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- Generalized operational amplifier theory: VC, CV and CC structures

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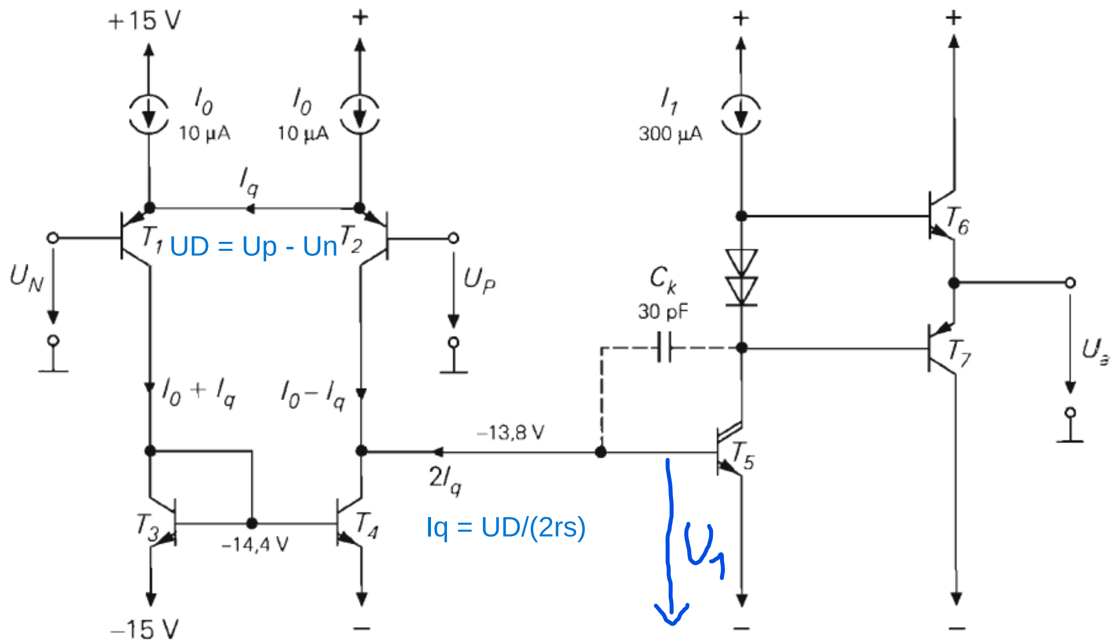
Exercice: Analysis of opamp structure

Admit that the sources I_0 and I_1 need a minimum overhead voltage of 1.0V to operate. U_{BE} = 0.6V, U_T = 25mV for all transistors and diodes.
Total resistance connected to node of the basis of T_5 R_1 = 2MΩ, of the collector of T_5 R_2 = 100kΩ. Base currents are negligible. Transconductance of T_5: $1/r_{S5}$ = 5mA/V.



What is the admissible input voltage range of U_N, U_P ? What is the possible output voltage range of U_a ?
Determine the gain $A_0 = U_a/(U_P-U_N)$ of this opamp.
Admit that the capacitor C_k determines the dynamic behaviour of the circuit. What is the cut-off frequency of the open-loop transfer function ? What is the maximum slew rate ?
If the opamp is used as a linear inverting stage, which gain can be realised at 10kHz ?

Simple transconductance amplifier

Basic VV operational amplifier structure, where the output stage was suppressed.

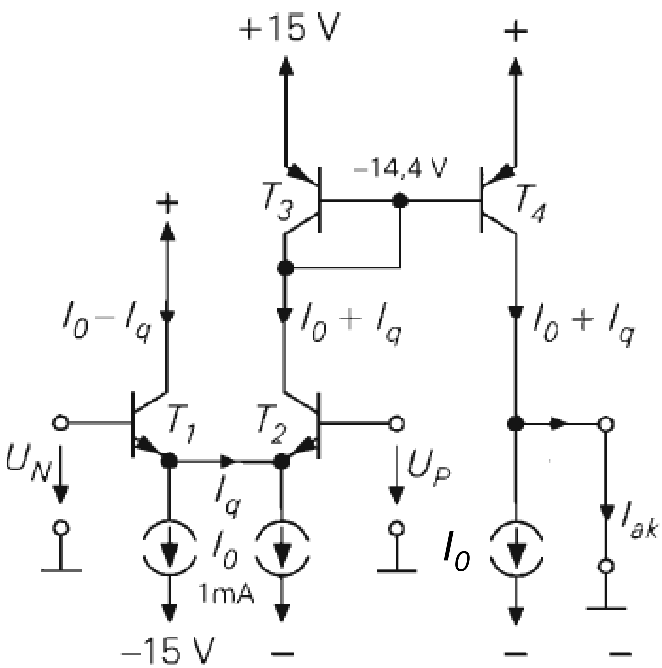
Transmission gain = transconductance:

$$S_D = \frac{I_q}{U_D} = \frac{1}{2r_S} = \frac{I_0}{2U_T}$$

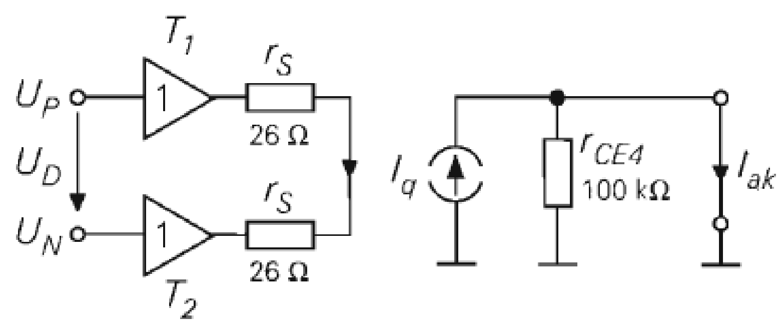
The transconductance can be set by inserting an additional emitter resistance R_E, between the two emitters of the differential stage.

