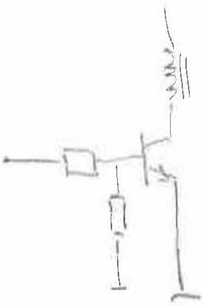
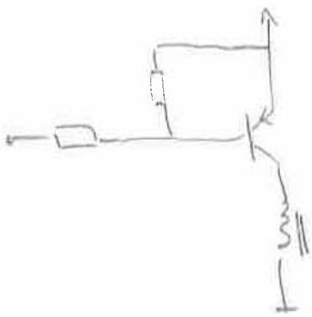
2 predavanje

=> Analogne sklopke

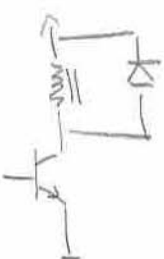
=> upravljanje i zaštita releja



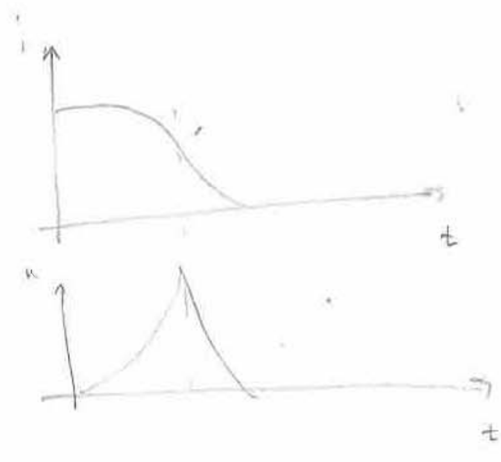
pnp

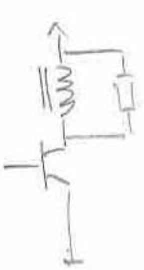


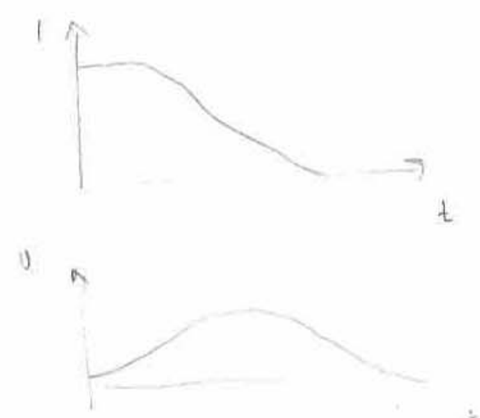
i) zaštita



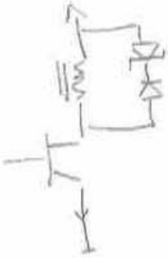
relej se gasi sporo







brže se prazni

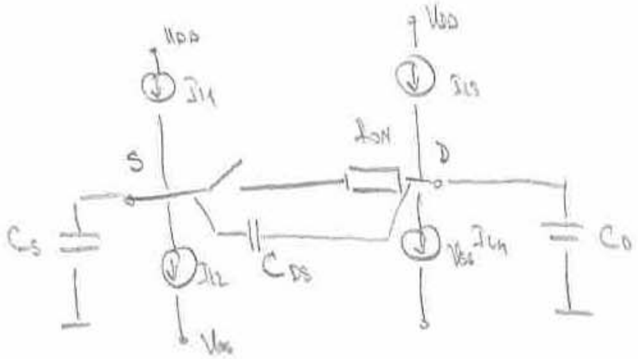


-> odstupanja realnih d. sklopki

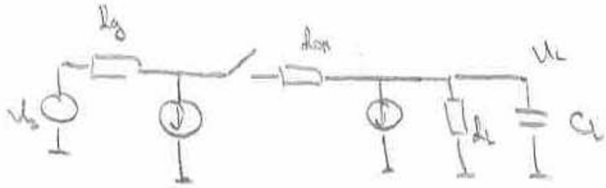
1) istosmjerne / DC
   - konačan otpor u vođenju
   - struje curenja

2) izmjenične
   - parazitni kapaciteti

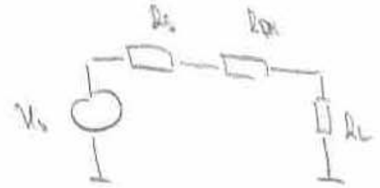
3) tranzijentne pogreške
   - injekcija naboja



1) istosmjerna odstupanja



$$\Delta U = I_L \cdot R_L \| \left(R_{ON} + R_g\right)$$



$$U_L = U_S \cdot \frac{R_L}{R_S + R_{ON} + R_L}$$

Za $R_S = \emptyset$

$$U_L = U_S \cdot \frac{R_L}{R_{ON} + R_L}$$

log

$$\log u_L = \log u_S + \log \frac{R_L}{R_{ON} + R_L}$$

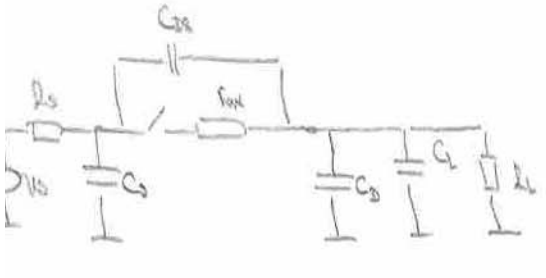
$$20 \log \frac{R_L}{R_{ON} + R_L} \leftarrow$$ Unesení gubitak (insertion loss)

ovisi o naponu napajanja ($u \uparrow \Rightarrow R_{ON} \downarrow$) i

temperaturi ($T \uparrow \Rightarrow R_{ON} \uparrow$)

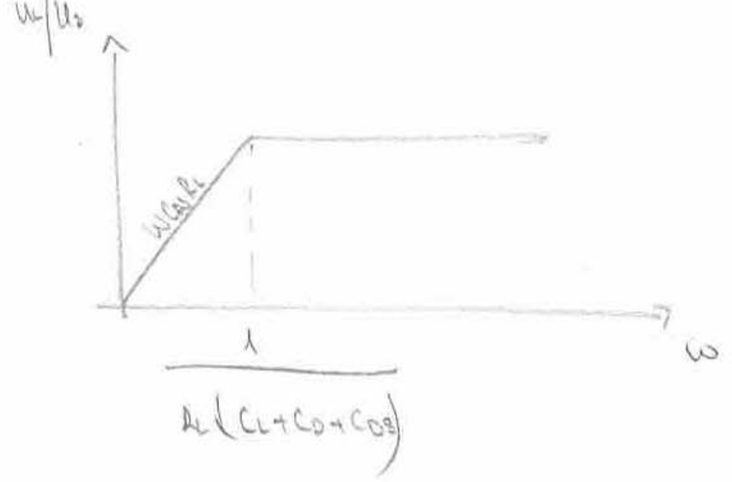
2) izmjenične pogreške

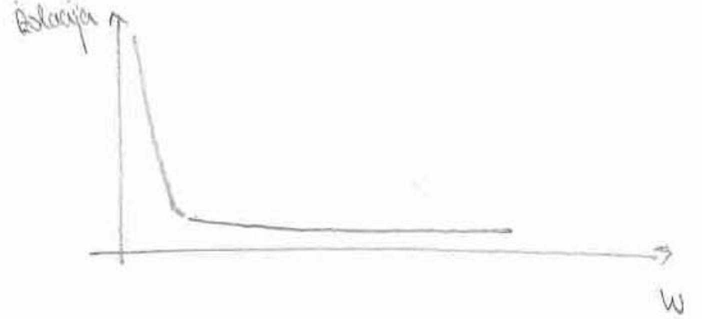
$\Rightarrow$ izolacija sklopke



$R_S = \emptyset$; C_S zanemarujemo

$$u_L = u_S \cdot \frac{R_L / \left[1 + j\omega (C_L + C_D) R_L\right]}{\frac{1}{j\omega C_{DS}} + \frac{R_L}{1 + j\omega (C_L + C_D) R_L}} = u_S \cdot \frac{j\omega C_{DS} R_L}{1 + j\omega R_L (C_L + C_D + C_{DS})}$$





izolacija lošija za $\uparrow C_{DS}$ i $\uparrow R_L$

manji R_L rezultira povećanim insertion loss-om

pr. 1)

2 bitni

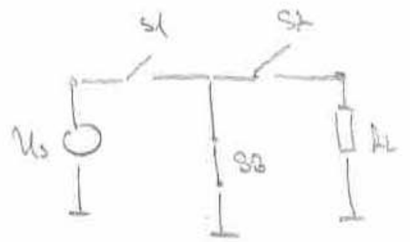
$R_S = 10\,\Omega$; $R_L = 100\,k\Omega$; $R_L = 10\,M\Omega$

$IL = \frac{100\,k\Omega}{10\,\Omega + 100\,k\Omega}$ $\qquad$ $IL = \frac{10\,M\Omega}{10\,\Omega + 10\,M\Omega}$

izolacija za 40 dB bolja

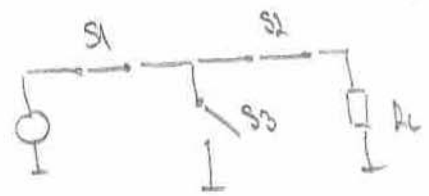
$C_{DS} = 0,1 - 5$ pF

⇒ T sklopka (dobar IL ; dobra izolacija)



S1 zaključana s R_{ON} S_3

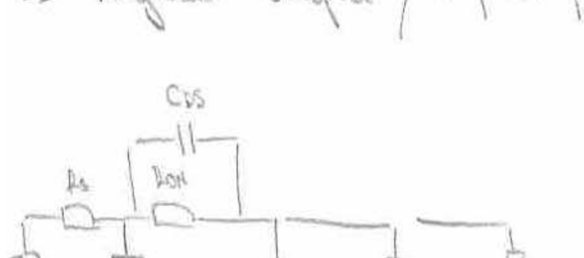
mana



R_{ON} S1

R_{ON} S2

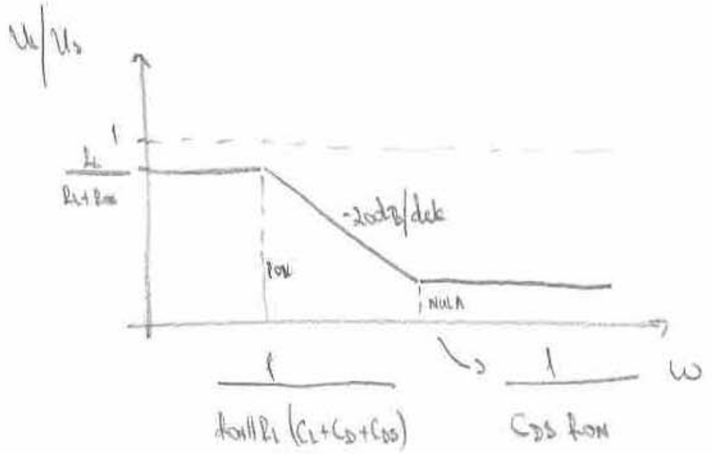
⇒ uključena sklopka / impedancija sklopke



$R_S = \phi$ ⇒ C_S zanemarujemo

$$U_L = U_S \cdot \frac{R_L / \left[1 + j\omega (C_L + C_D) R_L\right]}{R_{ON} / \left[1 + j\omega C_{DS} R_{ON}\right] + R_L / \left[1 + j\omega (C_L + C_D) R_L\right]}$$

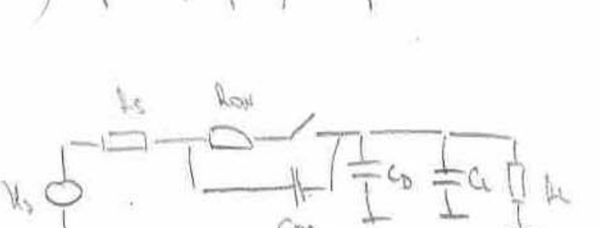
$$U_L = U_S \frac{R_L}{R_L + R_{ON}} \cdot \frac{1 + j\omega C_{DS} R_{ON}}{1 + j\omega R_{ON} \| R_L \cdot (C_L + C_D + C_{DS})}$$

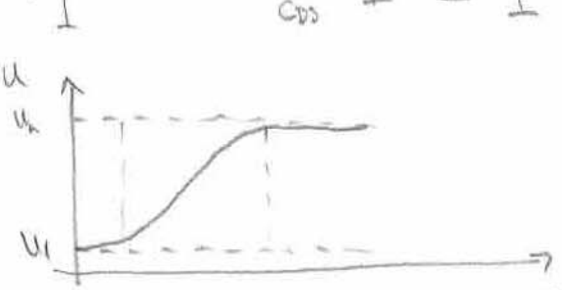


$$\frac{R_L}{R_{ON} + R_L} \cdot \frac{C_{DS} \cdot R_{ON}}{R_{ON} \| R_L \left(C_D + C_L + C_{DS}\right)}$$

3) tranzijentne pogreške

3.1) preklapanje / vrijeme smirivanja





$$\tau = \left[(R_S + R_{ON}) \| R_L\right] (C_L + C_D)$$

$$u(t) = (u_1 - u_2)\, e^{-t/\tau} + u_2$$

$$e(t) = |u(t) - u_2| = (u_1 - u_2)\, e^{-t/\tau}$$

$$\varepsilon \rightarrow \text{relat. pog.} = \frac{e(t)}{u_2} = \left| \frac{u_1 - u_2}{u_2} \right| e^{-t/\tau}$$

za $u_1 = \emptyset$ i $u_2 = u_{FS}$

$$\varepsilon = e^{-t/\tau}$$

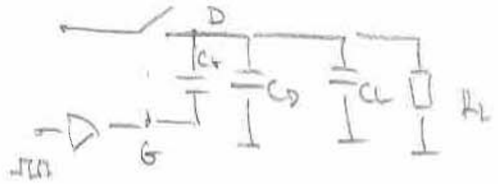
$$T_\varepsilon = -\tau \ln \varepsilon$$

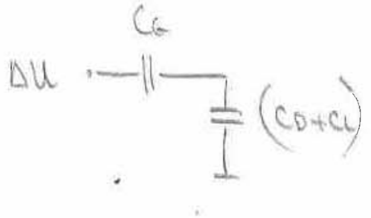
$$\tau_{\text{ON-OFF}} = R_\text{on}(C_L + C_D)$$

pr. 2)

$$\boxed{\begin{array}{l} e < \dfrac{LSB}{2} \\ e^{-t/\tau} < \dfrac{1}{2} \cdot \dfrac{1}{2^N} \end{array}}$$

