Lecture: Charge-sensitive amplifier and two-stage amplifier

The topics of this lecture are:

- Charge-sensitive amplifier
- Two-stage voltage amplifier

Charge-sensitive amplifier

Charge amplifiers are often used for amplifying sensor signals. This circuit has a very similar form to the voltage amplifier that we describer in Lecture 6. In this section, we will derive the transfer function of the charge amplifier.

Let us start with the voltage amplifier.

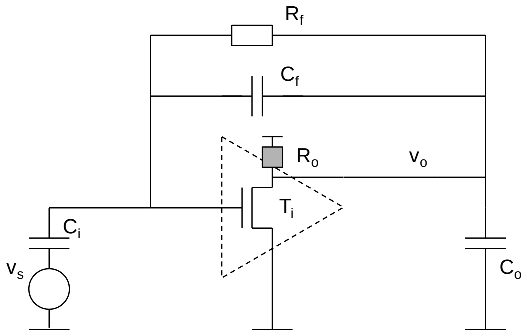


Figure 1: Spannungsverstärker

Its transfer function is (24):

$$v_o = -v_s \frac{C_i}{C_f} \alpha \frac{sT_f}{(sT_f+1)} \frac{1}{(sT_r+1)} \qquad (1B)$$

with

$$T_f = R_f C_f,\ T_r = \frac{sT_0\alpha}{\beta\times A},\ T_0 = R_o C'_o,\ \beta = \frac{C_f}{C_i^+ + C_f}, \alpha \equiv \frac{\beta\times A}{1+\beta\times A}, C_i^+ = C_i + C_g$$

We first convert the voltage source at the input to the current source.

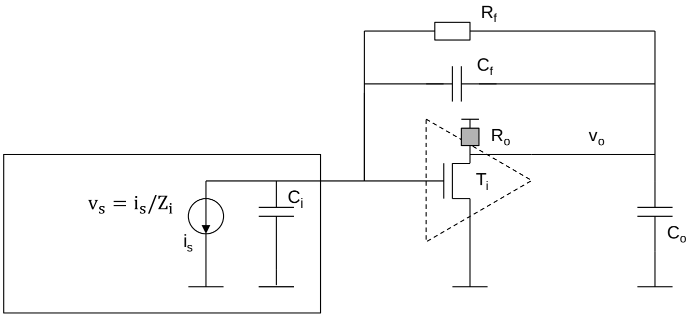


Figure 2: Umwandung der Spannungsquelle in Stromquelle

It holds

$$v_s = \frac{i_s}{Z_i} \qquad (2B)$$

Is is the current of the current source. **The input capacitance C_i is usually the capacitance of the sensor.**

Now let us derive the current gain, defined as v_o / i_s.

It holds (1B)

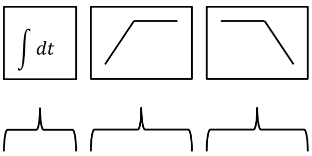
$$v_o = -v_s \frac{C_i}{C_f} \alpha \frac{sT_f}{(sT_f+1)} \frac{1}{(sT_r+1)}$$

If we use (2B), we get:

$$v_o = -\frac{i_s}{sC_i} \frac{C_i}{C_f} \alpha \frac{sT_f}{(sT_f+1)} \frac{1}{(sT_r+1)} = -\frac{i_s}{sC_f} \alpha \frac{sT_f}{(sT_f+1)} \frac{1}{(sT_r+1)} \qquad (3B)$$

Note that the gain is not dependent on C_i if βA is >> 1. This is quite useful because the sensor capacitance may be large and unknown.

The gain v_o/i_s is the combination of the integrator, high-pass and low-pass filter, Figure 3.



$$v_o = -\frac{i_s}{sC_f} \alpha \frac{sT_f}{(sT_f + 1)} \frac{1}{(sT_r + 1)}$$

Figure 3: Übertragungsfunktion des Ladungsverstärkers

The impulse response to a current pulse with the integral Q is shown in Figure 4?

