

# OSNOVE BIOMEDICINSKOG INŽENJERSTVA

DIFERENCIJALNI POJAČAVAČ

# DIFERENCIJALNI POJAČAVAČ

- **Polazna** osnova za projektovanje elektrofiziološkog pojačavača;
- Pojačava razliku signala na svojim ulaznim priključcima;
- Veliko diferencijalno pojačanje;
- **Visok** CMRR;
- **Mala ulazna** impedansa;

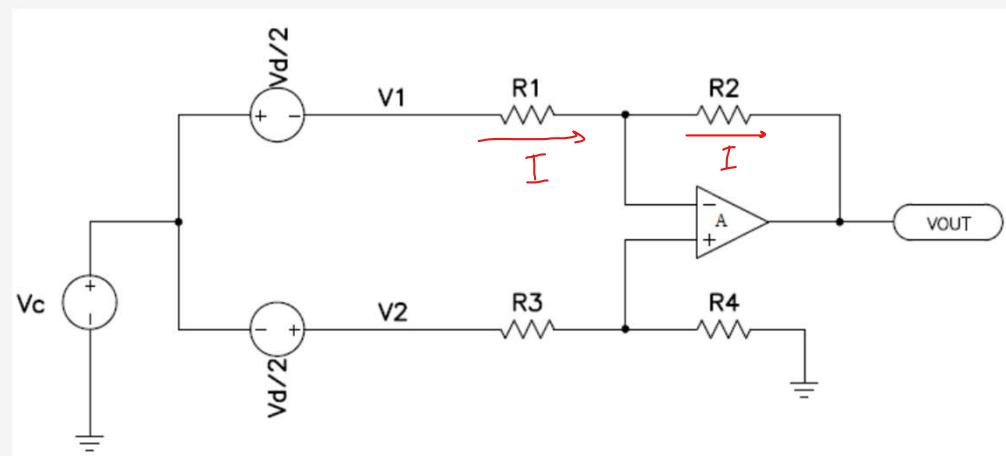
$$V_1 = V_C - \frac{V_D}{2}$$

$$V_2 = V_C + \frac{V_D}{2}$$

$$V^+ = \frac{R_4}{R_3 + R_4} \cdot V_2$$

Zbog postajanja negativne povratne sprege i velikog pojačanja u otvorenoj povratnoj sprezi, naponi na invertujućem i neinvertujućem **ulazu** su jednaki, tj.

$$V^- = V^+ = \frac{R_4}{R_3 + R_4} \cdot V_2$$



$$V_{OUT} = \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1} \right) \cdot V_C + \frac{1}{2} \cdot \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} + \frac{R_2}{R_1} \right) \cdot V_D$$

$$V_{OUT} = A_C \cdot V_C + A_D \cdot V_D$$

$$A_C = \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1}$$

$$A_D = \frac{1}{2} \cdot \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} + \frac{R_2}{R_1} \right)$$

# Diferencijalni pojačavač

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$A_d$  – Pojačanje diferencijalnog signala

$A_c$  – Slabljenje signala zajedničkog moda

$$CMRR_{dB} = 20\log\left(\frac{A_d}{A_c}\right) = 20\log\left(\frac{R_4 \cdot (R_1 + R_2) + R_2 \cdot (R_3 + R_4)}{2 \cdot (R_4 \cdot (R_1 + R_2) - R_2 \cdot (R_3 + R_4))}\right)$$

Da bi CMRR bio što je moguće veći, neophodno je **balansirati pojačavač**.

$$A_c = 0$$

$$\frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1} = 0 \Rightarrow \frac{R_4}{R_3} = \frac{R_2}{R_1}$$

$$A_d = \frac{R_2}{R_1}$$

# Diferencijalni pojačavač

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Ukoliko na ulaz pojačavača postavimo elektrode istih otpornosti, pojačanje pojačavača postaje:

$$A_D = \frac{R_2}{R_1 + R_E}$$

Ukoliko na ulaz pojačavača postavimo elektrode različitih otpornosti, pojačanje pojačavača postaje:

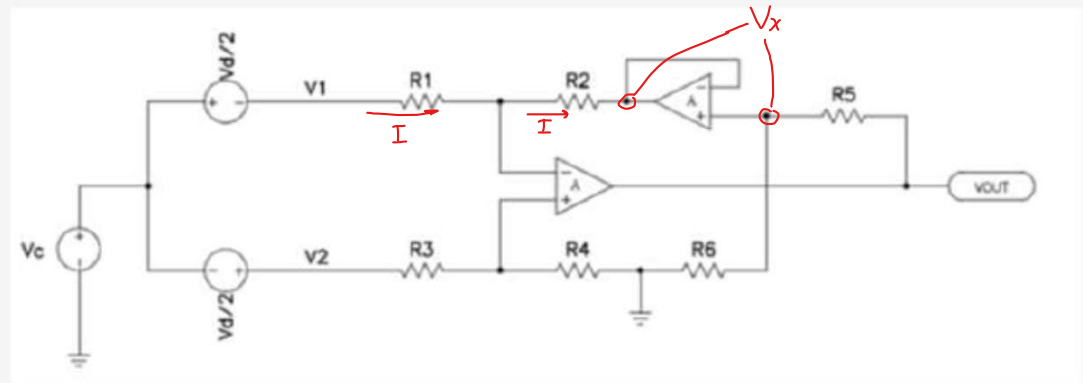
$$V_{OUT} = A_C \cdot V_C + A_D \cdot V_D$$

$$A_C = \left( \frac{R_2}{R_1 + R_2 + R_{E1}} \cdot \frac{R_1 + R_2 + R_{E1}}{R_1 + R_{E2}} - \frac{R_2}{R_1 + R_{E1}} \right)$$

$$A_D = \frac{1}{2} \cdot \left( \frac{R_2}{R_1 + R_2 + R_{E1}} \cdot \frac{R_1 + R_2 + R_{E1}}{R_1 + R_{E2}} + \frac{R_2}{R_1 + R_{E1}} \right)$$

## Modifikovani diferencijalni pojačavač

- Standardni diferencijalni pojačavač ima problem jednostavne promene diferencijalnog pojačanja;
- Problem promene pojačanja se može rešiti dodavanjem bafera i razdelnika napona u negativnu povratnu spregu;



$$V_{OUT} = \frac{R_5 + R_6}{R_6} \cdot \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1} \right) \cdot V_C + \frac{1}{2} \cdot \frac{R_5 + R_6}{R_6} \cdot \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} + \frac{R_2}{R_1} \right) \cdot V_D$$

$$V_{OUT} = A_C \cdot V_C + A_D \cdot V_D$$

$$A_C = \frac{R_5 + R_6}{R_6} \cdot \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1} \right)$$

$$A_D = \frac{1}{2} \cdot \frac{R_5 + R_6}{R_6} \cdot \left( \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} + \frac{R_2}{R_1} \right)$$

Na osnovu izraza za  $A_C$ , može se videti da modifikacija ne utiče na potiskivanje signala zajedničkog moda i da se balansiranje vrši isto kao kod standardnog diferencijalnog pojačavača.

