Fakultet elektrotehnike i računarstva
Zavod za elektroniku, mikroelektroniku, računalne i inteligentne sustave

Elektronika 2

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4. Frekvencijski odziv pojačala

Frekvencijski odziv

Pod utjecajem reaktancija → prijenosne funkcije pojačala su kompleksni brojevi

Frekvencijski odziv – odziv pojačala na sinusne signale različitih frekvencija

Uz linearni rad pojačala

$$u_{ul} = U_{ulm} \sin \omega t \qquad u_{iz} = U_{izm} \sin\left(\omega t + \phi\right)$$

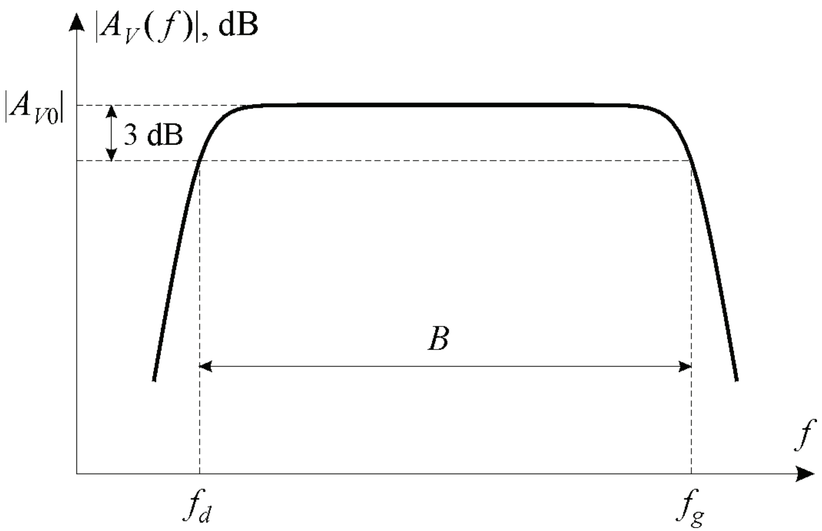
za svaku frekvenciju f određuje se amplituda i faza

$$\left|A_V(f)\right| = \frac{U_{izm}}{U_{ulm}} \qquad \measuredangle A_V(f) = \phi$$

naponsko pojačanje → kompleksni broj $A_V(f) = \left|A_V(f)\right| \exp(j\phi)$

Grafički prikaz frekvencijskog odziva → frekvencijska karakteristika

Amplitudna frekvencijska karakteristika izmjeničnog pojačala



granične frekvencije – pad pojačanja na

$A_{V0}/\sqrt{2}$ ili za 3 dB

$f_d \rightarrow$ donja granična frekvencija

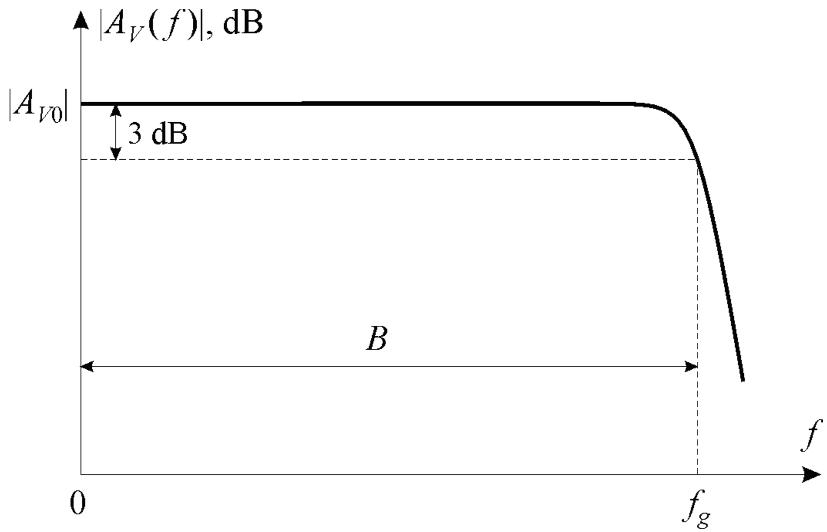
$f_g \rightarrow$ gornja granična frekvencija

$f_d < f < f_g \rightarrow$ područje srednjih frekvencija

pojačanje se smanjuje u području niskih frekvencija i u području visokih frekvencija

$B = f_g - f_d \rightarrow$ širina frekvencijskog pojasa

Amplitudna frekvencijska karakteristika istosmjernog pojačala



nema donje granične frekvencije – $f_d \rightarrow 0$

Polovi i nule prijenosne funkcije

Opći oblik prijenosne funkcije

$$A(s) = \frac{a_m s^m + a_{m-1} s^{m-1} + \cdots + a_0}{b_n s^n + b_{n-1} s^{n-1} + \cdots + b_0}$$

a_i, b_i $\rightarrow$ realni brojevi, $m \le n$

Određivanjem korijena

$$A(s) = \frac{a_0}{b_0} \frac{(1 + s/\omega_{z1})(1 + s/\omega_{z2}) \cdots (1 + s/\omega_{zm})}{(1 + s/\omega_{p1})(1 + s/\omega_{p2}) \cdots (1 + s/\omega_{pn})}$$

korijeni polinoma u brojniku $s = -\omega_{zi}$ $\rightarrow$ nule prijenosne funkcije

korijeni polinoma u nazivniku $s = -\omega_{pi}$ $\rightarrow$ polovi prijenosne funkcije

broj polova n $\rightarrow$ red prijenosne funkcije

Bodeov dijagram

Bodeov dijagram - dva grafa: amplitudna i fazna karakteristika u ovisnosti o frekvenciji

Crta se:

- amplituda - u decibelima,
- faza - u stupnjevima,
- frekvencija - u logaritamskom mjerilu.

Prijenosna funkcija → produkti i kvocijenti osnovnih članova

Bodeov dijagram:

- grafičko zbrajanje osnovnih članova
- frekvencijske karakteristike realnih pojačala dobro se aproksimiraju izlomljenim pravcima

Osnovni član – konstanta

Dio prijenosne neovisan o frekvenciji

$$A(j\omega) = \pm A_0$$

Amplituda

$$|A| = 20\log A_0,\ \text{dB}$$

Faza

$$\phi = 0^\circ \quad \text{za} \quad A(j\omega) = +A_0$$

$$\phi = -180^\circ \quad \text{za} \quad A(j\omega) = -A_0$$

Osnovni član – nula na frekvenciji 0

$$A(j\omega) = j\omega / \omega_1$$

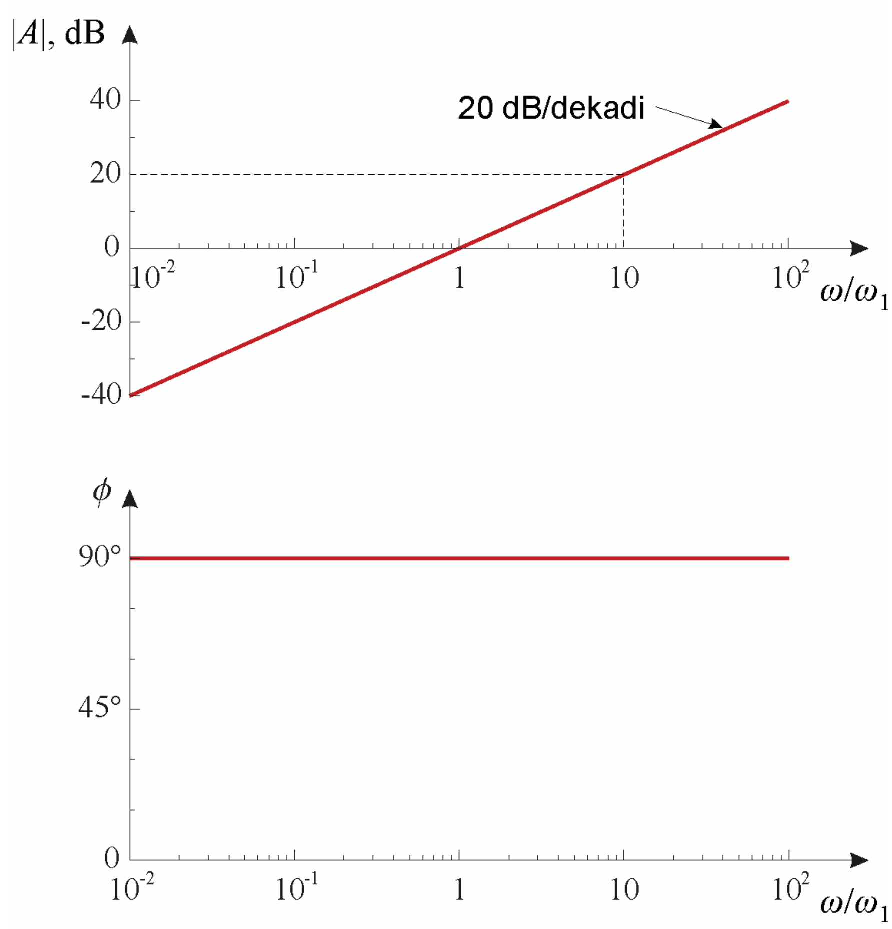
Amplituda

$$|A(j\omega)| = 20\log(\omega/\omega_1),\ \text{dB}$$

porast → + 20 dB/dekadi

Faza

$$\phi = \text{arctg}\left(\frac{\omega/\omega_1}{0}\right) = \text{arctg}(\infty) = 90°$$



Osnovni član – pol na frekvenciji 0

$$A(j\omega) = \frac{1}{j\omega/\omega_1}$$

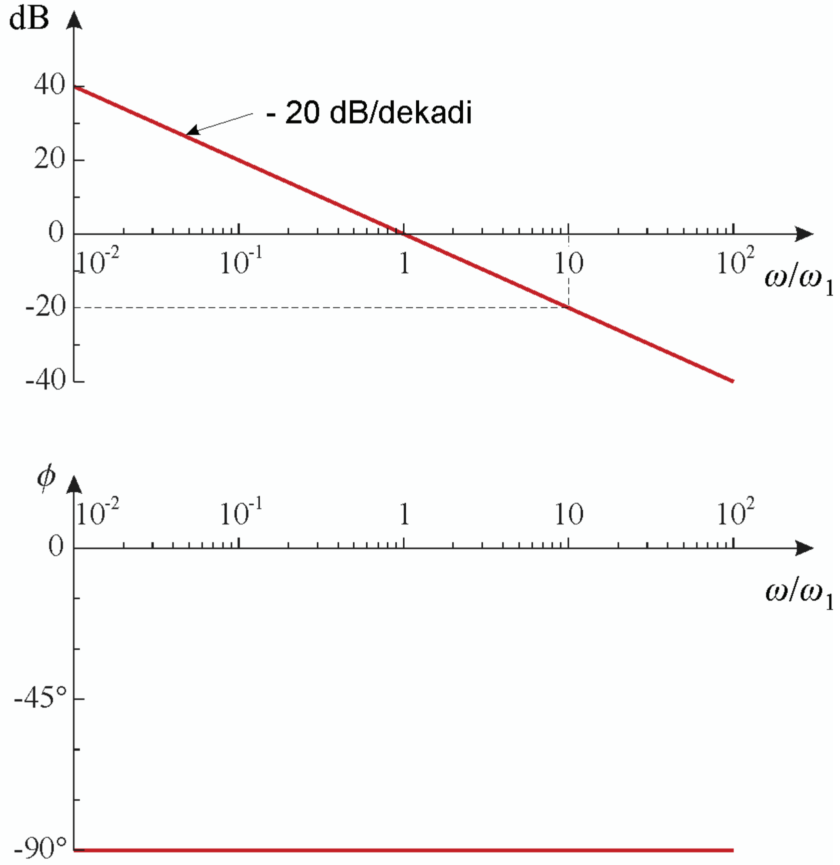
Amplituda

$$\left|A(j\omega)\right| = 20\log\left(1\right) - 20\log\left(\omega/\omega_1\right) =$$
$$= -20\log\left(\omega/\omega_1\right),\ \mathrm{dB}$$

pad → - 20 dB/dekadi

Faza

$$\phi = 0° - \mathrm{arctg}\left(\frac{\omega/\omega_1}{0}\right) =$$
$$= -\mathrm{arctg}\left(\infty\right) = -90°$$



Osnovni član – nula na frekvenciji ω_1 (1)

$$A(j\omega) = 1 + j\omega / \omega_1$$

Amplituda

$$\left|A(j\omega)\right| = \sqrt{1 + \left(\omega / \omega_1\right)^2}$$

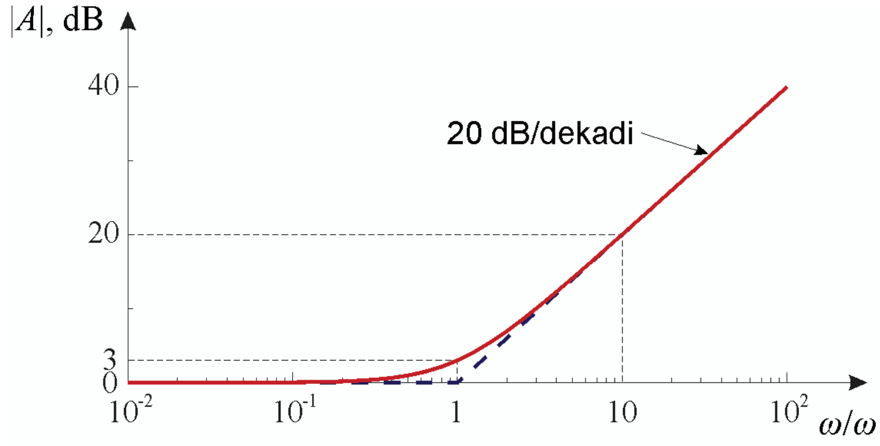
u decibelima

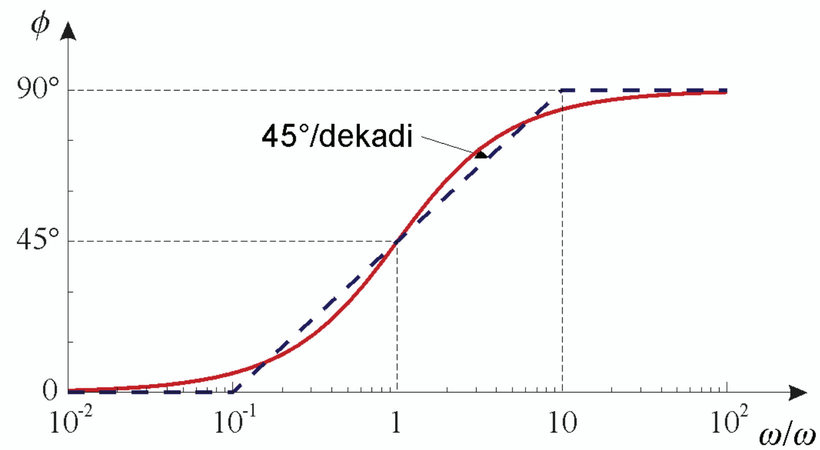
$$\left|A(j\omega)\right| = 20 \log \sqrt{1 + \left(\omega / \omega_1\right)^2}, \text{ dB}$$

za $\omega << \omega_1$ $\quad \left|A\right| \approx 20 \log(1) = 0, \text{ dB}$

za $\omega >> \omega_1$ $\quad \left|A\right| \approx 20 \log\left(\omega / \omega_1\right), \text{ dB}$

za $\omega = \omega_1$ $\quad \left|A\right| = 20 \log \sqrt{2} = 3 \text{ dB}$





Osnovni član – nula na frekvenciji ω_1 (2)

$$A(j\omega) = 1 + j\omega/\omega_1$$

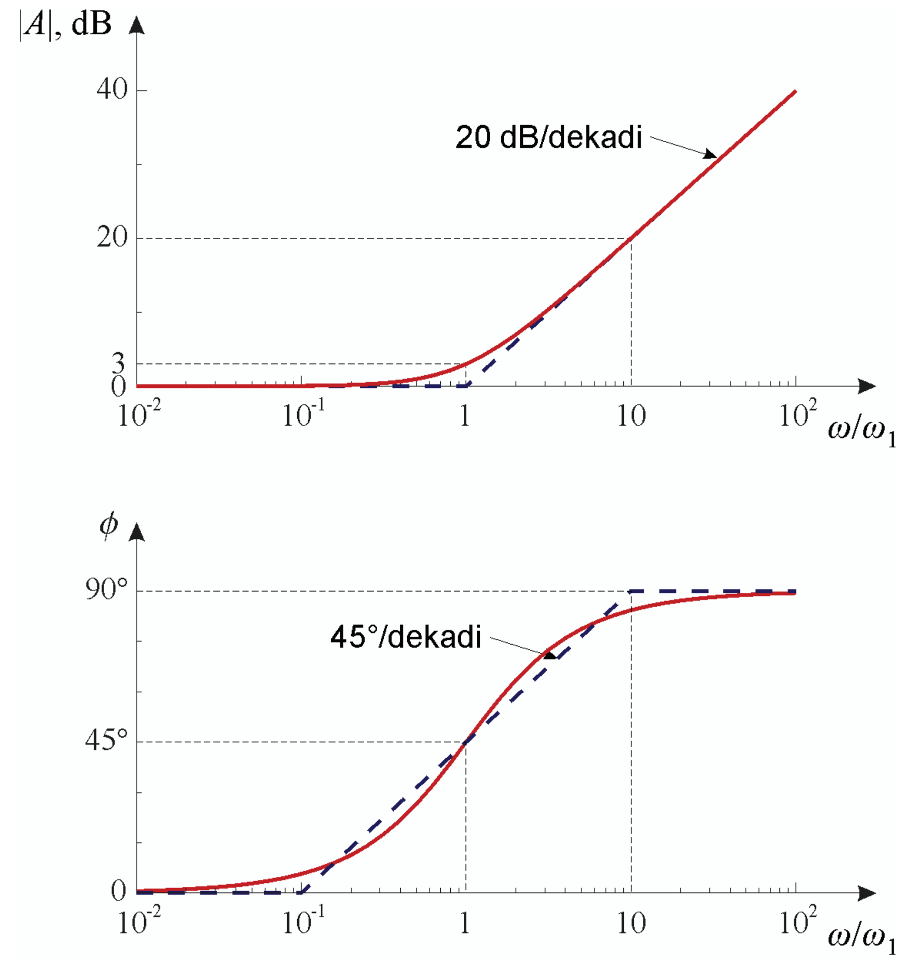
Faza

$$\phi = \operatorname{arc\,tg}\left(\omega/\omega_1\right)$$

za $\omega << \omega_1$ $\quad \phi \approx 0°$

za $\omega >> \omega_1$ $\quad \phi \approx 90°$

za $\omega = \omega_1$ $\quad \phi = 45°$



Osnovni član – pol na frekvenciji ω_1 (1)

$$A(j\omega) = \frac{1}{1 + j\omega/\omega_1}$$

Amplituda

$$|A(j\omega)| = \frac{1}{\sqrt{1 + (\omega/\omega_1)^2}}$$

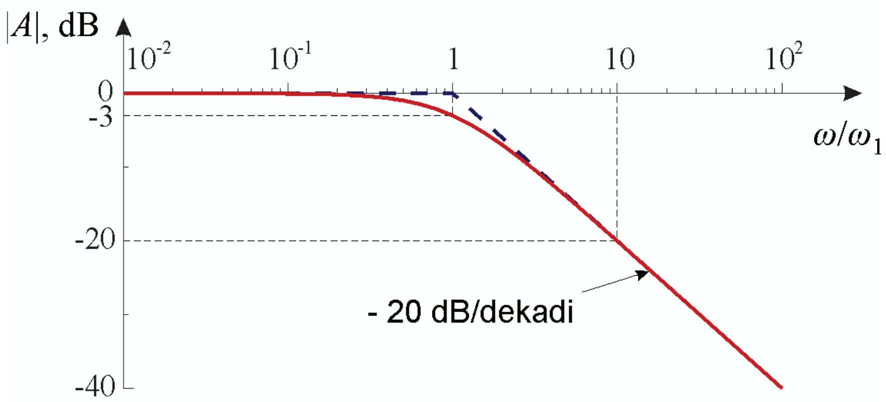
u decibelima

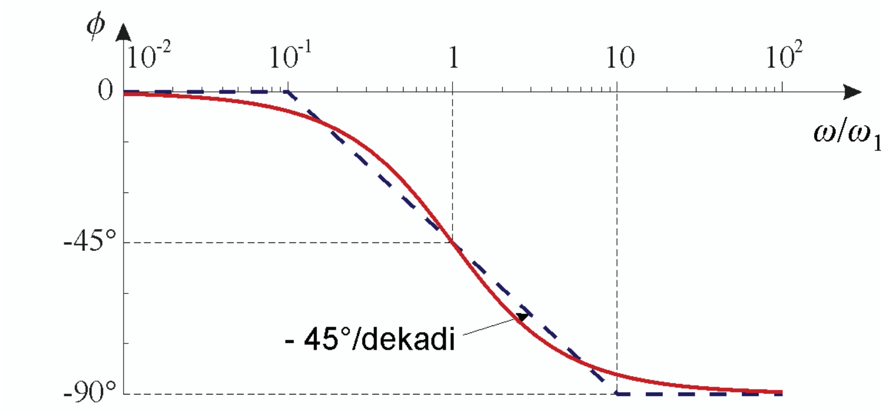
$$|A(j\omega)| = -20\log\sqrt{1 + (\omega/\omega_1)^2},\ \mathrm{dB}$$

