Electronics II. laboratory

Complementary power amplifiers

created by Fraskó Ádám,
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1 Aims

The aims of this measurement are to examine and measure basic complementary power amplifier circuits.

Circuits to be measured:

- Simple class B common collector amplifier
- Class AB amplifier with different voltage shifting solutions
- Creating higher current output for opamps using complementary transistors

1.1 Components

- BD139 NPN transistor
- BD140 PNP transistor
- 1x BC556 or BC558 PNP transistor
- 2x BC546 or BC548 NPN transistor
- 2x 1N4007 diode
- 4.7µF bipolar electrolytical capacitor
- Resistors: 12kΩ; 1,5kΩ; 750Ω; 150Ω; 2db 3,9Ω@2W, 15kΩ; 33Ω@5W
- Potmeters: 1kΩ; 470Ω
- µA741 opamp

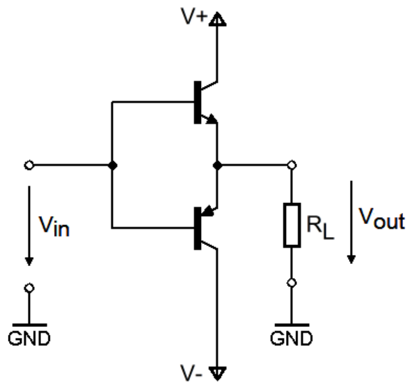
2 Theory

2.1 Power amplifiers

Power amplifiers or end-stage amplifiers have generally two main requirements: high output power and good linearity. These typically have low output resistance, high current gain and low (one or less than one) voltage gain.

There are many realisations of power amplifiers. An often used one is the complementary emitter follower (or common collector) circuit. This is also used as end-stage of operational amplifiers. In this laboratory we shall build such circuits from discrete components.

2.2 Complementary emitter follower (common collector)



1. Simple class B amplifier

The basic (simplest) complementary emitter follower circuit is shown on *figure 1*. It is made up of two class B common collector configurations built together, one with NPN and the other with PNP transistor. (Note the PNP transistor is vertically flipped to have the same current and voltage directions as for the NPN.) We use symmetric power supply voltage, thus the input can be pure AC. Thus the circuit will amplify the negative parts of the signal as well and have no lower frequency limit.

The V_{in} – V_{out} characteristic (*figure* 2.) shows that the output (emitter) follows the input with a difference of 0.6 – 0.7V, ie. the forward voltage of the transistors. With an AC input, in the positive half period T_1 pulls the output towards the positive supply and in the negative half period T_2 pulls the output towards the negative supply. If we neglect the saturation voltage of the transistors, then the maximal output voltage peak is the power supply voltage. If the load resistance is very small, the output voltage can decrease perceptibly.

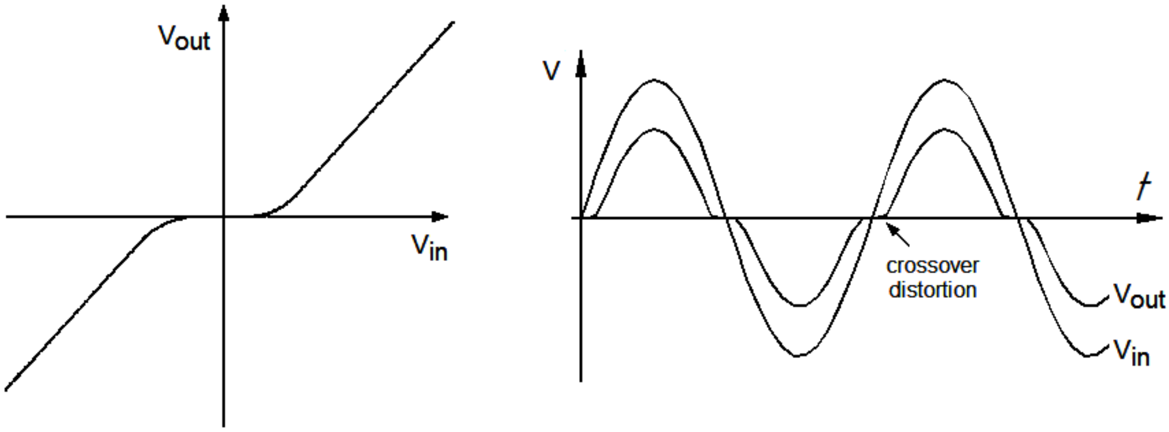
We can now determine the maximal sinusoidal ouput power (if using symmetric power supply):

$$V_{outpeak} \approx V_{\text{supply}}$$

$$V_{outrms} = \frac{V_{\text{supply}}}{\sqrt{2}}$$

$$P_{out} = \frac{V_{outrms}^2}{R_L} = \frac{\frac{V_{\text{supply}}^2}{\left(\sqrt{2}\right)^2}}{R_L} = \frac{V_{\text{supply}}^2}{2R_L}$$

