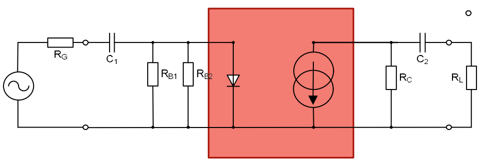
Wrocław University of Technology

BJT ampplifier -cutoff frequencies

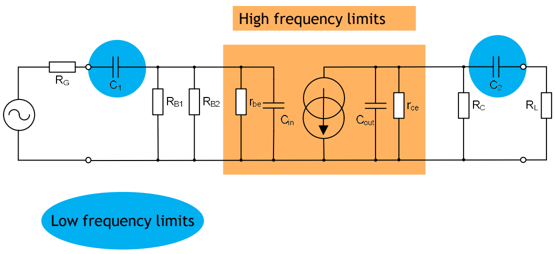
Wrocław University of Technology

Basic -cutoff frequencies



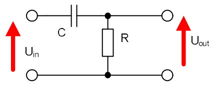
Wrocław University of Technology

Basic - low/high cutoff frequencies

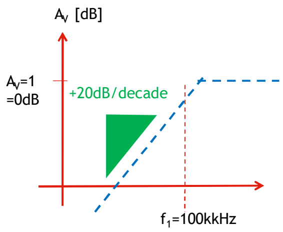


Wroclaw University of Technology

RC high pass filter
low cuoff frequency

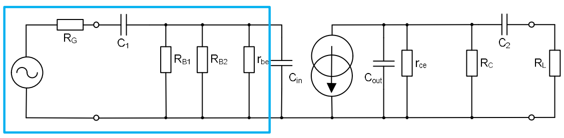


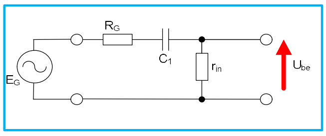
$$f_1 = \frac{1}{2\pi RC}$$



Wroclaw University of Technology

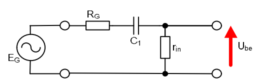
Low input cutoff frequencies

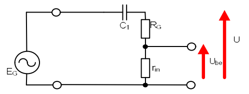




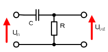
Wroclaw University of Technology

Input BJT
low frequencies





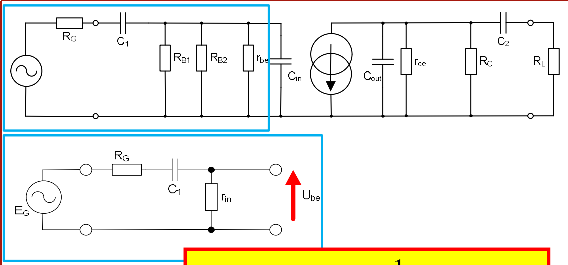
$$U_{be} = U\frac{r_{in}}{R_G + r_{in}}$$



$$f_1 = \frac{1}{2\pi RC}$$

$$f_{1in} = \frac{1}{2\pi(R_G + r_{in})C_1}$$

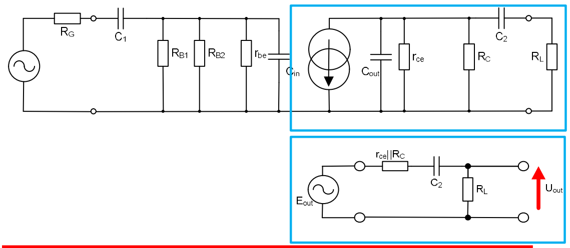
Low input cutoff frequencies



$$f_{1in} = \frac{1}{2\pi\left(R_G + R_{B1} \parallel R_{B2} \parallel r_{be}\right)C_1}$$