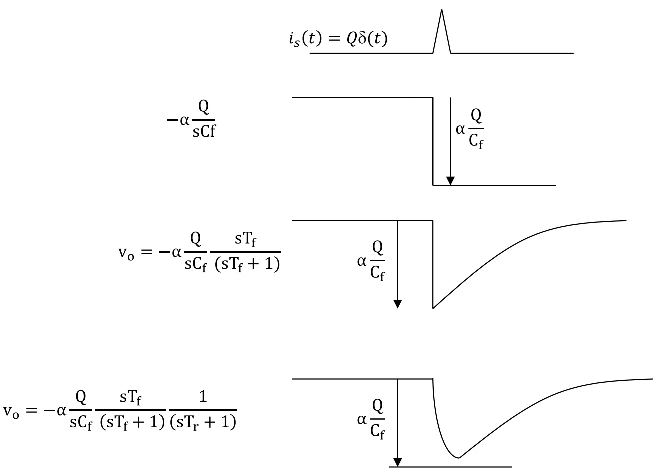


Figure 4: Impulsantwort des Ladungsverstärkers auf ein Stromimpuls mit dem Integral Q

Amplitude of the output signal depends on charge Q divided by C_f! The charge is linearly amplified, the output signal is proportional to Q and independent of the form of the input pulse. For this reason, we call the circuit charge-sensitive amplifier.

Two-stage voltage amplifier

We can see from formulas 1B (voltage amplifier) and 3B (charge sensitive amplifier) that the gain and rise time depend on the α parameter. α should be as close as possible to 1.

$\alpha \equiv \frac{\beta \times A}{1+\beta \times A}, \beta = \frac{C_f}{C_i^+ + C_f}, C_i^+ = C_i + C_g$ (4B)

The input capacitance C_i is often large and the capacitance in feedback C_f is small. We therefore need a large open loop gain A to have $\alpha \sim 1$. It is difficult to reach A >100 with an amplifier made of one transistor as shown in Figure 1.

Two-stage amplifier is used to achieve greater open loop gain. Figure 5 shows a two-stage voltage amplifier.

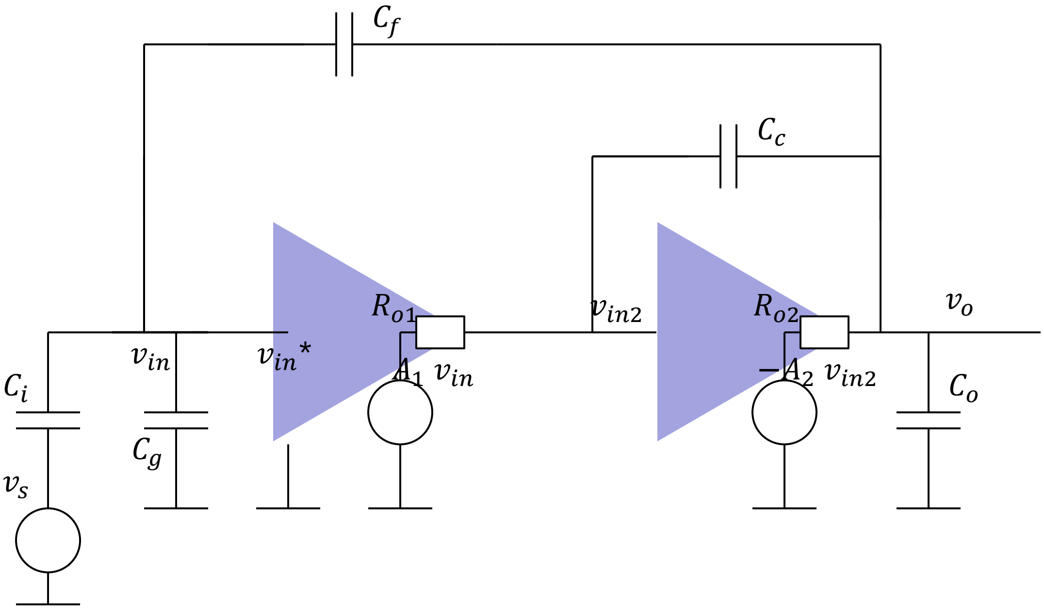


Figure 5

We will now calculate the transfer function using the Mason formula (5B).