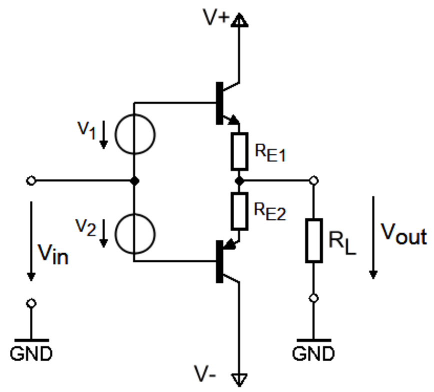
Naturally, the maximum output power is limited by the transistor's maximum allowed collector current. This basic circuit has the disadvantage that until the input signal reaches the forward voltage, the output is almost zero, thus it only works for larger amplitude input signals, and those are still distorted at the zero crossing (crossover distortion) (right side of *figure* 2).



2. Characteristic and time signal of class B amp.

2.3 Class AB amplifiers

The crossover distortion can be minimised if the transistors are forward biased (in DC), so any AC input is superposed on this DC value. This is actually what was done with the one transistor common emitter circuit that we learned earlier, where the base resistors create the bias.



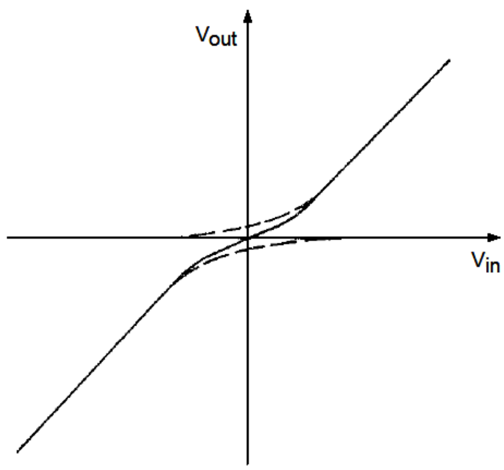
3. Operating point adjustment (class A or AB), theoretical model

In our theoretical model on *figure* 3, voltage generators supply the DC bias. In real circuits, as we shall soon see, we'll use other solutions.

Without AC input, both transistors have significant operating point collector current, which causes the efficiency of the circuit to be lower than class B circuits. In class A operation, this current is relatively high, with lower efficiency, but also the lowest distortion. The class AB solution moves the operating point lower (and much lower than the maximum current when the input is at peak), to have an efficiency better than class A, while distortion is slightly worse.

In the circuit on *figure 3.* two voltage generators provide the bias (V_{BE}, should be around 0.6V) for the transistors. (More correctly, the generators provide V_{BE} plus the voltage on the R_E resistors.) The operating point (DC) current is:

$$I_C = \frac{V_{R1}}{R_{E1}} = \frac{V_1 - V_{BE1}}{R_{E1}}; \quad v_{in} = 0 \ ; \ V_1 = V_2 \ ; R_{E1} = R_{E2}$$



4. Transfer characteristic of class AB amp

The transfer characteristic (*figure 4.*) shows that the transfer curves (dashed lines) of T_1 and T_2 are shifted on the horizontal axis. The sum of them will be the continuous line. Thus the crossover distortion is decreased compared to the previous (class B, without the V_{BE} bias) solution. Increasing the DC current the operating point moves "up" and the distortion becomes lower. The resistors R_{E1} and R_{E2} decrease the maximum output voltage (peak) (as the full output current flows through them). The output resistance of the amplifier is approximately equal to R_{E1} and R_{E2}. The max output voltage (if neglecting the saturation voltage of the transistor):