Output resistance:

$$r_a = \left.\frac{u_a}{i_a}\right|_{u_e=0} = r_{CE\ 4}$$



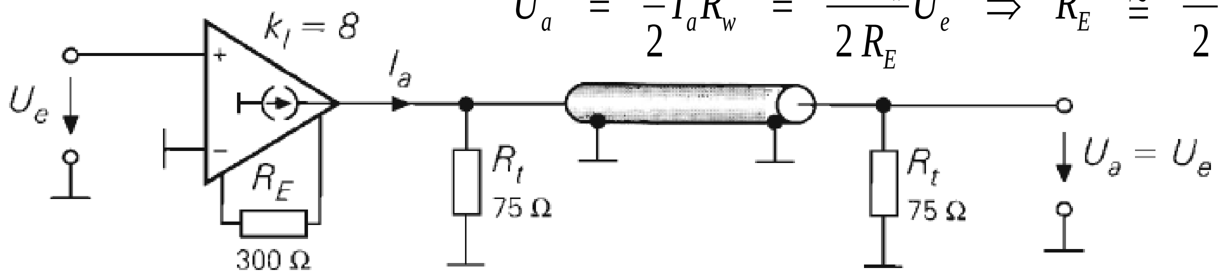
Because of the high output resistance, output voltage strongly dependant on load.



Coax line driver

Output resistance supposed to be large as compared to wave impedance R_w. To avoid reflections, line terminated on both ends with $R_t = R_w$.

$$U_a = \frac{1}{2} I_a R_w = \frac{k_I R_w}{2 R_E} U_e \Rightarrow R_E \cong \frac{k_I}{2} R_w$$

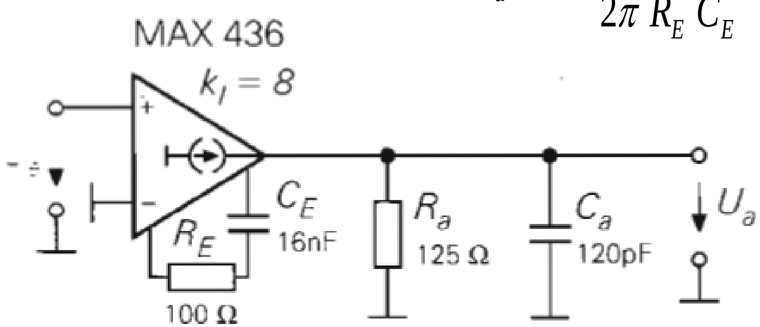


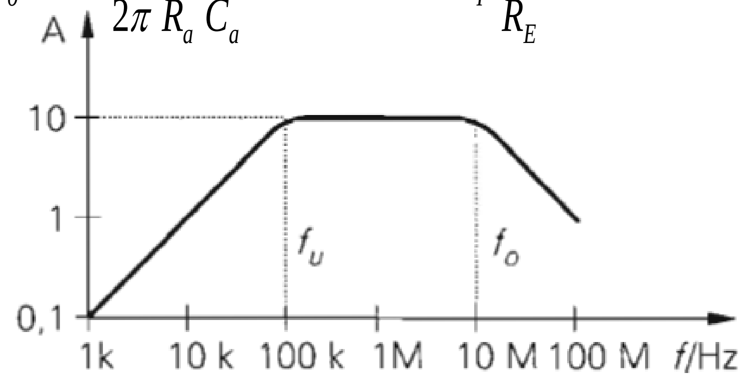
The particular choice of R_E gives $U_a = U_e$ which is an advantage for low voltage supply.

Passive bandpass

Emitter impedance is here complex, series RC yields high pass. Parallel RC output termination yields low-pass.

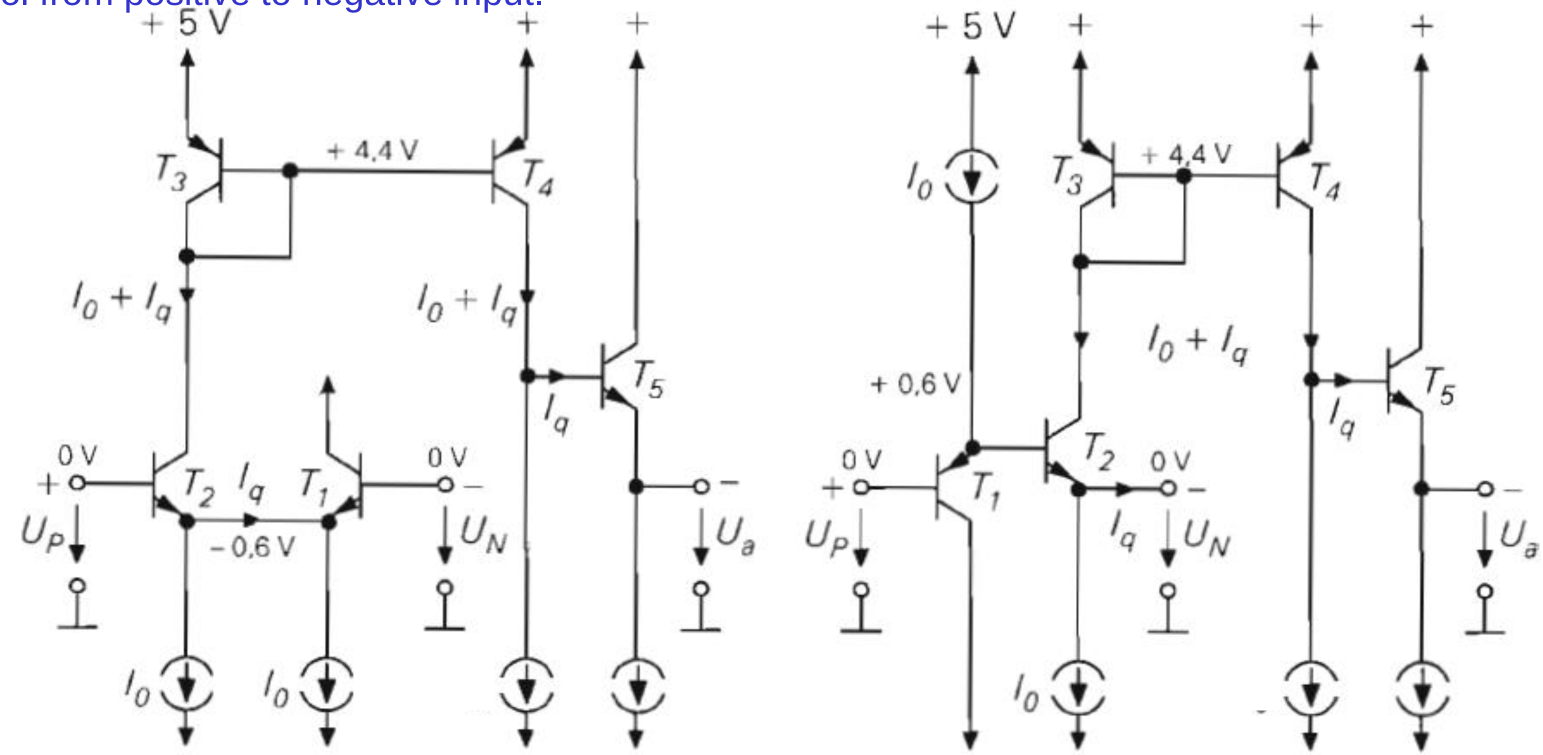
$$f_u = \frac{1}{2\pi R_E C_E} \quad f_o = \frac{1}{2\pi R_a C_a} \Rightarrow A \cong k_I \frac{R_a}{R_E}$$