Wroclaw University of Technology

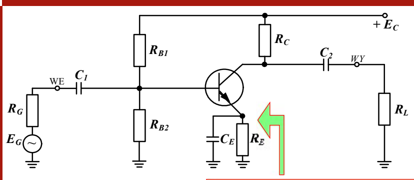
Low input cutoff frequencies



$$f_{1out} = \frac{1}{2\pi\left(R_C \parallel r_{ce} + R_L\right)C_2} = \frac{1}{2\pi\left(r_{outCE} + R_L\right)C_2}$$

Wroclaw University of Technology

CE amp BJT
low frequencies



$$f_{1E} = \frac{1}{2\pi r_{inE} C_E}$$

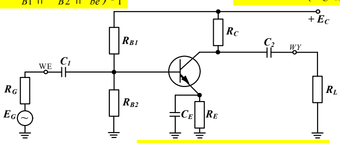
$$r_{inE} = R_E \parallel \left(\frac{r_{be} + R_{B1} \parallel R_{B2} \parallel R_G}{\beta}\right) \approx R_E \parallel \frac{1}{g_m}$$

$$f_{1E} = \frac{1}{2\pi\left(R_E \parallel \frac{r_{be} + R_{B1} \parallel R_{B2} \parallel R_G}{\beta}\right)C_E} \approx \frac{1}{2\pi\left(R_E \parallel \frac{1}{g_m}\right)C_E}$$

Low frequencies of CE - sum up

$$f_{1in} = \frac{1}{2\pi\left(R_G + R_{B1} \parallel R_{B2} \parallel r_{be}\right)C_1}$$

$$f_{1out} = \frac{1}{2\pi\left(R_C \parallel r_{ce} + R_L\right)C_2}$$

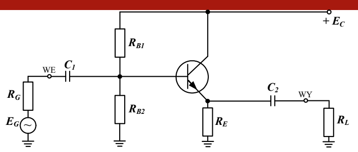


$$f_{1E} = \frac{1}{2\pi\left(R_E \parallel \frac{r_{be} + R_{B1} \parallel R_{B2} \parallel R_G}{\beta}\right)C_E}$$

$$f_1 \approx \sqrt{\left(f_{1in}\right)^2 + \left(f_{1out}\right)^2 + \left(f_{1E}\right)^2}$$

Wrocław University of Technology

Low frequencies of CC - sum up



$$f_{1in} = \frac{1}{2\pi\left(\underbrace{R_G + \underbrace{R_{B1} \parallel R_{B2} \parallel \underbrace{\left(r_{be} + \beta\left(R_E \parallel R_L\right)\right)}_{r_{inT}}}_{r_{inCC}}}\right)C_1}$$

$$f_{1out} = \frac{1}{2\pi\left(\underbrace{R_E \parallel r_{ce} \parallel \frac{r_{be} + R_{B1} \parallel R_{B2} \parallel R_G}{\beta}}_{r_{outCC}} + R_L\right)C_2}$$

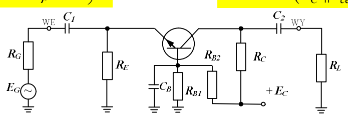
$$f_1 \approx \sqrt{\left(f_{1in}\right)^2 + \left(f_{1out}\right)^2}$$

Wrocław University of Technology

Low frequencies of CB - sum up

$$f_{1in} = \frac{1}{2\pi\left(R_G + R_E \parallel \frac{r_{be} + R_{B1} \parallel R_{B2}}{\beta}\right)C_1}$$

$$f_{1out} = \frac{1}{2\pi\left(R_C \parallel r_{ce} + R_L\right)C_2}$$



$$f_{1B} = \frac{1}{2\pi\left(R_{B1} \parallel R_{B2} \parallel \left(r_{be} + \beta\left(R_E \parallel R_G\right)\right)\right)C_B}$$

$$f_1 \approx \sqrt{\left(f_{1in}\right)^2 + \left(f_{1out}\right)^2 + \left(f_{1B}\right)^2}$$