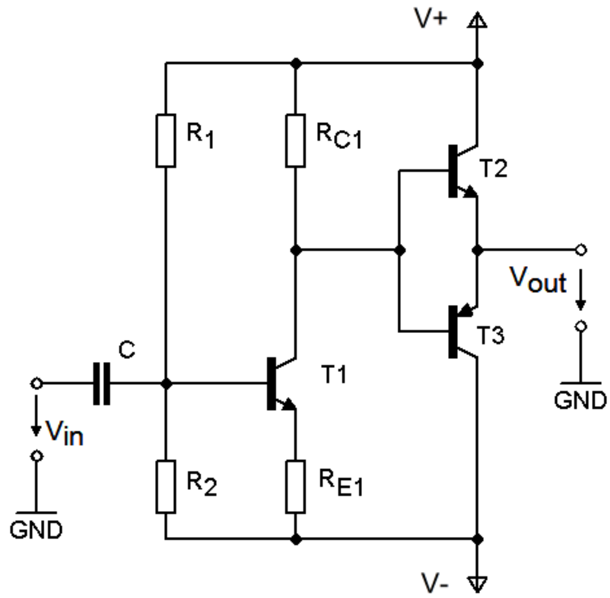
$$V_{outpeak} = V_{\mathrm{supply}} - I_{\mathrm{C}} R_{\mathrm{E1}}$$

2.4 Driving stage

The voltage gain of the output stage is less than one (being a common collector stage). Thus the input voltage should be of similar voltage as the required output signal. We shall use a common emitter amplifier as the driving stage, see *figure 5 and figure 6*.

Note that the common emitter stage is also operating from the symmetric power supply. Take care to use this fact for the calculations.

For a class B amplifier (*figure 5*) the driving stage's output is directly connected to the end stage's input (DC coupling). The driving stage not only provides voltage gain, but also can be used to change the output offset voltage (which is the DC voltage of the output, which normally should be zero). This is achieved by setting up the collector potential of the driving stage (by setting up R_{C1}).

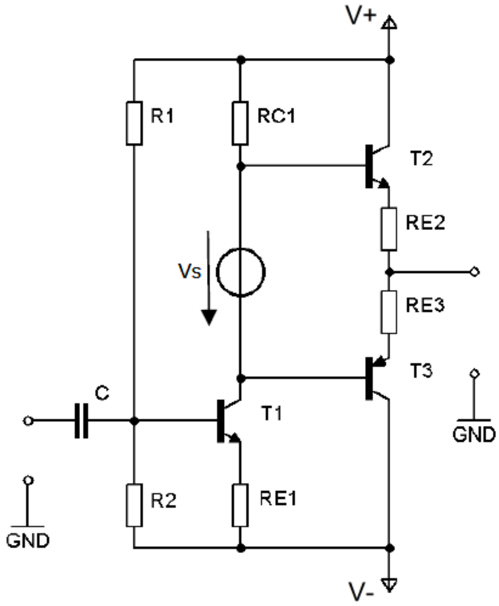


5.Class B end stage with common emiter driver

The driving stage's gain is (note it has no emitter capacitor):

$$A_{V1} \approx -\frac{R_{C1}}{R_{E1}}$$

To build a class AB end stage (*figure 6*), we put a voltage shifting (offset) circuit between R_{C1} and the collector of T_1. For simplicity, this shifter will be symbolized with an ideal voltage generator (V_S).



6. Class AB end stage with common emitter driver

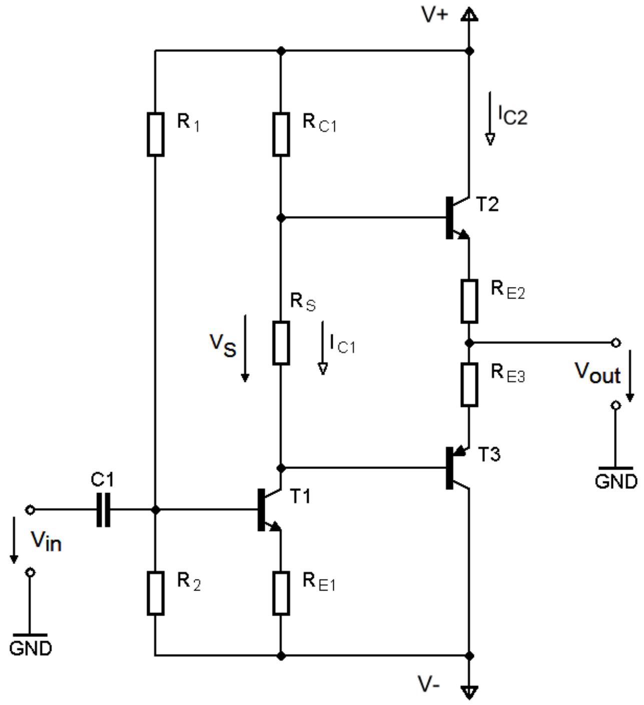
The generator's voltage is independent of its current, so it keeps a constant DC voltage between the bases of T_2 and T_3. The end stage operating point current:

$$I_C = \frac{V_{RE2}}{R_{E2}} = \frac{\frac{V_S}{2} - V_{BE2}}{R_{E2}} \; ; \mathrm{V}_{BE2} = V_{EB3} \; ; R_{E2} = R_{E3}$$

2.5 Solutions for voltage shifting (offset)

The voltage shifter (the voltage generator in previous chapter) can be realised with different components or circuits.