Transimpedance operational amplifier

Standard VV amplifier on left hand figure, CV amplifier for comparison on right hand figure:
I_q is not the total base current of T_5, but the signal part.
Elimination of T_1 of VV circuit leads to low impedance negative input. T_1 of CV circuit compensates U_{BE} threshold of T_2: $U_{D0} = 0$ by nature of the circuit, with output resistance r_S at negative input ⇒ additional arrow symbol from positive to negative input.

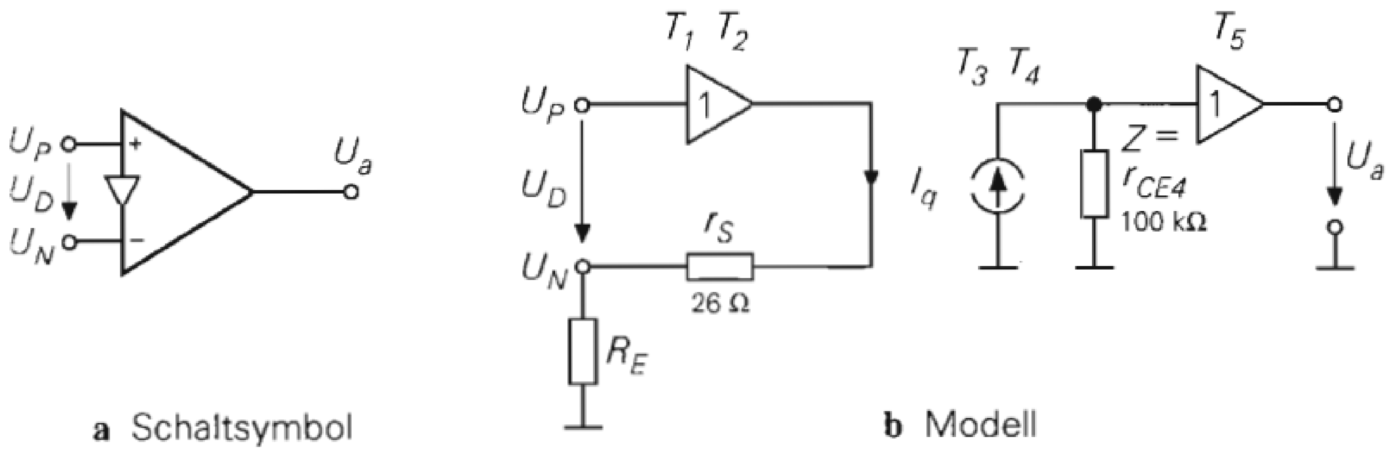


Transimpedance Z = r_{CE4}:
(internal resistance of high impedance node)

$$U_a = I_q Z = \frac{U_D}{r_S} Z \Rightarrow A_D = \frac{U_a}{U_D} = \frac{Z}{r_S} = \frac{U_A}{U_T}$$

Model of transimpedance operational amplifier

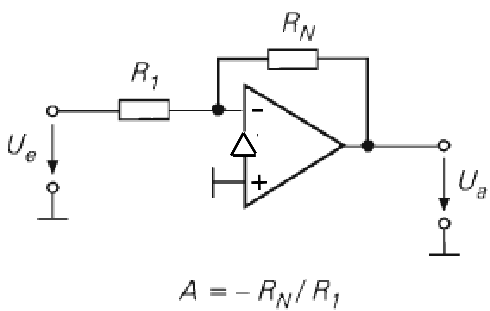
Input resistance R_E of N input to ground (Early resistance of I_0 current source).

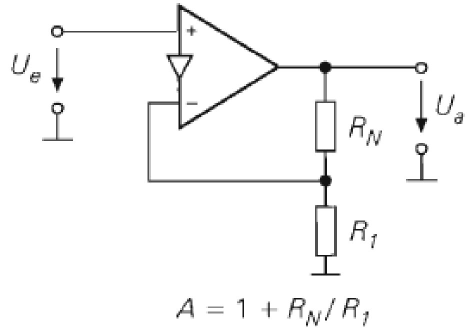


$$A_B = \frac{U_a}{U_P} = \frac{Z}{R_E + r_S}$$

Typical applications

Only resistive feedback is stable, capacitive feedback (e.g. integrator) is not.

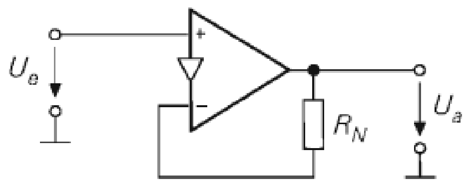


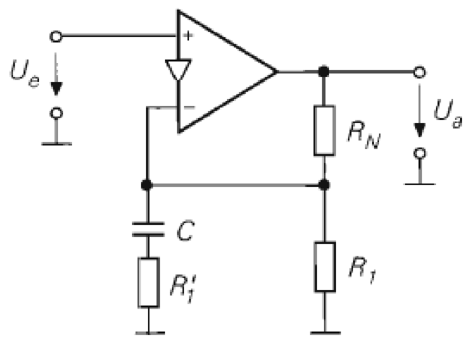


Inverting amplifier

Non-inverting amplifier

R_N determines loop gain, and is therefore to be selected as a function of amplifier type.
For high gain, non-inverting circuit has higher input resistance.