Low frequencies - sum up

f	CE	CC	CB
f_{1in}	x $\frac{1}{2\pi(R_G + R_{B1} \parallel R_{B2} \parallel r_{be})C_1}$	x $\frac{1}{2\pi(R_G + R_{B1} \parallel R_{B2} \parallel (r_{be} + \beta(R_E \parallel R_L)))C_1}$	$\frac{1}{2\pi\left(R_G + R_E \parallel \frac{r_{be}}{\beta}\right)C_1}$
f_{1out}	$\frac{1}{2\pi(R_C \parallel r_{ce} + R_L)C_2}$	$\frac{1}{2\pi\left(R_E \parallel \frac{r_{be} + R_{B1} \parallel R_{B2} \parallel R_G}{\beta} + R_L\right)C_2}$	x $\frac{1}{2\pi(R_C \parallel r_{ce} + R_L)C_2}$
$f_{1E(B)}$	$\frac{1}{2\pi\left(R_E \parallel \frac{r_{be} + R_{B1} \parallel R_{B2} \parallel R_G}{\beta}\right)C_E}$	NA	$\frac{1}{2\pi(R_{B1} \parallel R_{B2} \parallel (r_{be} + \beta R_E \parallel R_G))C_B}$
f_1	$f_1 \approx \sqrt{(f_{1in})^2 + (f_{1out})^2 + (f_{1E(B)})^2}$		

Wrocław University of Technology

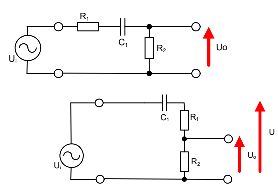
Low frequencies - sum up

f	CE	CC	CB
f_{1in}	x $\frac{1}{2\pi(R_G + r_{inCE})C_1}$	x $\frac{1}{2\pi(R_G + r_{inCC})C_1}$	x $\frac{1}{2\pi(R_G + r_{inCB})C_1}$
f_{1out}	$\frac{1}{2\pi(r_{outCE} + R_L)C_2}$	$\frac{1}{2\pi(r_{outCC} + R_L)C_2}$	$\frac{1}{2\pi(r_{outCB} + R_L)C_2}$
$f_{1E(B)}$	$\frac{1}{2\pi(R_E \parallel r_{outCC})C_E}$	-------	$\frac{1}{2\pi(r_{inCC(R_L \to R_G)})C_B}$

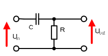
$$f_1 \approx \sqrt{(f_{1in})^2 + (f_{1out})^2 + (f_{1E(B)})^2}$$

