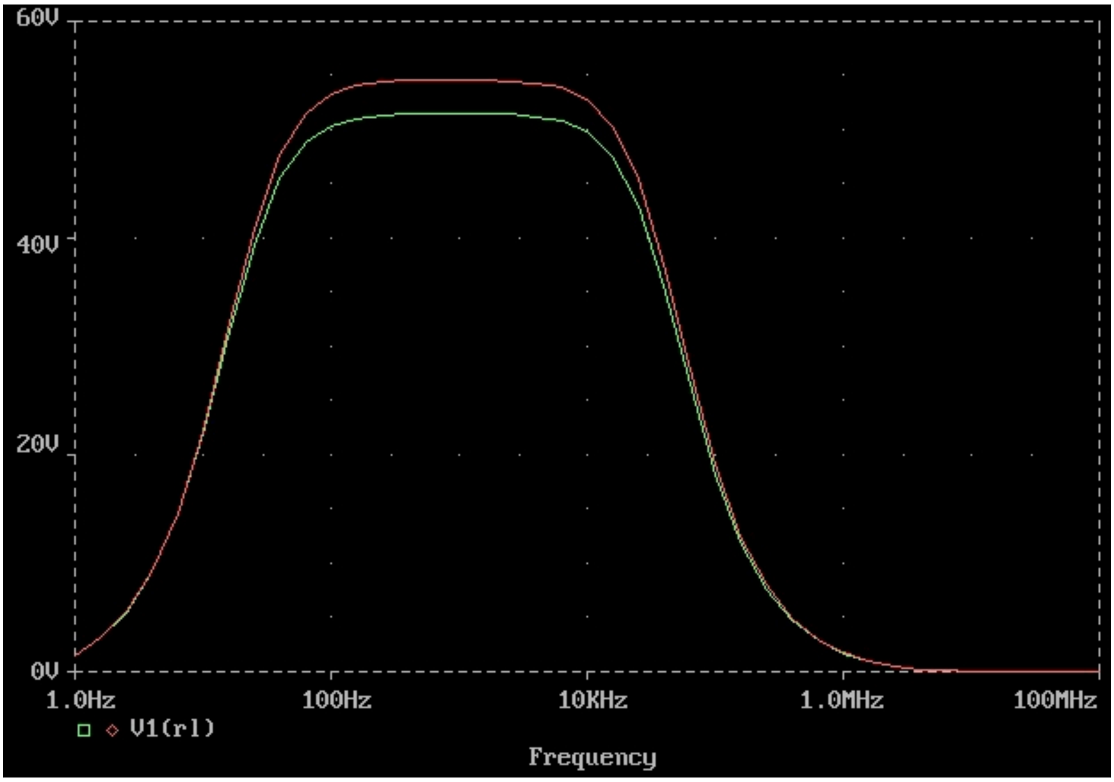
Design the amplifier from the second task using the Pspice simulator. Compare the hand calculations results with the Pspice results using the DC, AC and Transient analyses. Analyse the maximum output amplitude and THD for the output signal.

The amplifier schematic:



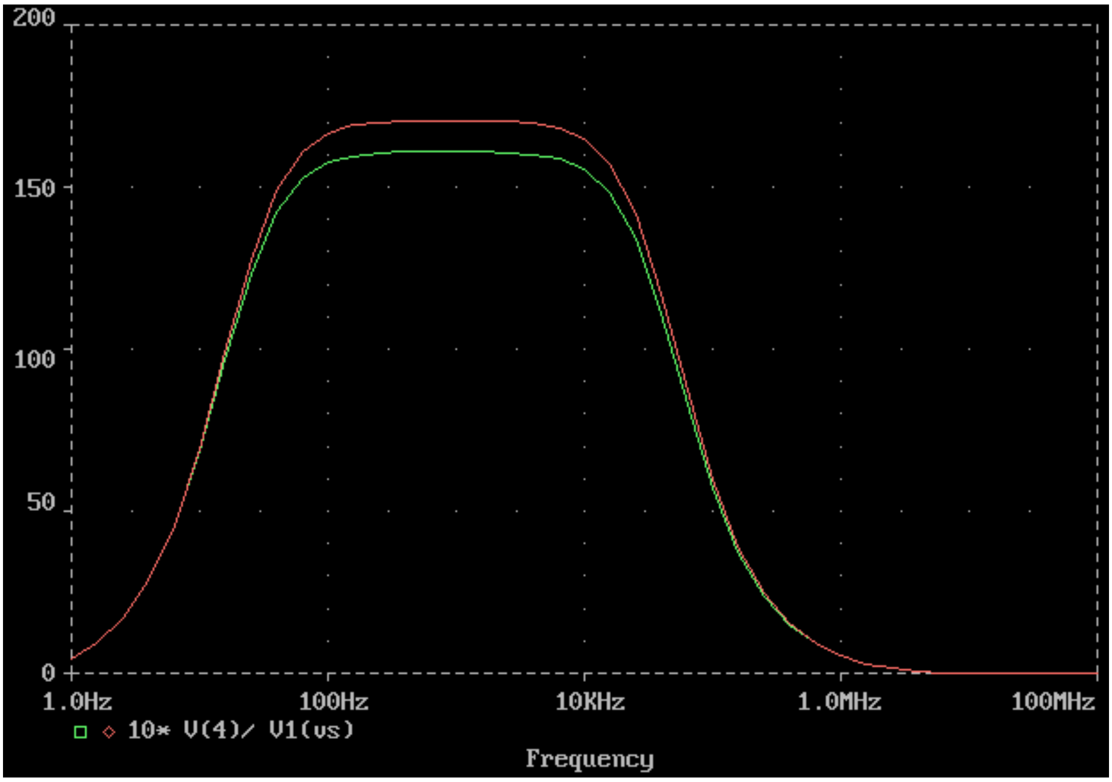
This image was made only as a reference. The analysis was performed in text mode. The zad3.out print is enclosed with the project documentation.

Below is the output voltage characteristic:

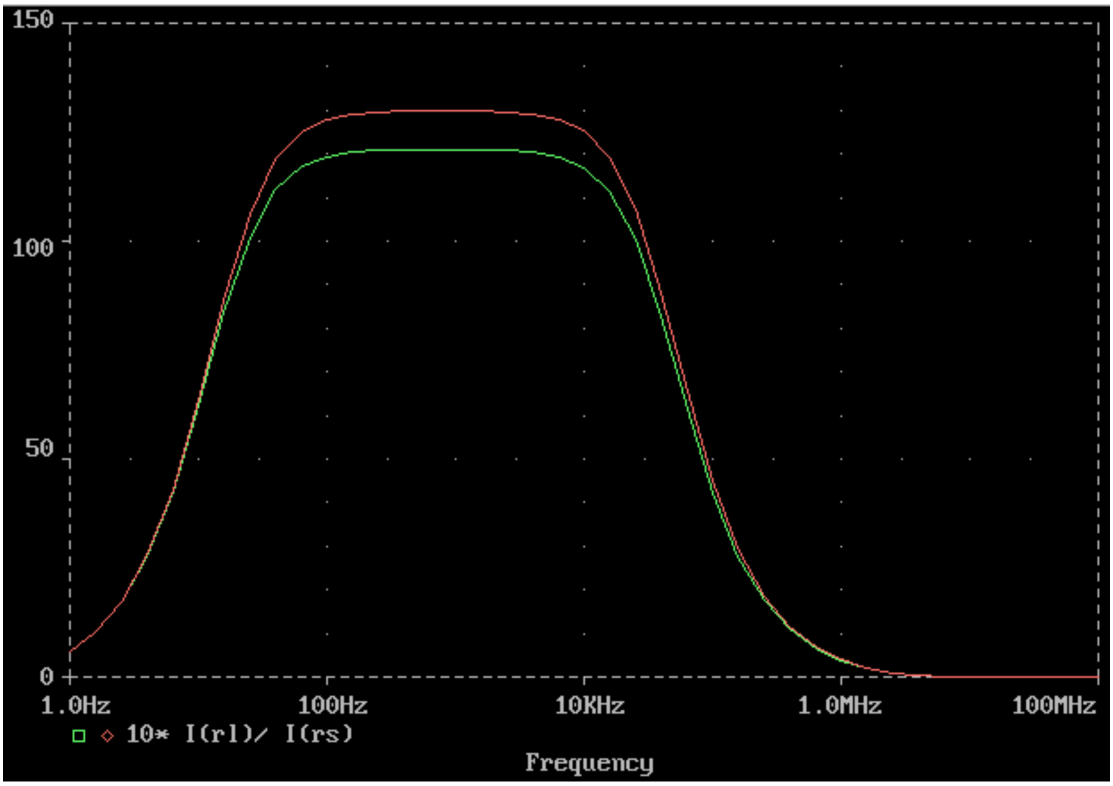


The lower and upper cut-off frequency slightly differs from the expected one due to the capacitor C_L added for better control of the bandwidth.