za $\omega << \omega_1$ $\quad |A| \approx -20\log(1) = 0,\ \mathrm{dB}$

za $\omega >> \omega_1$ $\quad |A| \approx -20\log(\omega/\omega_1),\ \mathrm{dB}$

za $\omega = \omega_1$ $\quad |A| = -20\log\sqrt{2} = -3\ \mathrm{dB}$





Osnovni član – pol na frekvenciji ω_1 (2)

$$A(j\omega) = \frac{1}{1 + j\omega/\omega_1}$$

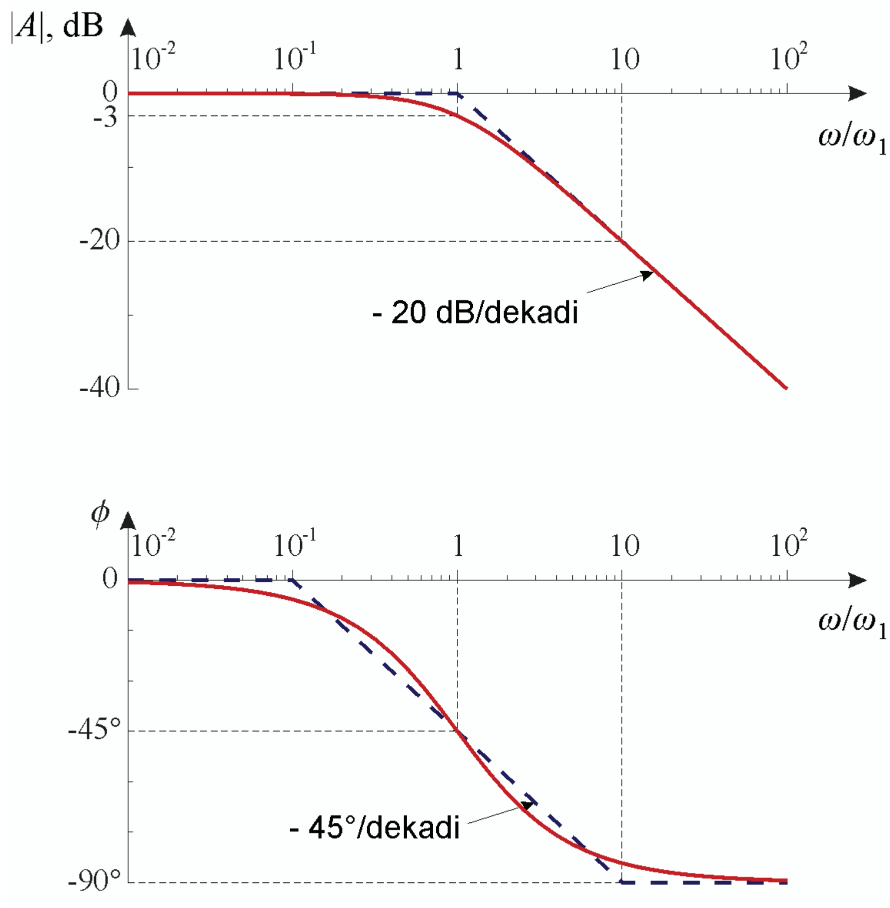
Faza

$$\phi = -\operatorname{arc\,tg}\left(\omega/\omega_1\right)$$

za $\omega << \omega_1$ $\qquad \phi \approx 0°$

za $\omega >> \omega_1$ $\qquad \phi \approx -90°$

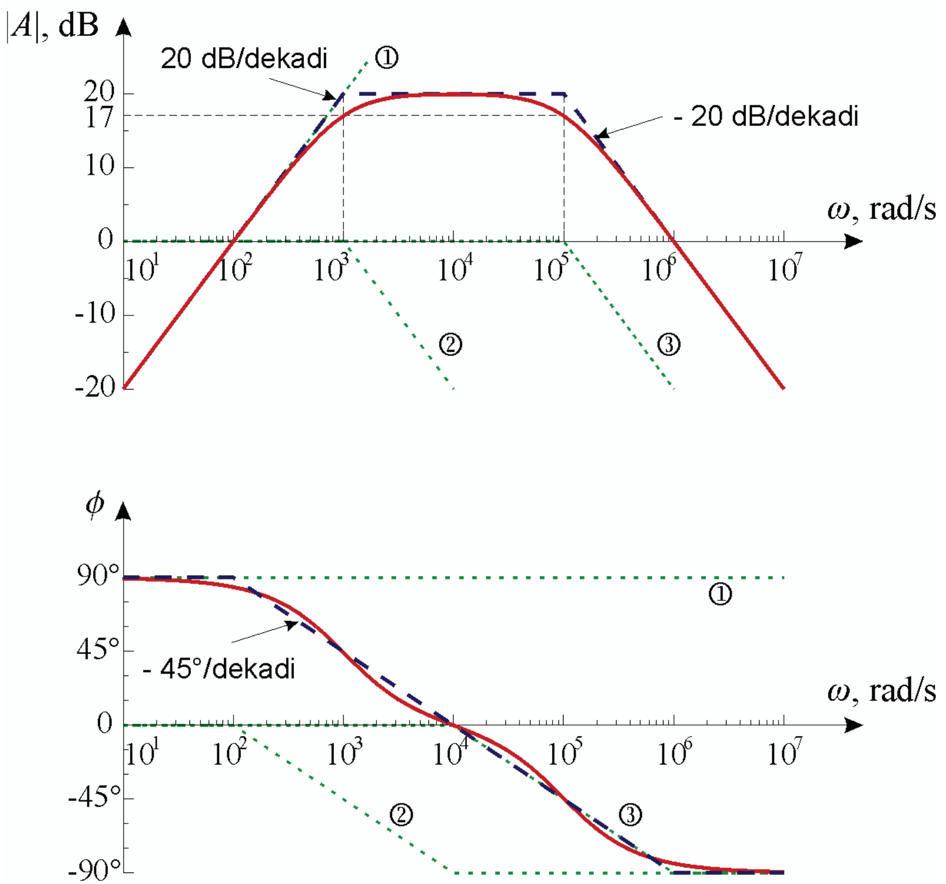
za $\omega = \omega_1$ $\qquad \phi = -45°$



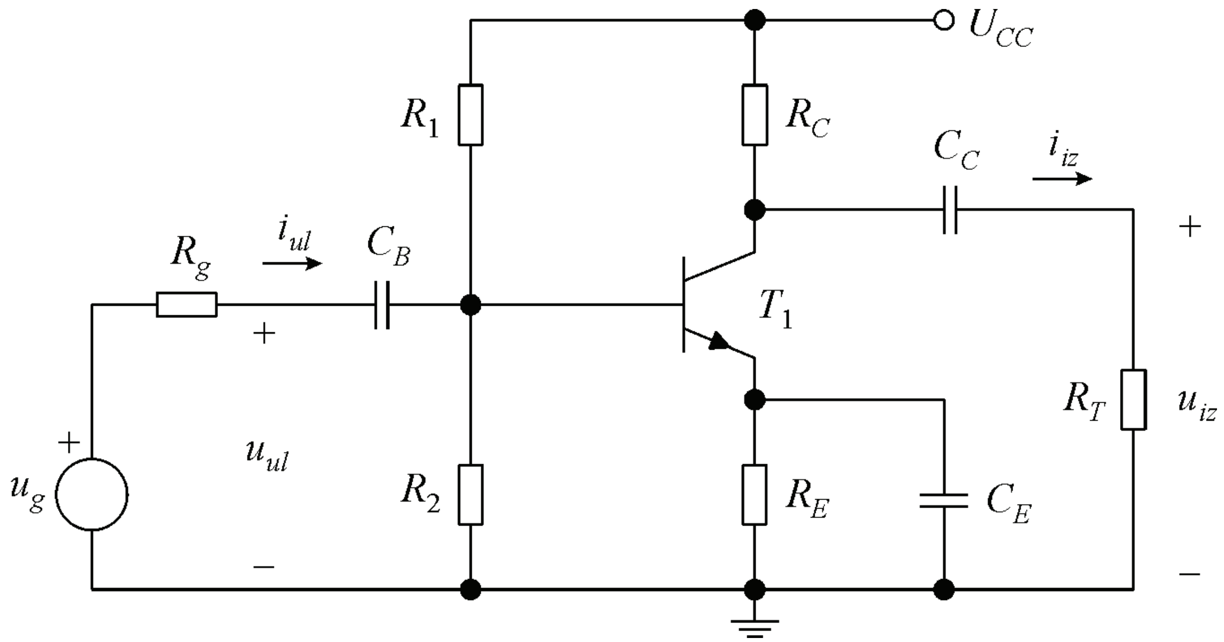
Primjer 4.1

Nacrtati Bodeov dijagram prijenosne funkcije

$$A(j\omega) = 10^6 \frac{j\omega}{(10^3 + j\omega)(10^5 + j\omega)}$$



Spoj zajedničkog emitera na niskim frekvencijama



Uključenje kapaciteta u dinamičku analizu

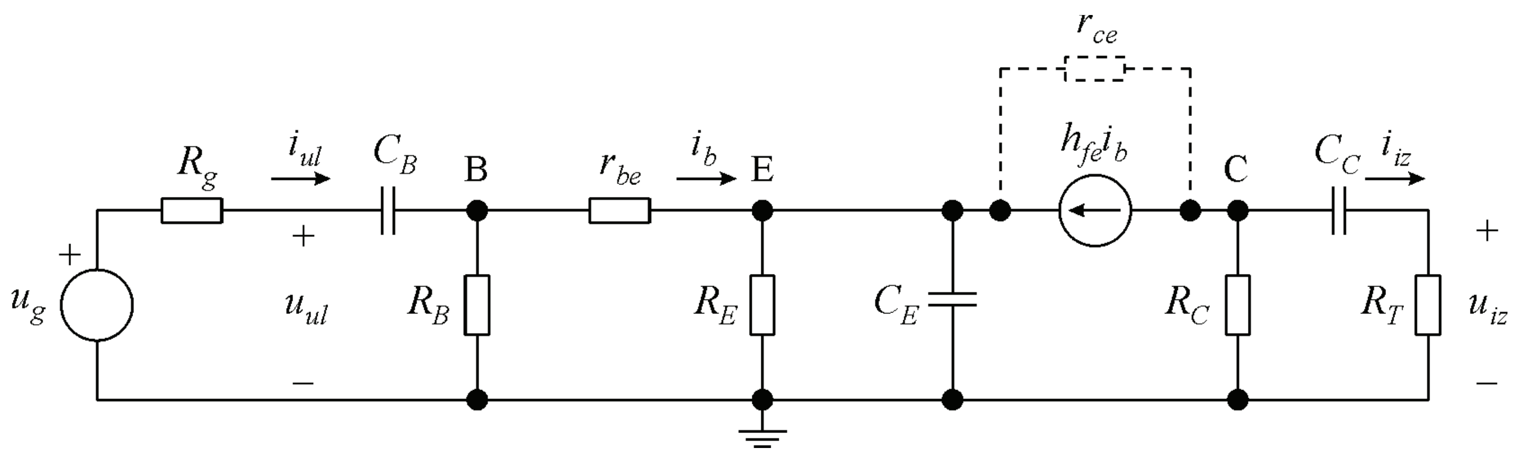
Dinamička analiza pojačala → za područja srednjih i niskih frekvencija

Impedancije kondenzatora $Z_C = 1/(j\omega C)$

Za svaki od kondenzatora treba ustanoviti na kojim frekvencijama smanjuje pojačanje

- C_B i C_C → vezni kondenzatori
  - – smanjenjem frekvencije predstavljaju sve veći otpor prolazu signala
  - – djeluju na niskim frekvencijama
- C_E → premosni kondenzator
  - – na višim frekvencijama kratko spaja emiter na masu → pojačalo radi bez degeneracije
  - – na niskim frekvencijama uključuje degenaraciju
  - – djeluje na niskim frekvencijama

Nadomjesna shema za niskofrekvencijsku analizu

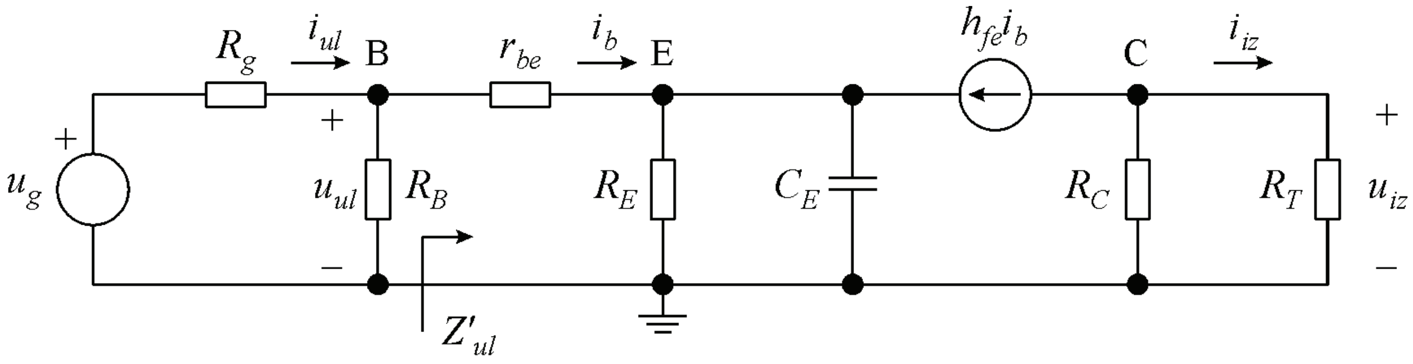


Istovremena analiza kompletne sheme → previše složena

Zbog tri kondenzatora → prijenosna funkcije pojačanja A_V ili A_I funkcija s tri pola → kompleksna jednadžba trećeg reda u nazivniku

Analiza pojačanja provodi se u dva koraka → posebno se određuje utjecaj C_E, a posebno utjecaj C_B i C_C

Utjecaj kondenzatora C_E (1)



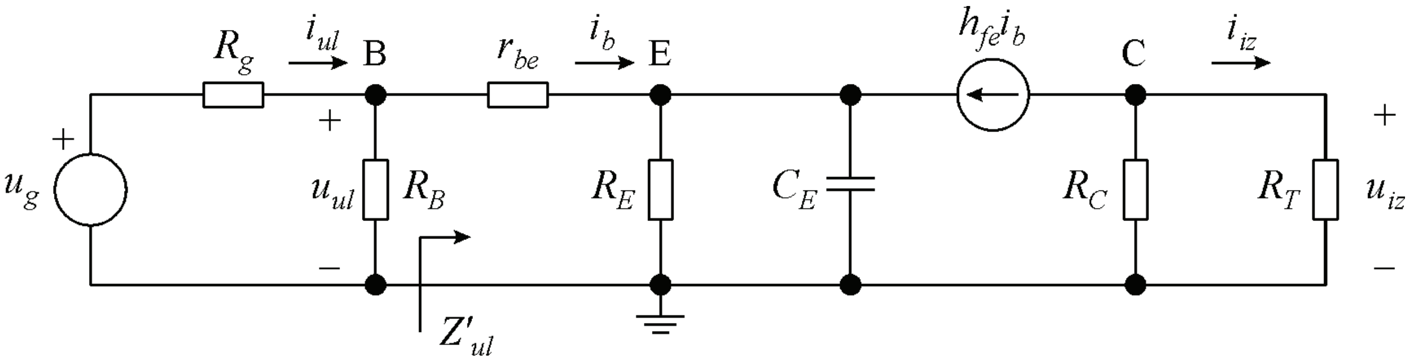
$$A_V = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{I_b}\frac{I_b}{U_{ul}}$$

$$\frac{U_{iz}}{I_b} = -h_{fe}\left(R_C \| R_T\right)$$

$$\frac{I_b}{U_{ul}} = \frac{1}{r_{be} + \left(1 + h_{fe}\right) Z_E}$$

$$Z_E = R_E \| \frac{1}{j\omega C_E} = \frac{R_E\left(1/ j\omega C_E\right)}{R_E + \left(1/ j\omega C_E\right)} = \frac{R_E}{1 + j\omega R_E C_E}$$

Utjecaj kondenzatora C_E (2)



$$\frac{I_b}{U_{ul}} = \frac{1}{r_{be} + \left(1 + h_{fe}\right)\dfrac{R_E}{1 + j\omega R_E C_E}} = \frac{1 + j\omega R_E C_E}{r_{be} + \left(1 + h_{fe}\right) R_E + j\omega r_{be} R_E C_E} =$$

$$= \frac{1}{r_{be} + \left(1 + h_{fe}\right) R_E} \frac{1 + j\omega R_E C_E}{1 + j\omega \left(\dfrac{r_{be}}{1 + h_{fe}} \Bigg\| R_E\right) C_E}$$

Naponsko pojačanje

$$A_V(j\omega) = \frac{U_{iz}}{U_{ul}} = A_{Vn} \frac{1 + j\omega / \omega_1}{1 + j\omega / \omega_2}$$

$$A_{Vn} = -h_{fe} \frac{R_C \,\|\, R_T}{r_{be} + \left(1 + h_{fe}\right) R_E}$$

Vremenske konstante

$$\tau_1 = \frac{1}{\omega_1} = R_E C_E$$

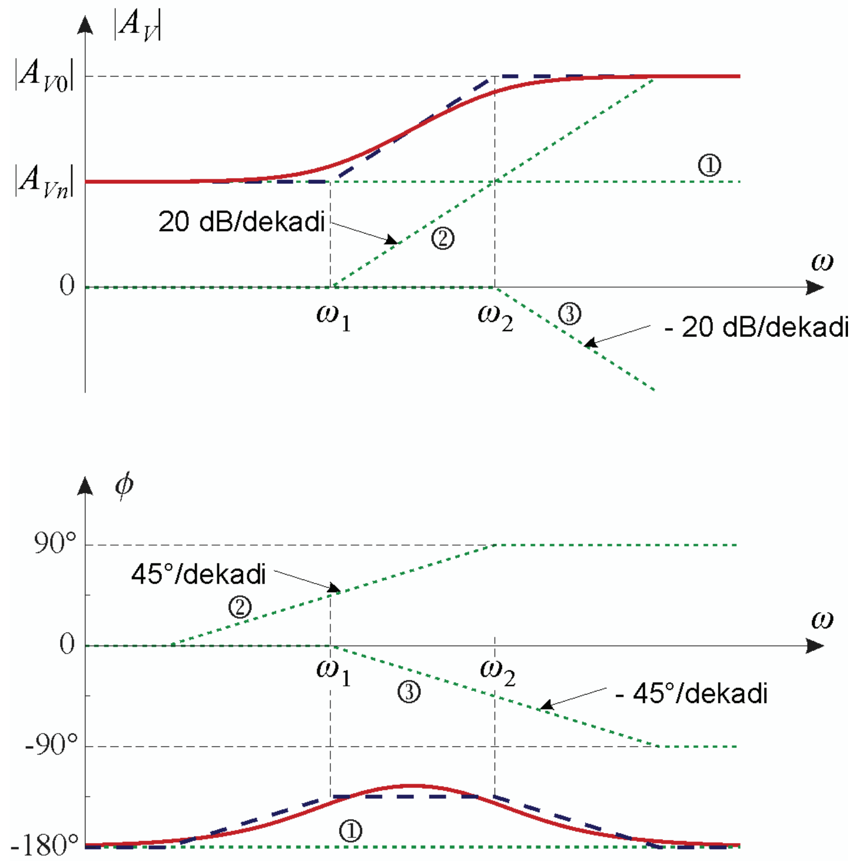
$$\tau_2 = \tau_E = \frac{1}{\omega_2} = \left(\frac{r_{be}}{1 + h_{fe}} \,\Big\|\, R_E \right) C_E$$

Pojačanje na srednjim frekvencijama

$$A_{V0} = \lim_{\omega \to \infty} A_V(j\omega) = A_{Vn} \frac{\omega_2}{\omega_1} = A_{Vn} \frac{\tau_1}{\tau_2} = -h_{fe} \frac{R_C \,\|\, R_T}{r_{be}}$$

Bodeov dijagram

$$A_V(j\omega) = A_{Vn} \cdot \left(1 + j\omega/\omega_1\right) \cdot \frac{1}{1 + j\omega/\omega_2}$$



Donja granična frekvencija

Definicija za $\omega = \omega_d \quad \rightarrow \quad |A_V| = |A_{V0}|/\sqrt{2}$