3.2) injektiranje naboja / charge injection





$$\Delta Q = \Delta U \cdot \left(C_G \parallel (C_D + C_L)\right)$$

$$= \Delta U_L \cdot (C_D + C_L)$$

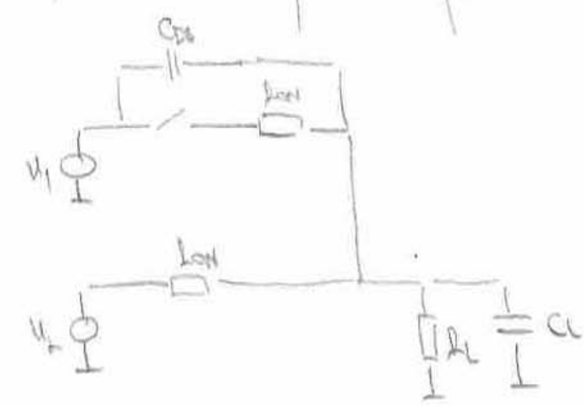
4) dodatne pogreške MUX (preslušavanje)

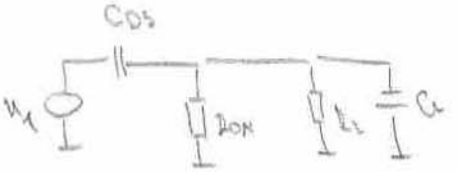
4.1) statičko preslušavanje (static crosstalk)

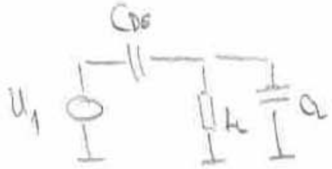
4.2) dinamičko preslušavanje

4.3) preslušavanje (vremenski) susjednih kanala

4.1) statičko preslušavanje



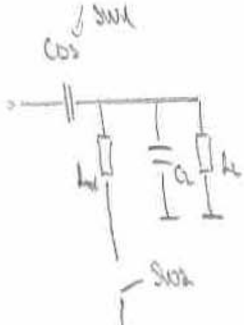


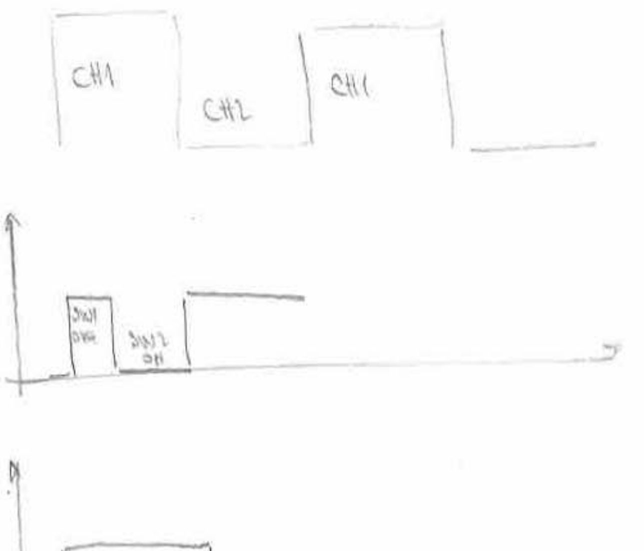


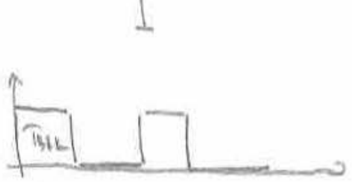
preslušavanje VF zbog izolacije

4.2) dinamičko preslušavanje

„break before make sklopke"





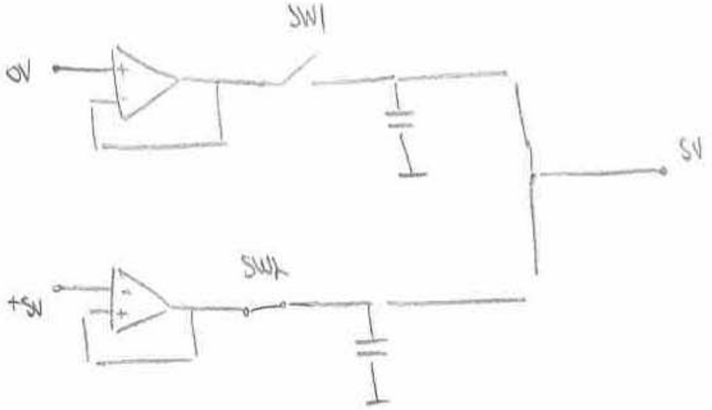


$$R_{EQ} = \frac{R_L \cdot 2T_{BB} + R_{ON}(T - 2T_{BB})}{T}$$

4.3) preslušavanje (mauski) susjednih kanala

odjacent channel crosstalk

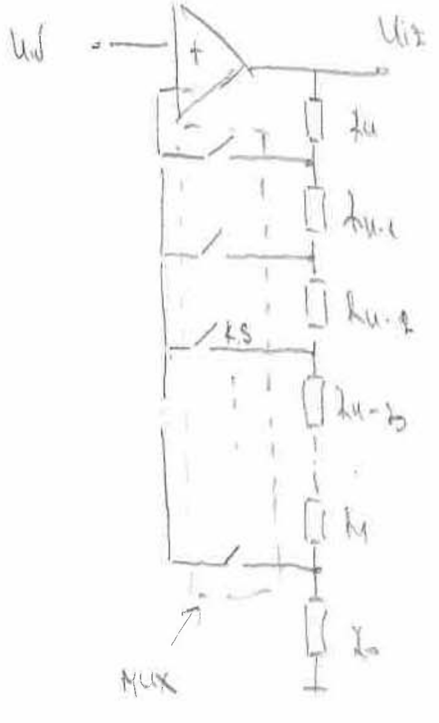
charge injection crosstalk



Zadaci iz Elektroničke instrumentacije

1. dio

1) Skicirajte shemu neinvertirajućeg program. pojačala i opišite način rada. O čemu ovisi točnost pojačanja takvog pojačala?



$$A = 1 + \frac{\sum_{i=r+1}^{n} R_i}{\sum_{i=0}^{r} R_i}$$

otpornička mreža (iznosi pojačanja tipično 1, 2, 5, 10, ..., 500, 1000)

Iznos pojačanja ovisi o :

1) tolerancijama otpora otpornika u težinskoj mreži
2) impedanciji sklopki

analogne sklopke u 76A

-> realni kratki spoj ima omski otpor između 10 Ω i 120 Ω ; utjecaj otpora sklopke u vođenju se minimizira ispravnim odabirom topologije ; na višim frekv. do izražaja dolaze parazitni kapaciteti sklopke

promjena pojačanja

nekada potrebno da se promijeni pojačanje i da se izlazni napon stabilizira je zbroj

-> vremena potrebnog za preklapanje sklopki

-> vremena smirivanja izlaznog napona pojačala

2) Opišite koje tehnologije analognih sklopki razlikujemo te ih usporedite

	Snaga	otpor u vođenju	max. frek. prebacivanja	otpor u nevođenju
Releji	1000V/25A	1mΩ	50-250 Hz	10^{10} Ω (zrak)
Reed-releji	200V/50mA	1mΩ - 1Ω	1kHz	10^{14} Ω (vakuum)
Poluvodičke diskretne	1000V/25A	10mΩ - 3Ω	10MHz	10^{10} Ω
Poluvodičke integrirane	50V/50mA	1Ω-200Ω	100 MHz (do GHz)	10^{10} Ω

-> elektromehaničke - minimalan R_{on}, spora, velike dimenzije

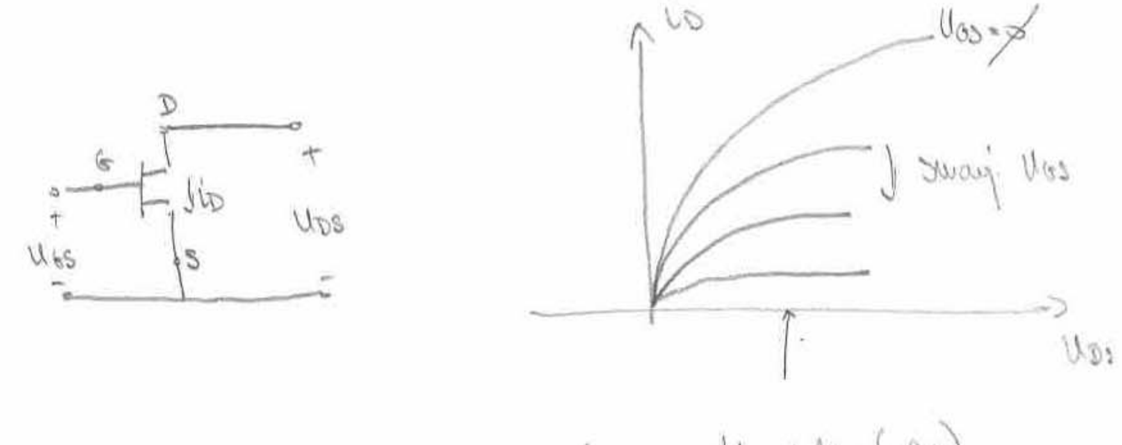
-> elektroničke (silicijske) - relativno veliki R_{on}, ovise o priključenom naponu i temperaturi

parazitni kapaciteti mogu utjecati na AC karakteristike cjelokupnog sklopa

3) Opišite analogne sklopke u integriranim krugovima, tehnologije u kojima se izvode te ih usporedite!

1) Idealna analogna sklopka

2) n-kanalna JFET sklopka

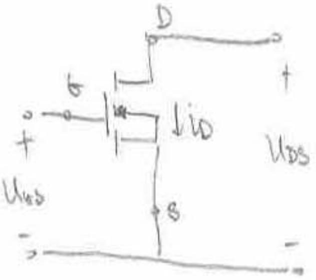


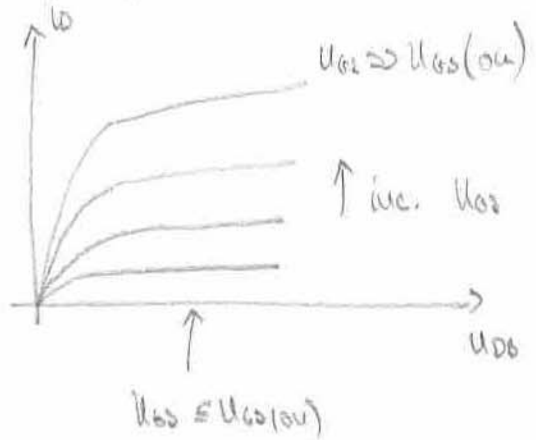
$u_{GS} \le u_{GS(off)}$

$$\frac{\partial i_d}{\partial u_{DS}} = \frac{1}{r_{DS(on)}}$$

3) p-kanalna JFET sklopka

4) n kanalna MOSFET sklopka



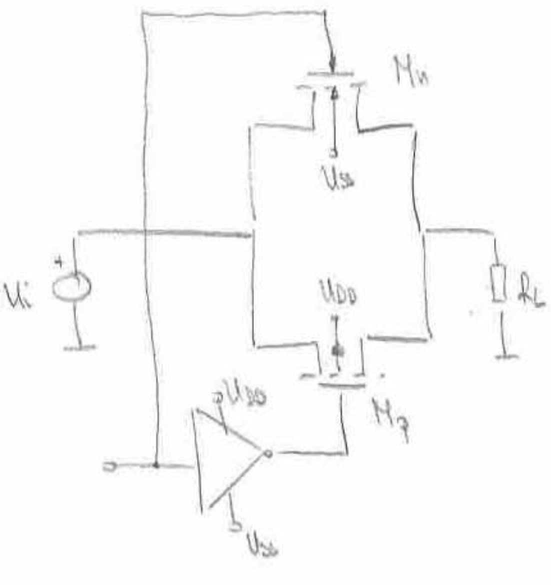


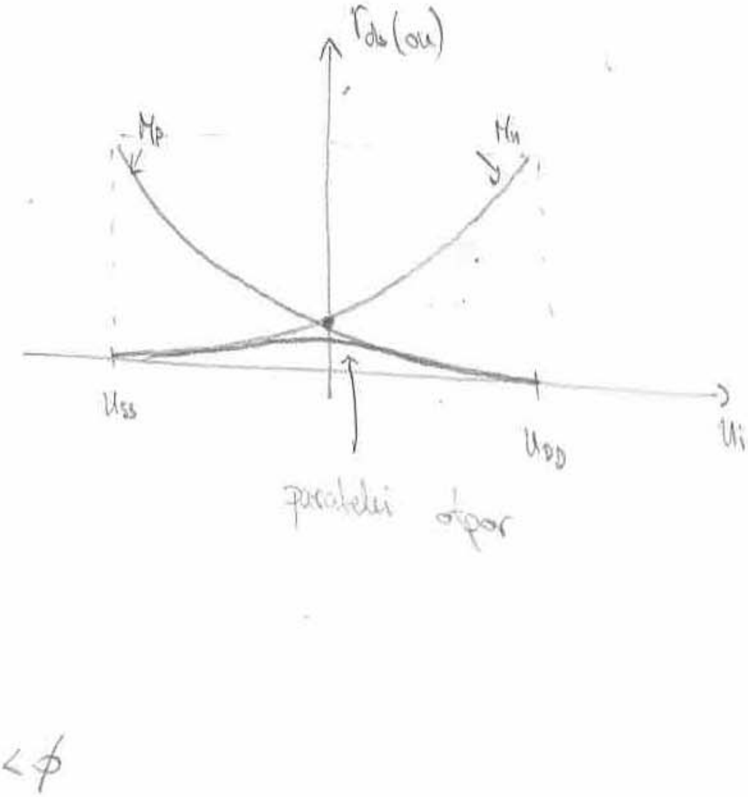
n-MOSFET : $U_{GS(ON)} > 0$

ON: $U_{GS} \ge U_{GS(ON)}$

OFF: $U_{GS} = \emptyset$

5) CMOS sklopka





ON: p-MOS : $U_{GS} \le U_{GS(ON)} < \emptyset$

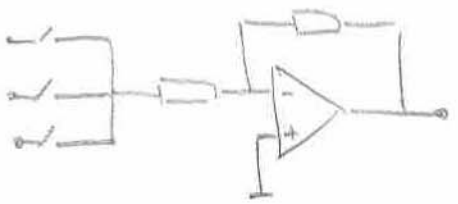
OFF: p-MOS : $U_{GS} \ge \emptyset$

4) Opišite koje načine rada razlikujemo kod analognih sklopki u integriranim krugovima

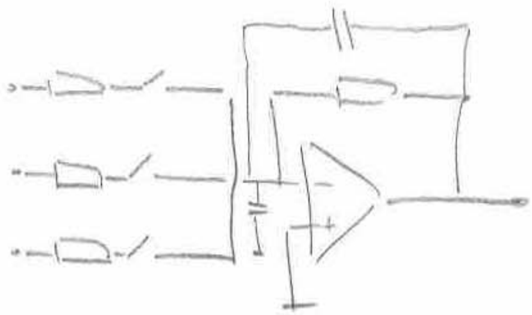
3. predavanje

4.4) spajanje sljedila na izlaz

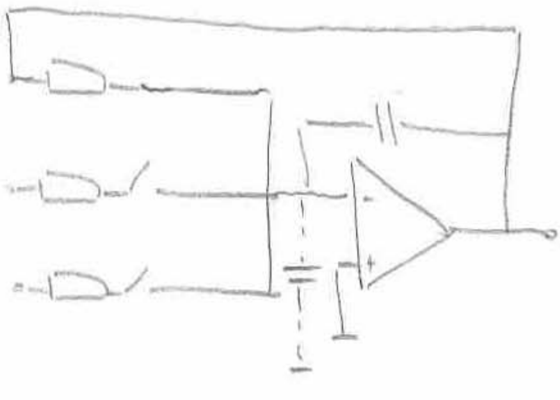
a)



b)

