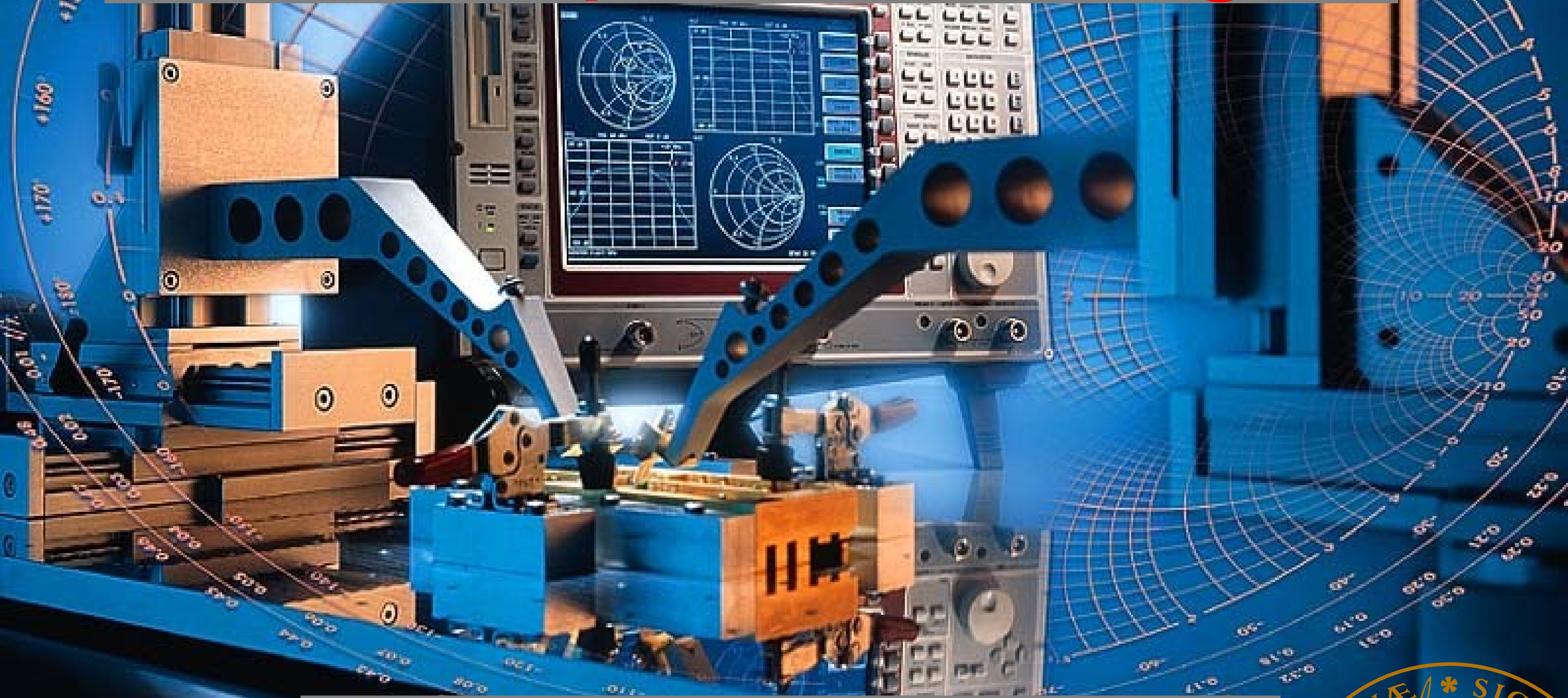
2019-11-04

Welcome to

RF Amplifier Design



Lars Ohlsson Fhager

Electrical and Information Technology

Johan Wernehag, EIT

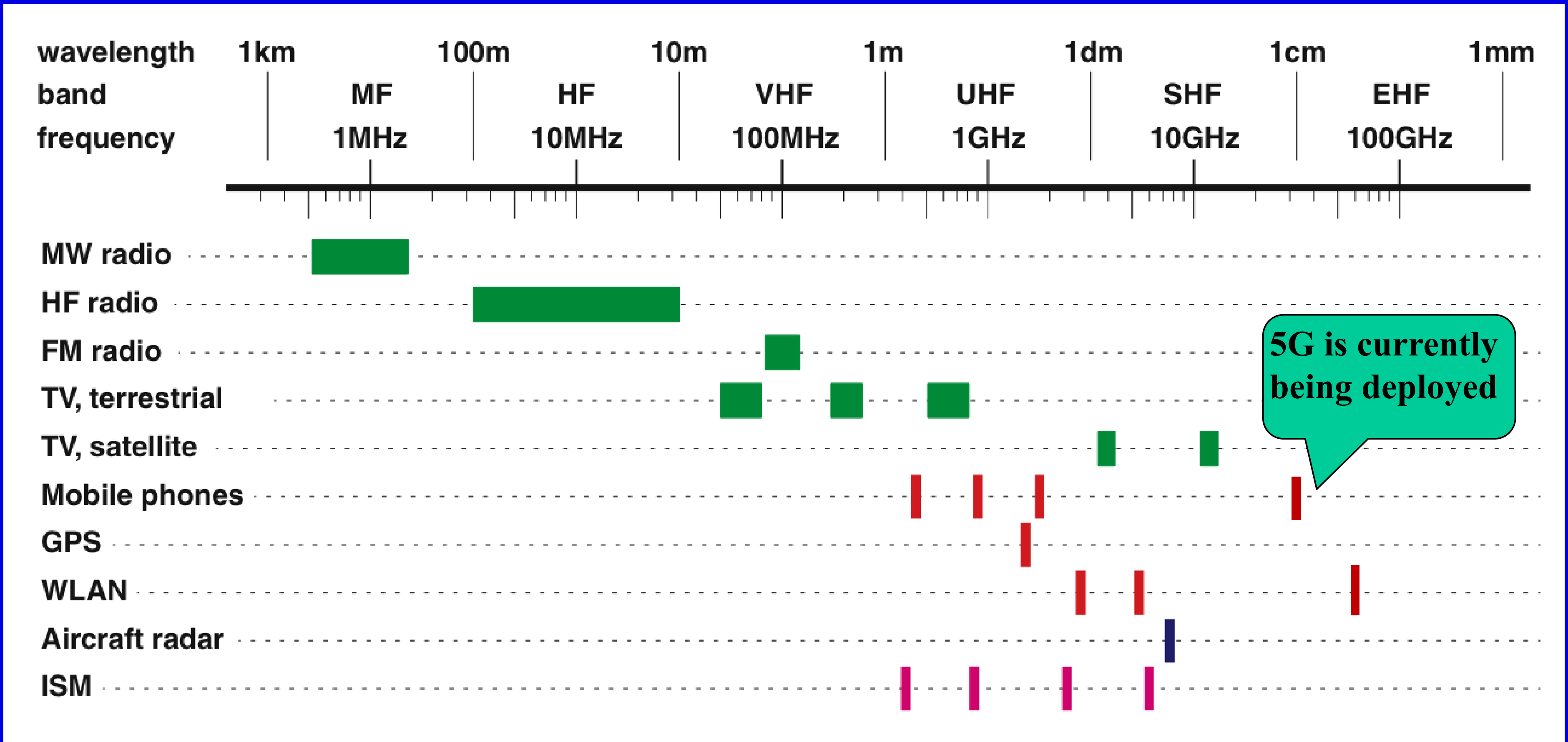
Lecture 1

- Introduction to RF Amplifier Design
- Information About the Course
- Resonant Circuits

RF Amplifier Design

- Objective
  - Analysis and design of radio- and microwave amplifiers by using
    - discrete, passive and active components
    - lumped and distributed components
  - Knowledge about components
  - Measurement technique