$A_{FB} = \frac{FF + A_{in}A_{ol}}{1-\beta A_{ol}}$ (5B)

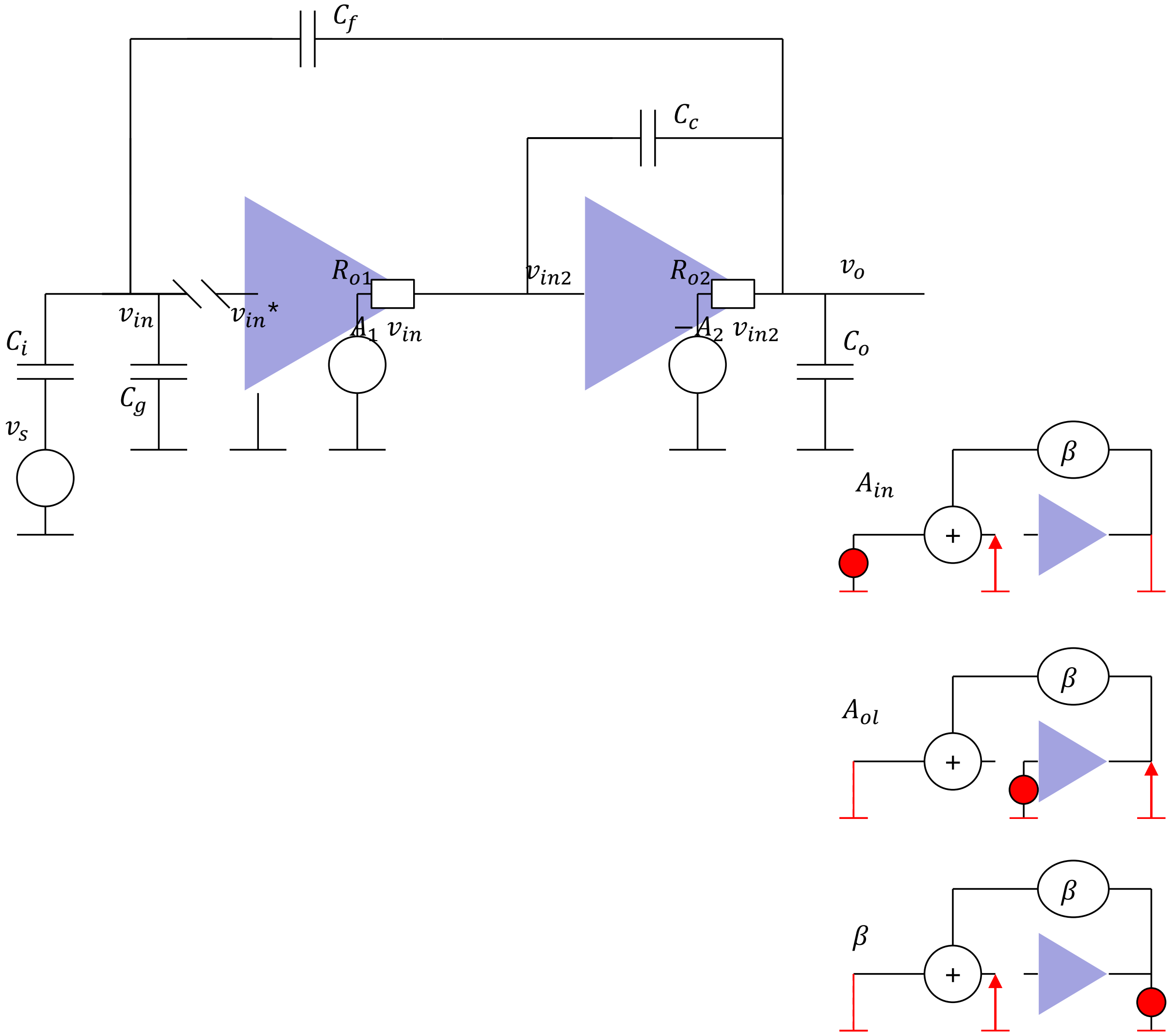


Figure 6

Figure 6 shows the test circuits for calculation of parameters A $_{in}$, A_{ol} and β. We will neglect the feed forward FF.

The A_{in} and β (Figure *7* and Figure *8*) have the same values as for a single-stage amplifier.

$A_{in} = \frac{sC_i}{s(C_i^+ + C_f)}$ (6B)