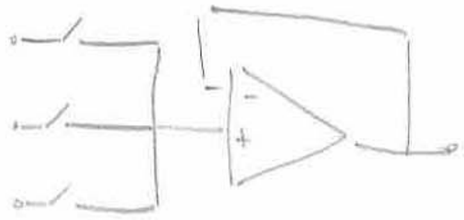


c)



neinvertirajuće varijante

a) invertirajuće



3. Programabilni sklopovi

1) Sample & hold

1.1) nesavršenosti

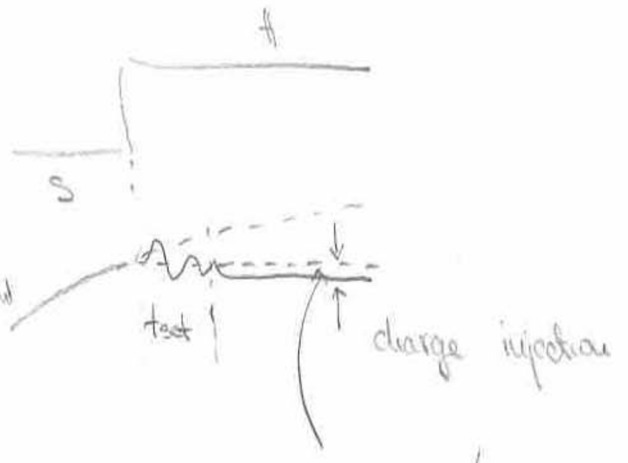
=> pogreške pojačanja
=> frekvencijska karak. sklopa
=> pomak nule
=> nelinearnost sljedila

sample

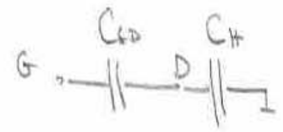
=> efektivno vrijeme otvaranja (aperture time)
=> vrijeme smirivanja (settling time)
=> injektiranje naboja (charge injection)

sample -> hold

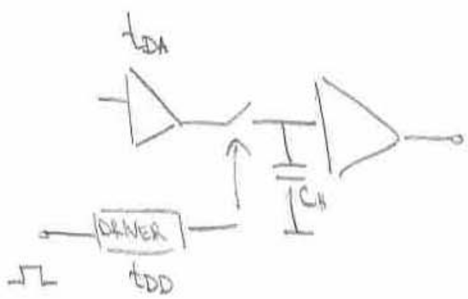
-> vrijeme smirivanja

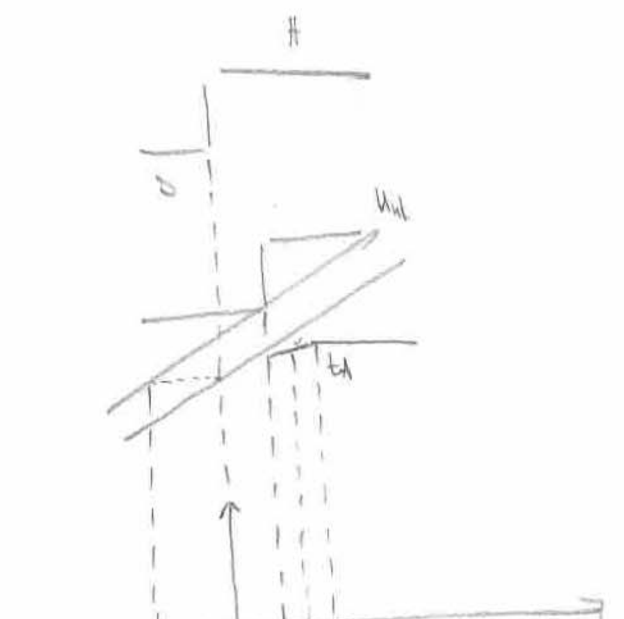


$$\Delta u = Q / C_H$$



-> aperturno vrijeme





$$\boxed{t_{eA} = t_{DD} + t_A/2 - t_{DA}}$$

-> aperturna nesigurnost (aperture jitter)

=> klizanje zadržanog napona (droop rate)

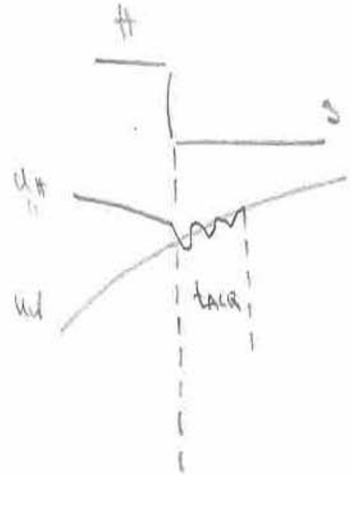
-> struje curenja

$$\frac{du}{dt} = \frac{I_{LKG}}{C_H}$$

hold

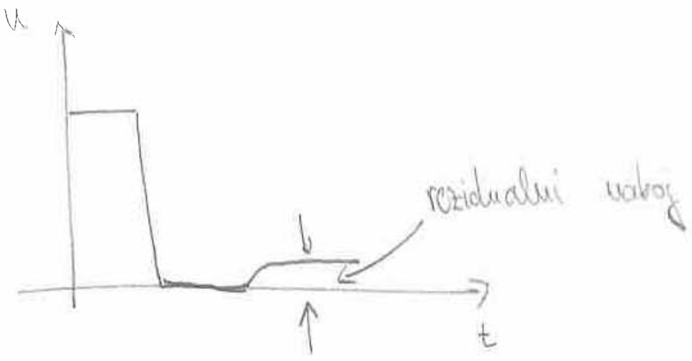
=> proklizavanje (feedthrough)

=> vrijeme akvizicije



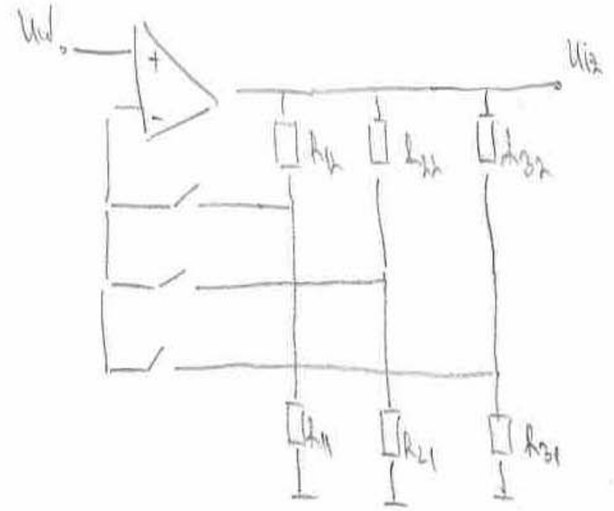
hold -> sample

⇒ pogreška uslijed dielektrične apsorbcije



1. auditorne vježbe

1.



$A_1 = 500$; $A_2 = 100$; $A_3 = 5$

odabir. $R_{11} = R_{21} = R_{31} = 1\,k\Omega$

$A = 1 + R_2 / R_1$

$A_1 = 500 \Rightarrow R_{12} = 499\,k\Omega$

$A_2 = 100 \Rightarrow R_{22} = 99\,k\Omega$

$A_3 = 5 \Rightarrow R_{32} = 4\,k\Omega$

$$dA = \frac{\partial A}{\partial R_1} dR_1 + \frac{\partial A}{\partial R_2} \cdot dR_2$$

$$dA = -\frac{R_2}{R_1^2} dR_1 + \frac{1}{R_1} dR_2 \quad / : A$$

$$\frac{dA}{A} = \frac{1}{A}\left[-\frac{R_2}{R_1}\cdot\frac{dR_1}{R_1} + \frac{R_2}{R_1}\cdot\frac{dR_2}{R_2}\right]$$

$$\frac{dA}{A} = 1/A \cdot R_2/R_1\left[-\frac{dR_1}{R_1} + \frac{dR_2}{R_2}\right]$$

1) najgori slučaj

$$\frac{dR_1}{R_1} = -\frac{dR_2}{R_2} = \delta$$

$$\left|\frac{dA}{A}\right| < \varepsilon$$

$$\frac{1}{A}\cdot R_2/R_1\cdot 2\delta < \varepsilon$$

$$\delta < \frac{\varepsilon A}{2\, R_2/R_1}.$$

$$\delta < \frac{\varepsilon}{2}\left(1 + R_2/R_1\right)$$

$$\delta < \frac{0{,}1\%}{2}\left(1 + \frac{1k\Omega}{499k\Omega}\right) = 0{,}05\,\%$$

2.

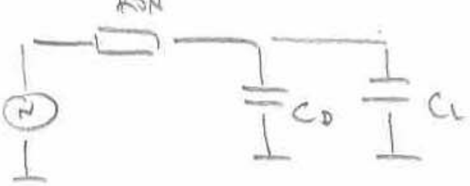
$U_u = 1V$

$f = 100\ kHz$

$R_{ON} = 100\ \Omega$

$C_D = 5\ pF$

$C_L = 15\ pF$

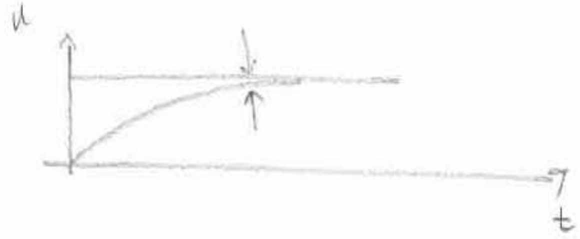


$$A = \frac{\frac{1}{j\omega(C_D+C_L)}}{R_{ON} + \frac{1}{j\omega(C_D+C_L)}} = \frac{1}{j\omega R_{ON}(C_D+C_L)+1}$$

$$\tau = R_{ON}(C_D+C_L) = 2\,ns$$

$$|A| = \frac{1}{\sqrt{1+\omega^2\tau^2}} = 1$$

$$\varphi = -\mathrm{arctg}(\omega\tau) = 0{,}07^\circ$$



$$1V \cdot e^{-t/\tau} < \frac{LSB}{2}$$

$$t_s = -\tau \ln\left(\frac{1}{2} LSB\right)$$

$$t_s = -2us \ln\left(\frac{1}{2} \frac{2V}{2^{16} \cdot 1V}\right)$$

3.

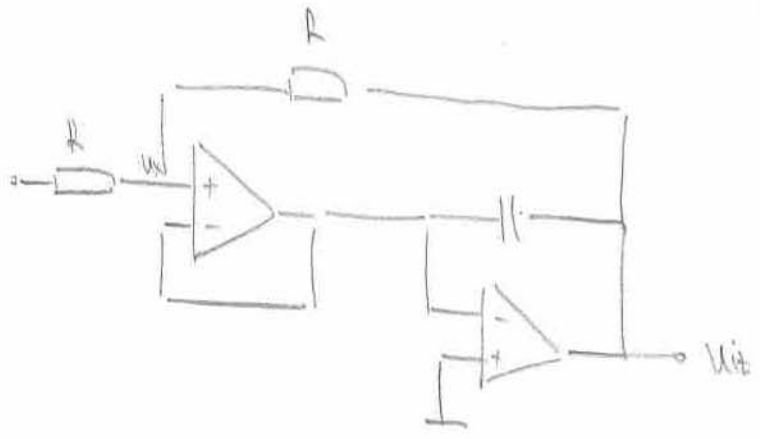
$C_{GD} = 1pF$

$C_H = 1nF$

$I_{CCG} = 1nA$

$U_{ul} = 1V$

$t = 50\mu s$



$$\frac{U_{ul} - U_x}{R} = \frac{U_x - U_{iz}}{R}$$

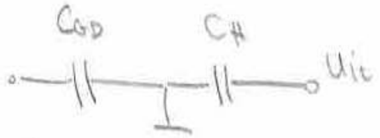
$$U_{ul} - U_x = U_x - U_{iz}$$

$$U_{ul} + U_{iz} = 2U_x$$

$$\boxed{U_x = 0}$$

$$\boxed{U_{ul} = -U_{iz}}$$

1) injekcija naboja



$$\left.\begin{aligned} \Delta Q_{GD} &= \Delta U_{GD} \cdot C_{GD} = -15V \cdot 1pF = -15\,pC \\ \Delta Q_H &= \Delta Q_{GD} \end{aligned}\right\} \Delta U_H = \Delta Q_H \cdot \frac{1}{C_H} = -15\,mV$$

$U_i(t) = U_i(t) - \Delta U_H = -1V + 15mV = -985\,mV$ za $t = 0$

$t = 50\ \mu s$

$C_H \cdot \Delta \hat{U}_i(t) = I_L \cdot \Delta t$

$$\Delta \hat{U}_i(t) = \frac{1\,nA \cdot 50\mu s}{C_H} = 50\,\mu V$$

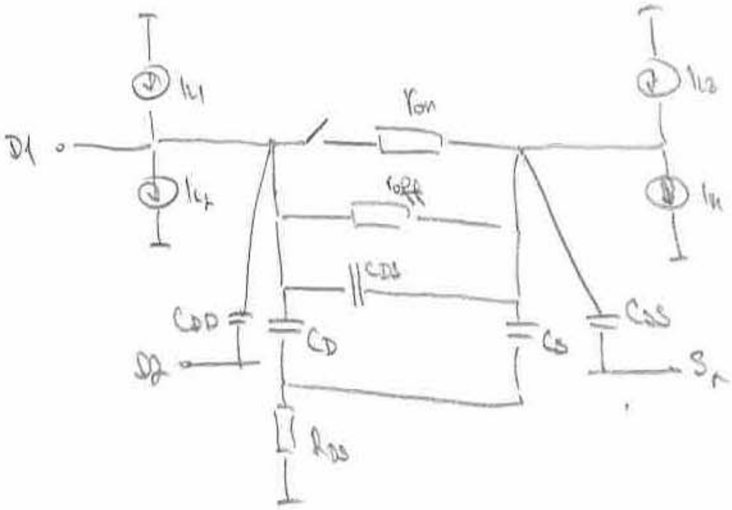
$U_i(t) = -985\,mV + 50\,\mu V = -935\,mV$

