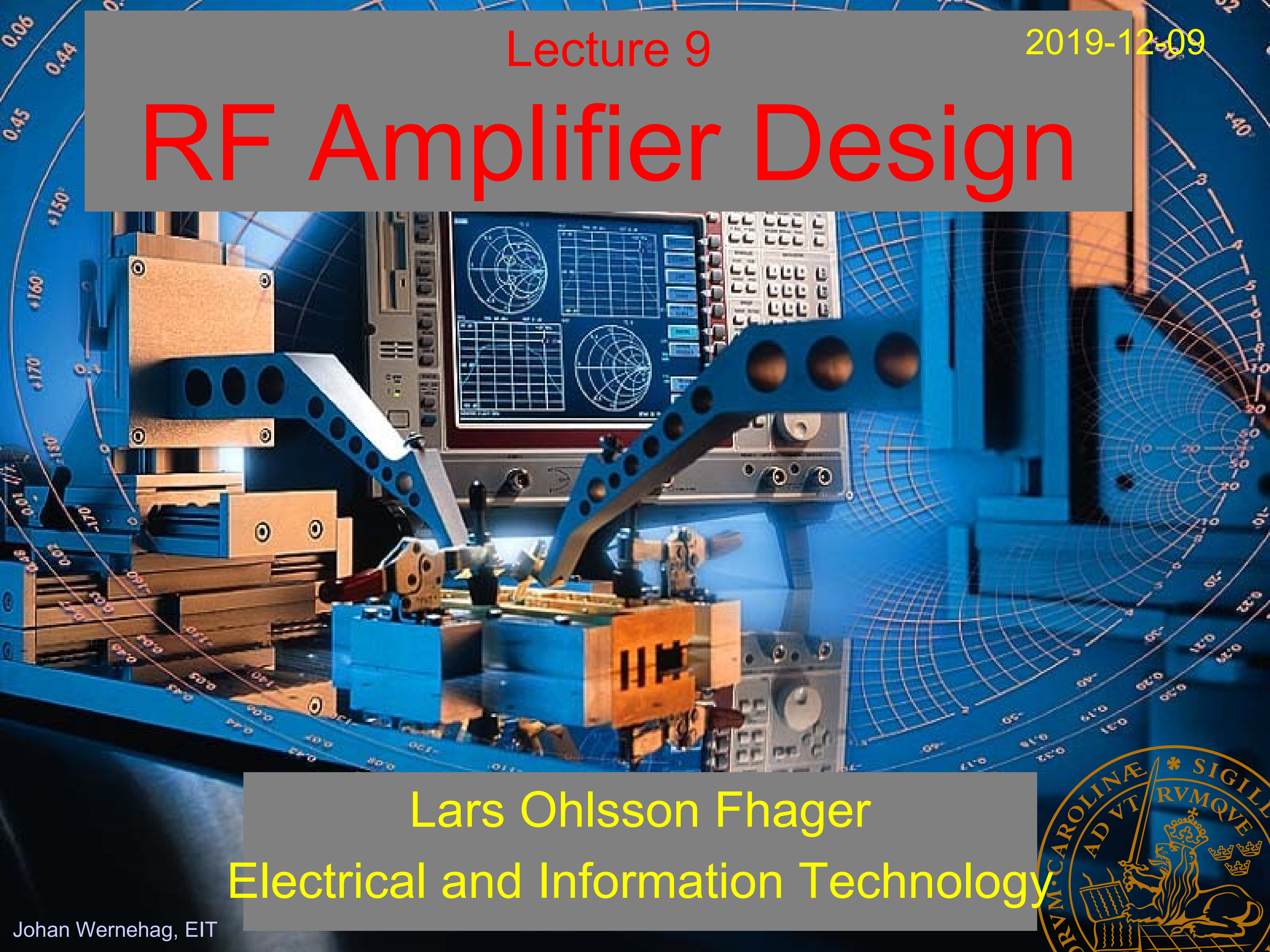
Lecture 9

2019-12-09

RF Amplifier Design



Lars Ohlsson Fhager

Electrical and Information Technology

Schedule Reminder

- Lab 3: Thursday, Dec 12, 8:15-12:00
  - Amplifier, IF and RF, characterisation
- Lab 4: Wednesday, Dec 18, 8:15-12:00
  - LC, negative resistance, and crystal oscillators
- Lab Catch-up: Friday, Dec 20, 8:15-12:00
  - Final laboratory session for those who for some reason were unable to attend another session

Schedule Reminder

- Also, make sure to correct and re-submit hand-in assignments

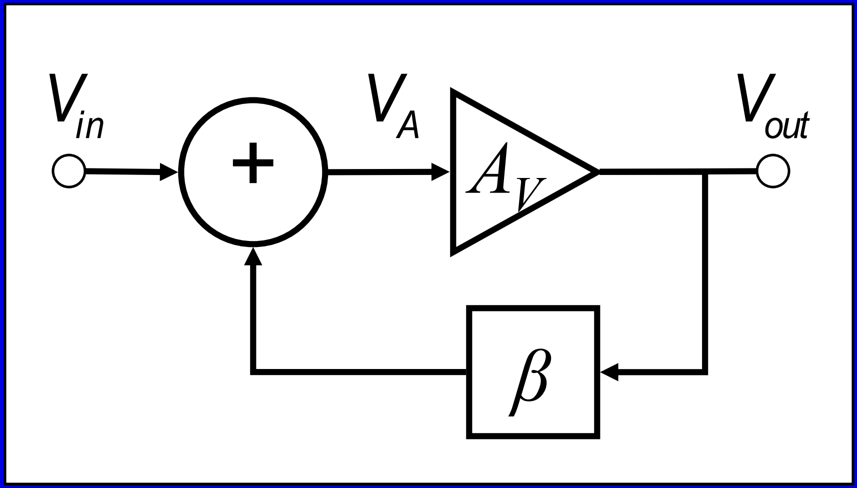
- Written Examination: Tuesday, Jan 14, 2020, 8:00-13:00 (5 h, starting at 8 sharp), E:2311
  - Allowed tools:
    (1) Radio Electronics – Formulas and Tables
    (2) Pocket calculator for complex numbers

Note: Laboratory sessions and hand-in assignments must be graded pass for admittance to examination.

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



$$V_{out} = A_v V_A$$

$$V_A = V_{in} + \beta V_{out}$$

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

- Barkhaussen oscillation criteria:

$$\boxed{A_v\beta = 1}$$

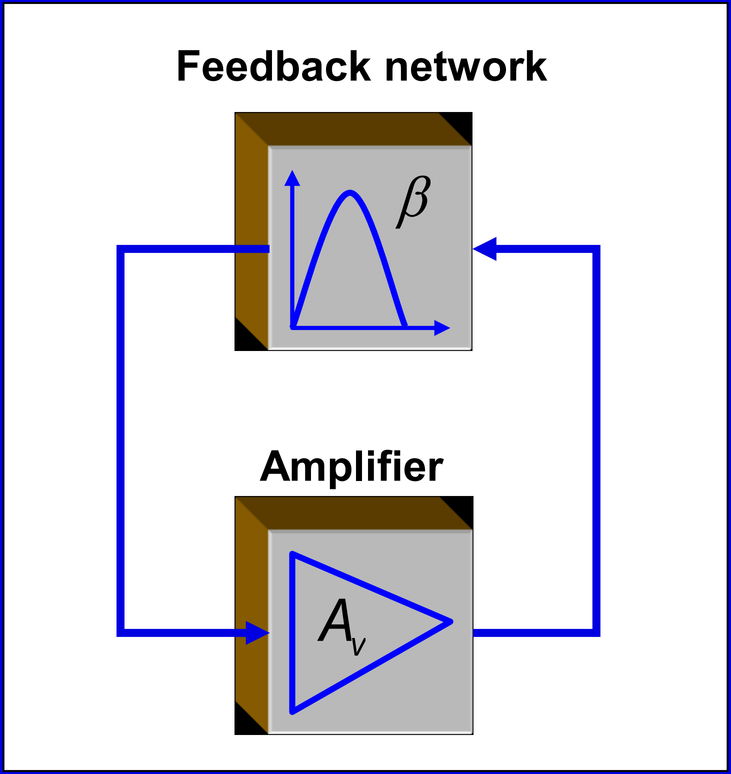
$A_v \cdot \beta$ is called the loop gain