Voltage offset with resistor



7. Voltage offset with resistor

The simplest is to use a resistor. The voltage offset is:

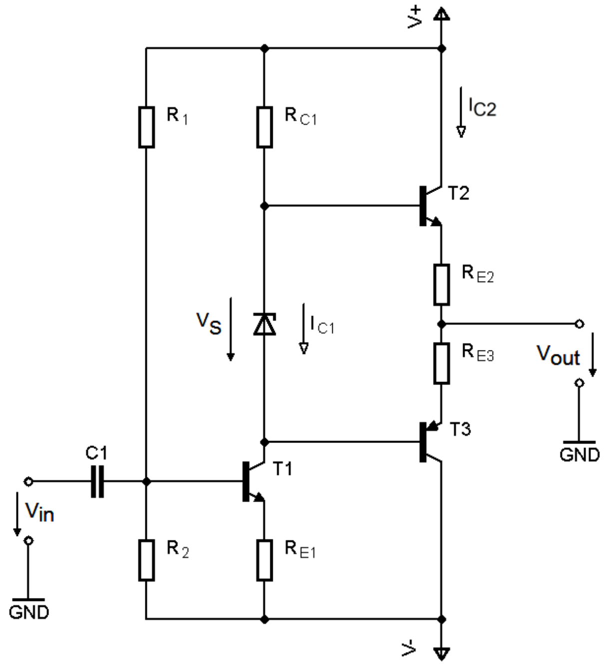
$$V_S = R_S \cdot I_{C1}$$

It is not very useful in practice, because the resistor doesn't keep its voltage constant – with AC input, part of the AC signal will fall on R_S and thus the AC voltage on the bases of the end stage transistor will be different, leading to distortion.

Voltage offset with Z-diode

We need a component that has a constant DC voltage on it, but zero AC voltage. This can be accomplished by a diode or Z-diode.

Let's see a version with a Z-diode. The V_S voltage will now be the breakdown voltage.

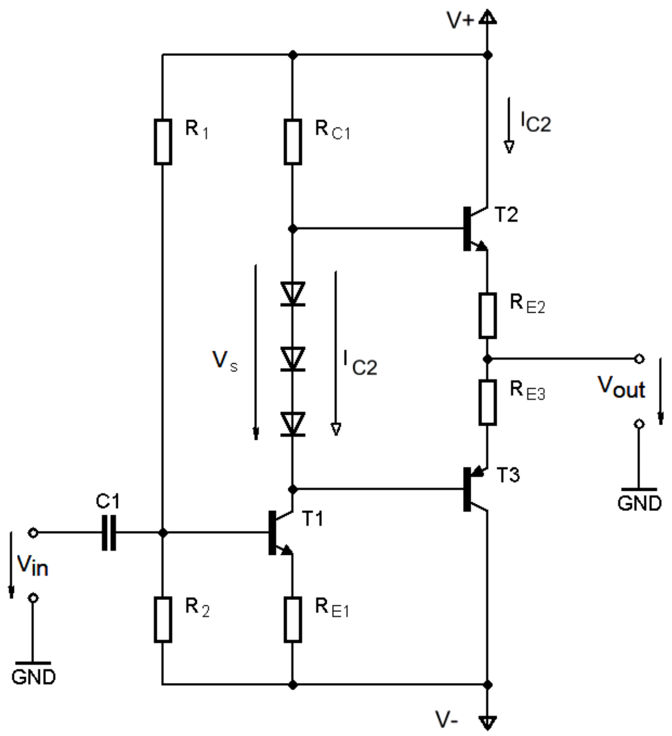


8. Voltage offset with Z-diode

This way we only need one component. However, it has a drawback.

As $V_S=V_{BE2}+V_{RE2}+V_{RE3}+V_{EB3}$, if V_S is greater, then greater voltage falls on R_{E2} and R_{E3}, which increases power loss and decreases the maximum output voltage. The smallest Z-diodes are around 2.4V, which is still much greater than $V_{BE2}+V_{EB3}$. Therefore this solution is less often used, for example when Darlington-pairs are used for the transistors (resulting in increased V_{BE}).