Zadaci iz Elektroničke instrumentacije

1. dio

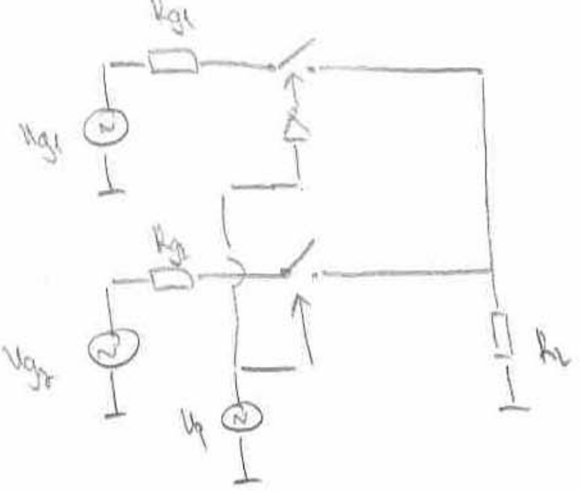
-> nastavak

4) Opišite koje načine rada razlikujemo kod analognih sklopki u integriranim krugovima

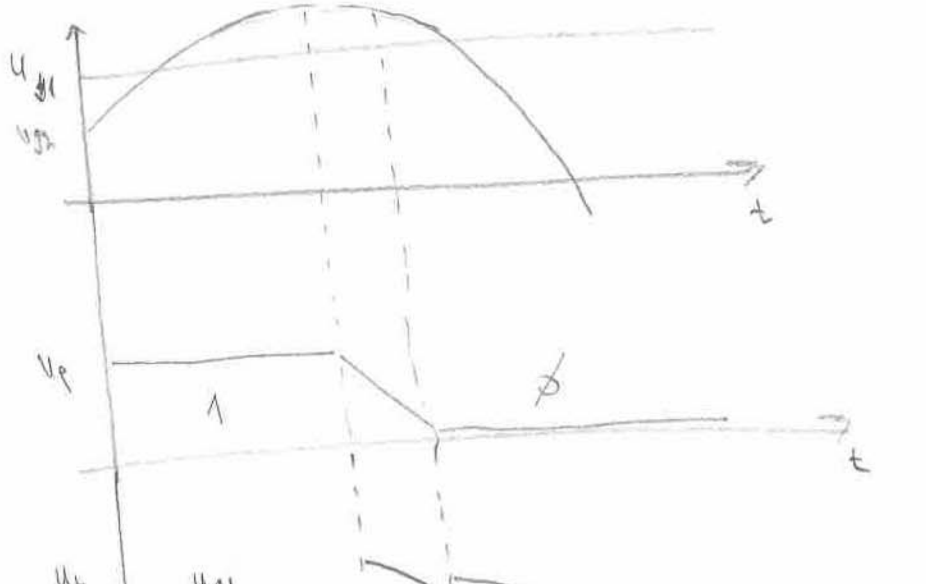


1) BBM (Break before make) - kod višepoložajnih sklopki prilikom promjene položaja događa se prvo se stari kontakt (tj. signal) prekine, pa se spoji novi (otvorena petlja pov. veze, zasićenje pojačala, oscilacije sklopova)

2) MBB (Make before break) - prvo se spoji novi signal, pa se odspoji stari (kratki spojevi, valovi različitih snaga)



vremenski dijagram



I auditorne

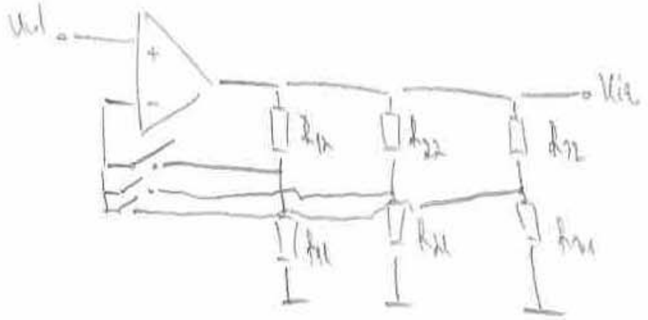
-> domaći rad

$A_1 = 500$

$A_2 = 100$

$A_3 = 5$

$\varepsilon = 0,1\%$



$R_{11} = R_{21} = R_{31} = 1\ k\Omega$

$A = 1 + R_{i2} / R_{i1}$

$A_1 = 1 + \frac{R_{12}}{R_{11}} \rightarrow \quad A_1 - 1 = \frac{R_{12}}{R_{11}} \Rightarrow R_{12} = (A_1 - 1) \cdot R_{11} = 499\ k\Omega$

$R_{22} = 99\ k\Omega$

$R_{32} = 4\ k\Omega$

$A = 1 + R_2 / R_1$

$$dA = \frac{\partial A}{\partial R_1} dR_1 + \frac{\partial A}{\partial R_2} dR_2$$

$$dA = \frac{-R_2}{R_1^2} dR_1 + \frac{1}{R_1} dR_2$$

$$dA = \frac{-R_2}{R_1} \frac{dR_1}{R_1} + \frac{R_2}{R_1} \cdot \frac{dR_2}{R_2} \quad : A$$

$$\frac{dA}{A} = \frac{1}{A} \left[-\frac{R_2}{R_1} \frac{dR_1}{R_1} + \frac{R_2}{R_1} \frac{dR_2}{R_2} \right]$$

$$\frac{dA}{A} = \frac{1}{A} \cdot \frac{R_2}{R_1} \left[-\frac{dR_1}{R_1} + \frac{dR_2}{R_2} \right]$$

najgori slučaj

$$\frac{dR_2}{R_2} = \delta = -\frac{dR_1}{R_1}$$

$$\frac{dA}{A} = \frac{1}{A} \cdot \frac{R_2}{R_1} \cdot 2\delta$$

pogreška pojačanja manja od 0,1 %

$$\left| \frac{dA}{A} \right| < \varepsilon$$

$$\left| \frac{1}{A} \cdot \frac{R_2}{R_1} \cdot 2\delta \right| < \varepsilon$$

$$2\delta < \frac{\varepsilon \cdot A \cdot R_1}{R_2}$$

$$\delta < \frac{\varepsilon A R_1}{2 R_2} = \varepsilon \cdot \frac{1}{2}\left(1 + R_2/R_1\right)\frac{R_1}{R_2}$$

$$\delta < \varepsilon \; \frac{1}{2}\left(1 + R_1/R_2\right)$$

Za $A = 500$

$R_1 = 1\,k\Omega$

$R_2 = 499\,k\Omega$

$$\delta < 5{,}01 \cdot 10^{-4}$$

2.

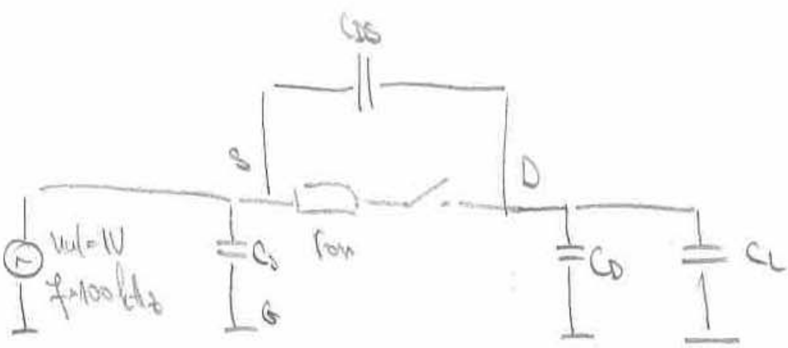
$u_{ul} = 1V$

$f = 100\,kHz$

$r_{on} = 100\,\Omega$

$C_D = 5pF$

$C_L = 15pF$



1/2 LSB

16-bitni ADP

±1V ulazni opseg

C_S ne igra nikakvu ulogu bez unutarnjeg otpora generatora ; a C_{DS} zanemarujemo u ON načinu rada

$$C = C_D + C_L$$

$$\tau = r_{on}C = r_{on}(C_D + C_L) = 100\Omega \cdot 20pF = 2nS$$

$$u_{iz} = u_{ul} \cdot \frac{\frac{1}{j\omega C}}{r_{on} + \frac{1}{j\omega C}} = u_{ul} \frac{\frac{1}{j\omega C}}{\frac{r_{on} j\omega C + 1}{j\omega C}}$$

$$= u_{ul} \frac{1}{1 + j r_{on}\omega C} = u_{ul} \frac{1}{1 + j\omega\tau}$$

$$|u_{i2}| = u_{ul} \frac{1}{\sqrt{1+\omega^2\tau^2}} \approx u_{ul}$$

$$\varphi = 0 - \operatorname{arctg}(\omega\tau) \approx -0{,}072^\circ$$

$$\text{IV.} \quad e^{-\frac{t_s}{\tau}} < \frac{1}{2} LSB$$

$\ln$

$$-\frac{t_s}{\tau} < \ln\left[\frac{1}{2} LSB\right]$$

$$t_s > -\tau \ln\left[1/2 \ LSB\right]$$

$$LSB = \frac{U_{FS}}{2^{16}} = 30{,}52 \, \mu V$$

3.

$C_{GD} = 1\,pF$

$C_H = 1\,nF$

$I_L = 1\,nA$

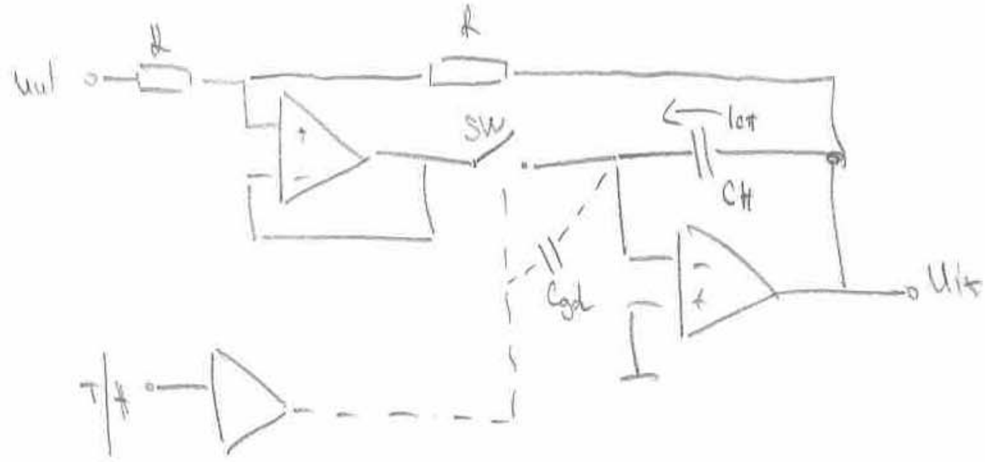
$U_{ul} = 1\,V$

$U_{iz} = 0$

$t = 50\,\mu s$

n-JFET

0 V - 15 V



$$\frac{U_{ul} - U_x}{R} = \frac{U_x - U_{iz}}{R} \quad / \cdot R$$

$$U_{ul} - U_x = U_x - U_{iz}$$

$$U_x = 0$$

$$U_{ul} = -U_{iz}$$

$$\Delta Q_{CGD} = -15V \cdot C_{GD} = -15\,pC$$

naboj koji je došao na C_H

$$\Delta U_{iz} = \frac{-\Delta Q_{CGD}}{C_H} = 0{,}015\,V$$

$$U_{iz} = -U_{ul} + \Delta U_{iz} = -0{,}985\,V$$

$T = 50\,\mu s$

$$C_H \cdot \Delta U_{iz}' = I_L \cdot T \Rightarrow \Delta U_{iz}' = \frac{I_L T}{C_H} \quad ; \quad U_{iz}' = U_{iz} + \Delta U_{iz}' = 0{,}935\,V$$

1.

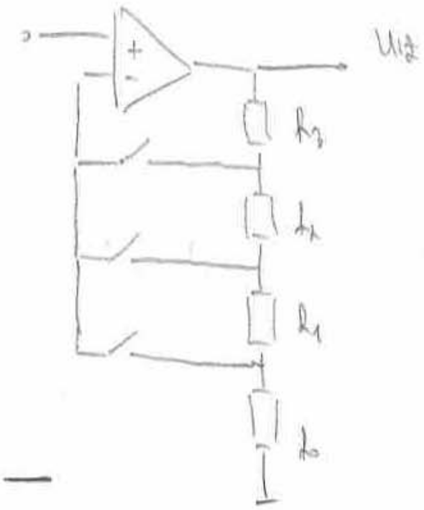
$A_1 = 5$

$A_2 = 100$

$A_3 = 500$

$\varepsilon = 0{,}1\,\%$

$R_0 = 1\,k\Omega$



$$A_1 = 1 + \frac{R_3}{R_2 + R_1 + R_0}$$

$$4 = \frac{R_3}{R_2 + R_1 + R_0} \Rightarrow \boxed{R_3 = 4R_2 + 4R_1 + 4R_0}$$

$$A_2 = 1 + \frac{R_3 + R_2}{R_1 + R_0}$$

$$99 = \frac{R_3 + R_2}{R_1 + R_0} \Rightarrow R_3 + R_2 = 99R_1 + 99R_0$$

$$\boxed{R_3 = 99R_1 + 99R_0 - R_2}$$

$$A_3 = 1 + \frac{R_1 + R_2 + R_3}{R_0}$$

$$499 = \frac{R_1 + R_2 + R_3}{R_0} \Rightarrow \boxed{499 R_0 = R_1 + R_2 + R_3}$$

$$4R_2 + 4R_1 + 4R_0 = 99R_1 + 99R_0 - R_2$$

$$95R_1 + 95R_0 - 5R_2 = 0$$

$$\boxed{95R_1 - 5R_2 = -95\ k\Omega}$$

$$4R_2 + 4R_1 + 4R_0 = -R_2 - R_1 + 499R_0$$

$$\boxed{5R_2 + 5R_1 = 495R_0}$$

$$\left.\begin{aligned} 95R_1 - \cancel{5R_2} &= -95\ k\Omega \\ 5R_1 + \cancel{5R_2} &= 495\ k\Omega \end{aligned}\right| +$$

$$R_3 = 4R_2 + 4R_1 + 4R_0$$

$$100R_1 = 400\ k\Omega$$

$$\boxed{R_3 = 400\ k\Omega}$$

$$\boxed{R_1 = 4\ k\Omega}$$

$$5R_2 + 5R_1 = 495\ k\Omega$$

$$5R_2 = 475\ k\Omega \Rightarrow \boxed{R_2 = 95\ k\Omega}$$

$\varepsilon = 0{,}1\ \%$

$$A = 1 + \frac{R_1 + R_2 + R_3}{R_0}$$

$$R_x = R_1 + R_2 + R_3 = 4991\ \Omega$$

$$A_3(1+\varepsilon) = 1 + \frac{R_x(1+\delta)}{R_0(1-\delta)}$$

$$\frac{R_x(1+\delta)}{R_0(1-\delta)} = 499{,}5$$

$$R_x(1+\delta) = 499{,}5\, R_0(1-\delta)$$

$$R_x + R_x\delta = 499{,}5\, R_0 - 499{,}5\, R_0\,\delta$$

$$\delta(R_x + 499{,}5\, R_0) = 499{,}5\, R_0 - R_x$$

$$\delta < \frac{499{,}5\, R_0 - R_x}{R_x + 499{,}5\, R_0}$$

$$\delta < 5{,}007 \cdot 10^{-4}$$

2.