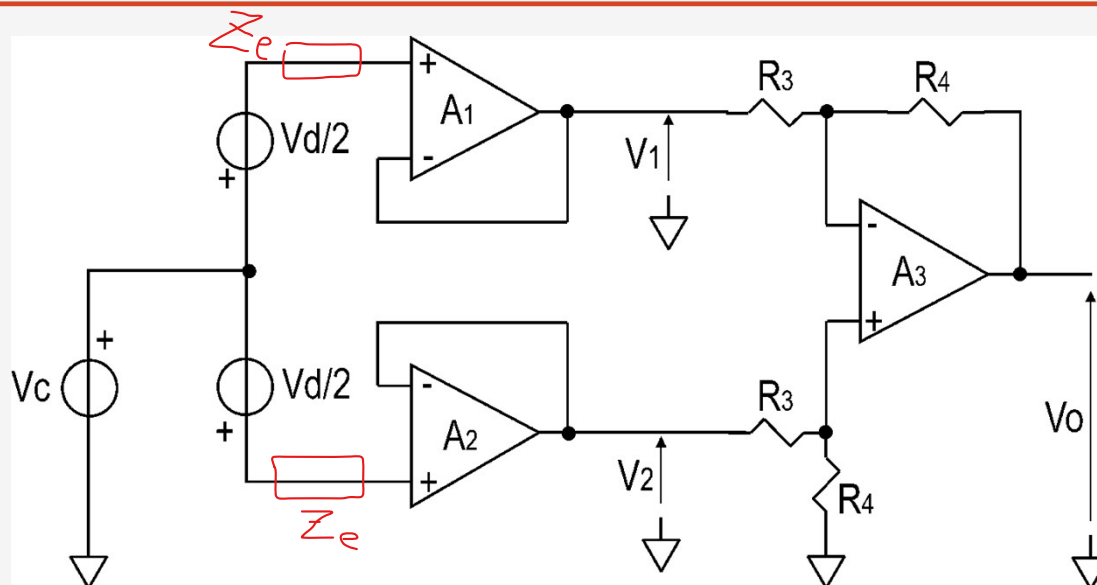
$$A_D = \frac{R_2}{R_1} \cdot \frac{R_5 + R_6}{R_6}$$

## Modifikovani diferencijalni pojačavač

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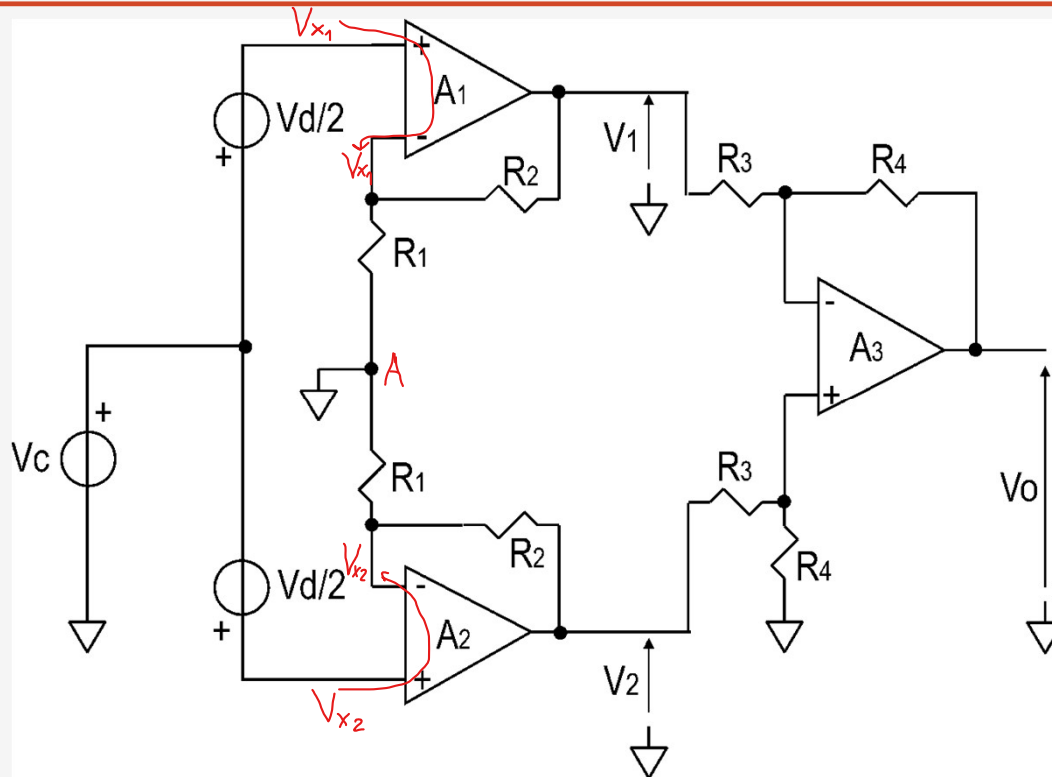
- Modifikacijom standardnog diferencijalnog pojačavača, rešen je problem jednostavne promene pojačanja;
- Pojačanje se može menjati u dva stepena. Preporuka je da se prvo postavi minimalna vrednost pojačanja pomoću otpornika R1 i R2, a u dodatnoj mreži da se postavi ostatak pojačanja;
- Jednostavna promena pojačanja se može implementirati ubacivanjem potencijometra umesto otpornika R5;
- Problem male ulazne impedanse ostaje nerešen;

## Baferovani diferencijalni pojačavač



$$V_1 = V_c - \frac{V_d}{2} \quad V_2 = V_c + \frac{V_d}{2} \quad V_o = \frac{R_4}{R_3} (V_2 - V_1)$$