Za pojačanje $A_V(j\omega) = A_{Vn} \dfrac{1 + j\omega/\omega_1}{1 + j\omega/\omega_2}$

$$|A_V| = |A_{Vn}| \frac{\sqrt{1 + \left(\omega_d/\omega_1\right)^2}}{\sqrt{1 + \left(\omega_d/\omega_2\right)^2}} = \frac{|A_{V0}|}{\sqrt{2}} = \frac{|A_{Vn}|}{\sqrt{2}} \frac{\omega_2}{\omega_1} \quad \rightarrow \quad \omega_d = \sqrt{\omega_2^2 - 2\omega_1^2}$$

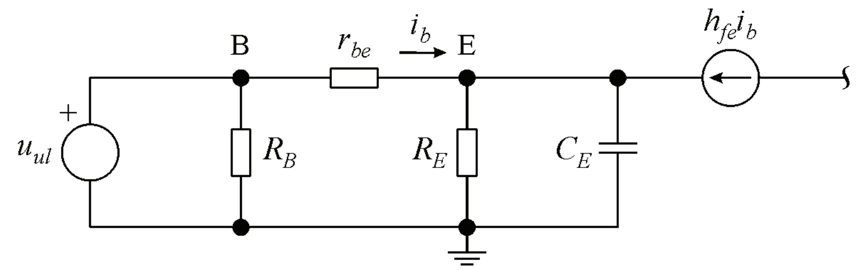
Za $\omega_2 >> \omega_1 \rightarrow \omega_d = \omega_2$

Uvjet za postojanje $\omega_d \quad \omega_2 > \sqrt{2}\,\omega_1 \quad \rightarrow \quad R_E > \left(\sqrt{2} - 1\right) \dfrac{r_{be}}{1 + h_{fe}}$

Vremenska konstanta τ_E

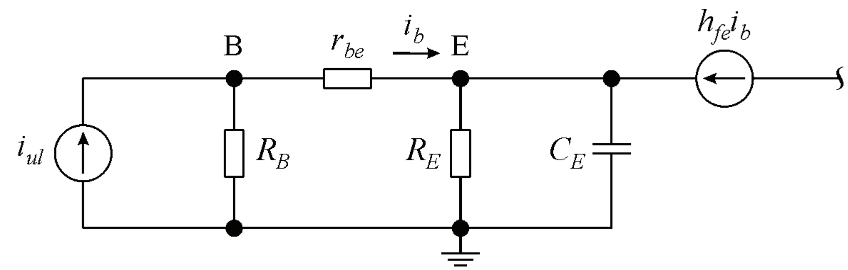
za naponsko pojačanje

$$\tau_E = \frac{1}{\omega_2} = \left(\frac{r_{be}}{1+h_{fe}} \middle\| R_E \right) C_E$$



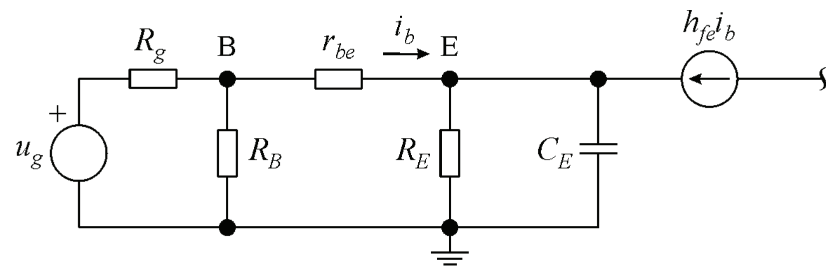
za strujno pojačanje

$$\tau_E = \frac{1}{\omega_2} = \left(\frac{r_{be}+R_B}{1+h_{fe}} \middle\| R_E \right) C_E$$

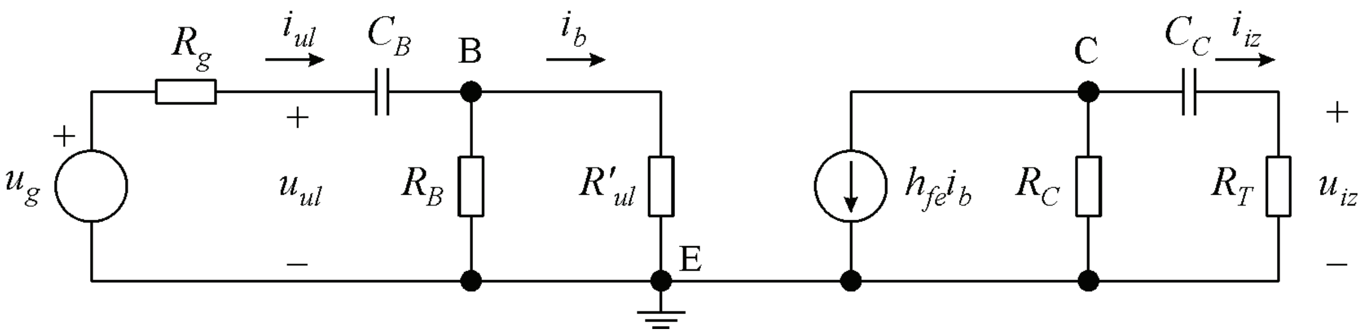


za konačni R_g

$$\tau_E = \frac{1}{\omega_2} = \left(\frac{r_{be}+R_g \| R_B}{1+h_{fe}} \middle\| R_E \right) C_E$$



Utjecaj kondenzatora C_B i C_C (1)

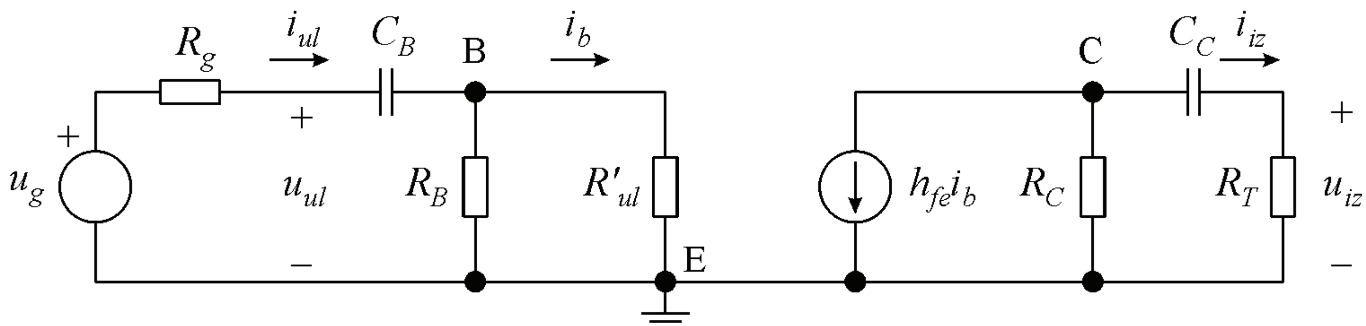


$$\text{za } \omega >> \omega_2 \quad \rightarrow \quad R'_{ul} = \frac{U_{ul}}{I_b} = r_{be}$$

$$\text{za } \omega << \omega_1 \quad \rightarrow \quad R'_{ul} = \frac{U_{ul}}{I_b} = r_{be} + \left(1 + h_{fe}\right) R_E$$

$$A_V = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{I_b} \frac{I_b}{U_{ul}}$$

Utjecaj kondenzatora C_B i C_C (2)



$$\frac{U_{iz}}{I_b}=\frac{U_{iz}}{I_{iz}}\frac{I_{iz}}{I_b}=R_T\left(-h_{fe}\right)\frac{R_C}{R_C+\dfrac{1}{j\omega C_C}+R_T}=-h_{fe}\left(R_C\,\|\,R_T\right)\frac{j\omega\left(R_C+R_T\right)C_C}{1+j\omega\left(R_C+R_T\right)C_C}$$

$$\frac{I_b}{U_{ul}}=\frac{I_b}{I_{ul}}\frac{I_{ul}}{U_{ul}}=\frac{R_B}{R_B+R'_{ul}}\frac{1}{\dfrac{1}{j\omega C_B}+R_B\,\|\,R'_{ul}}=\frac{1}{R'_{ul}}\frac{j\omega\left(R_B\,\|\,R'_{ul}\right)C_B}{1+j\omega\left(R_B\,\|\,R'_{ul}\right)C_B}$$

Naponsko pojačanje

$$A_V(j\omega) = \frac{U_{iz}}{U_{ul}} = A_{V1} \frac{j\omega/\omega_3}{1 + j\omega/\omega_3} \frac{j\omega/\omega_4}{1 + j\omega/\omega_4}$$

Pojačanje $$A_{V1} = -h_{fe} \frac{R_C \| R_T}{R'_{ul}}$$

$$\text{za } \omega >> \omega_2 \quad \rightarrow \quad A_{V1} = A_{V0} = -h_{fe} \frac{R_C \| R_T}{r_{be}}$$

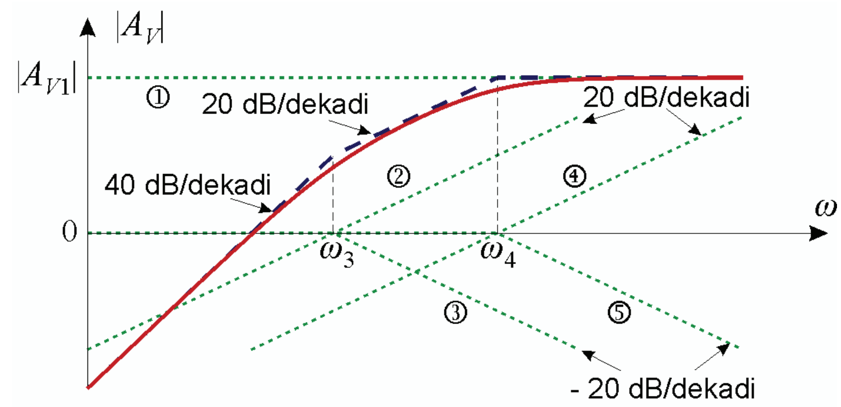
$$\text{za } \omega << \omega_1 \quad \rightarrow \quad A_{V1} = A_{Vn} = -h_{fe} \frac{R_C \| R_T}{r_{be} + \left(1 + h_{fe}\right) R_E}$$

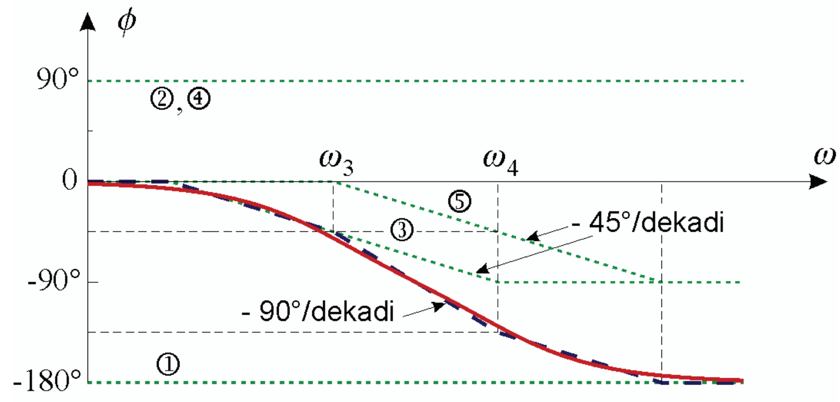
Vremenske konstante

$$\tau_3 = \tau_C = \frac{1}{\omega_3} = \left(R_C + R_T\right) C_C \qquad \tau_4 = \tau_B = \frac{1}{\omega_4} = \left(R_B \| R'_{ul}\right) C_B$$

Bodeov dijagram

$$A_V(j\omega) = A_{V1} \cdot \frac{j\omega}{\omega_3} \cdot \frac{1}{1 + j\omega/\omega_3} \cdot \frac{j\omega}{\omega_4} \cdot \frac{1}{1 + j\omega/\omega_4}$$





Donja granična frekvencija

Prijenosna funkcija $A_V(j\omega) = \dfrac{U_{iz}}{U_{ul}} = A_{V1} \dfrac{j\omega/\omega_3}{1+j\omega/\omega_3} \dfrac{j\omega/\omega_4}{1+j\omega/\omega_4}$

Uz $A_{V1} = A_{V0}$

$$|A_V| = |A_{V0}| \frac{\omega_d/\omega_3}{\sqrt{1+(\omega_d/\omega_3)^2}} \frac{\omega_d/\omega_4}{\sqrt{1+(\omega_d/\omega_4)^2}} = \frac{|A_{V0}|}{\sqrt{2}}$$

$$\omega_d^2 = \frac{\omega_3^2+\omega_4^2}{2} + \sqrt{\left(\frac{\omega_3^2+\omega_4^2}{2}\right)^2 + \omega_3^2\,\omega_4^2}$$

Za $\omega_4 >> \omega_3 \rightarrow \omega_d = \omega_4 \rightarrow \omega_4$ je dominantni pol

Za $\omega_4 = \omega_3 \quad \rightarrow \quad \omega_d = \sqrt{1+\sqrt{2}}\,\omega_4 = 1{,}55\,\omega_4$

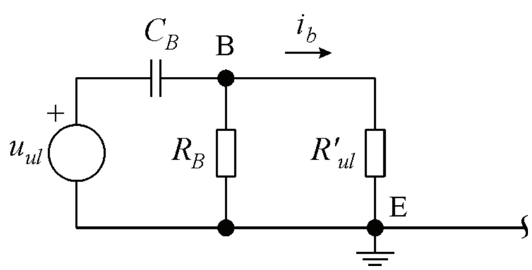
ω_d je viša od frekvencija ω_3 ili ω_4 ako je barem 4 puta viša od druge frekvencije $\rightarrow$ za $\omega_4 = 4\,\omega_3 \rightarrow \omega_d = 1{,}06\,\omega_4 \approx \omega_4$

Vremenske konstante τ_B i τ_C

$\tau_C = (R_C + R_T)\, C_C$ $\longrightarrow$ određuje se iz izlaznog kruga

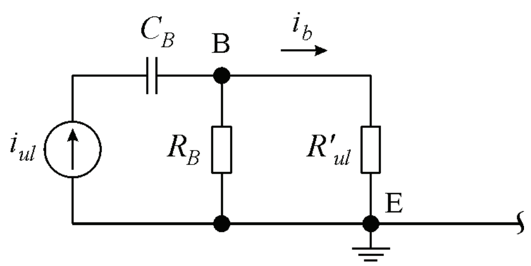
$\tau_B \longrightarrow$ ovisi o pojačanju

za naponsko pojačanje



$$\tau_B = \left(R_B \,\|\, R'_{ul}\right) C_B$$

za strujno pojačanje



$$\tau_B = \left(R_B \,\|\, R'_{ul} + \infty\right) C_B \rightarrow \infty$$

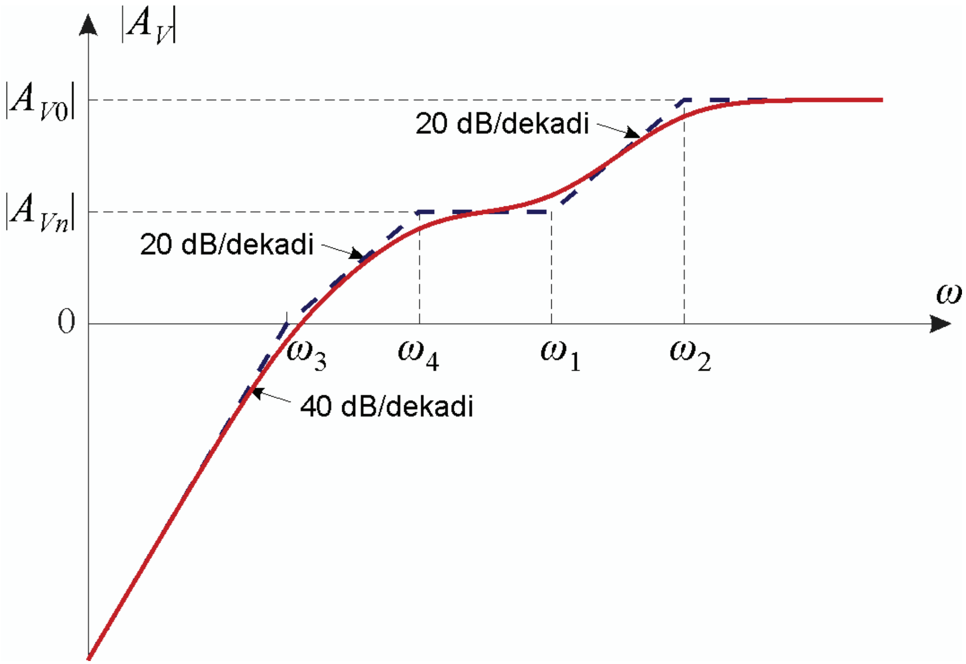
za konačni R_g

$$\tau_B = \left(R_B \,\|\, R'_{ul} + R_g\right) C_B$$

Ukupno djelovanje kondenzatora C_E, C_B i C_C (1)

za ω_1 i $\omega_2 > \omega_3$ i ω_4

$$A_V(j\omega) = \frac{U_{iz}}{U_{ul}} = A_{Vn} \frac{1 + j\omega/\omega_1}{1 + j\omega/\omega_2} \frac{j\omega/\omega_3}{1 + j\omega/\omega_3} \frac{j\omega/\omega_4}{1 + j\omega/\omega_4}$$



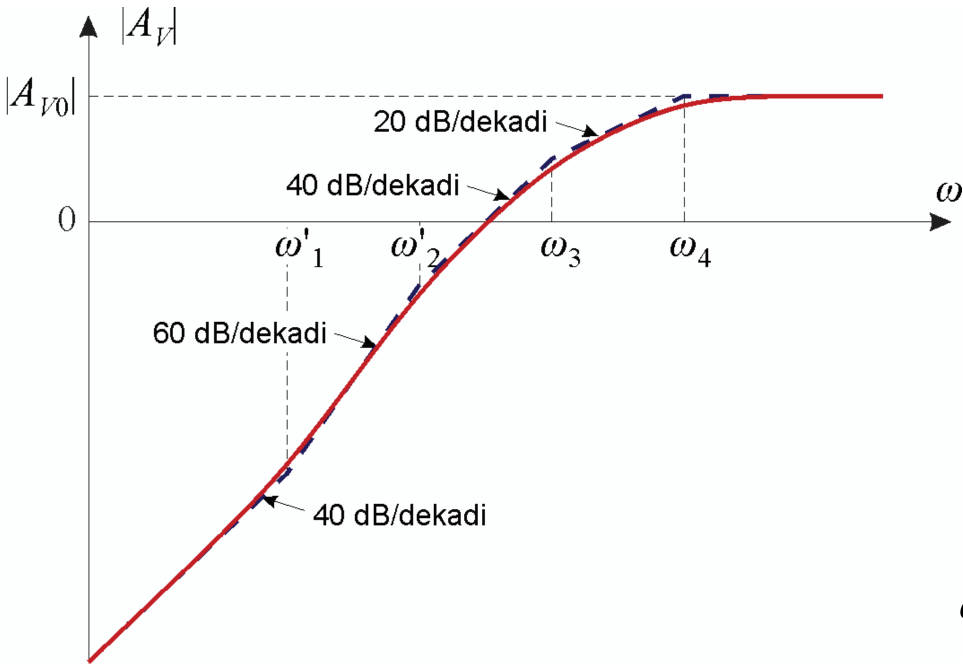
$$R'_{ul} = \frac{U_{ul}}{I_b} = r_{be} + \left(1 + h_{fe}\right) R_E$$

$$A_{V1} = A_{Vn}$$

$$\omega_d = \sqrt{\omega_2^2 - 2\omega_1^2}$$

Ukupno djelovanje kondenzatora C_E, C_B i C_C (2)

za ω_3 i $\omega_4 > \omega_1$ i ω_2



$$R'_{ul} = \frac{U_{ul}}{I_b} = r_{be}$$

$$A_{V1} = A_{V0}$$

$$\omega_d^2 = \frac{\omega_3^2 + \omega_4^2}{2} + \sqrt{\left(\frac{\omega_3^2 + \omega_4^2}{2}\right)^2 + \omega_3^2\,\omega_4^2}$$

Određivanje donje granične frekvencije

Na srednjim frekvencijama (svi se kondenzatori kratko spajaju)

$$A_{V0} = -h_{fe}\frac{R_C \| R_T}{r_{be}}$$

Vremenske konstante koje određuju pojedini kondenzatori (ostali se kondenzatori kratko spajaju)

$$\tau_B = \left(R_B \| r_{be}\right) C_B \qquad \tau_E = \left(\frac{r_{be}}{1+h_{fe}} \Bigg\| R_E\right) C_E \qquad \tau_C = \left(R_C + R_T\right) C_C$$