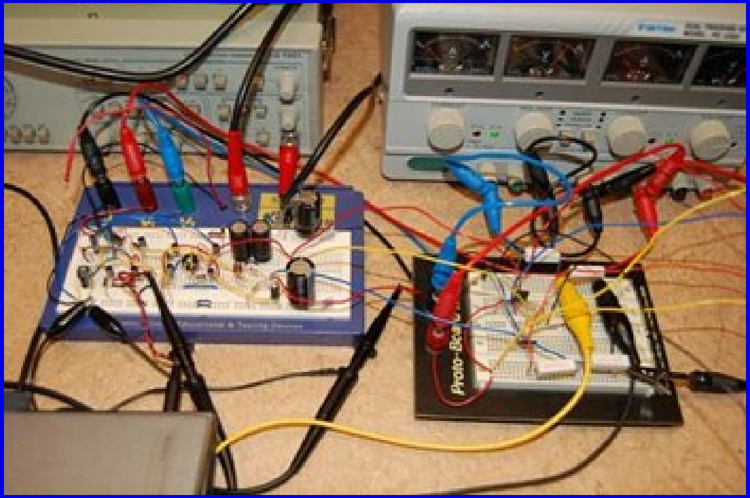
Some Applications

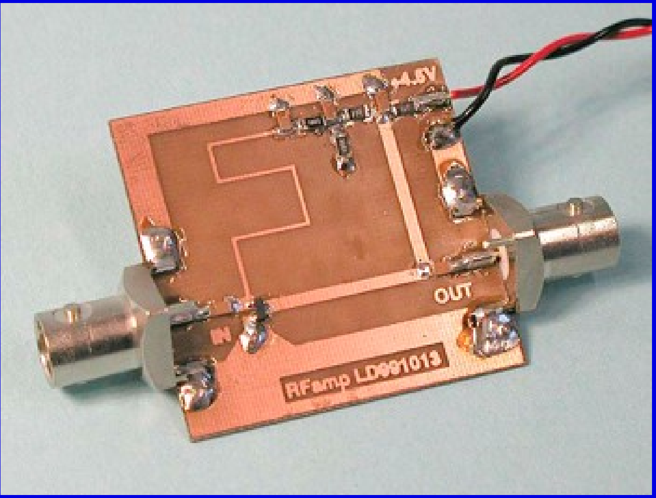


IEEE Microwave Bands

Band	Frequency range (GHz)
HF	0.003 - 0.030
VHF	0.030 - 0.300
UHF	0.300 - 1.000
L band	1.000 - 2.000
S band	2.000 - 4.000
C band	4.000 - 8.000
X band	8.000 - 12.000
Ku band	12.000 - 18.000
K band	18.000 - 27.000
Ka band	27.000 - 40.000
Millimetre	40.000 - 300.000
Sub millimetre	> 300.000

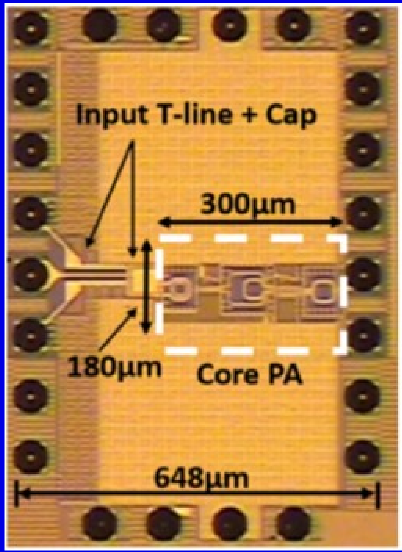
Find the differences:





Low Frequency

Radio Frequency



Millimetre Wave

Electronics

Callender et al. 2018
75 GHz FinFET PA

Comparison

Low frequency electronics

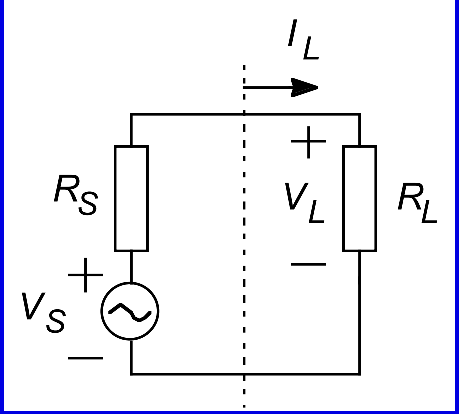
1. voltage or current interface between stages,
   “voltage matching” or “current matching”
2. small and large impedances are feasible
3. reactive components are often avoided - broadband circuits
4. parasitic reactance's in components limits the performance
5. the length of wires is in most cases uncritical

Radio (or mmWave) frequency electronics

1. voltage or current interfaces are not possible due to parasitics
2. small and large impedances are difficult to produce due to parasitics
3. reactive components are usable - band-pass circuits are used to improve the performance
4. parasitic reactance's in components does not necessarily limit the performance
5. the length and width of wires is in most cases critical
6. reactive components may be implemented by transmission lines

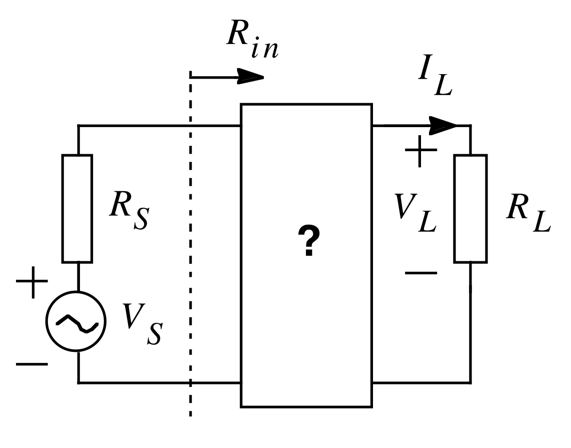
Power Instead of Voltage and Current (1)

- Voltage matching
  - at low frequencies it is possible to realize a high load resistance relative to the source,
    $R_S << R_L$
    i.e. the *“available voltage”* ends up at the load
- Current matching
  - at low frequencies it is possible to realize a low load resistance relative to the source,
    $R_S >> R_L$
    i.e. the *“available current”* ends up through the load
- Power matching
  - A source has besides an available voltage or current also an *“available power”*…



Power Instead of Voltage and Current (2)

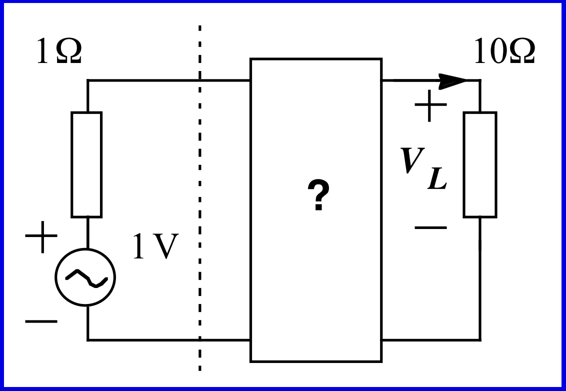
- Power matching
  - Instead of transferring available voltage or current to the load:
    transfer available power
  - From circuit theory:
    the transfer of power is maximized when
    $R_S = R_{in}$
  - or generally at complex conjugate matching
    $Z_S = Z^*_{in}$
  - If both R_s and R_L are fixed we may maximize the transfer of power and accordingly optimize the voltage and the current.



- We need a lossless matching network between R_s and R_L.