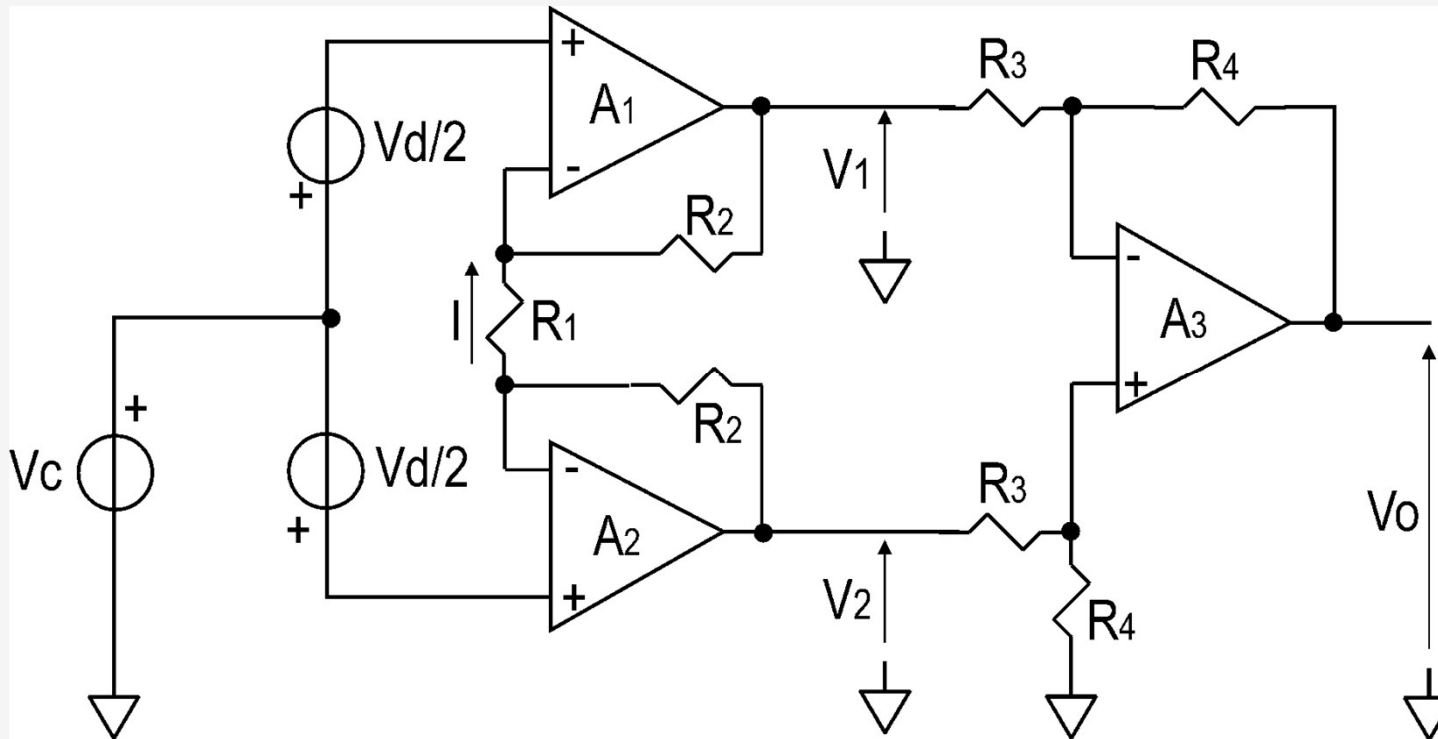
Ulazni stepen sa **neinvertujućim pojačavačima**



$$V_1 = \left(1 + \frac{R_2}{R_1}\right) \left(V_c - \frac{V_d}{2}\right) \quad V_2 = \left(1 + \frac{R_2}{R_1}\right) \left(V_c + \frac{V_d}{2}\right) \quad V_o = \frac{R_4}{R_3} (V_2 - V_1)$$