Donja granična frekvencija

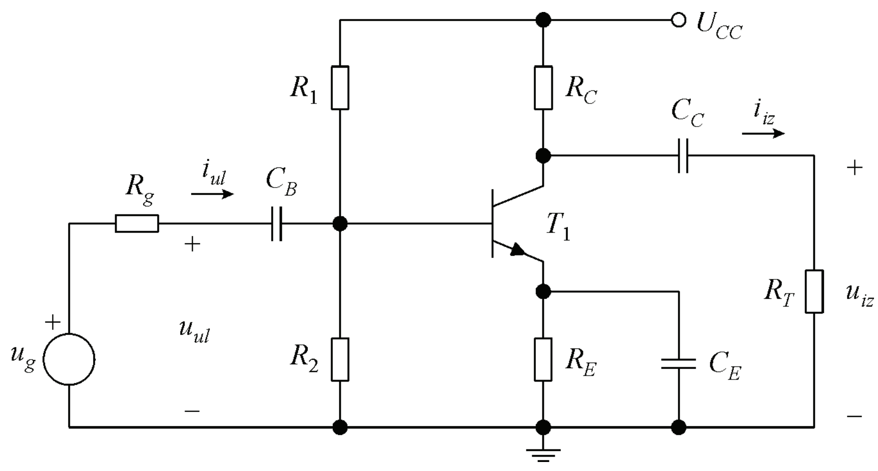
$$\omega_d = \max\left\{\omega_B,\ \omega_E,\ \omega_C\right\} = \max\left\{\frac{1}{\tau_B},\ \frac{1}{\tau_E},\ \frac{1}{\tau_C}\right\}$$

Uvjet → najviša frekvencija barem 4 puta viša od ostalih → dominantni pol

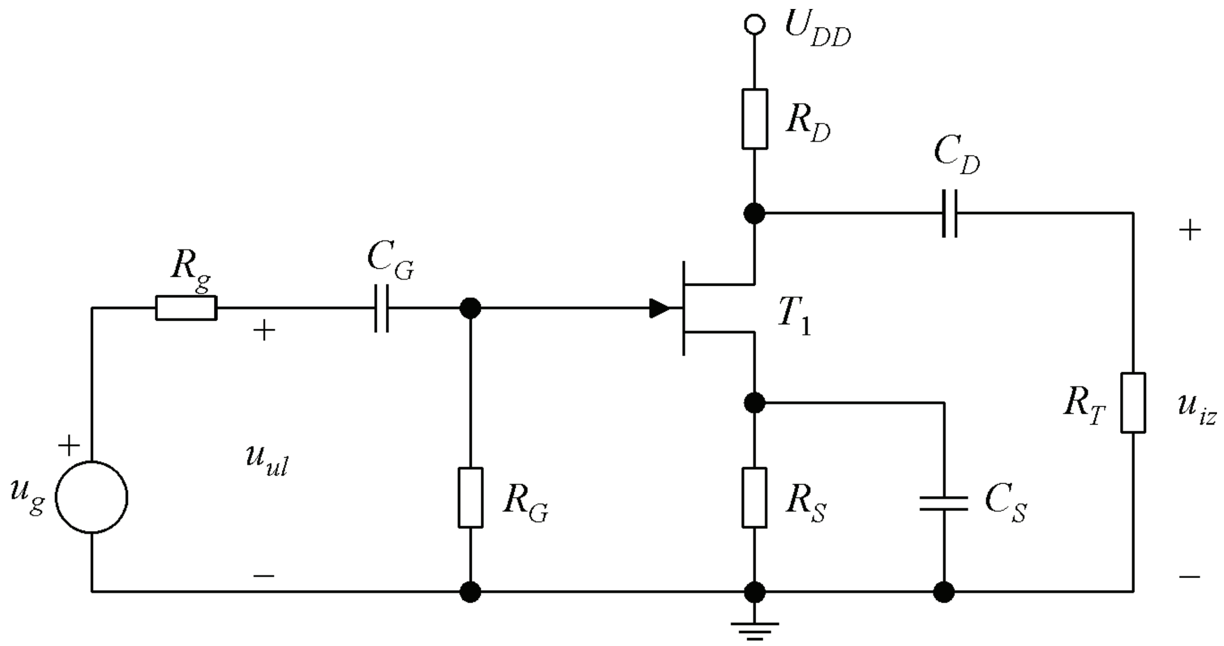
Ako ne → procjena $\omega_d \approx \dfrac{1}{\tau_B} + \dfrac{1}{\tau_E} + \dfrac{1}{\tau_C}$

Primjer 4.2

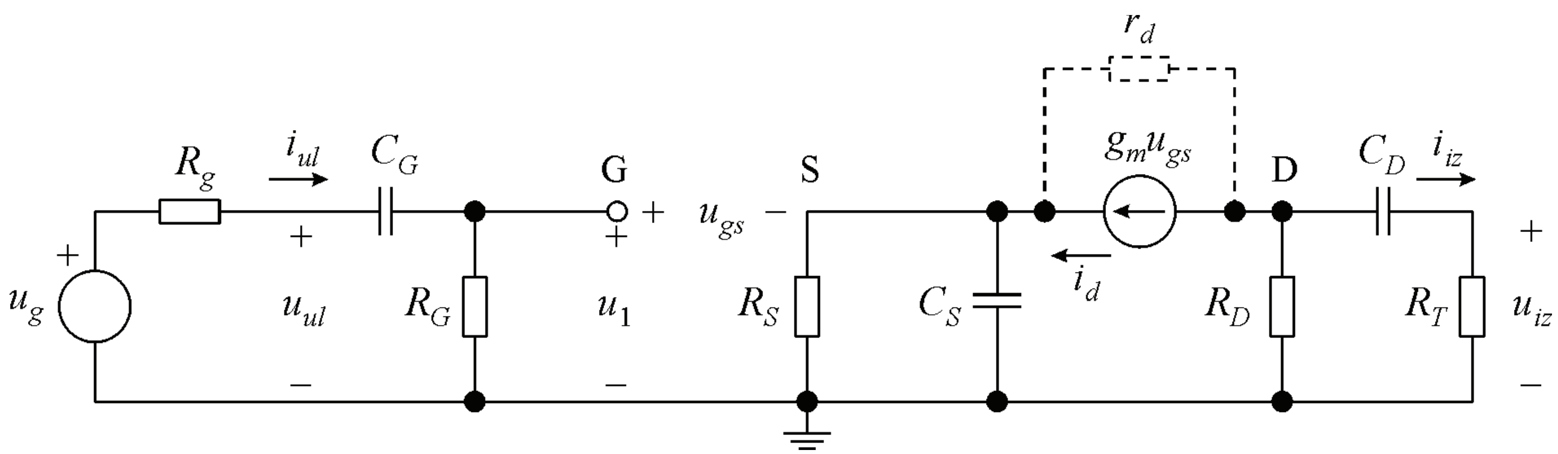
U pojačalu sa slike zadano je: $U_{CC} = 15$ V, $R_g = 500\ \Omega$, $C_B = 10\ \mu$F, $R_1 = 30$ kΩ, $R_2 = 11$ kΩ, $R_C = 2$ kΩ, $R_E = 1$ kΩ, $C_E = 100\ \mu$F, $C_C = 3\ \mu$F i $R_T = 1{,}2$ kΩ. Parametri bipolarnog tranzistora su $\beta \approx h_{fe} = 100$ i $U_\gamma = 0{,}7$ V. Zanemariti porast struje kolektora s naponom u_{CE} u normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25$ mV. Odrediti naponsko pojačanje $A_V = U_{iz}/U_{ul}$ na srednjim frekvencijama, te donju graničnu frekvenciju tog pojačanja.



Spoj zajedničkog uvoda na niskim frekvencijama



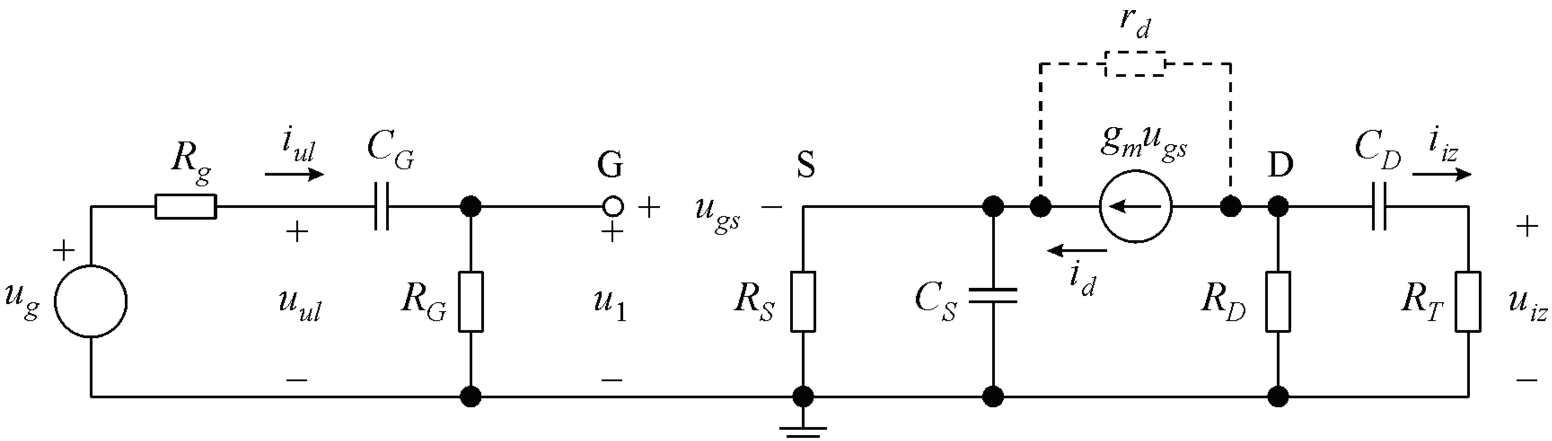
Niskofrekvencijska analiza (1)



$$A_V = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{I_d}\frac{I_d}{U_1}\frac{U_1}{U_{ul}}$$

$$\frac{U_{iz}}{I_d} = \frac{U_{iz}}{I_{iz}}\frac{I_{iz}}{I_d} = -R_T\frac{R_D}{R_D + \dfrac{1}{j\omega C_D} + R_T} = -\left(R_D \| R_T\right)\frac{j\omega\left(R_D + R_T\right)C_D}{1 + j\omega\left(R_D + R_T\right)C_D}$$

Niskofrekvencijska analiza (2)

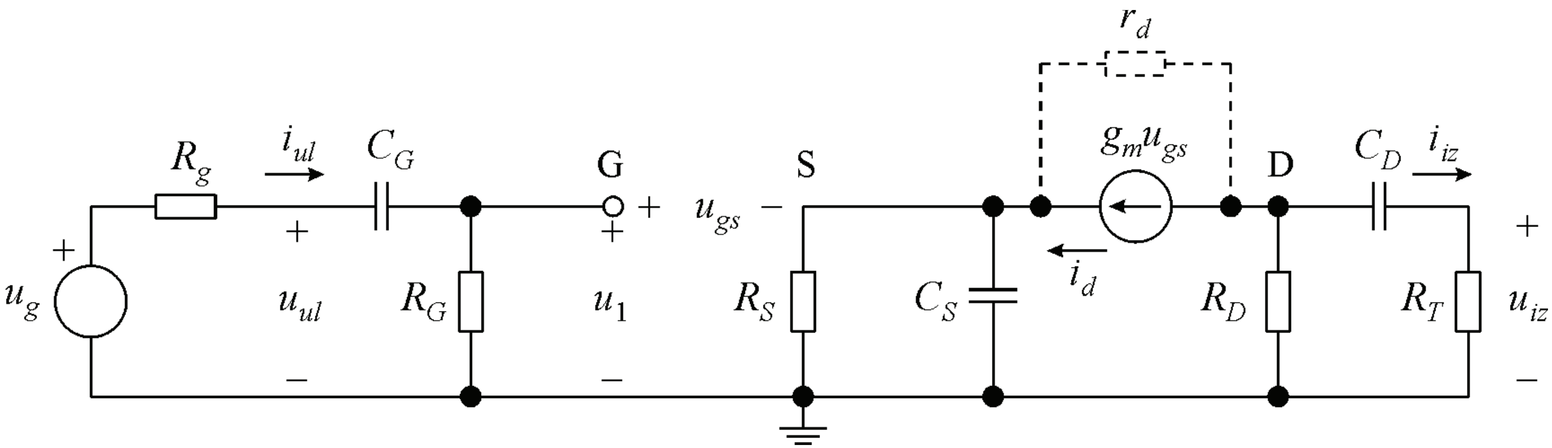


$$Z_S = R_S \| \frac{1}{j\omega C_S} = \frac{R_S\left(1/j\omega C_S\right)}{R_S + \left(1/j\omega C_S\right)} = \frac{R_S}{1 + j\omega R_S C_S}$$

$$I_d = g_m U_{gs} = g_m\left(U_1 - I_d Z_S\right)$$

$$\frac{I_d}{U_1} = \frac{g_m}{1 + g_m Z_S} = \frac{1}{1/g_m + \dfrac{R_S}{1 + j\omega R_S C_S}} = \frac{g_m}{1 + g_m R_S} \frac{1 + j\omega R_S C_S}{1 + j\omega\left(R_S \| 1/g_m\right) C_S} .$$

Niskofrekvencijska analiza (2)

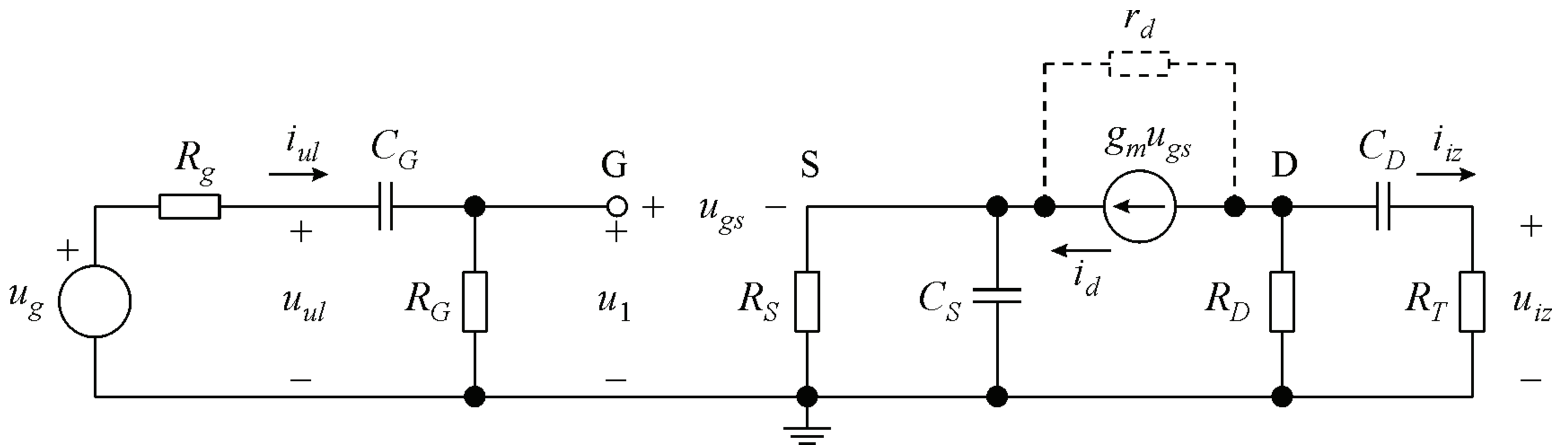


$$Z_S = R_S \| \frac{1}{j\omega C_S} = \frac{R_S (1/ j\omega C_S)}{R_S + (1/ j\omega C_S)} = \frac{R_S}{1+ j\omega R_S C_S}$$

$$I_d = g_m U_{gs} = g_m (U_1 - I_d Z_S)$$

$$\frac{I_d}{U_1} = \frac{g_m}{1+ g_m Z_S} = \frac{1}{1/g_m + \dfrac{R_S}{1+ j\omega R_S C_S}} = \frac{g_m}{1+ g_m R_S} \frac{1+ j\omega R_S C_S}{1+ j\omega (R_S \| 1/g_m) C_S} .$$

Niskofrekvencijska analiza (2)



$$\frac{U_1}{U_{ul}} = \frac{R_G}{\left(1/\,j\omega C_G\right) + R_G} = \frac{j\omega R_G C_G}{1 + j\omega R_G C_G}$$

Naponsko pojačanje (1)

$$A_V(j\omega) = \frac{U_{iz}}{U_{ul}} = A_{Vn} \frac{1 + j\omega/\omega_1}{1 + j\omega/\omega_2} \frac{j\omega/\omega_3}{1 + j\omega/\omega_3} \frac{j\omega/\omega_4}{1 + j\omega/\omega_4}$$

$$A_{Vn} = -\frac{g_m \left(R_D \| R_T\right)}{1 + g_m R_S}$$

Vremenske konstante

$$\tau_1 = \frac{1}{\omega_1} = R_S C_S$$

$$\tau_2 = \tau_S = \frac{1}{\omega_2} = \left(R_S \| \frac{1}{g_m}\right) C_S$$

$$\tau_3 = \tau_D = \frac{1}{\omega_3} = \left(R_D + R_T\right) C_D$$

$$\tau_4 = \tau_G = \frac{1}{\omega_4} = R_G C_G$$

Naponsko pojačanje (2)

Za ulazni izvor s konačnim unutarnjim otporom R_g

$$\tau_G = \left(R_G + R_g\right) C_G$$

Pojačanje na srednjim frekvencijama

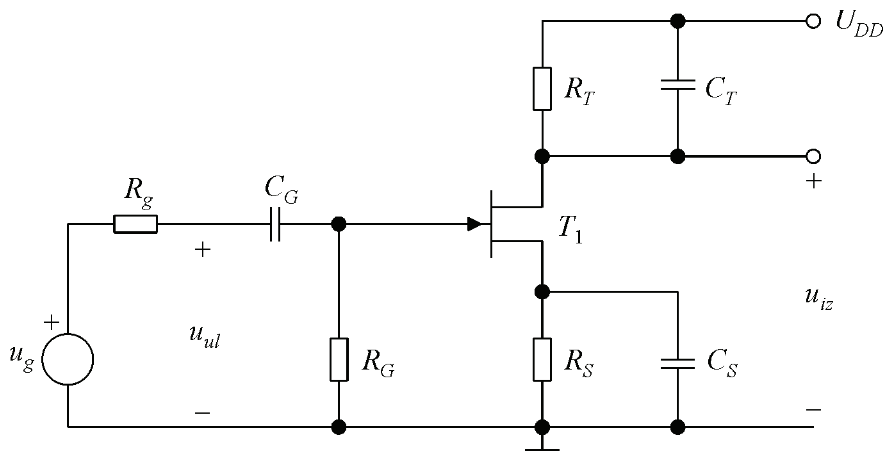
$$A_{V0} = A_{Vn}\frac{\omega_2}{\omega_1} = A_{Vn}\frac{\tau_1}{\tau_2} = A_{Vn}\frac{\omega_2}{\omega_1} = -\,g_m\left(R_D \,\|\, R_T\right)$$

Donja granična frekvencija

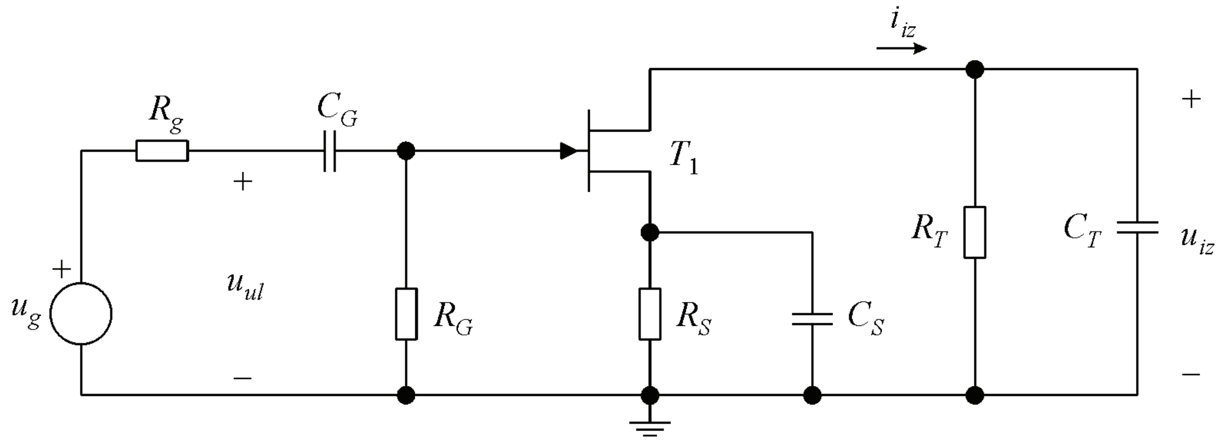
$$\omega_d = \max\left\{\omega_G,\ \omega_S,\ \omega_D\right\} = \max\left\{\frac{1}{\tau_G},\ \frac{1}{\tau_S},\ \frac{1}{\tau_D}\right\}$$

Primjer 4.3 (1)

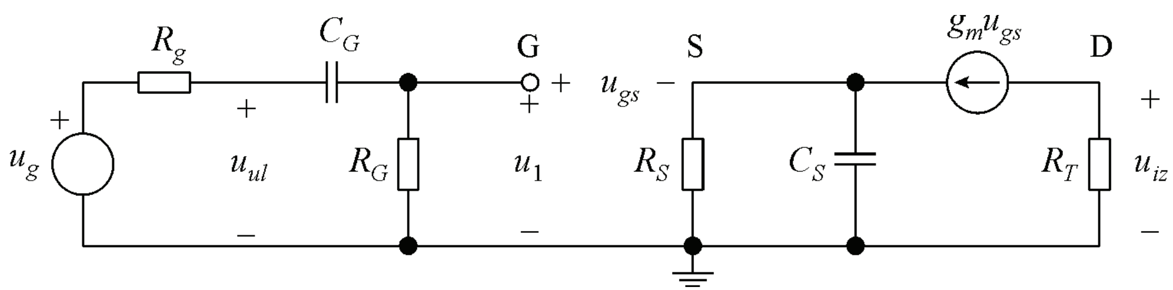
Za pojačalo na slici odrediti otpor otpornika R_S tako da struja odvoda spojnog FET-a u statičkoj radnoj točki bude $I_{DQ} = 1$ mA. Odrediti naponsko pojačanje $A_V = U_{iz}/U_{ul}$ na srednjim frekvencijama, te donju graničnu frekvenciju tog pojačanja. Zadano je: $U_{DD} = 12$ V, $R_g = 100\ \Omega$, $C_G = 5$ nF, $R_G = 1\ \mathrm{M\Omega}$, $R_T = 3\ \mathrm{k\Omega}$, $C_T = 10$ pF i $C_S = 20\ \mu$F. Parametri spojnog FET-a su $I_{DSS} = 16$ mA i $U_P = -2$ V. Zanemariti porast struje odvoda s naponom u_{DS} u području zasićenja.



