

Radio Design 101

Episode 1 - Transceivers and Filters

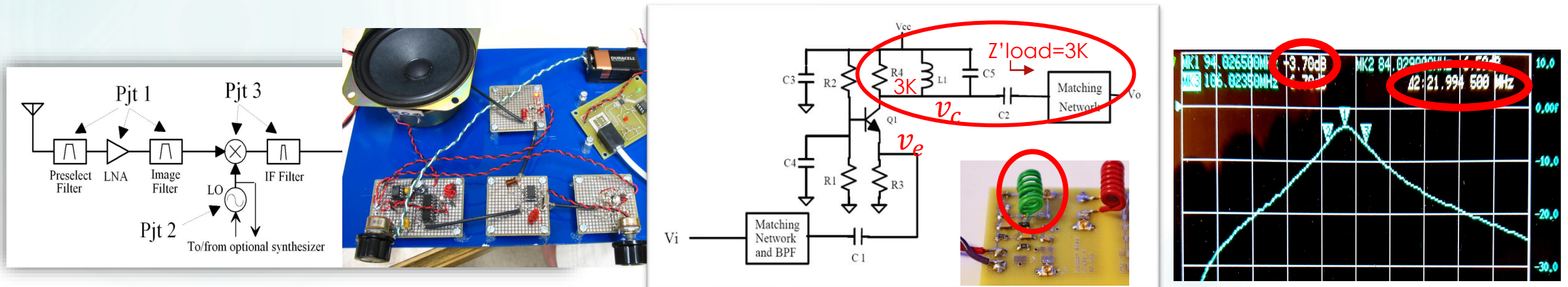
Slides downloaded from: <https://ecefiles.org/rf-design/>

Companion videos at: https://www.youtube.com/watch?v=r_p7AHsSOdw (part 1)

and: <https://www.youtube.com/watch?v=He0-X6FCLMo> (part 2)

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This episode, and the Radio Design 101 series of which it is a part, is based on a university-level senior-design course. However, it is intended for anyone interested in learning the nuts and bolts of electronics and radio circuits. In the first part of this episode, we focus on bandpass filters - including their application, design, and measurement. The second half goes into filter design in depth, including an overview of impedance matching networks. Later episodes in the series elaborate what is needed to create a full radio receiver – as well as how to do measurements, performance assessments, and improvements. Three epilogues to the series cover the latter material in detail.





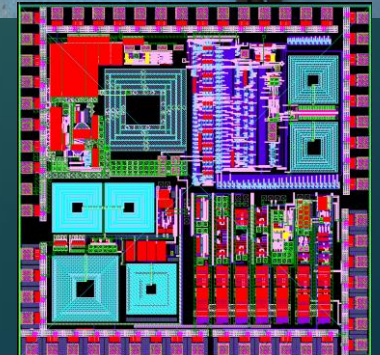
Radio Design 101

Episode 1

Bandpass Filters, Q, and Matching Networks

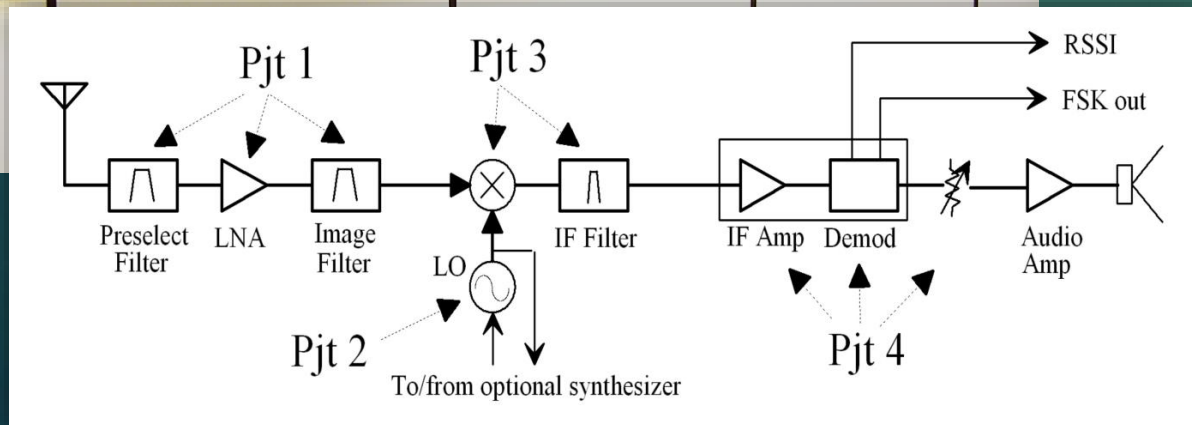
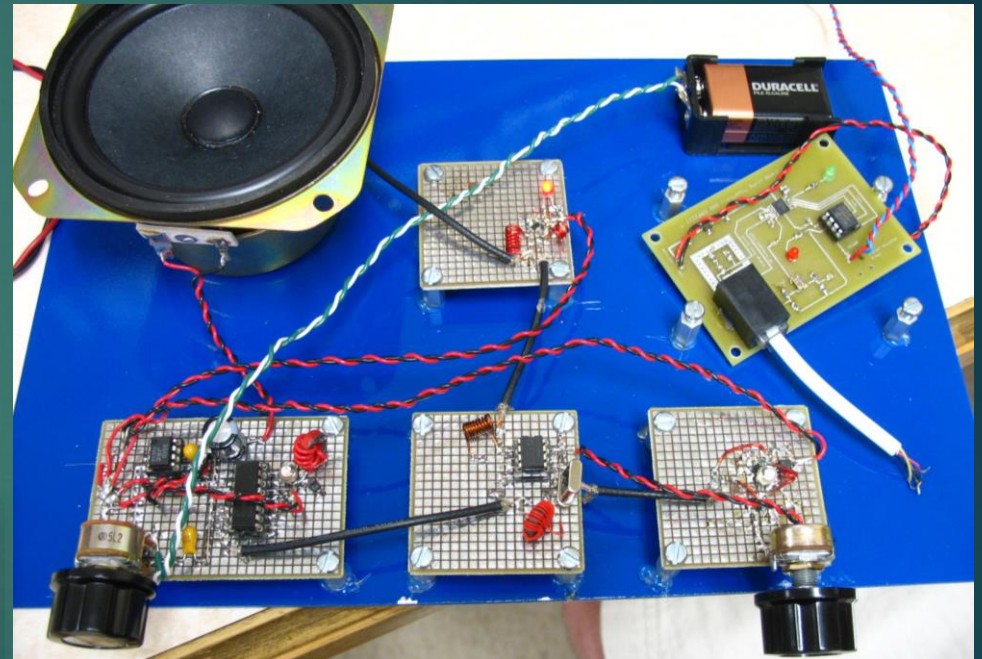
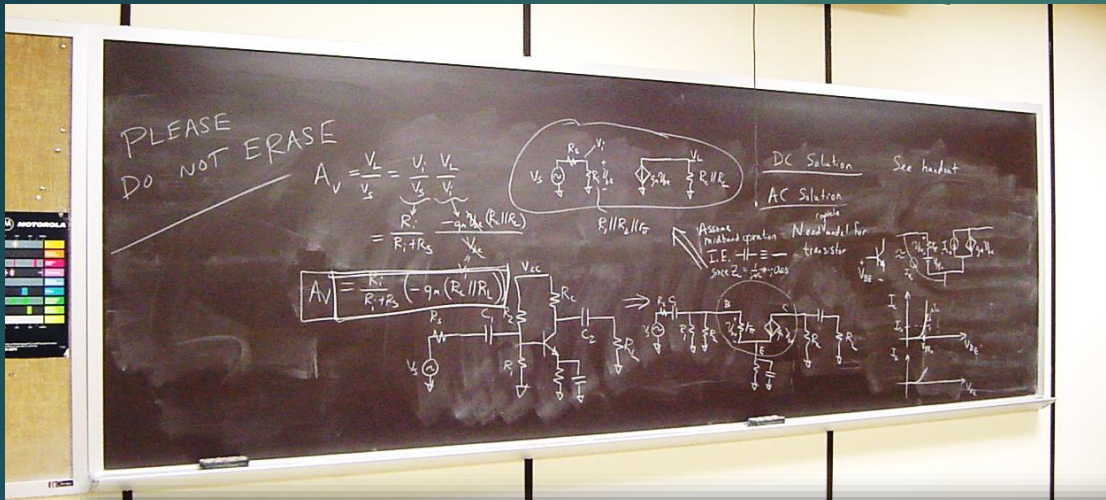
Radio Design 101 series

Applicable to all Radio/Wireless Circuit Design



Radio Design 101 series

Abstracted from a senior-design University class

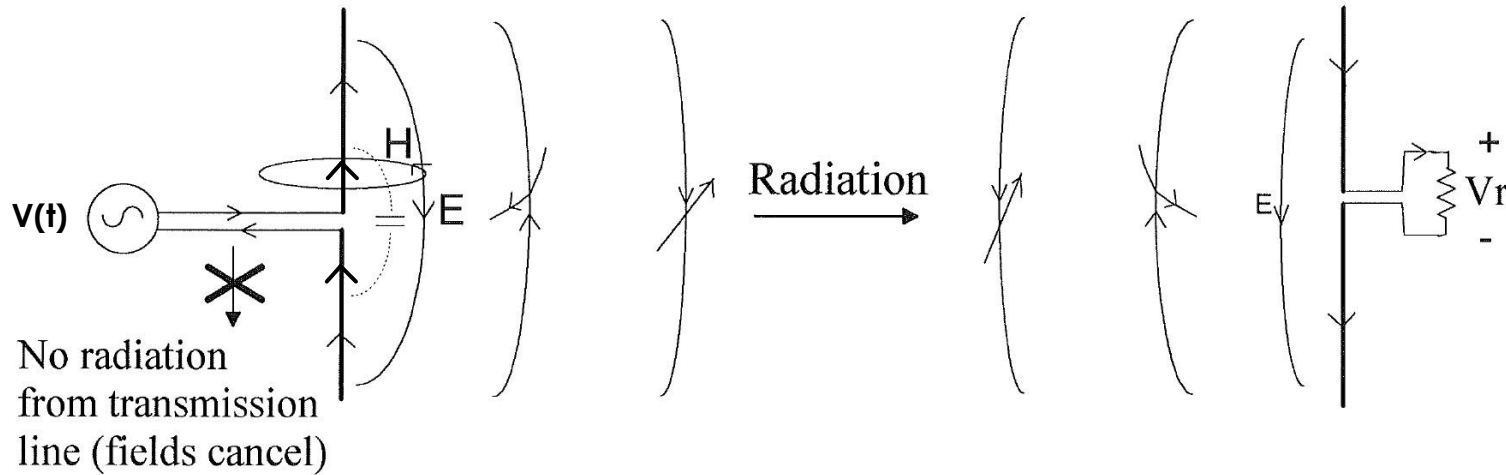


Outline of This Video

- Part 1
 - *Transmitters and Receivers*
 - *Impedances, Ohms Law, and Voltage dividers*
 - *1-pole Filters (Lowpass and Bandpass)*
- Part 2
 - *Quality Factor (Q)*
 - *Design Examples*
 - *Intro to Impedance Matching*
 - *Higher Order Filter Design*

Transmitters and Receivers

EM Field View



No radiation from transmission line (fields cancel)

Voltage Source sets up currents in tx antenna

Currents Launch E and H Fields

Fields induce voltage/current in rx antenna

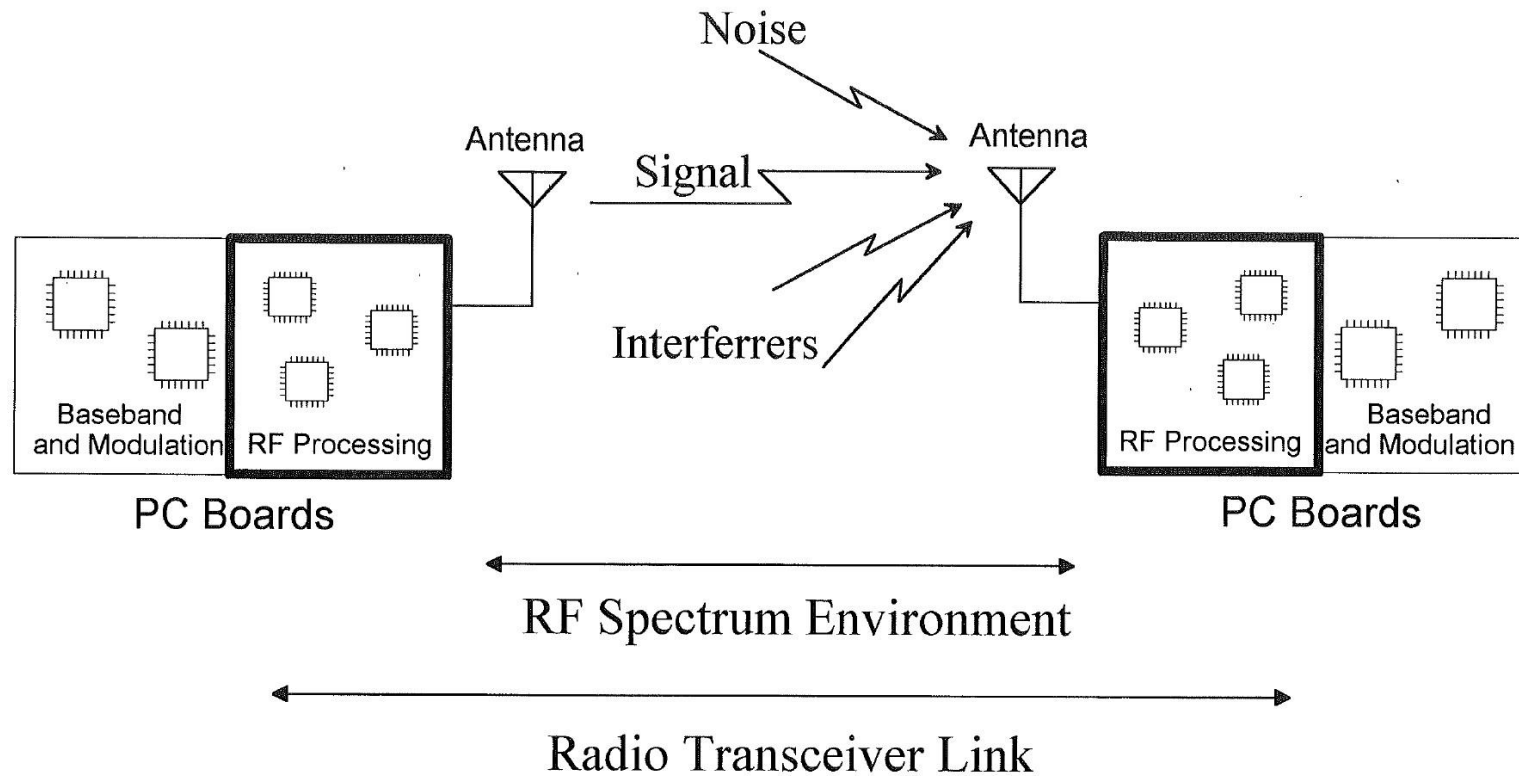
Voltage Source sets up currents in tx antenna

Currents Launch E and H Fields

Fields induce voltage/current in rx antenna

Transmitters and Receivers

System View



Receiver Design and Filters

From tuned-RF to Superhet and beyond...

