Written Test

Course code: TSTE08, Exam code: TENA

Analog and Discrete-time Integrated Circuits (ISY)

Date:	March 16, 2009
Time:	8-12
Place:	U1
Number of exercises:	5 (5 points max. for each exercise)
Grades:	10p for 3 (ECTS: C), 15p for 4 (ECTS: B), and 20p for 5 (ECTS:A).
Allowed material:	All types of calcuclators except laptops. All types of official tables and handbooks. Textbooks: Johns & Martin: Analog Integrated Circuit Design. Razavi: Design of Analog CMOS Integrated Circuits. Sedra&Smith: Microelectronic Circuits. Dictionaries.
Examiner and responsible teacher:	Sune Söderkvist
Course administrator:	Sune Söderkvist. Tel.: 281355, mail: sune@isy.liu.se
Visiting today:	Around 9.30 and 11.00 a.m.
Corrrect (?) solutions:	Solutions and results will be on the webb home page for the couse.

Graded exams are returned on examinator's office times, tuesdays and fridays at 11.00-13.00, during week no. 14 and 17.

Students instructions

- The CMOS transistor operation regions, small-signal parameters, and noise characteristics are found on the last page of this exam.
- Generally, do not just answer yes or no to a short question. You always have to answer with figures, formulas etc., otherwise no or fewer points will be given.
- You may write down your answers in Swedish or English.

Good Luck!

Exercise 1.

Determine Common Mode Range (CMR) and Output Range (OR) for the amplifier shown in **Figure 1**, when all transistors are saturated. Transistors **M1**, **M2** and **M7** are identical, and also transistors **M3**, **M4**, **M5** and **M6** are identical.
Express CMR and OR in design parameters I_D, α_n and α_p and treshold voltages V_{tn} and V_{tp}.

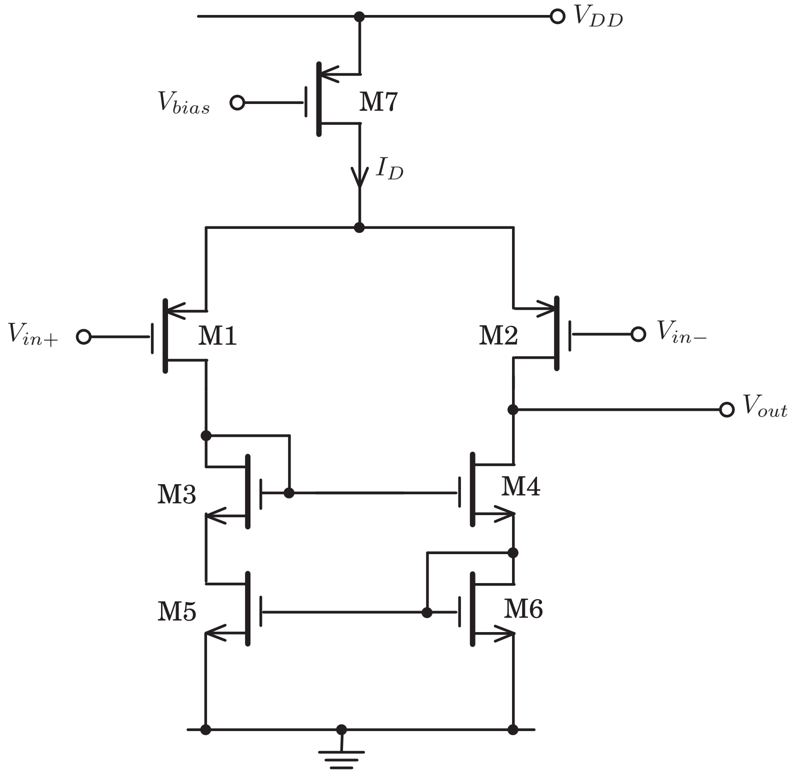

Figure 1: Amplifier.

Exercise 2.

Figure 2 shows an gain-boosting circuit.

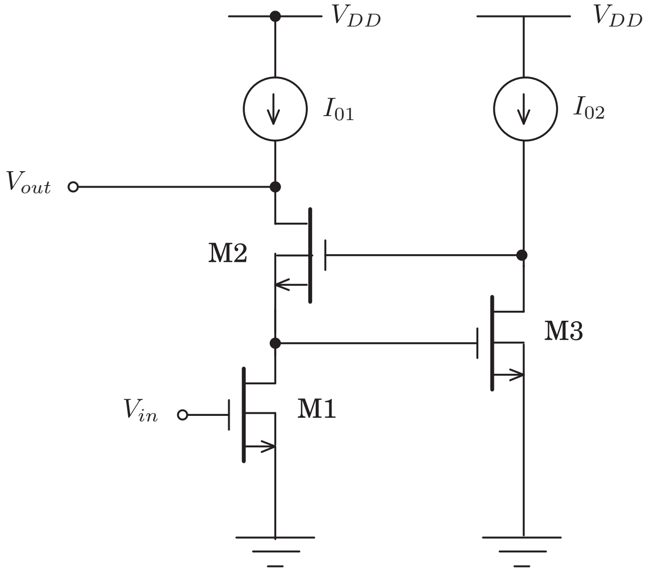

Figure 2: Gain-boosting circuit.