Primjer 4.3 (2)



Shema pojačala u dinamičkim prilikama



Nadomjesna shema za niskofrekvencijsku analizu

Ostali spojevi pojačala na niskim frekvencijama

Donju graničnu frekvenciju određuju vezni kondenzatori. Svaki u prijenosnu funkciju pojačala unosi član oblika

$$\frac{j\omega/\omega_i}{1+j\omega/\omega_i}$$

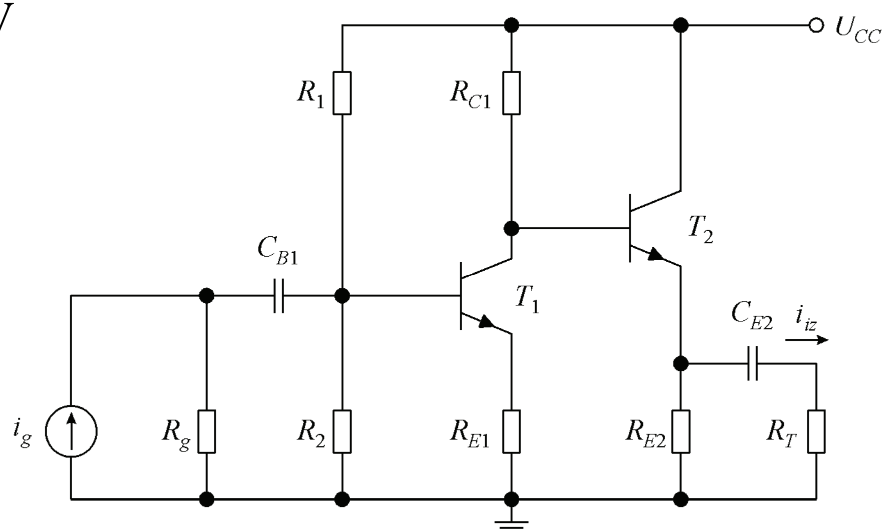
Karakteristične frekvencije ω_i određuju vremenske konstante $\tau_i = 1/\omega_i$ uzrokovane pojedinim veznim kondenzatorom.

Za određivanje donje granične frekvencije → proračun svih vremenskih konstanti → donja granična frekvencija najviša frekvencija ako je barem 4 puta veća od ostalih → ako nije može se procijeniti

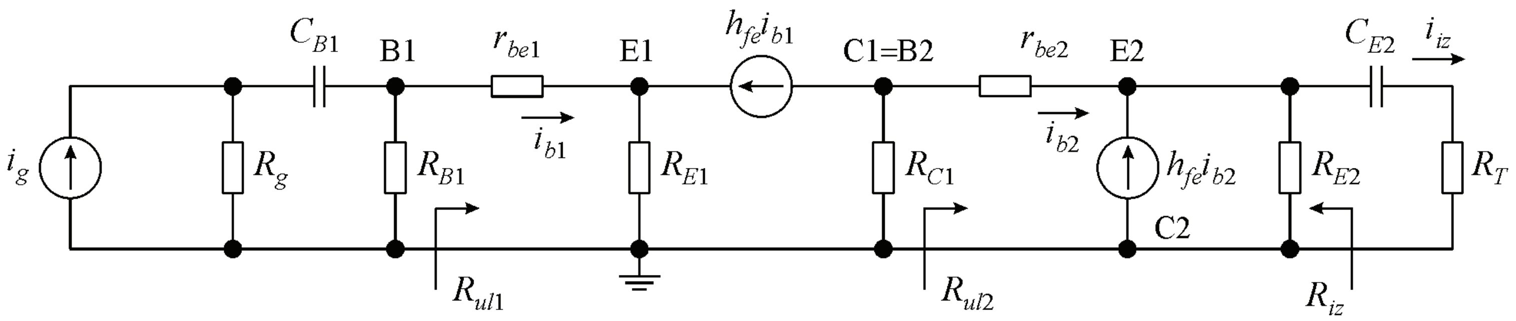
$$\omega_d \approx \sum_i \frac{1}{\tau_i}$$

Primjer 4.4 (1)

Za pojačalo na slici odrediti strujno pojačanje $A_{Ig} = I_{iz}/I_g$ na srednjim frekvencijama, te donju graničnu frekvenciju tog pojačanja. Zadano je: $U_{CC} = 15$ V, $R_g = 50$ kΩ, $C_{B1} = 0{,}2$ μF, $R_1 = 40$ kΩ, $R_2 = 10$ kΩ, $R_{C1} = 2$ kΩ, $R_{E1} = R_{E2} = 500$ Ω, $C_{E2} = 10$ μF i $R_T = 100$ Ω. Tranzistori imaju jednake parametre $\beta \approx h_{fe} = 100$ i $U_\gamma = 0{,}7$ V. Za oba tranzistora zanemariti porast struje kolektora s naponom u_{CE} normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25$ mV

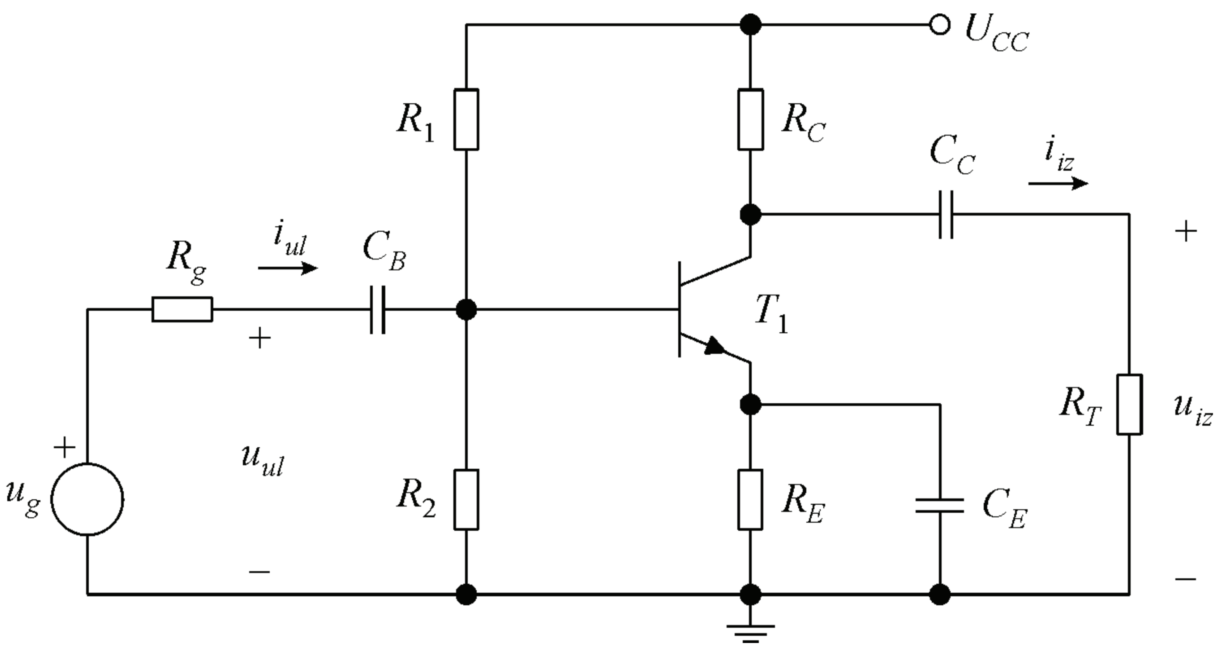


Primjer 4.4 (2)



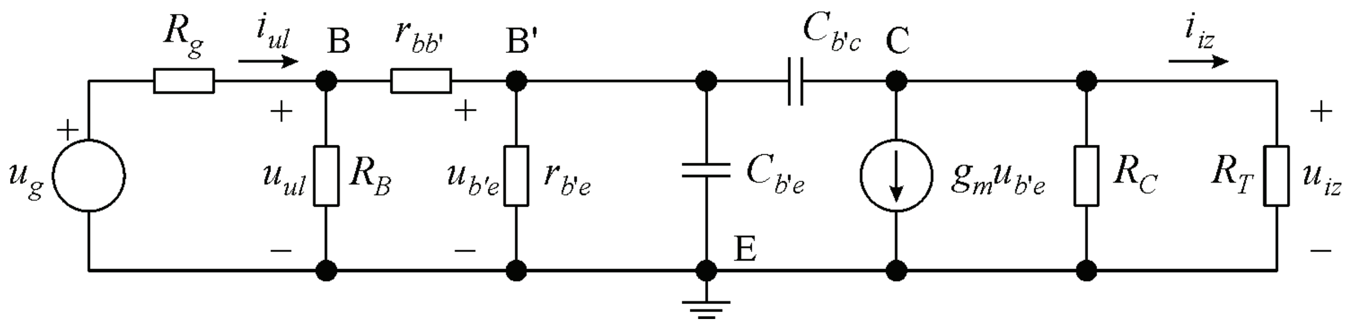
Nadomjesna shema za niskofrekvencijsku analizu

Spoj zajedničkog emitera na visokim frekvencijama



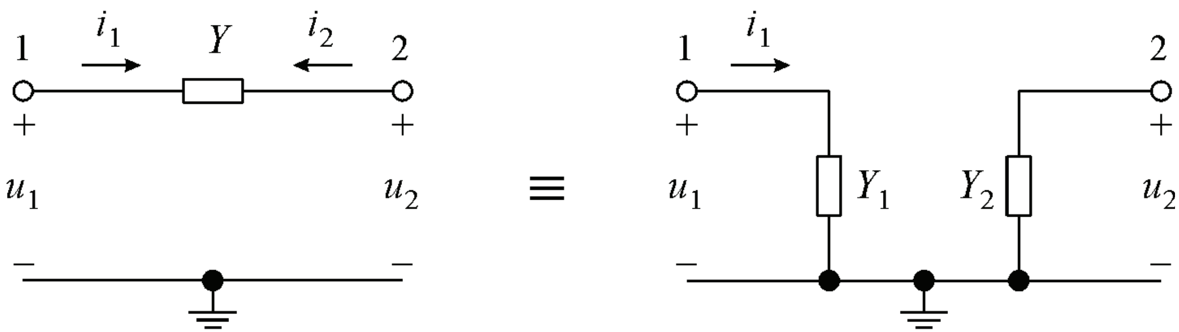
Nadomjesna shema za visokofrekvencijsku analizu

Na visokim frekvencijama djeluju kapaciteti tranzistora



Složenost analize uzrokuje kapacitet $C_{b'c}$ koji povezuje ulaznu i izlazni krug → pojednostavljenje analize primjenom Millerovog teorema

Millerov teorem



originalna mreža

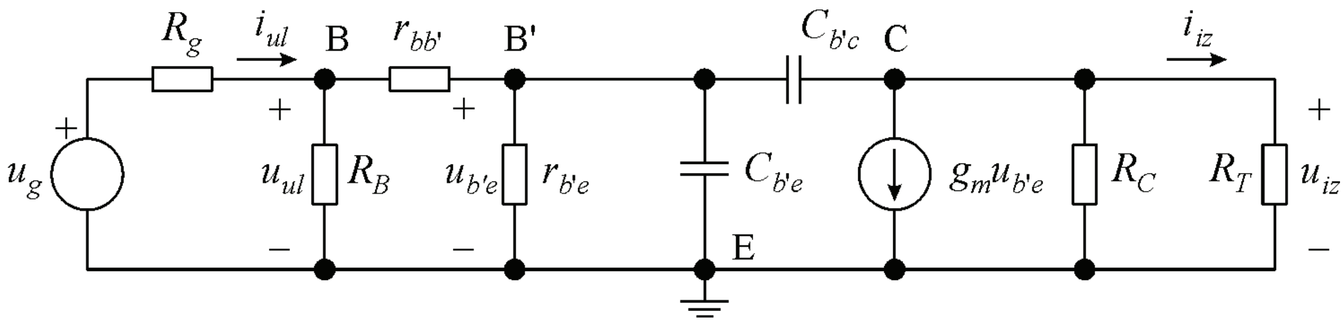
transformirana mreža

$$I_1 = Y(U_1 - U_2) = YU_1(1-K) = Y_1U_1 \quad \rightarrow \quad Y_1 = Y(1-K) \qquad K \equiv \frac{U_2}{U_1}$$

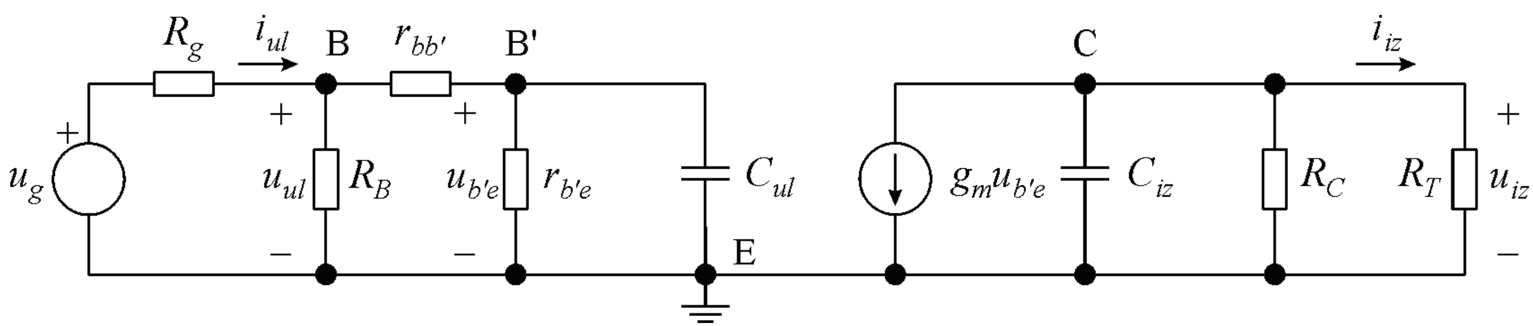
$$I_2 = Y(U_2 - U_1) = YU_2\left(1 - \frac{1}{K}\right) = Y_2U_2 \quad \rightarrow \quad Y_2 = Y\left(1 - \frac{1}{K}\right) = Y\frac{K-1}{K}$$

Za impedancije → $Z_1 = \dfrac{Z}{1-K} \quad Z_2 = Z\dfrac{K}{K-1}$

Primjena Millerovog teorema na kapacitet $C_{b'c}$

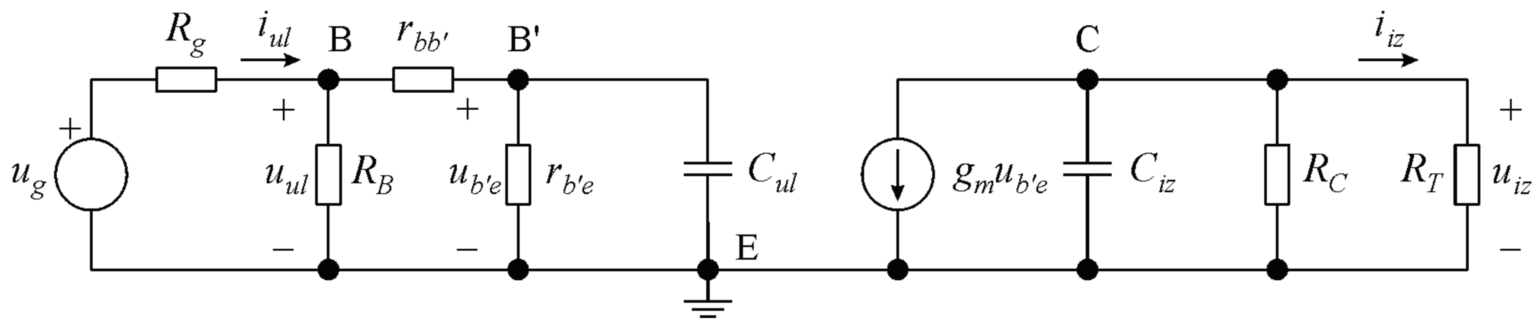


Preslikani kapacitet $C_{b'c} \rightarrow \quad C_{b'c,ul} = C_{b'c}(1-K) \quad C_{b'c,iz} = C_{b'c}\dfrac{K-1}{K} \quad K = \dfrac{U_{iz}}{U_{b'e}}$



$$C_{ul} = C_{b'e} + C_{b'c}(1-K) \qquad C_{iz} = C_{b'c}\frac{K-1}{K}$$

Aproksimacija prijenosne funkcije jednim polom (1)

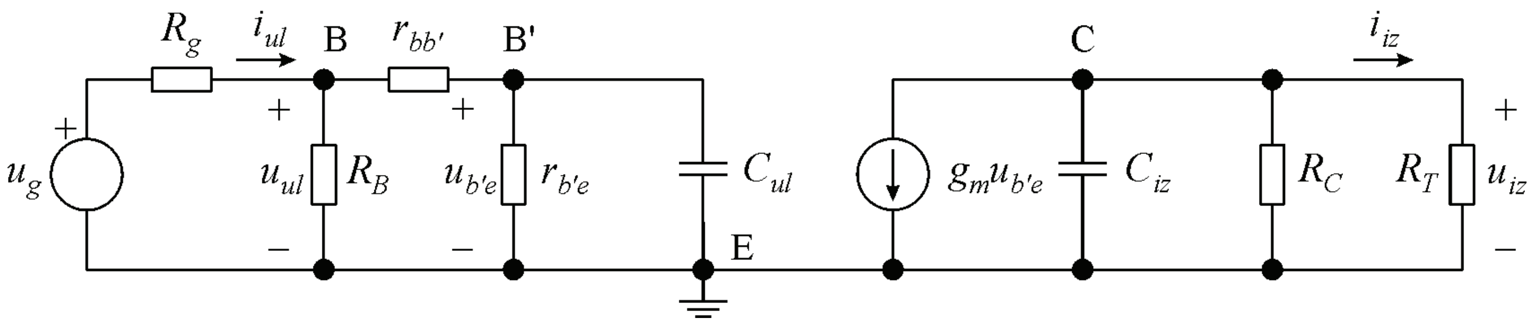


$C_{ul} >> C_{iz} \rightarrow \tau_{ul} >> \tau_{iz} \rightarrow \omega_{ul} << \omega_{iz} \rightarrow$ za proračun gornje granične frekvencije odspaja se C_{iz}

$$A_V = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{U_{b'e}} \frac{U_{b'e}}{U_{ul}}$$

$$\frac{U_{iz}}{U_{b'e}} = -g_m \left(R_C \| R_T \right) = K$$

Aproksimacija prijenosne funkcije jednim polom (2)



$$Z_{b'e} = r_{b'e} \,\|\, \frac{1}{j\omega C_{ul}} = \frac{r_{b'e}\left(1/\,j\omega C_{ul}\right)}{r_{b'e} + \left(1/\,j\omega C_{ul}\right)} = \frac{r_{b'e}}{1 + j\omega r_{b'e} C_{ul}}$$

$$\frac{U_{b'e}}{U_{ul}} = \frac{Z_{b'e}}{r_{bb'} + Z_{b'e}} = \frac{\dfrac{r_{b'e}}{1 + j\omega r_{b'e} C_{ul}}}{r_{bb'} + \dfrac{r_{b'e}}{1 + j\omega r_{b'e} C_{ul}}} = \frac{r_{b'e}}{r_{bb'} + r_{b'e} + j\omega r_{bb'} r_{b'e} C_{ul}} =$$

$$= \frac{r_{b'e}}{r_{bb'} + r_{b'e}} \frac{1}{1 + j\omega\left(r_{bb'} \,\|\, r_{b'e}\right) C_{ul}} \;.$$