Power Instead of Voltage and Current (3)

- reactive elements → no or low losses
  - available power may be preserved and transferred to the load, by that also the transfer of voltage and current optimized.
- drawback: not a broadband solution
- example:
  - without matching: V_L = 0.9 V
    P_L = 0.08 W
  - with matching: V_L = 1.6 V
    P_L = 0.25 W
  - x4 with matching



RF Amplifier Design Compared to Traditional (low frequency) Analog Electronics

- Transmission of power rather than voltage or current
- Reactive circuit elements - lumped or distributed
- New design methods
- Device models where parasitics must be considered
- Interesting measurements equipment

RF Amplifier Design ETIN50 Facts

- ECTS: 7.5
- Level A
- open for E4, N4, EEE, COM, etc.
- Literature: L. Sundström, G. Jönsson and H. Börjeson, “Radio Electronics”
- Teaching in period ht 2:
  - 9 lectures and 8 exercise slots
  - 4 compulsory laboratory exercises
  - 2 compulsory hand-in assignments
- Examination:
  - passed written exam
  - passed hand-in exercises
  - passed laboratory exercises

RF Amplifier design ETIN50 Contents

- Resonant circuits
- Transmission lines
- The Smith chart
- Matching
- IF amplifiers
- RF amplifiers
  - Z-, Y- and S-parameters
  - stability
  - power gain
  - noise properties
  - DC design
- Oscillators

ETIN50 – RF Amplifier Design - 2018 Ht2

Johan Wernehag The course replaces Radio Elektronics ETI032

week	day	date	time	room	activity	contents
1	mån	2018-11-05	13-15	E:3139	L1	Introduction, resonant circuits
	ons	2018-11-07	10-12	E:2311	L2	Waves on transmission lines
	ons	2018-11-07	13-15	E:4119	E1	Resonant circuits Ex: all in Exercises 1
2	mån	2018-11-12	13-15	E:3139	L3	The Smith chart, matching
	ons	2018-11-14	10-12	E:4119	E2	Transmission lines Ex: all in Exercises 2 except 2.6 and 2.9
	ons	2018-11-14	13-15	E:4119	E3	The Smith chart Ex: all in Exercises 4
	tor	2018-11-15	*	E:2427	Lab1	Resonant circuit and transmission line resonator
3	mån	2018-11-19	13-15	E:3139	L4	Matching (cont.), passive components
	ons	2018-11-21	10-12	E:2311	L5	Transistors, HF amplifiers, amplifier design (z, y, ABCD): 2-port representation of transistors, power gain definitions, stability
	ons	2018-11-21	13-15	E:4119	E4	Matlab demo, matching Ex: all in Exercises 5 except 5.5
	fre	2018-11-23	Hand in of the solution to hand-in assignment 1			Analysis of a network in the Smith chart and calculations in Matlab and deslib
4	mån	2018-11-26	13-15	E:3139	L6	Amplifier design: S-parameters, gain definitions, stability, RF measurements
	ons	2018-11-28	10-12	E:2311	L7	Amplifier design: design methodologies, noise optimization
	ons	2018-11-28	13-15	E:4119	E5	Matching, medium frequency amplifiers Ex: all in Exercises 6
	fre	2018-11-30	*	E:2427	Lab2	RF measurement techniques, S-parameter measurements on a transistor
5	mån	2018-12-03	13-15	E:3139	L8	Amplifier design: DC design
	ons	2018-12-05	10-12	E:4119	E6	2-port, S-parameters DC design, hand-in assignment 2 Ex: Exercises 9.1, 9.2 and 9.4
	ons	2018-12-05	13-15	E:4119	E7	Stability, design of RF amplifiers Ex: all in Exercises 8 except 8.3, 8.5, 8.6, 8.7, 8.9, 8.10, 8.12 and 8.14
	fre	2018-12-07	Hand in of the solution to hand-in assignment 2			Design of a low noise amplifier with specified properties
6	mån	2018-12-10	13-15	E:3139	L9	Oscillators
	tis	2018-12-11	*	E:4119	Lab3	RF amplifiers
	ons	2018-12-12	13-15	E:4119	E9	Analysis of IF amplifiers, oscillators Ex: all in Exercises 10 except 10.3
	fre	2018-12-14	*	E:2427	Lab4	Oscillators
7	mån	2018-12-17	13-15	E:3139	Q1	Preparation for the exam. Answering students questions
8	fre	2018-01-05	8-13	E:2311		Examination

* separate registration L = Lecture, E = Exercise, Lab = Lab exercise, Q = Question hour

Prerequisites

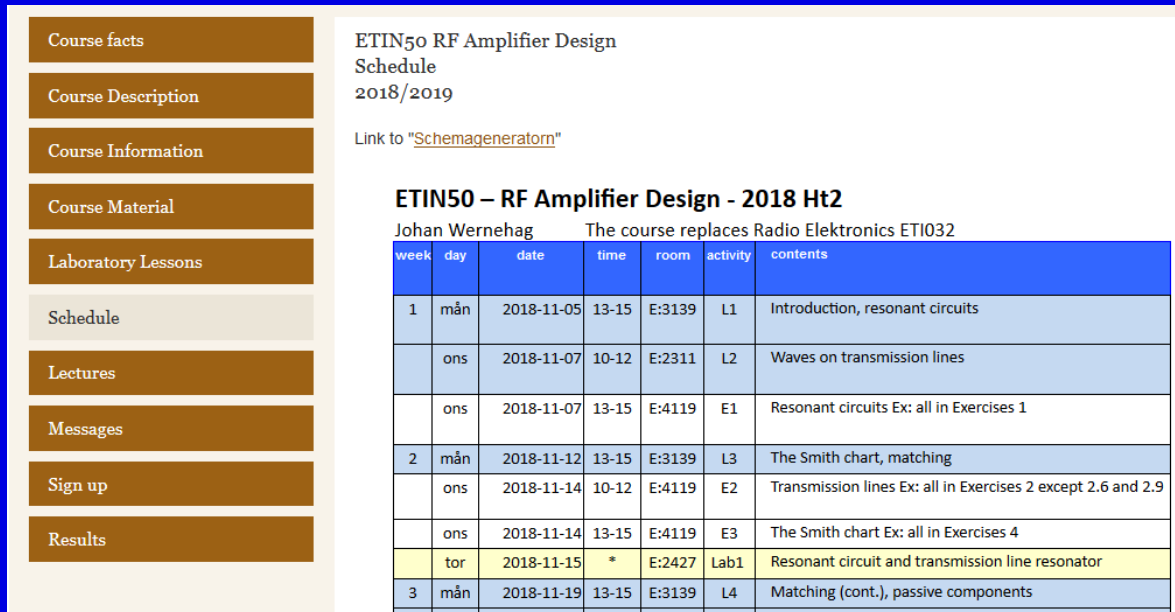
- Circuit Theory
- Analog Electronics
- Introduction to wireless systems EITF50 (or ETI031, ETIF05)

Course Materials

- Textbook: “Radio Electronics” (the blue book)
  (available as pdf at LU Canvas)
- Study materials (the green book) (available as pdf)
  - Exercises and solutions
  - Laboratory experiments
- Formulas and Tables (the red book)
- The complete package is sold at KFS

- Smith charts
- Deslib, toolbox for Matlab (available at LU Canvas)
- Example exam (available at the LU Canvas)

Schedule



Course facts
Course Description
Course Information
Course Material
Laboratory Lessons
Schedule
Lectures
Messages
Sign up
Results

ETIN50 RF Amplifier Design
Schedule
2018/2019

Link to "Schemageneratorn"

ETIN50 – RF Amplifier Design - 2018 Ht2

Johan Wernehag The course replaces Radio Elektronics ETI032

week	day	date	time	room	activity	contents
1	mån	2018-11-05	13-15	E:3139	L1	Introduction, resonant circuits
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	ons	2018-11-14	13-15	E:4119	E3	The Smith chart Ex: all in Exercises 4
	tor	2018-11-15	*	E:2427	Lab1	Resonant circuit and transmission line resonator
3	mån	2018-11-19	13-15	E:3139	L4	Matching (cont.), passive components

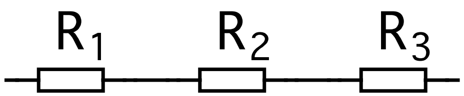
- Lectures and lessons
- Four compulsory laboratory exercises
- Two compulsory hand-in assignments
- Continuous assessment
- Written exam
- Home page: www.eit.lth.se/course/etin50
- LU Canvas: https://canvas.education.lu.se/ > ETIN50

Resonant Circuits

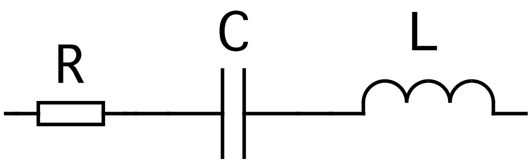
- Concepts
  - resonant circuit
  - resonant frequency
  - circuit Q
  - bandwidth
- Basic circuits
  - series resonant circuit
  - parallel resonant circuit
  - series-to-parallel conversion
  - capacitive and inductive taps
  - transformer