$\beta = \frac{sC_f}{s(C_i^+ + C_f)}$ (7B)

$$A_{in} = \frac{sC_i}{s(C_i^+ + C_f)}$$

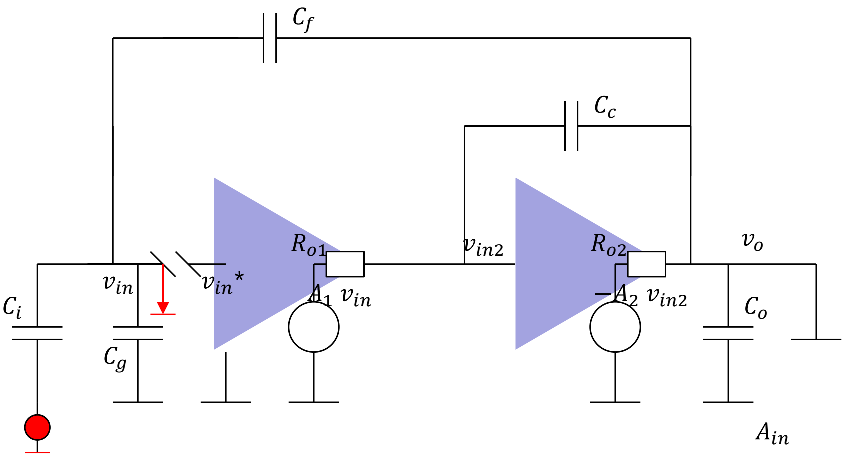


Figure 7

$$\beta = \frac{C_f}{C_i^+ + C_f}$$

$$A_{in} = \frac{sC_i}{s(C_i^+ + C_f)}$$

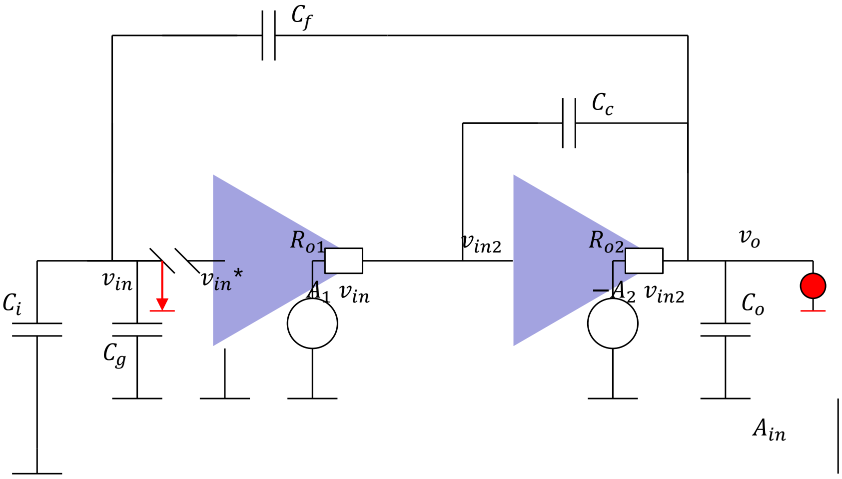


Figure 8

Let us calculate A_{ol}. The test circuit is shown in Figure 9.

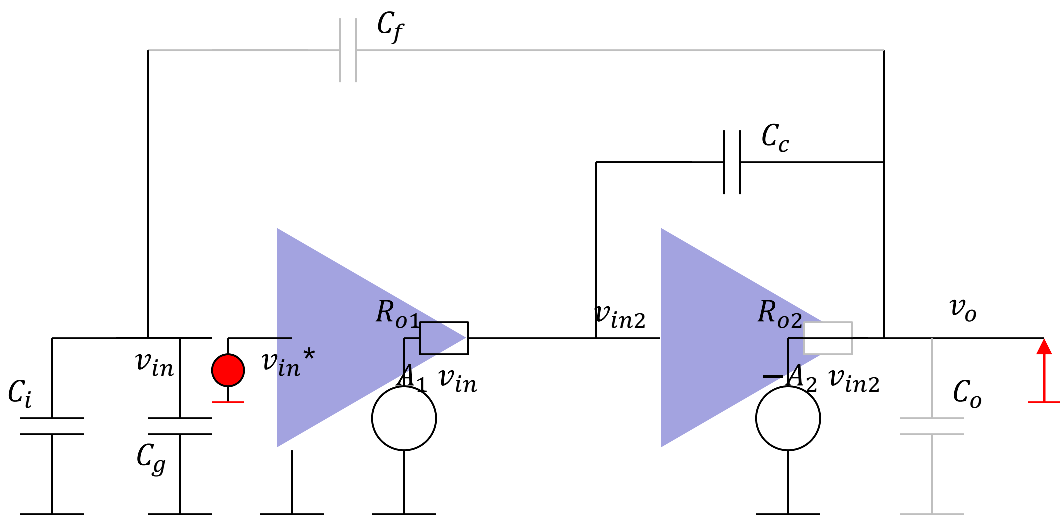


Figure 9

We will neglect the output resistance R_{o2} and assume $v_o = A_2 v_{in2}$. C_f and C_o can also be neglected.