Naponsko pojačanje

$$A_V(j\omega)=\frac{A_{V0}}{1+j\omega/\omega_{ul}}$$

$$A_{V0}=-g_m\left(R_C\|R_T\right)\frac{r_{b'e}}{r_{bb'}+r_{b'e}}$$

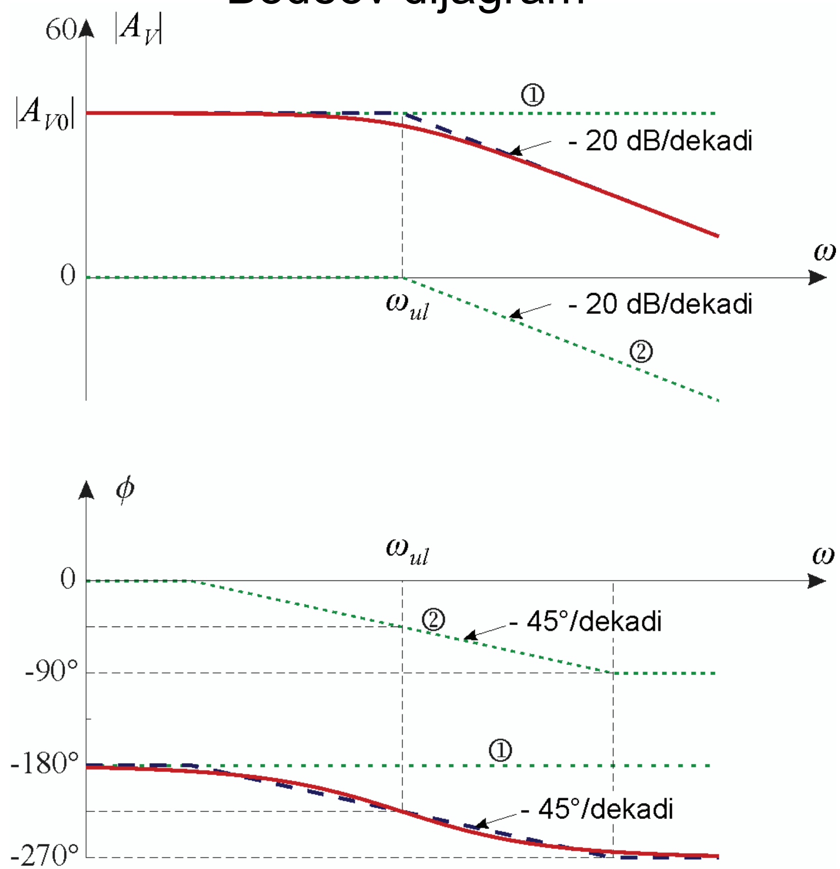
$$\tau_{ul}=\frac{1}{\omega_{ul}}=\left(r_{bb'}\|r_{b'e}\right)C_{ul}$$

Gornja granična frekvencija

$$\left|A_V\right|=\frac{\left|A_{V0}\right|}{\sqrt{1+\left(\omega_g/\omega_{ul}\right)^2}}=\frac{\left|A_{V0}\right|}{\sqrt{2}}$$

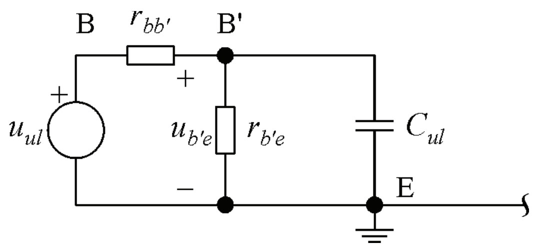
$$\omega_g=\omega_{ul}$$

Bodeov dijagram



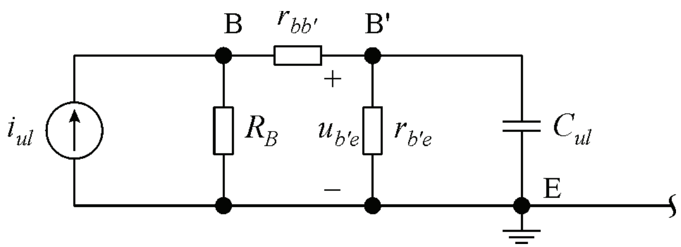
Vremenska konstanta τ_{ul}

za naponsko pojačanje



$$\tau_{ul} = \left(r_{bb'} \| r_{b'e}\right) C_{ul}$$

za strujno pojačanje



$$\tau_{ul} = \left[(R_B + r_{bb'}) \| r_{b'e} \right] C_{ul}$$

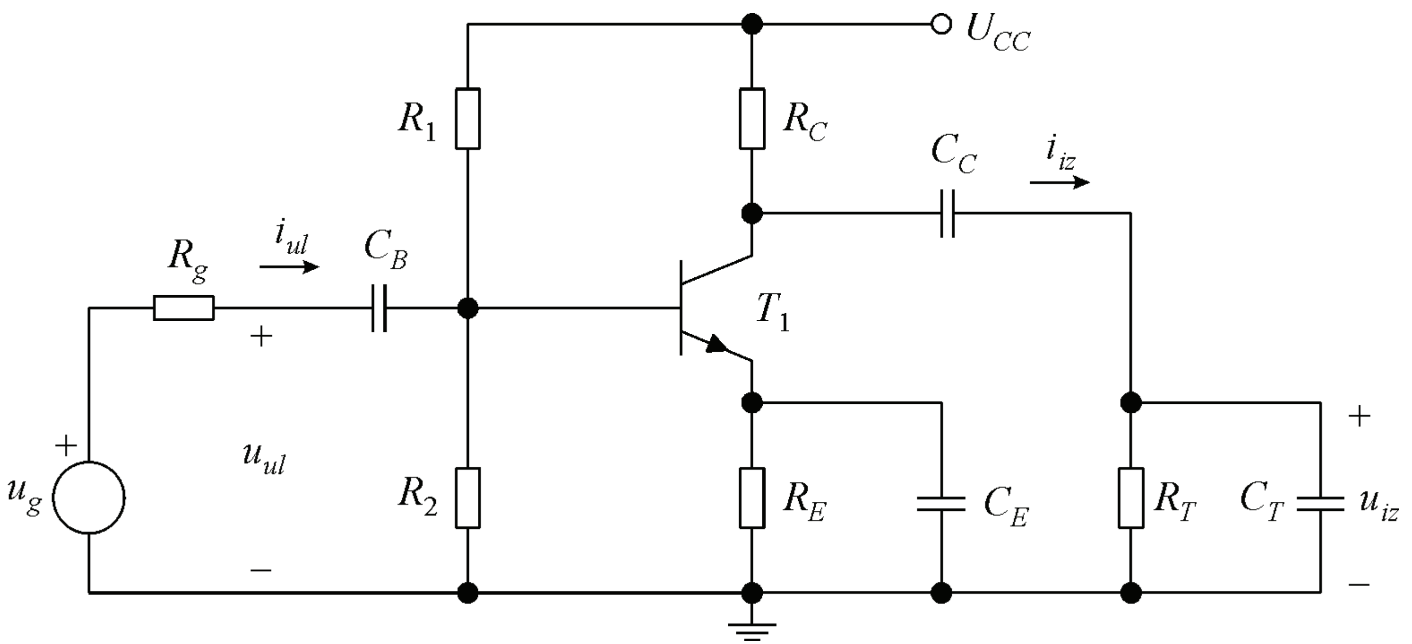
uz konačni R_g $\qquad \tau_{ul} = \left[(R_g \| R_B + r_{bb'}) \| r_{b'e} \right] C_{ul}$

Millerov efekt

$$C_{ul} = C_{b'e} + C_{b'c}\left[1 + g_m \left(R_C \| R_T\right)\right]$$

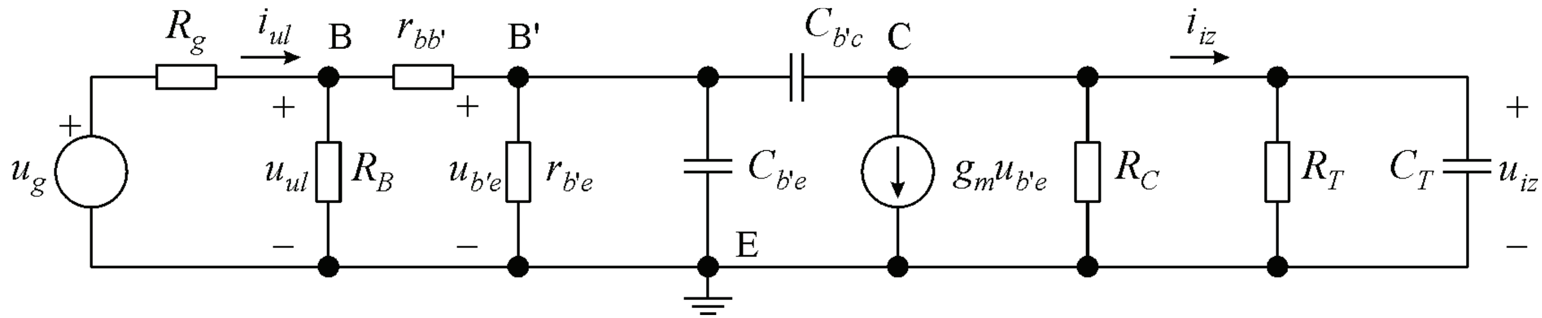
kapacitet $C_{b'c}$ spojen između izlaza i ulaza preslikava se u ulazni krug pomnožen s iznosom naponskog pojačanja → smanjenje gornje granične frekvencije

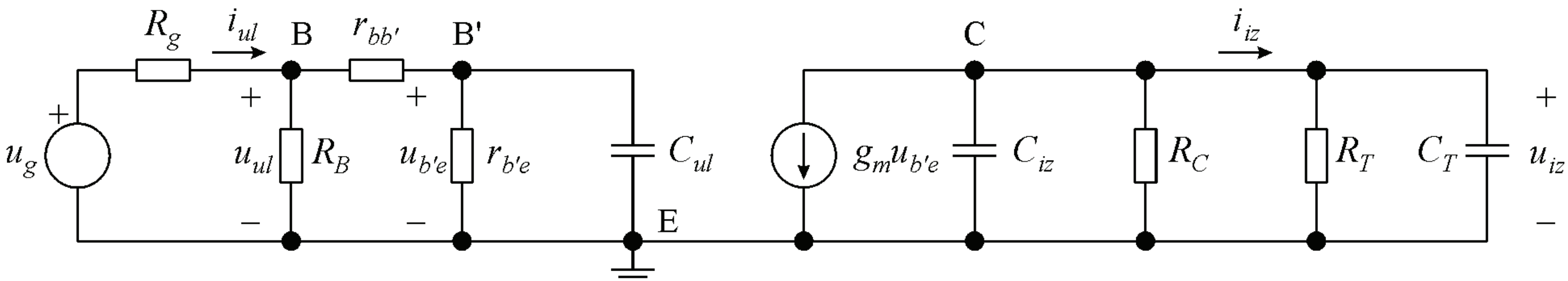
Utjecaj oba pola



$C_T \rightarrow$ kapacitivno opterećenje

Nadomjesna shema za visokofrekvencijsku analizu





kapacitet izlaznog kuga $C'_{iz} = C_{iz} + C_T = C_{b'c}\dfrac{K-1}{K} + C_T \approx C_{b'c} + C_T$

vremenska konstanta izlaznog kuga $\tau_{iz} = \dfrac{1}{\omega_{iz}} = \left(R_C \,\|\, R_T\right) C'_{iz}$

Određivanje gornje granične frekvencije

Na srednjim frekvencijama (svi se kondenzatori kratko odspajaju)

$$A_{V0} = -g_m \left(R_C \| R_T \right) \frac{r_{b'e}}{r_{bb'} + r_{b'e}}$$

Vremenske konstante koje određuju pojedini kapaciteti (drugi se kapacitet odspaja)

$$\tau_{ul} = \left(r_{bb'} \| r_{b'e} \right) C_{ul} \qquad \tau_{iz} = \frac{1}{\omega_{iz}} = \left(R_C \| R_T \right) C'_{iz}$$

Gornja granična frekvencija

$$\omega_g = \min\{\omega_{ul}, \omega_{iz}\} = \min\left\{ \frac{1}{\tau_{ul}}, \frac{1}{\tau_{iz}} \right\}$$

Uvjet → niža frekvencija barem 4 puta niža od više → dominantni pol

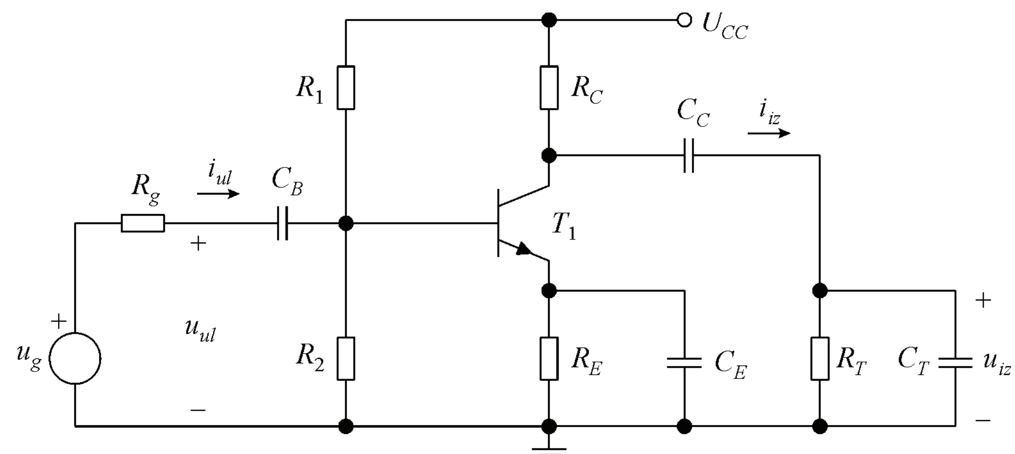
Ako ne → procjena $\omega_g \approx \dfrac{1}{\tau_{ul} + \tau_{iz}}$ općenito $\omega_g \approx \dfrac{1}{\sum_i \tau_i}$

Primjer 4.5

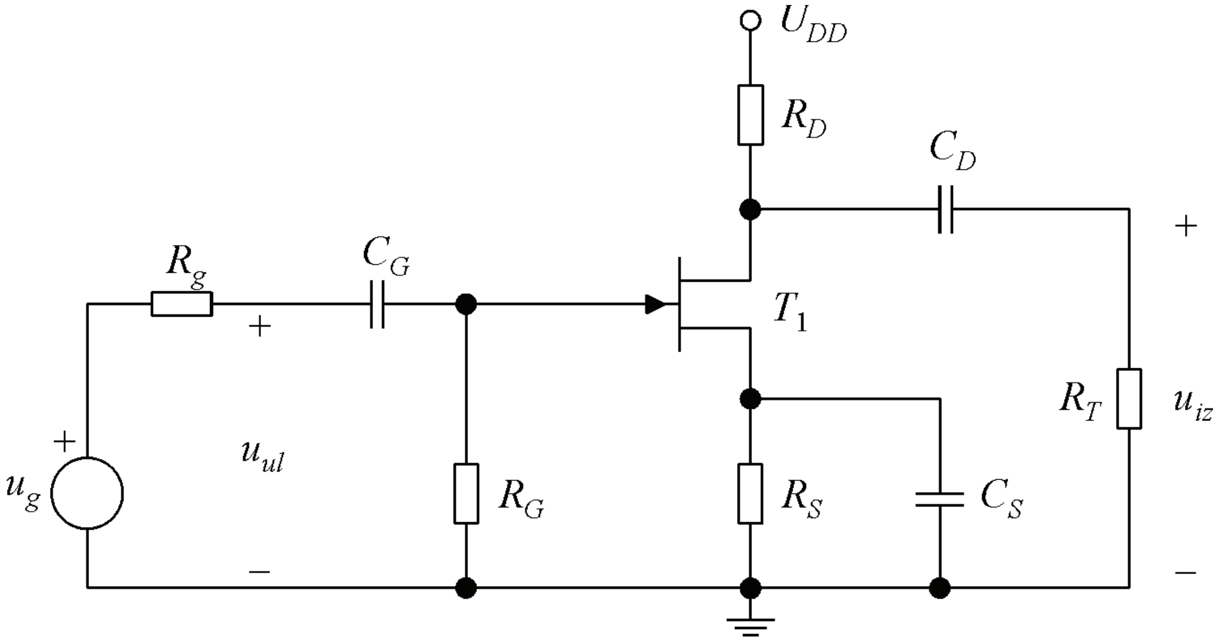
U pojačalu sa slike zadano je: $U_{CC} = 15$ V, $R_g = 500\ \Omega$, $C_B = 10\ \mu$F, $R_1 = 30$ kΩ, $R_2 = 11$ kΩ, $R_C = 2$ kΩ, $R_E = 1$ kΩ, $C_E = 100\ \mu$F, $C_C = 3\ \mu$F i $R_T = 1{,}2$ kΩ. Parametri bipolarnog tranzistora su $\beta \approx h_{fe} = 100$, $U_\gamma = 0{,}7$ V, $r_{bb'} = 50\ \Omega$, $C_{b'e} = 50$ pF i $C_{b'c} = 2$ pF. Zanemariti porast struje kolektora s naponom u_{CE} u normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25$ mV. Odrediti naponsko pojačanje $A_V = U_{iz}/U_{ul}$ na srednjim frekvencijama, te gornju graničnu frekvenciju tog pojačanja uz:

a) $C_T = 0$ i

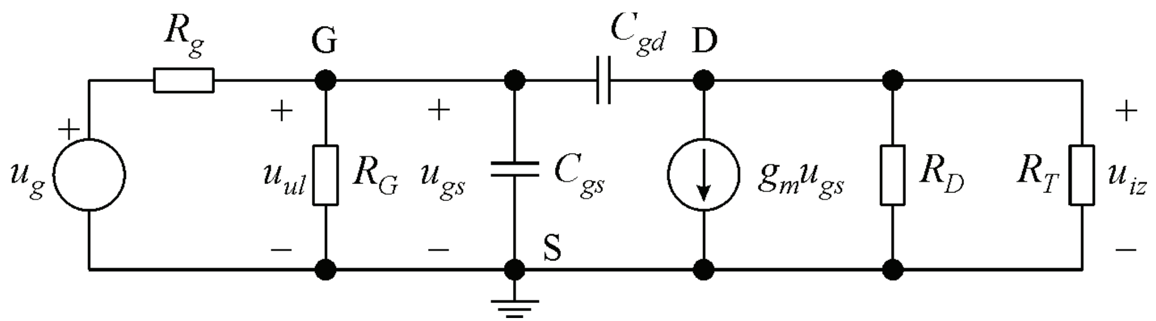
b) $C_T = 100$ pF.