a) Determine the transfer function $H(s) = \frac{V_{out}}{V_{in}}$ expressed in the parameters g_{m1}, g_{ds1}, g_{m2}, g_{ds2}, g_{m3} and g_{ds3} for the transistors **M1**, **M2** and **M3** respectively. The bias current-sources are ideal, and $g_m >> g_{ds}$ generically. (4p)

b) The transfer function $H = \frac{V_{out}}{V_{in}}$ also can be expressed in the design parameters W_1, L_1, W_2, L_2, W_3, L_3 and the bias currents I_{01} and I_{02}. I.e. H can be written as

$H = K \cdot f(W_1, L_1, W_2, L_2, W_3, L_3, I_{01}, I_{02})$ where K is a constant.

Your task now is to determine the function $f(W_1, L_1, W_2, L_2, W_3, L_3, I_{01}, I_{02})$.

You can assume that all L_i, $i = 1, 2, 3$, are identical, i.e. $L_i = L$.

(1p)

Exercise 3.

Figure 3 a) shows the construction of an operational amplifier (OP-amp.). The circuit consists of four different parts, noted by **A**,**B**, **C** and **D**.

a) Your task now is to name and to describe the function of each part. Also explain why these different parts are included in the OP-amp. construction.

Especially explain why the capacitor C_c is included in the circuit. (2p)

b) Using the small-signal equivalent in figur **Figure 3 b)** for stage **B** and **C**, derive transfer function V_{outC}/V_{in} for those two stages together. Assume that $g_m >> g_{ds}$ generically and determine DC-voltage gain A_0 and zeros and poles adherent to this transfer function. (3p)