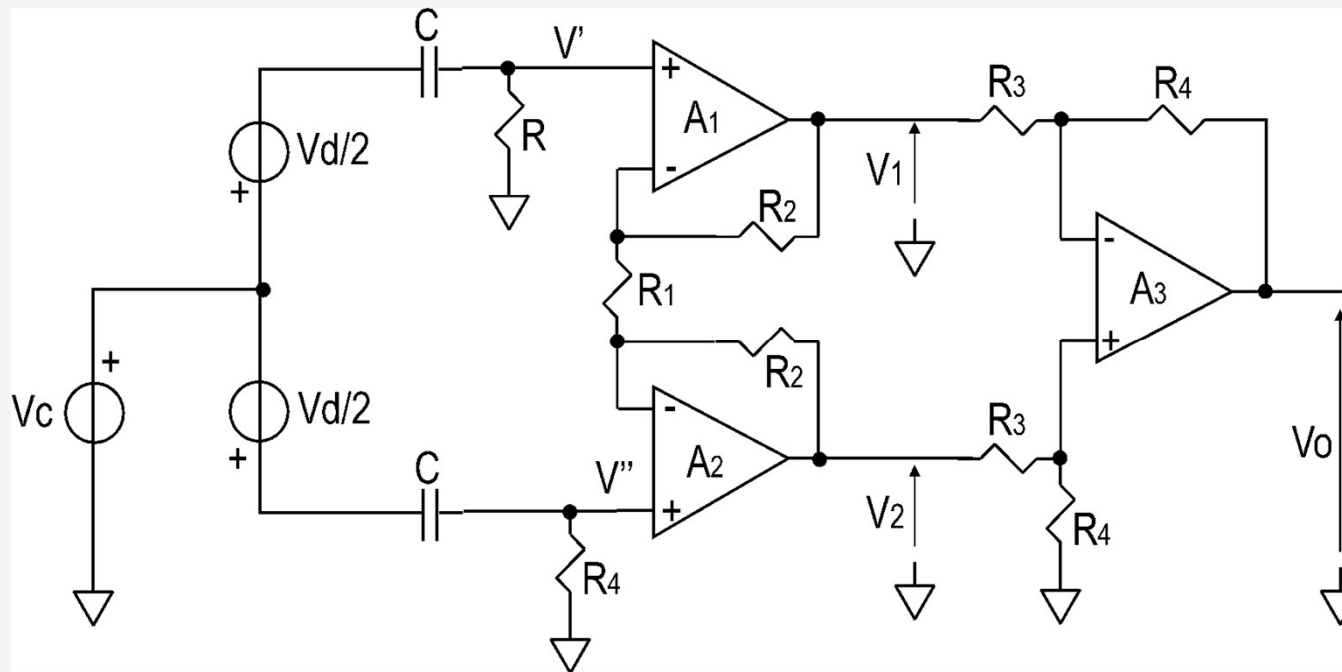


Instrumentacioni pojačavač sa tri operaciona pojačavača



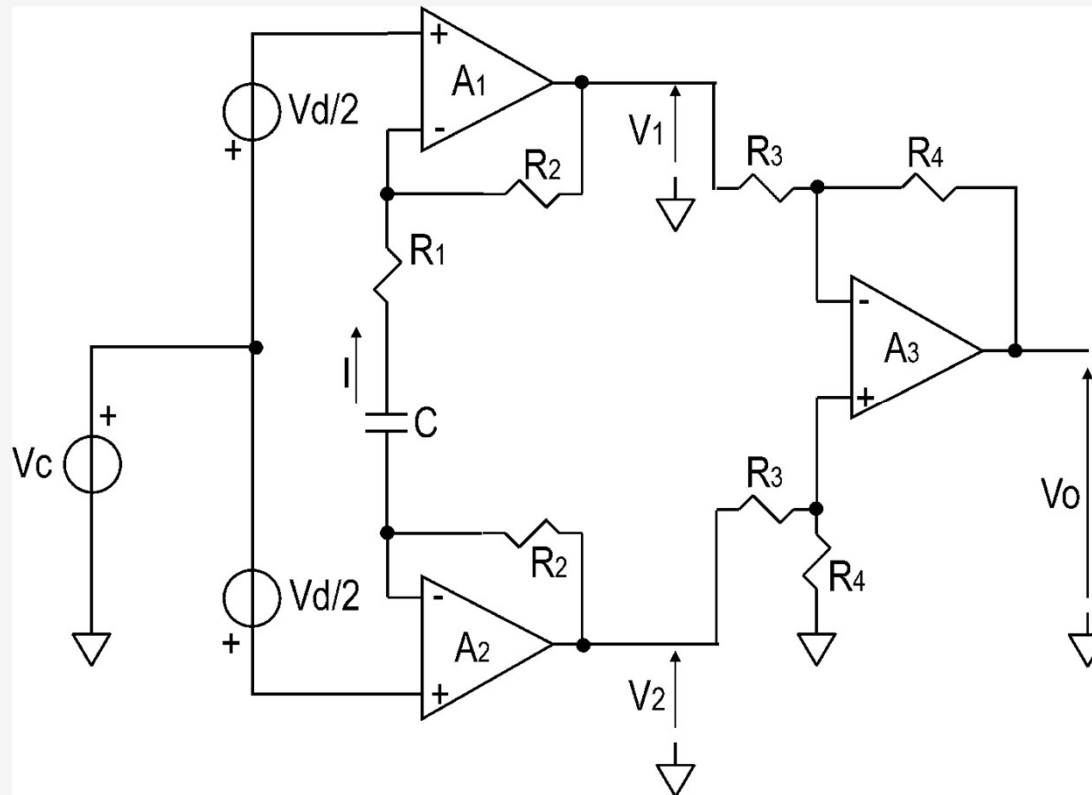
$$I = \frac{V_d}{R_1} \quad V_1 = V_c - \left(1 + \frac{2R_2}{R_1}\right) \frac{V_d}{2} \quad V_2 = V_c + \left(1 + \frac{2R_2}{R_1}\right) \frac{V_d}{2} \quad V_o = \frac{R_4}{R_3} (V_2 - V_1)$$

Potiskivanje jednosmerne komponente  
diferencijalnog signala na ulazu pojačavača



$$V' = \left( V_c - \frac{V_d}{2} \right) \frac{sCR}{1 + sCR} \quad V'' = \left( V_c + \frac{V_d}{2} \right) \frac{sCR}{1 + sCR} \quad V_o = \frac{R_4}{R_3} \left( 1 + \frac{2R_2}{R_1} \right) \frac{sCR}{1 + sCR} V_d$$

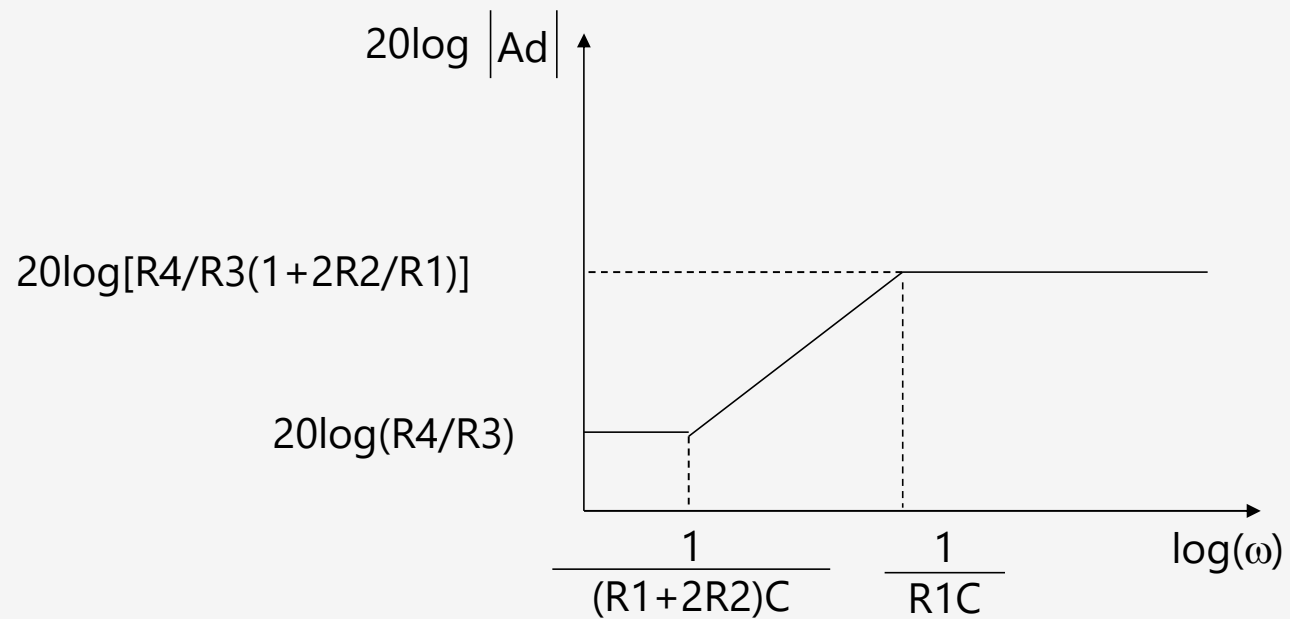
# Potiskivanje jednosmerne komponente diferencijalnog signala na ulazu pojačavača