Resonant Circuits

- Series circuits are handled by summing the impedances



$$R_{tot} = R_1 + R_2 + R_3$$



Series resonance

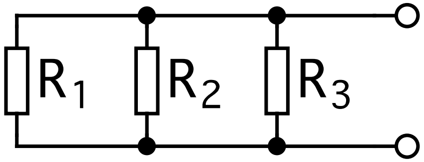
$$Z_{tot}(\omega) = R + j\omega L + \frac{1}{j\omega C} = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

The frequency that leaves a purely resistive impedance is called the resonant frequency:

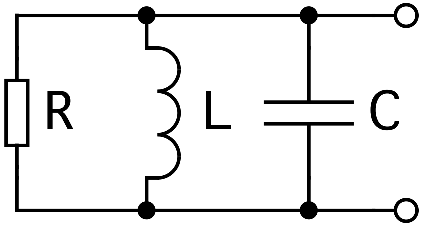
$$\omega_0 L - \frac{1}{\omega_0 C} = 0 \Rightarrow f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Resonant Circuits

- Parallel circuits are handled by summing the admittances



$$Y = \frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$



Parallel resonance

$$Y_{tot}(\omega) = \frac{1}{R} + \frac{1}{j\omega L} + j\omega C = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right)$$

The frequency that leaves a purely resistive admittance is called the resonant frequency:

$$\omega_0 C - \frac{1}{\omega_0 L} = 0 \Rightarrow f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

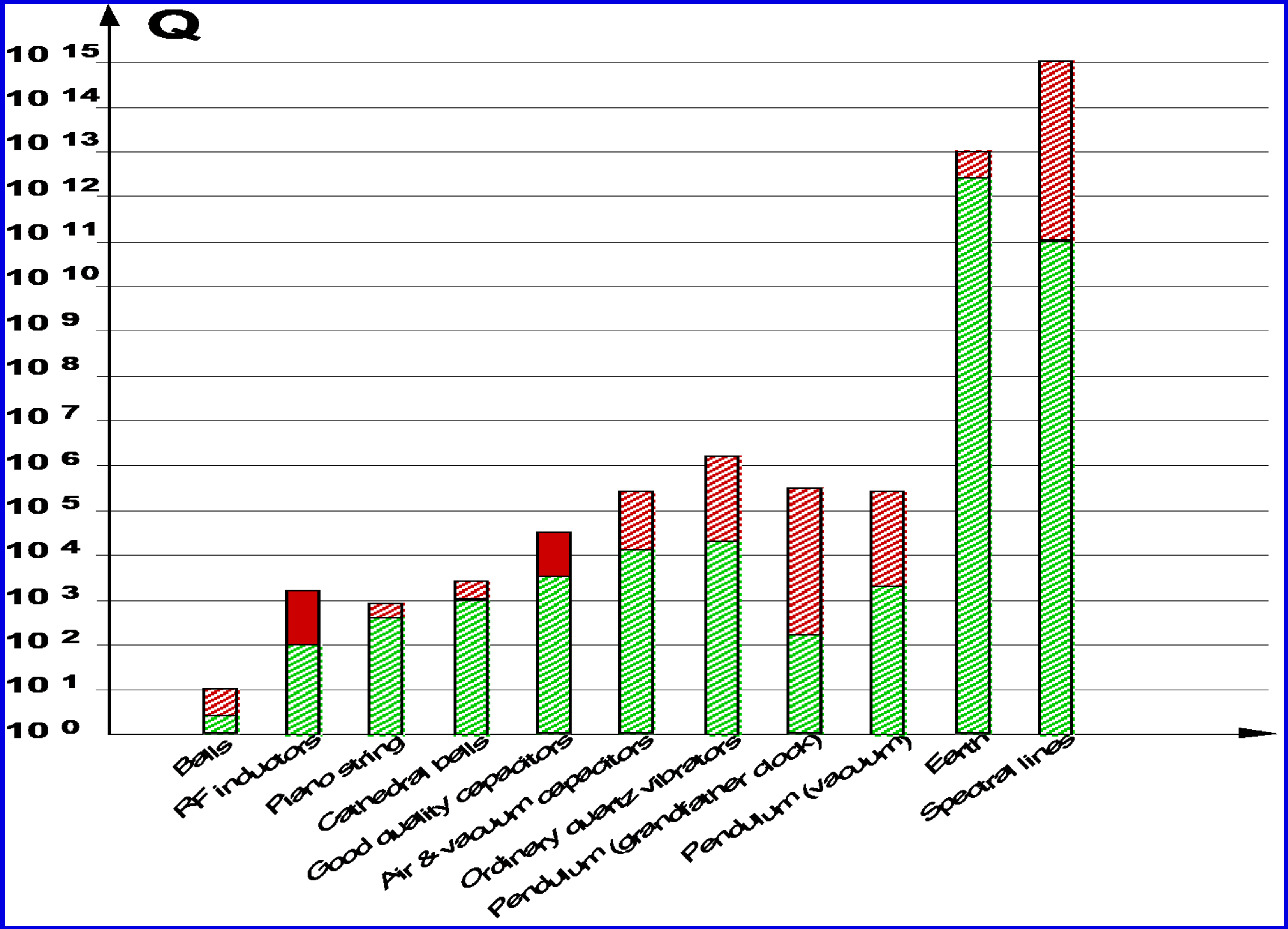
Circuit Q - Quality Factor

$$Q = 2\pi \frac{\text{maximum energy stored in the circuit}}{\text{energy dissipated per cycle}}$$

- is a measure of the maximum instantaneous stored energy related to the total energy dissipated in the circuit
  - Max. reactive energy / active energy
- is dimensionless
- is called “Q-värde” (”godhetstal” in Swedish)
- is also used for non-electronic systems
- is also applicable to non-resonant circuits such as
  - RC-circuit or
  - individual components such as a coil
- is equal to the ratio between the resonance frequency and the 3dB bandwidth:

$$Q = \frac{f_0}{B_{3dB}}$$

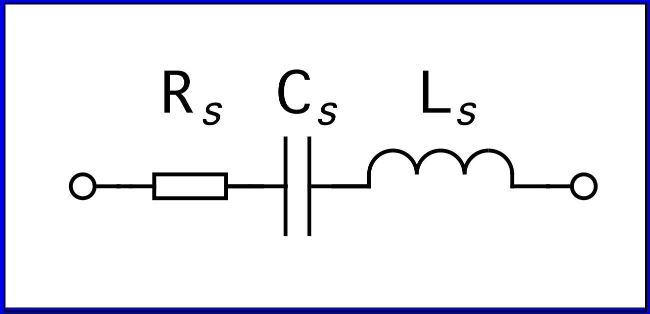
Quality Factor - Some Comparisons



Circuit Q

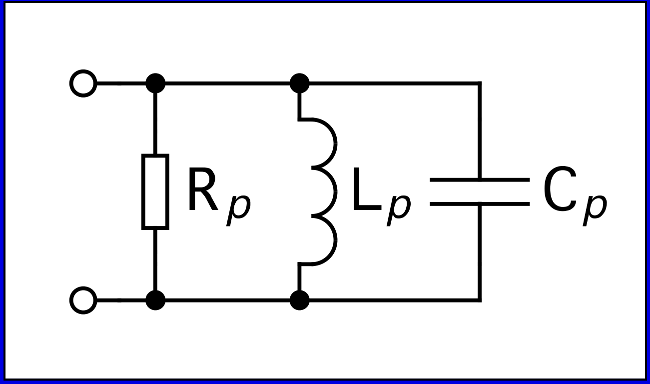
Series circuit *Q*

$$Q = \frac{|X|}{R_s} = \frac{\omega_0 L_s}{R_s} = \frac{1}{R_s \omega_0 C_s} = \frac{\sqrt{L_s / C_s}}{R_s}$$