Wrocław University of Technology

Input BJT
low frequencies



$$U_o = U\frac{R_2}{R_1 + R_2}$$

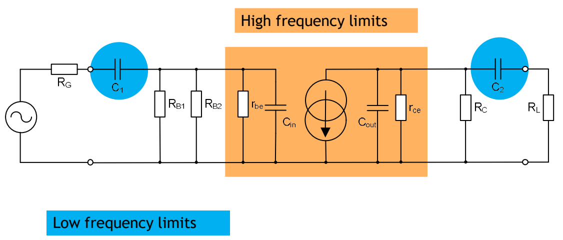


$$f_1 = \frac{1}{2\pi RC}$$

$$f_{1in} = \frac{1}{2\pi(R_1 + R_2)C_1}$$

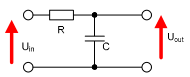
Wroclaw University of Technology

Basic - low/high cutoff frequencies

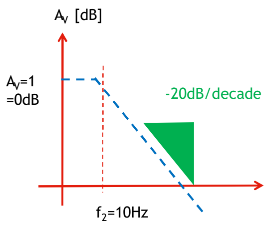


Wroclaw University of Technology

RC low pass filter

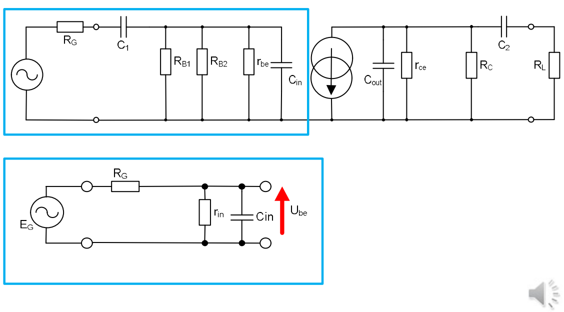


$$f_2 = \frac{1}{2\pi RC}$$

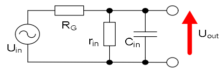


Wroclaw University of Technology

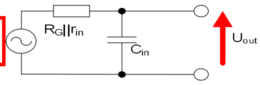
High input cutoff frequencies



Input BJT
high frequencies



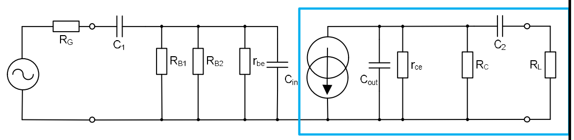
$$U = U_{in} \frac{r_{in}}{R_G + r_{in}}$$

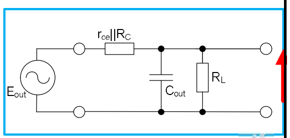


$$f_{2in} = \frac{1}{2\pi (R_G \parallel r_{in}) C_{in}}$$

Wroclaw University of Technology

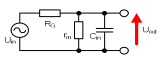
High input cutoff frequencies

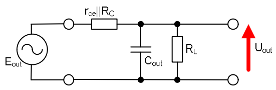




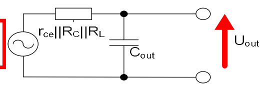
Wroclaw University of Technology

Output BJT
high frequencies



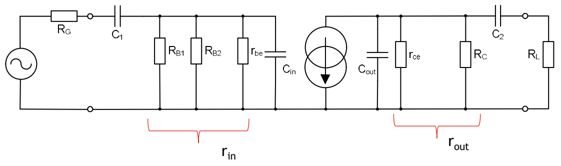


$$U_{in} = \frac{R_L}{R_L + r_{ce} \parallel R_C}$$



$$f_{2out} = \frac{1}{2\pi (r_{ce} \parallel R_C \parallel R_L) C_{out}} = \frac{1}{2\pi (r_{out} \parallel R_L) C_{out}}$$

Output & Input cutoff frequencies



$$f_{2in} = \frac{1}{2\pi\left(R_G \| r_{in}\right)C_{in}}$$

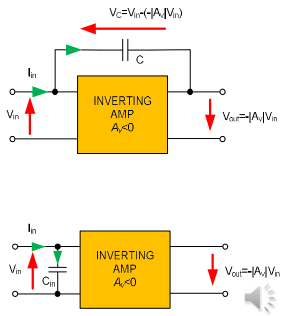
$$f_{2out} = \frac{1}{2\pi\left(r_{out} \| R_L\right)C_{out}}$$

The Miller effect

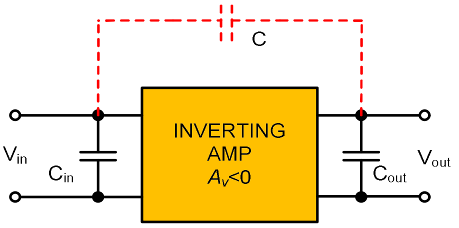
$$I_{in} = I_C = \frac{V_C}{1/sC} = \frac{V_{in} + V_{in}|A_v|}{1/sC} =$$

$$= \frac{V_{in}}{1/sC(1+|A_v|)} = \frac{V_{in}}{1/sC_{in}}$$

$$C_{in} = C\left(1 + |A_v|\right)$$



The Miller effect (inverting amp !!!!!!)