Oscillators Based on Feedback

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

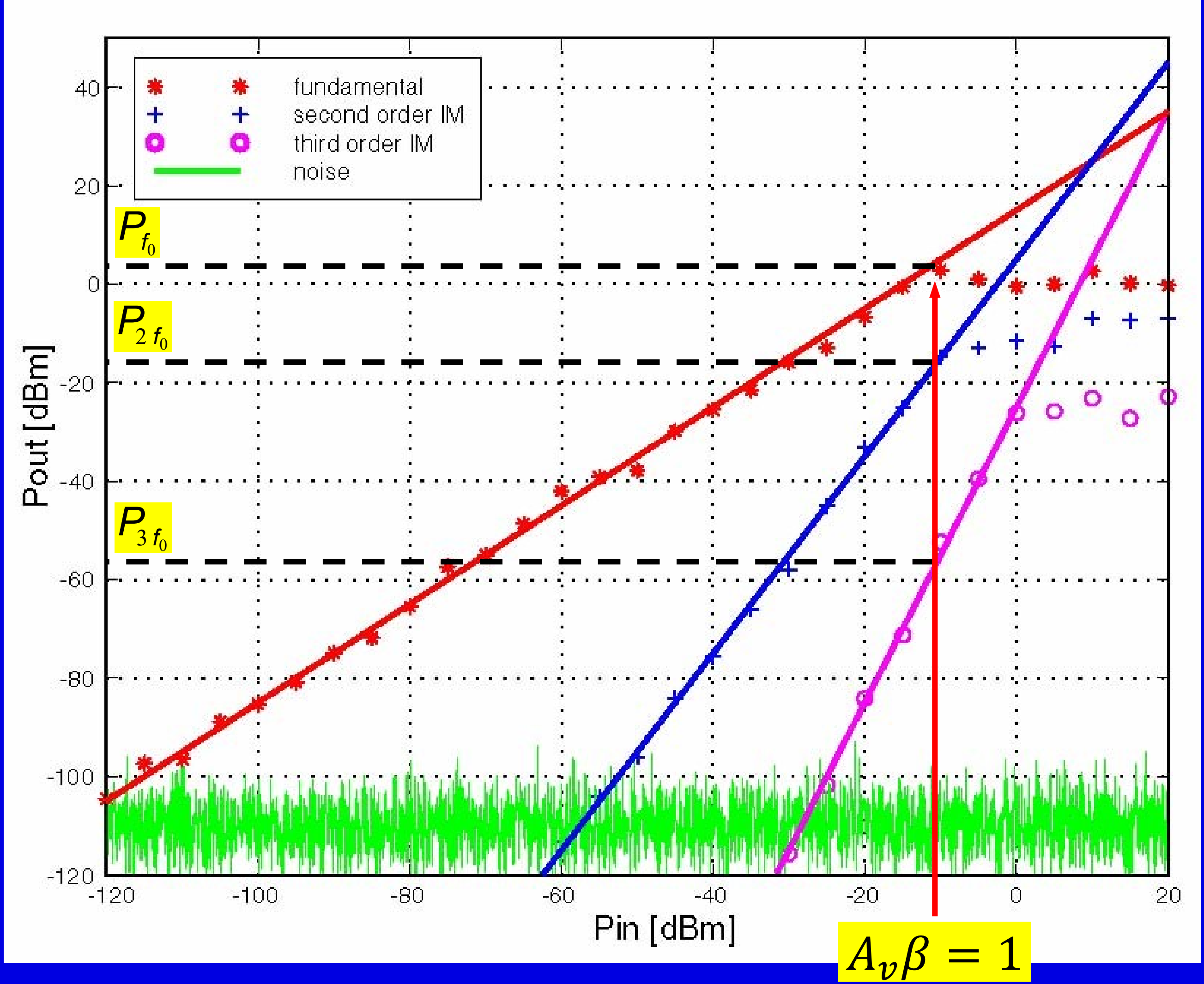
$$\boxed{A_v\beta = 1}$$

  - i.e. $|A_v\beta| = 1$
  - and $\arg(A_v\beta) = 0$



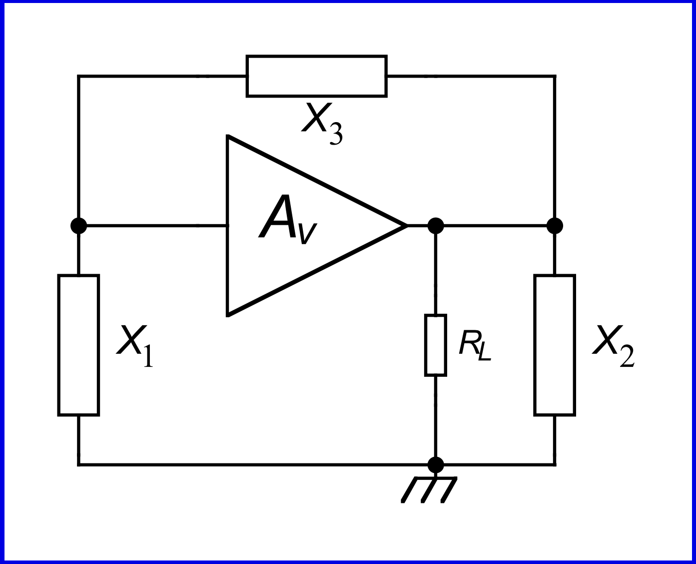
A_v = voltage gain
β = feedback factor

Output Power and Harmonic Distortion



$A_V\beta$ = 1 when the oscillator runs at constant amplitude, ↥
which must occur in the vicinity of gain compression

The Generalized Oscillator Model for LC Oscillators



- The phase criteria in Barkhaussen is fulfilled when

$$\boxed{X_1+X_2+X_3=0}$$

i.e. the circuit is at resonance

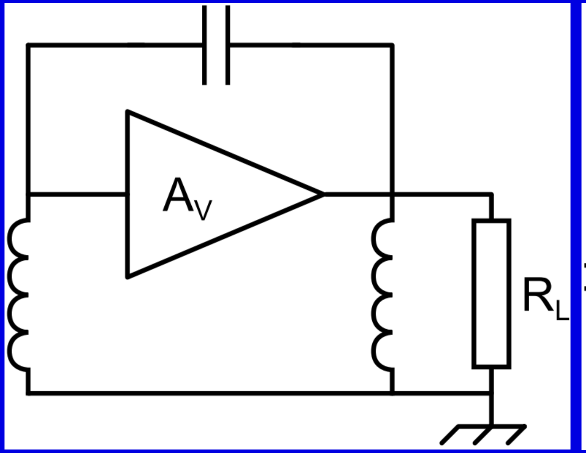
- The amplitude criteria in Barkhaussen is fulfilled when

$$\beta=\frac{1}{A_v}=\frac{X_1}{X_1+X_3}=\frac{X_1}{-X_2}=\frac{X_2+X_3}{X_2}$$

Tip: choose an expression for β where both reactance's are inductive or capacitive

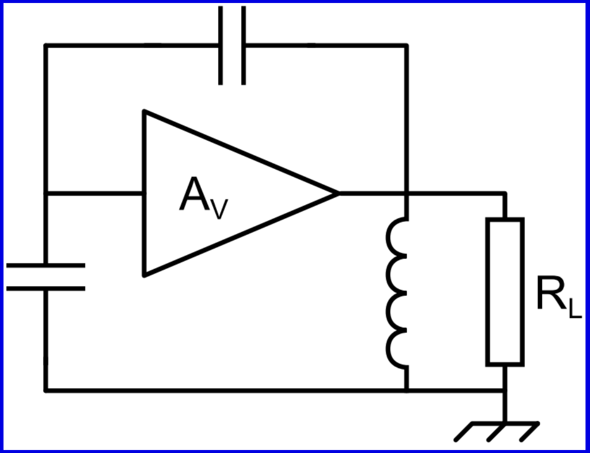
Oscillator Circuits

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



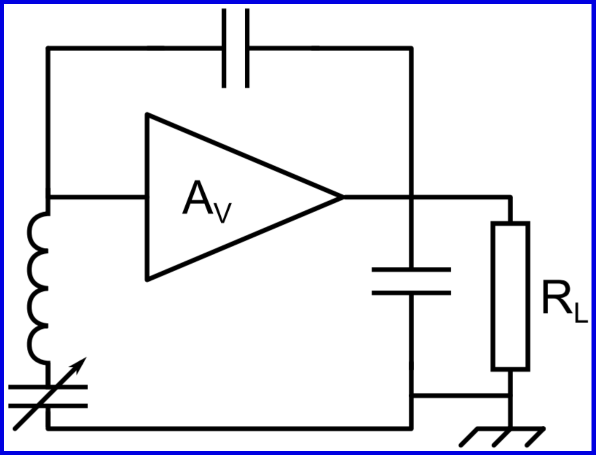
❖ one capacitive branch
❖ two inductive branches