Parallel circuit *Q*

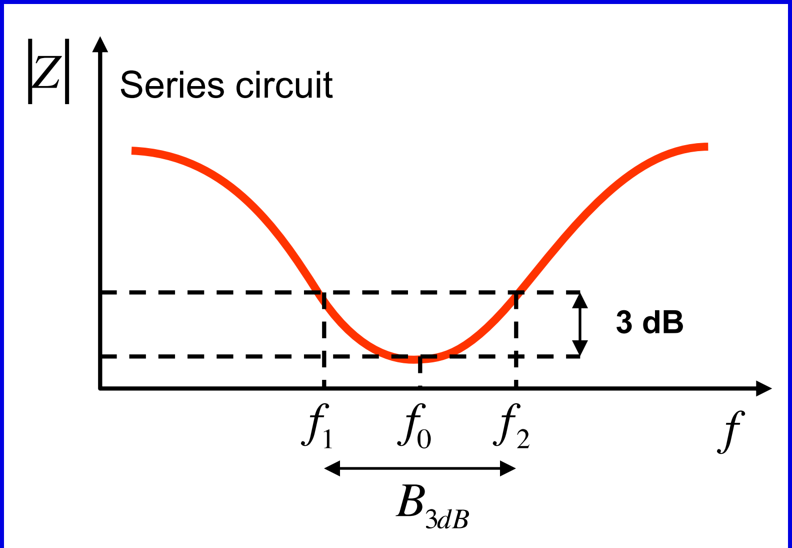
$$Q = \frac{R_p}{|X|} = R_p \omega_0 C_p = \frac{R_p}{\omega_0 L_p} = \frac{R_p}{\sqrt{L_p / C_p}}$$

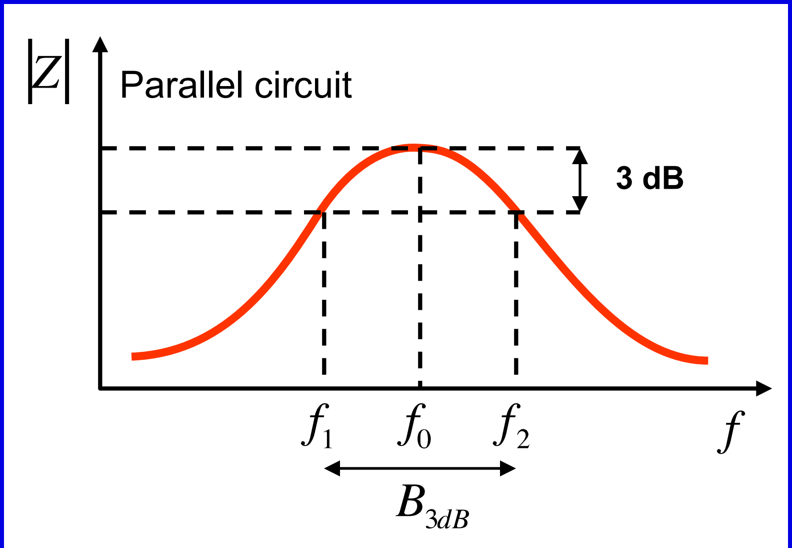


- Characteristic impedance $Z_0 = \sqrt{L / C}$ ohms

Bandwidth

- The 3dB-bandwidth is defined as the frequency range where the circuit impedance or admittance has changed 3dB.





$$B_{3dB} = f_2 - f_1 = \frac{f_0}{Q}$$

Bandwidth

- regarding the parallel circuit

$$Y(\omega) = G + j\left(\omega C - \frac{1}{\omega L}\right) = G + \frac{j}{\omega L}(\omega^2 LC - 1)$$

- set $\omega = \omega_0 + \Delta\omega$ and $\omega_0 = 1/\sqrt{LC}$:

$$Y(\omega) = G + \frac{j}{\omega L}\left(\left[\left(\frac{1}{\sqrt{LC}}\right)^2 + 2\Delta\omega\omega_0 + (\Delta\omega)^2\right]LC - 1\right) = $$

$$= G + \frac{j}{\omega L}(2\Delta\omega\omega_0 + (\Delta\omega)^2)LC$$

$$Y(\omega) \approx G + j2\Delta\omega C$$

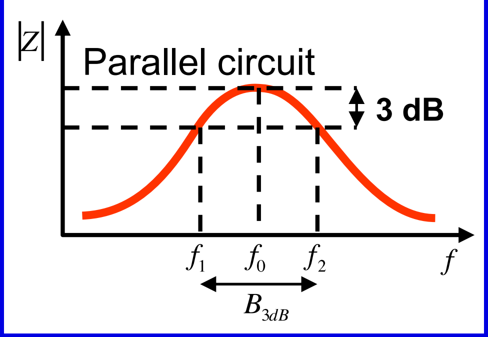
- Compare to a parallel RC-link with $R = 1/G,\ C' = 2C$ and $\omega = \Delta\omega$

Bandwidth (cont.)

- for small $\Delta\omega$ the circuit behaves like a parallel RC-link:

$$Y(\omega) \approx G + j2\Delta\omega C$$

- the bandwidth of an RC-link $= 1/RC$



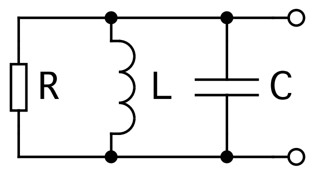
→ the one-sided bandwidth of parallel resonant circuit $= 1/2RC$