$R_L = 100\ \Omega$

$C_L = 8\ pF$

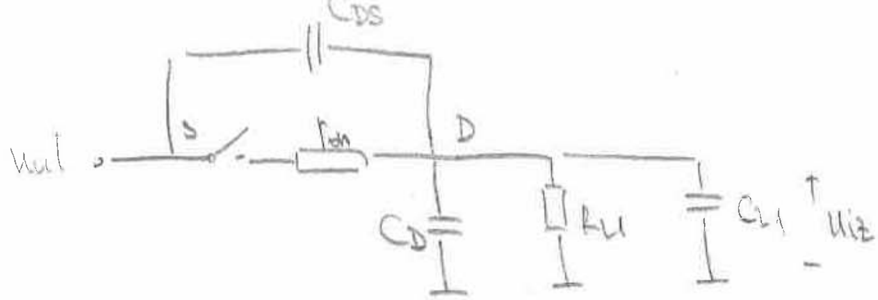
pro = 50dB na $f = 5 MHz$

$C_D = 8 pF$

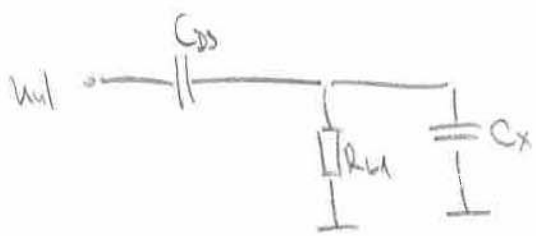
$C_{DS} = ?$

pro = ? na $f = 50\ kHz$

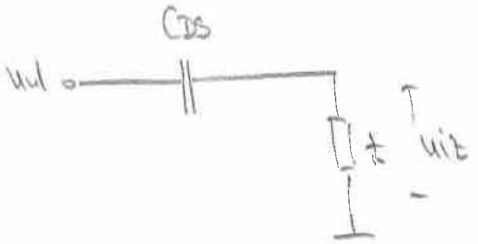
na $R_L = 10 k\Omega$ i $C_L = 10 pF$



r_{on} se zanemaruje u sklopu stvorena



$$C_X = C_D + C_{L1} = 16\ pF$$



$$Z = R_{L1} \parallel C_X$$

$$= \frac{R_{L1} \cdot \frac{1}{sC_X}}{R_{L1} + \frac{1}{sC_X}}$$

$$Z = \frac{R_{L1} \cdot \frac{1}{sC_x}}{\frac{sR_{L1}C_x + 1}{sC_x}} = \frac{R_{L1}}{1 + sR_{L1}C_x}$$

$s = j\omega$

$$Z = \frac{R_{L1}}{1 + j\omega R_{L1}C_x} = \frac{100\,\Omega}{1 + j2\pi \cdot 5 \cdot 10^6 \cdot 100 \cdot 16pF} = \frac{100}{1 + j0{,}0502}$$

$= 99{,}874 \angle -2{,}8738°$

$F_1 = 20\log|A| = -50\,dB$

$$A = \frac{u_Z}{u_{u1}}$$

$$u_Z\left(\frac{1}{Z} + sC_{DS}\right) = u_{u1} \cdot sC_{DS}$$

$$\frac{u_Z}{u_{u1}} = A = \frac{sC_{DS}}{\frac{1}{Z} + sC_{DS}} = \frac{sC_{DS}}{\frac{1 + sZC_{DS}}{Z}}$$

$$A = \frac{sZ C_{DS}}{1 + sZ C_{DS}} = \frac{j\omega Z \cdot C_{DS}}{1 + j\omega Z C_{DS}}$$

$$|A| = \frac{Z \cdot C_{DS} \cdot \omega}{\sqrt{1 + \omega^2 Z^2 C_{DS}^2}}$$

$$-50dB = 20 \log |A|$$

$$-\frac{5}{2} = \log |A|$$

$$|A| = 10^{-5/2}$$

$$\frac{Z \cdot C_{DS} \omega}{\sqrt{1 + \omega^2 Z^2 C_{DS}^2}} = 10^{-5/2} \quad /^2$$

$$\frac{Z^2 C_{DS}^2 \omega^2}{1 + \omega^2 Z^2 C_{DS}^2} = 10^{-5}$$

$$z^2 C_{DS}^2 W^2 = 10^{-5} + 10^{-5} W^2 z^2 C_{DS}^2$$

$$C_{DS}^2 \left(z^2 W^2 - 10^{-5} W^2 z^2 \right) = 10^{-5}$$

$$C_{DS}^2 \; z^2 W^2 \left(1 - 10^{-5}\right) = 10^{-5}$$

$$C_{DS} = \sqrt{\frac{10^{-5}}{z^2 W^2 \left(1 - 10^{-5}\right)}}$$

$$= \frac{10^{-5/2}}{z W \sqrt{1 - 10^{-5}}}$$

$= 1{,}0076$ pF

3. $t_{ap} = 200\,ns$

$I_L = 1\,nA$

12 bitni ADP

$f_{max} = ?$

$C_{min} = ?$

$\varepsilon < LSB/8$

$$\Delta U = \frac{du}{dt} t_{AP} \qquad du < LSB/8$$

$$\frac{du}{dt} = \frac{I_L}{C_H} = 2\pi f \cdot U_A$$

$$u_{ul} = U_A \sin(2\pi f t)$$

$$LSB = \frac{2U_A}{2^n} = \frac{2U_A}{2^{12}}$$

$$\frac{du}{dt} \cdot t_{AP} < LSB/8$$

$$2\pi f \cdot U_A \cdot t_{ap} < \frac{2U_A}{2^{12}} \quad / : U_A$$

$$2\pi f\, t_{ap} < \frac{2}{2^{12} \cdot 8} \quad / \quad \frac{1}{2\pi \cancel{f}\, t_{ap}}$$

$$f < \frac{\cancel{2}}{\cancel{2}\pi\, t_{ap}\, 2^{12} \cdot 2^3} = \frac{1}{2^{15}\, \pi\, t_{ap}} = 48{,}57\ Hz$$

$$\frac{I_L}{C_H} = 2\pi f U_A \Rightarrow C_H = \frac{I_L}{2\pi f U_A}$$

1. Auditorne vježbe

2. dio

4.

$C_H = 1nF$

$t_{ak} = 4{,}5\mu s$

$\pm 0{,}1\%$ $U_d = 10V$

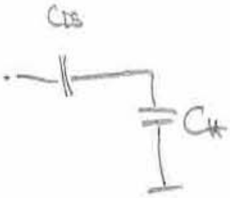
$$\frac{du}{dt} = \frac{I_L}{C_H}$$

manji C_H → brža akvizicija

→ brže klizanje

lošije preslušavanje (veće)

$$\left.\begin{array}{l} I = konst. \\ C_H' = 100pF \\ C_H = 1000pF \end{array}\right\} \quad \frac{du'}{dt} = 10\,\frac{du}{dt} = 10 \cdot 30mV/s = 300mV/s$$



$$F = 20\log\frac{C_{DS}}{C_H + C_{DS}} = -70\,dB$$

$$\frac{C_{DS}}{C_H + C_{DS}} = 10^{-7/2}$$

$$C_{DS}\left(1 - 10^{-7/2}\right) = 10^{-7/2}\, C_H$$

$$C_{DS} = \frac{10^{-7/2} \cdot C_H}{1 - 10^{-7/2}}$$

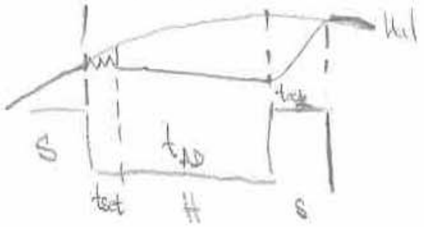
$= 0{,}316\, pF$

$$F' = 20\log\frac{C_{DS}}{C_H' + C_{DS}}$$

$= -50dB$

za $C_H' = 100pF$

5.



$$T_{min} = t_{set} + t_{AD} + t_{acq}$$

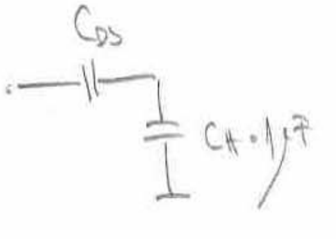
$$f = 1/T_{min} = 250\ kHz \rightarrow T_{min} = 1/250\ kHz$$

$$t_{AD} \leq \frac{1}{f_{max}} - t_{set} - t_{acq}$$

$$t_{AD} \leq 4000\ ns - 500\ ns - 2000\ ns$$

$$t_{AD} \leq 1500\ ns$$

$$t_{AD} \leq 1{,}5\ \mu s$$



$$F = 20 \log \frac{C_{DS}}{C_{DS} + C_H} \Rightarrow C_{DS} = 0{,}1\ pF$$

6.

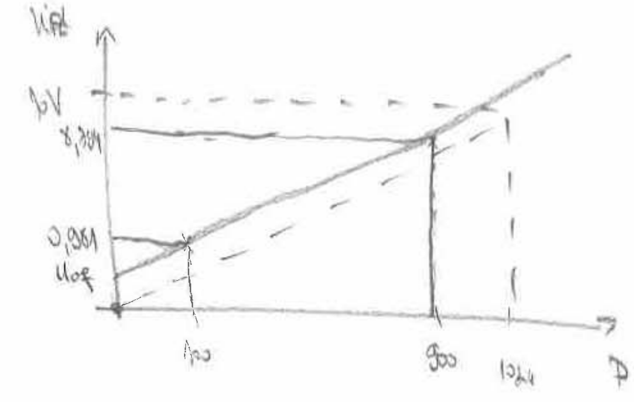
10 bitni DAP

$U_{ref} = 10V$

$U_{iz1} = 0,981V$

$U_{iz2} = 8,794V$

$$A_{ideal} = \frac{10V}{1024} = 9,765625 \ mV/bit$$



$$A_{stv} = \frac{8,794 - 0,981}{900 - 100} = 9,76625 \ mV/bit$$

$$\varepsilon = \left| \frac{A_{stv} - A_{ideal}}{A_{ideal}} \right| = 6,4 \cdot 10^{-7}$$

$U_{of} = 0,981 - A_{stv} \cdot 100 = 4,375 \ mV$

4. predavanje

3. prezentacija / 2. dio

1) Digitalno - Analogni pretvornici

1.1) naponska referenca

~ interna

- externa

=> s obzirom na opseg napona refer. izvora

~ DA s fiksnim naponom

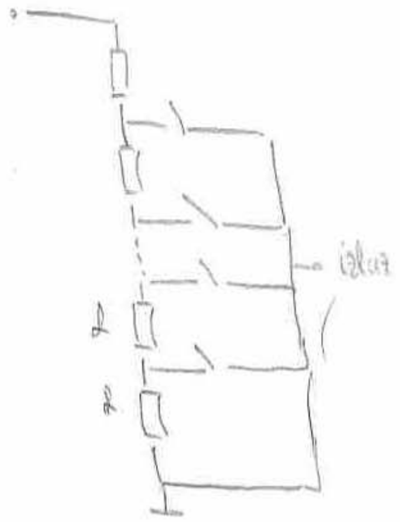
~ DA s promjenjivim iznosom reference (multiplicirajući DA pretvornici)

=> izlazni stupanj DAP

~ strujni

~ naponski

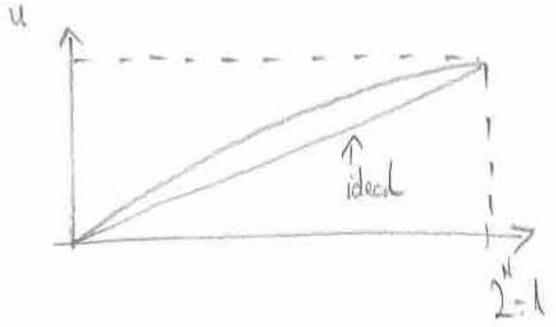
1.2) R niz (string DAC, Kelvinovo djelilo)



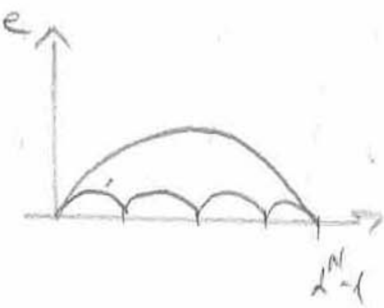
inherentno monoton → (poveć. digit. riječi napon na izlazu ne pada ⇒ povećava se)

veliki broj otpornika ⇒ nedostatak

potrebno ugađati svaki R ⇒ da bi se dobila bolja linearnost

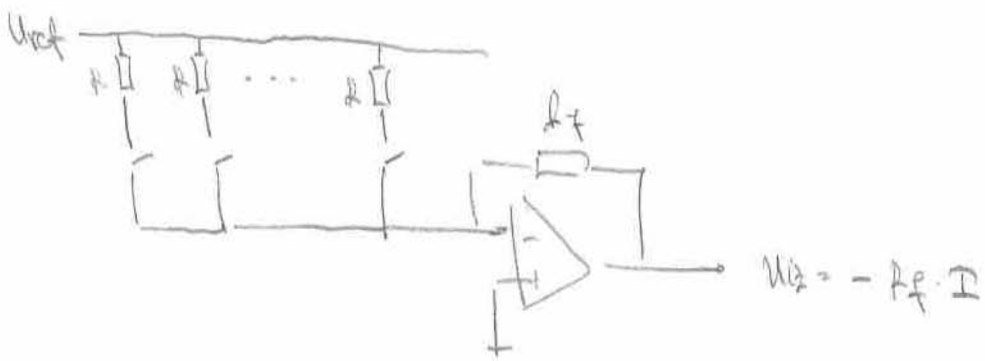


⇒

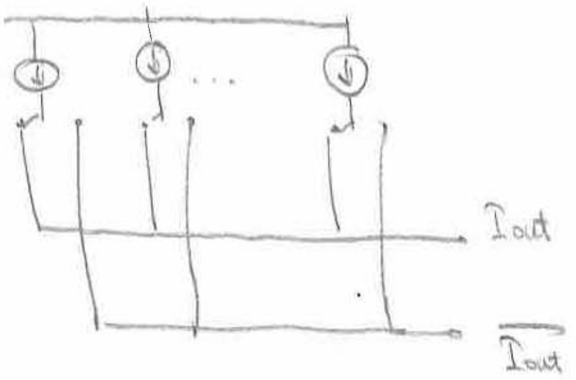


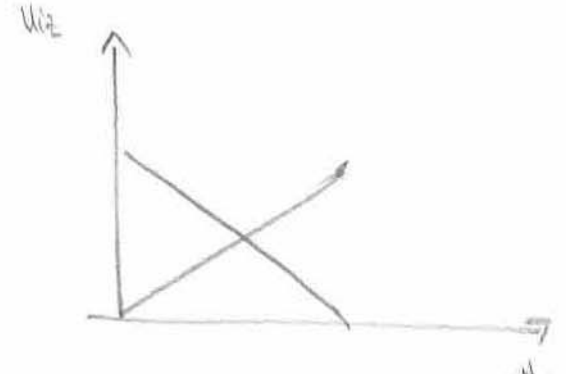
podešavanje otpornika na četvrtinama opsega

