High Frequency BJT Model
Cascode BJT Amplifier
Gain of 10 Amplifier – Non-ideal Transistor

Gain starts dropping at > 1MHz.

Why!
Because of internal transistor capacitances that we have ignored in our low frequency and mid-band models.
Sketch of Typical Voltage Gain Response for a CE Amplifier

\[ |A_v|(dB) \]

**Low Frequency Band**
- Due to external blocking and bypass capacitors.
- Internal C's o.c.

**Midband**
- ALL capacitances are neglected, i.e.
  - External C's s.c.
  - Internal C's o.c.

**High Frequency Band**
- Due to BJT parasitic capacitors \( C_\pi \) and \( C_\mu \).
- External C's s.c.

\[ BW = f_H - f_L \approx f_H \]
\[ GBP = |A_{v-mid}| BW \]
High Frequency Small-signal Model (Fwd. Act.)

Two capacitors and a resistor added.

A base to emitter capacitor, $C_{\pi}$

A base to collector capacitor, $C_{\mu}$

A resistor, $r_x$, representing the base terminal resistance ($r_x \ll r_{\pi}$)

\[
C_{\mu} = \frac{C_{\mu 0}}{V_{CB}^{m}} 
(1 + \frac{V_{CB}}{V_{0c}})
\]

\[
C_{\pi} = C_{de} + C_{je} \approx C_{de} + 2C_{je0} \approx C_{de}
\]

\[
C_{de} = \tau_F g_m
\]

$\tau_F$ = forward-base transit time

SPICE

$C_{JC} = C_{\mu 0}$

$C_{JE} = C_{je0}$

$TF = \tau_F$

$RB = r_x$
High Frequency Small-signal Model (IC)
**High Frequency Small-signal Model**

The transistor parasitic capacitances have a strong effect on circuit high frequency performance! They attenuate base signals, decreasing $v_{be}$ since their reactance approaches zero (short circuit) at high frequencies.

As we will see later, $C_\mu$ is the principal cause of this gain loss at high frequencies. At the base $C_\mu$ looks like a capacitor of value $k \times C_\mu$ connected between base and emitter, where $k > 1$ and may be $>> 1$.

This phenomenon is called the **Miller Effect**.
**Prototype Common Emitter Circuit**

At high frequencies
“low frequency”
capacitors are “short circuits”

High frequency
small-signal ac model
Multisim Simulation

\[ A_{v_{-\text{mid}}} = -g_m R_C = -204 \]
Introducing the Miller Effect

The feedback connection of $C_{\mu}$ between base and collector causes it to appear in the amplifier like a large capacitor $(1 - K)C_{\mu}$ has been inserted between the base and emitter terminals. This phenomenon is called the “Miller effect” and the capacitive multiplier “$1 - K$” acting on $C_{\mu}$ equals the CE amplifier mid-band gain, i.e. $K = A_{v-mid} = -g_m R_C$

NOTE: CB and CC amplifiers do not suffer from the Miller effect, since in these amplifiers, one side of $C_{\mu}$ is connected directly to ground.
**Miller's Theorem**

\[ A_{v-mid} = \frac{V_o}{V_{be}} \approx \frac{V_o}{V_{be}} = -g_m R_C \]

\[ Z = \frac{1}{2\pi f C_\mu} \]
**Miller's Theorem**

\[ I = I_1 + I_2 \]

\[ I_1 = I \]
\[ I_2 = -I \]

\[ V_1 \]
\[ A_v V_1 \]
\[ V_2 \]

\[ I = I_1 = \frac{V_1 - V_2}{Z} = \frac{V_1 - A_v V_1}{Z} = \frac{V_1}{Z} \]

\[ 1 - A_v \]

\[ \Rightarrow \]

\[ Z_1 = \frac{1}{1 - A_v} \]

\[ Z_2 = \frac{1}{j 2 \pi f C_\mu (1 - A_v)} \]

\[ Z = \frac{1}{j 2 \pi f C_\mu} \]

\[ Z_1 = \frac{Z}{1 - A_v} \]

\[ Z_2 = \frac{Z}{1 - \frac{1}{A_v}} \]

\[ \approx Z \]

**Ignored in practical circuits**
Common Emitter Miller Effect Analysis

Note: The current through $C_{\mu}$ depends only on $V_{be}$!