→ the double-sided bandwidth: $B_{3dB} = \omega_2 - \omega_1 = 1/RC$

→
$$\frac{B_{3dB}}{\omega_0} = \frac{1}{R\omega_0 C} = \frac{1}{Q}$$

Properties in the frequency domain

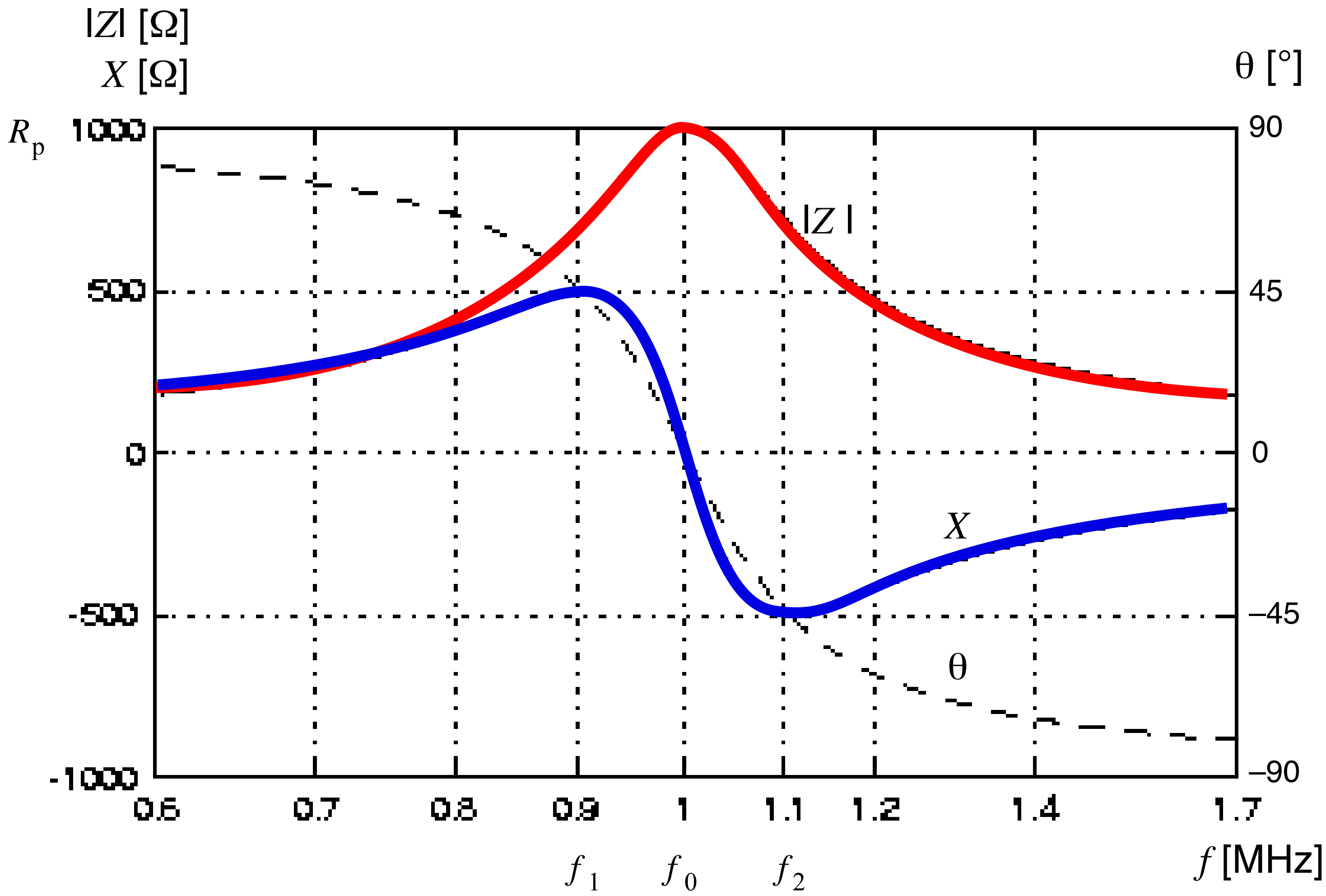
- Parallel resonant circuit



$$Y_p(\omega) = \frac{1}{R} + \frac{1}{j\omega L} + j\omega C = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right) =$$
$$= \frac{1}{R}\left(1 + jQ_p\left[\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right]\right)$$

- where $Q_p = \frac{R}{\omega_0 L} = R\omega_0 C = \frac{f_0}{f_2 - f_1} = \frac{f_0}{B_{3dB}}$

Parallel Resonance - an Example



$R_p = 1000\Omega$

$L_p = 31.8\mu H$

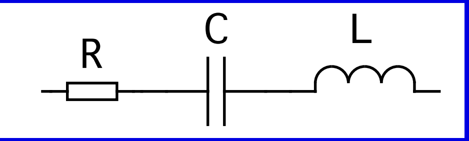
$C_p = 796pF$

$f_o = 1 MHz$

$Q_p = 5$

Properties in the Frequency Domain

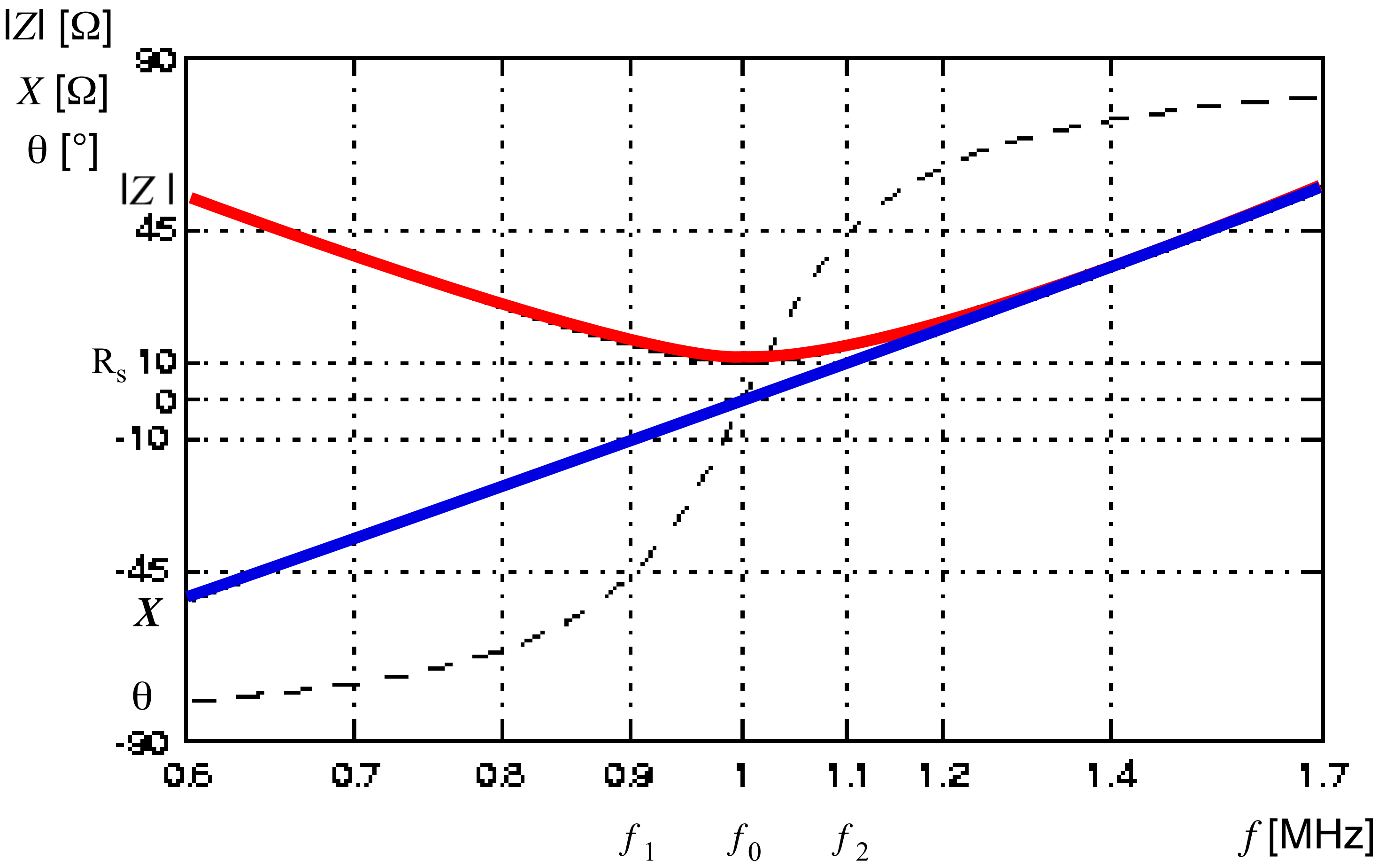
- Series resonant circuit



$$Z_s(\omega) = R + \frac{1}{j\omega C} + j\omega L = R + j\left(\omega L - \frac{1}{\omega C}\right) =$$
$$= R\left(1 + jQ_s\left[\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right]\right)$$

- where $Q_s = \frac{\omega_0 L}{R} = \frac{1}{R\omega_0 C} = \frac{f_0}{f_2 - f_1} = \frac{f_0}{B_{3dB}}$

Series Resonance - an Example



$R_s = 10\Omega$

$L_s = 7.96\text{nH}$

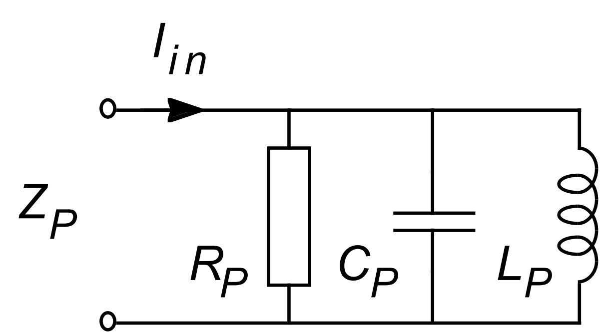
$C_s = 31.8\mu\text{F}$

$f_o = 1\text{MHz}$

$Q_s = 5$

The Current through Reactive Elements in Parallel Resonant Circuits

- at resonance $Z_P = R_P$



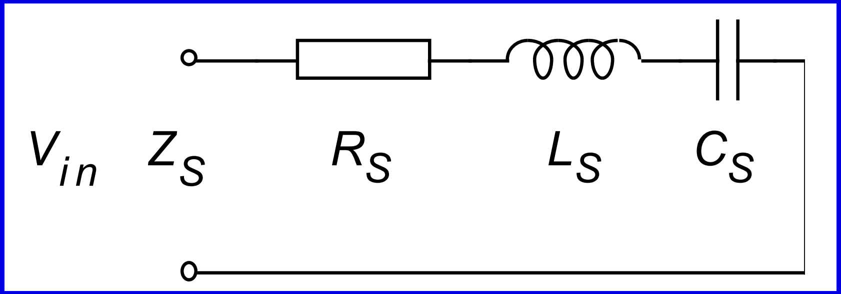
$$|I_L| = |I_C| = \frac{|V|}{Z} = \frac{I_{in} R_P}{\omega_0 L_P} = Q|I_{in}|$$

