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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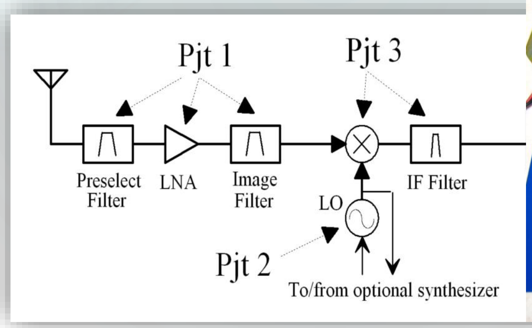
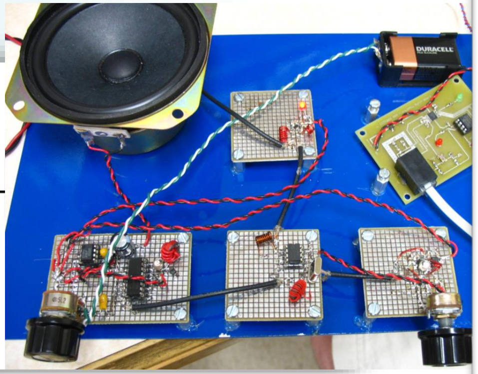
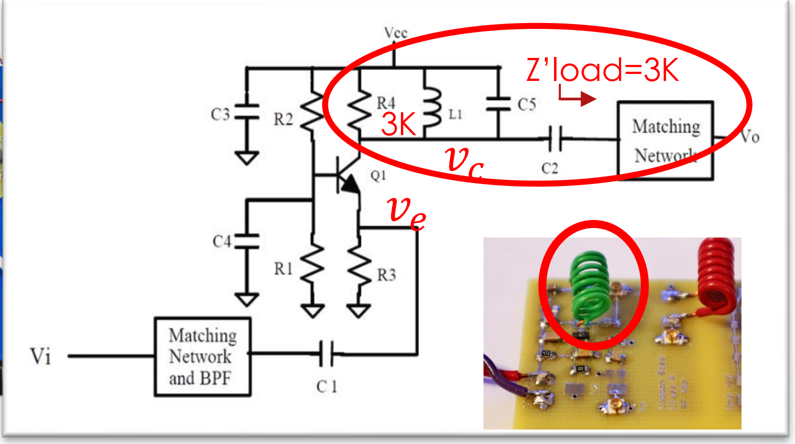
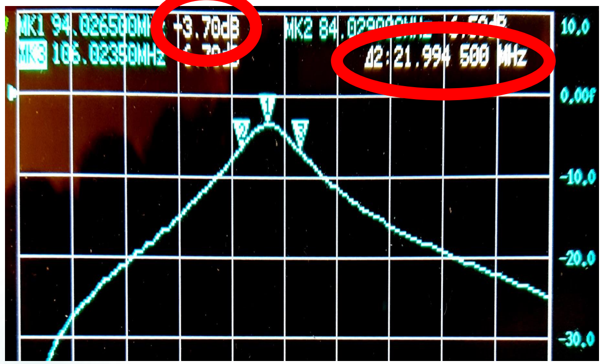
This episode, and the Radio Design 101 series of which it is a part, is based on a university-level senior-design course. However, it is intended for anyone interested in learning the nuts and bolts of electronics and radio circuits. In the first part of this episode, we focus on bandpass filters - including 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.









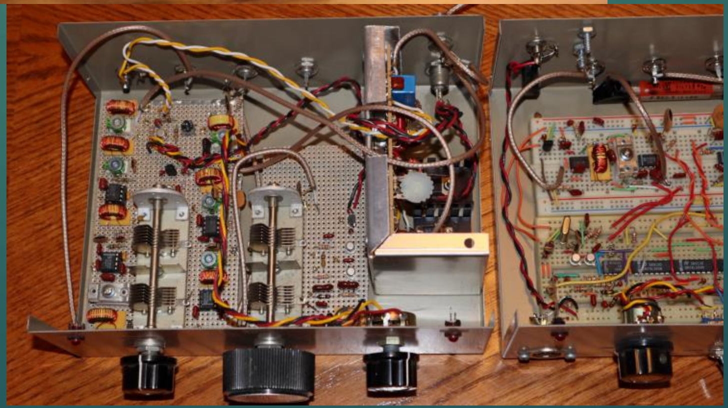
Radio Design 101

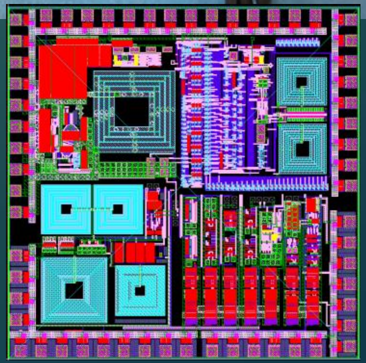
Episode 1

Bandpass Filters, Q, and Matching Networks

Radio Design 101 series

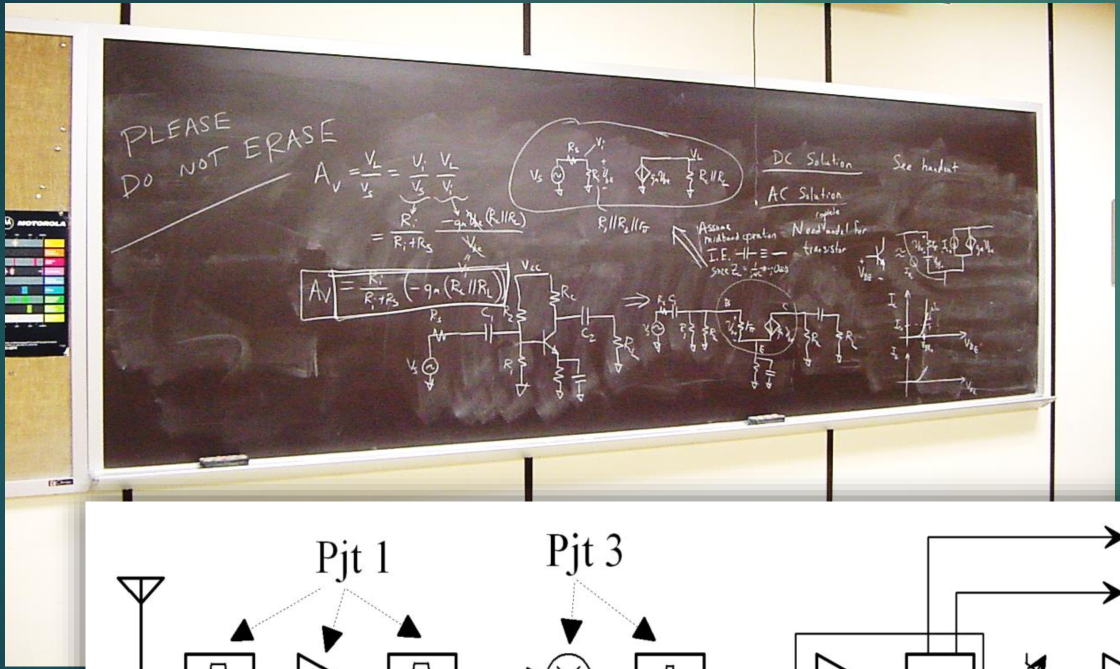
Applicable to all Radio/Wireless Circuit Design