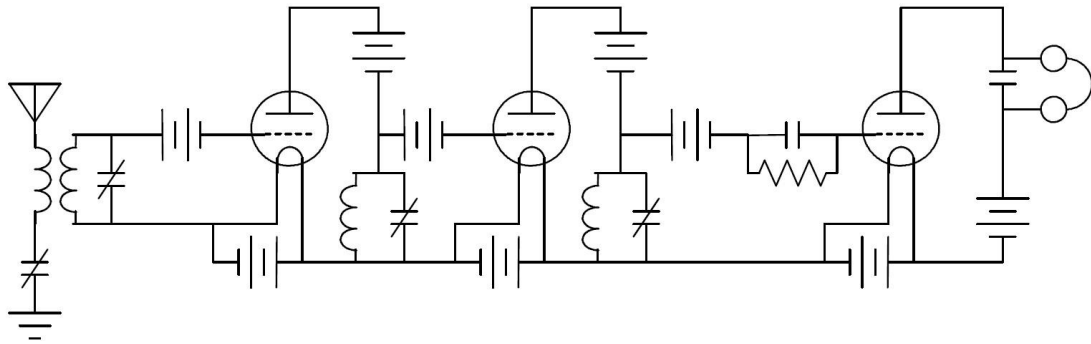


Figure 4.2: Early tuned-RF receiver circuit. [British patent no. 147,147]

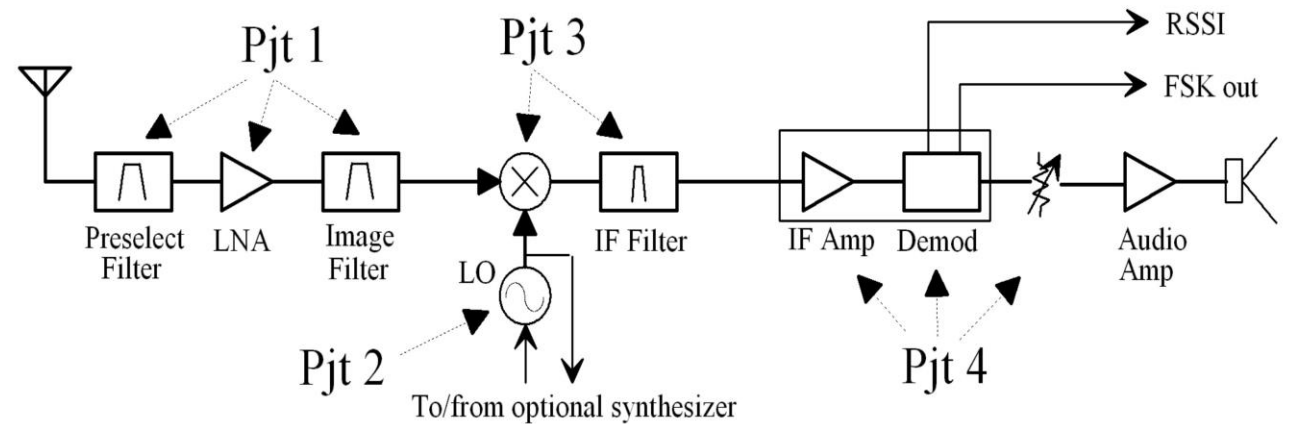


Figure 4.3: Early super-RF receiver circuit. [British patent no. 147,147]

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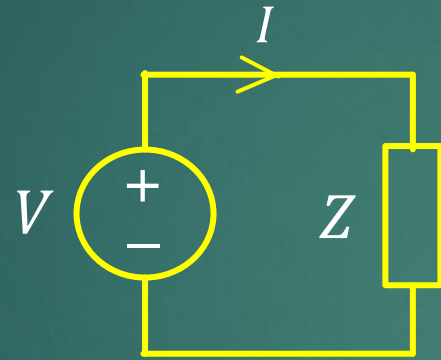
Part 1

- *EM Fields and Radio Architectures*
- *Impedances, Ohms Law, and Voltage dividers*
- *1-pole Filters (Lowpass and Bandpass)*

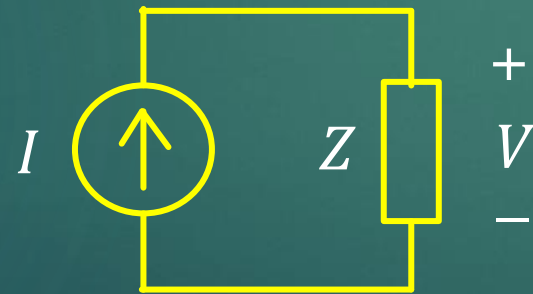
Part 2

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- *Design Examples*
- *Intro to Impedance Matching*
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Ohms Law



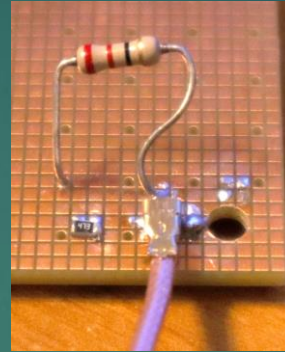
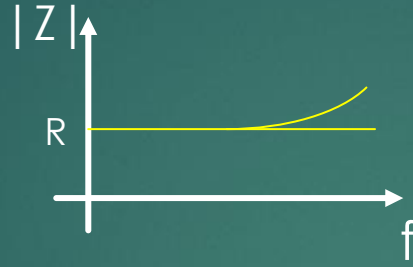
$$I = \frac{V}{Z}$$



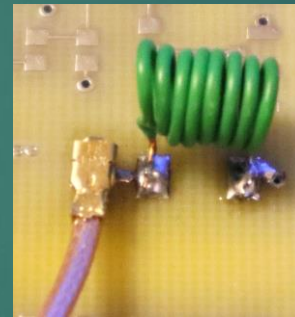
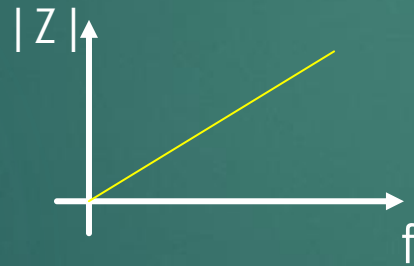
$$V = I Z$$

Impedances

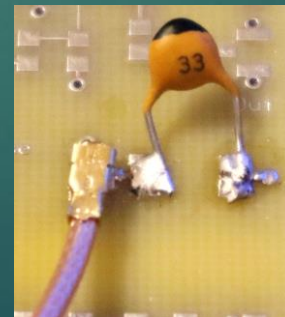
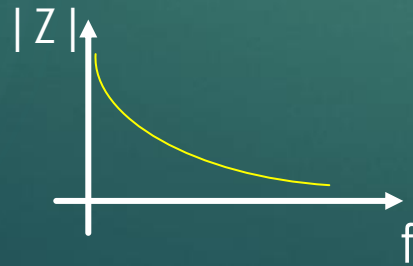
Resistor: $Z = R$



Inductor: $Z = j 2\pi f L$

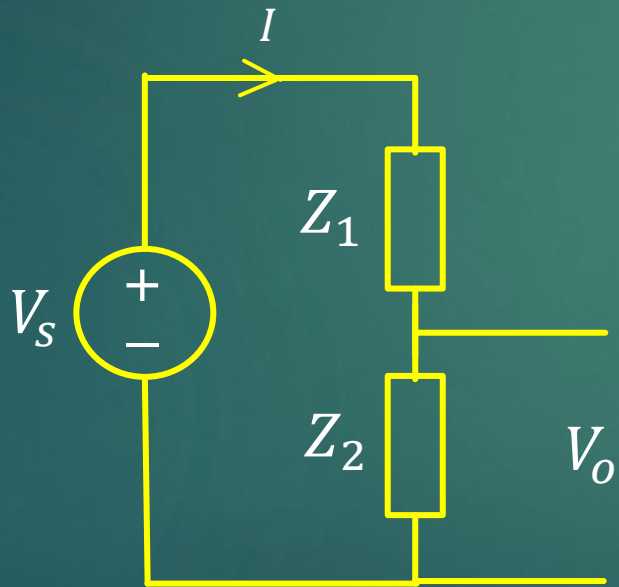


Capacitor: $Z = -j \frac{1}{2\pi f C}$



Voltage Divider

“The most important circuit in all of analog electronics” ! 😊

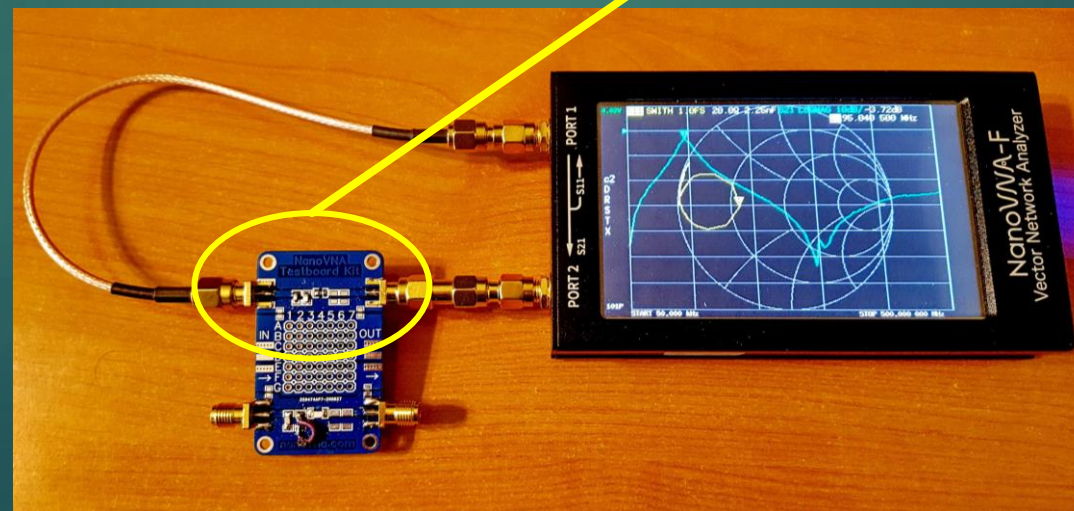
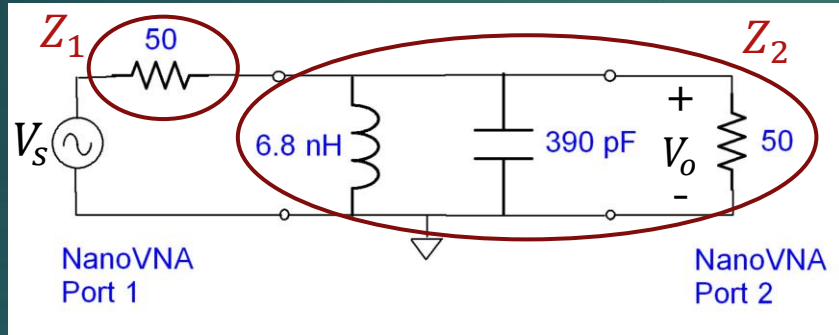


$$I = \frac{V_s}{Z_1 + Z_2}$$

$$V_o = I Z_2$$

So...
$$V_o = V_s \left[\frac{Z_2}{Z_1 + Z_2} \right]$$

Simple Bandpass Filter

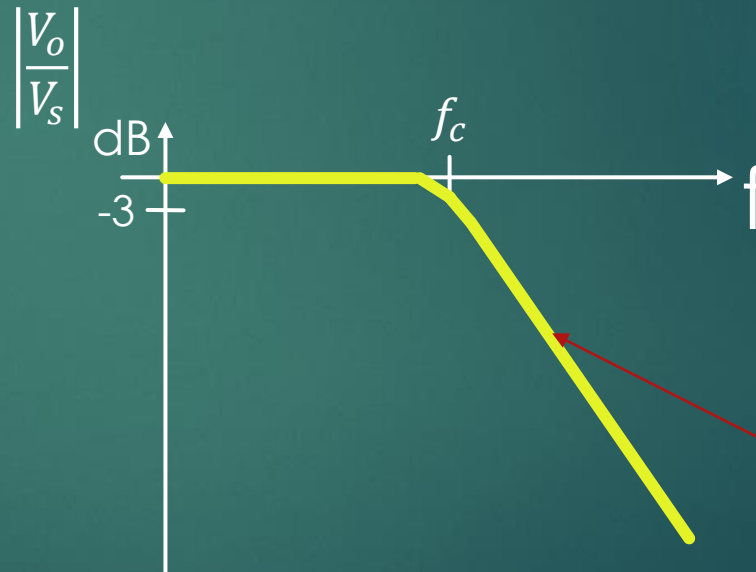
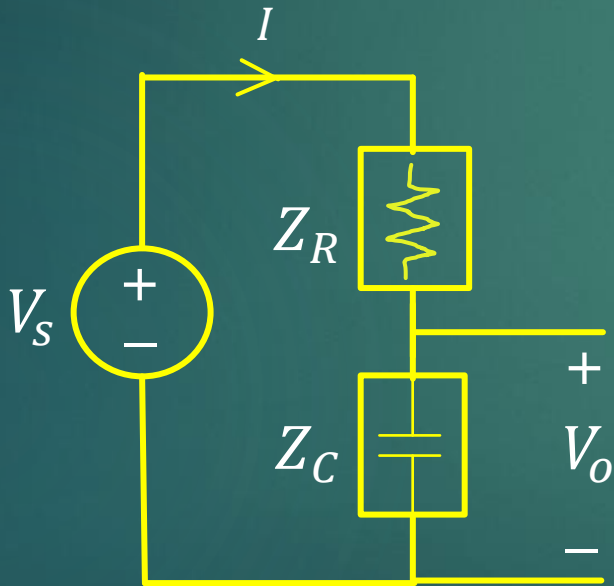


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Filters

1-Pole Lowpass: $V_o = V_s \left[\frac{Z_C}{Z_R + Z_C} \right]$



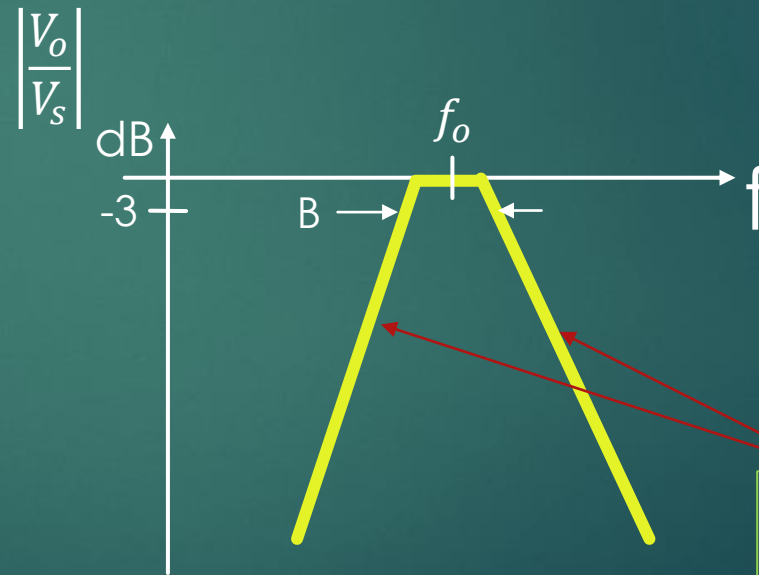
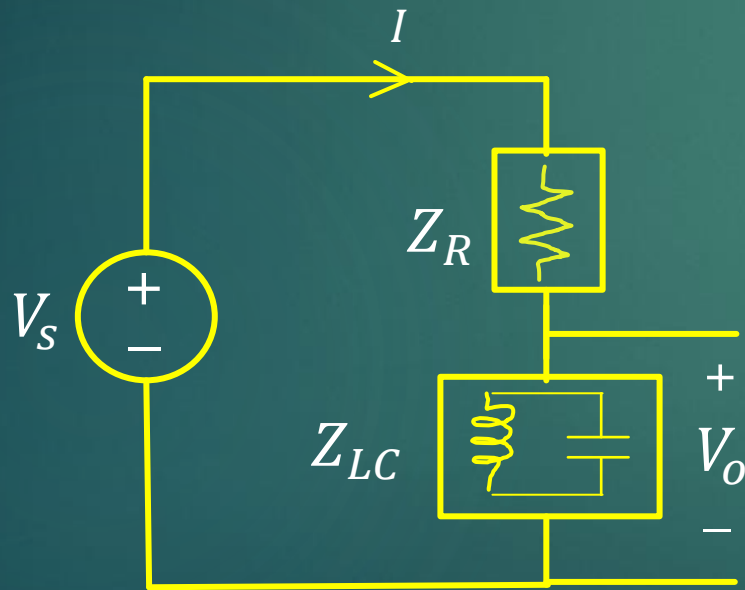
$$-20 \log_{10} \left| \frac{f}{f_c} \right| \text{ dB}$$

(for $f \gg f_c$)

Filters

“1-Pole” Bandpass:

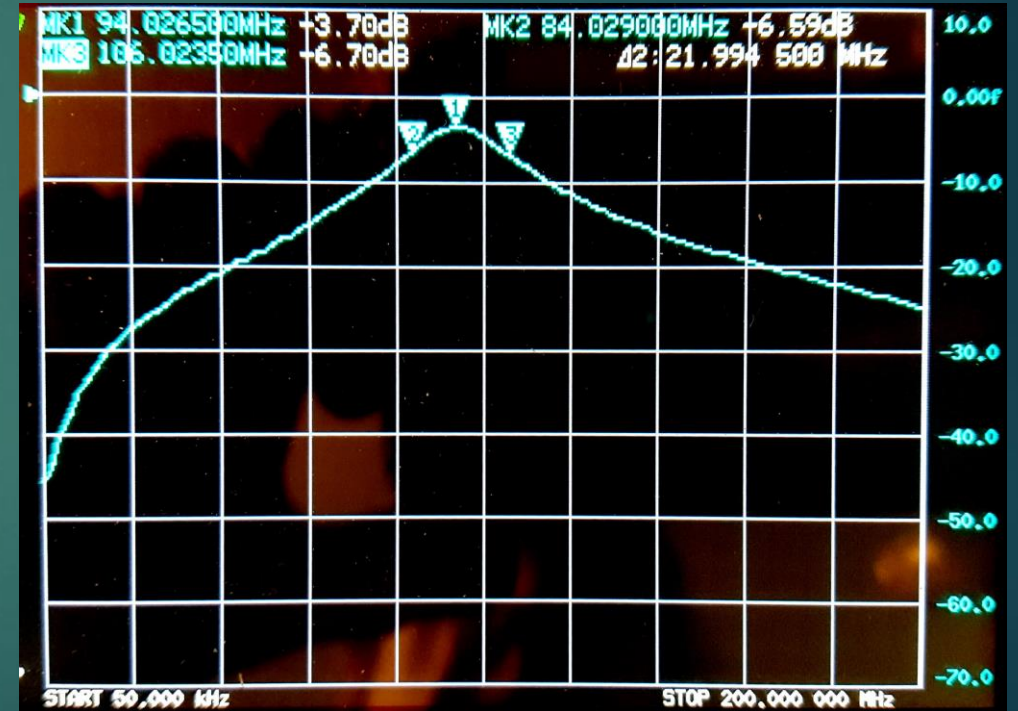
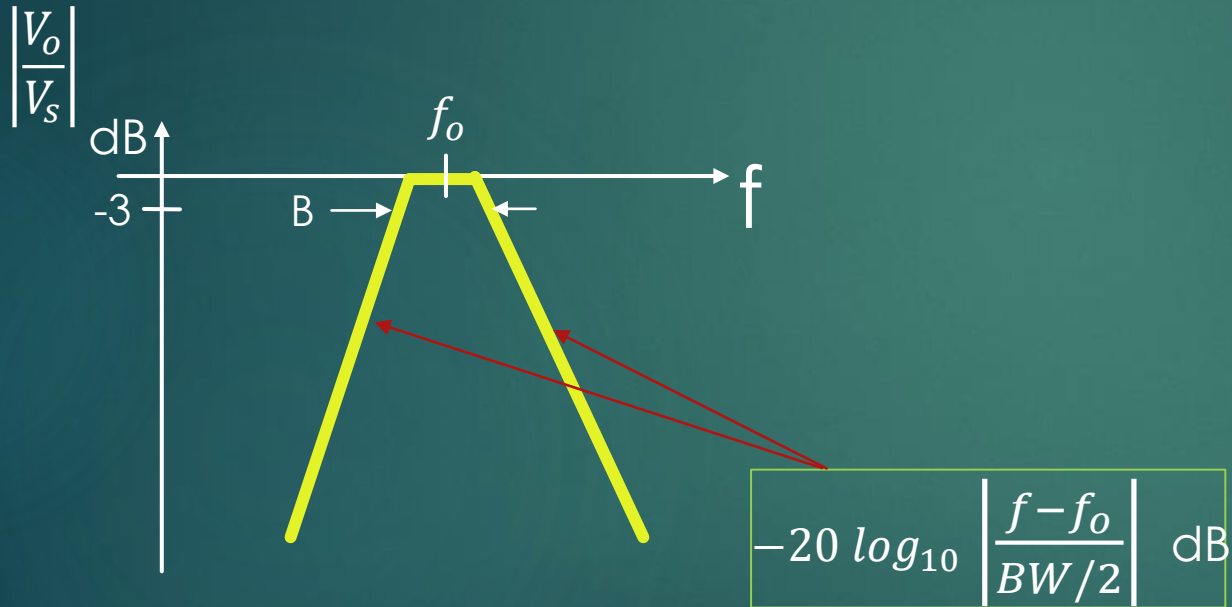
$$V_o = V_s \left[\frac{Z_{LC}}{Z_R + Z_{LC}} \right]$$



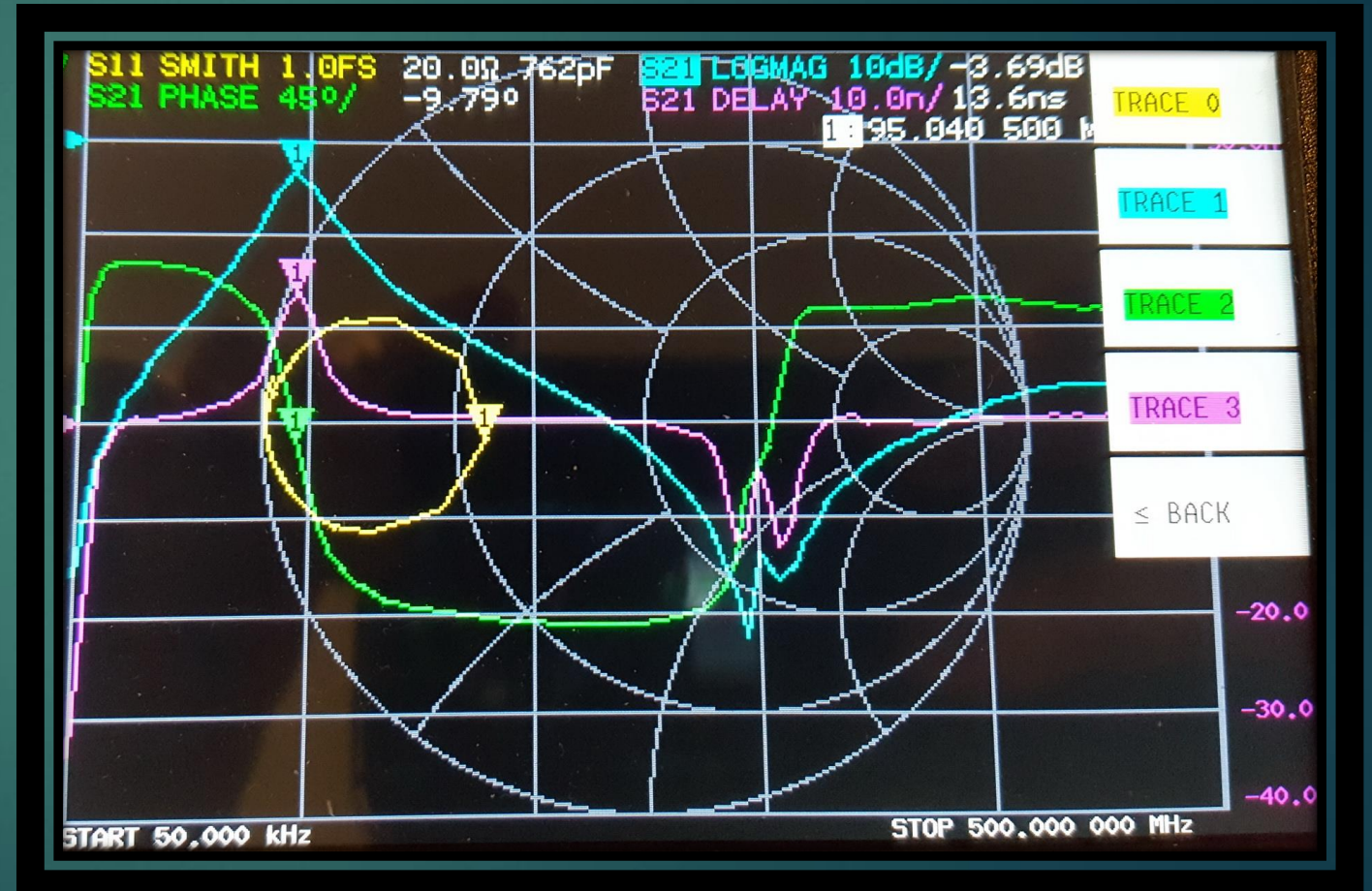
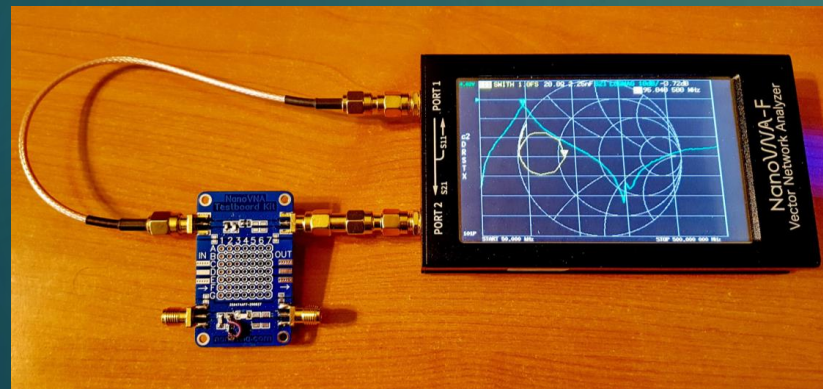
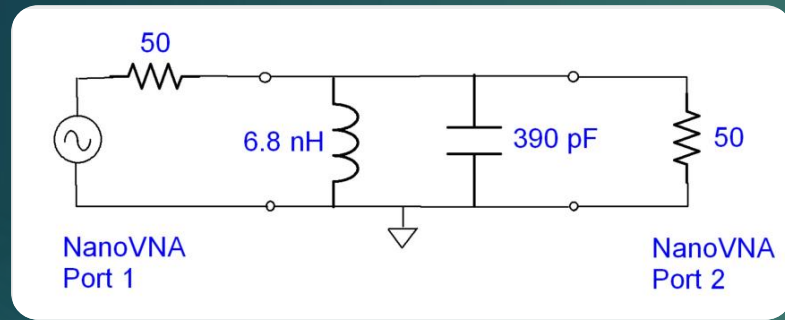
$$-20 \log_{10} \left| \frac{f - f_o}{B/2} \right| \text{ dB}$$

Real-world Performance

Measured with the NanoVNA



BPF Gain (or Insertion Loss), Impedance, Phase, and Group Delay



Filter Application Example

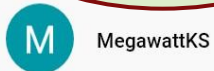


NanoVNA and Radio Frequency / Microwave Tech

10 videos • 203 views • Last updated on Feb 24, 2021

Public

Educational videos pertaining to the amazing NanoVNA instrument, and more generally to radio frequency (RF) and microwave technology underlying it, and the broader area of wireless hardware design.



NanoVNA Demonstrations - Coax line reflections and Smith charts

MegawattKS



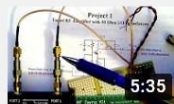
NanoVNA Calibration - When, Why, and How to cal a VNA

MegawattKS



NanoVNA - Measuring Impedances

MegawattKS



NanoVNA - Measuring S21 and S11 of a small-signal amplifier

MegawattKS



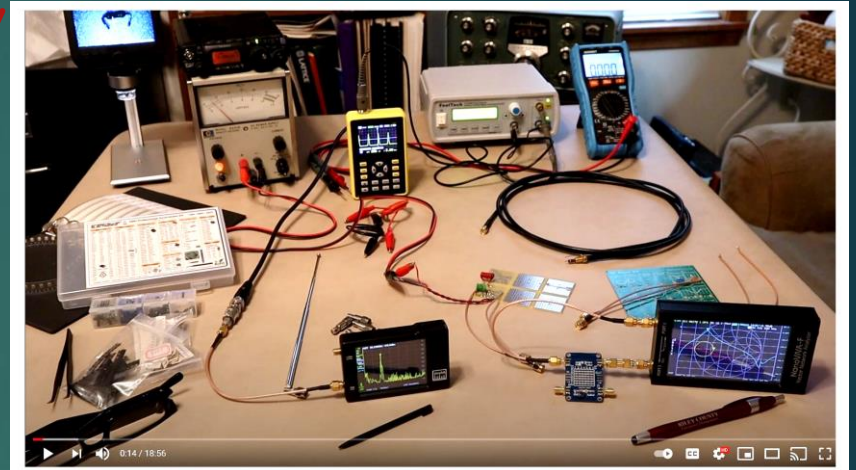
NanoVNA - Measuring RLC Components

MegawattKS

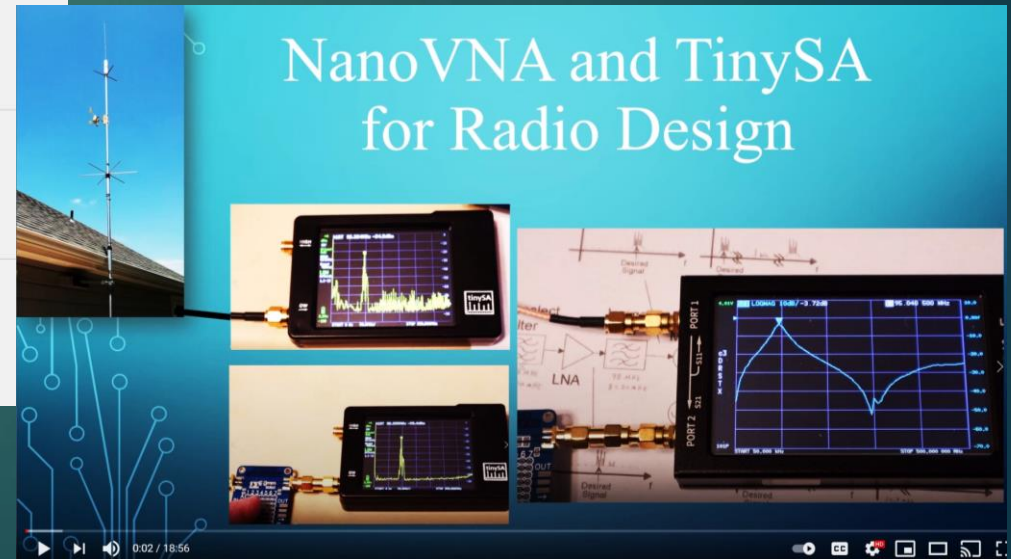


NanoVNA and TinySA for Radio Design

MegawattKS



NanoVNA and TinySA for Radio Design



Additional Resources

American Radio Relay League (ARRL)



What is [Amateur Radio](#) or Ham Radio

[Get Your License](#) | [Join/Renew](#) | [On the Air](#) magazine | [Media/PR](#)

A blue banner with a white audio waveform background. The text reads 'JUST GETTING STARTED?' in large white letters. Below it, 'Check out all of our new ham resources!' is written in white. On the right is the ARRL logo, a diamond shape containing an antenna, a resistor, and an inductor. A 'Learn More >' button is in the bottom right corner.

JUST GETTING STARTED?

Check out all of our
new ham resources!

Learn More >

Coming in Part 2

Part 1

- *Transmitters and Receivers*
- *Impedances and Ohms Law*
- *Voltage dividers* (the most important analog circuits !)
- *1-pole Filters* (Lowpass and Bandpass)

Part 2

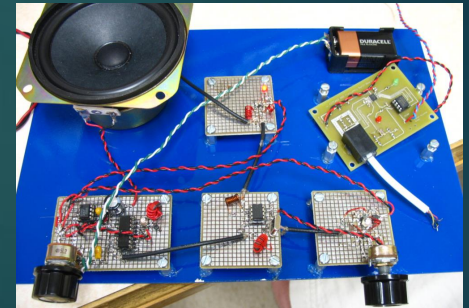
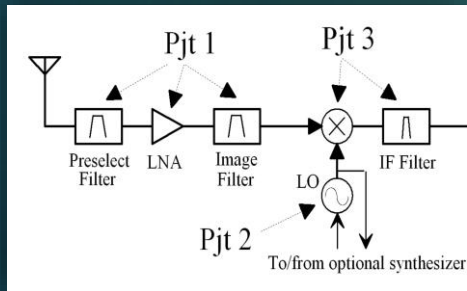
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Episode 1