Determine effect of $C_{\mu}$:

Using phasor notation:

$$I_{Rc} = -g_m V_{be} + I_{C_{\mu}}$$

or

$$V_o = \left( -g_m V_{be} + I_{C_{\mu}} \right) R_C$$

where

$$I_{C_{\mu}} = \left( V_{be} - V_o \right) j \omega C_{\mu}$$

$$I_{C_{\mu}} = \left( V_{be} + g_m V_{be} R_C - I_{C_{\mu}} R_C \right) / V_o$$
Common Emitter Miller Effect Analysis II

From slide 7:

\[ I_{C_{\mu}} = \left( V_{be} + g_m V_{be} R_C - I_{C_{\mu}} R_C \right) j \omega C_{\mu} \]

Collect terms for \( I_{C_{\mu}} \) and \( V_{be} \):

\[
\left( 1 + j \omega R_C C_{\mu} \right) I_{C_{\mu}} = \left( 1 + g_m R_C \right) j \omega C_{\mu} V_{be}
\]

\[
I_{C_{\mu}} = \frac{1 + g_m R_C}{1 + j \omega R_C C_{\mu}} j \omega C_{\mu} V_{be} \approx \left( 1 + g_m R_C \right) j \omega C_{\mu} V_{be} = j \omega C_{eq} V_{be}
\]

Miller Capacitance \( C_{eq} \):

\[
C_{eq} = (1 - A_v) C_{\mu} = (1 + g_m R_C) C_{\mu}
\]
\[ C_{eq} = (1 - A_v) C_\mu = (1 + g_m R_C) C_\mu \]
Common Emitter Miller Effect Analysis III

\[ C_{eq} = \left( 1 + g_m R_C \right) C_\mu \]

For our example circuit:

\[ 1 + g_m R_C = 1 + 0.040 \cdot 5100 = 205 \]

\[ C_{eq} = (205) \cdot 2 \, pF \approx 410 \, pF \]
Simplified HF Model

Thevenin Equiv.

\[
V_s' = V_s \frac{R_B || r_\pi}{R_B || r_\pi + R_S}
\]

\[
R_S' = r_\pi || (R_B || R_S)
\]

\[
R_L' = r_o || (R_C || R_L)
\]
**Simplified HF Model**

\[ C_{eq} = (1 + g_m R_C) C_\mu \]

\[ C_{tot} = C_\pi + C_{eq} \]

\[ R_L = r_o || (R_C || R_L) \]

\[ R'_S = r_\pi || (R_B || R_S) \]

\[ V'_s = V_s \frac{R_B}{R_B || r_\pi + R_S} \]
Simplified HF Model

\[ C_{\text{tot}} = C_{\pi} + (1 + g_m R_C) C_{\mu} \]

\[ V_{be} = \frac{1}{1/j\omega C_{\text{tot}} + R_S'} V_{s}' \]

\[ A_v(f) = \frac{V_o}{V_s} \approx \frac{-g_m R_L'}{1 + j 2\pi f C_{\text{tot}} R_S'} = \frac{-g_m R_L'}{1 + j f f_H} \]

\[ A_{v-mid} = -g_m R_L' \text{ and } f_H = \frac{1}{2\pi C_{\text{tot}} R_S} \]

\[ R_L' = r_o || (R_C || R_L) \]

\[ R_S' = r_{\pi} || (R_B || R_S) \]

\[ V_{s}' = V_s \frac{R_B}{R_B || r_{\pi} + R_S} \]
The relationship \( i_c = \beta i_b \) does not apply at high frequencies \( f > f_H \)!

Using the relationship \(-i_c = f(V_{\pi})\) – find the new relationship between \( i_b \) and \( i_c \). For \( i_b \) (using \textit{phasor notation} \( (I_x \text{ & } V_x) \) for \textit{frequency domain analysis}):

\[
@ \text{node B'}: \quad I_b = \left( \frac{1}{r_{\pi}} + j \omega (C_{\pi} + C_{\mu}) \right) V_{\pi} \quad \text{where} \quad r_{x} \approx 0 \quad \text{(ignore} \ r_{x} \text{)}
\]
Frequency-dependent $h_{fe}$ or “beta”

\[ I_b = \left( \frac{1}{r_{\pi}} + j\omega(C_\pi + C_\mu) \right) V_\pi \]

@ node C: \[ I_c = (g_m - j\omega C_\mu) V_\pi \text{ (ignore } r_o \text{)} \]