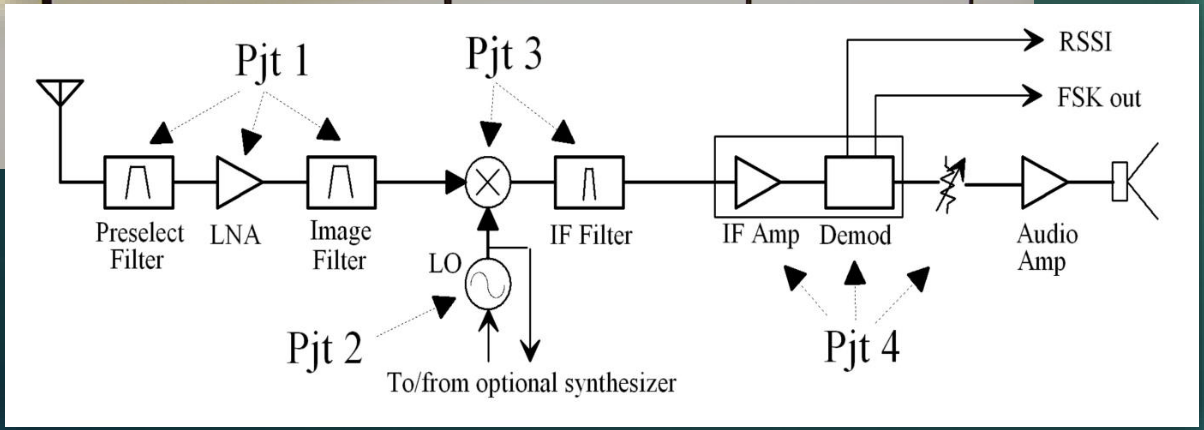


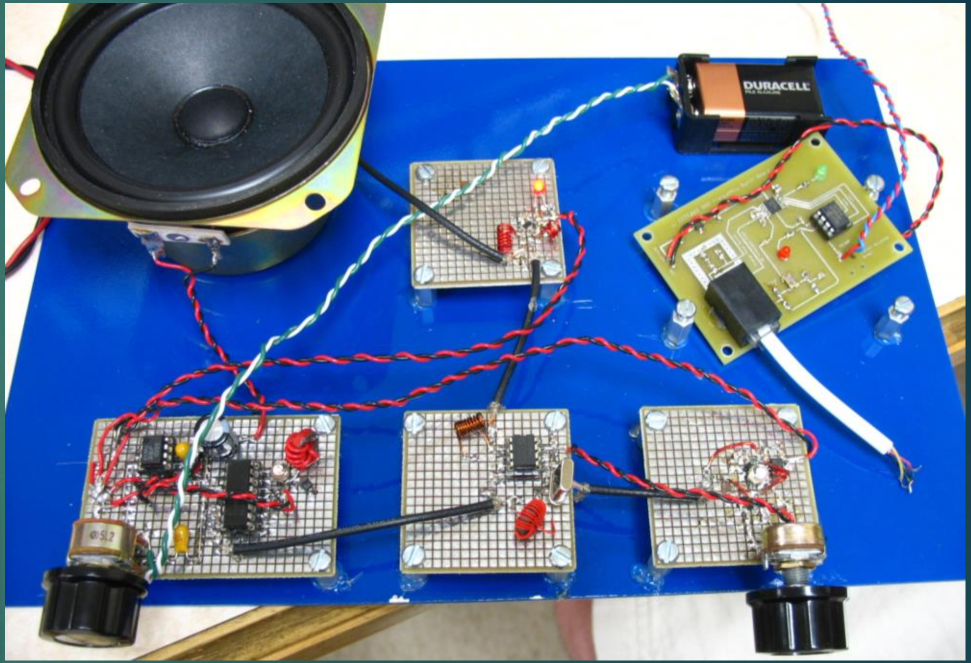


Radio Design 101 series

Abstracted from a senior-design University class







Outline of This Video

Part 1

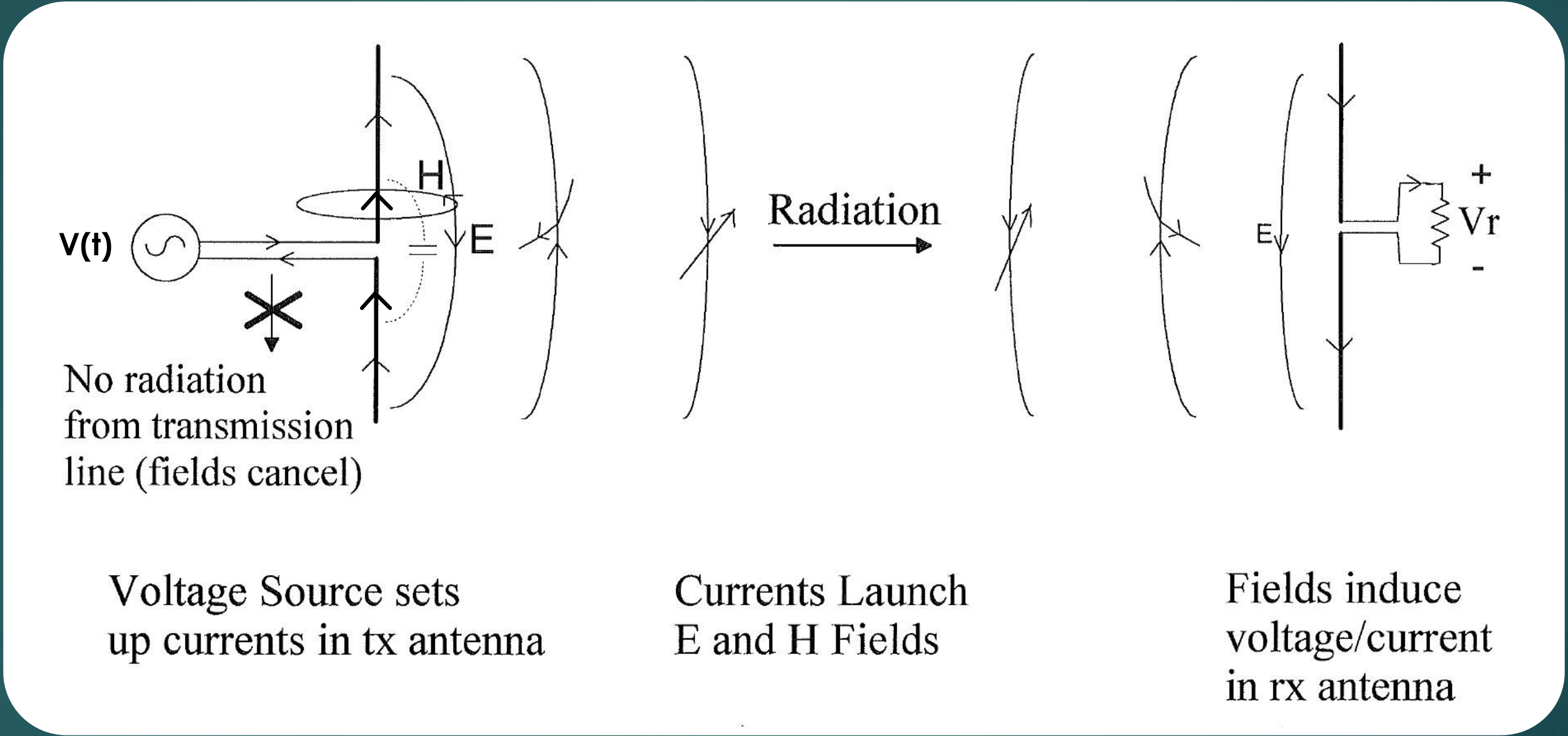
- ***Transmitters and Receivers***
- ***Impedances, Ohms Law, and Voltage dividers***
- ***1-pole Filters (Lowpass and Bandpass)***

Part 2

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

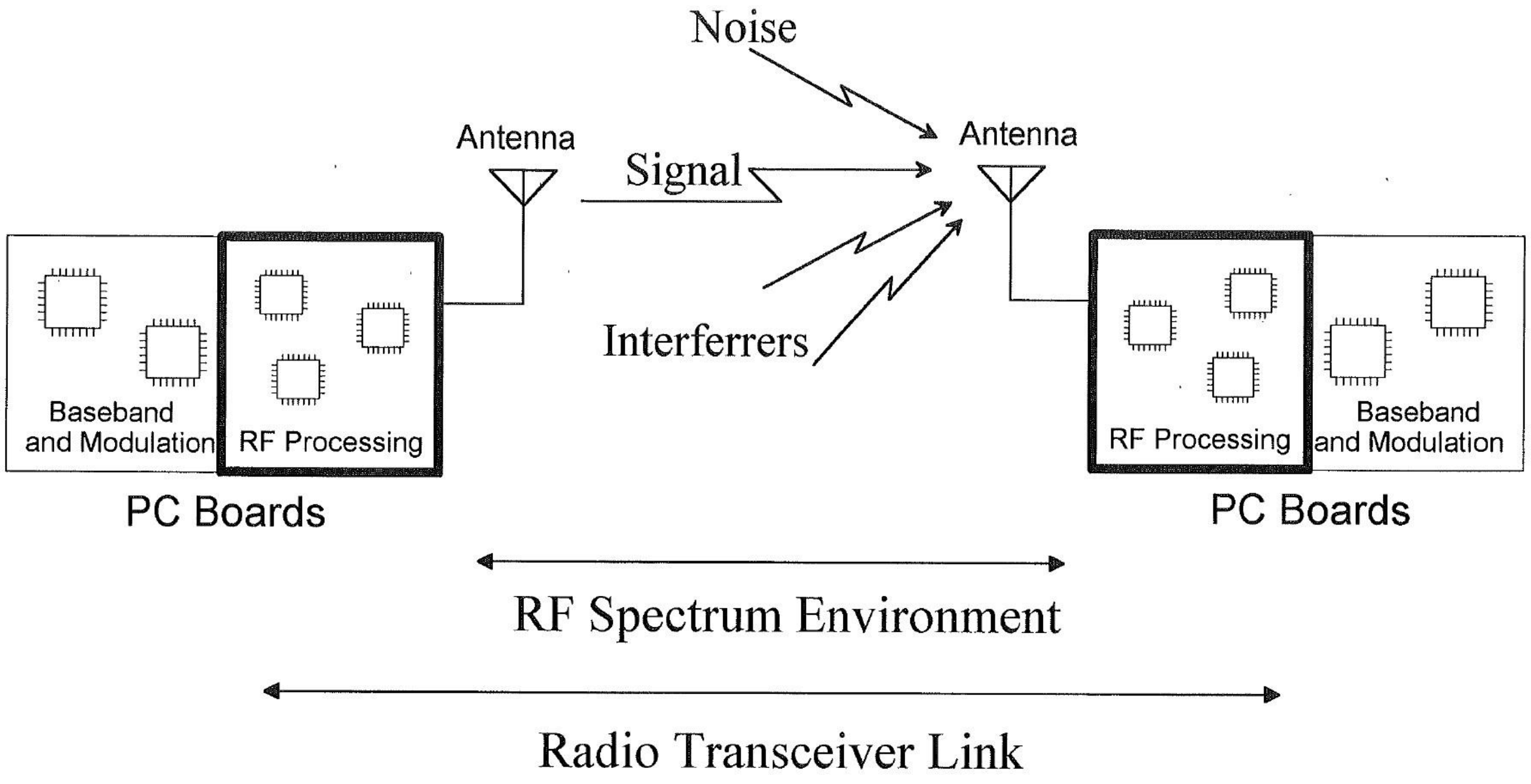
Transmitters and Receivers

EM Field View



Transmitters and Receivers

System View



Receiver Design and Filters

From tuned-RF to Superhet and beyond…

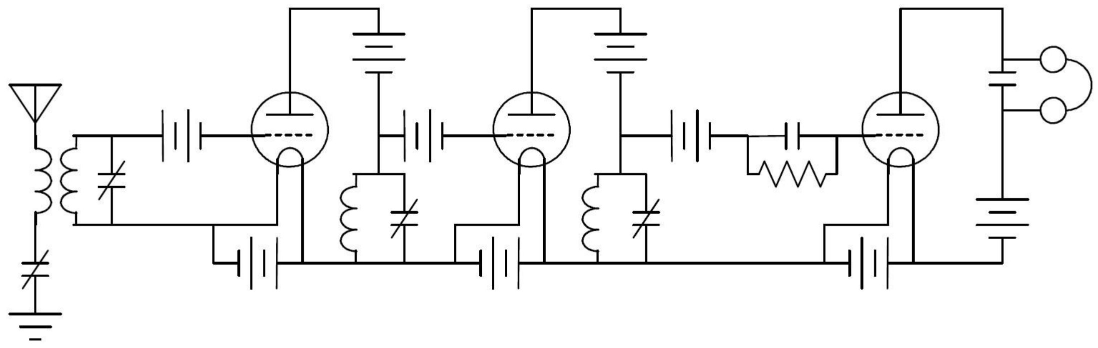
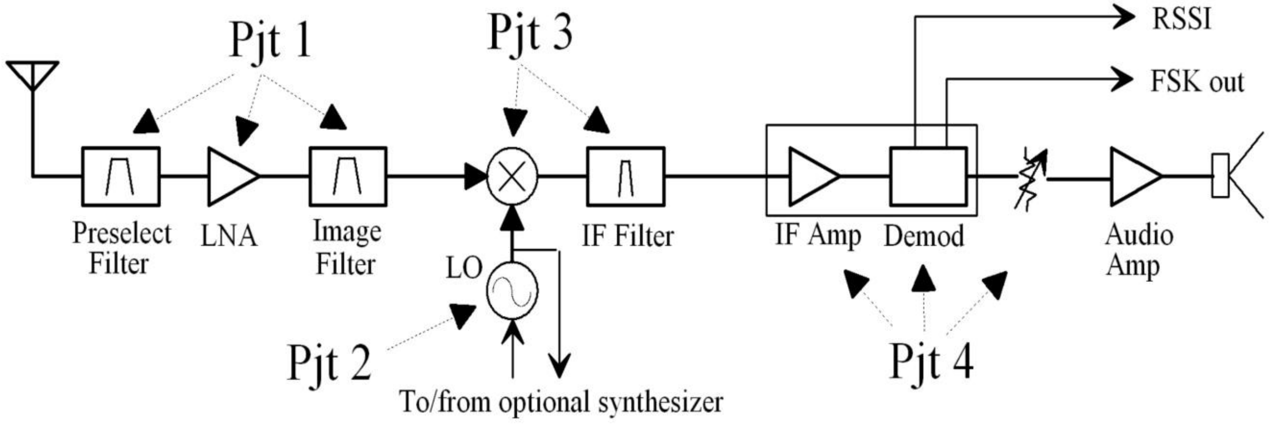


Figure 4.2: Early tuned-RF receiver circuit. [British patent no. 147,147]



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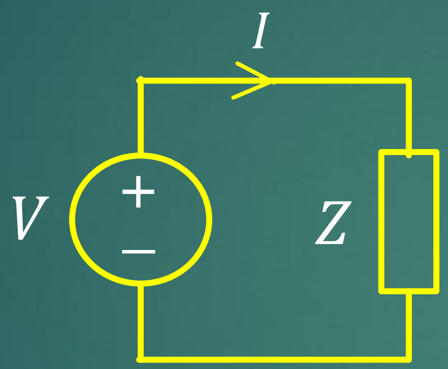
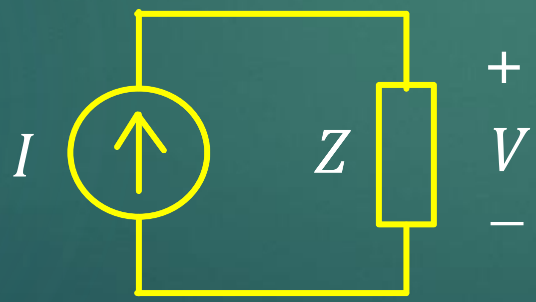
Ohms Law