Bandpass Filters, Q, and Matching Networks

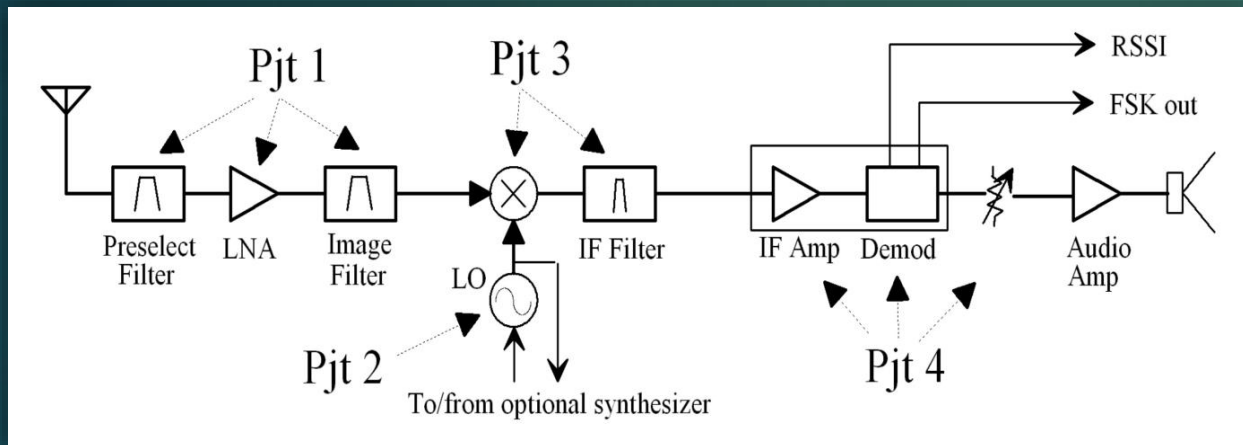
Part 2



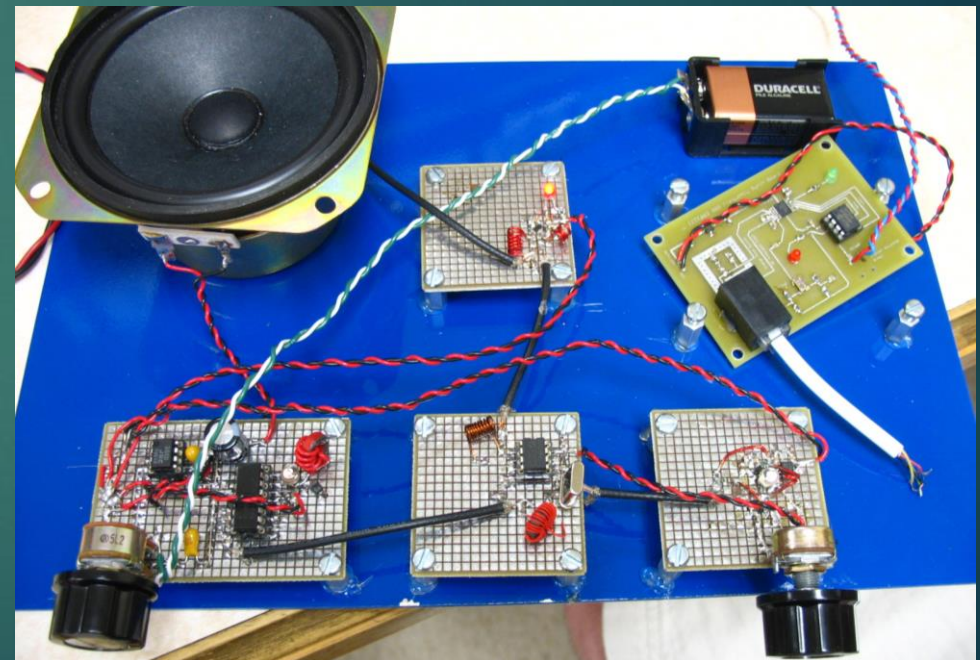
Part 1 Review

Abstracted from a senior-design University class

Semester Project: **FM Broadcast Receiver**

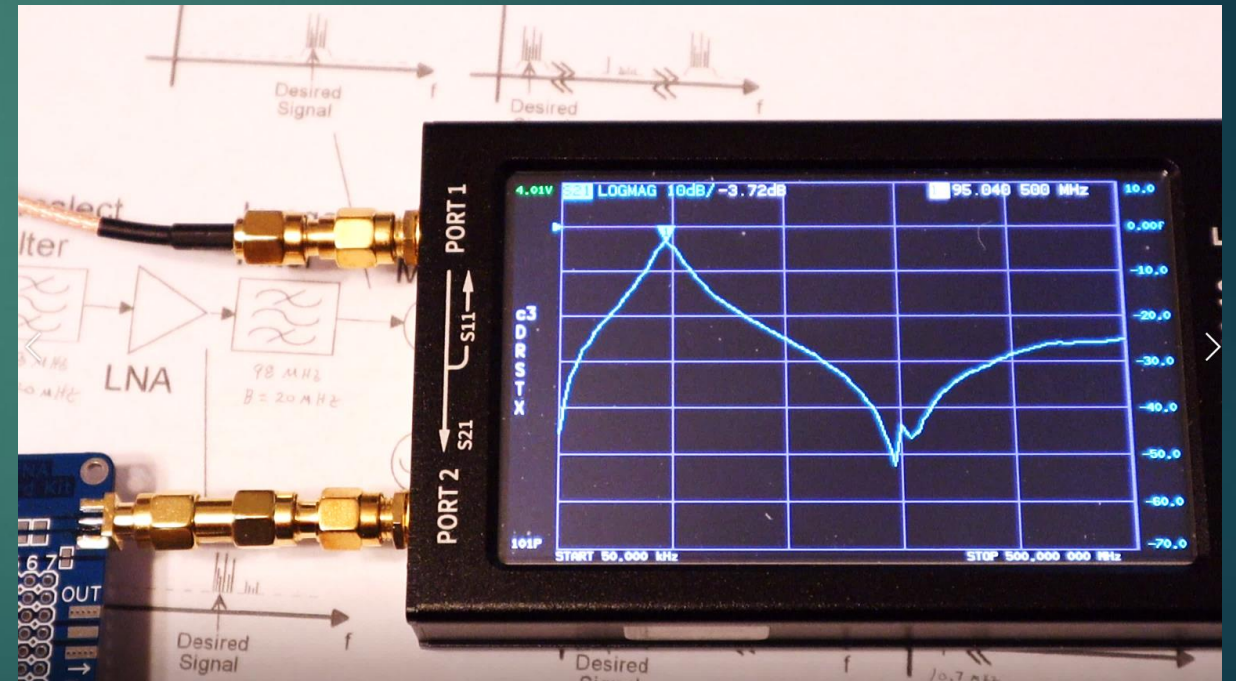
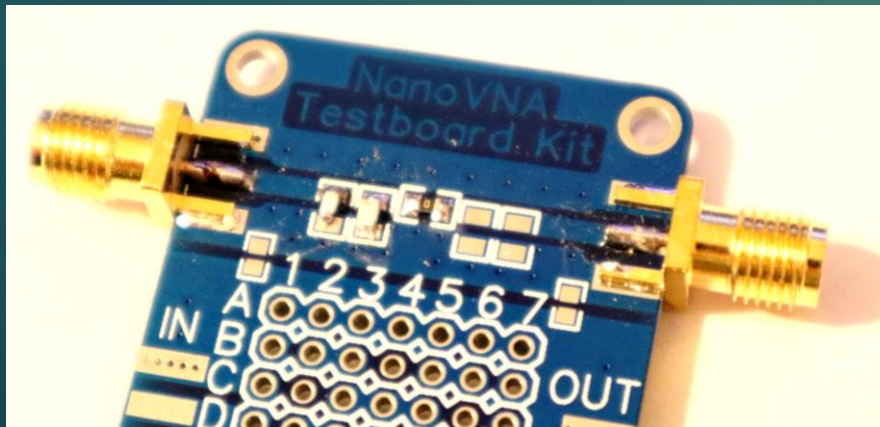
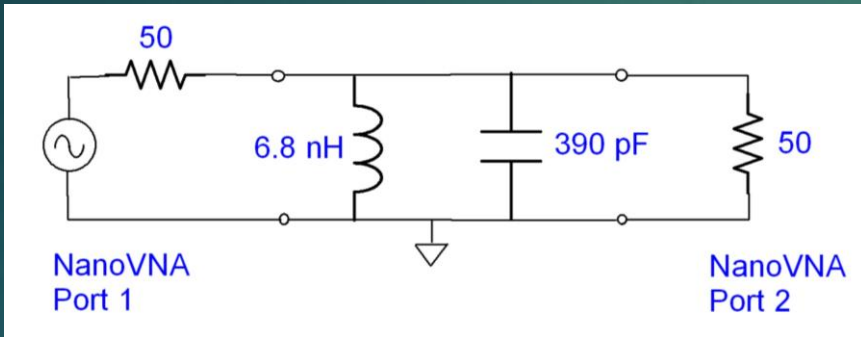


Alternative Projects: **VHF Weather Radio Receiver**
Amateur Radio Receivers
Any radio/wireless system !



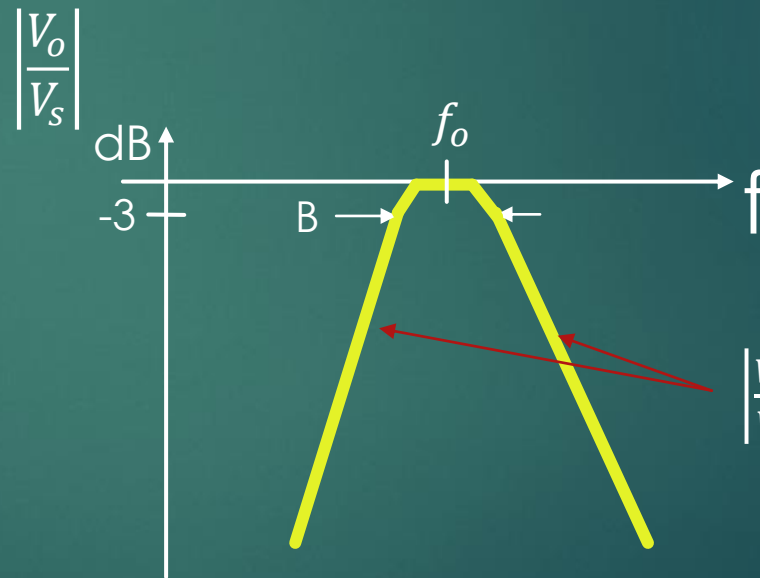
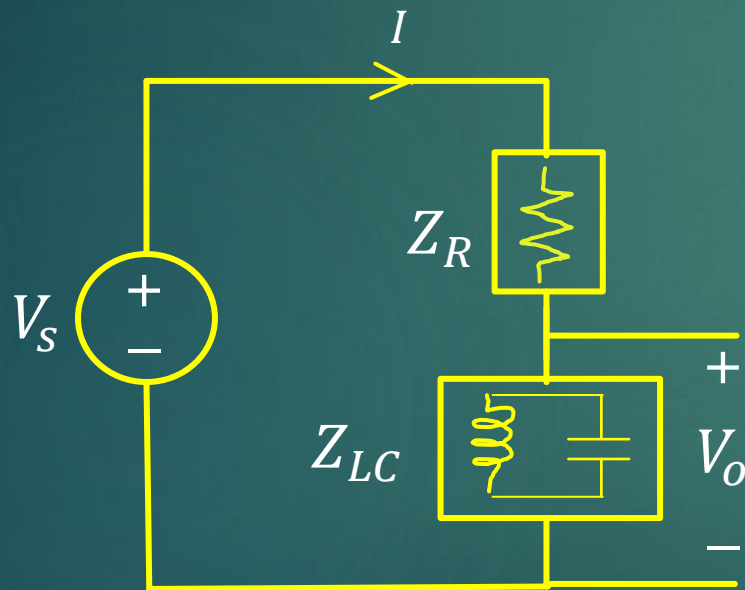
Part 1 Review

1-Pole Bandpass filter



Part 1 Review

Circuit Analysis: $V_o = V_s \left[\frac{Z_{LC}}{Z_R + Z_{LC}} \right]$



$$\left| \frac{V_o}{V_s} \right| = -20 \log_{10} \left| \frac{f - f_o}{B/2} \right| \text{ dB}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad B = \left| \frac{f_o}{Q} \right|$$

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- *1-pole Filters (Lowpass and Bandpass)*

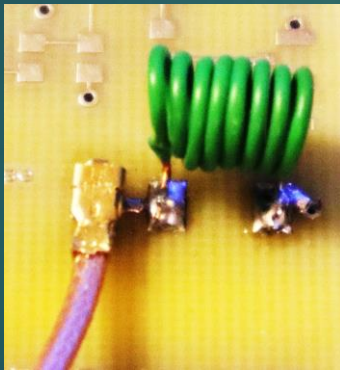
Part 2

- *Quality Factor (Q)*
- *Design Examples*
- *Intro to Impedance Matching*
- *Higher Order Filter Design*

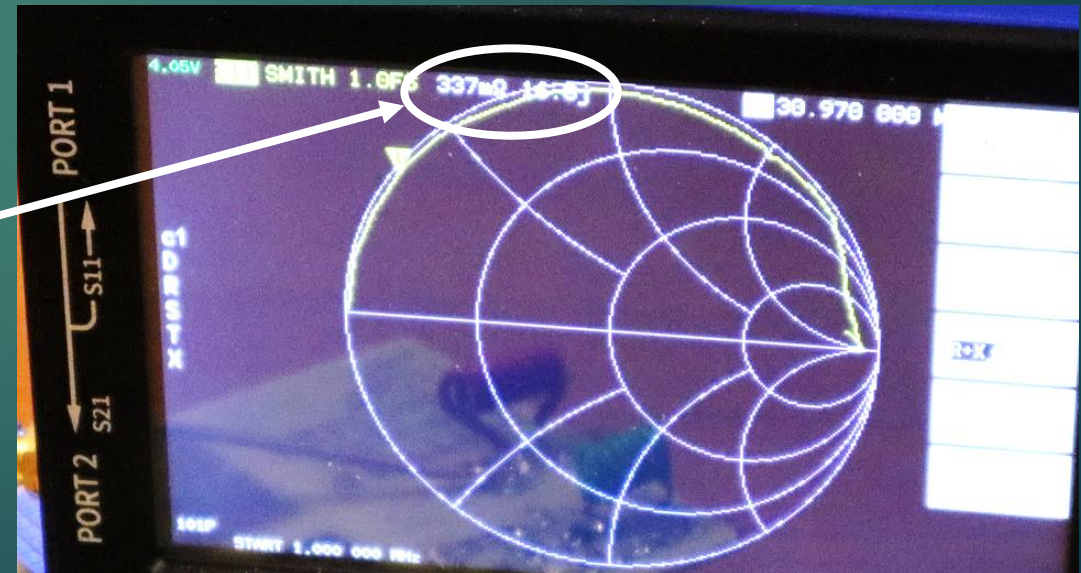
What's "Q"

A key RF design parameter

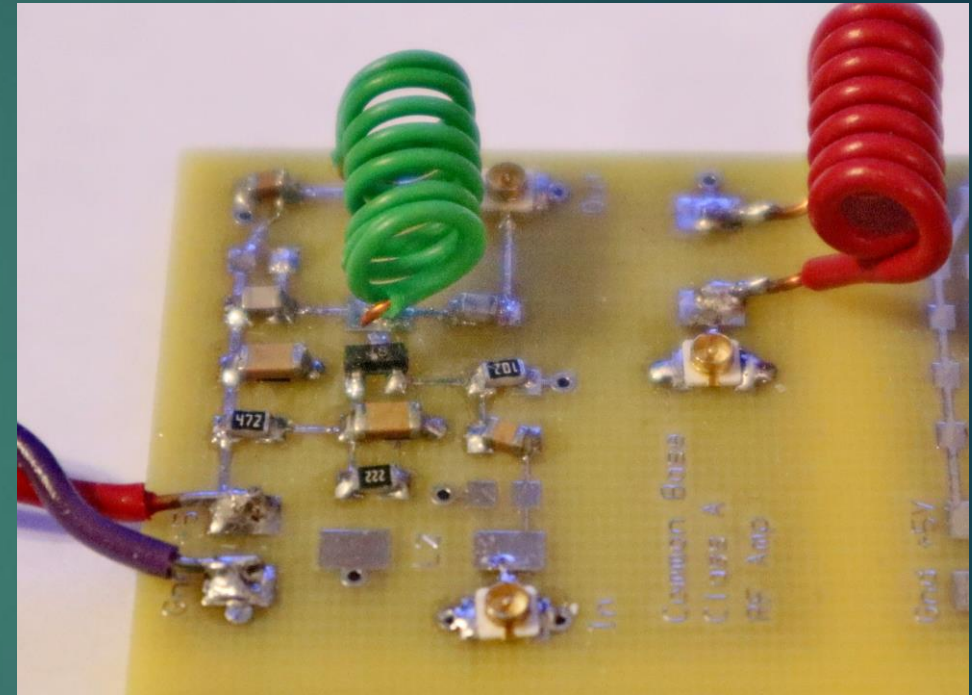
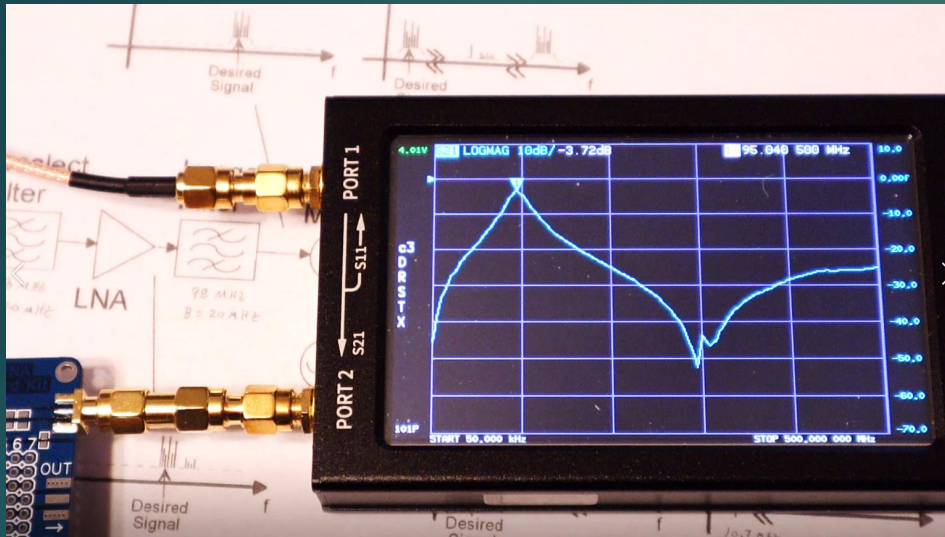
- of resonant-circuits, filters, matching networks, etc.
- of underlying reactive components (e.g. L, C)



$$\begin{aligned} Q &= X/R \\ &= 16.6/0.337 \\ &= 49 \quad (@30 \text{ MHz}) \end{aligned}$$



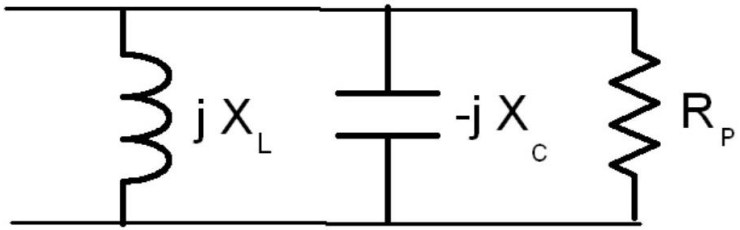
What's it good for ?