Leads to a new relationship between the $I_b$ and $I_c$:

\[ h_{fe} = \frac{I_c}{I_b} = \frac{g_m - j\omega C_\mu}{\frac{1}{r_{\pi}} + j\omega(C_\pi + C_\mu)} \]
Frequency Response of $h_{fe}$

$$h_{fe} = \frac{g_m - j \omega C_\mu}{1 + j \omega (C_\pi + C_\mu) r_\pi}$$

Multiplying N&D by $r_\pi$:

$$h_{fe} = \frac{(g_m - j \omega C_\mu) r_\pi}{1 + j \omega (C_\pi + C_\mu) r_\pi}$$

Factoring N to isolate $g_m$:

$$h_{fe} = \frac{(1 - j \omega \frac{C_\mu}{g_m}) g_m r_\pi}{1 + j \omega (C_\pi + C_\mu) r_\pi}$$

$$g_m = \frac{I_C}{V_T} \quad r_\pi = \beta \frac{V_T}{I_C}$$

For small $\omega = \omega_{low}$:

$$\omega_{low} \frac{C_\mu}{g_m} \ll 1 < \frac{1}{10}$$

And:

$$\omega_{low} (C_\pi + C_\mu) r_\pi \ll 1 < \frac{1}{10}$$

Note: $\omega_{low} (C_\pi + C_\mu) r_\pi = \omega_{low} (C_\pi + C_\mu) \frac{\beta}{g_m} \gg \omega_{low} \frac{C_\mu}{g_m}$

We have: $h_{fe} = g_m r_\pi = \beta$
Frequency Response of $h_{fe}$ cont.

\[
\begin{align*}
    h_{fe} &= \frac{(1 - j \omega \frac{C_\mu}{g_m}) g_m r_\pi}{1 + j \omega (C_\pi + C_\mu) r_\pi} = \frac{1 - j \frac{\omega}{\omega_z}}{1 + j \frac{\omega}{\omega_\beta}} g_m r_\pi = \frac{1 - j \frac{f}{f_z}}{1 + j \frac{f}{f_\beta}} \beta \\
    \omega_\beta &= (C_\pi + C_\mu) r_\pi = (C_\pi + C_\mu) \frac{\beta}{g_m} \gg \frac{C_\mu}{g_m} \implies f_z \gg f_\beta
\end{align*}
\]

Hence, the lower break frequency or $-3$dB frequency is $f_\beta$

\[
    f_\beta = \frac{1}{2 \pi (C_\pi + C_\mu) r_\pi} = \frac{g_m}{2 \pi (C_\pi + C_\mu) \beta}
\]

the upper: \[ f_z = \frac{1}{2 \pi C_\mu / g_m} = \frac{g_m}{2 \pi C_\mu} \]

where \( f_z > 10 f_\beta \)
**Frequency Response of $h_{fe}$ cont.**

Using Bode plot concepts, for the range where: $f < f_\beta$

\[ h_{fe} = g_m r_\pi = \beta \]

For the range where: $f_\beta < f < f_z$ s.t. $|1 - j f / f_z| \approx 1$

We consider the frequency-dependent numerator term to be 1 and focus on the response of the denominator:

\[ f_\beta < f < f_z \]

\[ h_{fe} \approx \frac{g_m r_\pi}{\left(1 + j \frac{f}{f_\beta}\right)} = \frac{\beta}{\left(1 + j \frac{f}{f_\beta}\right)} \]
**Frequency Response of \( h_{fe} \) cont.**

Neglecting numerator term:

\[
h_{fe} = \frac{g_m r_{\pi}}{1 + j \frac{f}{f_\beta}} = \frac{\beta}{1 + j \frac{f}{f_\beta}}
\]

And for \( f / f_\beta >> 1 \) (but \( < f / f_z \)):

\[
|h_{fe}| \approx \frac{\beta}{f_z} = \beta \frac{f_\beta}{f}
\]

Unity gain bandwidth:

\[
|h_{fe}| = 1 \Rightarrow \beta \frac{f_\beta}{f} \quad |f = f_\Gamma = 1 \Rightarrow f_T = \beta f_\beta
\]

\[
f_T = \frac{\omega_T}{2\pi} = \beta \frac{f_\beta}{f}
\]

BJT unity-gain frequency or GBP
Frequency Response of $h_{fe}$ cont.