- Colpitts



❖ two capacitive branches
❖ one inductive branch

- Clapp

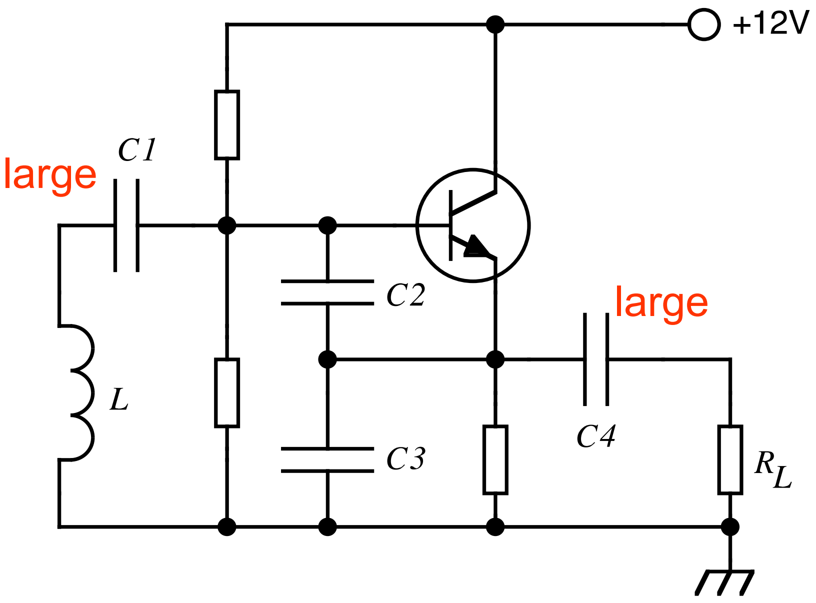


❖ a variation of the Colpitts oscillator

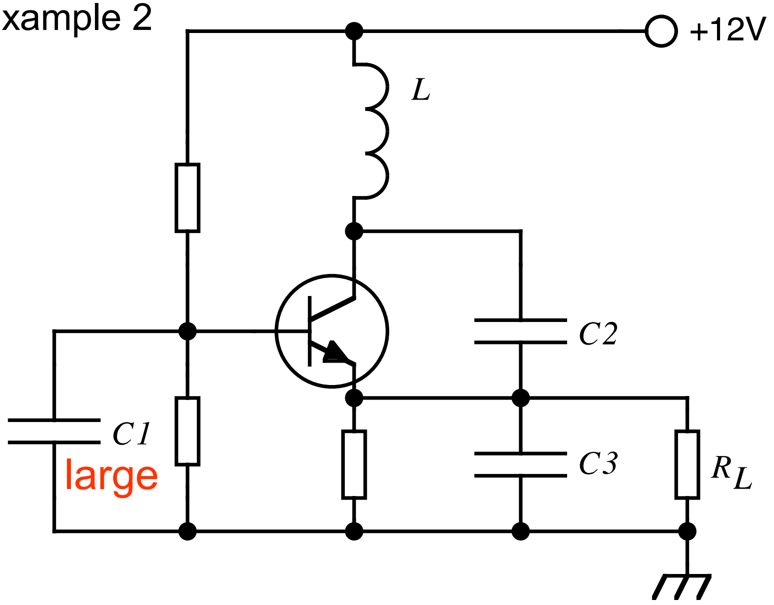
Depending on the selected transistor configuration (CE, CB or CC) there are a lot more variations.

Oscillator Analysis

Example 1

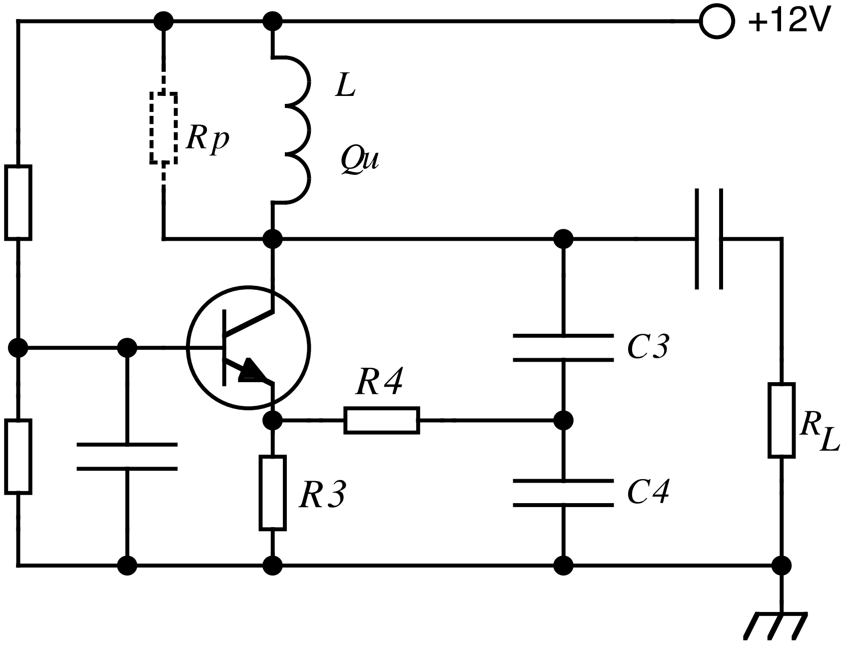


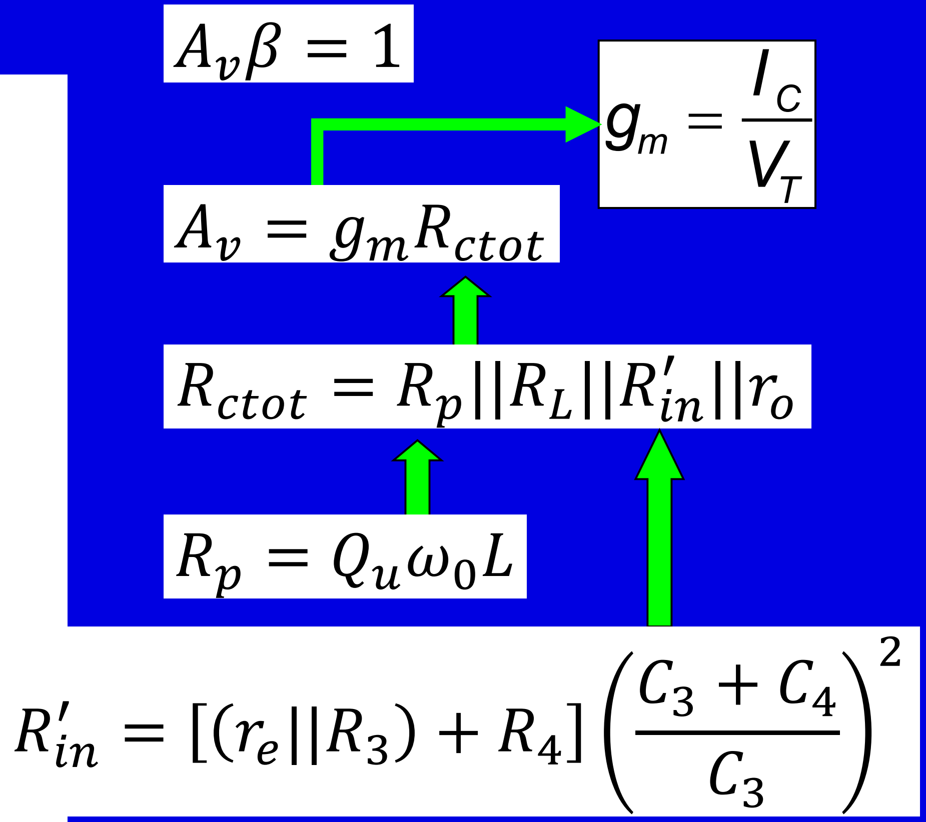
Example 2



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 β
7. check if the Barkhaussen criteria is fulfilled