- Sets bandwidth
- Affects power and insertion losses
- Used in designing filters and matching networks

Parallel Resonant Circuit Q

Parallel LC circuit



- How do we pick L & C for desired center frequency f_o and bandwidth B ?

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

$$X_o = 2\pi f_o L$$

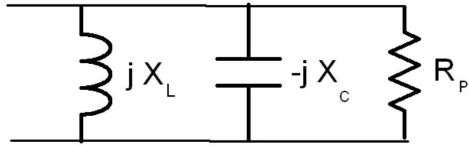
$$X_o = \frac{1}{2\pi f_o C}$$

$$Q = \frac{R_p}{X_o}$$

$$B = \frac{f_o}{Q}$$

Parallel vs Series Resonators

Parallel LC circuit



$$Z \rightarrow R_p @ f = f_o$$

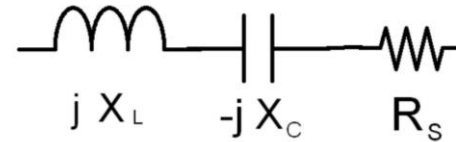
$$Z \rightarrow 0 \text{ for } f \rightarrow 0$$

$$Z \rightarrow 0 \text{ for } f \rightarrow \infty$$

$$Q = \frac{R_p}{X_o}$$

Big $R_p \Rightarrow$ High Q

Series LC circuit



$$Z \rightarrow R_s @ f = f_o$$

$$Z \rightarrow \infty \text{ for } f \rightarrow 0$$

$$Z \rightarrow \infty \text{ for } f \rightarrow \infty$$

$$Q = \frac{X_o}{R_s}$$

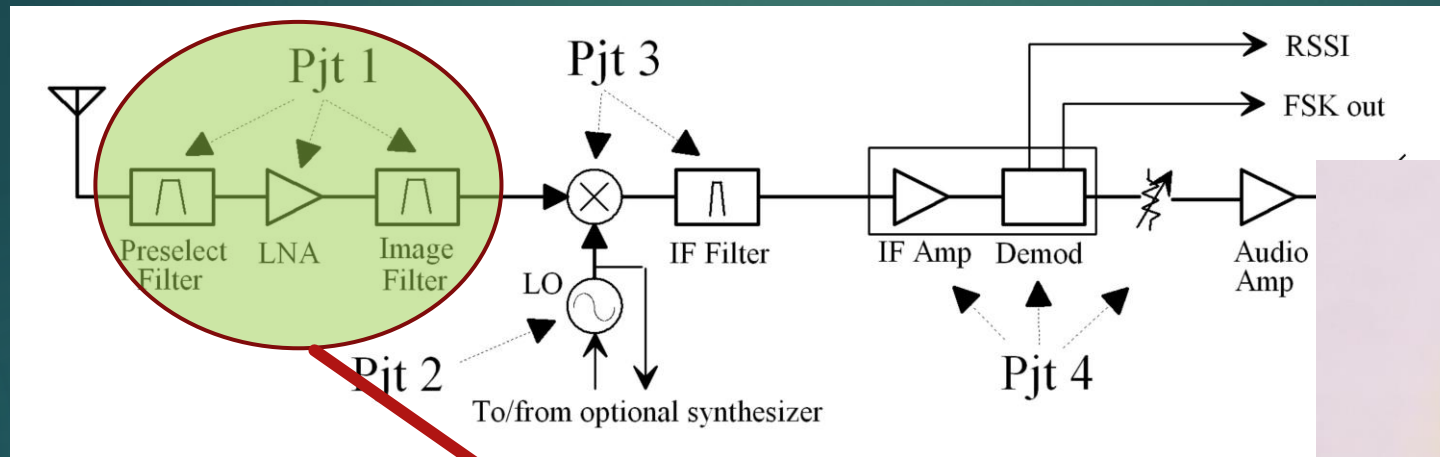
Small $R_s \Rightarrow$ High Q

Outline of This Video

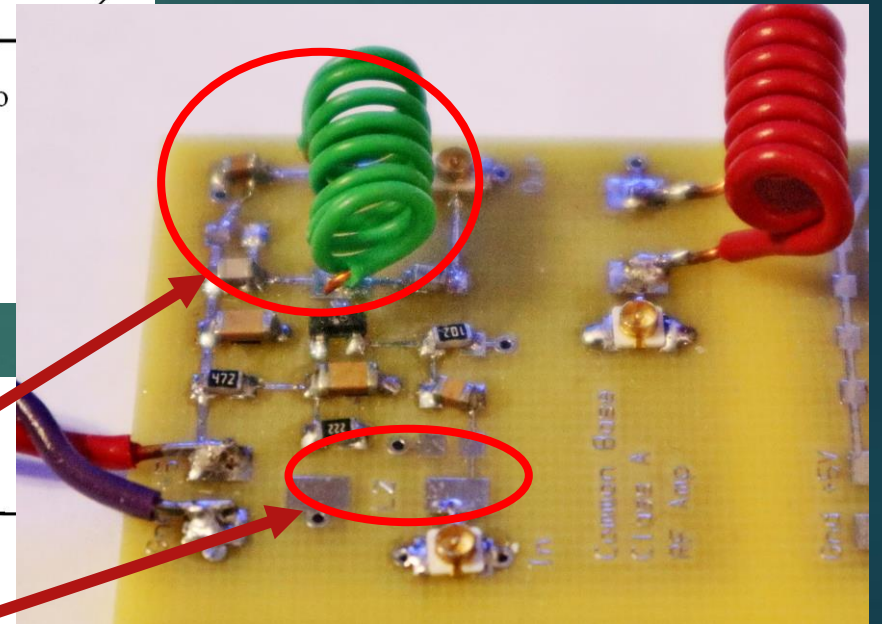
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Receiver and Filter Design

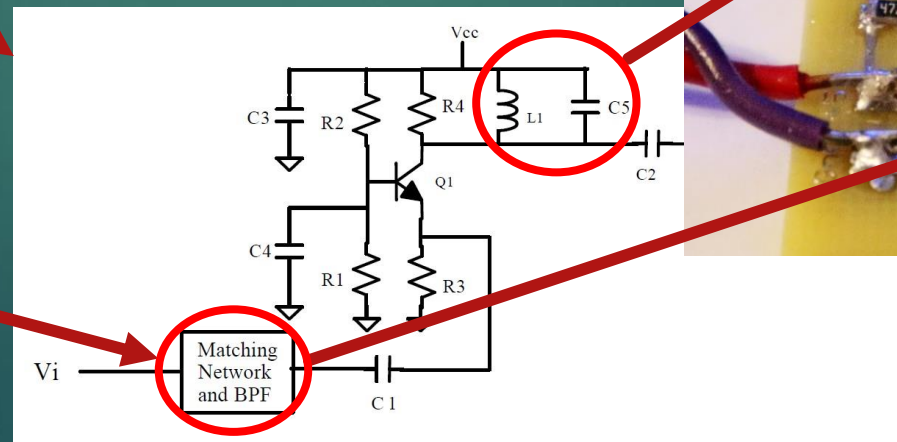
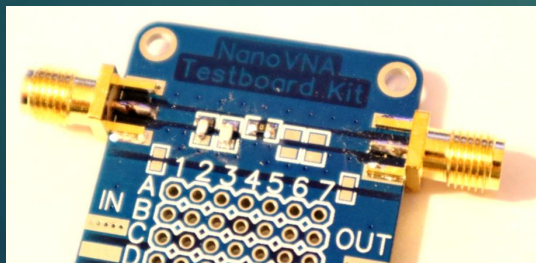
Block Diagram



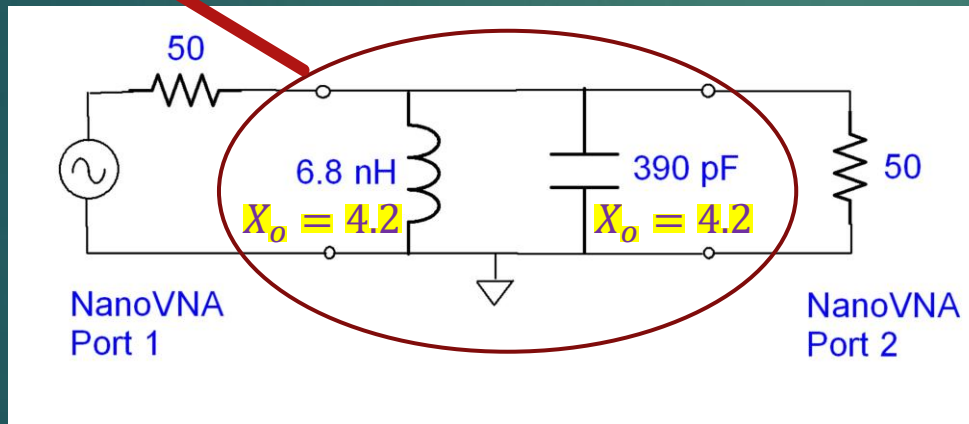
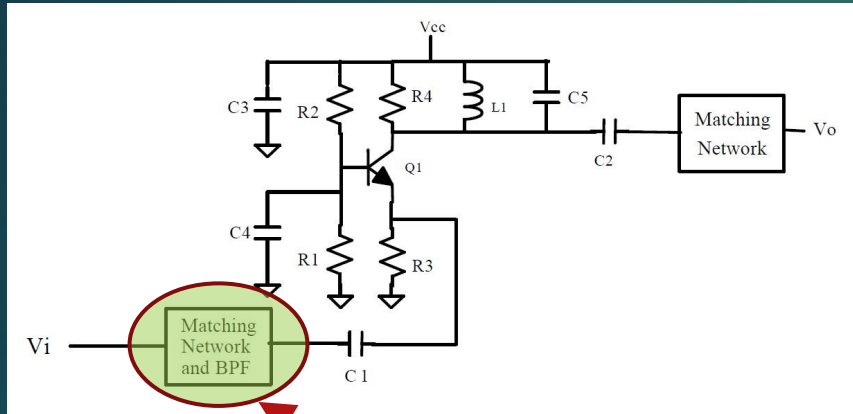
Layout/Build



Subcircuits



Example 1: Pre-select Filter



Analysis :

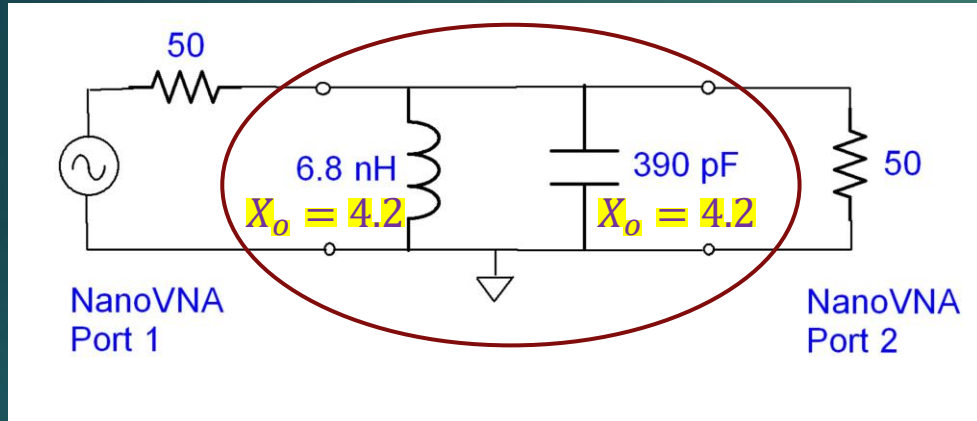
$$L = 6.8 \text{ nH} \quad C = 390 \text{ pF}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 100 \text{ MHz} \quad X_o = X @ 100 \text{ MHz} = 4.2$$

$$R = 50 || 50 = 25 \quad Q = R/X_o = 25/4.2 = 6$$

$$\text{So... } B = \frac{100 \text{ MHz}}{6} = 17 \text{ MHz}$$

Example 1: Pre-select Filter



Design: !

Start with desired f_o and B

$$f_o = 100 \text{ MHz} \quad B = 17 \text{ MHz}$$

Find “selectivity Q” needed:

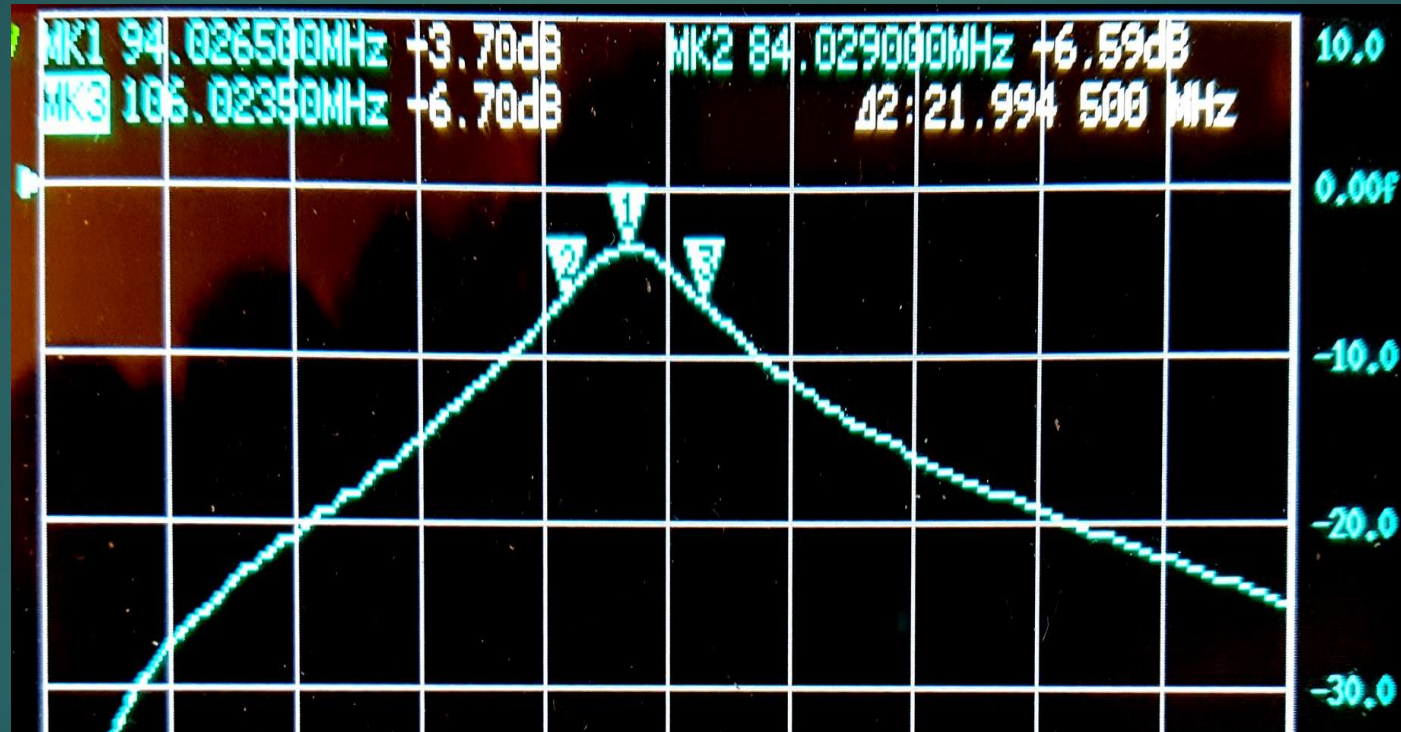
$$Q = \frac{f_o}{B} = \frac{100}{17} = 6$$

Solve for X_o and then L, C needed:

$$X_o = \frac{R}{Q} = \frac{25}{6} = 4.2$$

$$L = \frac{X_o}{2\pi f_o} = 6.7 \text{ nH} \quad C = \frac{1}{2\pi f_o X_o} = 380 \text{ pF}$$