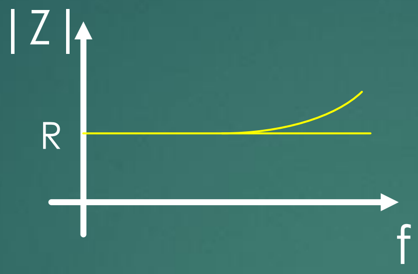
$$I = \frac{V}{Z}$$

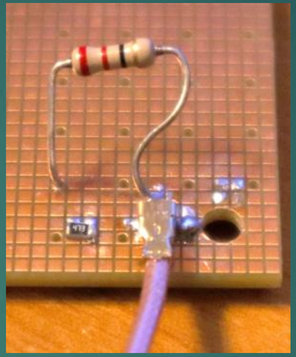


$$V = I\,Z$$

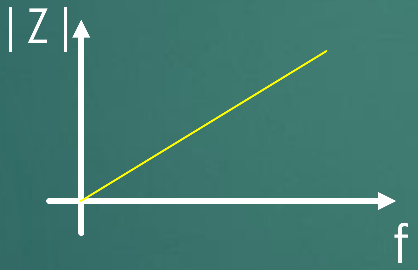
Impedances

Resistor: $Z = R$

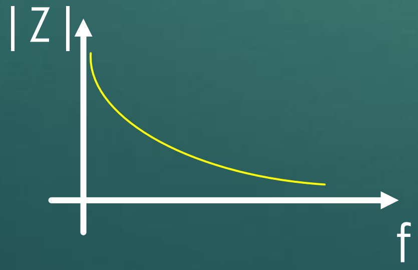


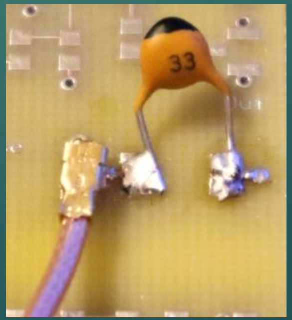


Inductor: $Z = j\,2\pi f L$



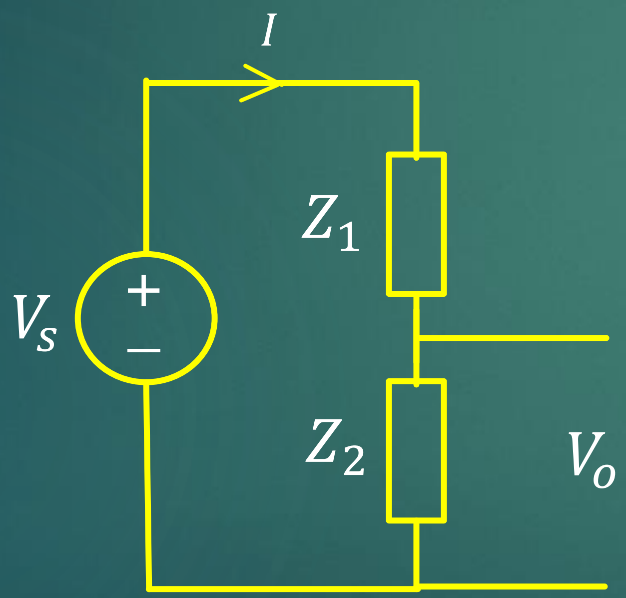
Capacitor: $Z = -j\,\frac{1}{2\pi f C}$





Voltage Divider

"The most important circuit in all of analog electronics" ! ☺

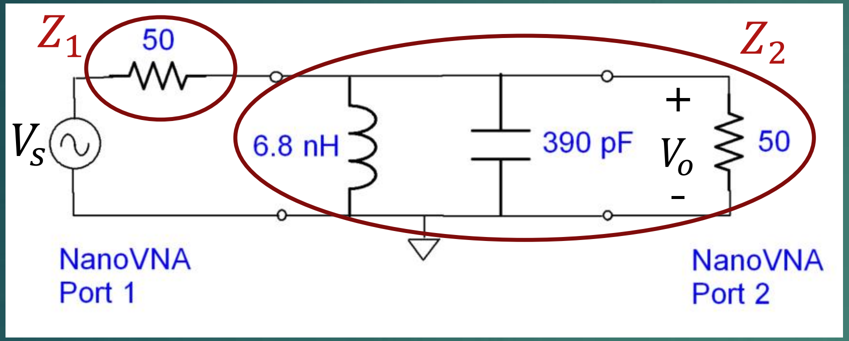


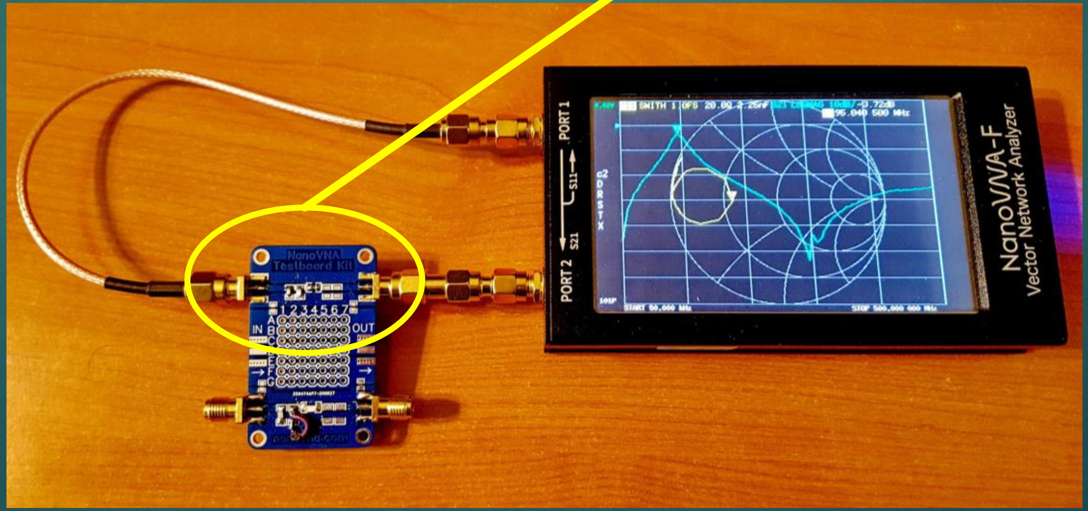
$$I = \frac{V_s}{Z_1 + Z_2}$$

$$V_o = I\,Z_2$$

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

Simple Bandpass Filter





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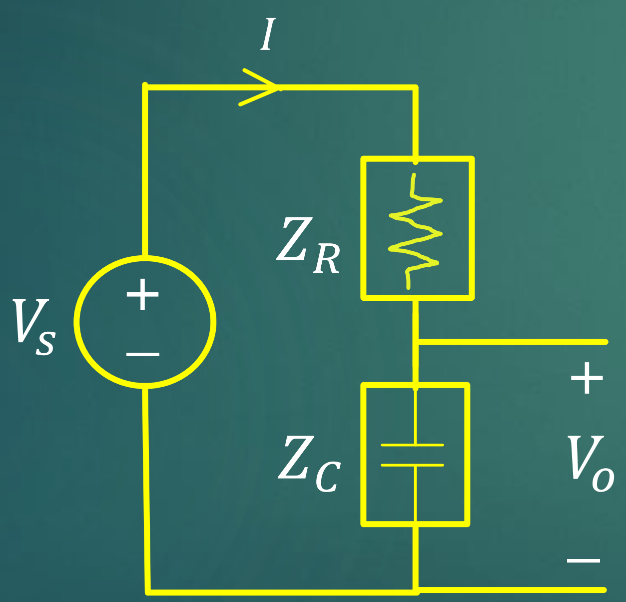
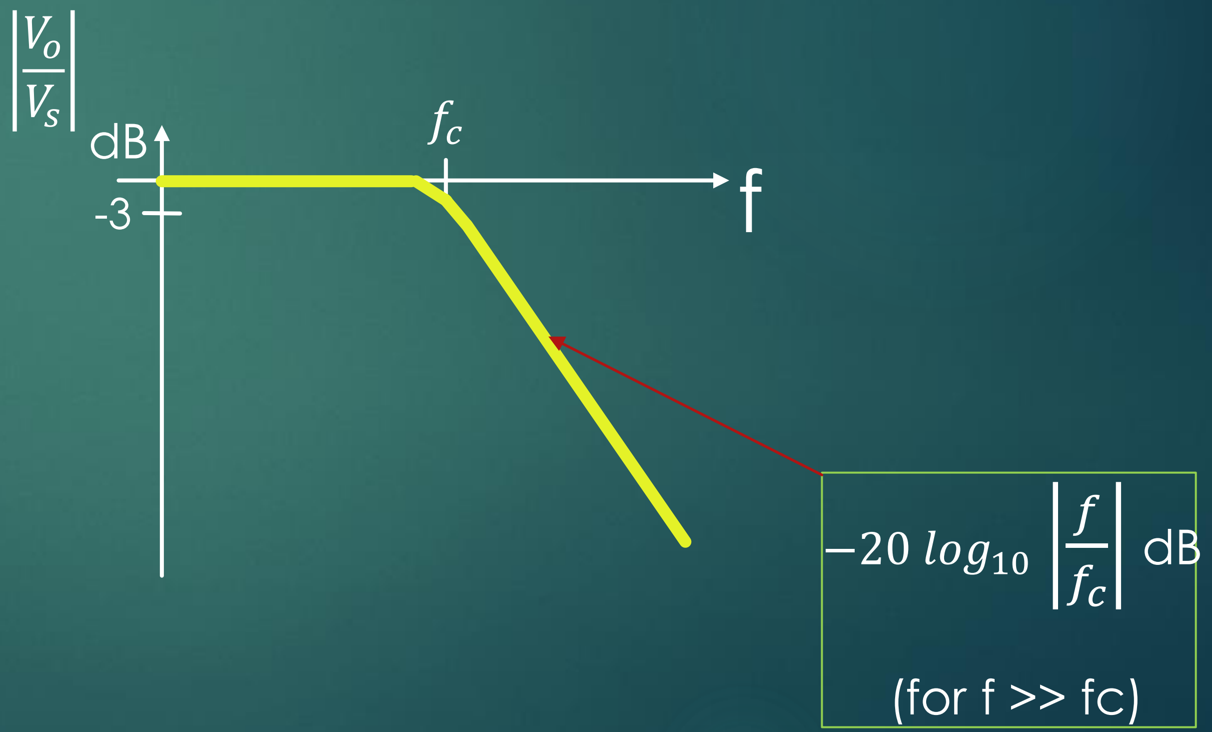
Filters

1-Pole Lowpass:

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

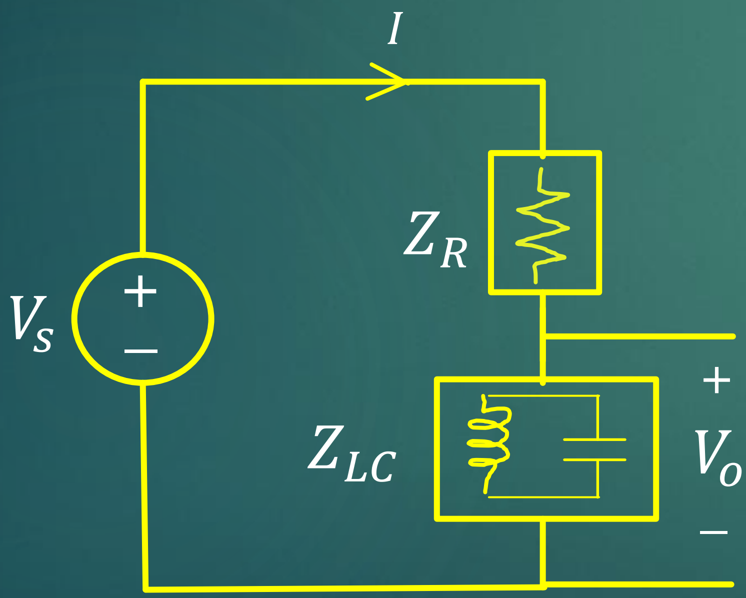


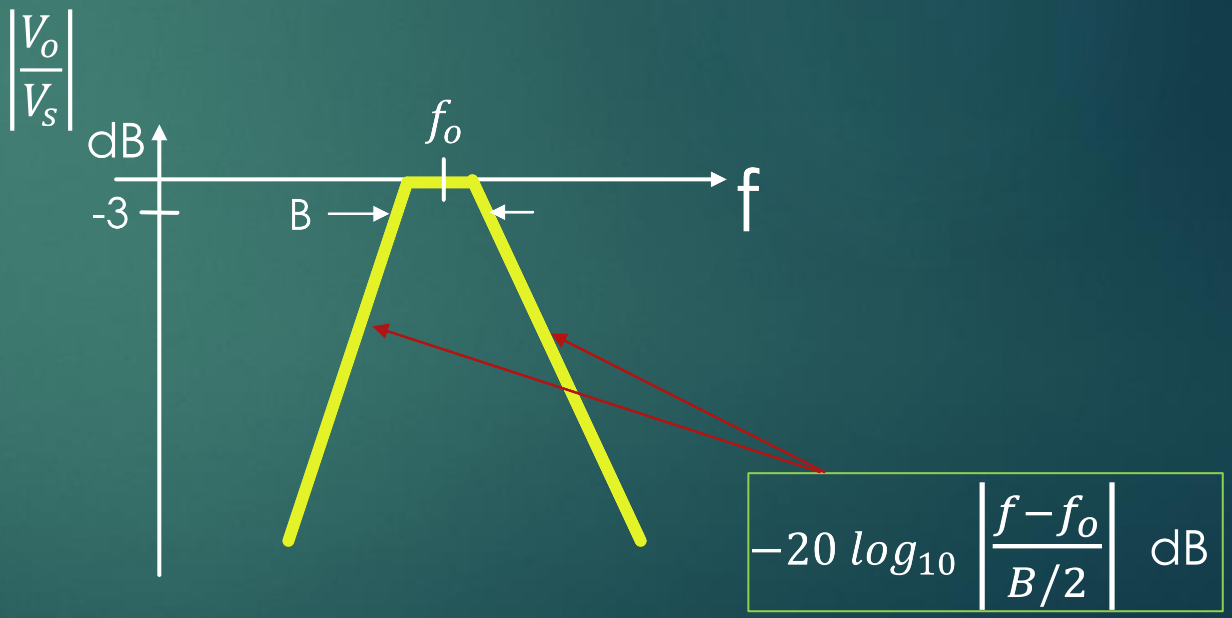


Filters

"1-Pole" **Bandpass**:

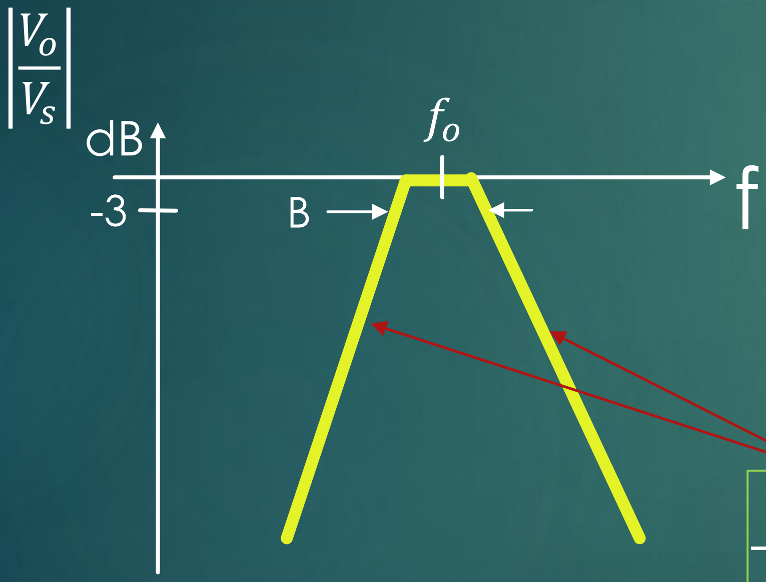
$$V_o = V_s\left[\frac{Z_{Lc}}{Z_R+Z_{Lc}}\right]$$



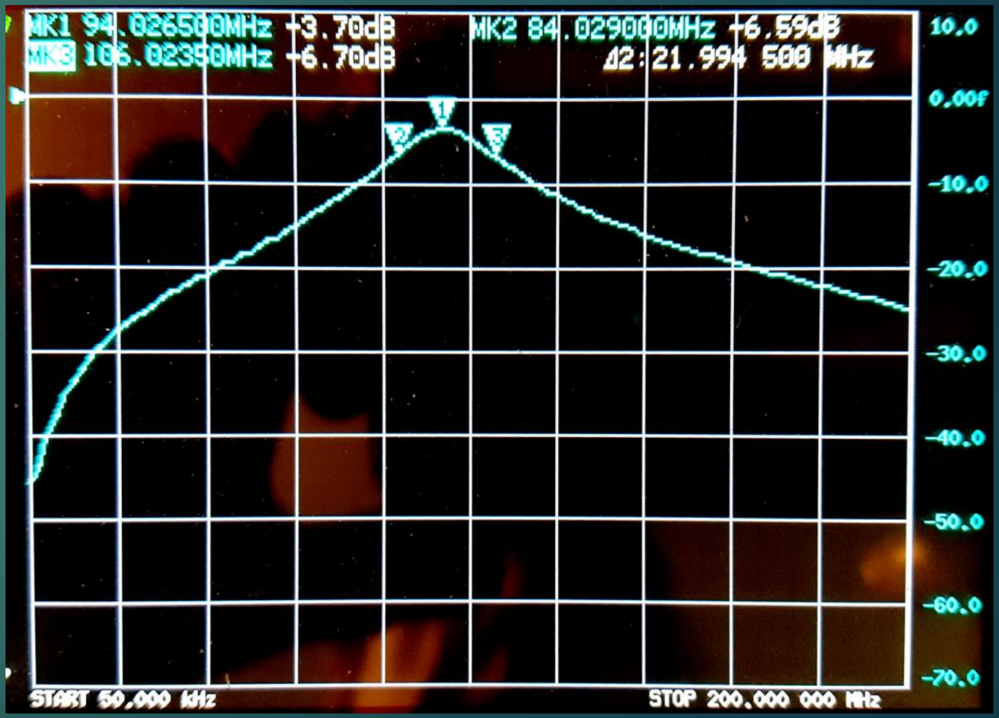


Real-world Performance

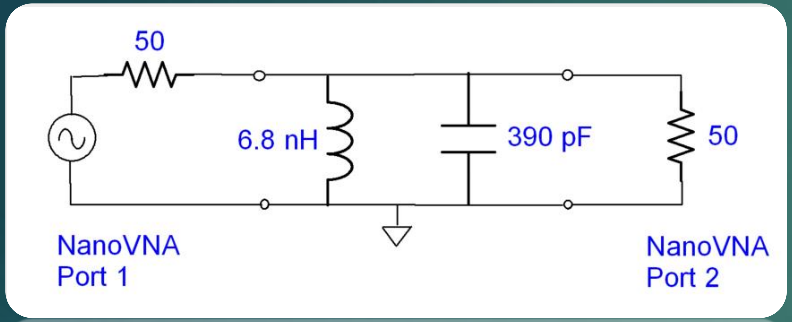
Measured with the NanoVNA

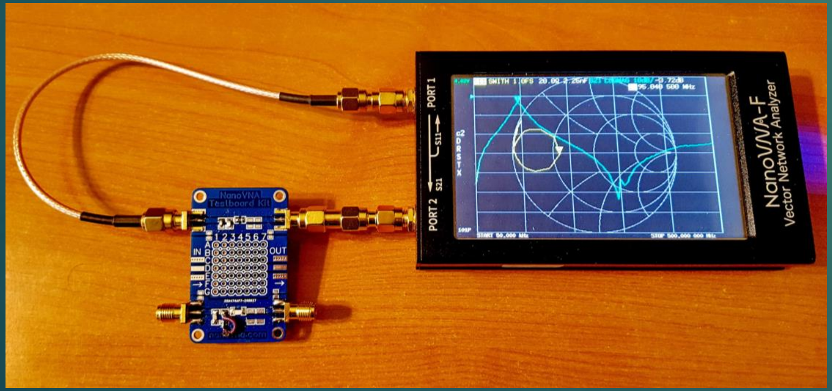


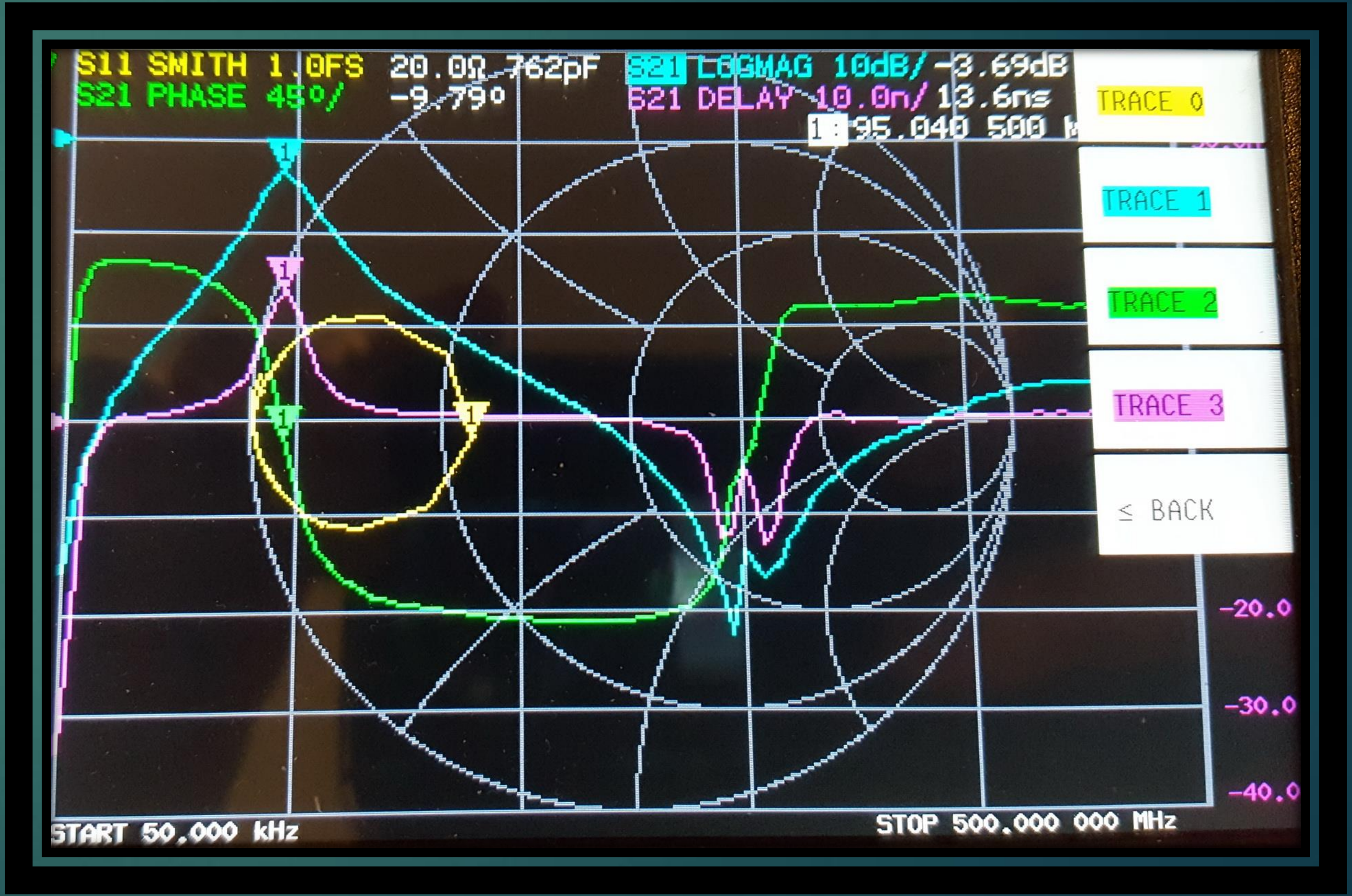
$$-20\ log_{10}\left|\frac{f-f_o}{BW/2}\right|\ \text{dB}$$