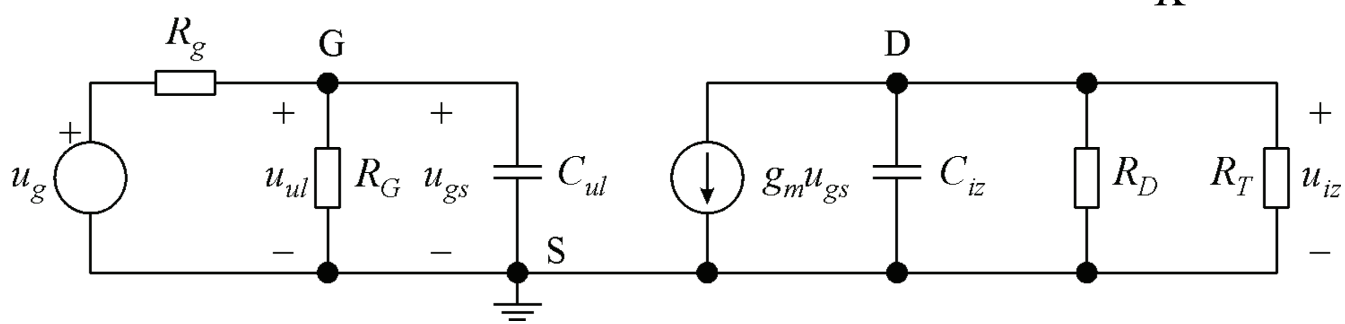
Spoj zajedničkog uvoda na visokim frekvencijama



Nadomjesna shema za visokofrekvencijsku analizu

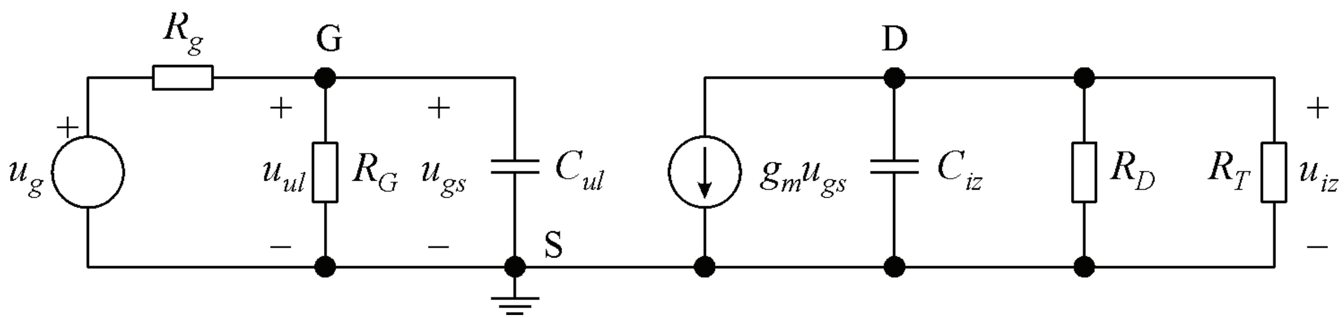


Preslikani kapacitet $C_{gd} \rightarrow \; C_{gd,ul} = C_{gd}\left(1-K\right) \quad C_{gd,iz} = C_{gd}\dfrac{K-1}{K} \quad K = \dfrac{U_{iz}}{U_{gs}} = \dfrac{U_{iz}}{U_{ul}} = A_V$



$$C_{ul} = C_{gs} + C_{gd}\left(1-K\right) \qquad C_{iz} = C_{gd}\frac{K-1}{K} \approx C_{gd}$$

Visokofrekvencijska analiza



$$A_V = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{U_{gs}} \frac{U_{gs}}{U_{ul}}$$

$$\frac{U_{iz}}{U_{gs}} = -g_m \frac{\frac{1}{j\omega C_{iz}}\left(R_D \| R_T\right)}{\frac{1}{j\omega C_{iz}} + \left(R_D \| R_T\right)} = \frac{-g_m\left(R_D \| R_T\right)}{1 + j\omega\left(R_D \| R_T\right)C_{iz}}$$

Naponsko pojačanje

$$A_V(j\omega) = \frac{A_{V0}}{1 + j\omega/\omega_{iz}}$$

$$A_{V0} = -g_m\left(R_D \| R_T\right) \qquad \tau_{iz} = \frac{1}{\omega_{iz}} = \left(R_D \| R_T\right)C_{iz} \approx \left(R_D \| R_T\right)C_{gd}$$

Gornja granična frekvencija

$$\omega_g = \omega_{iz}$$

uz konačni $R_g \rightarrow$ utječe i vremenska konstanta ulaznog kruga

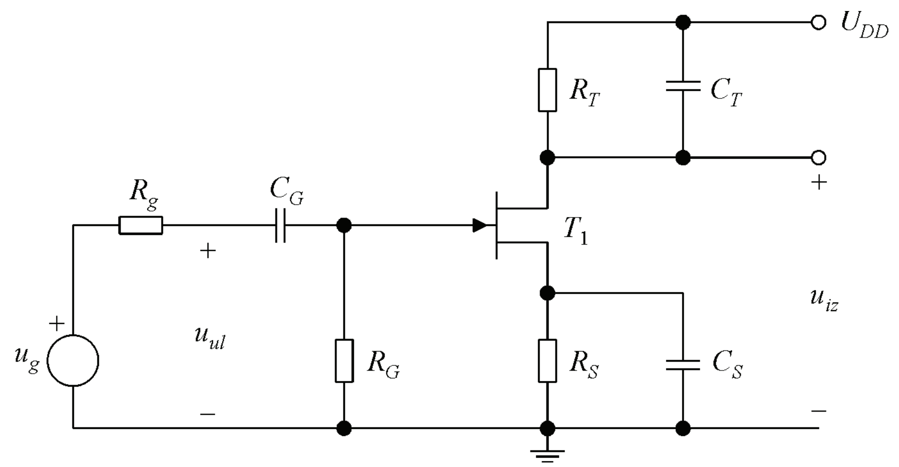
$$\tau_{ul} = \frac{1}{\omega_{ul}} = \left(R_g \| R_G\right)C_{ul}$$

$$\omega_g = \min\left\{\omega_{ul},\ \omega_{iz}\right\} = \min\left\{\frac{1}{\tau_{ul}},\ \frac{1}{\tau_{iz}}\right\}$$

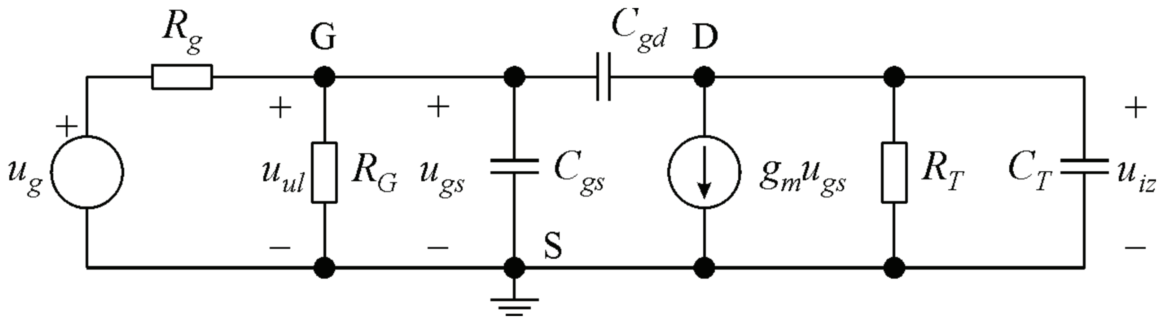
Millerov efekt $\quad C_{ul} = C_{gs} + C_{gd}\left[1 + g_m\left(R_D \| R_T\right)\right]$

Primjer 4.6 (1)

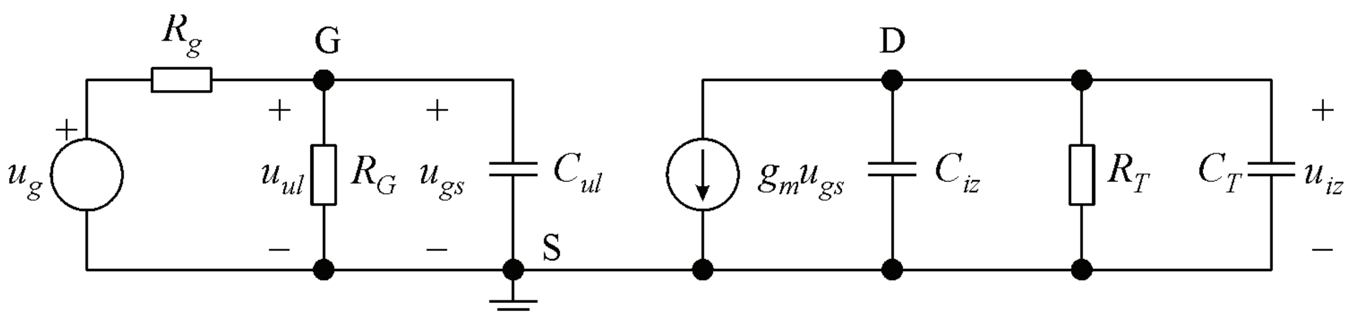
Za pojačalo iz primjera 4.3 odrediti naponsko pojačanje $A_{Vg} = U_{iz}/U_g$ na srednjim frekvencijama, te gornju graničnu frekvenciju tog pojačanja. Kapaciteti FET-a su $C_{gs} = 3$ pF i $C_{gs} = 2$ pF.



Primjer 4.6 (2)

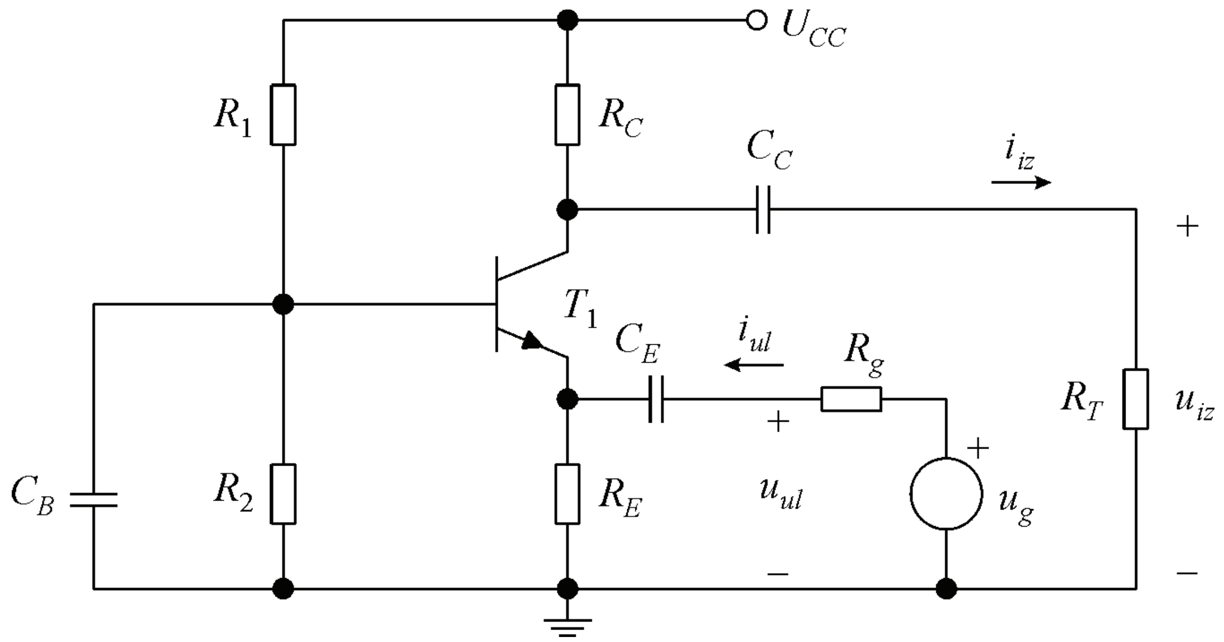


Nadomjesna shema za visokofrekvencijsku analizu

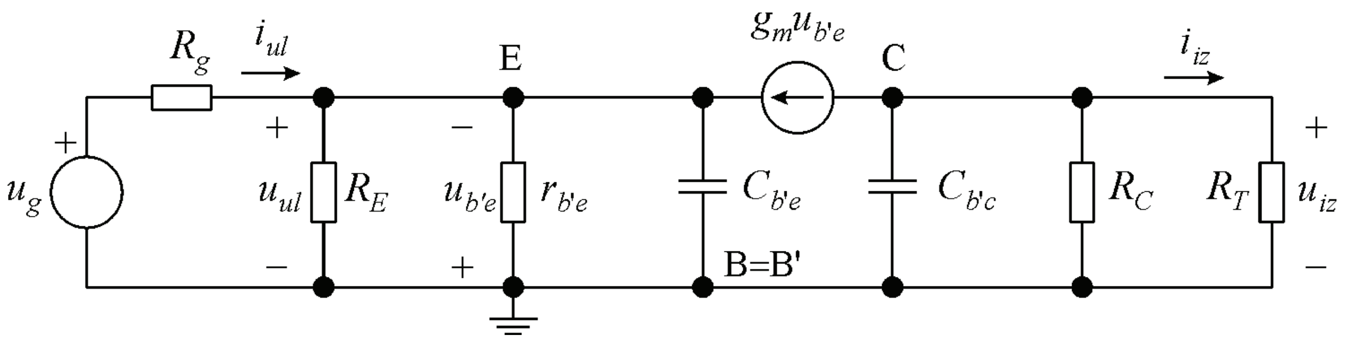


Primjena Millerovog teorema

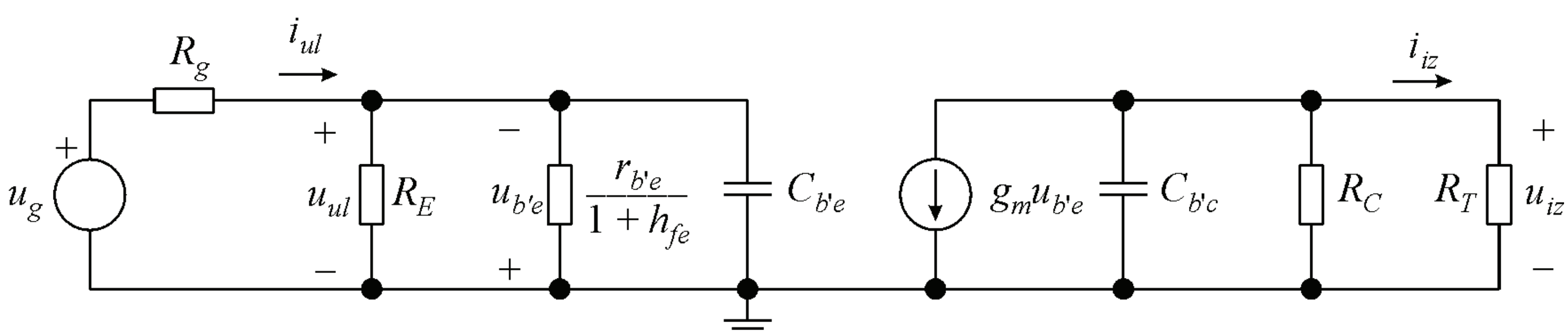
Spoj zajedničke baze na visokim frekvencijama



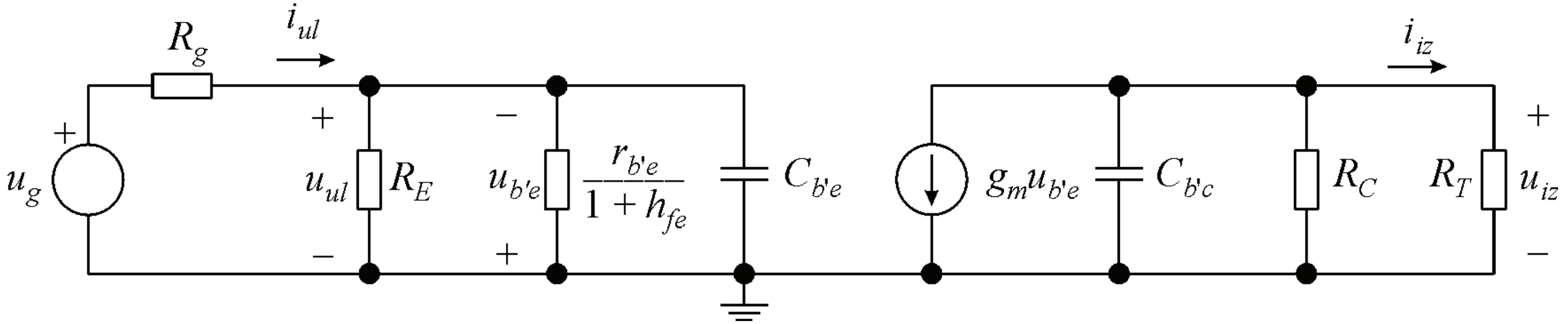
Nadomjesna shema za visokofrekvencijsku analizu



$$I_{ul} = \frac{1}{R_E} U_{ul} - \left(\frac{1}{r_{b'e}} + j\omega C_{b'e} \right) U_{b'e} - g_m U_{b'e} = \left(\frac{1}{R_E} + \frac{1 + h_{fe}}{r_{b'e}} + j\omega C_{b'e} \right) U_{ul}$$



Visokofrekvencijska analiza



$$Z_C = \frac{1}{j\omega C_{b'c}} \Big\| \left(R_C \| R_T\right) = \frac{\left(1/j\omega C_{b'c}\right)\left(R_C \| R_T\right)}{\left(1/j\omega C_{b'c}\right) + \left(R_C \| R_T\right)} = \frac{\left(R_C \| R_T\right)}{1 + j\omega\left(R_C \| R_T\right)C_{b'c}}$$

$$A_V = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{-U_{b'e}} = g_m Z_C = \frac{g_m\left(R_C \| R_T\right)}{1 + j\omega\left(R_C \| R_T\right)C_{b'c}}$$

Naponsko pojačanje

$$A_V(j\omega)=\frac{A_{V0}}{1+j\omega/\omega_{iz}}$$

$$A_{V0}=g_m\left(R_C \| R_T\right) \qquad \tau_{iz}=\frac{1}{\omega_{iz}}=\left(R_C \| R_T\right)C_{b'c}$$

Gornja granična frekvencija $\omega_g=\omega_{iz}$

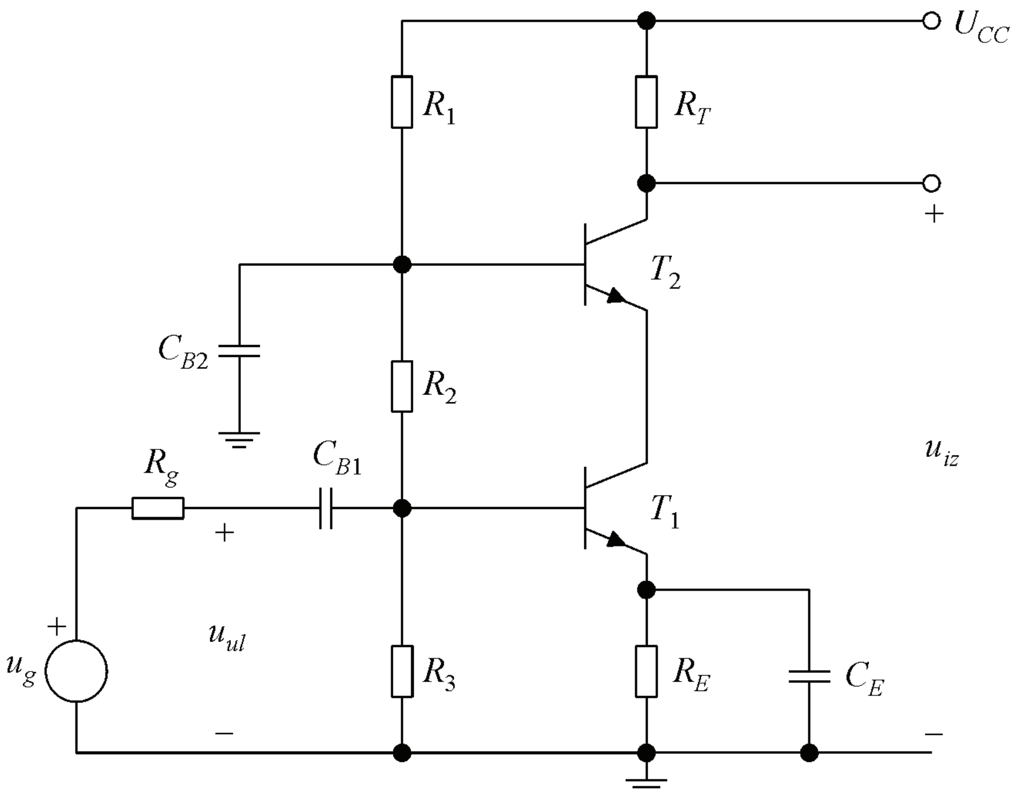
uz konačni $R_g \rightarrow$ utječe i vremenska konstanta ulaznog kruga

$$\tau_{ul}=\frac{1}{\omega_{ul}}=\left(\frac{r_{b'e}}{1+h_{fe}}\left\| R_E \right\| R_g\right)C_{b'e}$$

$$\omega_g=\min\left\{\omega_{ul},\ \omega_{iz}\right\}=\min\left\{\frac{1}{\tau_{ul}},\ \frac{1}{\tau_{iz}}\right\}$$

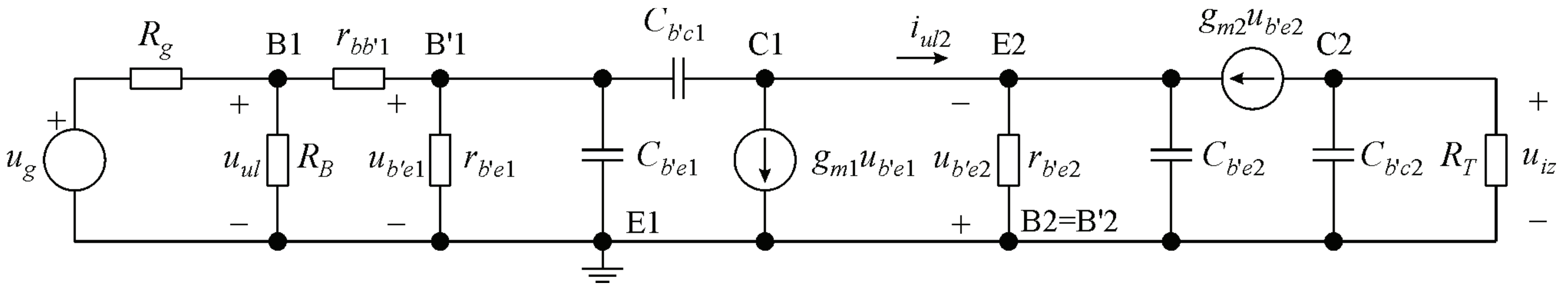
Nema Millerovog efekta → obje su vremenske konstante male