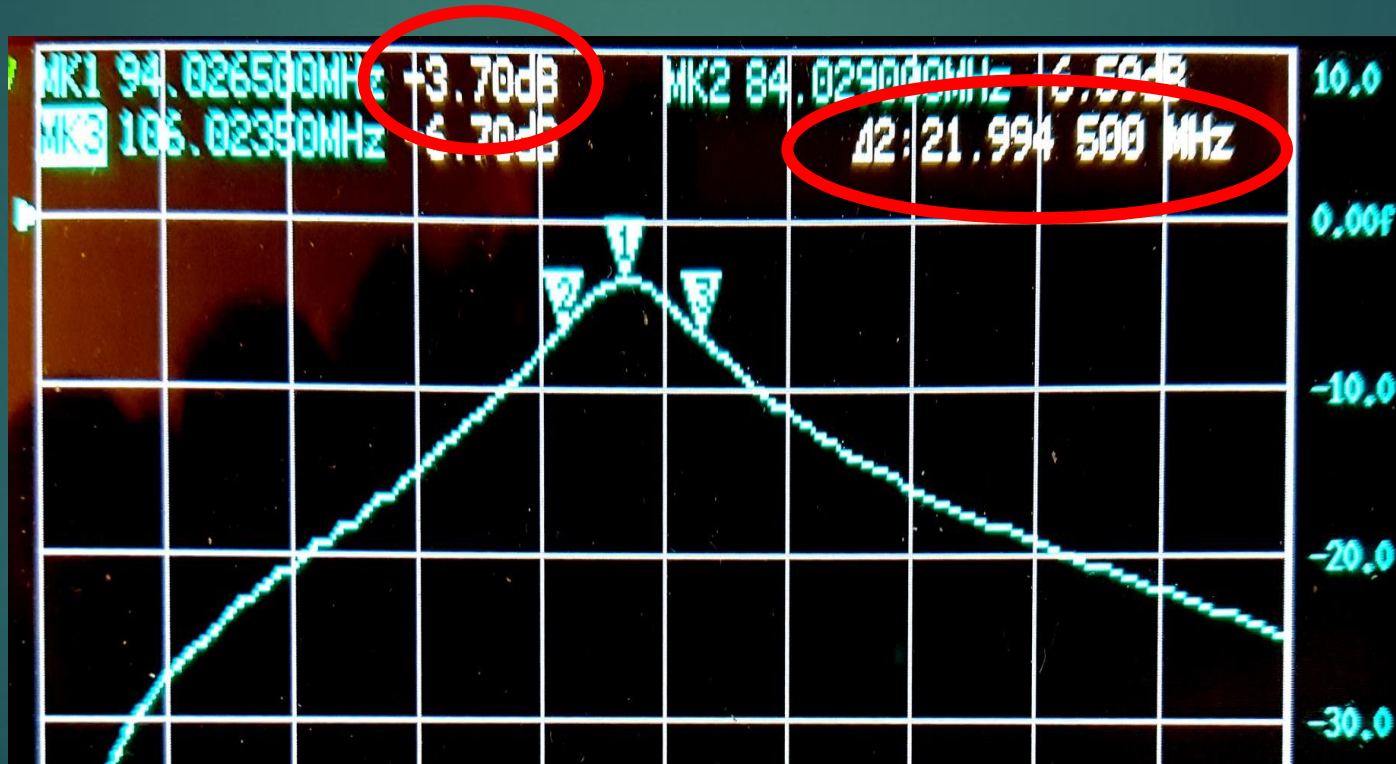
S21 Measurement



50 kHz to 200 MHz

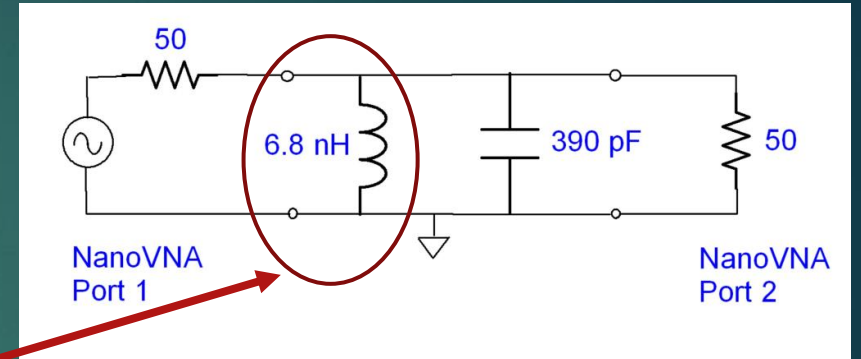
Component Parasitics Issues

- Why is in-band insertion loss almost 4 dB ?
- Why is bandwidth wider than designed 17 MHz value ?

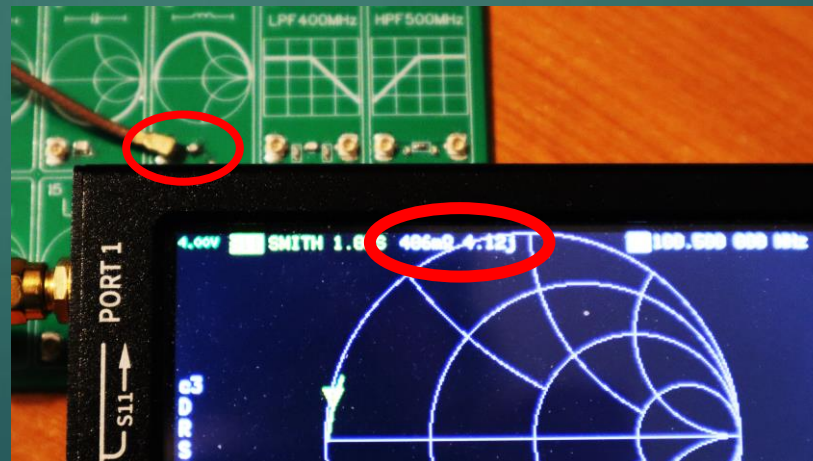
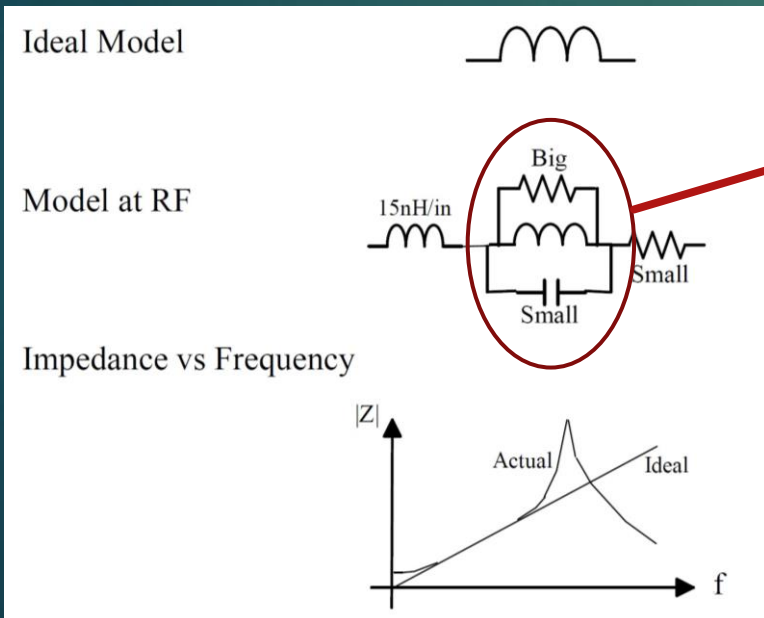


Component Parasitics Issues

- Additional 'parasitic' R from inductor (and capacitor) lowers effective parallel-circuit R, and hence Q



Inductor Parasitics !



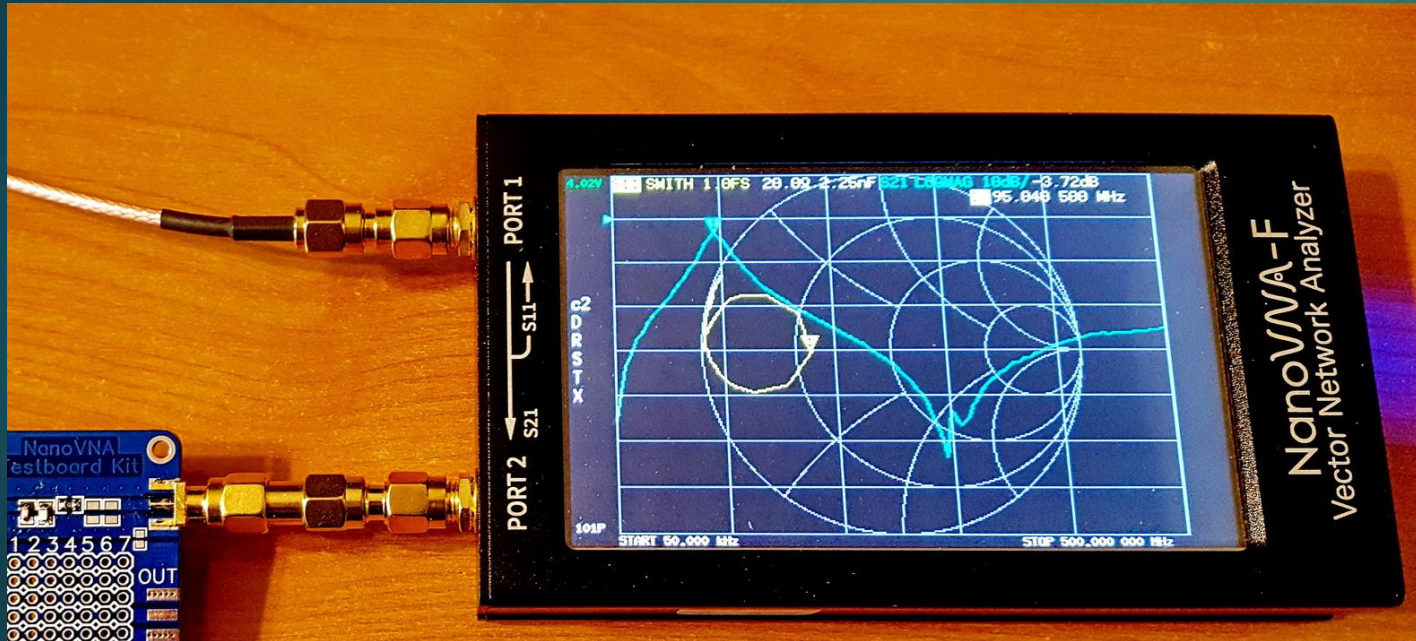
$$Q_{inductor} = \frac{4.12 \text{ Ohms}}{0.406 \text{ Ohms}} = 10$$

So "BIG" = (10)(4.12) = 41 Ohms

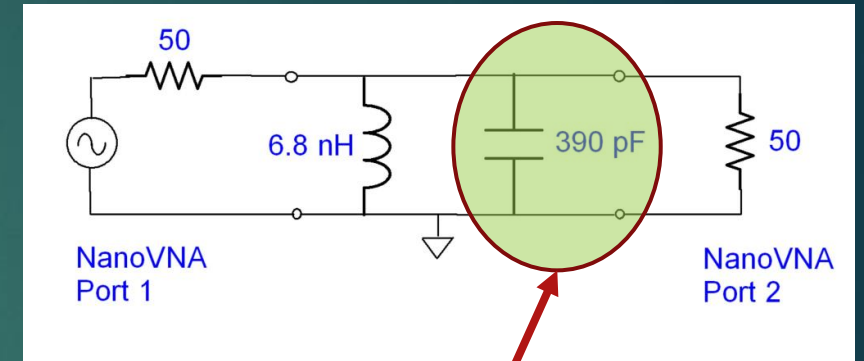
Not the ideal values of infinity !

Capacitor Parasitics

- Why does response go back up at high frequencies ?



50 kHz to 500 MHz



Capacitors

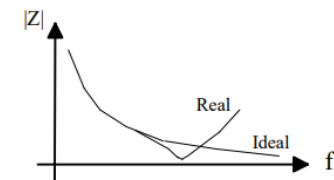
Ideal model



Model at RF

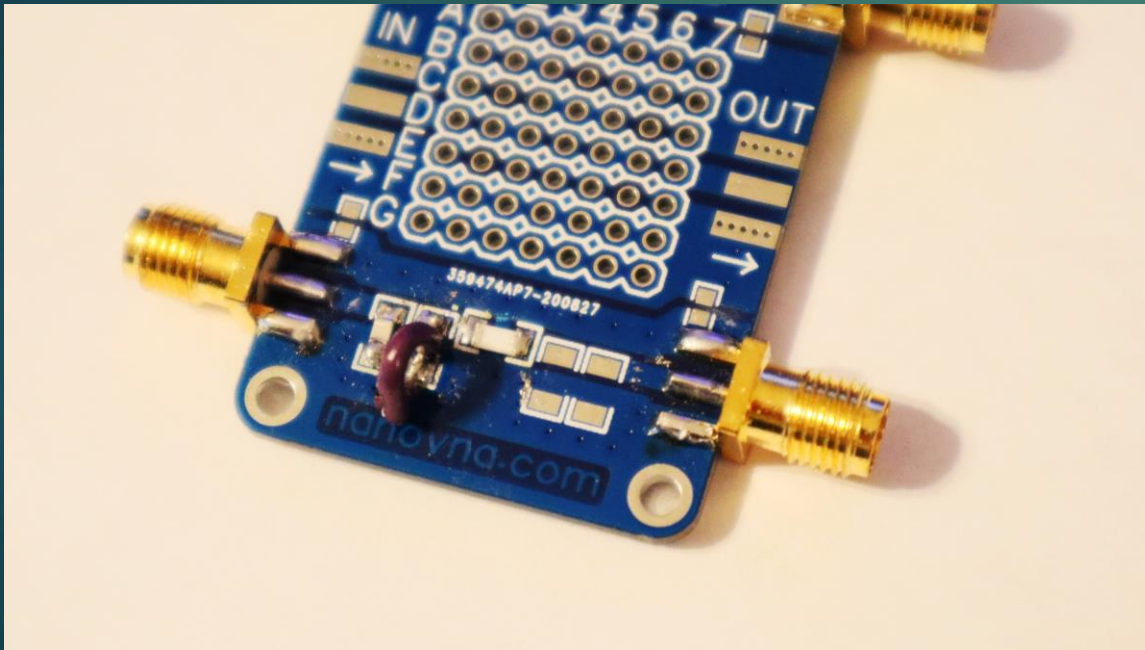


Impedance vs. Frequency



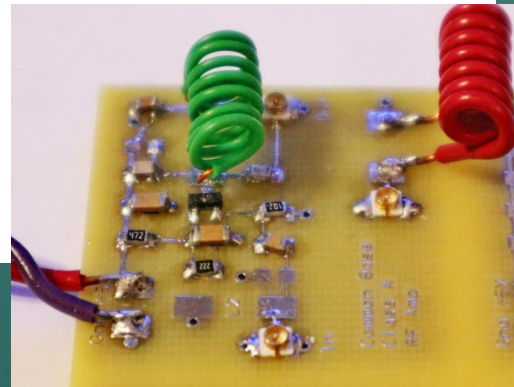
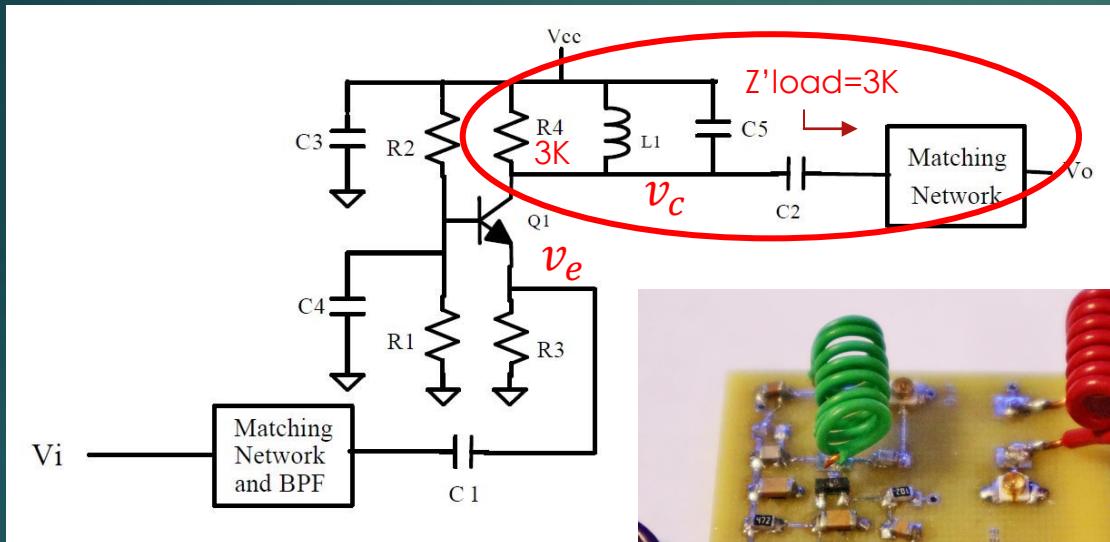
Filter Improvement

Use higher-Q inductor !



NOTE: L for a single turn inductor, or a wire is very roughly 20 nH per inch of length (or 1 nH / mm)
So 6.8 nH is less than one turn !