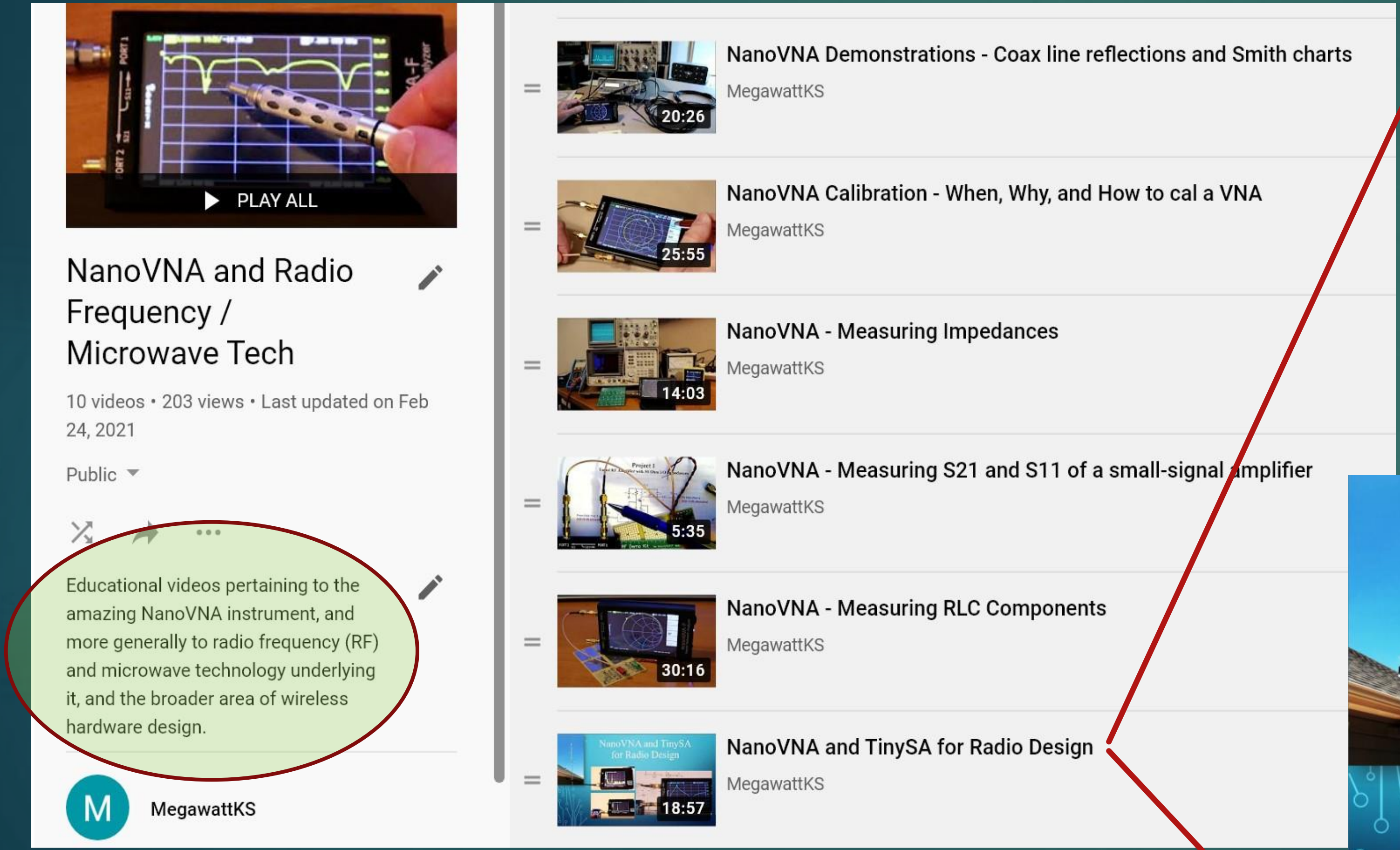
BPF Gain (or Insertion Loss), Impedance, Phase, and Group Delay

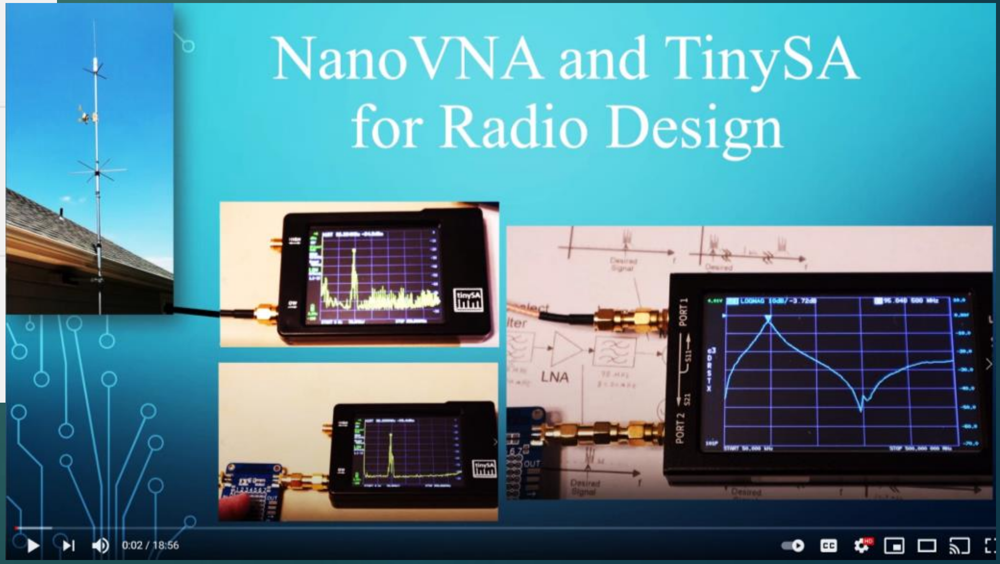






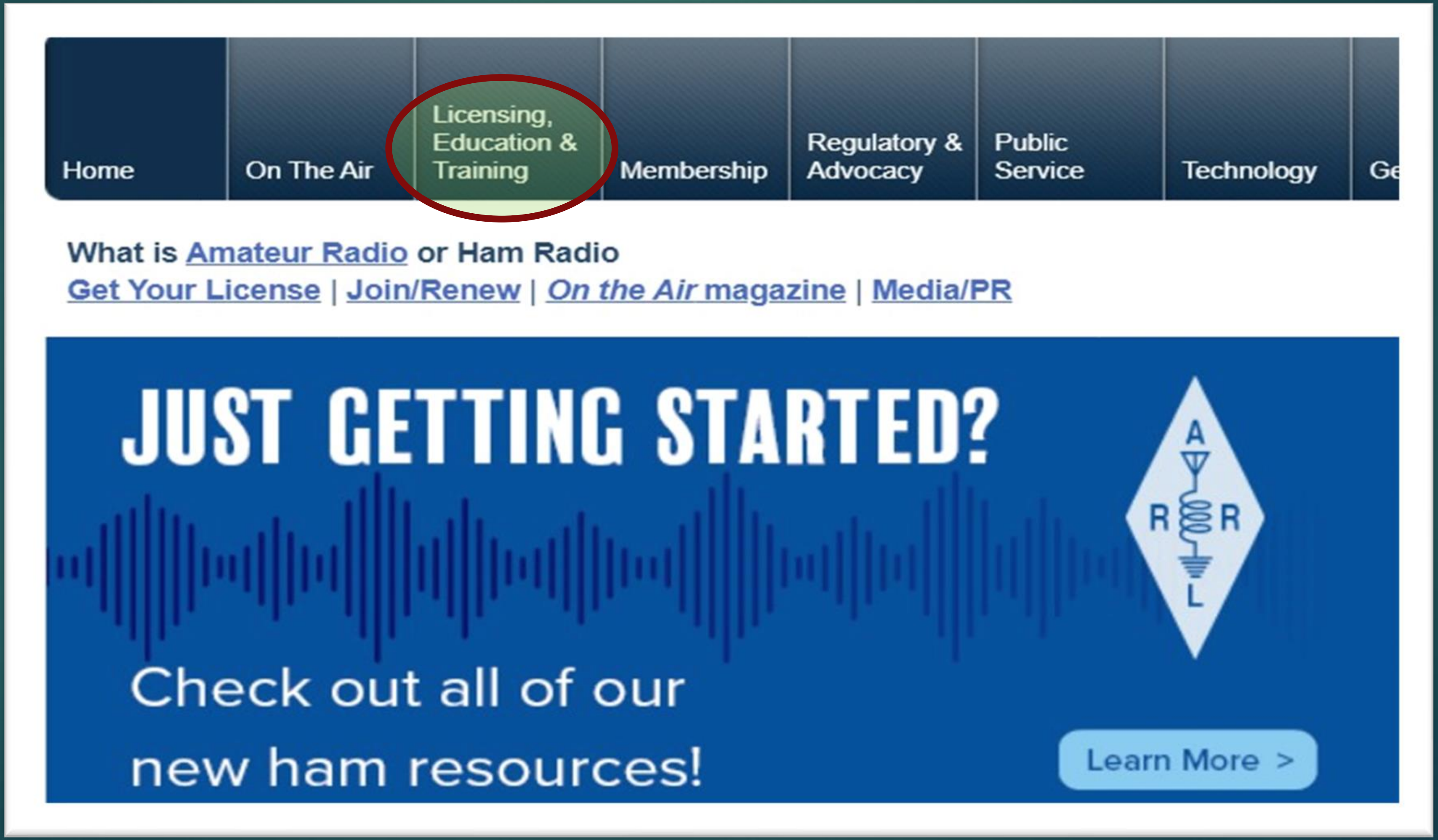
Filter Application Example





Additional Resources

American Radio Relay League (ARRL)



Coming in Part 2

Part 1

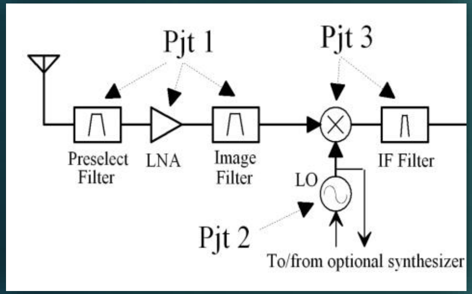
- *Transmitters and Receivers*
- *Impedances and Ohms Law*
- *Voltage dividers* *(the most important analog circuits !)*
- *1-pole Filters* *(Lowpass and Bandpass)*