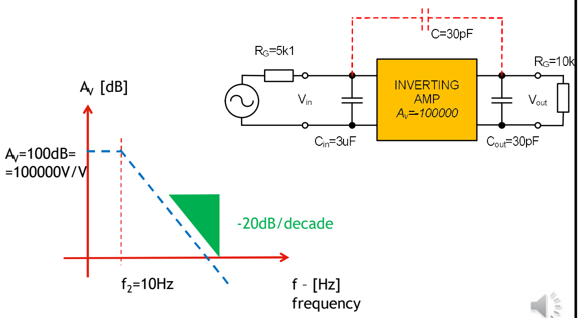


$$C_{in} = C\left(|A_v| + 1\right)$$

$$C_{out} = C\left(\frac{|A_v| + 1}{|A_v|}\right)$$

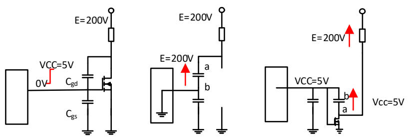
Wroclaw University of Technology

The Miller effect - an example



Wroclaw University of Technology

Miller effect in MOSFET



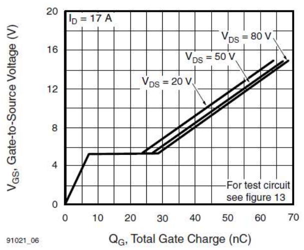
ΔU_{Cgd} = E+Vcc

$$\Delta Q = C_{gs} \cdot Vcc + C_{gd}\,(E + Vcc) = Vcc\left(C_{gs} + C_{gd}\left(1 + \frac{E}{Vcc}\right)\right)$$

$$C_{in} = C_{eb} + C_{bc}\,(1 + |A_v|)$$

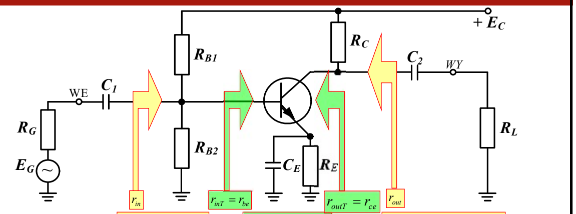
Wroclaw University of Technology

Miller effect for power MOSFET switching transistors



Wroclaw University of Technology

Summary of CE amp BJT
medium frequencies



$$r_{in} = \underbrace{R_{B1} \parallel R_{B2}}_{R_B} \parallel r_{be}$$

$$r_{out} = r_{ce} \parallel R_C \underset{r_{ce} >> R_C}{\approx} R_C$$

$\varphi_T \approx 26mV$

$V_A \approx 50 \div 300V$

$U_{CEQ}, I_{CQ} - \text{Q} - point$

$\beta_{AC} \approx \beta_{DC}$

$$g_m = \frac{I_{CQ}}{\varphi_T}$$

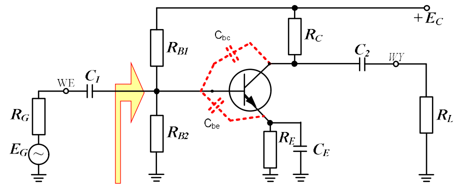
$$r_{be} = \frac{\beta}{g_m}$$

$$r_{ce} = \frac{V_A + U_{CEQ}}{I_{CQ}}$$

$$k_{Veff} = \underbrace{-g_m \cdot \underbrace{R_{LOAD}}_{R_L \| r_{out}}}_{k_V} \cdot \underbrace{\gamma_V}_{\frac{r_{in}}{r_{in}+R_G}}$$