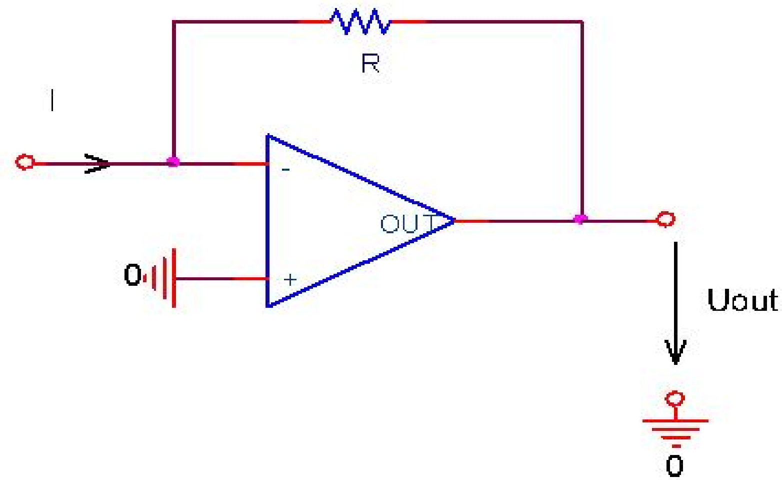


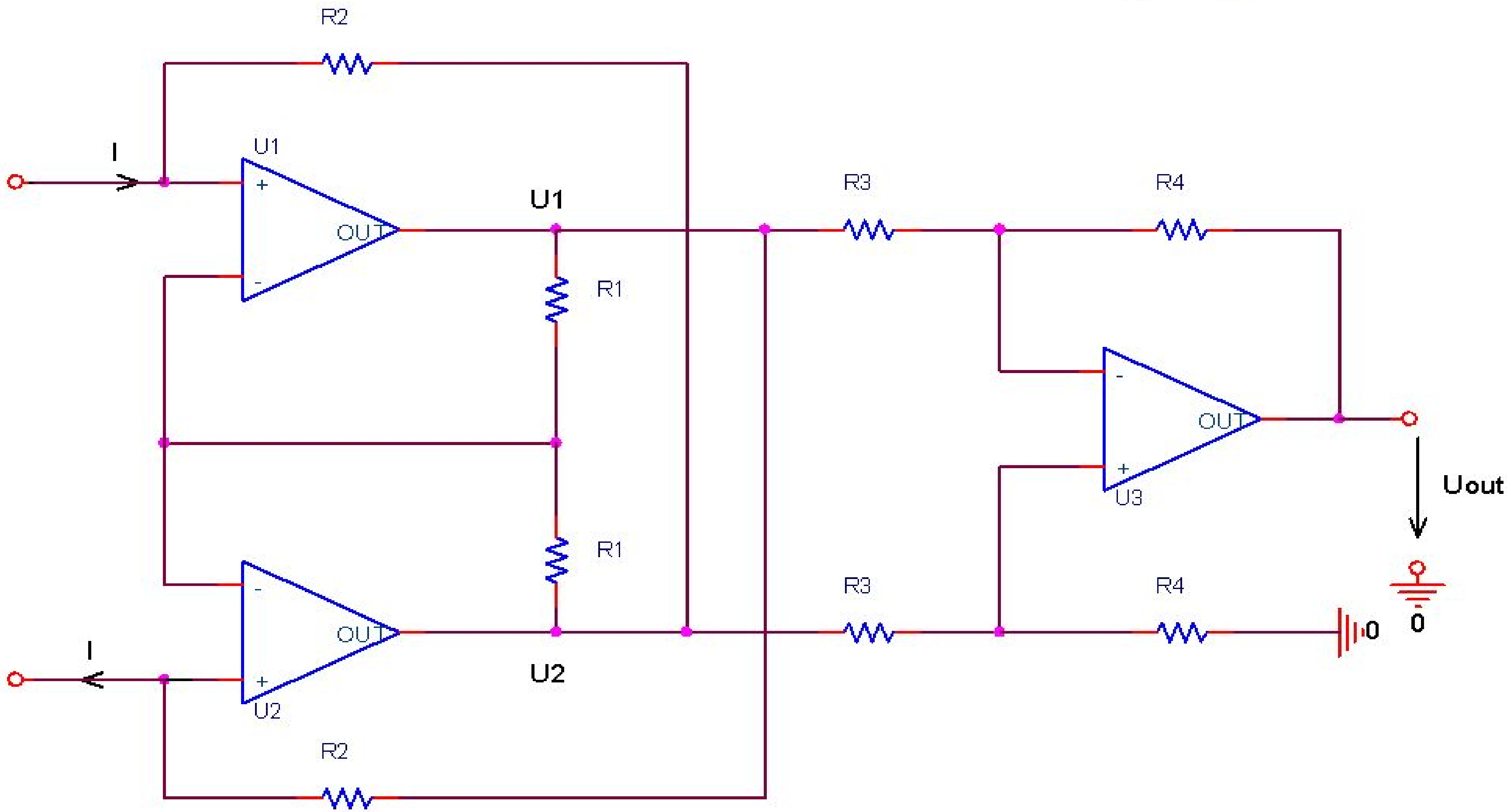
Voltage follower

Compensation of low pass behaviour of loop gain

Current to voltage conversion

Determine the transfer characteristic of the following circuits:

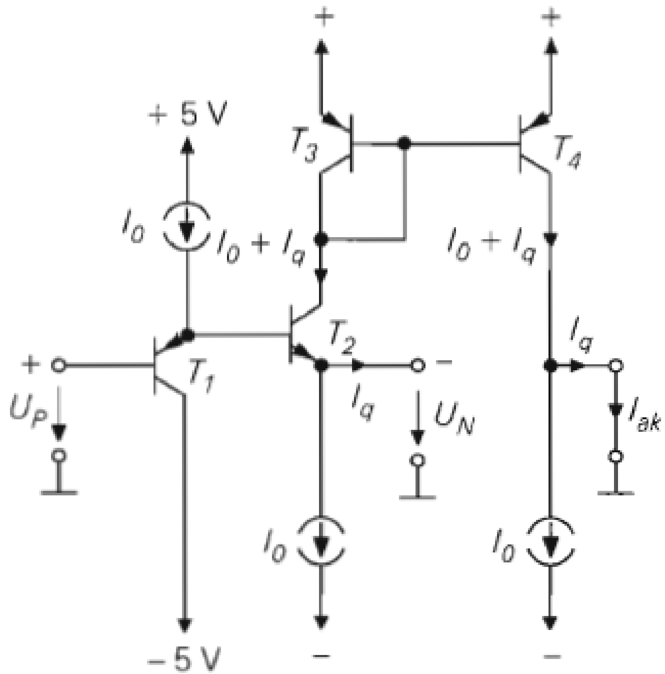




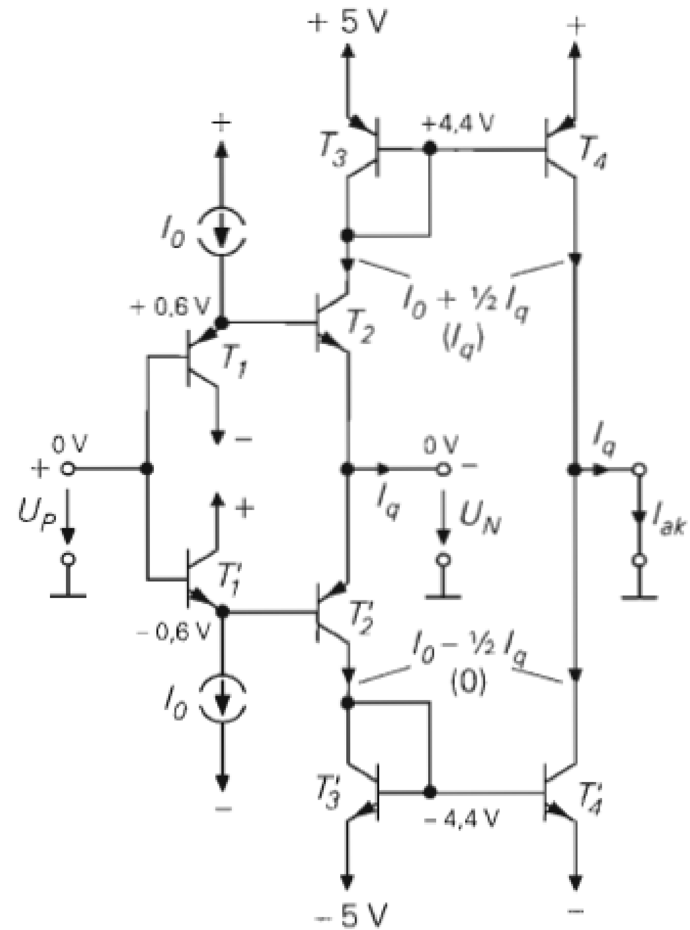
Current amplifier circuit

As compared to CV amplifier: emitter follower at output omitted.

Current gain defined by mirror T_3, T_4



Circuit idea



Realisation, e.g. OPA660

Symbols and model of current amplifier

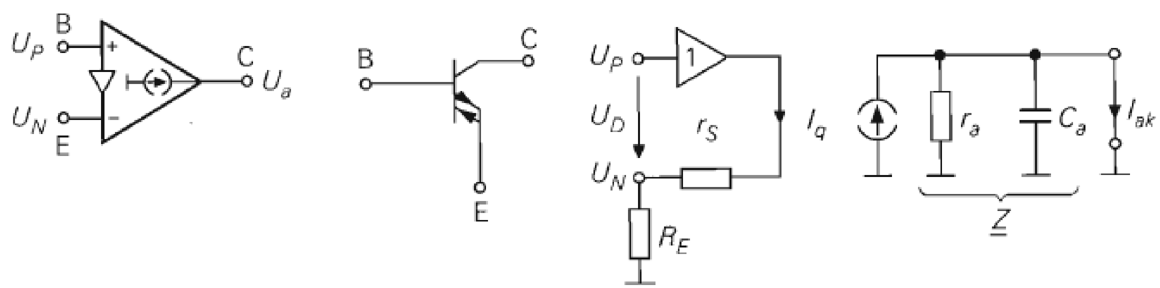
This current amplifier behaves like a transistor:

- **Collector current = emitter current**
- Base input resistance high, emitter input resistance low
- **Collector output resistance high**

Differences from a simple transistor:

- Collector current has inverted direction
- **U_{BE} = 0 (the 'perfect' transistor!)**
- Operating point internally defined
- **Emitter and collector currents can flow in both directions**

Trade name: *Diamond transistor* (Burr Brown)



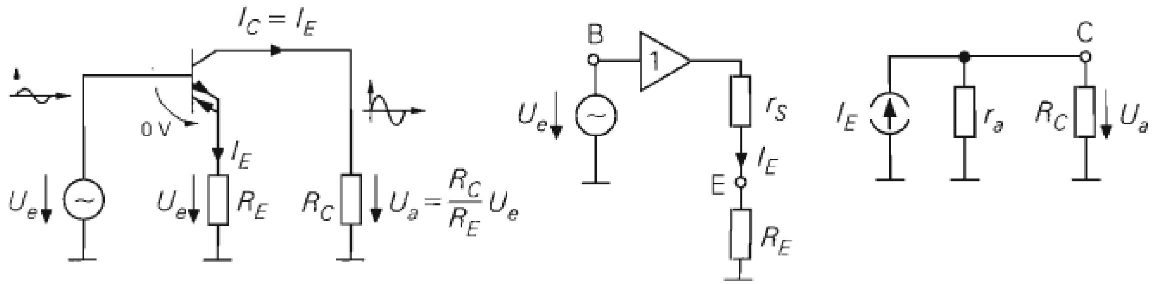
a OPV Schaltsymbol **b** Transistor Schaltsymbol **c** Modell

$$S = \frac{I_{ak}}{U_D} = \frac{1}{r_S}$$ with external resistance R_E at emitter: $$S_B = \frac{I_{ak}}{U_P} = \frac{1}{r_S + R_E}, \quad A_B = S_B R = \frac{R}{r_S + R_E}$$

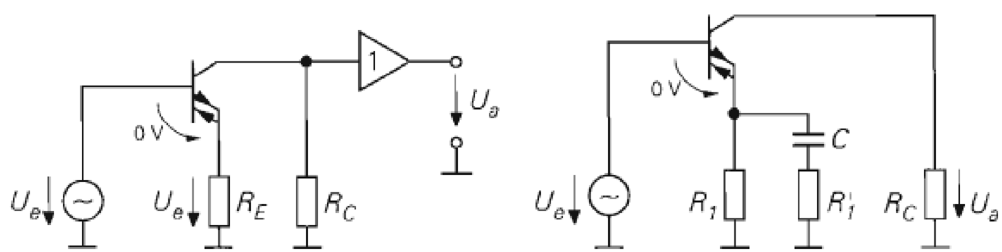
Emitter coupling of current amplifier

Emitter circuit = current feedback at inverting input

Common emitter circuit, and model:



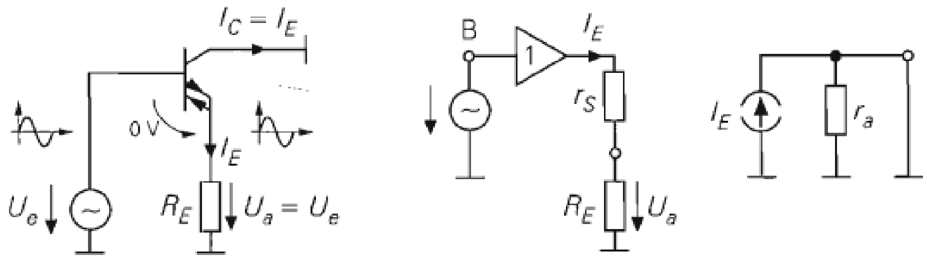
Emitter circuit followed by collector circuit to avoid influence of load on gain.
High frequency gain drop counter-acted by reduction of R_E:



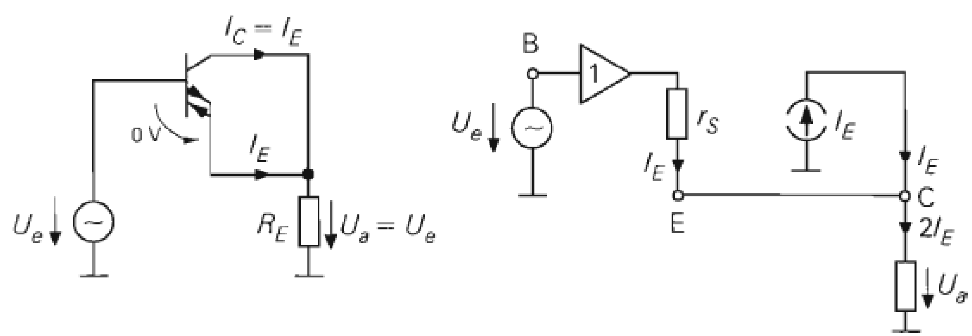
Remark: Develop the gain and impedance relations of circuits on slides 11…20 as exercice.

Collector coupling of current amplifier

Collector circuit = output at emitter, collector grounded (operating point internall**y fixed)**

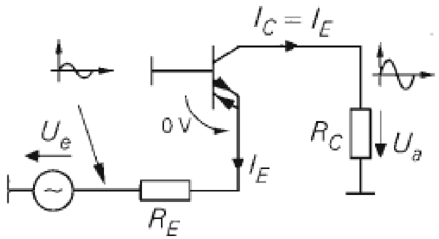


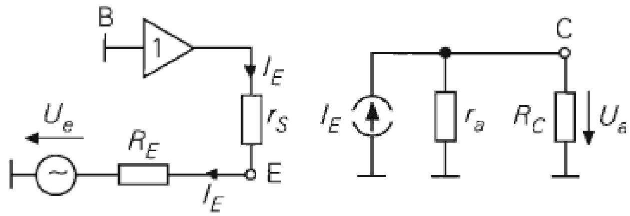
Alternatively, collector and emitter can be connected together to obtain twice the output current: The output resistance is halved.



Base coupling of current amplifier

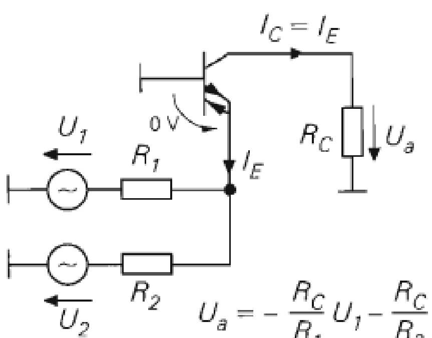
Base circuit = input at emitter, collector is output



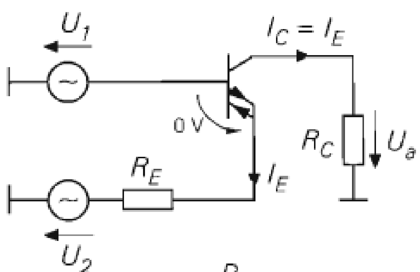


Compared to simple transistors, the gain in emitter and base circuits has changed sign.

The base circuit can be used for addition and together with the emitter circuit for subtraction:



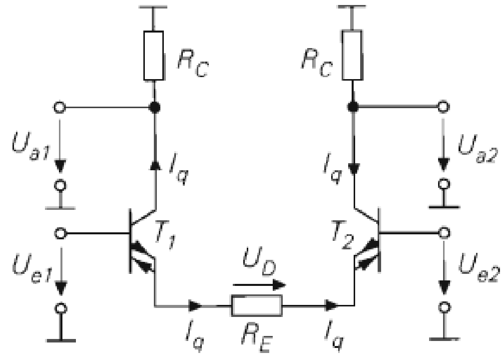
$$U_a = -\frac{R_C}{R_1} U_1 - \frac{R_C}{R_2} U_2$$



$$U_a = \frac{R_C}{R_E} (U_1 - U_2)$$

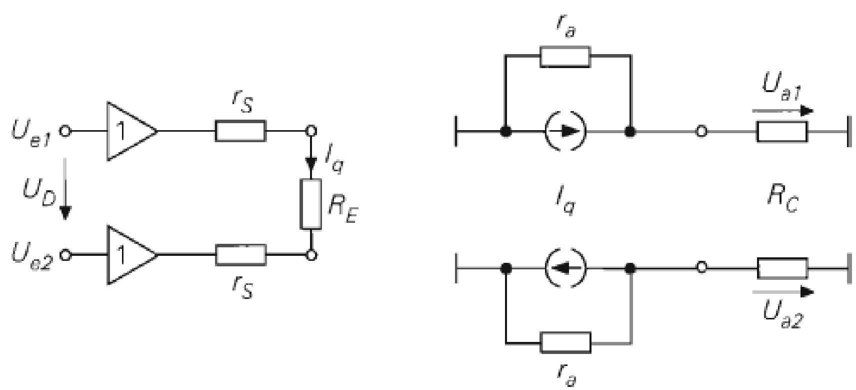
Difference amplifier with two current amplifiers

Collector resistances grounded since operating point internally determined.
E.g. MAX435, OPA2662 (duals)



R_E determines the gain.