1.2) Niz strujnih izvora

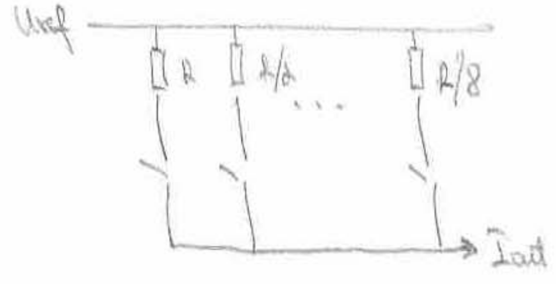


1.3.1) preusmjeravanje struje (current steering DAC)





1.4) Težinska mreža



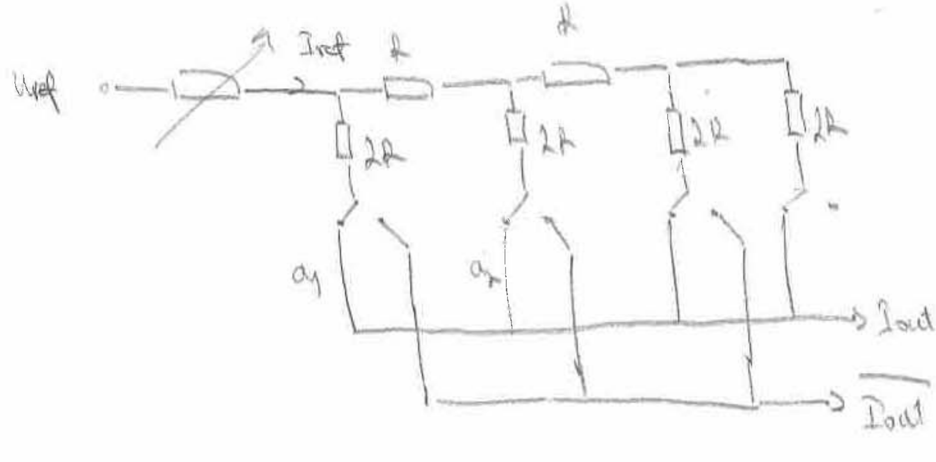
Zahtijeva precizne otpornike i precizne strujne izvore

1.5) R-2R ljestvica

1.5.1) strujni izlaz

1.5.2) naponski izlaz

1.5.1) strujni izlaz



$$I_{ref} = \frac{U_{ref}}{R}$$

$$I_1 = \frac{I_{ref}}{2} \quad ; \quad I_2 = \frac{I_1}{2} = \frac{I_{ref}}{4}$$

$$U_{iz} = -R_f \cdot I_{uk} = -R_f \cdot \sum_{i=1}^{n} a_i \cdot \frac{I_{ref}}{2^i}$$

$$= -R_f \cdot I_{ref} \cdot \sum_{i=1}^{n} a_i \frac{1}{2^i}$$

$$= -R_f \cdot I_{ref} \cdot \frac{1}{2^n}\left(a_1 \cdot 2^{n-1} + a_2 \cdot 2^{n-2} + \ldots + a_n\right)$$

$R_f = R$

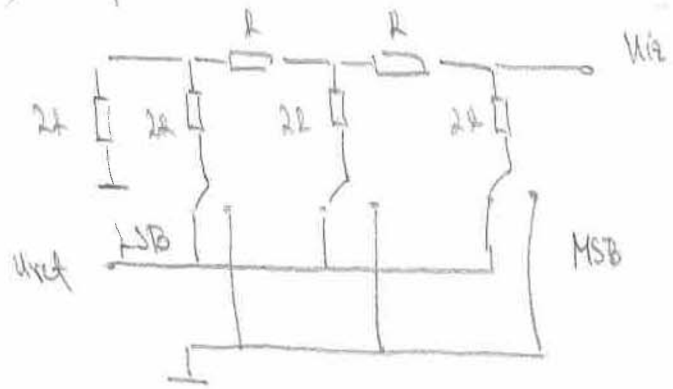
$$= -R \cdot \frac{U_{ref}}{R}\left(a_1 \cdot 2^{n-1} + a_2 2^{n-2} + \ldots + a_n\right)$$

$$= -U_{ref} \cdot N / 2^n$$

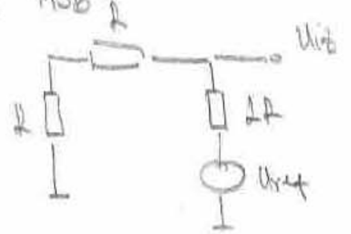
konst. opterećenje U_{ref} (U_{ref} ovisi o teretu)

sklopke stalno na niskom potenc. (virtualni spoj ili masa)

1.5.2) naponski izlaz

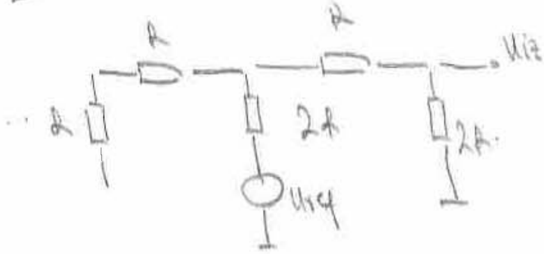


za MSB



$U_{iz} = U_{ref}/2$

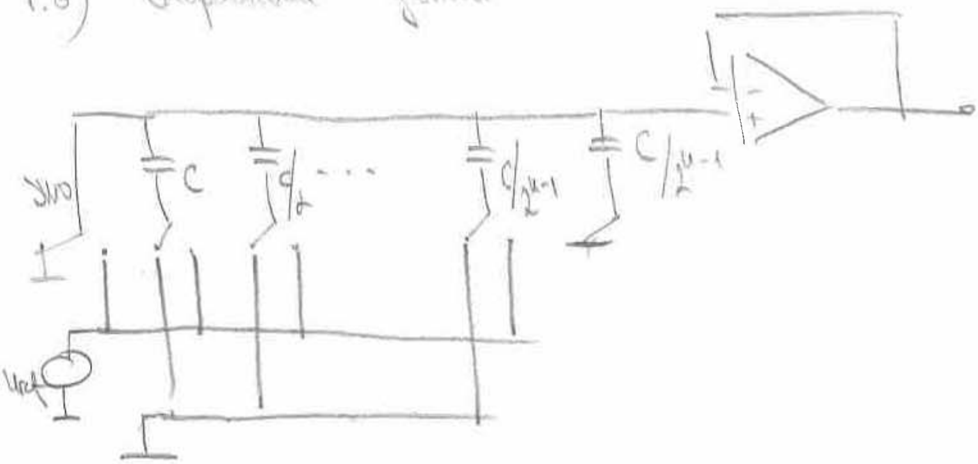
za MSB - 1



$$U_{iz} = \frac{3R \| 2R}{3R \| 2R + 2R} \cdot \frac{2R}{3R} U_{ref} = \frac{6/5\ R}{16/5\ R} \cdot \frac{2}{3} U_{ref} = U_{ref}/4$$

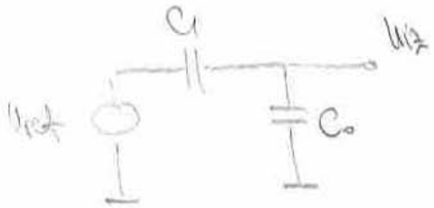
izlazni otpor ne ovisi o kod —

1.6) Kapacitivna ljestvica



SW0 → 1 reset

SW0 → 2 sample

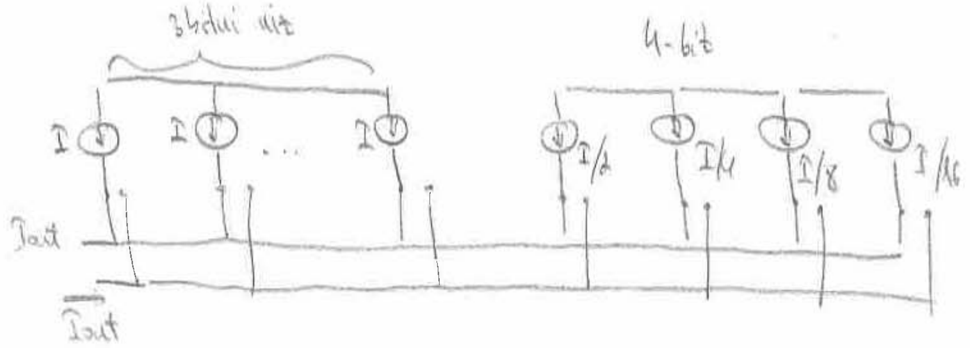


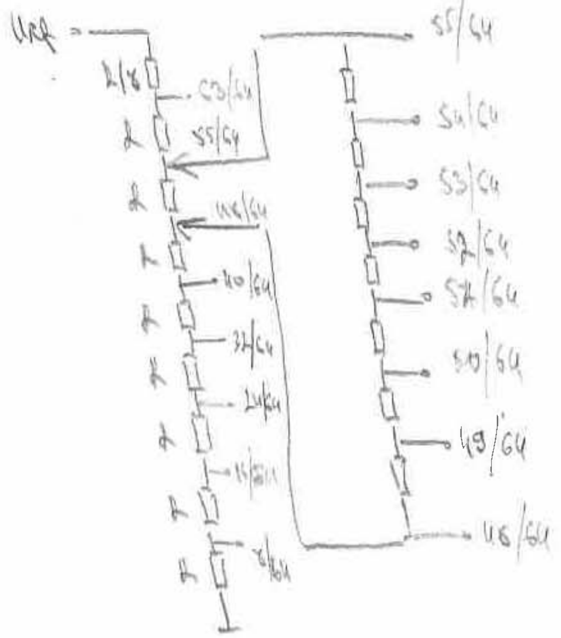
$$U_{iz} = U_{ref} \cdot \frac{C_1}{C_1 + C_0} = U_{ref} \cdot \frac{C_1}{C_{uk}} = U_{ref} \cdot \frac{a_{n-1} \cdot C + a_{n-2} \cdot \frac{C}{2} + \dots + a_0 \cdot \frac{C}{2^{n-1}}}{C + C/2 + \dots + \frac{C}{2^{n-1}} + \frac{C}{2^{n-1}}}$$

$$U_{iz} = U_{ref} \cdot \frac{a_{n-1} \cdot C + \dots + a_0 \frac{C}{2^{n-1}}}{2C}$$

$$U_{iz} = U_{ref}/2^n \left(a_{n-1} \cdot 2^{n-1} + \dots + a_0\right)$$

17) Segmentirani DAC





$$\frac{R \cdot 7R}{R+7R} = 7/8 \; R$$

6. predavanje

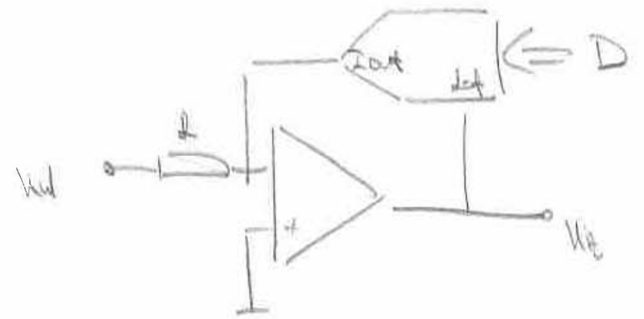
3. prezentacija / 3. dio

1.8) Multiplicirajući DAP

- => kvadratni
- => četverokvadratne

1.8.1) Izvedba MDAP-a

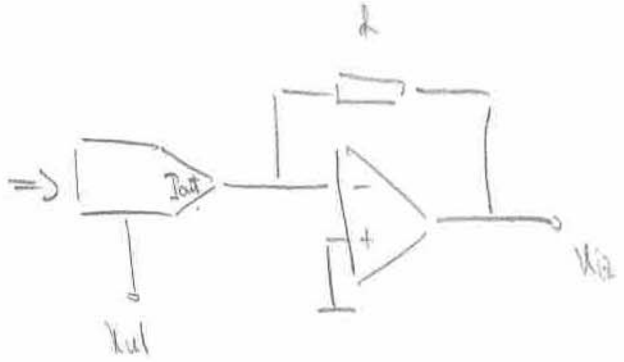
- => PGA s multiplicirajućim DAP-ovima



$$I_{out} = I_{ref} \cdot \frac{2^n}{2^N}$$

$$\frac{U_{ul}}{R} = -I_{ref} \cdot \frac{2^n}{2^N} = -\frac{U_{iz}}{R} \cdot \frac{2^n}{2^N} \quad / \cdot R$$

$$\frac{U_{iz}}{U_{ul}} = -\frac{2^N}{2^n}$$ razlučivost



$$\frac{U_{iz}}{U_{ul}} = -\frac{2^n}{2^N}$$

1.87) Pogreške pojačanja uslijed

1) integralne nelinearnosti MDAP-a

2) pogreška pojačanja DAP-a

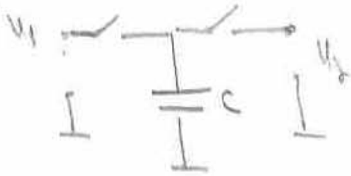
$U_{iz} = U_{ref} \cdot D$

daci grešku

$$\frac{U_{iz}}{U_{ul}} = -\frac{2^N}{(2^n + x) \cdot (1 + \gamma)}$$

1.88) svi otpornici relativno mali / može se postići veće pojačanje

2) Sklopovi s preklapanim kapacitetima



$U_1 > U_2$

$\Delta Q = C \cdot (U_1 - U_2)$

$I_{sr} = \Delta Q \, f_{clk} = \Delta Q \cdot \frac{1}{T} = C \cdot \Delta U \cdot f_{cl}$

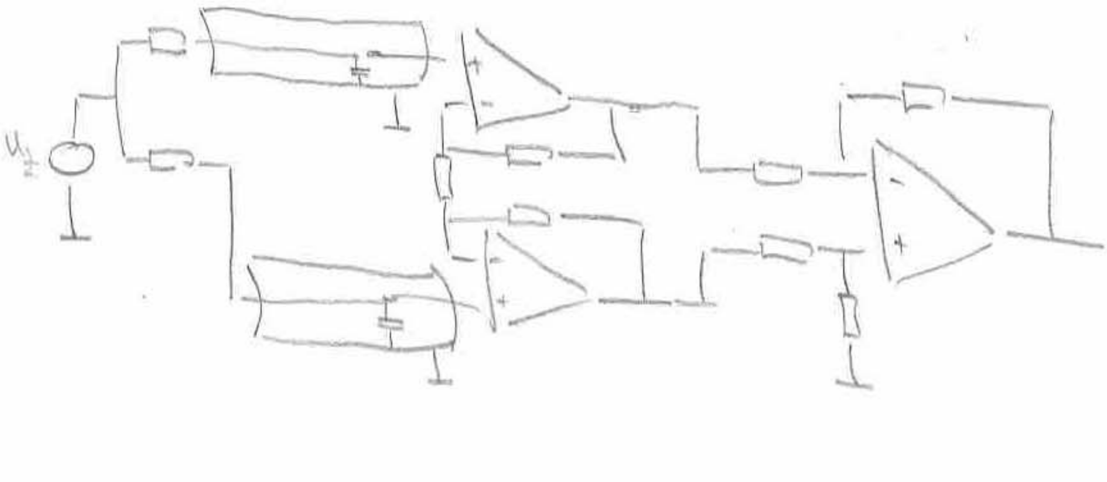
$$\frac{\Delta U}{I_{sr}} = \frac{1}{C \cdot f_{clk}} = R_{ekv}$$

4. prezentacija / Diferencijalna, instrumentacijska i izolacijska pojačala

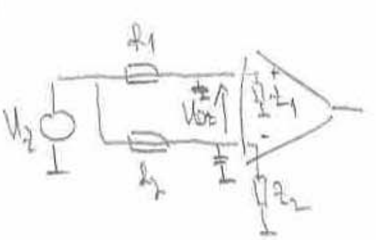
1) Pojačala

- ⇒ diferencijalna
- ⇒ instrumentacijsko
  - ~ šum
- ⇒ oklapanje / zaštitna elektroda
- ⇒ izolacijsko poj.
- ⇒ chopperско poj.
- ⇒ auto-zero poj.