Calculation of A_V and β





$$A_v\beta = 1$$

$$g_m = \frac{I_C}{V_T}$$

$$A_v = g_m R_{ctot}$$

$$R_{ctot} = R_p||R_L||R_{in}'||r_o$$

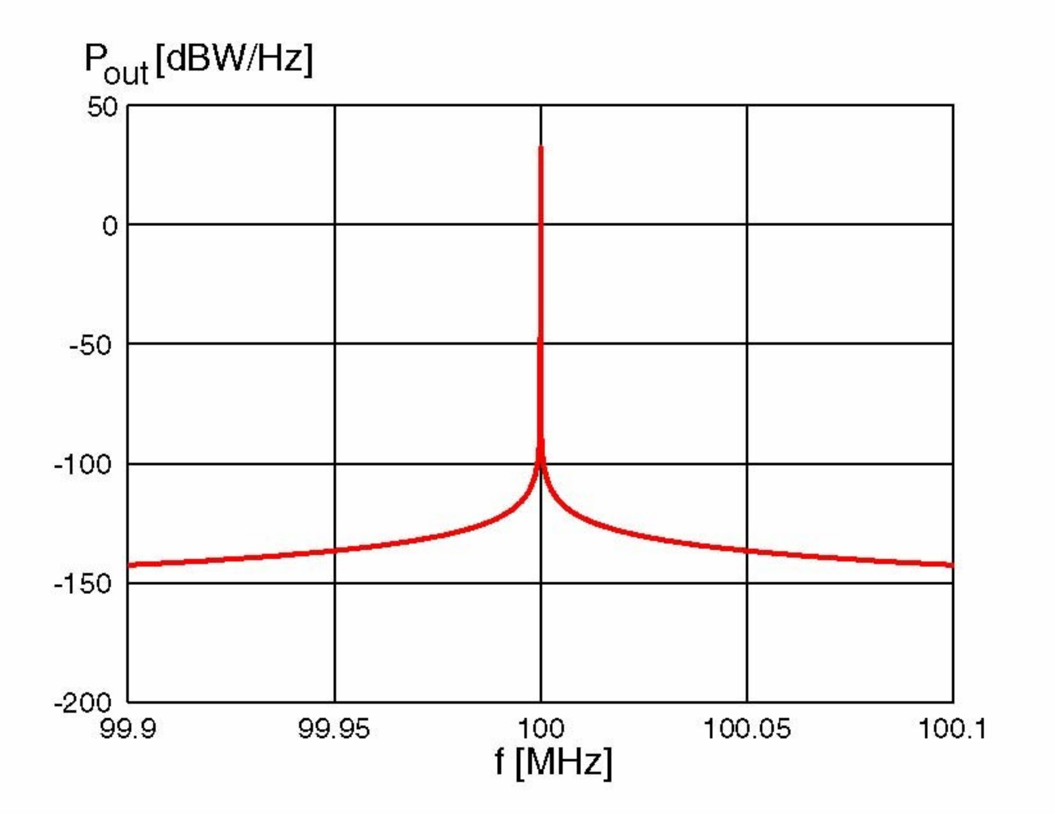
$$R_p = Q_u \omega_0 L$$

$$R_{in}' = [(r_e||R_3) + R_4]\left(\frac{C_3 + C_4}{C_3}\right)^2$$

$$\beta = \frac{(r_e||R_3)}{(r_e||R_3) + R_4}\frac{C_3}{C_3 + C_4}$$

compare with lab 4!

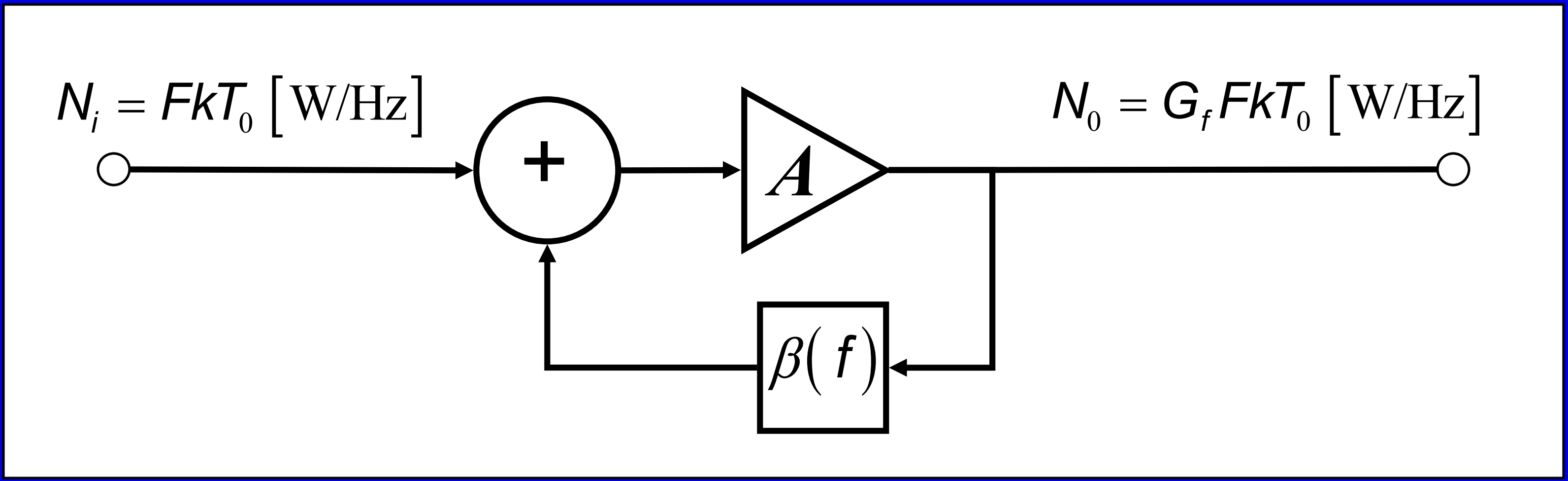
Oscillator Noise



- The noise level increases close to the resonant frequency as

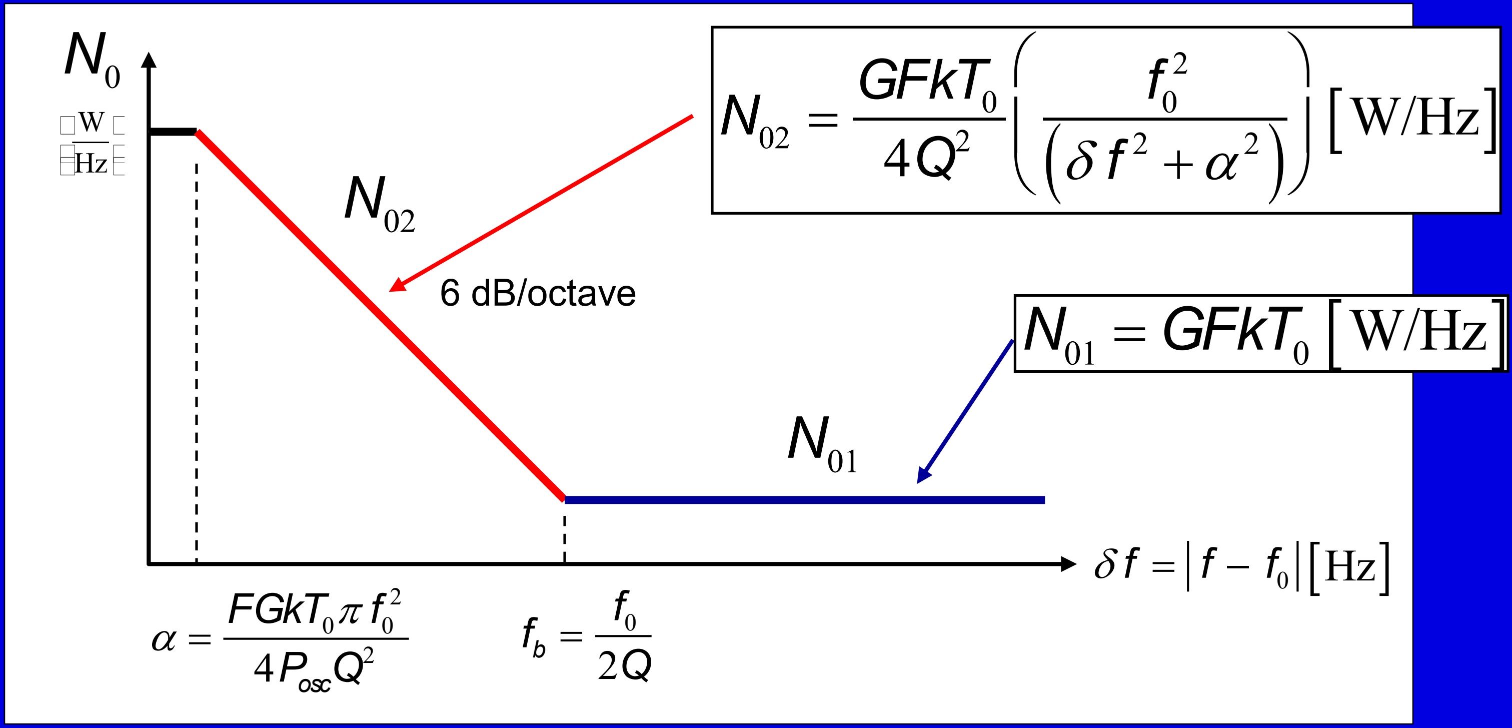
$$A_f = \frac{A}{1-\beta A} \qquad A_f \to \infty \text{ when } f \to f_0$$