Model:



Application example: high bandwidth precision rectifier

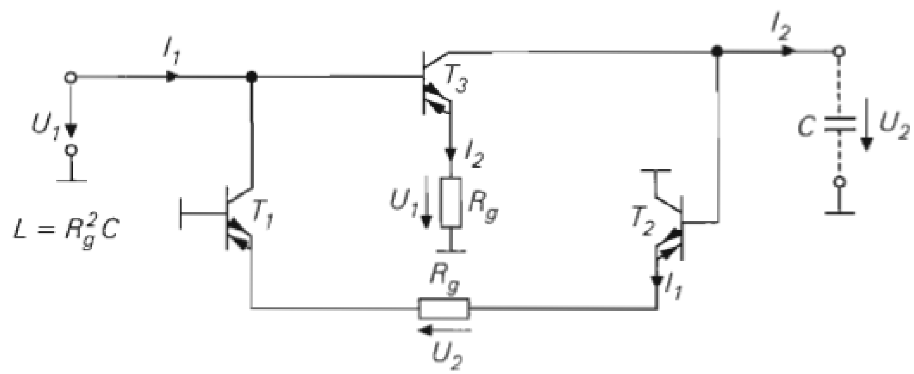
Gyrator with current amplifiers

Gyrator = dual of a transformer

$$I_1 = \frac{1}{R_G} U_2$$

$$I_2 = \frac{1}{R_G} U_1$$

E.g. SHC615



Interesting property: inductance simulation with C at port 2: *$L = R_g^2\, C$*

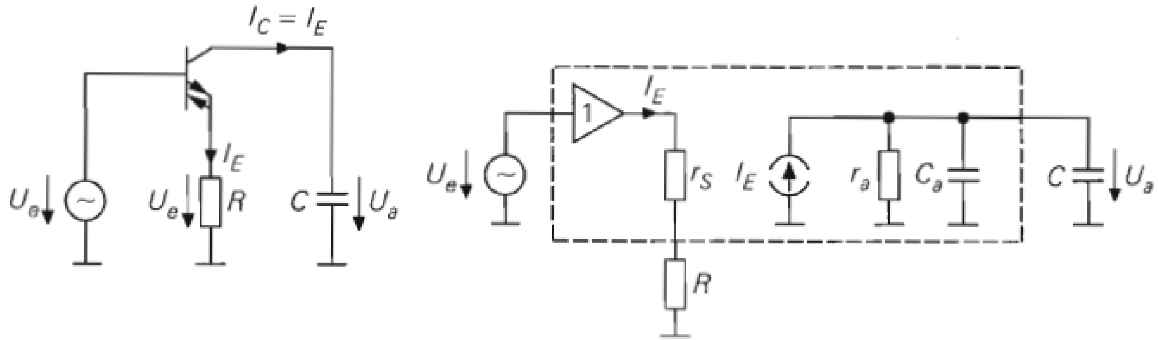
With C at ports 1 and 2, a parallel resonant circuit is realized.

Integrator with current amplifier

Integrator = capacitor fed by current source.

Non-inverting integrator!

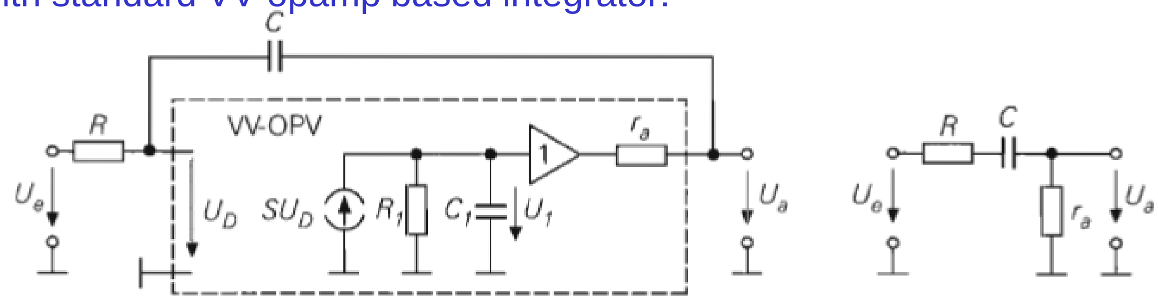
Voltage output should be run through impedance converter.



$r_a(C_a$+$C)$ represents a lower frequency limit of the integrator.

Upper frequency limit very high.

Comparison with standard VV opamp based integrator:

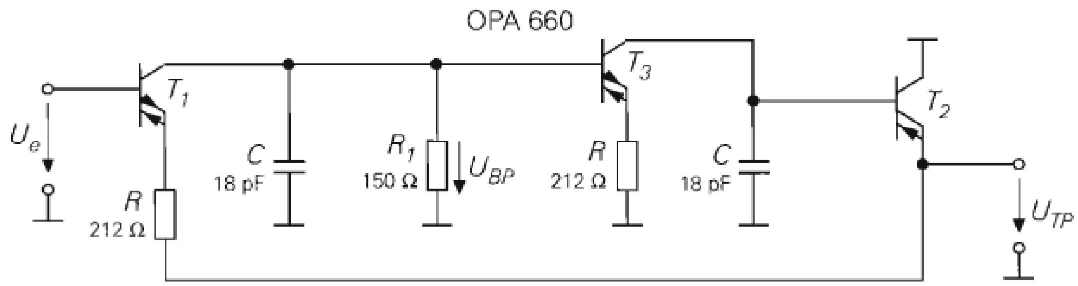


f_T is upper frequency limit.

Second order band-/low- pass with current amplifier

Active high frequency filters based on integrators.