\[ \beta = 100 \quad r_\pi = 2500 \Omega \quad C_\pi = 12 \, \text{pF} \quad C_\mu = 2 \, \text{pF} \quad g_m = 40 \cdot 10^{-3} \, \text{S} \]

\[ \omega_\beta = \frac{1}{(C_\pi + C_\mu) r_\pi} = \frac{10^{12} \cdot 10^{-3}}{(12 + 2) \cdot 2.5} = 28.57 \cdot 10^6 \, \text{rps} \]

\[ f_\beta = \frac{\omega_\beta}{2\pi} = \frac{28.57}{6.28} \cdot 10^6 \, \text{Hz} = 4.55 \, \text{MHz} \quad f_T = \beta f_\beta = 455 \, \text{MHz} \]

\[ \omega_z = \frac{g_m}{C_\mu} = \frac{40 \cdot 10^{-3} \cdot 10^{12}}{2} \, \text{Hz} = 20 \cdot 10^9 \, \text{rps} \]

\[ f_z = \frac{\omega_z}{2\pi} = 3.18 \cdot 10^9 \, \text{Hz} = 3180 \, \text{MHz} \]


// f_T Bode Plot  
Beta=100;  
KdB= 20*log10(Beta);  
fz=3180;  
fp=4.55;  
f= 1:1:10000;  
term1=KdB*sign(f);  //Constant array of len(f)  
term2=max(0,20*log10(f/fz));  //Zero for f < fz;  
term3=min(0,-20*log10(f/fp));  //Zero for f < fp;  
BodePlot=term1+term2+term3;  
plot(f,BodePlot);
\( h_{fe} \) Bode Plot

\[ \text{hfe (dB)} \quad \text{hfe vs. Frequency} \]

\[ \text{Freq. (MHz.)} \]

\[ f_T \]
Multisim Simulation

Insert 1 ohm resistors – we want to measure a current ratio.

\[ h_{fe} = \frac{I_c}{I_b} = \frac{g_m - j\omega C_\mu}{\frac{1}{r_{\pi}} + j\omega(C_\pi + C_\mu)} \]
Simulation Results

Low frequency $|h_{fe}|$

Theory:

$f_T = \beta f_\beta = 455 \text{ MHz}$

Unity Gain frequency about 440 MHz
The Cascode Amplifier

• A two transistor amplifier used to obtain simultaneously:
  1. Reasonably high input impedance.
  2. Reasonable voltage gain.
  3. Wide bandwidth.

• None of the conventional single transistor designs will satisfy all of the criteria above.
• The cascode amplifier will satisfy all of these criteria.
• A cascode is a CE Stage cascaded with a CB Stage.

(Historical Note: the cascode amplifier was a cascade of grounded cathode and grounded grid vacuum tube stages – hence the name “cascode,” which has remained in modern terminology.)
The Cascode Amplifier

Comments:
1. $R_1$, $R_2$, $R_3$, and $R_C$ set the bias levels for both $Q1$ and $Q2$.
2. Determine $R_E$ for the desired voltage gain.
3. $C_{in}$ and $C_{byp}$ are to act as “open circuits” at dc and act as “short circuits” at all operating frequencies $f > f_{min}$.
Cascode Mid-Band Small Signal Model

\[ R_B = R_2 \parallel R_3 \]
Cascode Small Signal Analysis

1. Show reduction in Miller effect
2. Evaluate small-signal voltage gain

**OBSERVATIONS**

a. The emitter current of the CB Stage is the collector current of the CE Stage. (This also holds for the dc bias current.)

\[ i_{e1} = i_{c2} \]

b. The base current of the CB Stage is:

\[ i_{b1} = \frac{i_{e1}}{\beta + 1} = \frac{i_{c2}}{\beta + 1} \]

c. Hence, both stages have about same collector current \( i_{c1} \approx i_{c2} \) and same \( g_m', r_e, r_\pi \).
The input resistance $R_{in1}$ to the CB Stage is the small-signal “$r'_{el}$” for the CB Stage, i.e.

$$i_{bl} = \frac{i_{e1}}{\beta + 1} = \frac{i_{c2}}{\beta + 1}$$

The CE output voltage, the voltage drop from Q2 collector to ground, is:

$$v_{c2} = v_{el} = -r_{\pi}i_{bl} = -\frac{r_{\pi}}{\beta + 1}i_{c2} = -\frac{r_{\pi}}{\beta + 1}i_{e1}$$

herefore, the CB Stage input resistance is:

$$R_{in1} = \frac{v_{el}}{-i_{e1} \beta + 1} = r'_{el}$$

$$A_{vCE\text{-Stage}} = \frac{v_{c2}}{v_s} \approx -\frac{R_{in1}}{R_E} = -\frac{r_e}{R_E} < 1 \Rightarrow C_{eq} = \left(1 + \frac{r_e}{R_E}\right)C_\mu < 2C_\mu$$
Cascode Small Signal Analysis - cont.