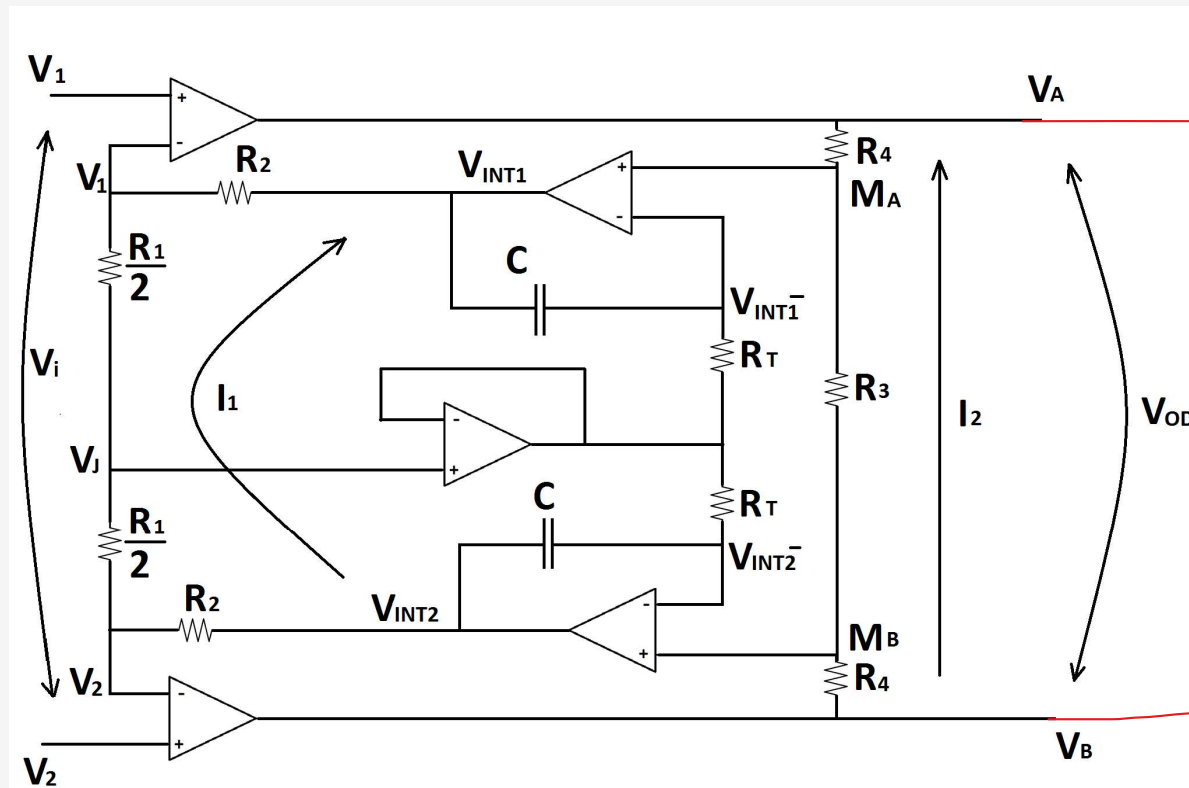
$$I = \frac{V_d}{R_1 + \frac{1}{sC}} \quad V_1 = V_c - \left(1 + \frac{2R_2}{R_1 + \frac{1}{sC}}\right) \frac{V_d}{2} \quad V_2 = V_c + \left(1 + \frac{2R_2}{R_1 + \frac{1}{sC}}\right) \frac{V_d}{2} \quad V_o = \frac{R_4}{R_3} \frac{1 + sC(R_1 + 2R_2)}{1 + sCR_1} V_d$$

## Frekvencijska karakteristika pojačavača

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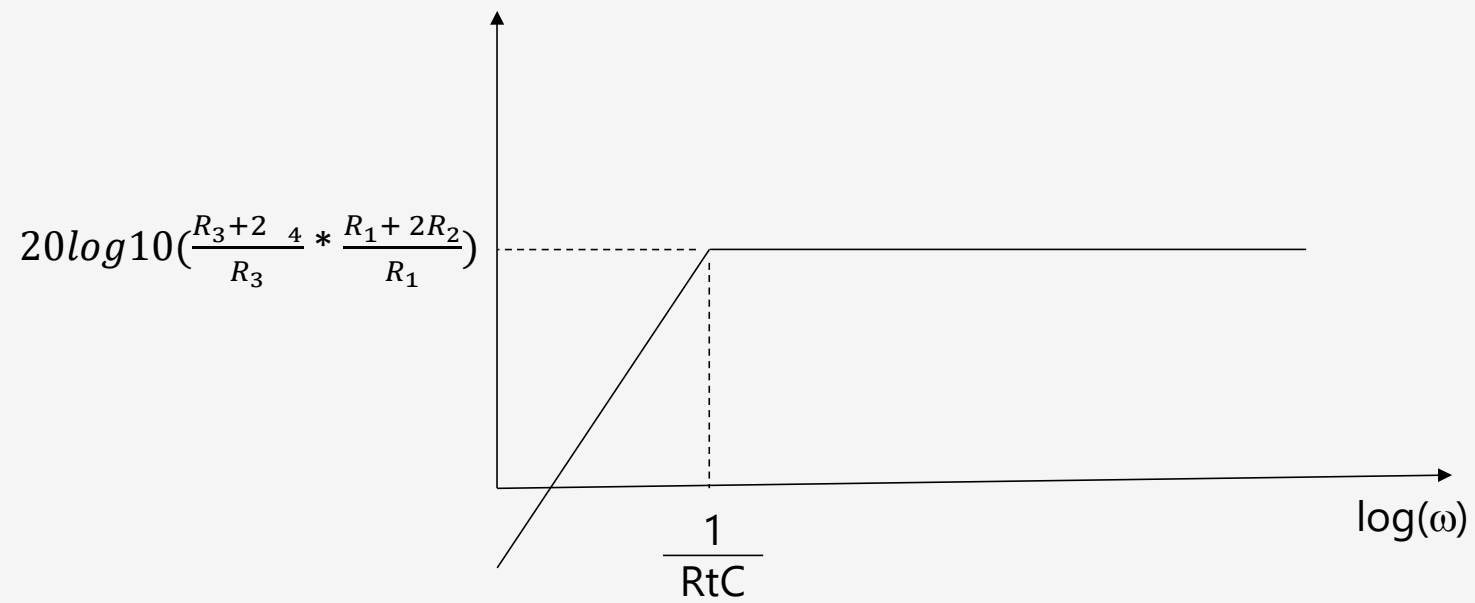
# Potiskivanje jednosmerne komponente diferencijalnog signala na ulazu pojačavača