Noise Model of the Oscillator



$$\boxed{A_f(f) = \frac{A}{1-\beta(f)A}} \qquad \boxed{G_f = A_f^2} \qquad \boxed{\beta(f) = \frac{\beta_0}{1 + jQ\dfrac{2\left|f - f_0\right|}{f_0}}}$$

Noise Spectrum



$$N_{02} = \frac{GFkT_0}{4Q^2}\left(\frac{f_0^2}{\left(\delta f^2 + \alpha^2\right)}\right) [\mathrm{W/Hz}]$$

$$N_{01} = GFkT_0 \, [\mathrm{W/Hz}]$$

$$\alpha = \frac{FGkT_0 \pi f_0^2}{4 P_{osc} Q^2}$$

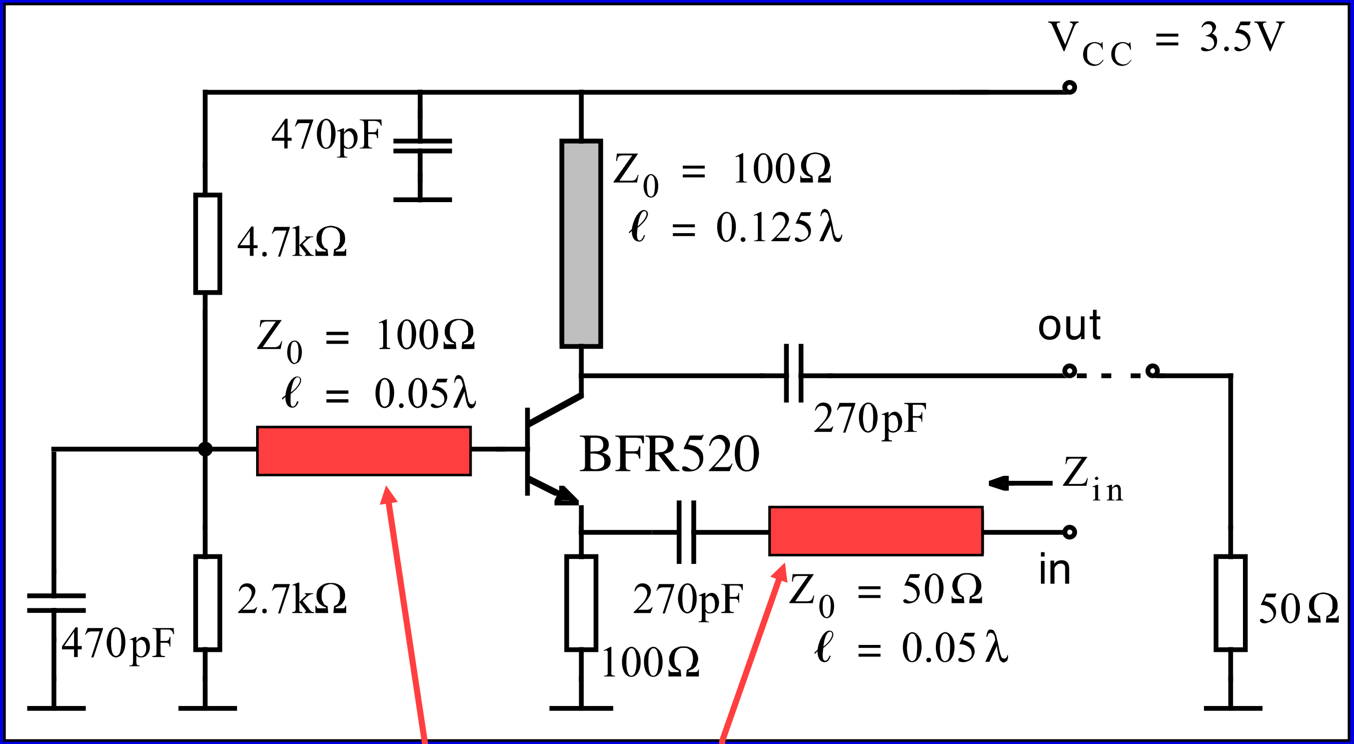
$$f_b = \frac{f_0}{2Q}$$

- 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?

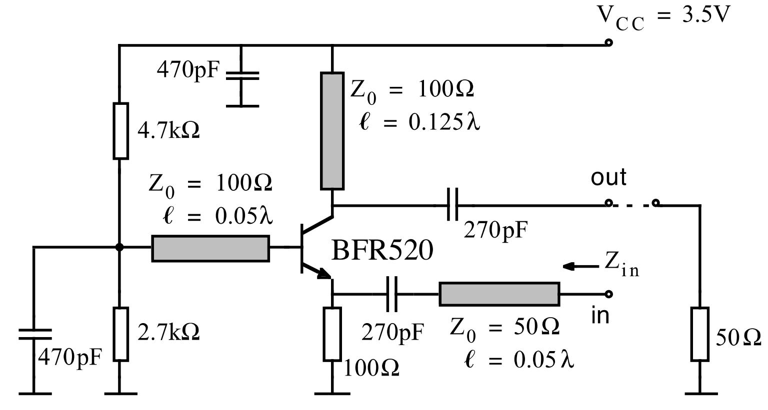


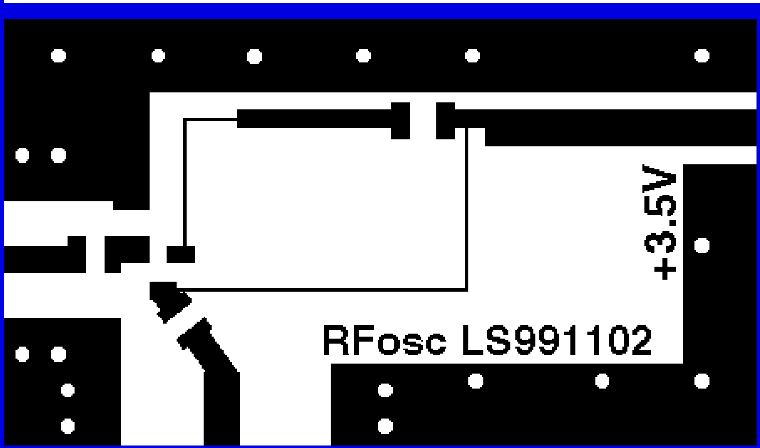
A serial inductor (a short-circuited stub) is inserted to the base to intentionally make the transistor unstable

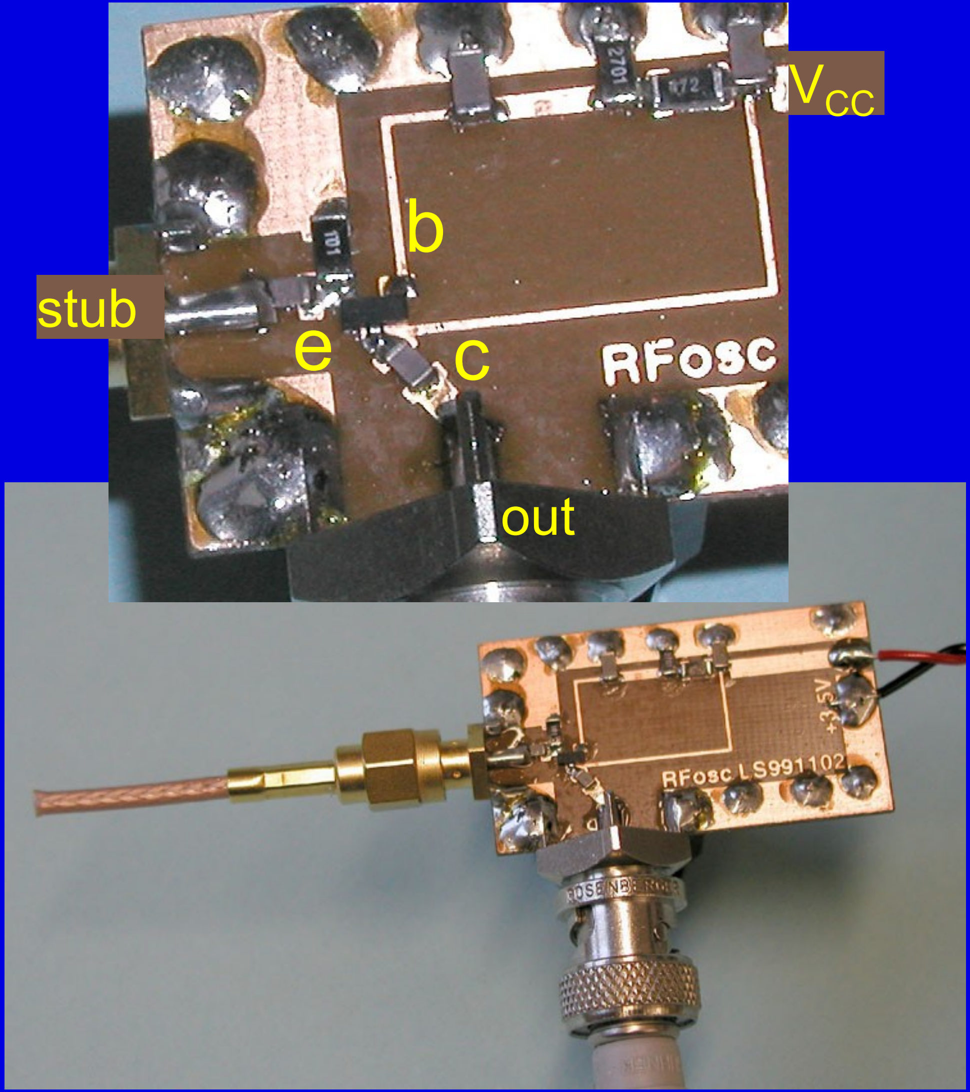
A resonator (an open stub) is connected to the input to set the resonant frequency