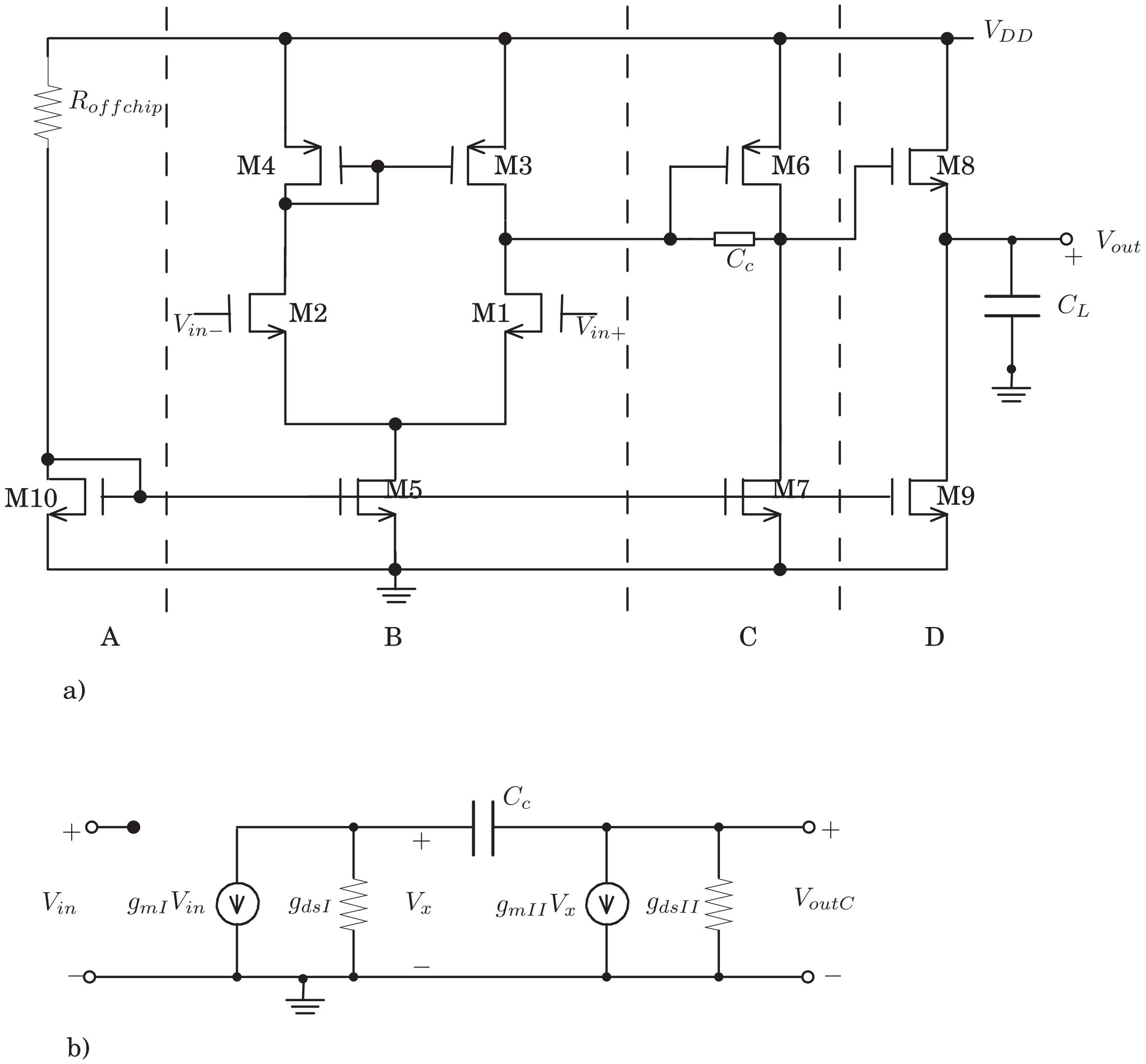

Figure 3: Operational amplifier.

Exercise 4.

Here we will study how the flicker noise at the gate of transistor **M2** in the gain stage in **Figure 4** affects the output voltage. Thus, your problem is to derive the spectral density R_{out} on the node V_{out} caused by the flicker noise of transistor **M2**.
The transistors **M1** and **M2** have parameters g_{m1}, g_{ds1} and g_{m2}, g_{ds2} respectively.

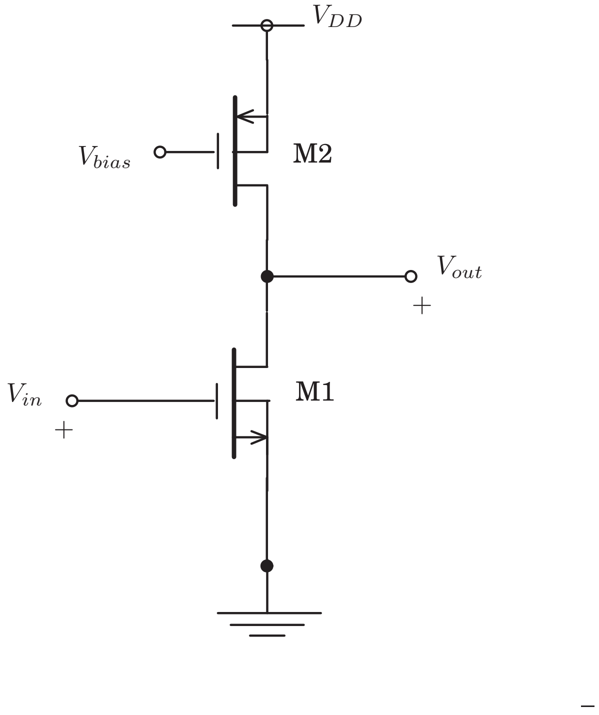

Figure 4: Gain stage.

Exercise 5.

Figure 5 shows an analog reference filter and a signal flow graph received after first synthesizing a leapfrog filter and then using a LDI-transformation followed by $z^{-1/2}$ propagation. In next step, intending to realize a SC-filter, the factors $z^{-1/2}$ in $\frac{R}{R_g}z^{-1/2}$ and $\frac{R}{R_L}z^{-1/2}$ are deleted, among other things. That is actually equivalent to replacing R_g and R_L with $R_g z^{-1/2}$ and $R_L z^{-1/2}$ respectively.

Now focus R_g and show that this operation means that R_g changes to a resistor R_g' parallel to a capacitor C_x.

To compensate for that new capacitor you can change the value of capacitor C_1 in the original analog reference filter. Determine the expression for this new capacitor C_1'!

Also determine the constant s_0 so that a cut-off frequency $f_{ac} = 100$ kHz for the analog filter will give a cut-off frequency $f_c = 100$ kHz for the SC-filter. Sample period is $T = 1\ \mu$s.