Two integrators followed by an impedance converter form second order stage:

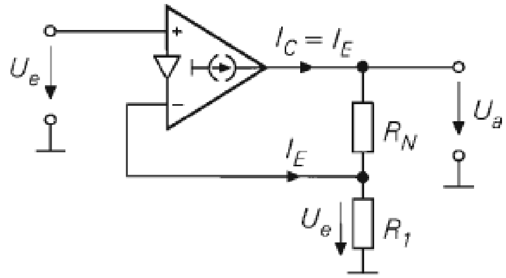


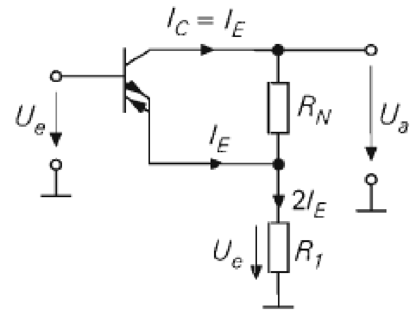
Values are for Butterworth design with f_g = 30MHz
Assuming $r_S = 10\Omega$ and Ca = 6pF.
Operates up to 300MHz.

f_g and quality factor can be set independantly.

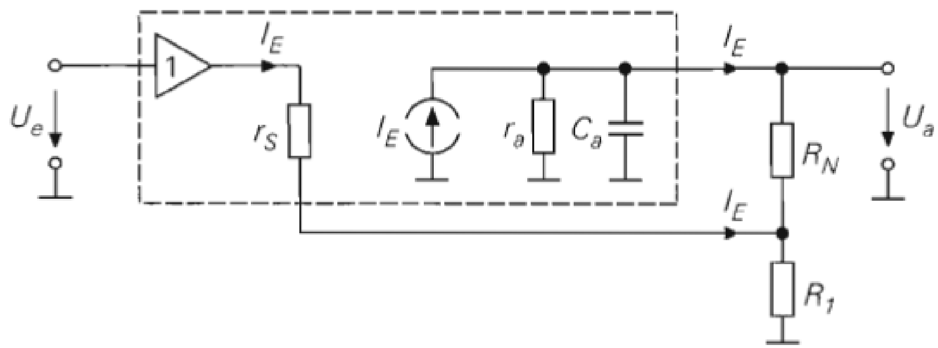
Applications with voltage feedback

Feed back part of the output to inverting input, using voltage divider.





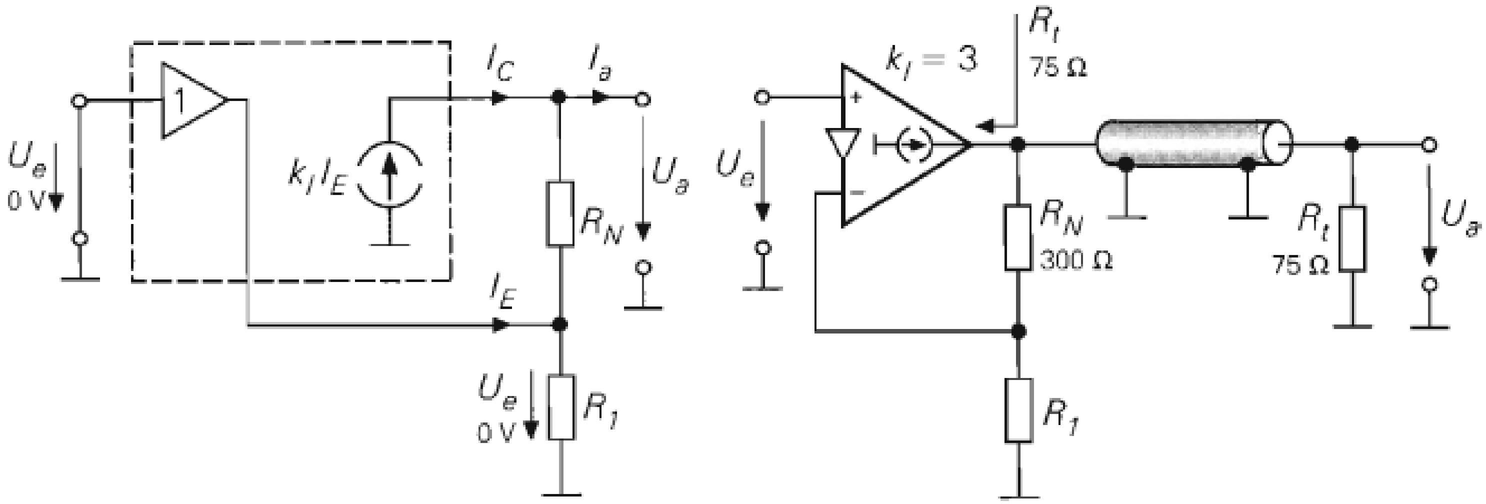
'Direct feedback' since no impedance conversion at out- and inputs.
Corner frequency $\omega_g = 2/(R_N C_a)$



Output resistance $r_a = R_N/(k_I+1)$ with $k_I = I_C/I_E$
Gain and output resistance can be set from outside ⇒ trade name *drive-R-amplifier* (Comlinear)

Active termination

With output resistance determined by R_N.
Reduced power dissipation in R_N, as compared to VC amplifier.



Current amplifier

- Determine the transfer relations of the circuits in slides 11…20
- How does the output resistance of the circuit in slide 20 depend on R_N? Determine the transfer gain of the same circuit.
- Determine the transfer function describing the dynamic behaviour of the circuit in slide 18.

Low noise 75 Ohm driver

Propose a circuit based on a MAX436 and an OP37 amplifier capable of driving a 75 Ohm load with the noise floor of the output determined by the OP37 amplifier.

Determine the bandwidth of the driver and check its stability with 300pF capacitive load.
If an instability occurs, propose an appropriate circuit modification.

Books

Tietze, Schenk: *Halbleiter-Schaltungstechnik*, Springer 1999 (11th ed.), ISBN 3-540-64192-0

This book was used as a basis for the present presentation, the illustrations are taken from it.

Millman: *Microelectronics: Digital and Analog Circuits and Systems*, McGraw-Hill 1984, ISBN 0-07-066410-2

Chatelain, Dessoulavy: *Electronique* , Traité d'électricité: vol VIII, PPUR 1982, ISBN 2-604-00010-5

Gray, Meyer: *Analysis and Design of Analog Integrated Circuits*, Wiley 1984 (2nd ed.), ISBN 0-471-81454-7

Jung: *OpAmp Application Handbook*, Analog Devices 2005, ISBN 0-750-67844-5

Mancini: *OpAmps for everyone*, Texas Instruments 2002