The second amplifier represents a capacitive load for the first amplifier. How large is this capacitive load? An amplifier with negative gain -A and capacitive feedback C has an input capacitance of C(1+A). We can verify this result by imagining a C-meter - Figure *10*.

A "C-Meter" measures the capacitance by generating a current I_{test} and by measuring how much the voltage on the capacitor (ΔU) has risen after time ΔT - Figure *10* (left). The capacitance can be determined with the following formula:

$$I_{test} = C\frac{\Delta U}{\Delta T} \Rightarrow C = I_{test}\frac{\Delta T}{\Delta U}$$

Smaller voltage change means greater capacitance.

Let us now assume that exactly the same current flows into the capacitor with amplifier Figure *10* (right).

The voltage between the capacitor electrodes after the time ΔT is the same as when we have a capacitor without amplifier:

$$\Delta U = \frac{I_{test}}{C}\Delta T$$

The voltage at the input of the amplifier changes by approximately:

$$\Delta U_{in} = \frac{\Delta U}{A+1} \ll \Delta U$$

The voltage at the output changes by:

$$\Delta U_{out} = -\Delta U\frac{A}{A+1} \sim \Delta U$$

The difference ΔU_{in} - ΔU_{out} is U.

Since the C-meter measures a voltage change that is A + 1 smaller than ΔU, it interprets as a capacitance that is A + 1 larger than C.

If we connect a resistor to the input of the amplifier with C, the amplifier behaves as a large capacitor with the capacitance (A + 1) C. The time constant is correspondingly large. Such an increase of the capacitance is called the Miller effect.

The capacitive load for the first stage is therefore $1{+}A_2C_c$.

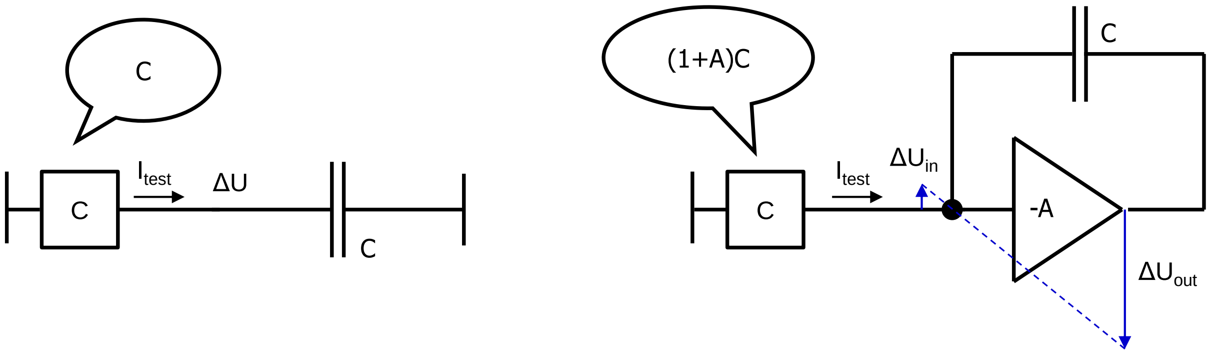


Figure 10

We can simplify the two-stage amplifier by replacing the second amplifier with a load capacitance $(1+A_2)\ C_c$ and a voltage-controlled voltage source – Figure *11*.