Negative Resistance Oscillator

Lab 4







Conditions for Oscillation in a Two-Port

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

$$\Delta = S_{11}S_{22} - S_{21}S_{12}$$

$$\left.\begin{array}{l} \Gamma_{IN}\Gamma_{S} = 1 \\ \\ \Gamma_{UT}\Gamma_{L} = 1 \end{array}\right\} \text{Express this in impedance!}$$

$$\Gamma_{IN}\Gamma_{S} = \frac{R_{IN} + jX_{IN} - Z_0}{R_{IN} + jX_{IN} + Z_0} \square \frac{R_S + jX_S - Z_0}{R_S + jX_S + Z_0} = 1$$

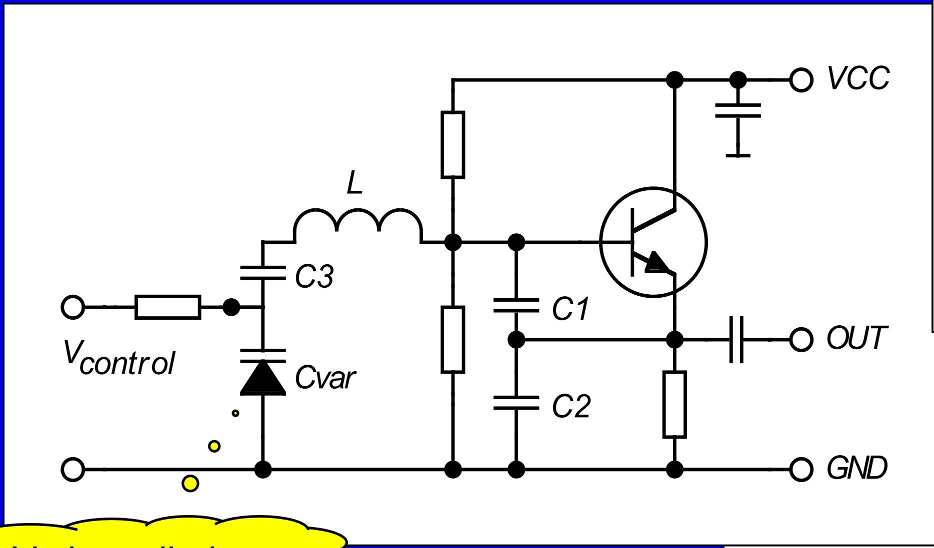
→

$$R_{IN} + R_S = 0$$

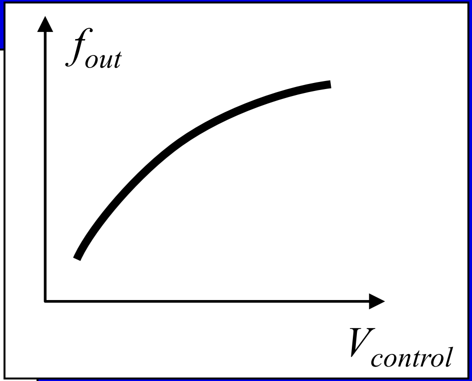
$$X_{IN} + X_S = 0$$

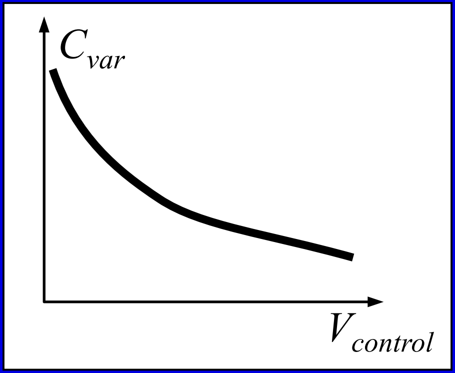
Voltage Controlled Oscillator (VCO)