Voltage offset with series diodes

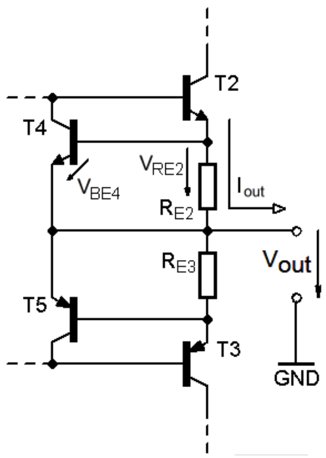


9. Voltage offset with series diodes

The most often used variation is to have series diodes in forward bias (*figure 9*). It is easy to make and the voltage can be adjusted by the number of diodes (add up the forward voltages). The DC current of T1 will determine the actual forward voltage of the diodes (but will stay around 0.6...0.7V).

2.6 Output current limit

As the name implies, power amplifiers use high power and therefore the output transistors will need to be protected from too much current and heat. Temperature control is partly realized by using transistor packages which contain metal parts that can be connected to a heat sink. The other part is making sure the current on the transistors doesn't exceed the limit. *Figure 10* shows a simple current limit using two extra transistors. Similar techniques are used for example in dissipative voltage regulators as well.



10. Output current limit

If I_{out} increases, then V_{RE2} (on R_{E2}) also increases. As V_{RE2} reaches around 0.6..0.7 volts, transistor T_4 will turn on and "redirect" more and more of the base current of T_2. Thus T_2 will have less collector current, which is also the output current. Therefore the output current is limited. (This works if T_2's base current is sourced from a limited supply.)

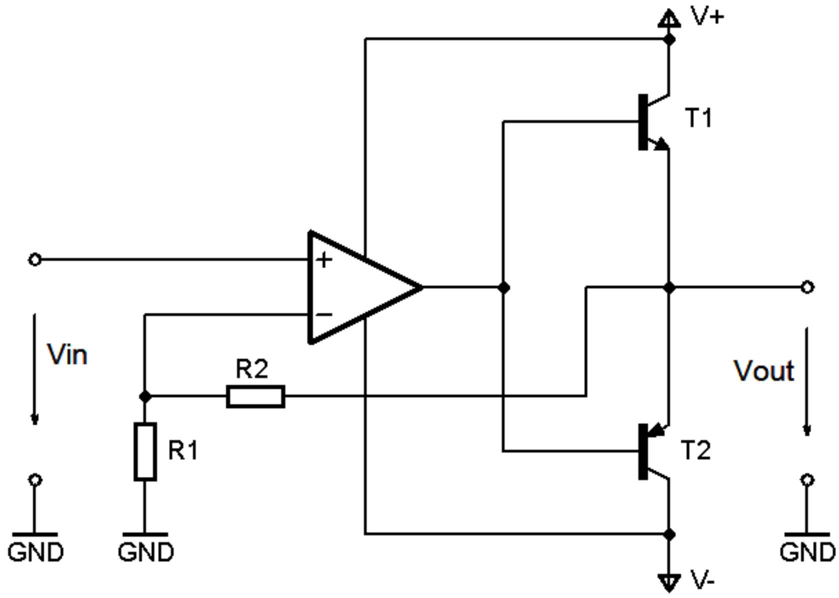
Approximately (because the transistor turns on gradually):

$$I_{out\max} = \frac{V_{BE4}}{R_{E2}} \approx \frac{0.7V}{R_{E2}}$$

As the output stage is symmetrical, the same is true for the other output transistor and its current.

2.7 Extending the current of an opamp

The complementary end stage can also be used to give higher current output for an operational amplifier. Ie. now the previous stage is not a common emitter stage, but an opamp's output. (The opamp's output is also a complementary end stage, just it is designed for lower currents, usually not more than 20mA.)



11. Extending the output current for opamp

The circuit on *figure 11.* is a class B end stage. As we already learned, these have a high cross-over distortion. However, the opamp can compensate for this. We can see that the negative feedback comes from the output of the end stage. The opamp in negative feedback tries to have close to 0V between its inputs, thus it tries to have to output signal follow the input signal in shape, so it increases the output to compensate for the forward voltage drop. Thus there will be a voltage equal to a forward voltage between the opamp's output and the common emitter point, thus the smallest input signal will appear on the output. The gain is the well-known gain of the non-inverting circuit:

$$A_V = 1 + \frac{R_2}{R_1}$$

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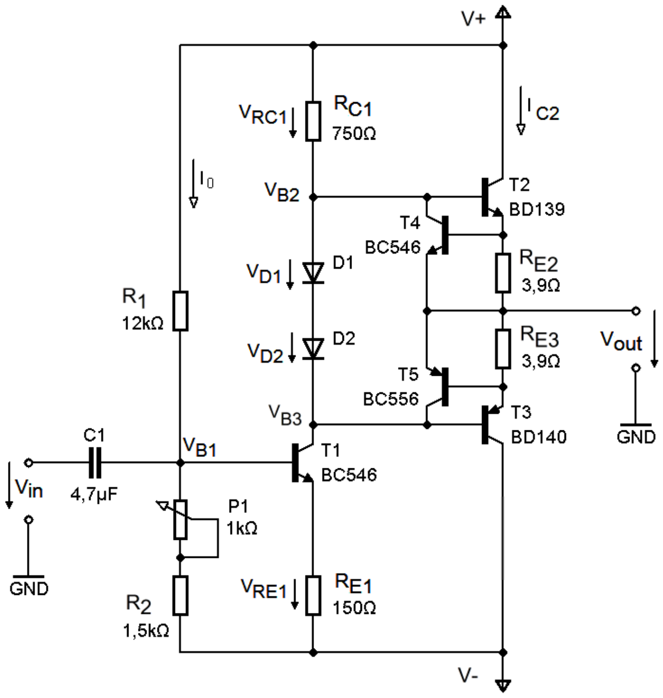
Calculation (homework)

2.8 Class AB amplifier



Parameters:

$V_{supply}= \pm 12V$

R_1=12kΩ; R_2=1.5kΩ; R_{C1}=750Ω; R_{E1}=150Ω; R_{E2}=3.9Ω; R_{E3}=3.9Ω; P1=500Ω (50%)

$V_{D1}=V_{D2}$=0,7V;
$V_{BE1}=V_{BE4}=V_{EB5}$=0,6V;
$V_{BE2}=V_{EB3}$=0,6V

Calculate these values:

a) I_0; V_{B1}; V_{RE1}; I_{E1}; I_{C1}; V_{RC1}

b) V_{B2}; V_{B3}; I_{C2}

c) V_{OUT_OFFSET}

d) I_{OUT_MAX}

Note: the values given for V_D and V_{BE} are just estimations. While in previously learned circuits these estimations' error didn't matter much, here they do. Now the output current depends upon the difference of V_D and V_{BE} and so the estimation errors will matter greatly. In such cases we can do a worst case or maximum calculation (such as here having V_D higher and V_{BE} lower).

2.9 Opamp with complementary transistors

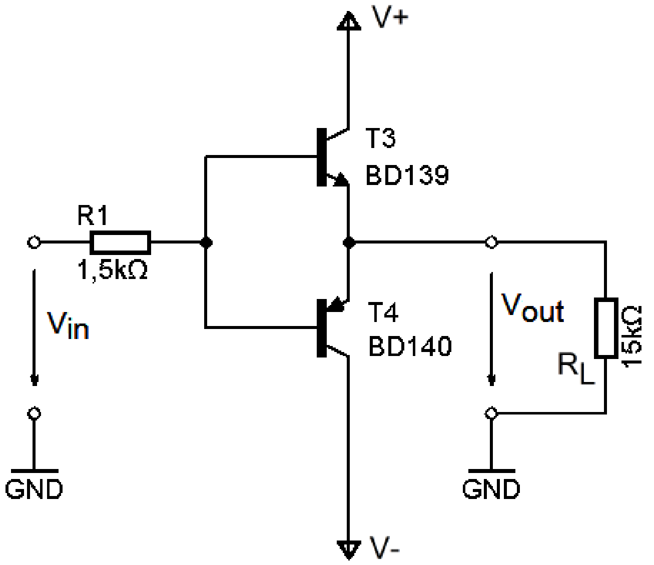
Calculate the total gain of the circuit from figure 11.

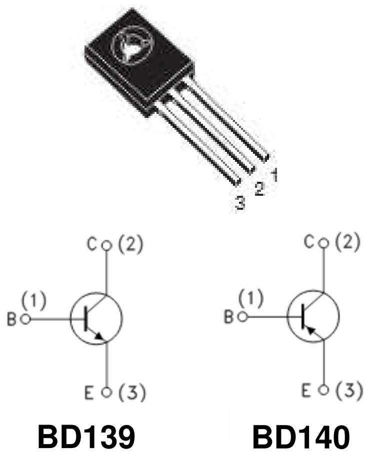
$V_{supply}= \pm 12V$; R_1=1.5kΩ; R_2=15kΩ

3 Measurements

These circuits are sensitive to power supply voltage and load capacity. If the output has some unwanted high frequency components, then try putting a 100nF capacitor in parallel with the power supply (as near to the circuit as possible).