Part 2

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

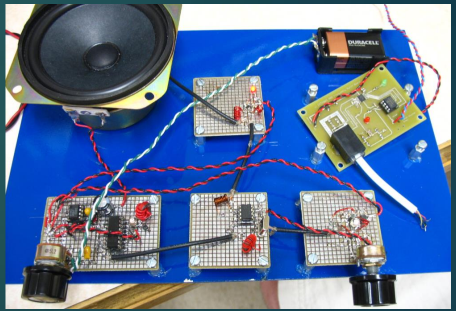
Radio Design 101

Episode 1



Bandpass Filters, Q, and Matching Networks

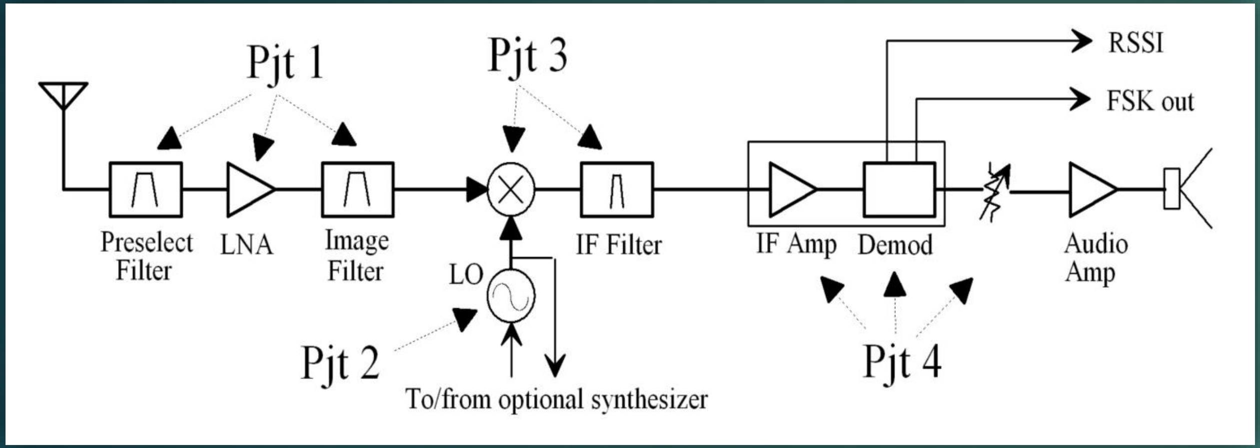
Part 2

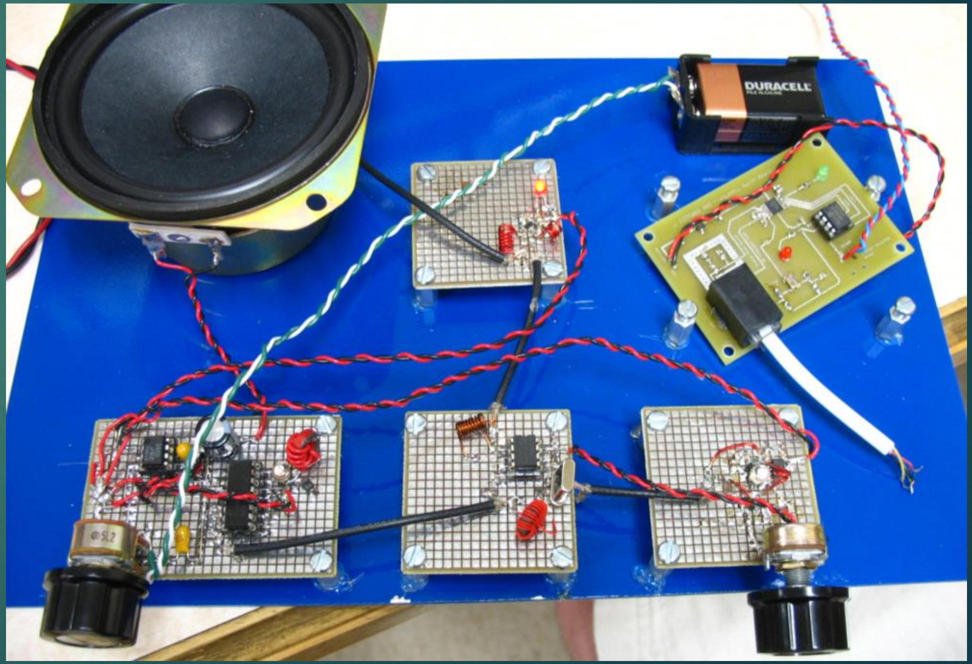


Part 1 Review

Abstracted from a senior-design University class

Semester Project: FM Broadcast Receiver

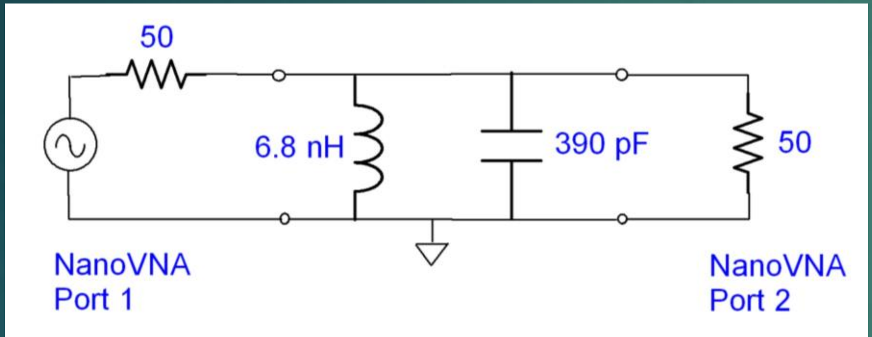


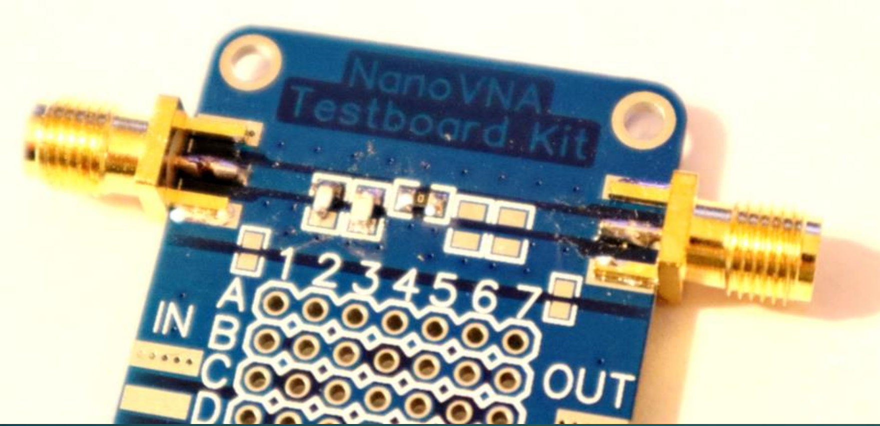


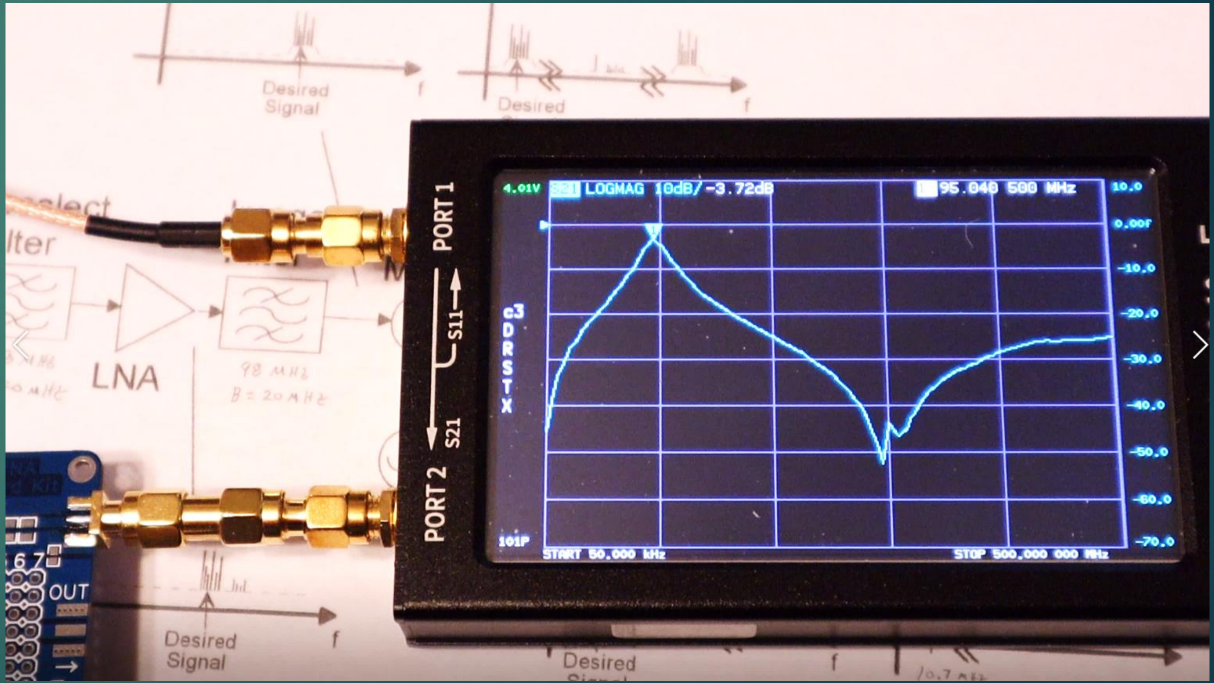
Alternative Projects: VHF Weather Radio Receiver
Amateur Radio Receivers
Any radio/wireless system !

Part 1 Review

1-Pole Bandpass filter

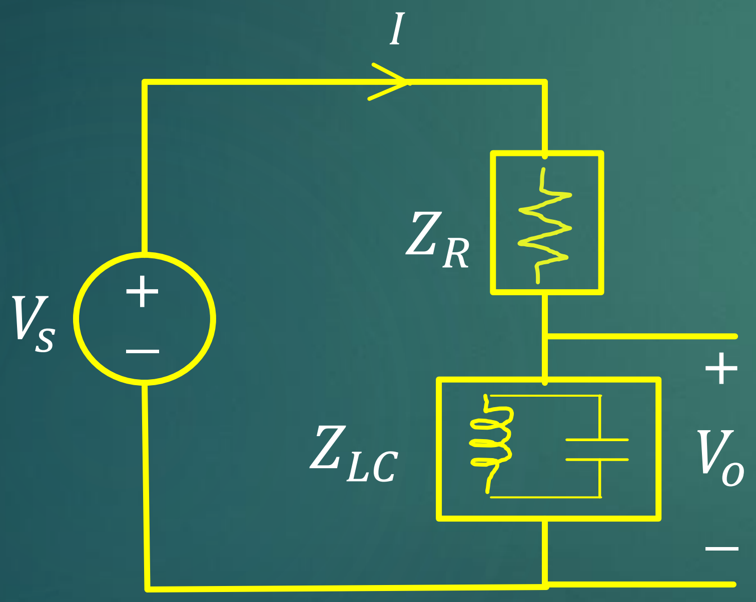


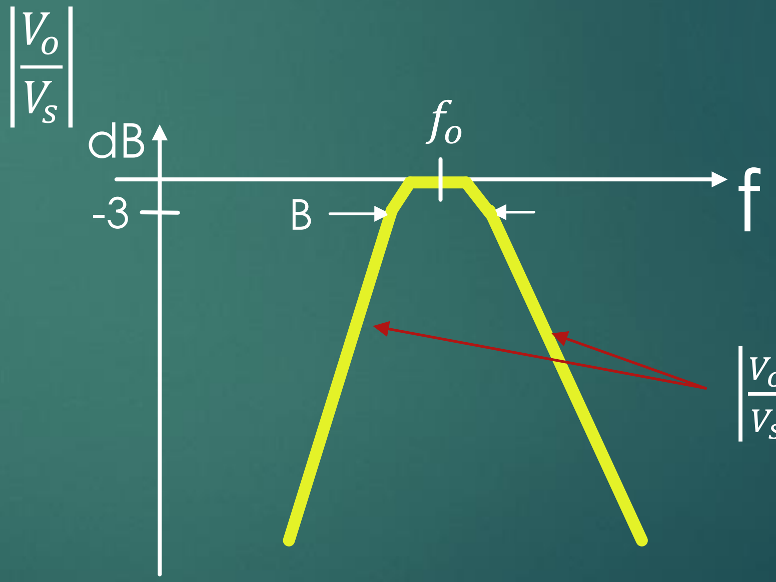




Part 1 Review

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





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

$f_o = \frac{1}{2\ \pi \sqrt{L\ C}}$ $\boldsymbol{B} = \left|\frac{\boldsymbol{f_o}}{\boldsymbol{Q}}\right|$

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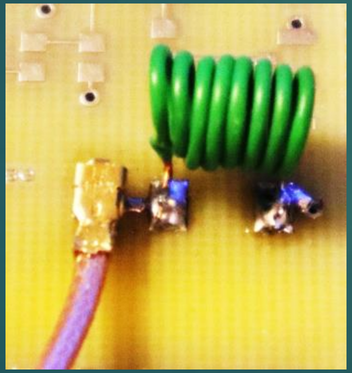
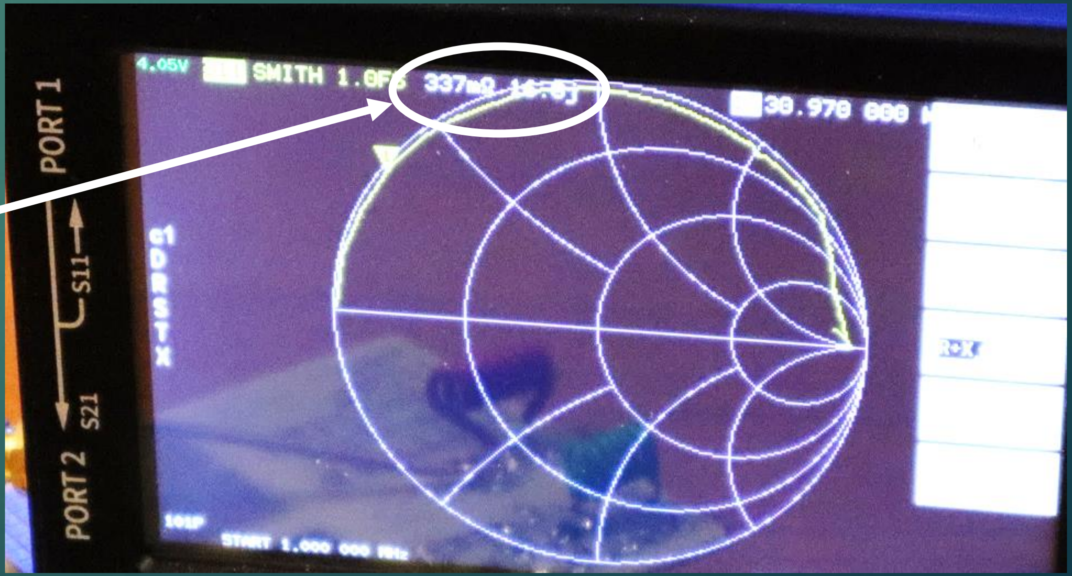
What’s “Q”