Wroclaw University of Technology

Summary of CE BJT amp
input characteristic

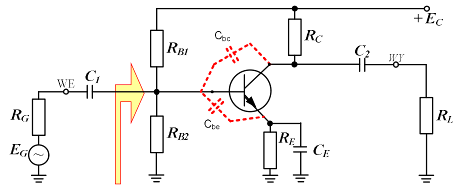


$$C_{inCE} = C_{be} + C_{bc}(1 + |A_v|)$$

$$r_{in} = \underbrace{R_{B1} \parallel R_{B2}}_{R_B} \parallel r_{be}$$

Wroclaw University of Technology

Summary of CE amp BJT
upper cutoff frequency



$$C_{inCE} = C_{be} + C_{bc}(1 + |A_v|)$$

$$r_{inCE} = \underbrace{R_{B1} \parallel R_{B2}}_{R_B} \parallel r_{be}$$

$$f_{2in} = \frac{1}{2\pi(R_G \parallel r_{inCE})C_{inCE}}$$

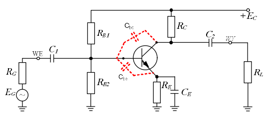
Sumary of CE amp BJT
high frequencies

$C_{be}+C_{bc}=\frac{g_m}{2\cdot\pi\cdot f_T}$

$g_m=\frac{I_{CQ}}{\varphi_T}$

$$C_{inCE}=C_{be}+C_{bc}(1+|A_v|)\approx\frac{g_m}{2\cdot\pi\cdot f_T}+C_{bc}|A_v|$$

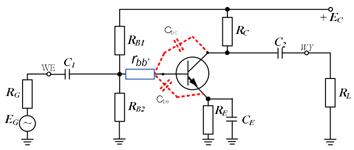
$$r_{in}=\underbrace{R_{B1}\parallel R_{B2}}_{R_B}\parallel r_{be}$$



$$f_{2in}=\frac{1}{2\pi(R_G\parallel r_{in})C_{in}}$$

Wroclaw University of Technology

....taking $r_{bb'}$ into account



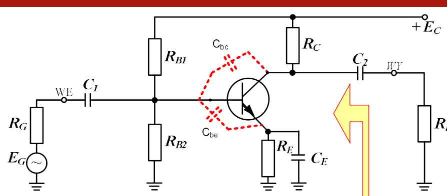
$$f_{2in}=\frac{1}{2\pi((R_G\parallel R_B+r_{bb'})\parallel r_{be})C_{in}}$$

....very important for v.h.f.

.....when R_G is small and commeasurate with $r_{bb'}$

Wroclaw University of Technology

Summary of CE BJT amp
output characteristic



$$C_{outCE}=C_{bc}+C_{parasitic}$$

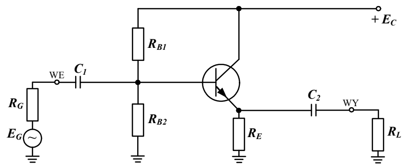
$$r_{outCE}=r_{ce}\parallel R_C$$

$$f_{2out}=\frac{1}{2\pi(R_L\parallel R_C\parallel r_{ce})(C_{bc}+C_{para})}$$

Wrocław University of Technology

Sumary of CC amp BJT
high frequencies

$\varphi_T \approx 26mV$
$U_{EY} \approx 50 \div 300V$
U_{CEQ}, I_{CQ} – pkt.pracy
β, f_T, c_{bc} } z katalogu
$r_{bb'}$ dla m.cz. = 0



$$g_m = \frac{I_{CQ}}{\varphi_T}$$

$$r_{ce} = \frac{U_{EY} + U_{CEQ}}{I_{CQ}}$$

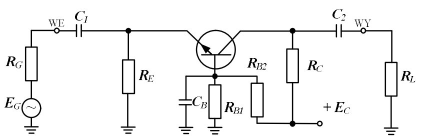
$$c_{be} = \frac{g_m}{2 \cdot \pi \cdot f_T} - c_{bc}$$

$$f_{2in} = \frac{1}{2 \cdot \pi \cdot R_G \| R_B \cdot \left(c_{bc} + \dfrac{c_{be}}{g_m \cdot r_{ce} \| R_E \| R_L} \right)}$$

$$f_{2out} >> f_{2in}$$

Wrocław University of Technology

Sumary of CB amp BJT
high frequencies



$$f_{2in} = \frac{1}{2\pi \left(R_G \| R_E \| \dfrac{r_{be}}{\beta} \right) C_{be}}$$