The voltage amplification characteristic:

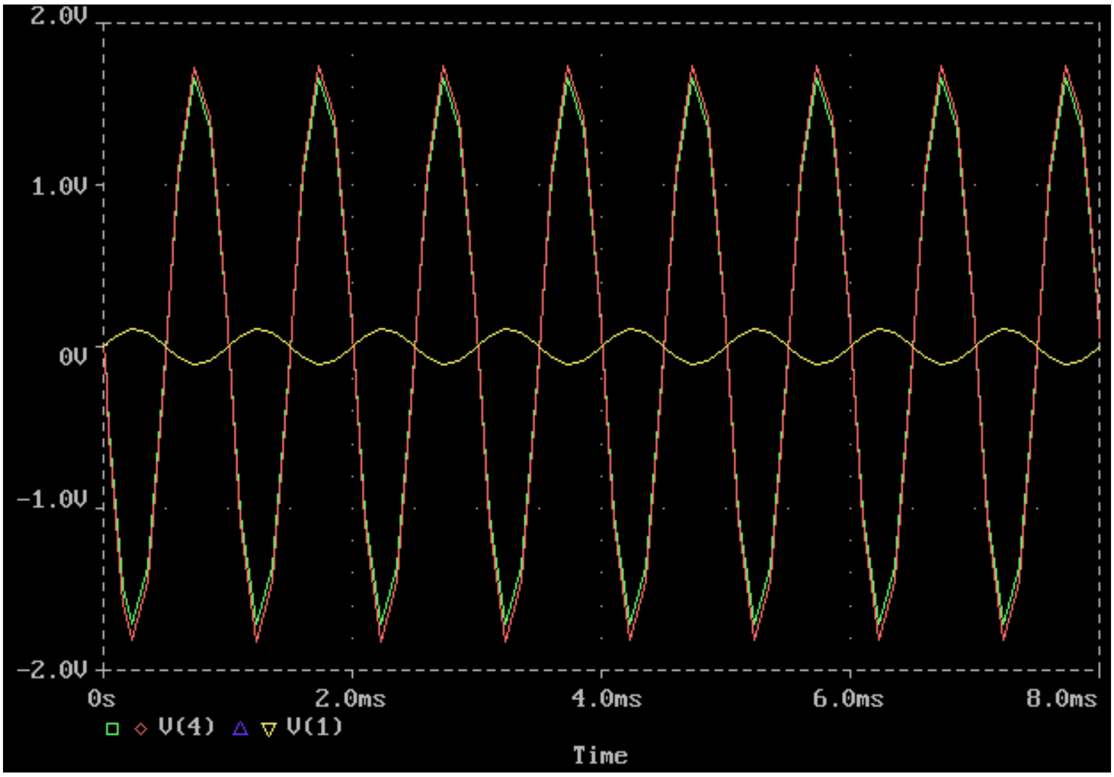


The efficient voltage amplification factor for T=27°C is slightly lower than that which was calculated. This is a fault of precision. As was anticipated, along with the temperature growth the amplifier's parameters have worsened. The effective amplification factor is lower.



The value of the efficient current amplification are satisfyingly similar to those calculated in task 2. As seen in the graph above the currrent amplification factor grows with the temperature.

Below is the simulation of the input and output signals:



This illustrates the dependency of the input and output signals. The output signal has a reverse phase to the input signal. The efficient voltage amplification grows with the temperature.

	Hand calculations	**T=27°C**	**T=52°C**
k_v	202.717	188.292	176.103
k_i	139.368	120.93	129.83
f_L	22Hz	21.343Hz	22.414Hz
f_H	42kHz	39.708kHz	39.483kHz

The results from the simulation differ from the ones that were calculated by hand, though the differences are not of a significant rank and are due to the lack of precision of all hand calculations in general.

Temperature aberrations have an unfavorable influence on the properties of BJT amplifiers. This is why designing a circuit the designer should also estimate it's behaviour in various ambient conditions. The negative feedback introduced by R_E stabilizes the Q-point of the amplifier. It reduces the influence of temperature to the circuit's properties.