3.1 Class B complementary emitter follower (common collector)





12.

V_{supply}= **±6V**.

Crossover distortion and maximum output range

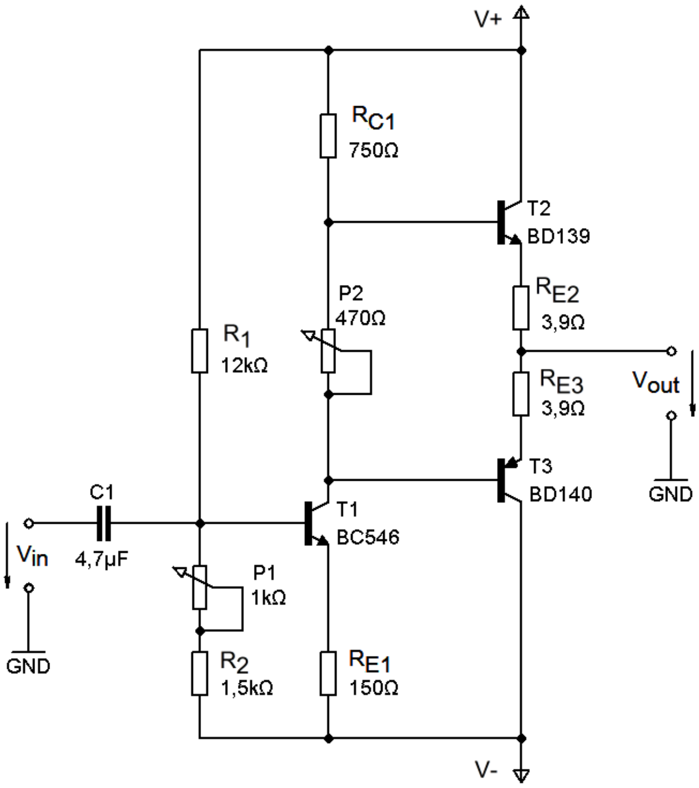
a) Set up 1kHz 3V_p sinewave on the function generator (remember: always check the signal on the scope first) and connect it to the amplifier's input. Display v_{in} and v_{out} on the scope.

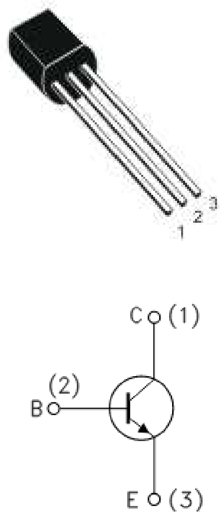
b) Set input to 20V_{pp}! Watch the output signal get distorted (draw it!) and explain the reason.

c) Continue with the previous setting and slowly increase +V_{supply} and examine the output. Draw the output signal when +V_{supply}= 8V and 12V.

d) Repeat the exercise by changing –V_{supply}.

3.2 Class AB amplifier





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13.

V_{supply}= **±12V**.

Operating point values and output OFFSET

a) Set all potmeters to 0Ω. Measure the following DC voltages: V_{R2}; V_{RE1}; V_{RC1}; V_{C1}; $V_{OUT\text{-}OFFSET}$.

b) Use potmeter P_1 to set the output offset voltage (ie. the DC voltage at the output) to as close to 0V as possible. (Write down the measured offset and the value of P1.)

Class B and AB operation

a) Use 1Vp 1kHz sinewave as input. Use 15kΩ load. Display v_{in} and v_{out} on the scope!

b) Slowly change potmeter P2 to adjust the operating point of the circuit. Do this until the crossover distortion is minimal. This will also change the OFFSET voltage, so use P1 potmeter to set the offset back to zero volts! Display v_{out} again. (Draw all the signals in the lab report of course...)