LDI-transform:

$$s = s_0(z^{1/2} - z^{-1/2})$$

$$\omega_a = 2s_0 \sin\frac{\omega T}{2}$$

Hint: Study $\frac{1}{\frac{z^{1/2}}{R_g}}$

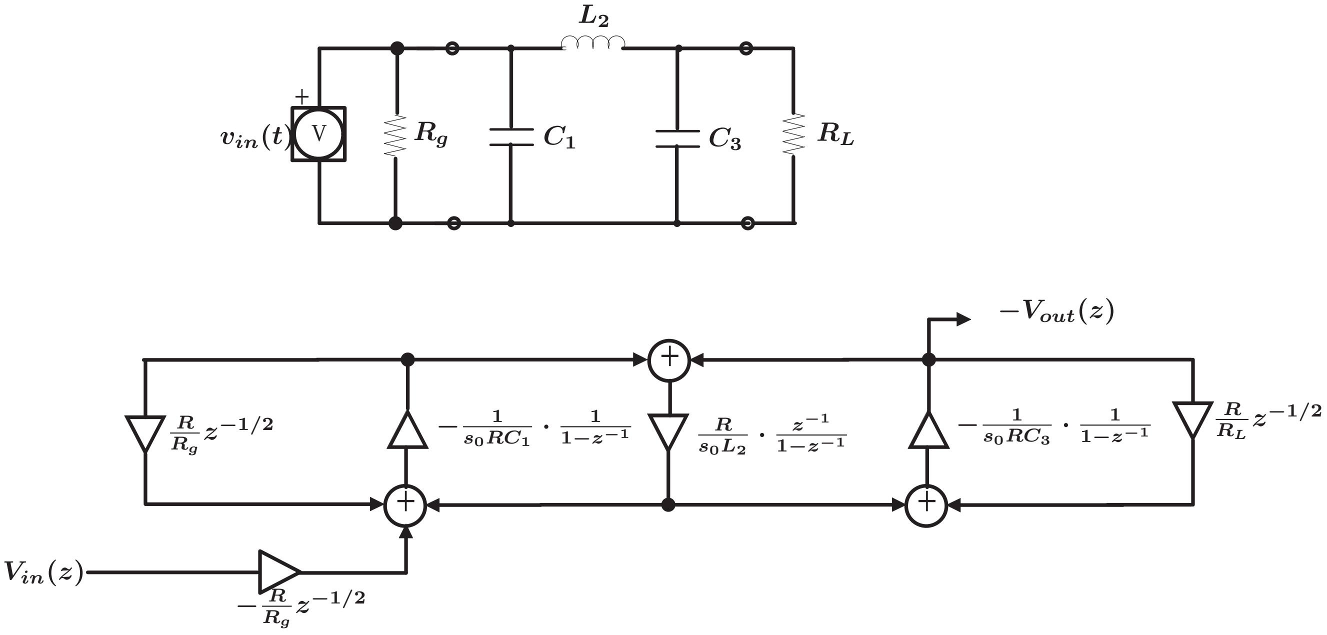

Figure 5: Analog filter and signal flow graph.

Transistor formulas and noise

1 CMOS transistors

Current and threshold voltage formulas and operating regions for an NMOS transistor

Cut-off: $V_{GS} < V_t$ $\quad I_D \approx 0$

Linear: $V_{GS} - V_t > V_{DS} > 0$ $\quad I_D = \alpha(2(V_{GS} - V_t) - V_{DS})V_{DS}$

Saturation: $0 < V_{GS} - V_t < V_{DS}$ $\quad I_D = \alpha(V_{GS} - V_t)^2(1 + \lambda(V_{DS} - V_{eff}))$

$V_{DSsat} = V_{eff} = V_{GS} - V_t$

All regions: $V_t = V_{t,0} + \gamma(\sqrt{2\phi_F - V_{BS}} - \sqrt{2\phi_F})$

Small-signal parameters

Linear: $g_m \approx 2\alpha V_{DS}$ $\quad g_{ds} \approx 2\alpha(V_{GS} - V_t - V_{DS})$

Saturation: $g_m \approx 2\sqrt{\alpha I_D}$ $\quad g_{ds} \approx \lambda I_D$

Constants: $\alpha = \frac{1}{2}\mu_{0n} C_{ox}\frac{W}{L}$ $\quad \lambda = \sqrt{\frac{K_s\epsilon_0}{2qN_A\phi_0}} \cdot \frac{1}{L}$ $\quad \gamma = \frac{\sqrt{2qN_AK_s\epsilon_0}}{C_{ox}}$

2 Circuit noise

Thermal noise in CMOS transistors
The thermal noise spectral density at the gate of a CMOS transistor is

$$V^2(f) = \frac{8kT}{3} \cdot \frac{1}{g_m}$$

Thermal noise in resistors
The thermal noise spectral density of a resistor is modeled as a parallel noise current source

$$I^2(f) = \frac{4kT}{R}$$

Flicker noise in CMOS transistors
The flicker noise spectral density at the gate of a CMOS transistor is

$$V^2(f) = \frac{K}{WLC_{ox}f}$$