Now, find the CE collector current in terms of the input voltage $v_s$:

Recall $i_{c1} \approx i_{c2}$

\[
i_{b2} \approx \frac{v_s}{R_S || R_B + r_\pi + (\beta + 1) R_E}
\]

\[
i_{c2} = \beta i_{b2} \approx \frac{\beta v_s}{R_S || R_B + r_\pi + (\beta + 1) R_E} \approx \frac{\beta v_s}{(\beta + 1) R_E}
\]

for bias insensitivity: $(\beta + 1) R_E \gg R_S || R_B + r_\pi$

\[
i_{c1} \approx i_{e1} = i_{c2} \approx i_{e2}
\]

\[
i_{c2} \approx \frac{v_s}{R_E}
\]

\[
v_o = -i_{c2} R_C
\]

\[
A_v = \frac{v_o}{v_s} = \frac{-R_C}{R_E}
\]

OBSERVATIONS:

1. Voltage gain $A_v$ is about the same as a stand-alone CE Amplifier.
2. HF cutoff is much higher than a CE Amplifier due to the reduced $C_{eq}$. 

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Cascode Biasing

1. Choose $I_{E1}$ – make it relatively large to reduce $R_{in1} = r_e = V_T / I_{E1}$ to push out HF break frequencies.

2. Choose $R_C$ for suitable voltage swing $V_{C1}$ and $R_E$ for desired gain.

3. Choose bias resistor string such that its current $I_I$ is about 0.1 of the collector current $I_{C1}$.

4. Given $R_E$, $I_{E2}$ and $V_{BE2} = 0.7\, V$ calc. $R_3$.

5. Need to also determine $R_1$ & $R_2$. 

\[ \alpha_2 I_{E2} = I_{C2} = I_{E1} = \frac{1}{\alpha_1} I_{C1} \Rightarrow I_{C1} \approx I_{E2} \]
Cascode Biasing - cont.

Since the CE-Stage gain is very small:

a. The collector swing of Q2 will be small.

b. The Q2 collector bias \( V_{C2} = V_{B1} - 0.7 \text{ V} \).

6. Set \( V_{B1} - V_{B2} = 1 \text{ V} \Rightarrow V_{CE2} = 1 \text{ V} \)

This will limit \( V_{CB2} \), \( V_{CB2} = V_{CE2} - V_{BE2} = 0.3 \text{ V} \)
which will keep Q2 forward active.

7. Next determine \( R_2 \). Its drop \( V_{R2} = 1 \text{ V} \)
with the known current.

\[
V_{CE2} = V_{C2} - V_{Re} = V_{C2} - (V_{B2} - 0.7 \text{ V}) = V_{B1} - 0.7 \text{ V} - V_{B2} + 0.7 \text{ V} = V_{B1} - V_{B2}
\]
Cascode Biasing - cont.

8. Then calculate $R_3$.

$$R_3 = \frac{V_{B2}}{I_1}$$

where $V_{B2} = 0.7V + I_E R_E$

Note: $R_1 + R_2 + R_3 = \frac{V_{CC}}{I_1}$

9. Then calculate $R_1$.

$$R_1 = \frac{V_{CC}}{0.1 I_C} - R_2 - R_3$$
Cascode Bias Summary

SPECIFIED: \( A_v, V_{CC}, V_{C1} \) (CB collector voltage);

SPECIFIED: \( I_E \) (or \( I_C \)) directly or indirectly through \( BW \).

DETERMINE: \( R_C, R_E, R_1, R_2 \) and \( R_3 \).

SET: \( V_{B1} - V_{B2} = 1 \ V \Rightarrow V_{CE2} = 1 \ V \)

\[ I_{C2} = I_{E1} \approx I_{C1} \approx I_{E2} = I_C \]

\[ R_C = \frac{V_{C1}}{I_C} \quad R_E = \frac{R_C}{|A_v|} \]

\[ R_1 + R_2 + R_3 = \frac{V_{CC}}{I_1} = \frac{V_{CC}}{0.1 I_C} \]

\[ R_2 = \frac{V_{B1} - V_{B2}}{I_1} = \frac{1 V}{0.1 I_C} \]

\[ R_3 = \frac{V_{B2}}{I_1} = \frac{0.7 V + I_E R_E}{0.1 I_C} \]

\[ R_1 = \frac{V_{CC}}{0.1 I_C} - R_2 - R_3 \]
Cascode Bias Example

Cascode Amp

Typical Bias Conditions
1. Choose $I_{E1}$ to set $r_e$.
Try $I_{E1} = 5\ mA \Rightarrow r_e = 0.025\ V/I_e = 5\ \Omega$.