Kaskodno pojačalo na visokim frekvencijama



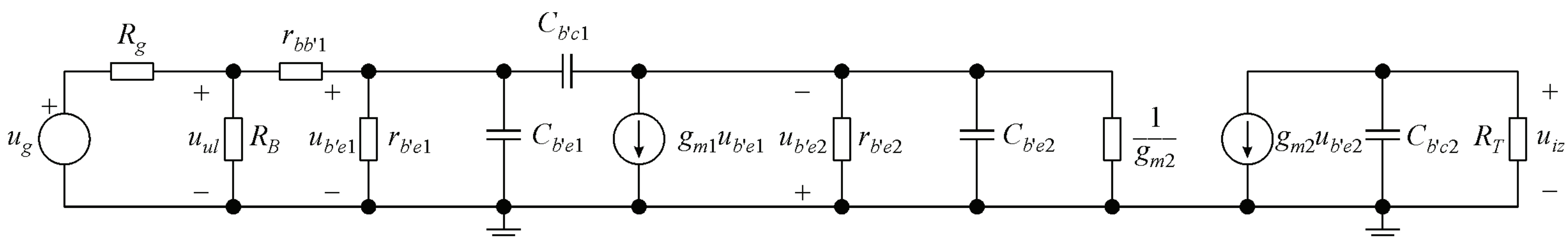
- Pojačalo u spoju zajedničkog emitera → dobra svojstva na srednjim i lošija na visokim frekvencijama
- Pojačalo u zajedničke baze → lošija svojstva na srednjim i dobra na visokim frekvencijama
- Kaskodno pojačalo → objedinjuje dobra svojstva

Nadomjesna shema za visokofrekvencijsku analizu (1)

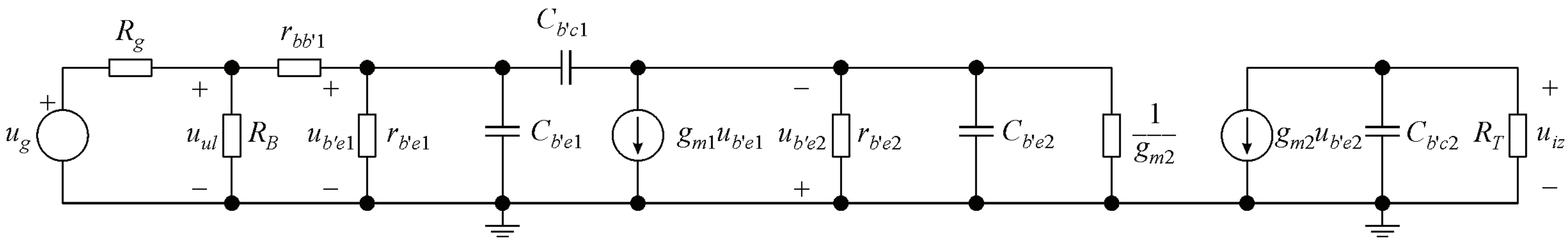


$$R_B = R_2 \| R_3$$

$$I_{ul2} = -\left(\frac{1}{r_{b'e2}} + j\omega C_{b'e2} + g_{m2}\right) U_{b'e}$$



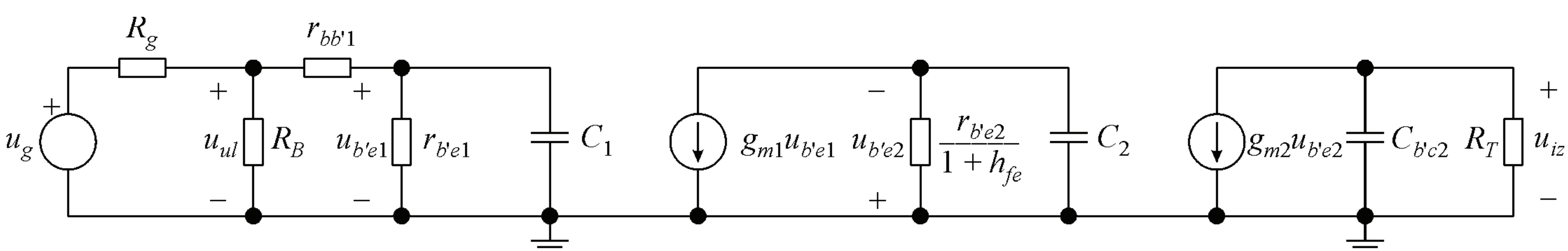
Nadomjesna shema za visokofrekvencijsku analizu (2)



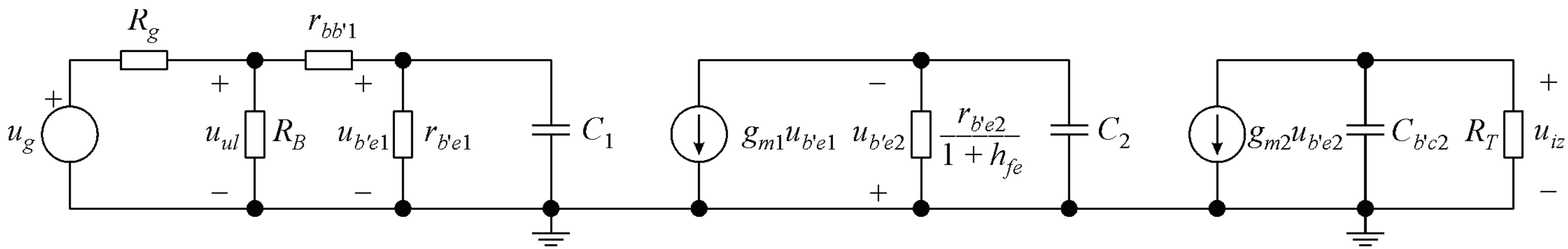
$$K = \frac{-U_{b'e2}}{U_{b'e1}} = -\,g_{m1}\frac{r_{b'e2}}{1+h_{fe2}} = -\frac{h_{fe1}}{r_{b'e1}}\frac{r_{b'e2}}{1+h_{fe2}} \approx -1$$

$$C_{b'c1,ul} = C_{b'c1}\left(1-K\right) \approx 2\,C_{b'c1} \quad \rightarrow \quad C_1 \approx C_{b'e1} + 2C_{b'c1}$$

$$C_{b'c1,ul} = C_{b'c1}\frac{K-1}{K} \approx 2\,C_{b'c1} \quad \rightarrow \quad C_2 \approx 2C_{b'c1} + C_{b'e2}$$



Naponsko pojačanje



$$A_{V0} = \frac{U_{iz}}{U_{ul}} = \frac{U_{iz}}{U_{b'e2}}\frac{U_{b'e2}}{U_{b'e1}}\frac{U_{b'e1}}{U_{ul}} \approx -g_{m2} R_T \frac{r_{b'e1}}{r_{bb'1}+r_{b'e1}}$$

$$\tau_1 = \frac{1}{\omega_1} = \left(r_{b'e1} \| r_{bb'1}\right) C_1 \qquad \tau_2 = \frac{1}{\omega_2} = \frac{r_{b'e2}}{1+h_{fe2}} C_2 \qquad \tau_3 = \frac{1}{\omega_3} = R_T C_{b'c2}$$

1. stupanj → mali iznos naponskog pojačanja zbog malog ulaznog otpora
   2. stupnja → smanjen Millerov efekt → smanjena vremenska konstanta τ_1

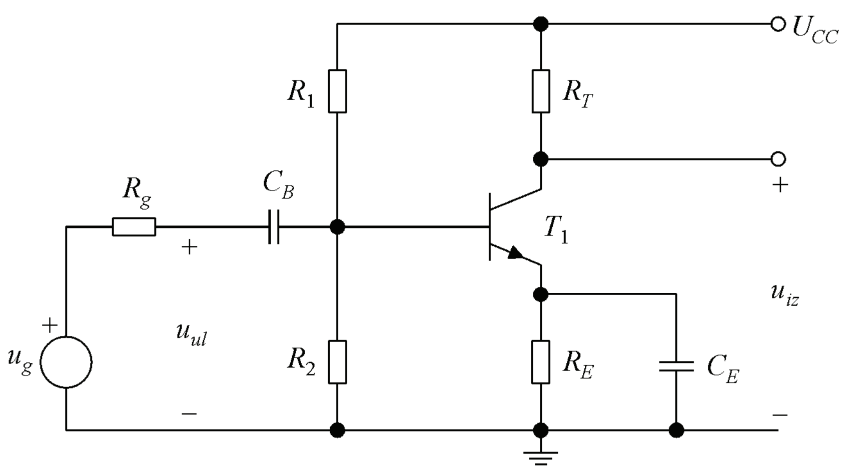
Male vremenske konstante τ_2 i τ_3

Povećana gornja granična frekvencija

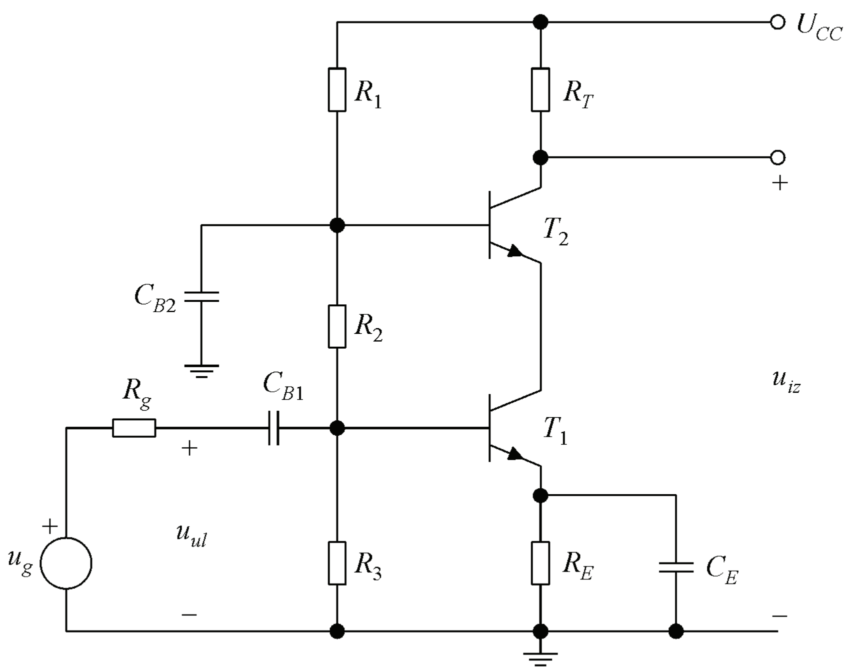
Primjer 4.7 (1)

Odrediti naponsko pojačanje $A_V = U_{iz}/U_{ul}$ na srednjim frekvencijama, te gornju graničnu frekvenciju tog pojačanja za pojačalo u spoju zajedničkog emitera sa slike a i za kaskodno pojačalo sa slike b. Zajednički podaci za oba pojačala su: $U_{CC} = 15$ V, $R_g = 500\ \Omega$, $R_E = 1{,}1\ \mathrm{k}\Omega$ i $R_T = 1\ \mathrm{k}\Omega$. Dodatni podaci za pojačalo sa slike a su: $R_1 = 5{,}5\ \mathrm{k}\Omega$ i $R_2 = 2\ \mathrm{k}\Omega$, a za pojačalo sa slike b: $R_1 = 4\ \mathrm{k}\Omega$, $R_2 = 1{,}5\ \mathrm{k}\Omega$ i $R_3 = 2\ \mathrm{k}\Omega$. Impedancije kondenzatora C_B, C_E, C_{B1} i C_{B2} su zanemarivo male u području srednjih i visokih frekvencija. Svi tranzistori imaju jednake parametre $\beta \approx h_{fe} = 100$, $U_\gamma = 0{,}7$ V, $r_{bb'} = 100\ \Omega$, $C_{b'e} = 50$ pF i $C_{b'c} = 1$ pF. Zanemariti porast struje kolektora s naponom u_{CE} u normalnom aktivnom području. Naponski ekvivalent temperature $U_T = 25$ mV. Usporediti dobivene rezultate.

Primjer 4.7 (2)

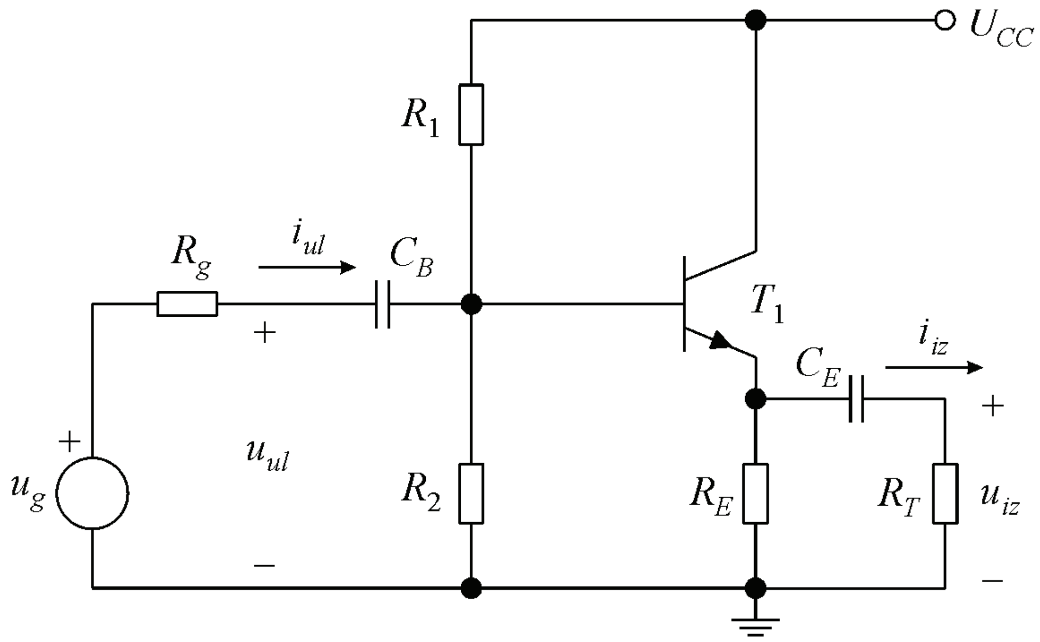


a)

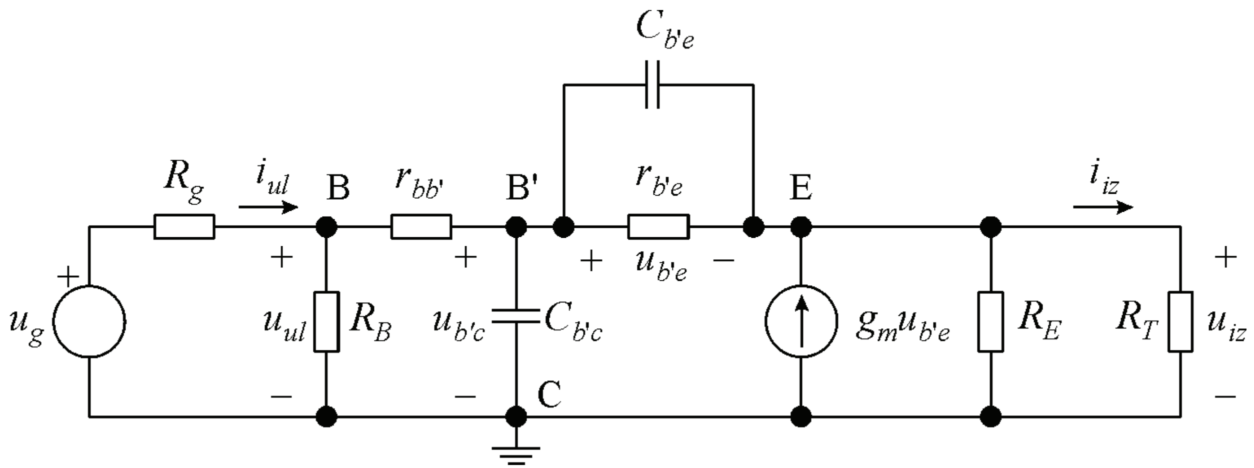


b)

Emitersko sljedilo na visokim frekvencijama



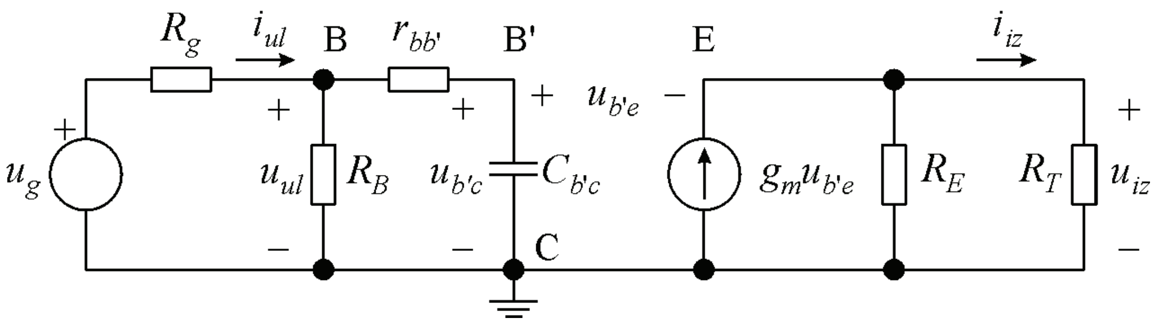
Nadomjesna shema za visokofrekvencijsku analizu



$$A_{V0} = U_{iz}/U_{ul} \approx 1 \quad \rightarrow \quad K = \frac{U_{iz}}{U_{b'c}} \approx \frac{U_{iz}}{U_{ul}} = A_{V0} \approx 1$$

Preslikavanje – $r_{b'e} \rightarrow \infty$, $C_{b'e} \rightarrow 0$ – $r_{b'e}$ i $C_{b'e}$ mogu se izostaviti

Visokofrekvencijska analiza



$$U_{iz} = g_m \left(R_E \| R_T \right) U_{b'e}$$

$$\frac{U_{b'c}}{U_{ul}} = \frac{1/\,j\omega C_{b'c}}{r_{bb'} + 1/\,j\omega C_{b'c}} = \frac{1}{1 + j\omega r_{bb'} C_{b'c}}$$

$$U_{b'e} = U_{b'c} - U_{iz} = \frac{U_{ul}}{1 + j\omega r_{bb'} C_{b'c}} - U_{iz}$$

Naponsko pojačanje

$$A_V(j\omega) = \frac{U_{iz}}{U_{ul}} = \frac{A_{V0}}{1 + j\omega/\omega_{ul}}$$

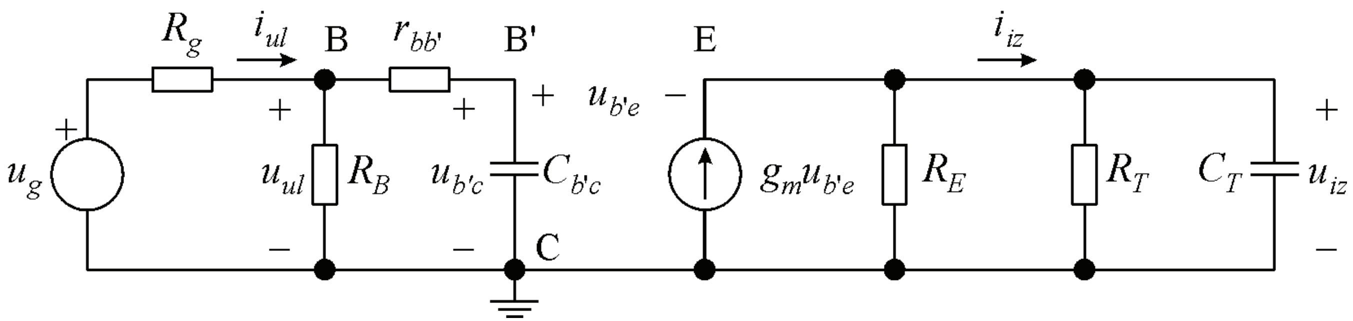
$$A_{V0} = \frac{g_m\left(R_E \| R_T\right)}{1 + g_m\left(R_E \| R_T\right)} \qquad \tau_{ul} = \frac{1}{\omega_{ul}} = r_{bb'} C_{b'c}$$

Gornja granična frekvencija $\rightarrow \omega_g = \omega_{ul}$

uz konačni R_g

$$\tau_{ul} = \left(r_{bb'} + R_g \| R_B\right) C_{b'c}$$

Naponsko pojačanje – uz kapacitivno opterećenje



$$\tau_{iz} = \frac{1}{\omega_{iz}} = \left(R_E \| R_T\right) C_T$$

$$\omega_g = \min\left\{\omega_{ul},\ \omega_{iz}\right\} = \min\left\{\frac{1}{\tau_{ul}},\ \frac{1}{\tau_{iz}}\right\}$$