Lecture 9

• Oscillators
  – Oscillators Based on Feedback
  – Requirements for Self-Oscillation
  – Output Power and Harmonic Distortion
• Tuned LC Oscillators
• Oscillator Noise
• Negative Resistance Oscillators
• Voltage Controlled Oscillators (VCO)
• Resonators
• Crystal Oscillators (XO)
• Some Good Practical Advice about Oscillator Design
Black’s Feedback Model

\[ V_{out} = A_v \cdot V_A \]

\[ V_A = V_{in} + \beta V_{out} \]

\[ A_f = \frac{V_{out}}{V_{in}} = \frac{A_v}{1 - A_v \beta} \]

- Barkhaussen oscillation criteria:

\[ A_v \cdot \beta = 1 \quad A_v \cdot \beta \text{ is called the loop gain} \]
Oscillators Based on Feedback

- If the oscillator runs at constant amplitude it complies with the Barkhausen oscillation criteria:

\[ A_v \cdot \beta = 1 \]

- i.e.

\[ |A_v \cdot \beta| = 1 \]

- and

\[ \arg(A_v \cdot \beta) = 0 \]

- \( A_v \) = voltage gain
- \( \beta \) = feedback factor
$A_v \cdot \beta = 1$ when the oscillator runs at constant amplitude.
The Generalized Oscillator Model for LC Oscillators

- The phase criteria in Barkhaussen is fulfilled when
  \[ X_1 + X_2 + X_3 = 0 \]
  i.e. the circuit is at resonance

- The amplitude criteria in Barkhausen is fulfilled when
  \[ \beta = \frac{1}{A_v} = \frac{X_1}{X_1 + X_3} = \frac{X_1}{-X_2} = \frac{X_2 + X_3}{X_2} \]

Tip: choose an expression for \( \beta \) where both reactance's are inductive or capacitive
Oscillator Circuits

- The feedback network in LC oscillators may be configured in different ways:
  - Hartley
  - Colpitts
  - Clapp

- Hartley:
  - one capacitive branch
  - two inductive branches

- Colpitts:
  - two capacitive branches
  - one inductive branch

- Clapp:
  - a variation of the Colpitts oscillator

Depending on the selected transistor configuration (CE, CB or CC) there are a lot more variations.

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1. determine the amplifier configuration (CE, CB or CC)?

2. identify components that determines the frequency and feedback?

3. draw the generalized oscillator model

4. calculate the voltage gain $A_V$

5. calculate the resonant frequency $f_0$

6. calculate the feedback factor $\beta$

7. check if the Barkhaussen criteria is fulfilled
Calculation of $A_V$ and $\beta$

\[ A_v \cdot \beta = 1 \]

\[ A_v = g_m \cdot R_{ctot} \]

\[ R_{ctot} = R_p // R_L // R_n // r_o \]

\[ R_p = Q_u \cdot \omega_0 L \]

\[ R_n = \left( (r_e // R_3) + R_4 \right) \cdot \left( \frac{C_3 + C_4}{C_3} \right)^2 \]

\[ \beta = \frac{(r_e // R_3)}{(r_e // R_3) + R_4} \cdot \frac{C_3}{C_3 + C_4} \]

compare with lab 4!
Oscillator Noise

- The noise level increases close to the resonant frequency as $A_f \to \infty$ when $f \to f_0$

$$A_f = \frac{A}{1 - \beta A}$$
Noise Model of the Oscillator

\[ N_i = FkT_0 \text{[W/Hz]} \]

\[ A_f(f) = \frac{A}{1 - \beta(f)A} \]

\[ G_f = A_f^2 \]

\[ \beta(f) = \frac{\beta_0}{1 + jQ\frac{2|f - f_0|}{f_0}} \]

\[ N_0 = G_f FkT_0 \text{[W/Hz]} \]

\[ N_i = FkT_0 \text{[W/Hz]} \]
Noise Spectrum

To achieve low phase noise choose:
- a high-Q resonant circuit
- a low noise amplifier
- as low gain as possible
- high power level in the oscillator

The noise consists of both amplitude and phase noise
- if a limiter is used the amplitude noise will be suppressed and the total noise level is reduced by 3 dB
Negative Resistance Oscillators

Lab 4

Which transistor configuration is used?

A serial inductor (a short-circuited stub) is inserted to the base to intentionally make the transistor unstable.

A resonator (an open stub) is connected to the input to set the resonant frequency.

V_C = 3.5V
Negative Resistance Oscillator

Lab 4

![Circuit Diagram]

$V_{CC} = 3.5V$

$Z_0 = 100\Omega$
$\ell = 0.05\lambda$

$Z_0 = 100\Omega$
$\ell = 0.125\lambda$

BFR520

270pF

50Ω

470pF

2.7kΩ

470pF

270pF

100Ω

270pF

50Ω

stub

out

b
c

+3.5V

RFosc LS991102

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Conditions for Oscillation in a Two-Port

\[ K = \frac{1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{12}S_{21}|} < 1 \]

\[ \Delta = S_{11}S_{22} - S_{21}S_{12} \]

\[ \Gamma_{IN}\Gamma_S = 1 \]

\[ \Gamma_{UT}\Gamma_L = 1 \]

Express this in impedance!

\[ \Gamma_{IN}\Gamma_S = \frac{R_{IN} + jX_{IN} - Z_0}{R_{IN} + jX_{IN} + Z_0} \cdot \frac{R_S + jX_S - Z_0}{R_S + jX_S + Z_0} = 1 \]

\[ R_{IN} + R_S = 0 \]

\[ X_{IN} + X_S = 0 \]
Voltage Controlled Oscillator (VCO)

Clapp oscillator

Negative resistance oscillator

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Varicap Diode

Forward bias

Reversed bias

Ex.: BB811

Diode capacitance $C_d = f(V_R)$

$f = 1 \text{ MHz}$

$C_d(V_R) = \frac{C_j(0)}{\left(1 + \left|\frac{V_R}{V_j}\right\right)^M}$

$V_R = \text{reverse voltage}$

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Resonators

• In order to improve the Q-factor, instead of or as a compliment to the LC circuit, you may use:
  
  – Transmission line
    • microstrip resonator
    • coaxial resonator
  
  – Ceramic resonator
  
  – Quartz crystal
The Quartz Crystal (Xtal)

Symbol

equivalent circuit diagram

\[ L = 5 \, \text{mH} \]
\[ C_p \approx 10 \, \text{pF} \]
\[ C_s \approx 50 \, \text{fF} \]
\[ r < 3 \, \Omega \]
\[ Q \approx 10^5 \]
The Impedance of a Crystal

\[ Z_{\text{Xtal}}[\Omega] = R + jX \]

Series resonant frequency
Parallel resonant frequency

\[ Z \rightarrow r(Q^2 + 1) \]

\[ X \rightarrow \infty \]

\[ X \rightarrow -\infty \]
Crystal Oscillators

- circuit examples

- series resonance
- parallel resonance
- parallel resonance

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Pierce Crystal Oscillator

Compare with lab 4!
Some Good Practical Advice about Oscillator Design

• Generally:
  – select components of high quality
  – use buffer amplifier
  – use filtered and well stabilized supply voltage
  – apply good shielding

• For high frequency stability:
  – design the resonant circuit for high Q
  – use a ceramic resonator alternatively a quartz crystal
  – ”pre-aging” of crystals
  – the oscillator may be enclosed in a temperature controlled oven
  – frequency control by temperature sensor and varicap diode

• Low phase noise:
  – design the resonant circuit for high Q
  – use low noise amplifier
  – use as low gain as possible
  – let the oscillator operate at a high power level