2. Set desired gain magnitude. For example if $A_V = -10$, then $R_C/R_E = 10$.

3. Since the CE stage gain is very small, $V_{CE2}$ can be small, i.e. $V_{CE2} = V_{B1} - V_{B2} = 1\ V$. 
Cascode Bias Example cont.

Specs:

\[ V_{CC} = 12 \, V \quad V_{C1} = 7 \, V \quad I_C = 5 \, mA \quad \left| A_v \right| = \frac{R_C}{R_E} = 10 \]

\[ \beta = 100 \]

Determine \( R_C \) for \( V_{C1} = 7 \, V \).

\[ R_C = \frac{V_{CC} - V_{C1}}{5 \cdot 10^{-3}} = \frac{5 \, V}{5 \cdot 10^{-3}} = 1000 \, \Omega \]

\[ R_E = \frac{R_C}{\left| A_v \right|} = \frac{R_C}{10} = 100 \, \Omega \]
**Cascode Bias Example cont.**

\[ V_{CC} = 12 \quad R_C = 1 \, k\Omega \quad I_C = 5 \, mA. \quad R_E = 100 \, \Omega \]

Make current through the string of bias resistors \( I_1 = 0.1 \, I_C = 0.5 \, mA. \)

\[
R_1 + R_2 + R_3 = \frac{V_{CC}}{I_1} = \frac{12}{5 \cdot 10^{-4}} = 24 \, k\Omega
\]

Calculate the bias voltages (base side of Q1, Q2):

\[
V_{R1} = V_{CC} - I_C R_E - 1.7 \, V = 12 \, V - 0.5 \, V - 1.7 \, V = 9.8 \, V
\]

\[
V_{R2} = V_{B1} - V_{B2} = 1 \, V
\]

\[
V_{R3} = V_{B2} = I_C R_E + 0.7 = 5 \cdot 10^{-3} \cdot 100 + 0.7 = 1.2 \, V
\]
Cascode Bias Example cont.

\[ V_{B2} = 5 \cdot 10^{-4} R_3 = 1.2 \text{ V} \]
\[ R_3 = 2.4 \text{ k}\Omega \]

\[ V_{B1} - V_{B2} = 5 \cdot 10^{-4} R_2 = 1.0 \text{ V} \]
\[ R_2 = 2 \text{ k}\Omega \]

Recall: \( R_1 + R_2 + R_3 = 24 \text{ k}\Omega \)

\[ R_1 = 24000 - 2.400 - 2000 = 19.6 \text{ k}\Omega \]

\[ V_{CC} = 12 \text{ V}, \quad R_C = 1 \text{ k}\Omega, \quad V_{B2} = 1.2 \text{ V}, \]
\[ I_C = 5 \text{ mA}, \quad R_E = 100 \text{ \Omega}, \quad V_{B1} - V_{B2} = 1.0 \text{ V} \]
\[ \beta = 100 \]

\[ r_e = 5 \, \Omega \Rightarrow I_C = 5 \, mA \]

\[ V_{C1} = 7 \, V \]

\[ |A_v| = \frac{R_C}{R_E} = 10 \]

\[ R_1 = 19.6 \, k\Omega \]
\[ R_2 = 2 \, k\Omega \]
\[ R_3 = 2.4 \, k\Omega \]
\[ R_C = 1 \, k\Omega \]
\[ R_E = 100 \, \Omega \]

**NOTE:** \( R_B = R_2 \parallel R_3 = 1.09 \, k\Omega \ll \beta R_E = 10 \, k\Omega \)

\[ f_{H} = \frac{1}{2\pi C_{tot} R'_S} \]

\[ C_{tot} = C_\pi + (1 + \frac{r_e}{R_E}) C_\mu \]

\[ = C_\pi + 1.05 C_\mu \]

If \( C_\pi = 12 \, pF \)

\( C_\mu = 2 \, pF \)

\( C_{tot} = 14.1 \, pF \)

\[ f_{H\text{cascode}} = 225.8 \, MHz \]

For CE with \( |A_v| = 10 \)

\[ f_{HCE} = 94 \, MHz \]