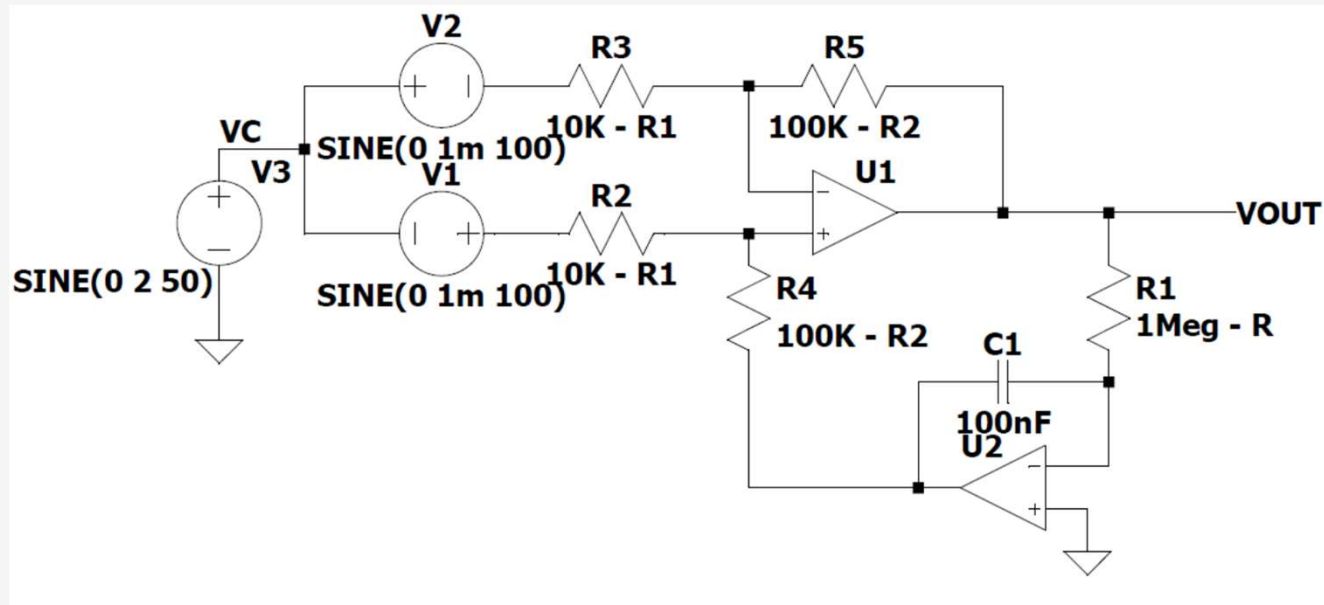
$$\frac{V_{OD}}{V_i}(s) = \frac{R_3 + 2R_4}{R_3} * \frac{R_1 + 2R_2}{R_1} * \frac{sRC_T}{1 + sCR_T}$$

## Frekvencijska karakteristika pojačavača

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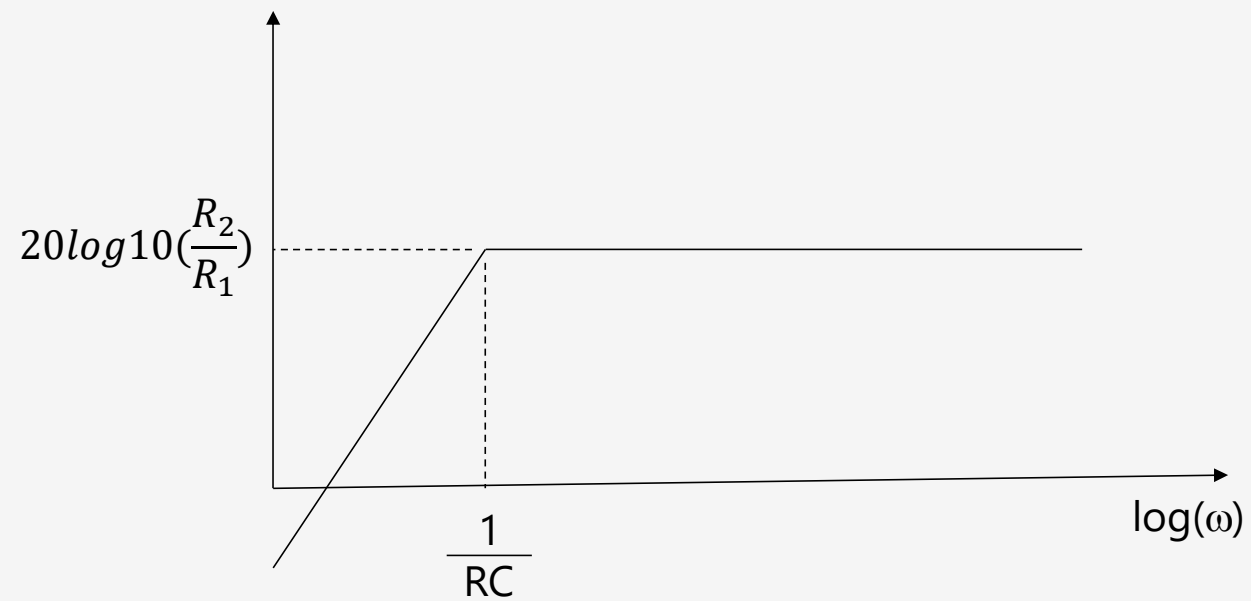
# Potiskivanje jednosmerne komponente diferencijalnog signala u diferencijalnom pojačavaču



$$\frac{V_o(s)}{V_i(s)} = \frac{R_2}{R_1} \frac{sRC}{1 + sRC}$$

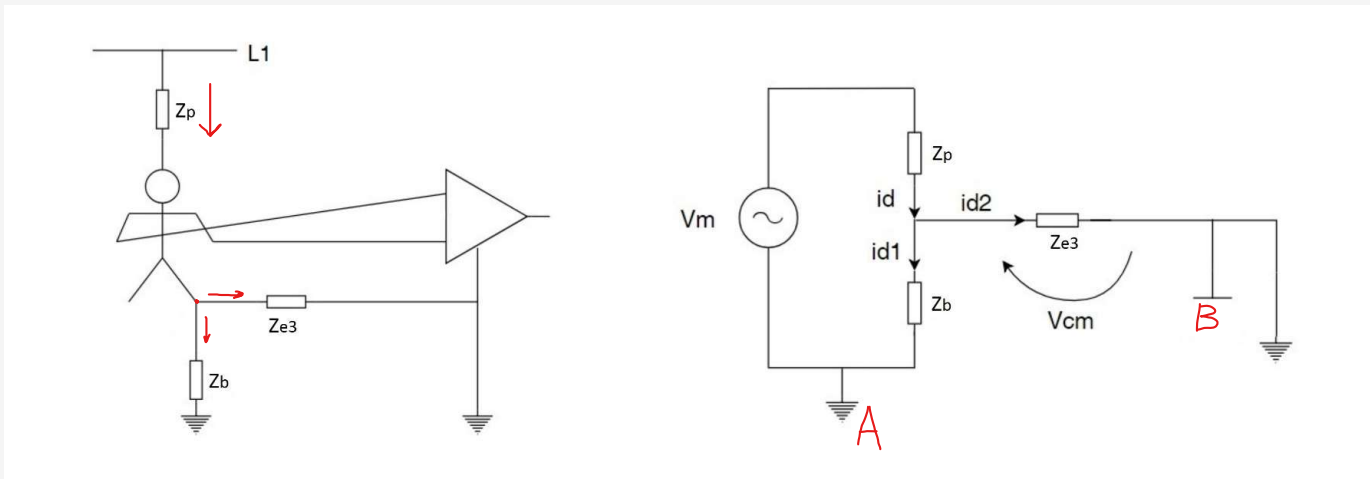
## Frekvencijska karakteristika pojačavača