$$f_{2out} = \frac{1}{2\pi (R_C \| R_L \| r_{ce})(C_{bc} + C_{para})}$$

Wrocław University of Technology

High frequencies - sum up

f	CE	CC	CB
f_{2in}	x $f_{2in} = \frac{1}{2\pi(R_G \| (R_B \| r_{be}))C_{in}}$ $C_{in} = C_{be} + C_{bc}(1 + \|A_v\|)$	x $f_{2in} = \frac{1}{2 \cdot \pi \cdot R_G \| r_{inCC} \left(c_{bc} + \frac{c_{be}}{g_m \cdot r_{ce} \| R_E \| R_L} \right)}$	$f_{2in} = \frac{1}{2\pi \left(R_G \| \left(R_E \| \frac{r_{be}}{\beta} \right) \right) C_{be}}$
f_{2out}	$f_{2out} = \frac{1}{2\pi(R_L \| (R_C \| r_{bc}))(C_{bc} + C_{para})}$	$f_{2out} >> f_{2in}$	x $f_{2out} = \frac{1}{2\pi(R_L \| (R_C \| r_{ce}))(C_{bc} + C_{para})}$
Just about	~f_T/β	<f_T	~f_T

$$f_{2in} = \frac{1}{2\pi(R_G \| r_{in})C_{in}}$$

$$f_{2out} = \frac{1}{2\pi(r_{out} \| R_L)C_{out}}$$

$$f_2^{-1} \approx \sqrt{(f_{2in})^{-2} + (f_{2out})^{-2}}$$

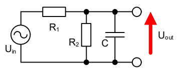
$$C_{be} + C_{bc} = \frac{g_m}{2\pi f_T}$$

$$g_m = \frac{I_{CQ}}{\varphi_T}$$

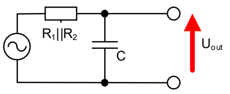
NOTICE: in formulas do not included $r_{bb'}$ for h.f.

Wrocław University of Technology

Output BJT
high frequencies



$$U_{in}^{T} = U_{in}\frac{R_2}{R_2 + R_1}$$



$$f_2 = \frac{1}{2\pi(R_1 \| R_2)C}$$

Wrocław University of Technology

High frequencies - sum up

f	CE	CC	CB
C_{in}	x $C_{in} = C_{be} + C_{bc}(1 + \lvert A_V \rvert)$	x $c_{bc} + \frac{c_{be}}{g_m \cdot r_{ce} \| R_E \| R_L}$	C_{be}
C_{out}	$C_{bc} + C_{para}$	C_{para} $f_{2out} >> f_{2in}$	x $C_{bc} + C_{para}$
Just about	$\sim f_T/\beta$	$< f_T$	$\sim f_T$