@ ω_0

- example: $I_{in} = 1\ \text{A}, Q = 200 \Rightarrow |I_L| = |I_C| = 200\ \text{A}$

The Voltage at Reactive Elements in Series Resonant Circuits

- at resonance $Z_S = R_S$

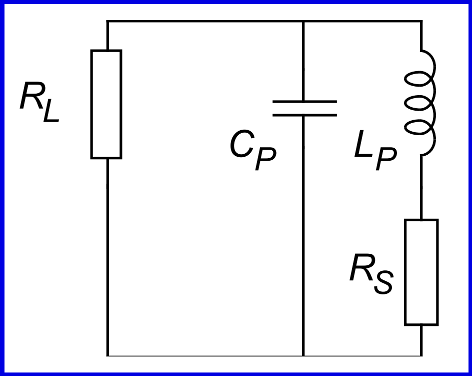


$$|V_L| = |V_C| = Z|I| = \omega_0 L_S \frac{V_{in}}{R_S} = Q|V_{in}|$$

@ ω_0

- example: $V_{in} = 1\text{ V}, Q = 200 \Rightarrow |V_L| = |V_C| = 200\text{ V}$

Series-to-Parallel Conversion



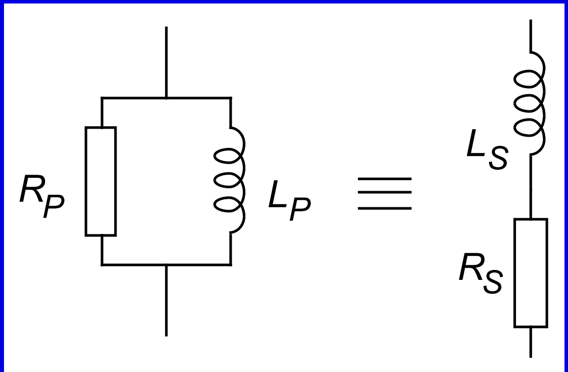
- Example of usage:
  - the circuit is loaded by a parallel resistance R_L
  - the loss in the coil is specified as series resistance R_S

- What is the overall circuit Q?

- Solution:
  - convert the series resistance R_S to an equivalent parallel resistance R_P
  - calculate the parallel connection to R_L
  - calculate the circuit Q

Series-to-Parallel Conversion (cont.)

- Coil with losses



$$R_s + j\omega_0 L_s = R_p || j\omega_0 L_p = \frac{(\omega_0 L_p)^2 R_p + j\omega_0 L_p R_p^2}{R_p^2 + (\omega_0 L_p)^2}$$ *

$$Q = Q_S = \frac{\omega_0 L_S}{R_S} = Q_P = \frac{R_P}{\omega_0 L_P}$$

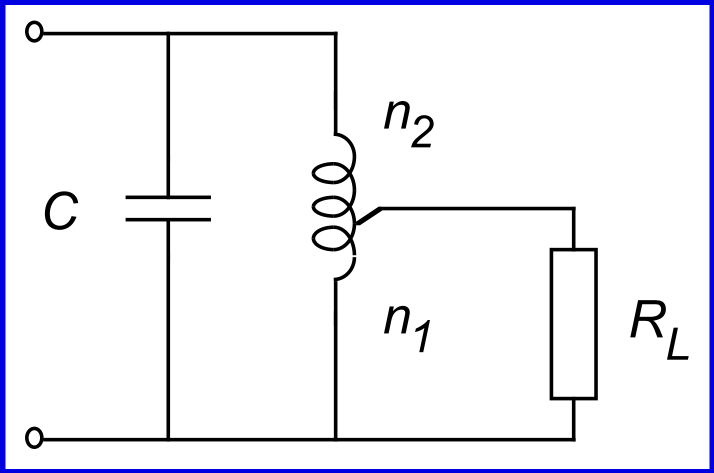
- solve: $R_P = R_S(1 + Q^2), L_P = L_S\left(\frac{1 + Q^2}{Q^2}\right)$ (valid only close to ω_0)

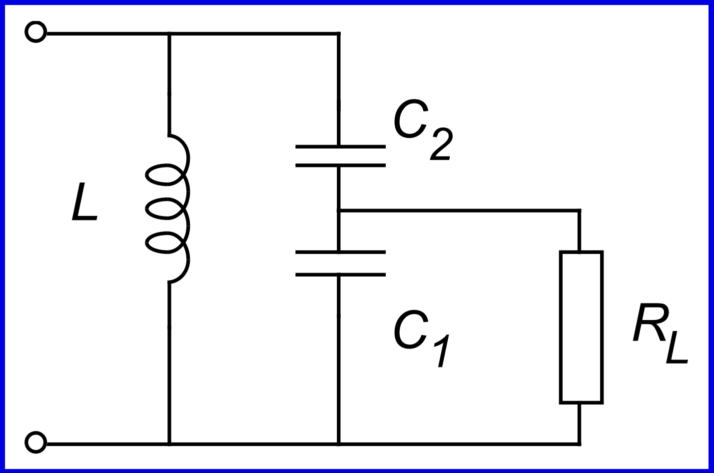
Series-to-Parallel Conversion (cont.)

- Inductance
- $$R_P = R_S(1+Q^2), L_P = L_S\left(\frac{1+Q^2}{Q^2}\right)$$ (valid only close to ω_0)
- Capacitance
- $$R_P = R_S(1+Q^2), C_P = C_S\left(\frac{Q^2}{1+Q^2}\right)$$ (valid only close to ω_0)
- or generally
- $$R_P = R_S(1+Q^2), X_P = X_S\left(\frac{1+Q^2}{Q^2}\right)$$ (valid only close to ω_0)

Capacitive and Inductive Tap

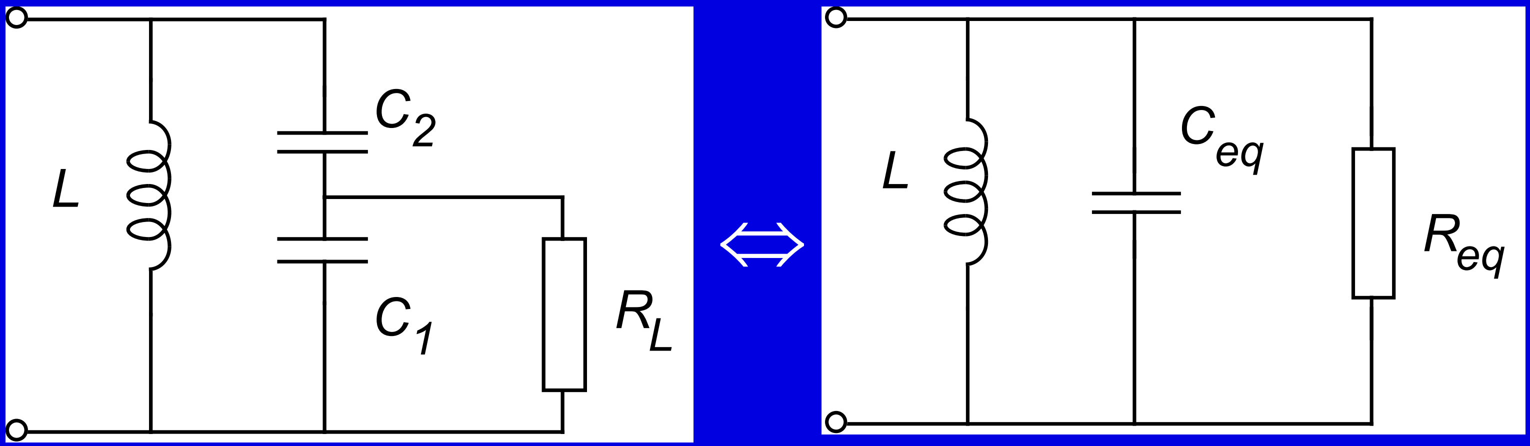
- The properties of basic resonant circuits are limited as the bandwidth and circuit Q are determined by the losses and the load.
- By a capacitive or inductive tap in the resonant circuit the bandwidth is set independently from the load value.
- Example:





Capacitive Tap

- Equivalent model

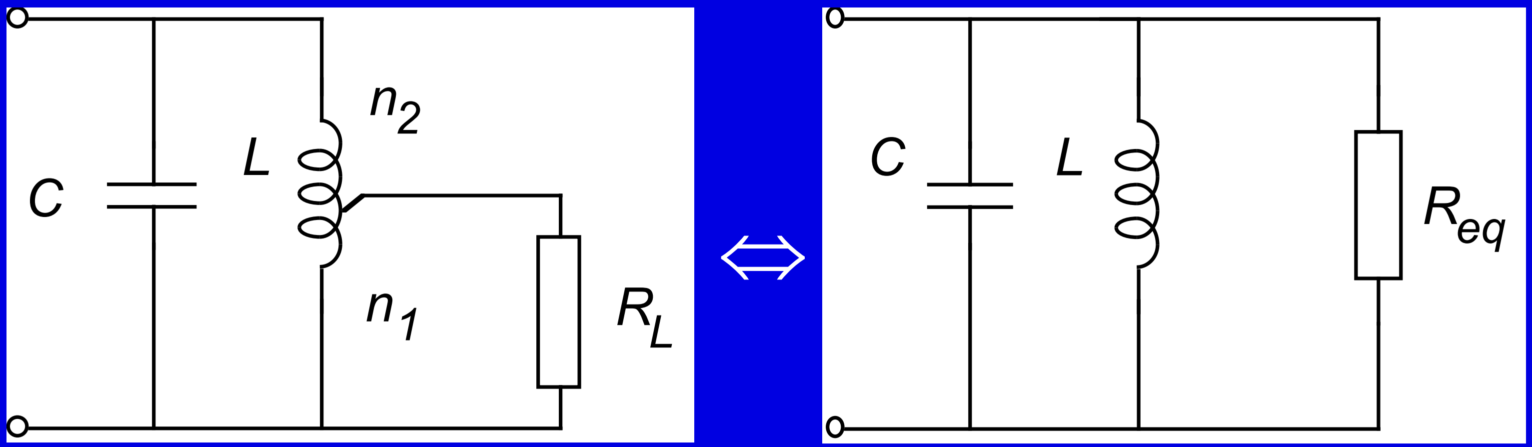


- $$R_{eq} = R_L \left(\frac{C_1 + C_2}{C_2} \right)^2, C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$ if $R_L >> X_{C1}$ (unloaded circuit)

- if the tap is considered as loaded the conversion has to be performed in several steps by successive parallel → series → parallel conversion

Inductive Tap

- Equivalent model

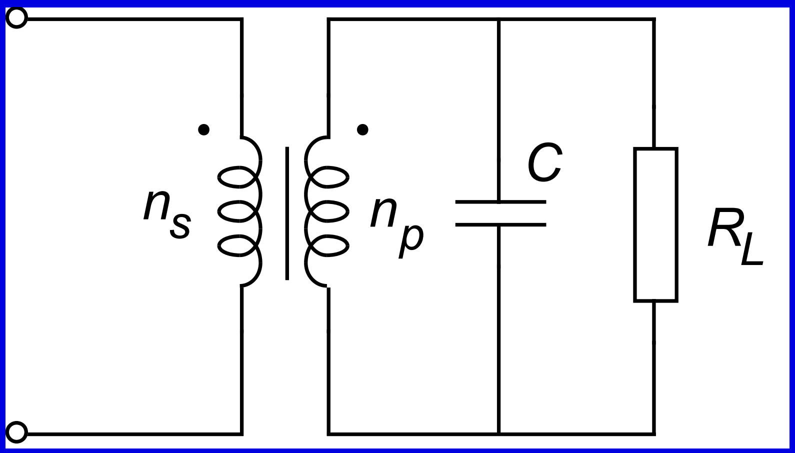


$$R_{eq} = R_L \left(\frac{n_1 + n_2}{n_1} \right)^2$$

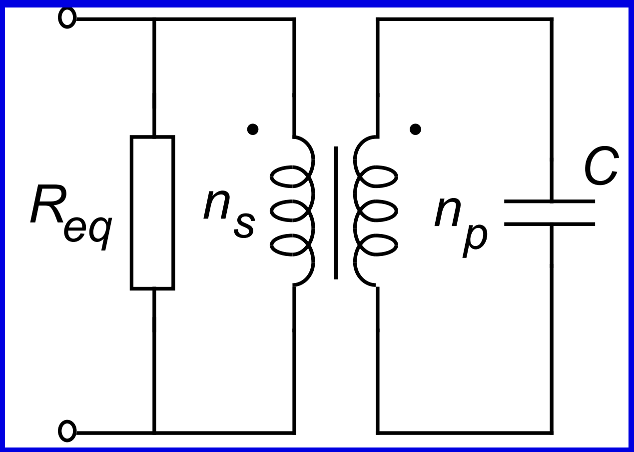
- valid if the tap may be considered as unloaded i.e. $Q \geq 10$ and with unity coupling $k = 1$

Transformer

- Equivalent model



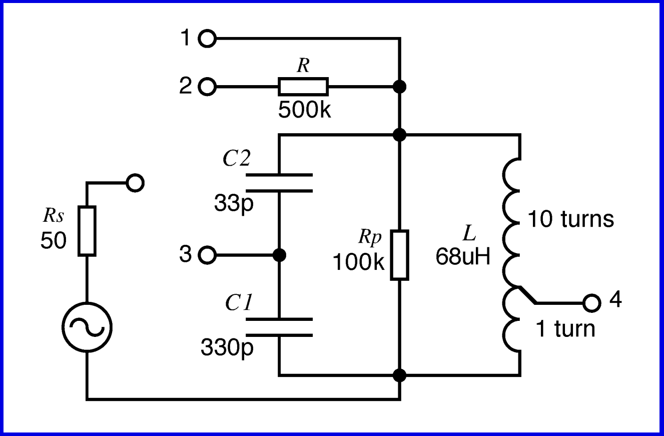
⇔



$$R_{eq} = R_L \left(\frac{n_s}{n_p} \right)^2$$

- valid if the transformer may be considered as unloaded i.e. $Q \geq 10$, and with unity coupling $k = 1$

How to connect the parallel resonant circuit



The unloaded circuit:

- Resonant frequency

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC_{eq}}} = \frac{1}{2\pi}\sqrt{\frac{1}{68\cdot 10^{-6}\cdot 30\cdot 10^{-12}}} = 3.5\text{MHz}$$

- Circuit Q

$$Q = \frac{Rp}{|X|} = \frac{Rp}{|\omega_0 L|} = \frac{100\cdot 10^{3}}{2\pi\cdot 3.5\cdot 10^{6}\cdot 68\cdot 10^{-6}} = 67$$

- Bandwidth

$$B_{3\text{dB}} = \frac{f_0}{Q} = \frac{3.5\cdot 10^{6}}{67} = 52\text{kHz}$$

Connect the external load or source:

① Direct

$$Q = \frac{Rp//50\Omega}{|X|} = 0.03 \Rightarrow B_{3\text{dB}} = 105\text{MHz}$$

② Series R

$$Q = \frac{Rp//500\text{k}\Omega}{|X|} = 56 \Rightarrow B_{3\text{dB}} = 63\text{kHz}$$

The voltage decreases by a factor 10^4

③ Capacitive tap

$$Q = \frac{Rp//Rs'}{|X|}$$

f_0 decreases due to loading of *C1*

The voltage increases

AC coupled

④ Inductive tap

as capacitive tap but

f_0 increases due to loading of *n1*

DC coupled