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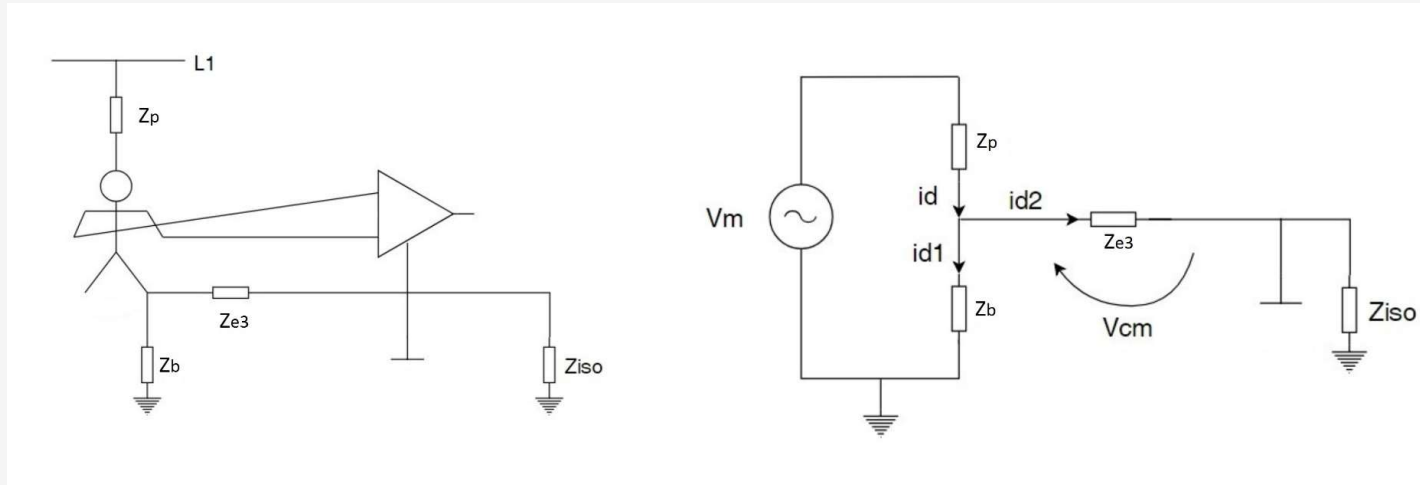
## Treća elektroda - uzemljena



$$Z_{e3} \ll Z_b \rightarrow i_{d2} \approx i_d$$

$$V_{cm} = Z_{e3} i_d$$

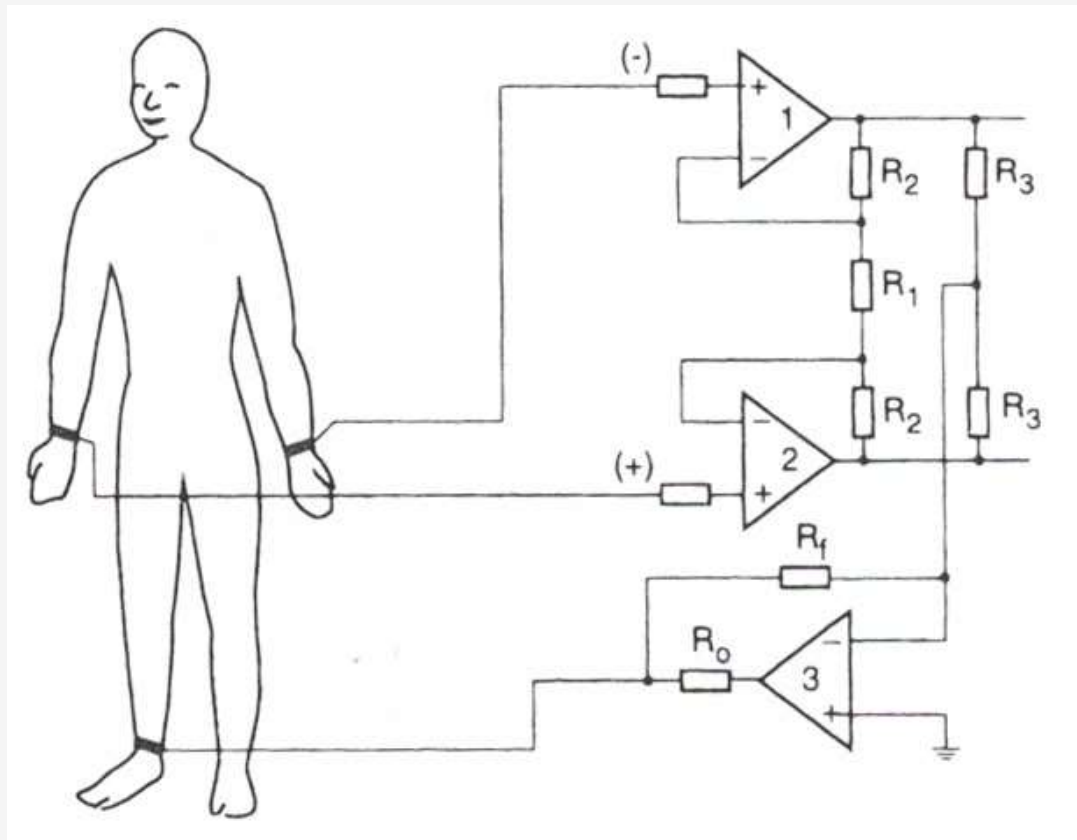
## Treća elektroda – spojena na masu izolovanog pojačavača



$$i_{d2} = i_d \frac{Z_b}{Z_b + Z_{e3} + Z_{iso}} \quad V_{cm} = i_{d2} Z_{e3}$$

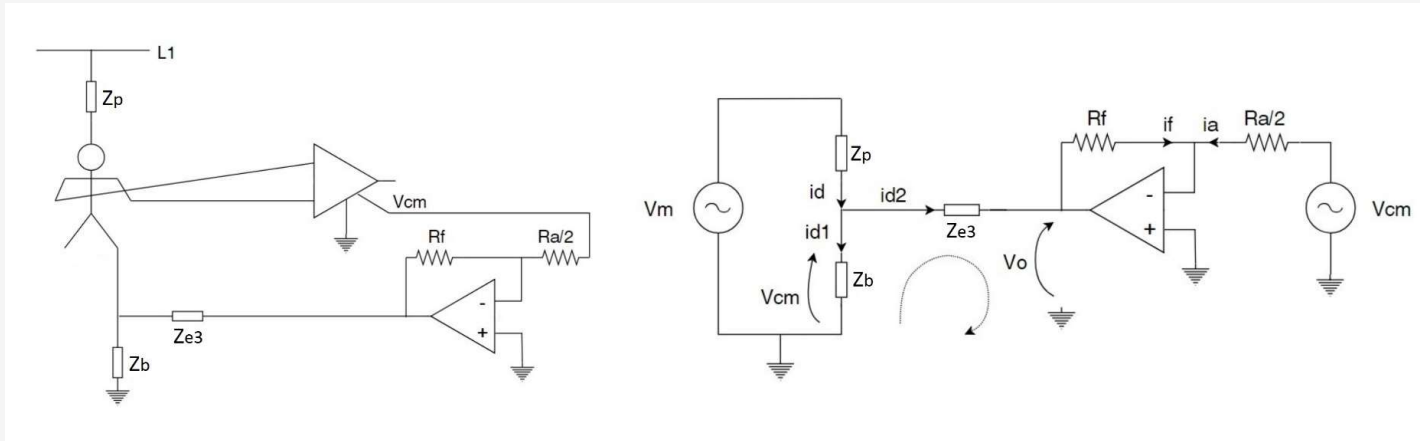
$$V_{cm} = \frac{Z_b}{Z_b + Z_{e3} + Z_{iso}} Z_{e3} i_d$$