Example 2: RF Amp + Image Filter



$$L = 160 \text{ nH} \quad C = 16 \text{ pF}$$

$$f_o = 100 \text{ MHz} \quad X @ 100 \text{ MHz} = 100$$

$$R = 1.5 \text{ K} \quad \text{So } Q = 1500/100 = 15$$

$$\text{So ... } B = \frac{100 \text{ MHz}}{15} = 6.7 \text{ MHz}$$

$$A'_v = \frac{v_c}{v_e} = g_m Z$$

$$\text{where } g_m \cong \frac{I_c}{0.03}$$

$$\text{and } Z = R4 \parallel Z_{L1} \parallel Z_{C5} \parallel Z'_{Load}$$

Take home assignment: 😊

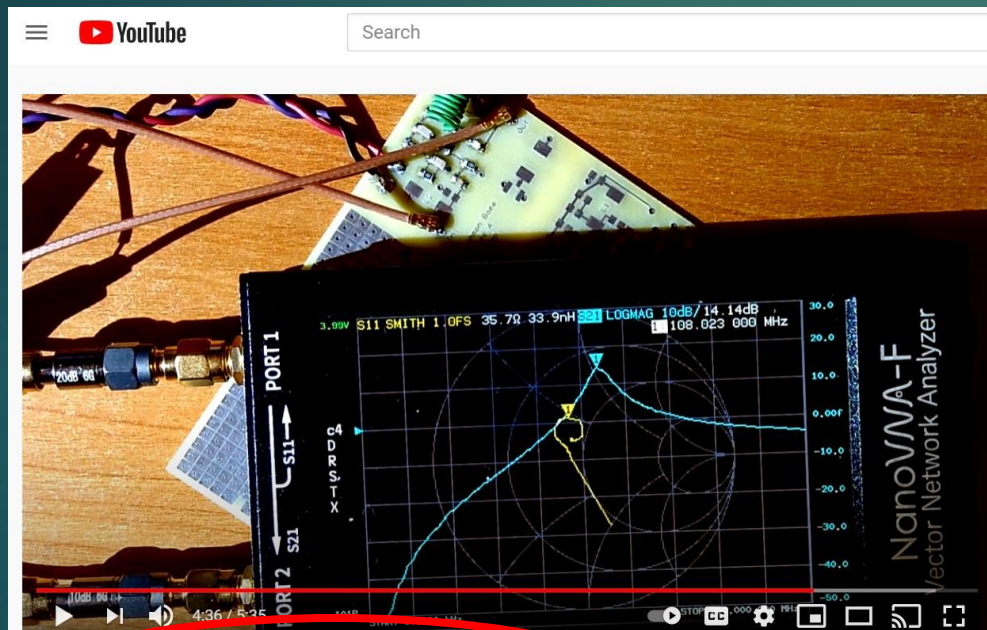
Redesign for 98 MHz center

And 20 MHz bandwidth.

(How realizable is required inductor ?)

System Level Testing

Videos from the NanoVNA series...



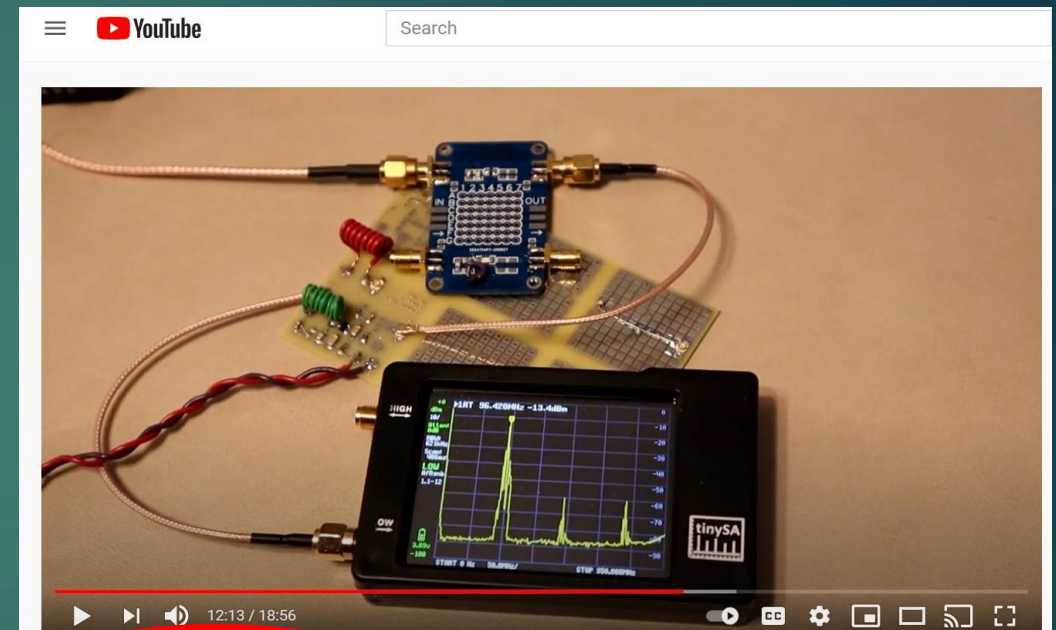
NanoVNA - Measuring S21 and S11 of a small-signal amplifier

1,763 views · Dec 21, 2020

MegawattKS

Measuring a small-signal RF amplifier with a vector network analyzer (VNA). Highlights need for attenuators and shows how well the NanoVNA is able to calibrate through 20 dB of port 1 attenuation.

ANALYTICS EDIT VIDEO



NanoVNA and TinySA for Radio Design

2,399 views · Feb 22, 2021

MegawattKS

Using the NanoVNA and TinySA to illustrate how radio / wireless devices work. This video concentrates on showing the front-end filtering and amplification in a superhet FM broadcast band receiver design. It also overviews some key instruments that have become reasonably

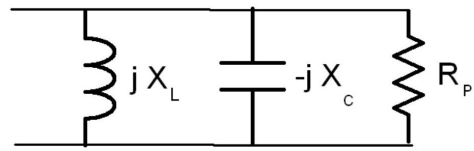
ANALYTICS EDIT VIDEO

Outline of This Video

- Part 1
 - *Transmitters and Receivers*
 - *Impedances, Ohms Law, and Voltage dividers*
 - *1-pole Filters (Lowpass and Bandpass)*
- Part 2
 - *Quality Factor (Q)*
 - *Design Examples*
 - *Intro to Impedance Matching*
 - *Higher Order Filter Design*

Parallel vs Series Resonators

Parallel LC circuit



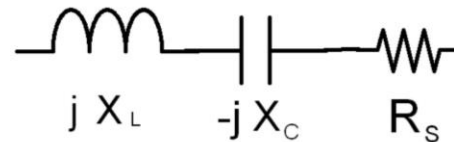
$$Z \rightarrow R_p @ f = f_o$$

$$Z \rightarrow 0 \text{ for } f \rightarrow 0$$

$$Z \rightarrow 0 \text{ for } f \rightarrow \infty$$

$$Q = \frac{R_p}{X_o}$$

Series LC circuit



$$Z \rightarrow R_s @ f = f_o$$

$$Z \rightarrow \infty \text{ for } f \rightarrow 0$$

$$Z \rightarrow \infty \text{ for } f \rightarrow \infty$$

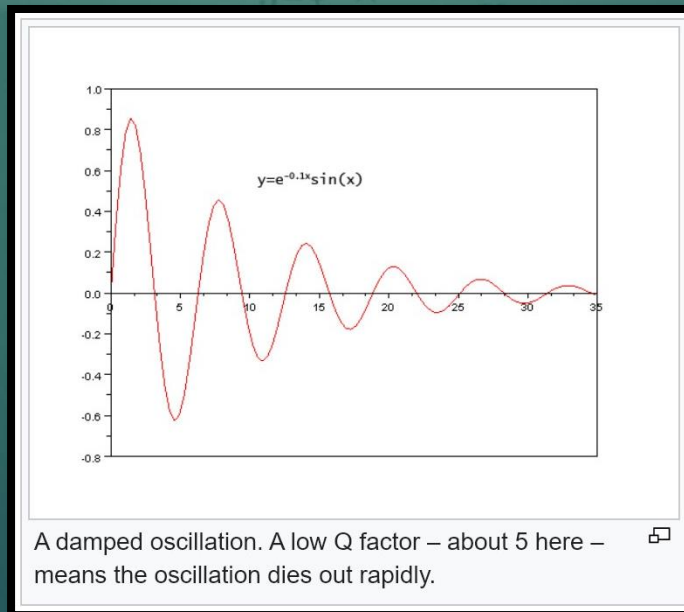
$$Q = \frac{X_o}{R_s}$$

Physics Definition of Q

Coils and condensers [edit]

The other common nearly equivalent definition for Q is the ratio of the energy stored in the oscillating resonator to the energy dissipated per cycle by damping processes:^{[8][9][5]}

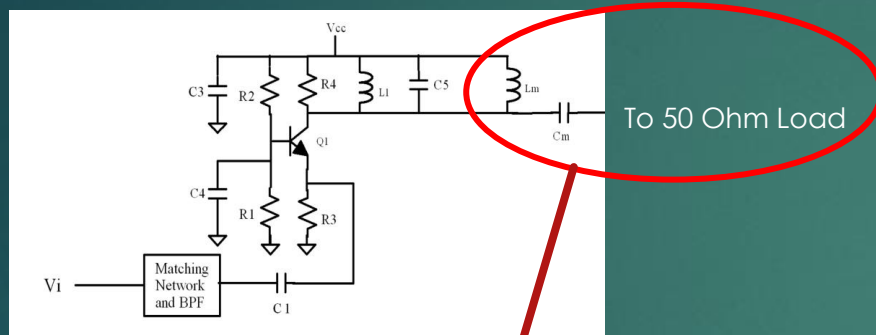
$$Q \stackrel{\text{def}}{=} 2\pi \times \frac{\text{energy stored}}{\text{energy dissipated per cycle}} = 2\pi f_r \times \frac{\text{energy stored}}{\text{power loss}}.$$



See: https://en.wikipedia.org/wiki/Q_factor

Introduction to Matching Networks

Use LC networks and series vs parallel resonance viewpoints to convert one load resistance to another !



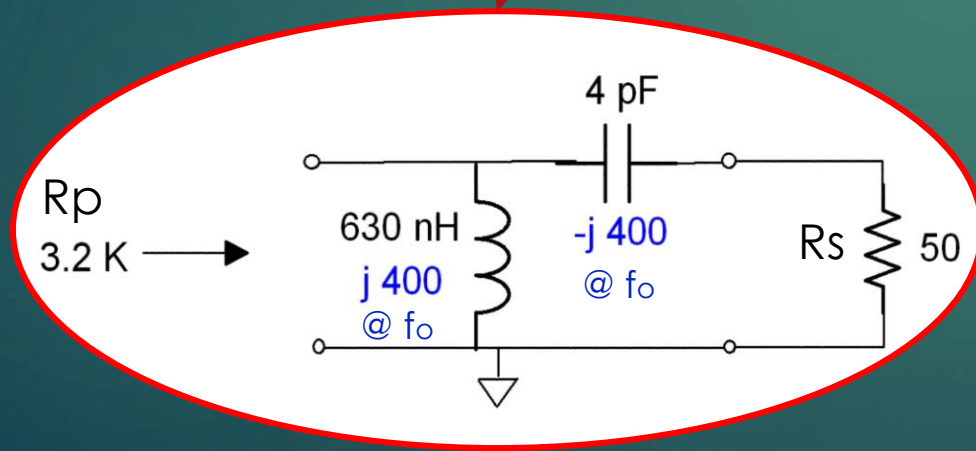
Viewed from load (series resonant circuit view):

$$Q = \frac{X_o}{R_s} = \frac{400}{50} = 8$$

Viewed from amplifier (parallel resonant circuit view):

$$Q = 8 \quad \text{and} \quad Q = \frac{R_p}{X_o}$$

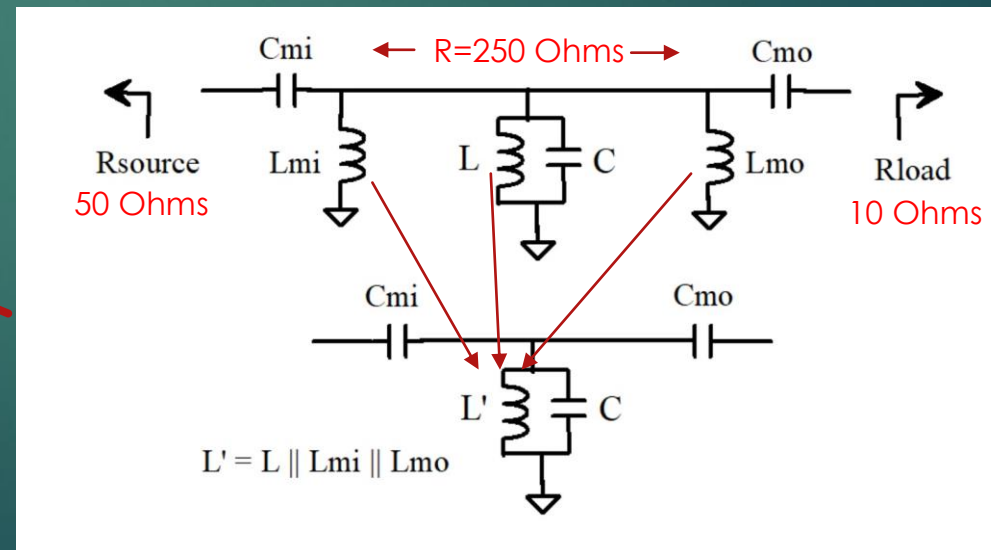
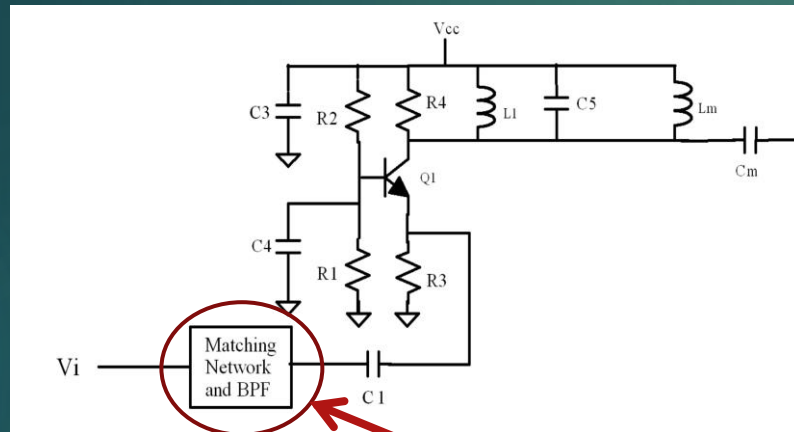
$$\Rightarrow R_p = Q X_o = Q^2 R_s = 3.2 \text{ K Ohms}$$



NOTES: This is *approximate*. In general: $R_p = (1+Q^2) R_s$
Only works well near resonant frequency f_o

Matching Networks in Filters

Use matching networks to make filters more “realizable” and compatible with different source/load impedances...