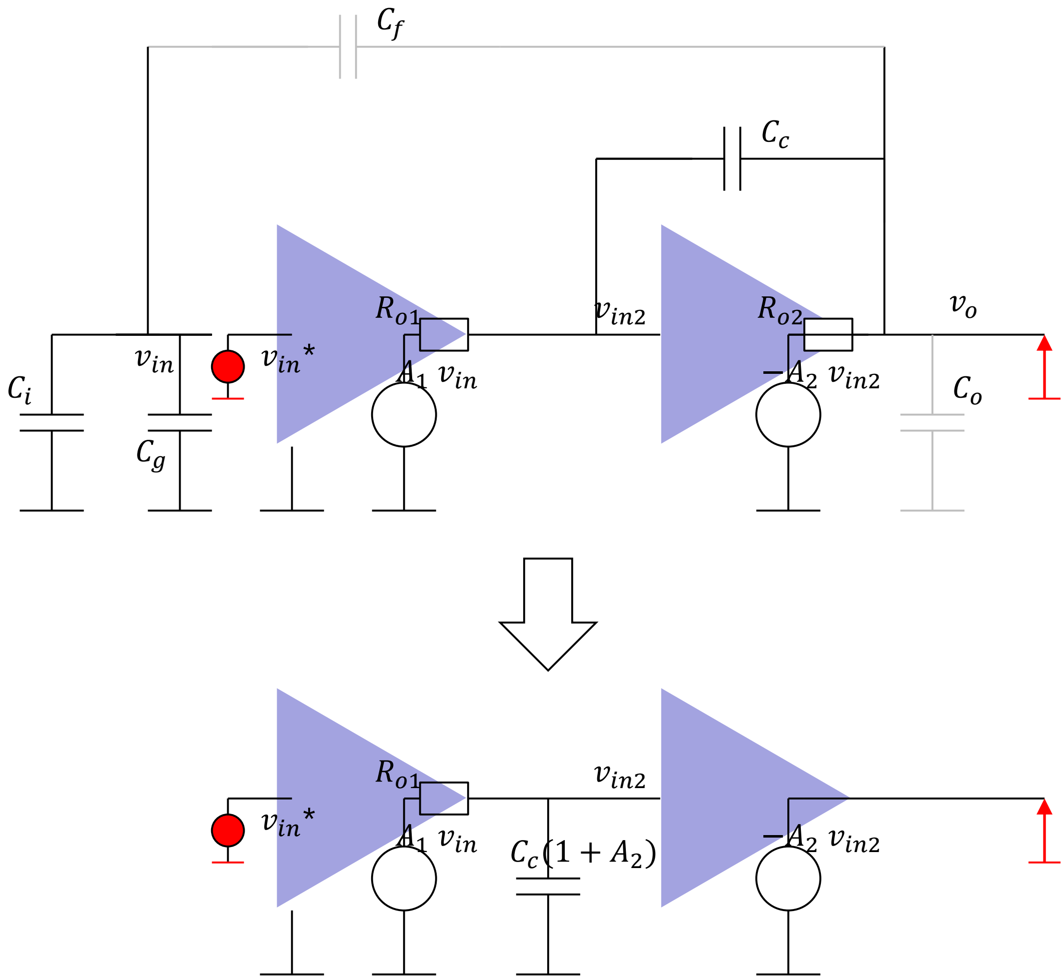


Figure 11

The open loop gain A_{ol} is:

$$A_{ol} = -A_1 A_2 \frac{1}{sR_{o1}(1+A_2)C_c+1}$$

or

$A_{ol} = -A\frac{1}{sT_o+1}$ (8B)

with

$T_o = R_{o1}(1 + A_2)C_c$

and

$A = A_1A_2$

By inserting these results in Mason formula, we get the transfer function:

$$A_{fb} = -\frac{C_i}{C_f}\frac{\beta\times A}{(1+\beta\times A)}\frac{1}{\left(\frac{sT_0}{1+\beta\times A}+1\right)} = -\frac{C_i}{C_f}\alpha\frac{1}{\left(\frac{sR_{o1}\,A_2C_c\alpha}{\beta\times A_1A_2}+1\right)} = -\frac{C_i}{C_f}\alpha\frac{1}{\left(\frac{sR_{o1}C_c\alpha}{\beta\times A_1}+1\right)} \quad (9B)$$

In the case of amplifiers based on transistors, the following applies: $A = g_m R_o$. Therefore:

$$A_{fb} = -\frac{C_i}{C_f}\alpha\frac{1}{\left(\frac{sC_c\alpha}{\beta\times g_{m1}}+1\right)}, \alpha\equiv\frac{\beta\times A}{1+\beta\times A},\ A = g_{m1}R_{o1}g_{m2}R_{o2} \quad (10B)$$

For comparison, in the case of the single-stage amplifier, we had:

$$A_{fb} = -\frac{C_i}{C_f}\alpha\frac{v_s}{\left(\frac{sC'_o\alpha}{\beta g_m}+1\right)}, \alpha\equiv\frac{\beta\times A}{1+\beta\times A},\ A = g_mR_o \quad (11B)$$

Equations 10B and 11B are almost identical. In the case of the two-stage amplifier, the time constant depends on C_c and in the case of the single-stage amplifier, on C_o. Large open loop gain can be easily achieved with the two-stage amplifier.