1.1) oklapanje i zaštitna elektroda



dif.



$$U_{DZ} = U_Z \cdot \left(\frac{Z_1}{R_1 + Z_1} - \frac{Z_2}{R_2 + Z_2} \right)$$

zajed. smetnja U_Z

$$Z_1 = Z_2 = Z$$

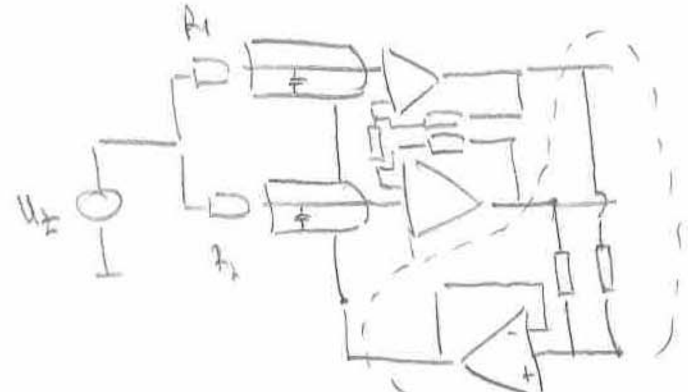
$$Z >> R_1, R_2$$

$$U_{DZ} = U_Z \frac{\Delta R}{Z}$$

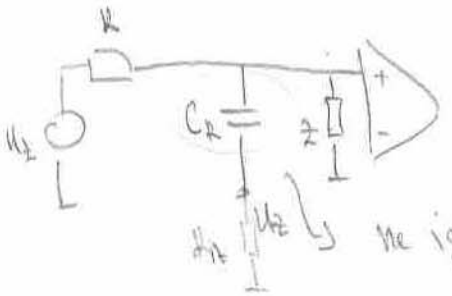
difer. napon kao posljedica zajedničke smetnje

sklapanje se dodaje rasipni kapacitet ali smanjuje ulaznu imped. pojačala => povećava se U_{DZ}

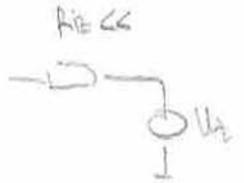
negativna strana sklapanja (izbjegava se korištenjem zaštitne elektrode ~ guard)



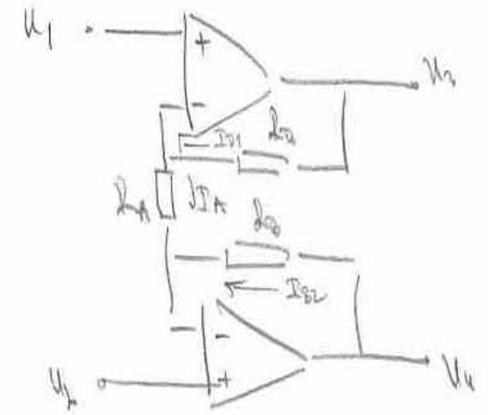
guard



} ne igra ulogu (kratko spojen) => guarding



C_R preko imped. izlaznog sljedila spojen na masu



$$I_{B1} = I_A$$

$$\frac{U_3 - U_1}{R_B} = \frac{U_1 - U_2}{R_A}$$

$$I_A = - I_{B2}$$

$$\frac{U_1 - U_2}{R_A} = \frac{U_2 - U_4}{R_B}$$

$$\boxed{\begin{aligned} U_3 &= -\frac{R_B}{R_A} \cdot U_2 + \left(1 + \frac{R_B}{R_A}\right) U_1 \\ U_4 &= \left(1 + \frac{R_B}{R_A}\right) U_2 - \frac{R_B}{R_A} U_1 \end{aligned}}$$

$$U_4 - U_3 = \left(1 + \frac{2 R_B}{R_A}\right) U_2 - \left(1 + 2\frac{R_B}{R_A}\right) U_1$$

$$\boxed{U_4 - U_3 = \left(1 + 2\, R_B/R_A\right)\left(U_2 - U_1\right)}$$

$$\frac{U_4 + U_3}{2} = \frac{U_2 + U_1}{2}$$

$$U_{D,ul} = U_2 - U_1$$

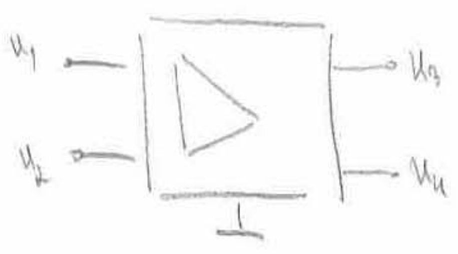
$$U_{D,iz} = \left(1 + 2R_2 / R_1\right) U_{D,ul}$$

$$U_{Z,iz} = U_{Z,ul}$$

2. auditorne vježbe / 1. dio

1.

dif. poj. / simetrično



$$u_3 = c_{11} u_1 + c_{12} \cdot u_2$$

$$u_4 = c_{21} u_1 + c_{22} u_2$$

$$u_{D,ul} = u_1 - u_2 \qquad u_{D,iz} = u_3 - u_4$$

$$u_{Z,ul} = \frac{1}{2}(u_1 + u_2) \qquad u_{Z,iz} = \frac{1}{2}(u_3 + u_4)$$

$$\begin{bmatrix} u_{D,iz} \\ u_{Z,iz} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} u_{D,ul} \\ u_{Z,ul} \end{bmatrix}$$

$$\begin{bmatrix} u_{D,iz} \\ u_{Z,iz} \end{bmatrix} = \begin{bmatrix} A_D & A_Z \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} u_{D,ul} \\ u_{Z,ul} \end{bmatrix}$$

$$A_D = \left.\frac{u_{D,iz}}{u_{D,ul}}\right|_{u_{Z,ul}=\emptyset} \quad ; \quad A_Z = \left.\frac{u_{D,iz}}{u_{Z,ul}}\right|_{u_{D,ul}=\emptyset}$$

faktor potiskivanja / rejekcije (CMRR)

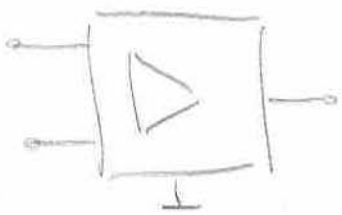
$$CMRR = \rho = \left|\frac{A_D}{A_Z}\right| = H = F = \left|\frac{\left.\frac{u_{D,iz}}{u_{D,ul}}\right|_{u_{Z,ul}=\emptyset}}{\left.\frac{u_{D,iz}}{u_{Z,ul}}\right|_{u_{D,ul}=\emptyset}}\right|$$

faktor diskriminacije

$$F_D = \frac{A_D}{\left.\frac{U_{Z,iz}}{U_{Z,ul}}\right|_{U_{D,ul}=\phi}} = \frac{A_D}{a_{22}}$$

$$a_{21} = \phi$$

osnovično pojačalo / dif.



$$U_{iz} = \begin{bmatrix} A_D & A_Z \end{bmatrix} \begin{bmatrix} U_{D,ul} \\ U_{Z,ul} \end{bmatrix}$$

$U_{D,ul} = 1\mu V$; $U_{Z,ul} = 2V$

$\rho = 80\,dB = 10^4$

$F_D = 80\,dB = 10^4$

$A_D = 1000$

$$A_Z = \frac{A_D}{\rho} = 0{,}1$$

$$a_{22} = \frac{A_D}{F_D} = 0{,}1$$

$$a_{21} = \phi$$

$U_{D,iz} = A_D \cdot U_{D,ul} \pm A_Z \cdot U_{Z,ul}$

$= 1000 \cdot 1\mu V \pm 0{,}1 \cdot 2V$

$= 1mV \pm 0{,}2V$

$U_{Z,iz} = a_{22}\, U_{Z,ul}$

$= 0{,}1 \cdot 2V$

$= 0{,}2V$

Čest slučaj / 2. stupnja

$$u_{iz} = \begin{bmatrix} A_{D2} & A_{Z2} \end{bmatrix} \begin{bmatrix} A_{D1} & A_{Z1} \\ \phi & a_{22} \end{bmatrix} \begin{bmatrix} u_{D,ul} \\ u_{Z,ul} \end{bmatrix}$$

$$u_{iz} = \begin{bmatrix} A_{D2}A_{D1} & A_{D2}A_{Z1} + A_{Z2}a_{22} \end{bmatrix} \begin{bmatrix} u_{D,ul} \\ u_{Z,ul} \end{bmatrix}$$

$$\rho = \left| \frac{A_{D,uk}}{A_{Z,uk}} \right| = \left| \frac{A_{D2}A_{D1}}{A_{D2}A_{Z1} + A_{Z2}a_{22}} \right| = \left| \frac{1}{\frac{A_{Z1}}{A_{D1}} + \frac{A_{Z2}}{A_{D2}} \frac{a_{22}}{A_{D1}}} \right|$$

$$1/\rho = \frac{1}{\frac{A_{D1}}{A_{Z1}}} + \frac{1}{\frac{A_{D2}}{A_{Z2}}} \cdot \frac{1}{\frac{A_{D1}}{a_{22}}}$$

$$1/\rho = \frac{1}{\rho_1} + \frac{1}{\rho_2} \cdot \frac{1}{F_{D1}}$$

2.

dif. poj. s asimetr. izlazom

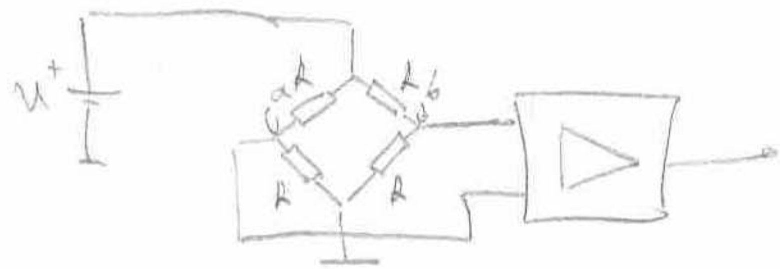
$A_D = 1000$

$U_{D,ul} = 1mV$

$U = 10V$

$\rho = 80dB = 10^4$

$U_{D,iz} = ?$



$$U_{D,ul} = U_a - U_b$$

$$U_a = \frac{1}{2}\left(U + U_{D,ul}\right) = 5{,}0005\,V$$

$$U_b = 1/2\left(U - U_{D,ul}\right) = 4{,}9995\,V$$

$$U_{Z,ul} = 1/2\left(U_a + U_b\right) = 5V$$

$$U_{iz} = \begin{bmatrix} A_D & A_Z \end{bmatrix} \begin{bmatrix} U_{D,ul} \\ U_{Z,ul} \end{bmatrix}$$

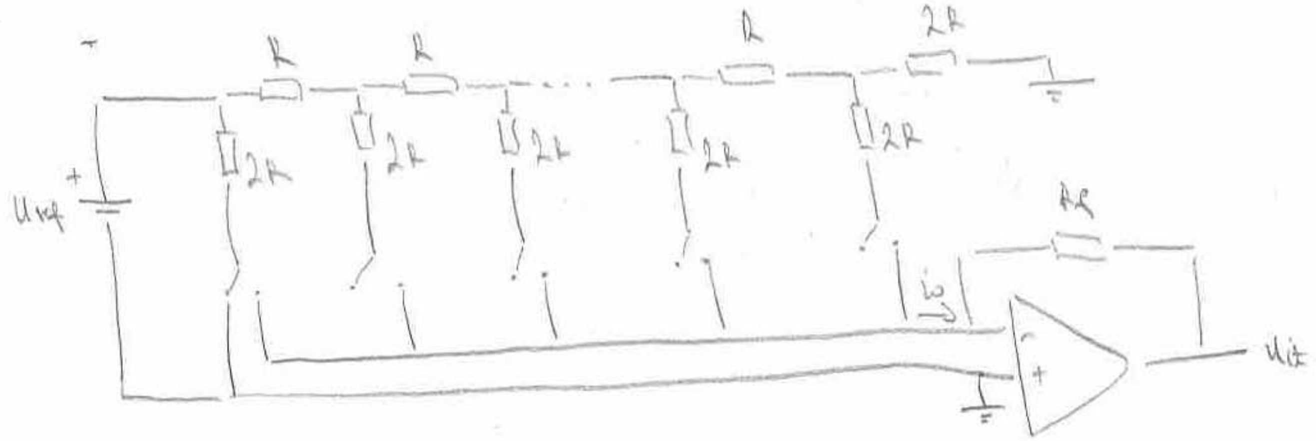
$$U_{iz} = A_D U_{D,ul} \pm A_Z \cdot U_{Z,ul}$$

$$\left(\rho = \frac{A_D}{A_Z} \Rightarrow A_Z = A_D / \rho = 0{,}1 \right.$$

$$U_{D\,iz} = \left(1 \mp 0{,}5\right)V$$

2 Kratka provjera znanja

1.