Clapp oscillator

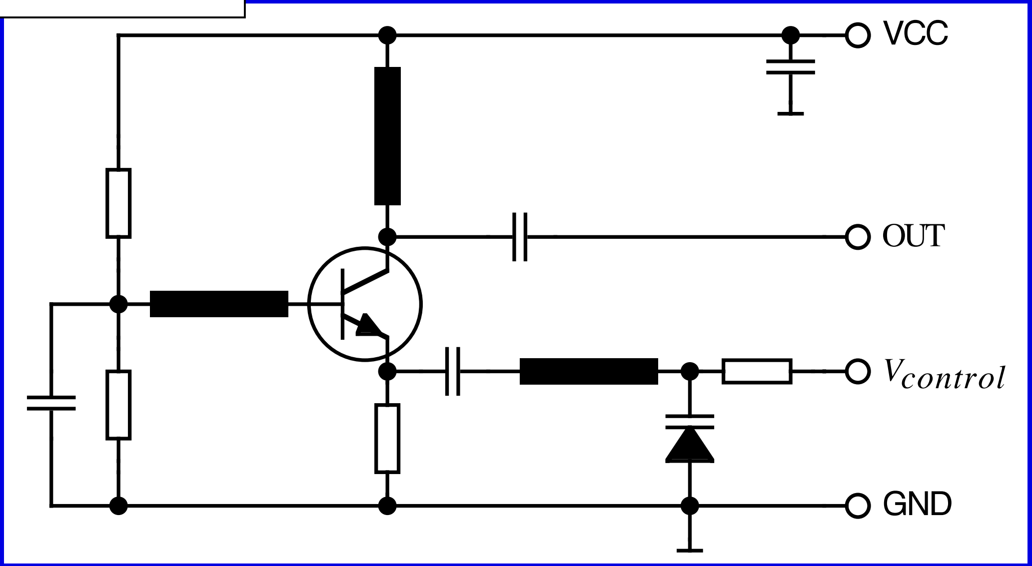


Varicap diode



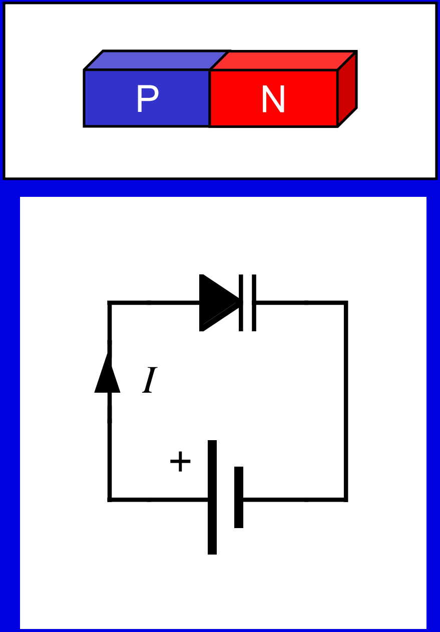


Negative resistance oscillator

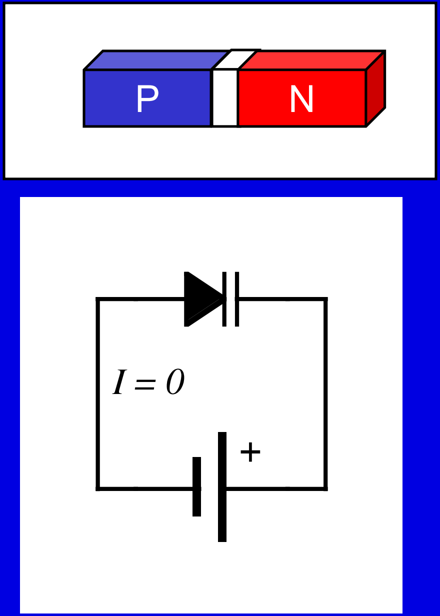


Varicap Diode

Forward bias

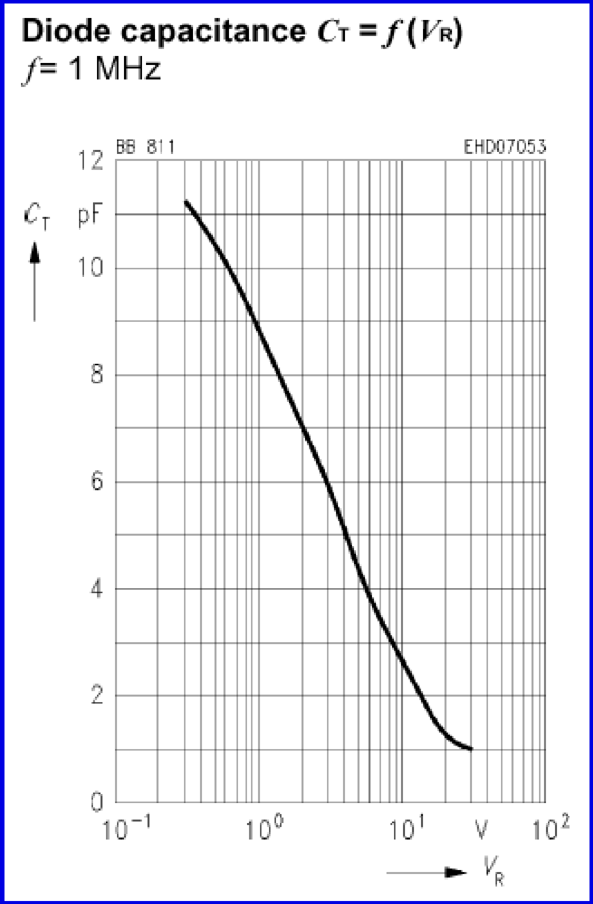


Reversed bias



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

Ex.: BB811

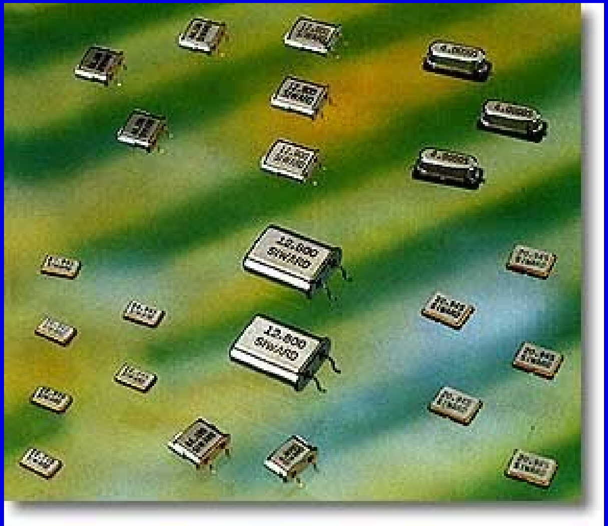


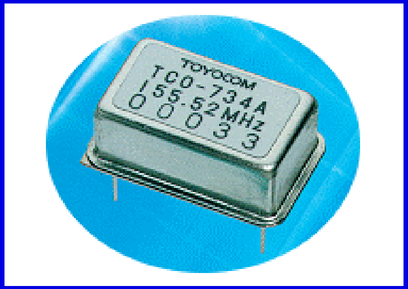
V_R = reverse voltage

Resonators

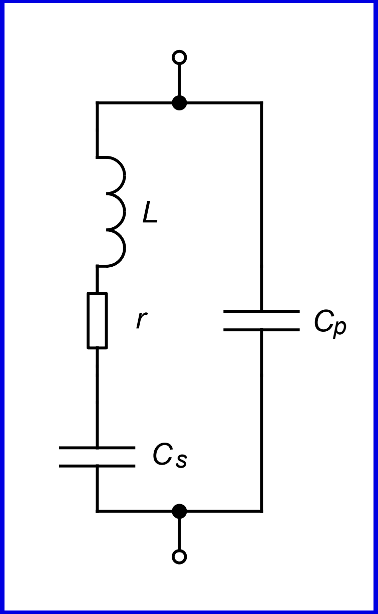
- In order to improve the Q-factor, instead of or as a compliment to the LC circuit, you may use:
  - Transmission line
    - microstrip resonator
    - coaxial resonator
  - Ceramic resonator
  - Quartz crystal

The Quartz Crystal (Xtal)