A key RF design parameter

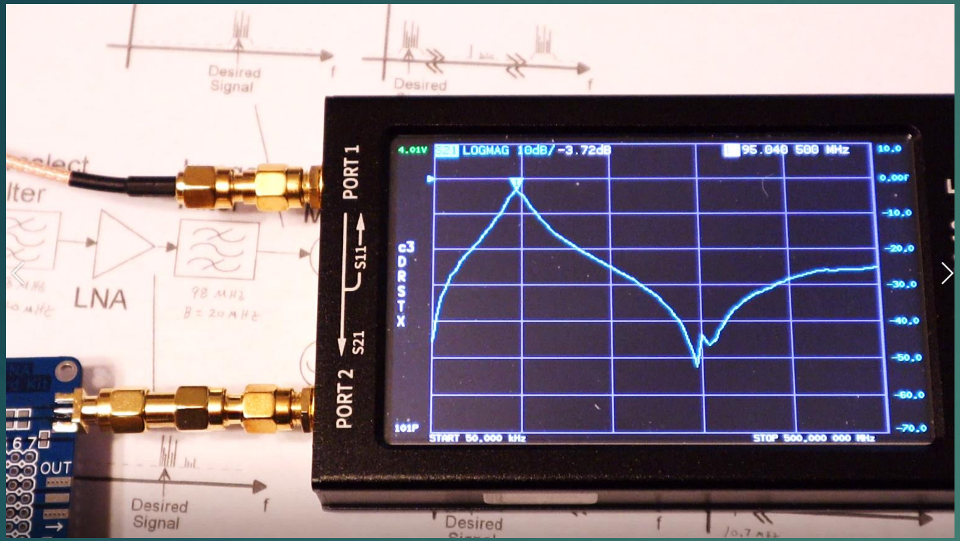
- of resonant-circuits, filters, matching networks, etc.
- of underlying reactive components (e.g. L, C)

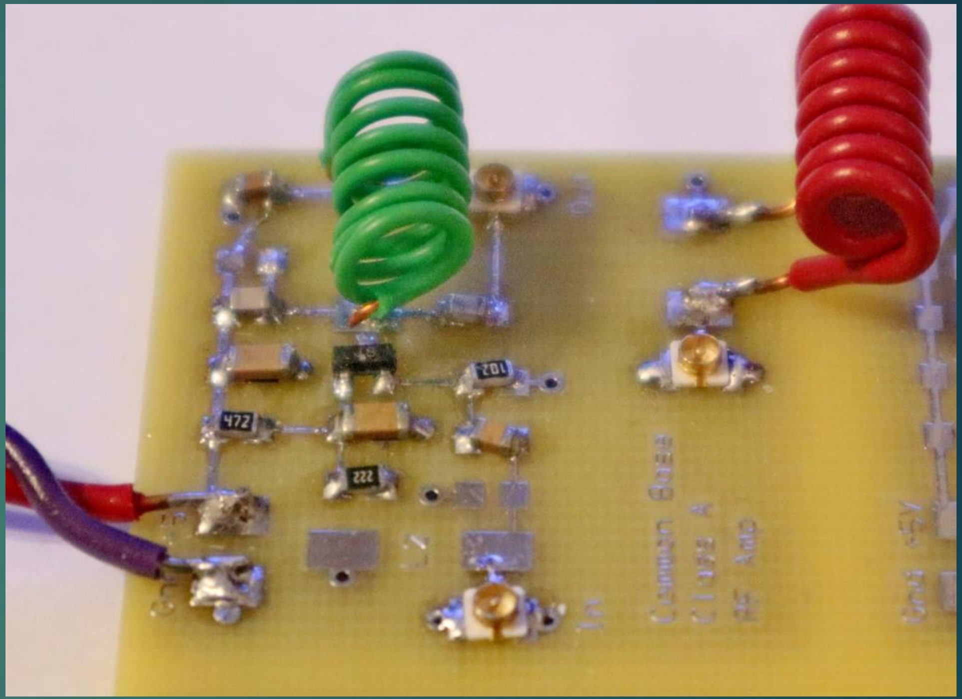


Q = X/R
= 16.6/0.337
= 49 (@30 MHz)



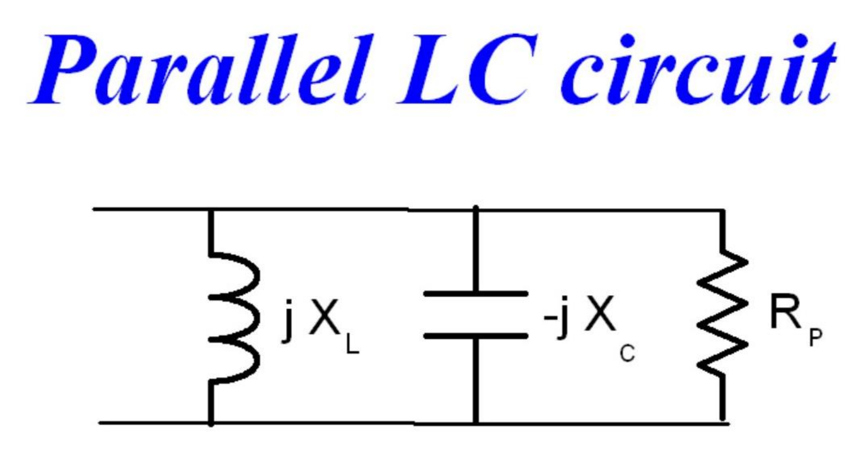
What's it good for ?





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

Parallel Resonant Circuit Q



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

$$f_o = \frac{1}{2\,\pi\,\sqrt{L\,C}}$$

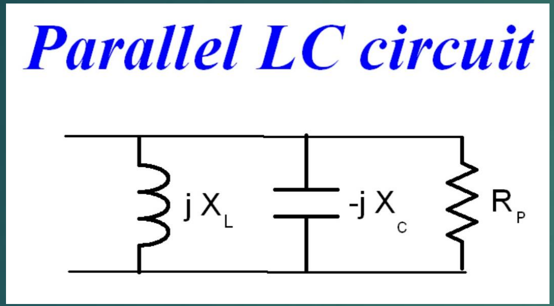
$$X_o = 2\,\pi\,f_o\,L$$

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

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

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

Parallel vs Series Resonators

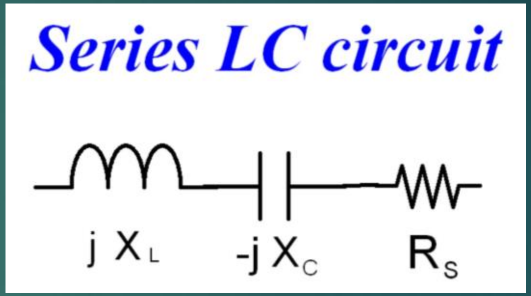


$$Z \rightarrow R_P \; @ \; f = f_o$$

$$Z \rightarrow 0 \quad for \quad f \rightarrow 0$$
$$Z \rightarrow 0 \quad for \quad f \rightarrow \infty$$

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

$Big\ Rp \Rightarrow$ High Q



$$Z \rightarrow R_S \; @ \; f = f_o$$

$$Z \rightarrow \infty \quad for \quad f \rightarrow 0$$
$$Z \rightarrow \infty \quad for \quad f \rightarrow \infty$$

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

Small $Rs \Rightarrow$ High Q

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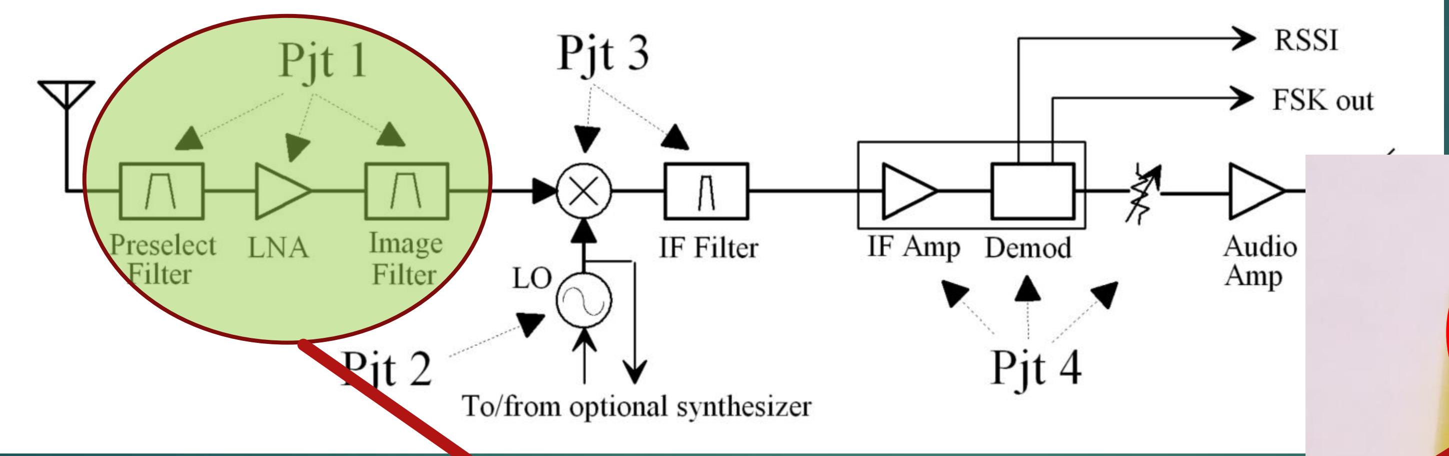
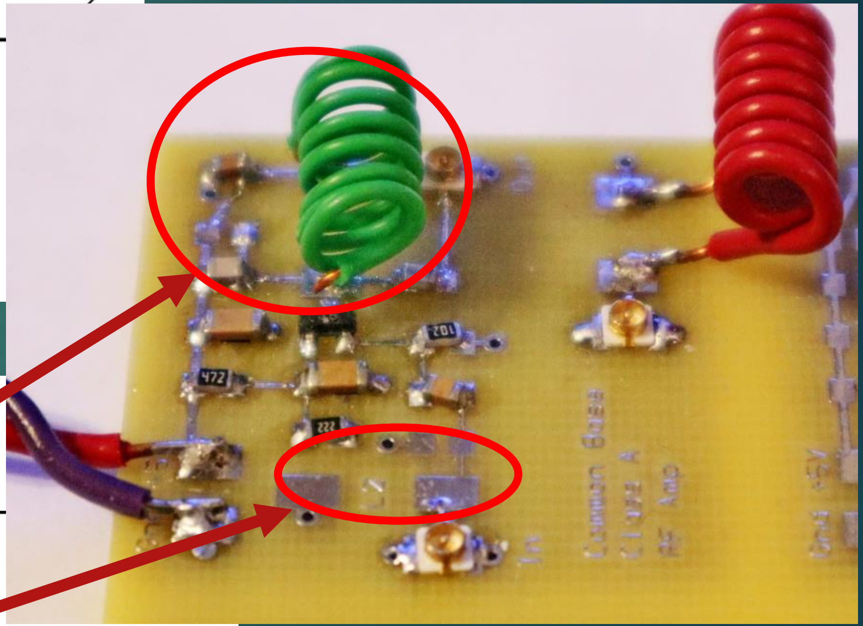
Receiver and Filter Design