u strujnom načinu

$R = R_f = 15\,k\Omega$

$U_{ref} = 5V$

4-bitni pretvornik

$a_1 a_2 a_3 a_4 = \overset{3\,2\,1\,0}{1101}_{(2)}$

$U_{iz} = ?$

$$U_{iz} = -R_f \cdot i_0$$

$$i_0 = \frac{U_{ref}}{R} \cdot D$$

$$U_{iz} = -\cancel{\frac{R_f}{R}} \cdot U_{ref} \left(\frac{a_1}{2^1} + \frac{a_2}{2^2} + \frac{a_3}{2^3} + \dots + \frac{a_n}{2^n} \right)$$

$$U_{iz} = -U_{ref} \left(\frac{1}{2} + \frac{1}{4} + \frac{1}{16} \right)$$

$$U_{iz} = -U_{ref} \left(\frac{8+4+1}{16} \right)$$

$$U_{iz} = -U_{ref} \left(13/16 \right)$$

$$U_{iz} = -4{,}0625V$$

2.

dif. poj. sa simetr. izlazom

$A_D = 1000$

$\rho = 100\ dB$

$F_D = 120\ dB$

$U_Z = 5V$

$U_{D,ul} = 2mV$

$U_{D,iz} = ?$

$$\begin{bmatrix} U_{D,iz} \\ U_{Z,iz} \end{bmatrix} = \begin{bmatrix} A_D & A_Z \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} U_{D,ul} \\ U_{Z,ul} \end{bmatrix}$$

$$\rho = 20 \log \left| \frac{A_D}{A_Z} \right|$$

$$5 = \log \left| \frac{A_D}{A_Z} \right| \Rightarrow \frac{A_D}{A_Z} = 10^5 \Rightarrow \boxed{A_Z = \frac{A_D}{10^5}}$$

$$a_{21} = \emptyset$$

$$F_D = \frac{A_D}{\left.\frac{U_{Z,iz}}{U_{Z,ul}}\right|_{U_{D,ul}=\emptyset}} = \frac{A_D}{a_{22}}$$

$$120\ dB = 20 \log \left| \frac{A_D}{a_{22}} \right|$$

$$6 = \log \left| \frac{A_D}{a_{22}} \right| \Rightarrow \frac{A_D}{a_{22}} = 10^6 \Rightarrow \boxed{a_{22} = \frac{A_D}{10^6}}$$

$$2\times 2 \qquad 2\times 1 \quad \Rightarrow \quad 2\times 1$$

$$\begin{bmatrix} U_{D,iz} \\ U_{Z,iz} \end{bmatrix} = \begin{bmatrix} A_D & A_Z \\ \emptyset & a_{zz} \end{bmatrix} \begin{bmatrix} U_{D,ul} \\ U_{Z,ul} \end{bmatrix}$$

$$\begin{bmatrix} U_{D,iz} \\ U_{Z,iz} \end{bmatrix} = \begin{bmatrix} A_D U_{D,ul} \pm A_Z U_{Z,ul} \\ a_{zz} U_{Z,ul} \end{bmatrix}$$

$$U_{D,iz} = A_D U_{D,ul} \pm A_Z U_{Z,ul}$$

$$= (2 \pm 0{,}05)\,V$$

$$U_{Z,iz} = A_D / 10^6 \; U_{Z,ul}$$

$$= 5\,\mu V$$

6 predavanje

4. prezentacija

1) Čoperska pojačala

2) Auto-zero pojačalo

3) Izolacijska pojačala

Mali signali => male amplitude $< 10 \mu V$ i sporo promjenjivi (istos

npr. tenzometarski most ($0{,}4 \mu V/g$)

k-tip termopar ($40{,}7 \mu V/°C$)

mjerni lanac

~ vrlo mali napon pomaka

~ vrlo mali temperaturni i vremenski pomak

~ vrlo mali $1/f$ šum

čoperska i auto-zero pojačala tipično:

~ $1 \mu V$ pomaka

~ $20 nV/°C$

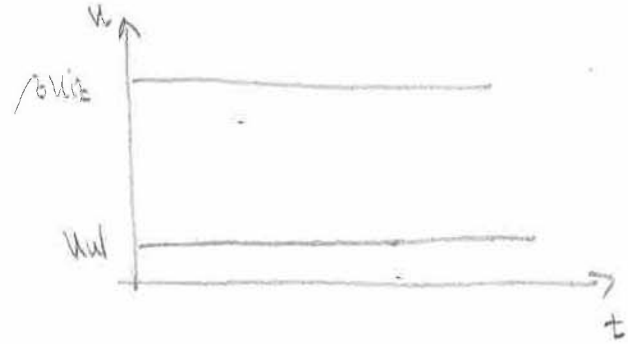
~ $20 nV/$mjesec

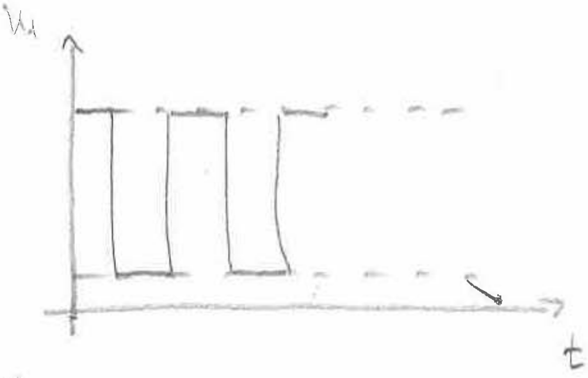
1) Čopersko - pojačalo

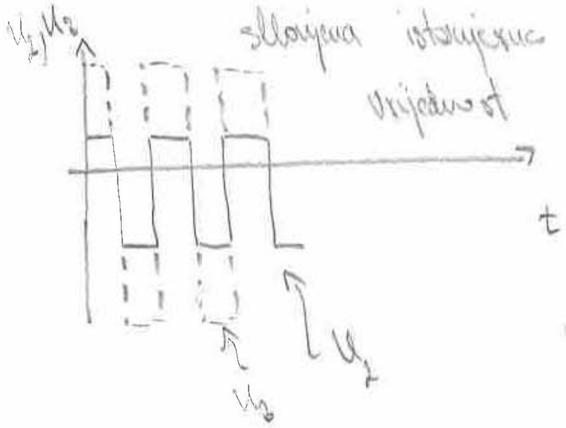
C1 ~ sklanja istosmjernu komponentu

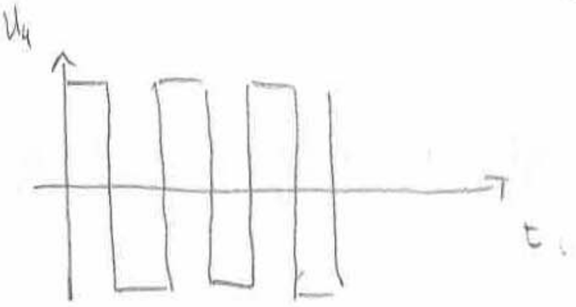
C2 ~ izmjenično pojačalo (A1)

A2 ~ integrator



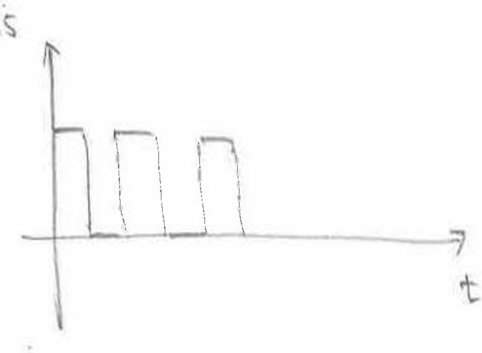


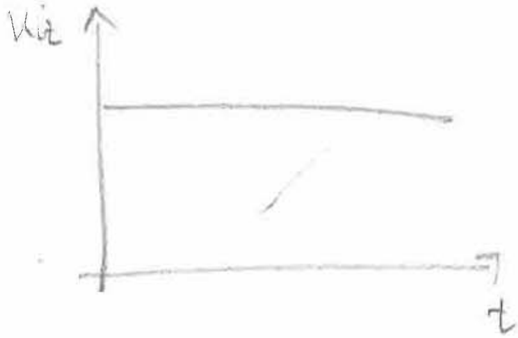




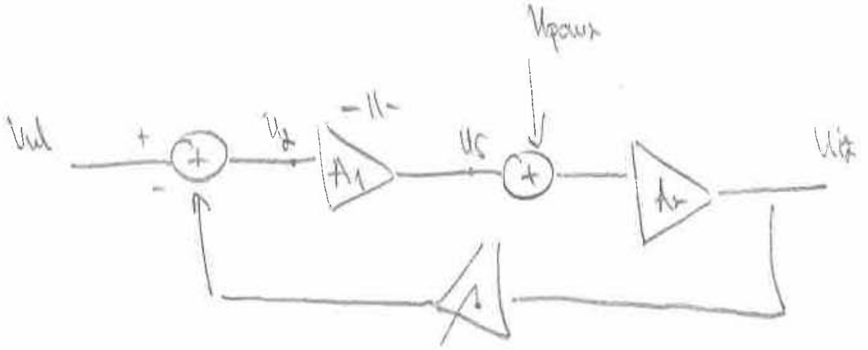
$u_4 = u_2$

nema pogreške koju unosi A1





integracijom u_5 dobiva se u_{iz}



$$U_2 = U_{ul} - \beta U_{iz}$$

$$U_5 = A_1 U_2 = A_1 (U_{ul} - \beta U_{iz})$$

$$U_{iz} = A_2 (U_5 + U_{šum}) = A_2 \left(A_1 (U_{ul} - \beta U_{iz}) + U_{šum} \right)$$

$$U_{iz} = A_2 A_1 U_{ul} - A_2 A_1 \beta U_{iz} + A_2 U_{šum}$$

$$U_{iz} (1 + A_2 A_1 \beta) = A_2 A_1 U_{ul} + A_2 U_{šum}$$

$$U_{iz} = \frac{A_2 A_1 U_{ul} + A_2 U_{šum}}{1 + A_2 A_1 \beta}$$

$$U_{iz} = \frac{A_2 A_1}{1 + \beta A_1 A_2} U_{ul} + \frac{A_2}{1 + A_1 A_2 \beta} U_{šum}$$

$A_2 A_1 >> \beta$ i $A_1 >> A_2$ i $\beta = R_1 / (R_1 + R_2)$

$U_{iz} = \frac{1}{\beta} U_{ul} + \frac{1}{\beta A_1} U_{pom2}$; $1/\beta = 1 + R_2 / R_1$

frekv. domena

2 mixera

1) signal se preselio na frekv. prebacivanja (harmonike) — pomaknuli smo signal iz područja ~ 0 Hz na više frekvencije (spektar)

2) pojačalo pojačava signal / unosi pogreške (bijeli šum i 1/f pogreške)

3) 2. mixanje vraća signal u osnovnu frekvenciju i a grešku pomiče na frekvenciju harmonika → usporedivo s izvornim signalom

4) filtriranje signala → šum se 1. puta mix-a

2) Auto-zero pojačalo

2.1) auto-zero faza (određuje se napon pomaka)

S1 na "a"

S2 na "a"

$$U_{iz2}^{a} = U_{pom2} \cdot A_2 - B_2 \cdot U_{iz2}^{a}$$

$$U_{iz2}^{a}(1 + B_2) = U_{pom} \cdot A_2$$

$$U_{iz2}^{a} = \frac{U_{pom2} A_2}{1 + B_2} = \frac{A_2}{1 + B_2} U_{pom2}$$

2.2) pojačanje signala

S1 na "b"

S2 na "b"

$$U_{iz2}^{b} = (U_{ul} + U_{pom2}) A_2 - B_2 \cdot U_{iz2}^{a}$$

$$U_{iz2}^{b} = (U_{ul} + U_{pom2}) A_2 - B_2 \cdot \frac{A_2}{1 + B_2} U_{pom2}$$

$$U_{iz2}^{b} = U_{ul} A_2 + \frac{A_2}{1 + B_2} U_{pom2}$$

$$U_{iz1}^{b} = \left(U_{ul} + U_{pom}\right) A_1 + B_1 U_{iz2}^{b}$$

$$U_{iz1}^{b} = \left(U_{ul} + U_{pom1}\right) A_1 + B_1 \cdot \left\{ U_{ul} A_2 + \frac{A_2}{1+B_2} U_{pom2} \right\}$$

$$U_{iz1}^{b} = \left(A_1 + A_2 B_1\right) U_{ul} + A_1 U_{pom1} + \frac{B_1 A_2}{1+B_2} U_{pom2}$$

za $A_1 = A_2$; $B_2 = B_1 \gg 1$

$$U_{iz1}^{b} = A \cdot B\, U_{ul} + A U_{pom1} + A U_{pom2}$$

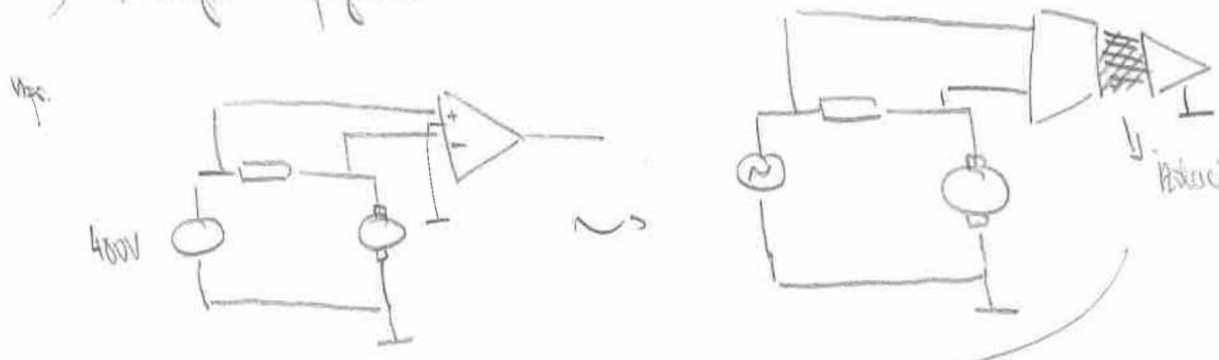
$$U_{iz1}^{a} = U_{iz1}^{b}$$

2.2) nedostatci:

~ intermodulacije

npr. signal 200Hz, $f_s = 4$kHz $\}$ u spektru peak-ovi na 3800Hz ; 4200Hz ...

3) Izolacijsko pojačalo



~ optički spregnuto
~ elektromagnetski spregnuto (induktivno)
~ kapacitivno

3.1) Optički spregnuto

$$i_2 + \frac{u_c}{R_4} = -\frac{u_1}{R_1}$$

$$i_2 = f(u_2) \; ; \; u_2 = f^{-1}(i_2)$$

$$\frac{u_c}{R_4'} + i_2' + i_3 = \emptyset$$

$u_c = \emptyset$; AC -> analiza

$$i_2' = -i_3 = u_3 / R_3$$

$$i_2' = f(u_2)$$

$$u_3 / R_3 = f(u_2) = f\left(f^{-1}(u_1 / R_1) \right)$$

$$u_3 / R_2 = u_1 / R_1$$