equivalent circuit diagram



$L = 5 \text{ mH}$

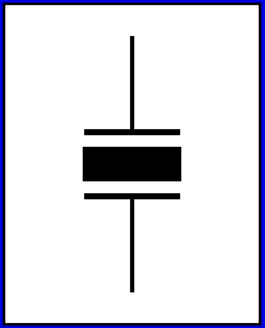
$C_p \approx 10 \text{ pF}$

$C_s \approx 50 \text{ fF}$

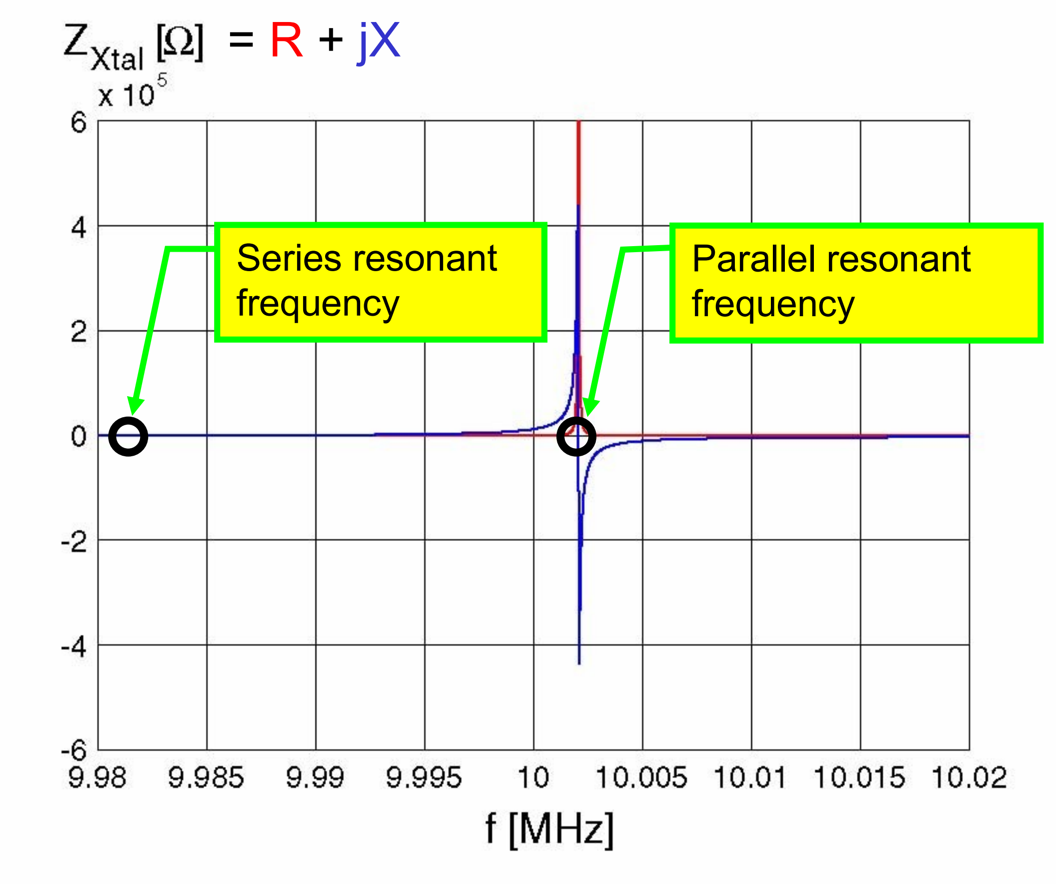
$r < 3\,\Omega$

$Q \,\square\, 10^5$

Symbol

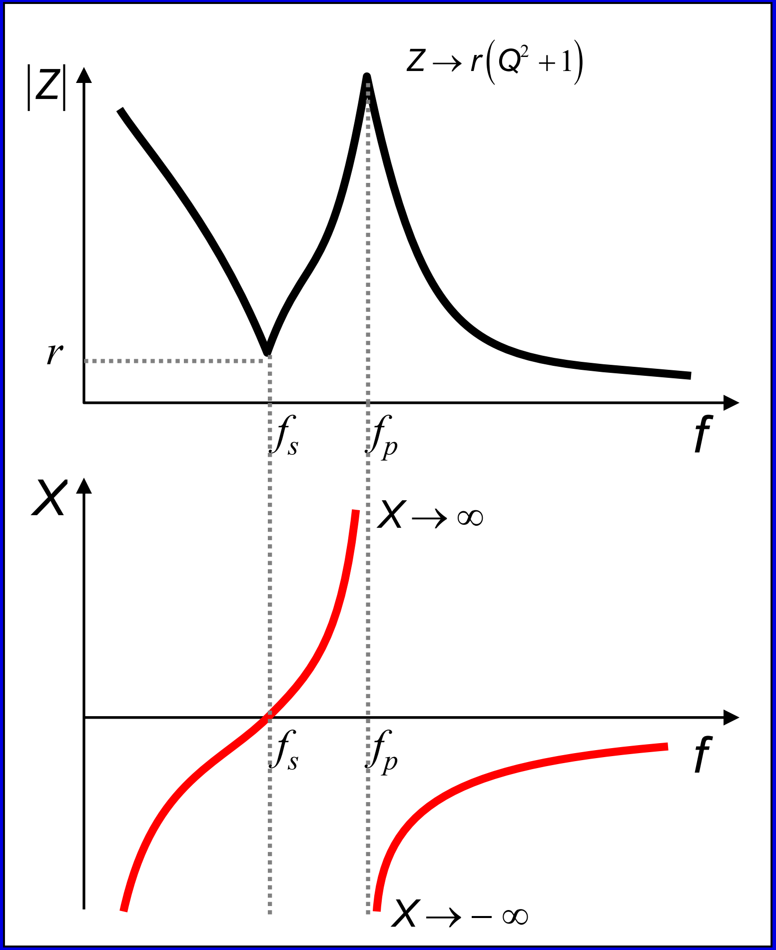


The Impedance of a Crystal



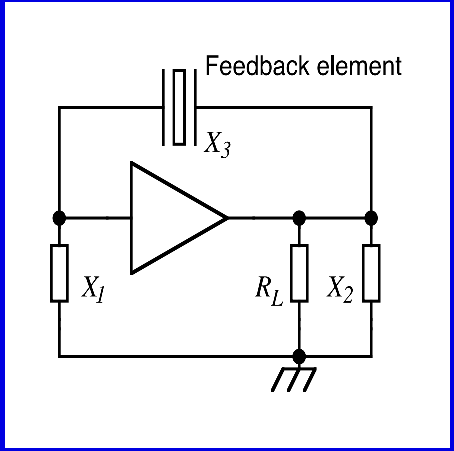
Series resonant frequency

Parallel resonant frequency

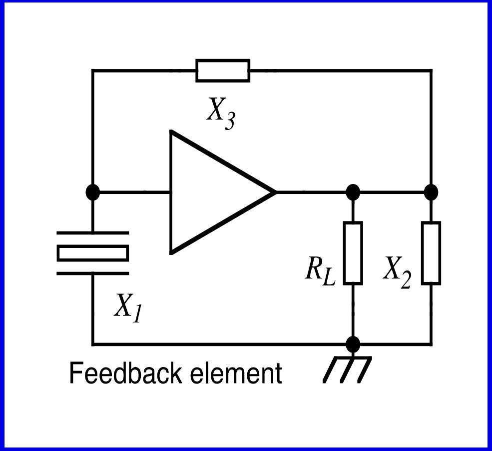


Crystal Oscillators

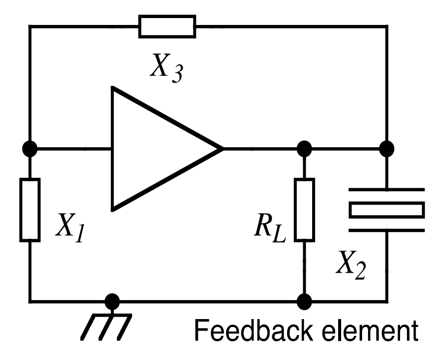
- circuit examples



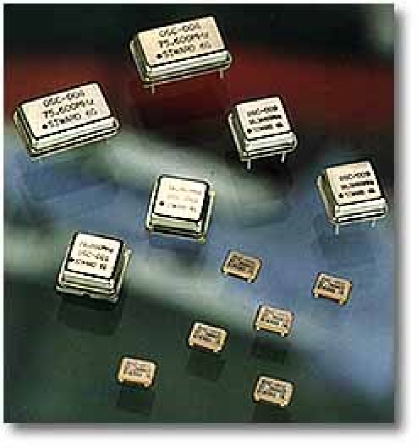
series resonance



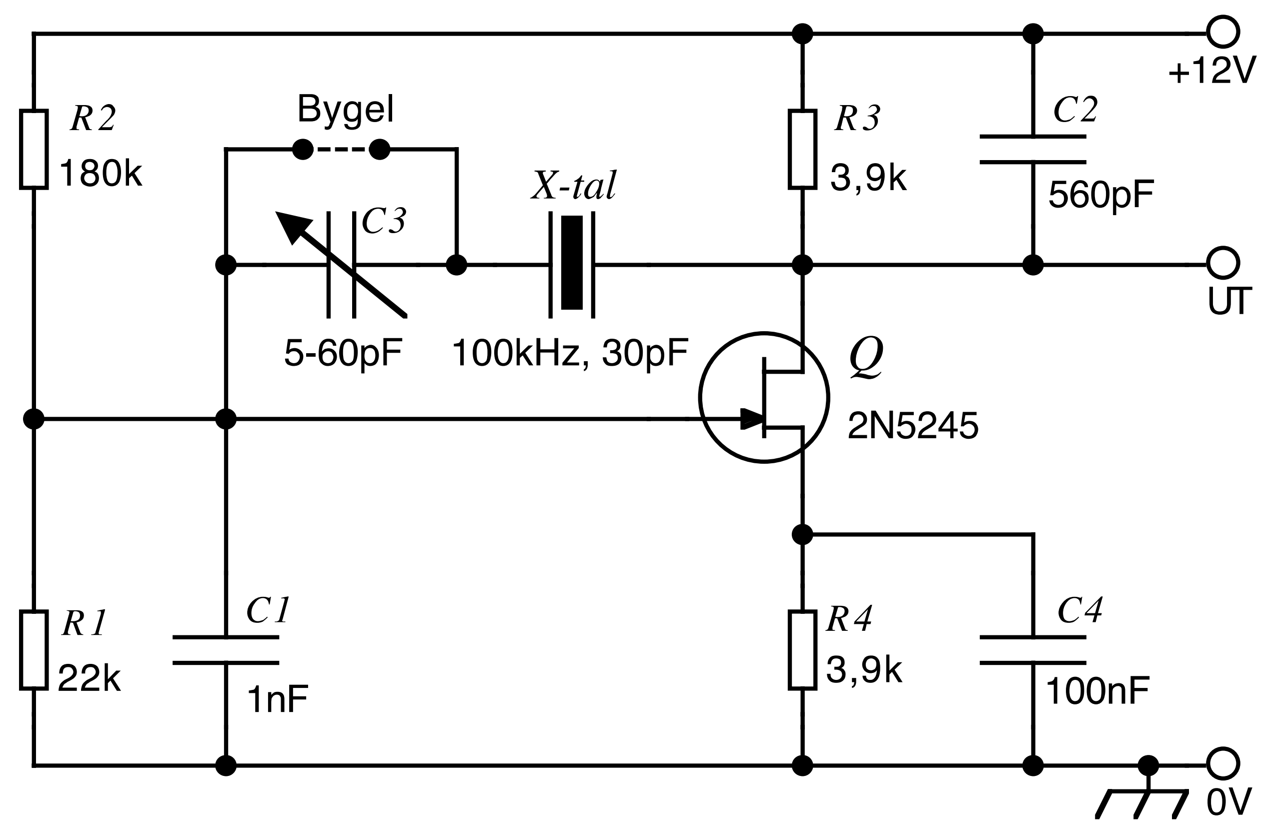
parallel resonance



parallel resonance



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