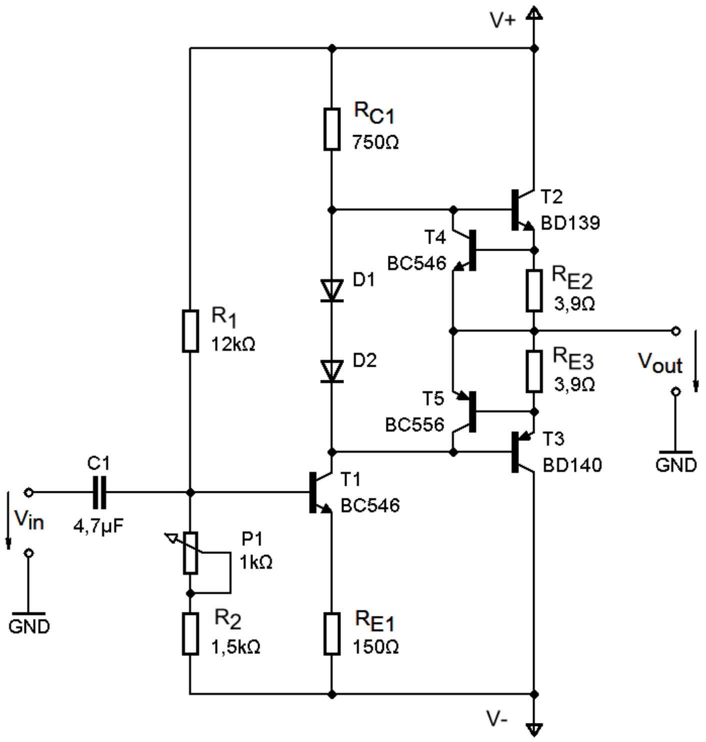
c) Replace potmeter P2 with 2 diodes (1N4007 type) (similarly to *figure 14.*) (turn off power supply first). Set OFFSET to zero again using P1.

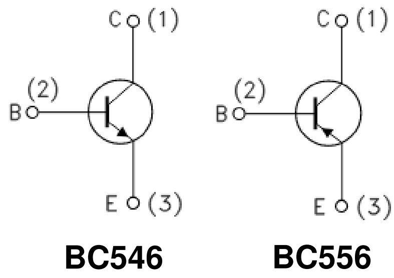
d) Measure how much you can increase the input signal before the output starts to be visibly distorted. Do this for the positive and for the negative peak separately.

e) Change input signal to $1V_p$. Use R_L=33Ω. Display and measure the output signal. What causes the changes (in output voltage and input max range)?

Output current limit

Change our circuit by adding the current limit:



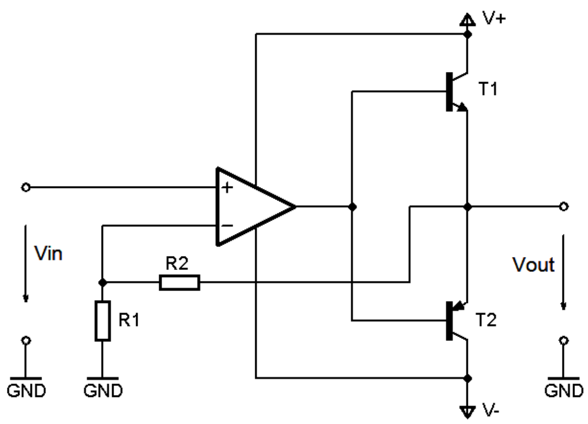


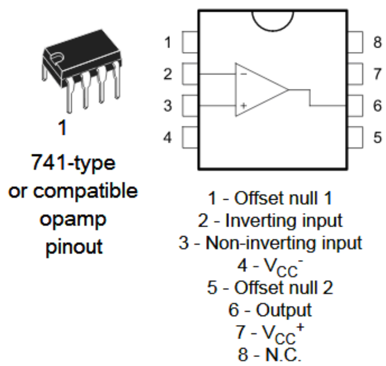
14. Amplifier with output current limit

V_{supply}= ±12V. **R_L=33Ω**. Increase the input amplitude until the effect of current limit on the output becomes visible on the output signal. Measure peak of output voltage. Find the max current using the formula:

$$I_{out\max} = \frac{V_{out\max}}{R_L}$$

3.3 Extending the output current of opamps using complementary transistors





15. Complementary end stage after opamp

V_{supply}= ±12V; R_1=1.5kΩ; R_2=15kΩ

Set input V_p= 600mV. Display input and output signals without load and with 33Ω load. How much is the maximum voltage range in those cases?

4 Test questions

1. Draw a simple class B complementary emitter follower amplifier circuit. What is the main disadvantage of this?
2. Draw the transfer characteristic of the class B complementary emitter follower. Draw the input and output signals (for sinewave input).
3. What determines mainly the maximum output voltage range of the complementary emitter follower amplifier?
4. Draw a simple class AB complementary amplifier and its transfer characteristic.
5. Briefly discuss voltage offset solutions and their advantages/disadvantages.
6. Draw a class AB amplifier with output current limit. What is the maximum current if R=3,9Ω is used?
7. How can we extend the output current of opamps?