$$f_{2in} = \frac{1}{2\pi(R_G \| r_{in})C_{in}}$$

$$f_{2out} = \frac{1}{2\pi(r_{out} \| R_L)C_{out}}$$

$$f_2^{-1} \approx \sqrt{(f_{2in})^{-2} + (f_{2out})^{-2}}$$

$$C_{be} + C_{bc} = \frac{g_m}{2 \cdot \pi \cdot f_T}$$

$$g_m = \frac{I_{CQ}}{\varphi_T}$$

Uwaga: tabela nie uwzględnia $r_{bb'}$ istotną przy dużych częstotliwościach

Wrocław University of Technology

CE-CC-CB comparison

$R_B = R_{B1} \| R_{B2}$ $\quad r_{be}/\beta = 1/g_m$

Para-meter	configuration		
	CE	CC	CB
$A_V = \frac{u_{be}}{u_L}$	$-\beta\frac{R_C \| R_L \| r_{ce}}{r_{be}}$	$\frac{R_E \| R_L \| r_{ce}}{R_E \| R_L \| r_{ce} + r_{be}/\beta}$	$-\beta\frac{R_C \| R_L \| r_{ce}}{r_{be}}$
$A_I = \frac{i_b}{i_L}$	$\frac{-R_C \| r_{ce}}{R_C \| r_{ce} + R_L}\beta$	$\frac{R_E}{R_E + R_L}\beta$	$\frac{-R_C \| r_{ce}}{R_C \| r_{ce} + R_L}$
$r_{in} = \frac{u_{be}}{i_{b(e)}}$	$R_B \| r_{be}$	$(\beta(R_E \| R_L) + r_{be}) \| R_B$	$\left(\frac{r_{be}}{\beta}\right) \| R_E$
$r_{out} = \frac{u_{out}}{i_{c(e)}}$ (e) - for CB	$R_C \| r_{ce}$	$\left(\frac{(R_B \| R_G) + r_{be}}{\beta}\right) \| R_E$	$R_C \| r_{ce}$

Wrocław University of Technology

CE-CC-CB general comparison

Para-meter	configuration		
	CE	CC	CB
$A_V = \frac{u_{be}}{u_L}$	***High*** (10-200)	***<1***	***High*** (10-200)
$A_I = \frac{i_b}{i_L}$	***High*** (10-200)	***High*** (10-200)	***<1***
$r_{in} = \frac{u_{be}}{i_{b(e)}}$	***Medium*** (0.5k-5k)	***High*** (10k-1M)	***Low*** (10Ω-500Ω)
$r_{out} = \frac{u_{out}}{i_{c(e)}}$ (e) - for CB	***Medium*** (0.5k-5k)	***Low*** (10Ω-500Ω)	***Medium*** (0.5k-5k)

Wrocław University of Technology

Sumary of BJT with feedback
high frequencies

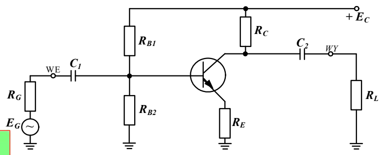
$\phi_T \approx 26mV$

$U_A \approx 50 \div 300V$

U_{CEQ}, I_{CQ} – Q-poin

$\left.\begin{matrix}\beta \\ f_T \\ c_{bc}\end{matrix}\right\}$ data sheet

$r_{bb'}$ for l.f. $r_{bb'} = 0$



$$g_m = \frac{I_{CQ}}{\phi_T}$$

$$c_{be} = \frac{g_m}{2 \cdot \pi \cdot f_T} - c_{bc}$$

$$c_{in} = c_{be} \frac{r_{be}}{r_{be} + (\beta + 1) R_E} + c_{bc} \left(1 + |k_u|\right)$$

$$k_u \approx \frac{R_C}{R_E}$$

$$r_{in} = \underbrace{R_{B1} \| R_{B2}}_{R_B} \| \left[r_{be} + R_E(\beta + 1)\right]$$

$$f_{2in} = \frac{1}{2\pi C_{in} \left(r_{in} \| R_G\right)}$$

Wrocław University of Technology

Sumary - cutoff frequencies

- RC circuits for high (f2) and low (f1) cutoff frequencies

$$f_{1in} = \frac{1}{2\pi (R_G + r_{in}) C_1}$$

$$f_{2in} = \frac{1}{2\pi (R_G \| r_{in}) C_{in}}$$

$$f_{1out} = \frac{1}{2\pi (r_{out} + R_L) C_2}$$

$$f_{2out} = \frac{1}{2\pi (r_{out} \| R_L) C_{out}}$$

f1 are limited by capacitors in series with in/out and sum of resistors

f2 are limited by capacitors in parallel with in/out and parallel connection of resistors

Wrocław University of Technology

Problems

- Draw schematic diagram of BJT amplifier (transistor as model) showing cut-off frequencies elements
- Explain Miller effect.
- Estimate low- and high-cut off frequencies for given RC diagrams.
- Compare high cut-off frequencies for BJT in CE, CC, CB configurations.