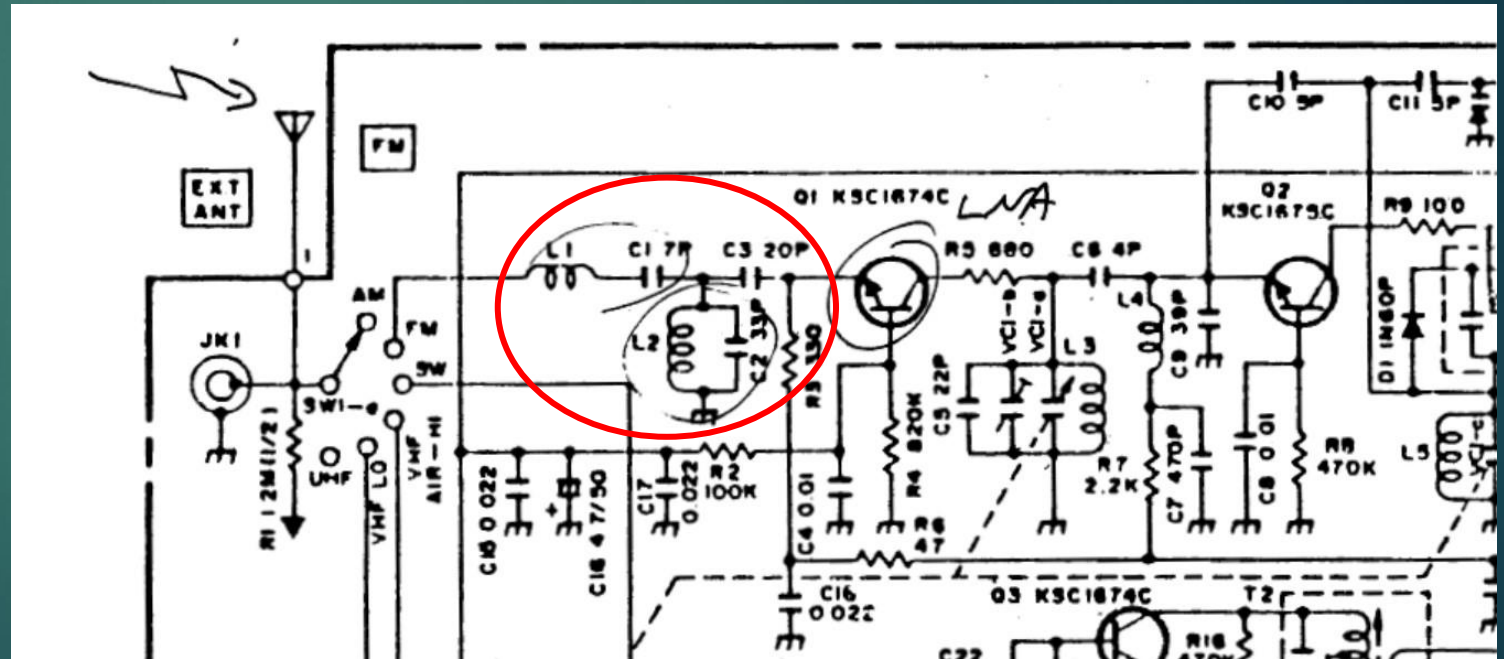
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More Bandpass Filter Examples

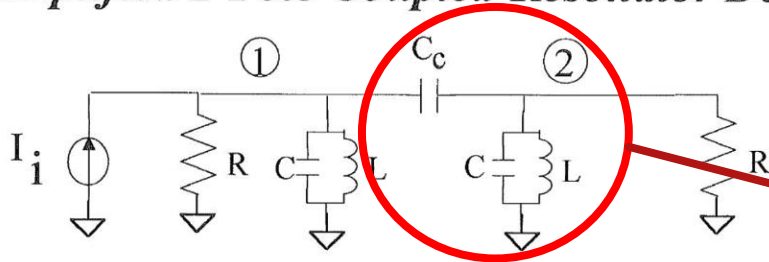


2-pole preselect BPF, plus matching



Coupled Resonator Designs

Simplified 2-Pole Coupled-Resonator Design



Design Equations

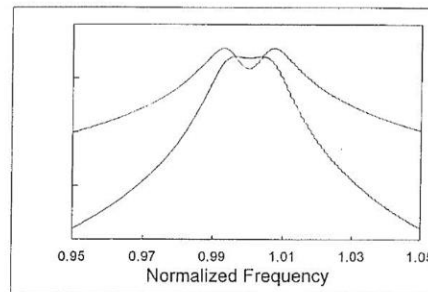
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

$$Q_{res} = \frac{R}{X|_f}$$

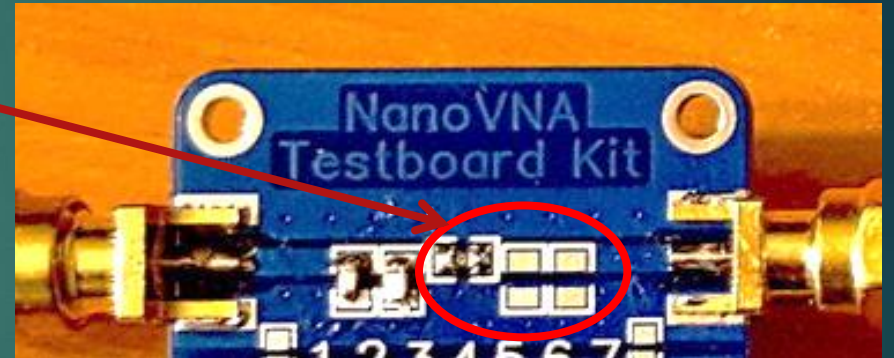
$$C_c \sim \frac{C}{Q}$$

$$B \sim \frac{f_o}{\sqrt{2}Q_{res}}$$

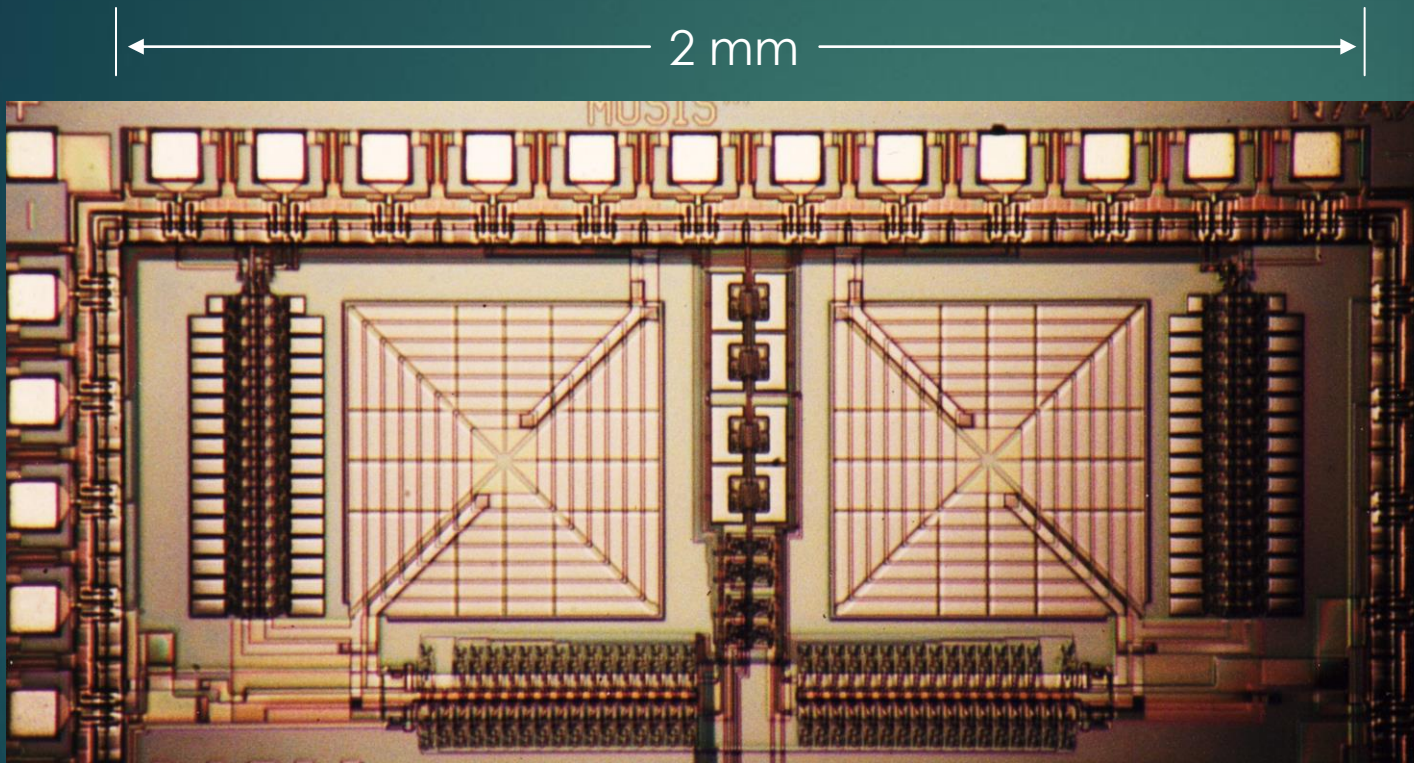
Response to Nodes 1 and 2



Just add a second identical LC resonator and swap 0 Ohm resistor with a small capacitor C_c



Coupled Resonator BPF IC Using On-chip "Spiral" Inductors



NOTE: Spiral inductors are also used in integrated RF amplifiers, oscillators, and frequency synthesizer ICs

Magnetically coupled resonators:

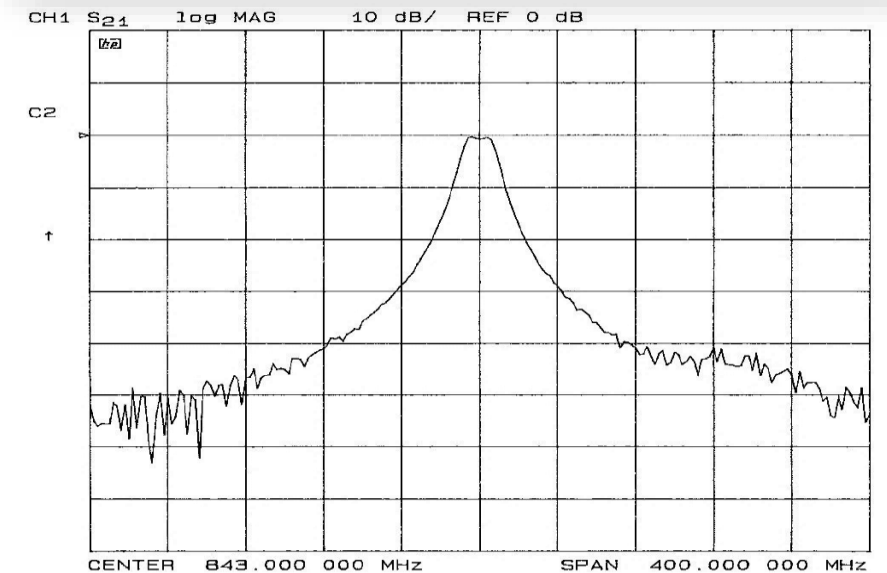
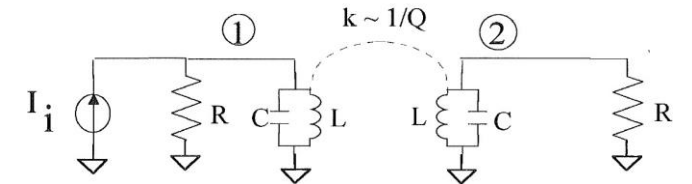
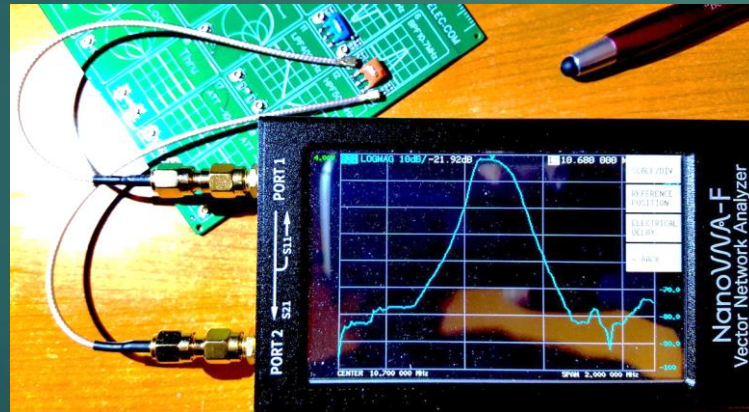
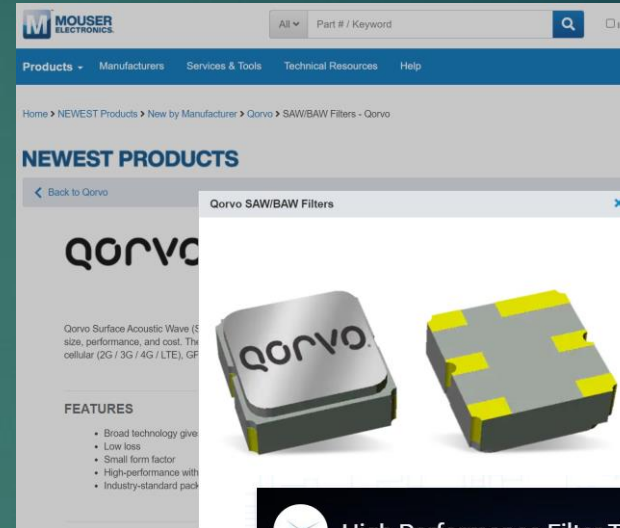
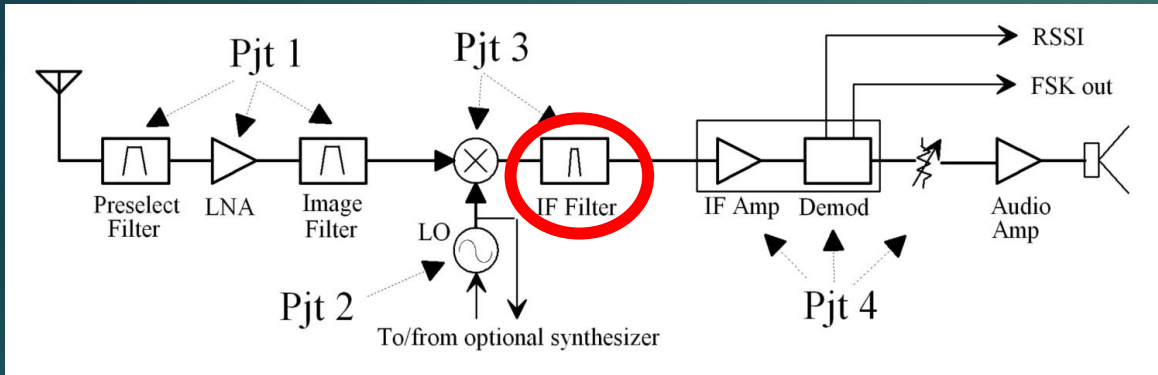


Fig. 9. Measured filter response: 843 MHz center, 10 dB/div vertical, 40 MHz/div horizontal.

From research publication:
"Q-enhanced LC bandpass filters for integrated wireless applications",
IEEE Transactions on Microwave Theory and Techniques 46 (12), 2577-2586

Ceramic IF and BAW RF Filters



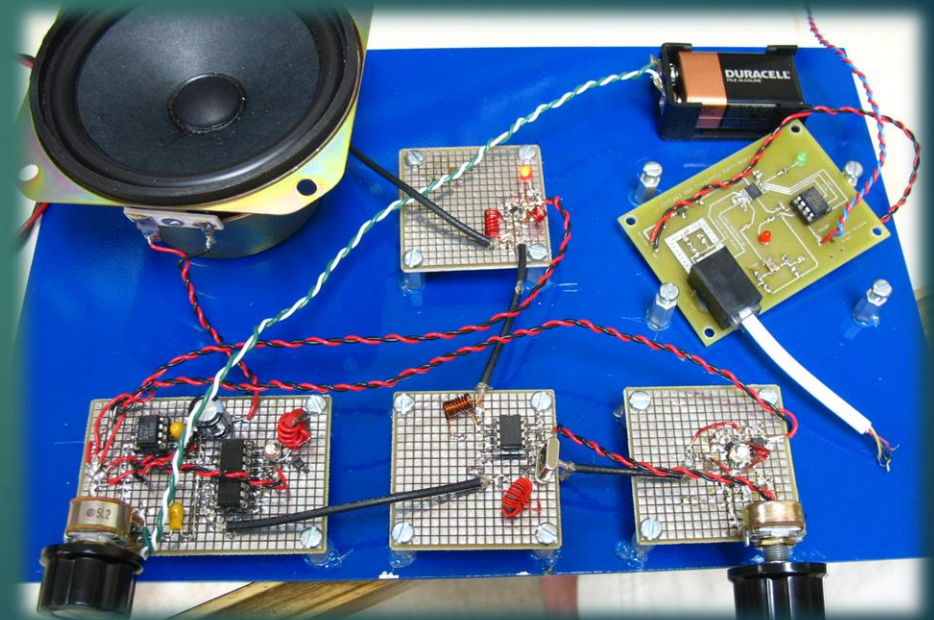
Topic Review

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- Part 2
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Possible Radio Design 101

Future Videos

- *Impedance Matching Network Design*
- *Amplifiers*
- *Local Oscillators*
- *Mixers*
- *Demodulators*
- *Frequency Synthesizers*



Book Recommended in Class

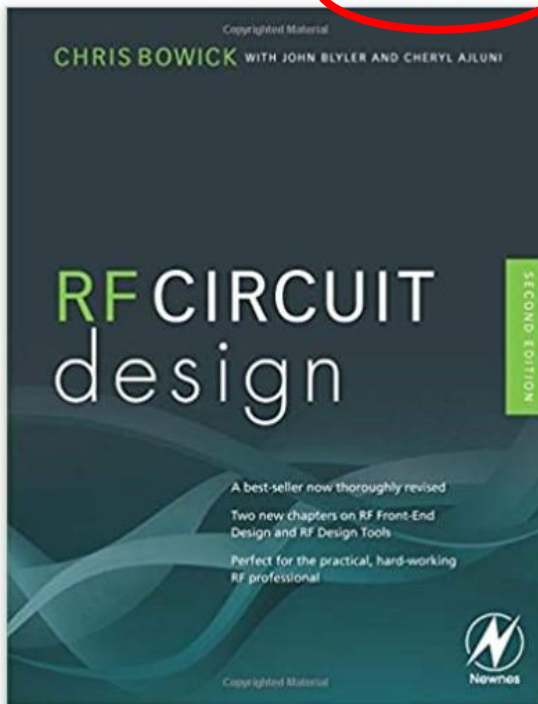
Books > Engineering & Transportation > Engineering

RF Circuit Design 2nd Edition

by Christopher Bowick (Author)

★★★★★ 97 ratings

[Look inside ↓](#)



Available Samples: Kindle Paperback

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*Thanks For
Watching !*