## DRL kolo - Driven Right Leg



# DRL kolo kod uzemljenog pojačavača

## Driven Right Leg



$$\frac{2V_{cm}}{R_a} + \frac{V_o}{R_f} = 0$$

$$V_o = -\frac{2R_f}{R_a} V_{cm}$$

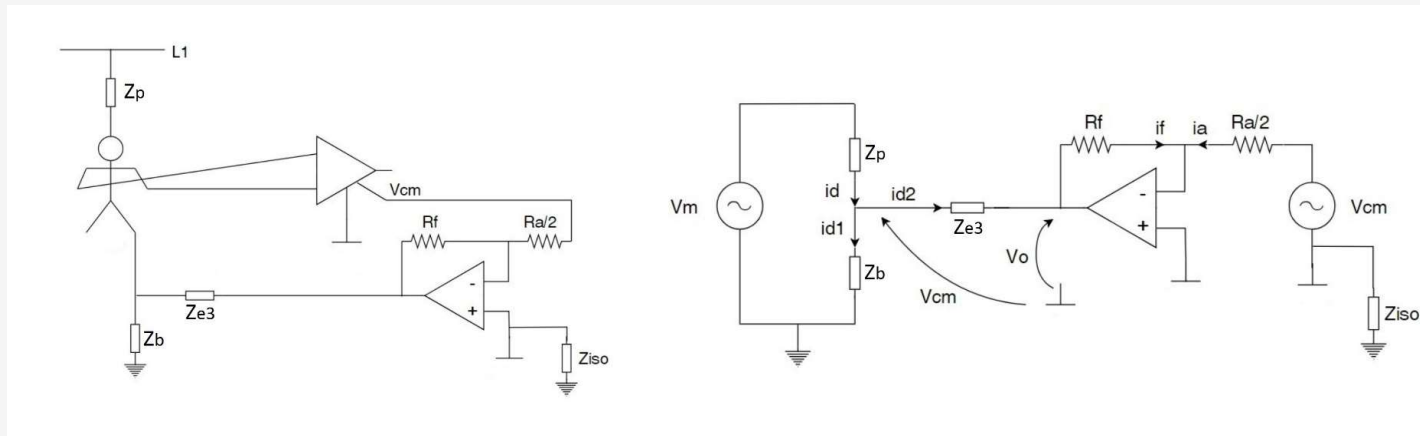
$$V_{cm} = V_o + Z_{e3} i_{d2}$$

$$Z_b \gg Z_{e3} \rightarrow i_{d2} \approx i_d$$

$$V_{cm} = V_o + Z_{e3} i_d \quad V_{cm} = -\frac{2R_f}{R_a} V_{cm} + Z_{e3} i_d \quad V_{cm} \left( 1 + \frac{2R_f}{R_a} \right) = Z_{e3} i_d \quad V_{cm} = \frac{1}{\left( 1 + \frac{2R_f}{R_a} \right)} Z_{e3} i_d$$

# DRL kolo kod izolovanog pojačavača

## Driven Right Leg



$$i_{d2} \approx i_d \frac{Z_b}{Z_b + Z_{e3} + Z_{iso}} \quad \frac{2V_{cm}}{R_a} + \frac{V_o}{R_f} = 0 \quad V_o = -\frac{2R_f}{R_a} V_{cm} \quad V_{cm} = V_o + Z_{e3} i_{d2}$$

$$V_{cm} = -\frac{2R_f}{R_a} V_{cm} + Z_{e3} i_{d2} \quad V_{cm} = \frac{Z_{e3}}{\left(1 + \frac{2R_f}{R_a}\right)} i_{d2} \quad V_{cm} = \frac{1}{\left(1 + \frac{2R_f}{R_a}\right)} \frac{Z_b}{Z_b + Z_{e3} + Z_{iso}} Z_{e3} i_d$$

# Komercijalni pojačavači – AD8232 Analog Devices

## FEATURES

Fully integrated single-lead ECG front end  
Low supply current: 170  $\mu$ A (typical)  
Common-mode rejection ratio: 80 dB (dc to 60 Hz)  
Two or three electrode configurations  
High signal gain ( $G = 100$ ) with dc blocking capabilities  
2-pole adjustable high-pass filter  
Accepts up to  $\pm 300$  mV of half cell potential  
Fast restore feature improves filter settling  
Uncommitted op amp  
3-pole adjustable low-pass filter with adjustable gain  
Leads off detection: ac or dc options  
Integrated right leg drive (RLD) amplifier  
Single-supply operation: 2.0 V to 3.5 V  
Integrated reference buffer generates virtual ground  
Rail-to-rail output  
Internal RFI filter  
8 kV HBM ESD rating  
Shutdown pin  
20-lead, 4 mm  $\times$  4 mm LFCSP and LFCSP\_SS package  
Qualified for automotive applications

## APPLICATIONS

Fitness and activity heart rate monitors  
Portable ECG  
Remote health monitors  
Gaming peripherals  
Biopotential signal acquisition

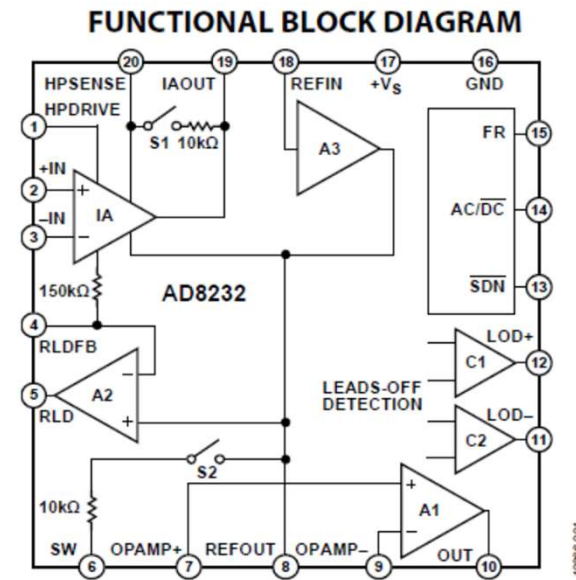


Figure 1.

## Komercijalni pojačavači – AD8232 Analog Devices