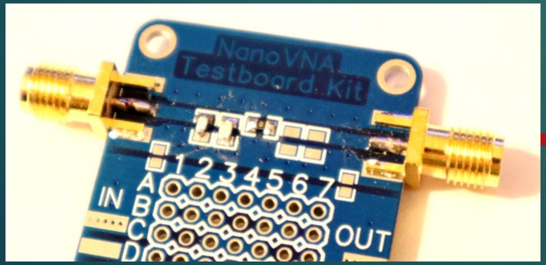
Block Diagram

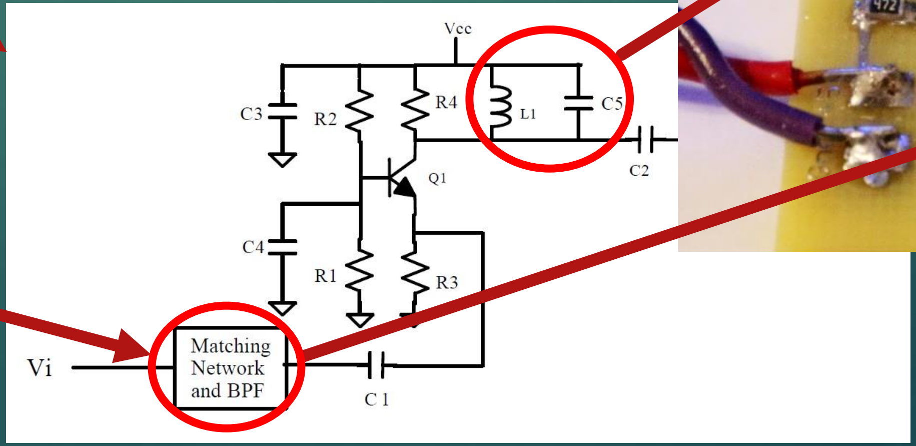


Layout/Build

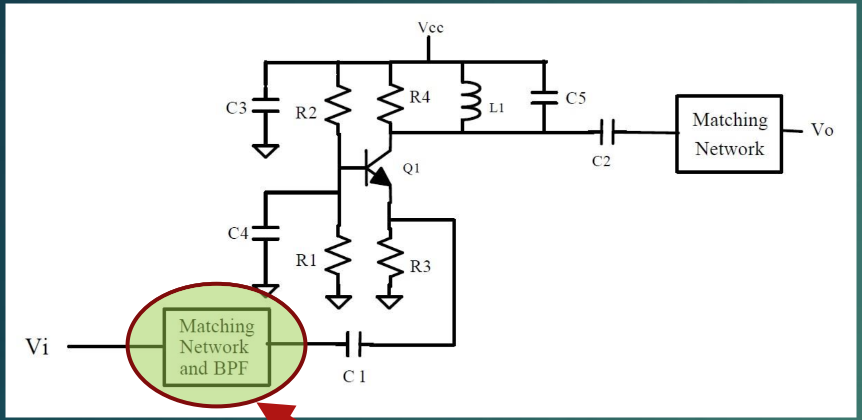


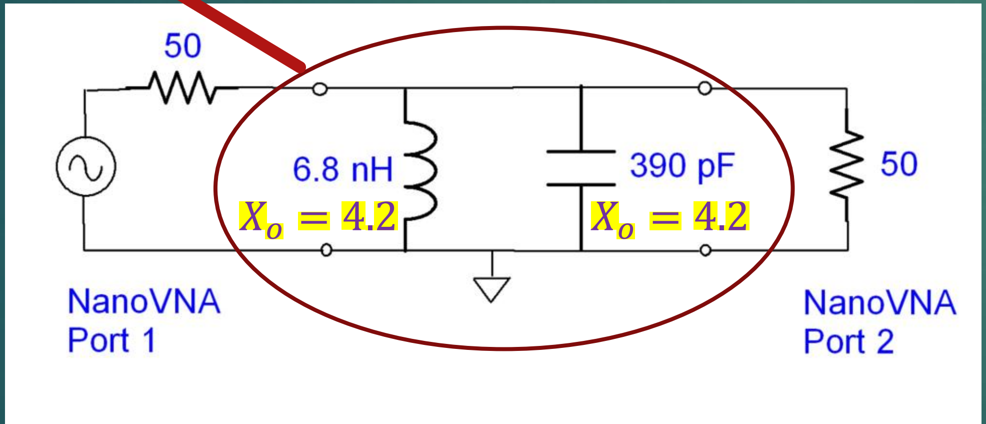
Subcircuits





Example 1: Pre-select Filter





Analysis :

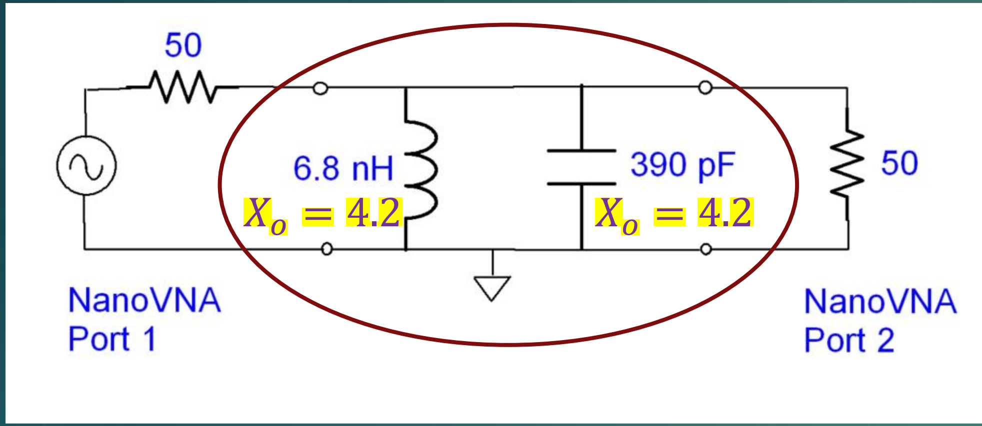
L = 6.8 nH   C = 390 pF

$f_o = \frac{1}{2\,\pi\,\sqrt{L\,C}} = 100\ MHz$ $X_o = X\ @\ 100\ MHz = 4.2$

$R = 50||50 = 25$ Q = R/Xo = 25/4.2 = 6

So… $B = \frac{100\ MHz}{6}$ = 17 MHz

Example 1: Pre-select Filter



Design: !

Start with desired f_o and B

$fo = 100\ MHz$ B = 17 MHz

Find "selectivity Q" needed:

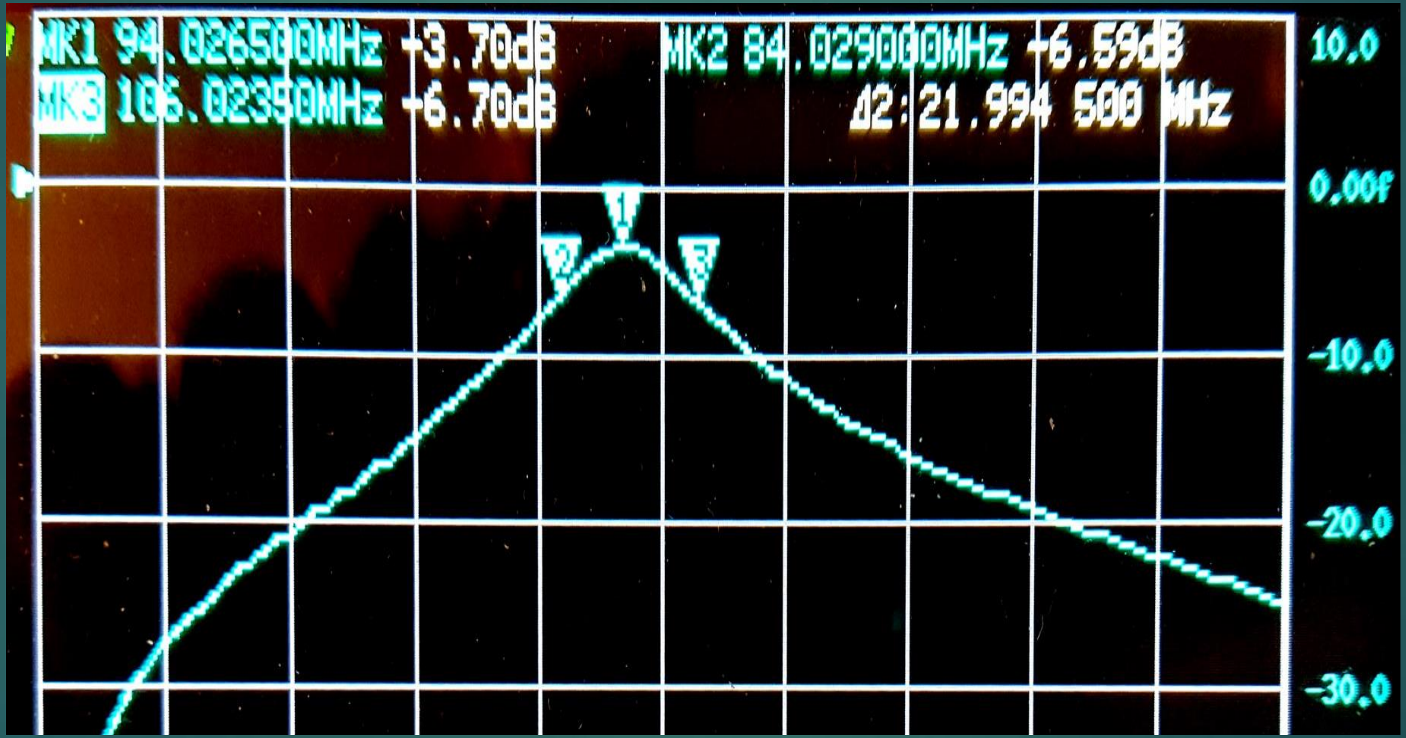
$$Q = \frac{fo}{B} = \frac{100}{17} = 6$$

Solve for X_o and then L, C needed:

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

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

S21 Measurement



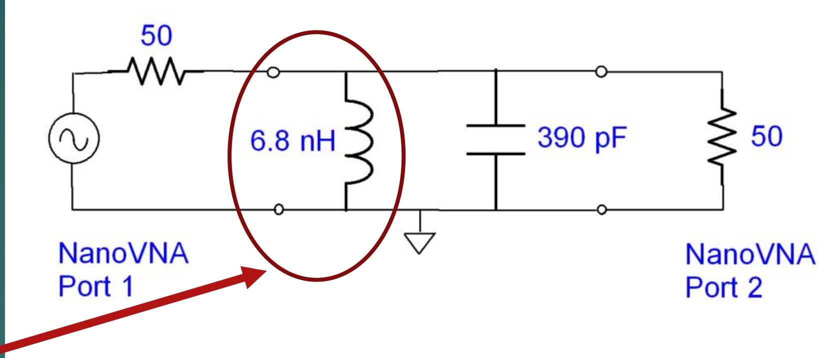
50 kHz to 200 MHz

Component Parasitics Issues

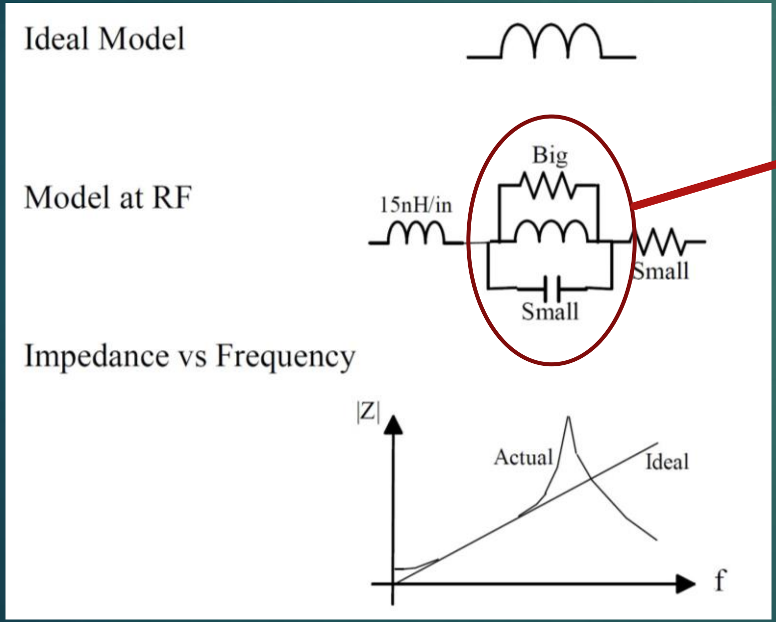
- **Why is in-band insertion loss almost 4 dB ?**
- **Why is bandwidth wider than designed 17 MHz value ?**

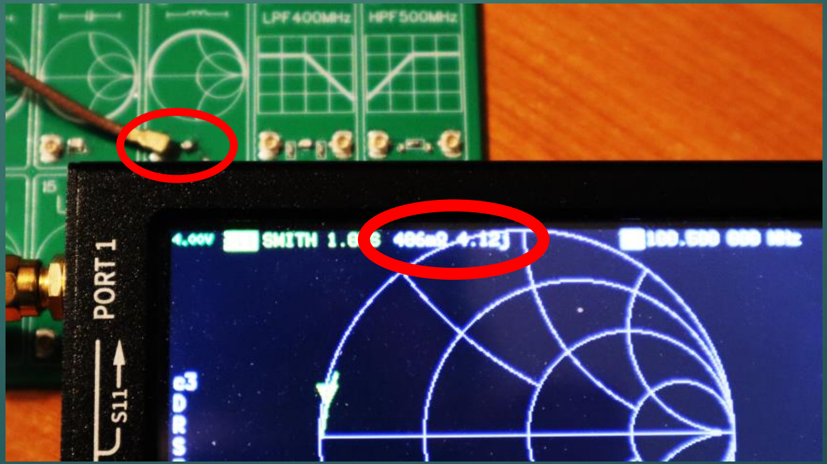
Component Parasitics Issues

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



Inductor Parasitics !





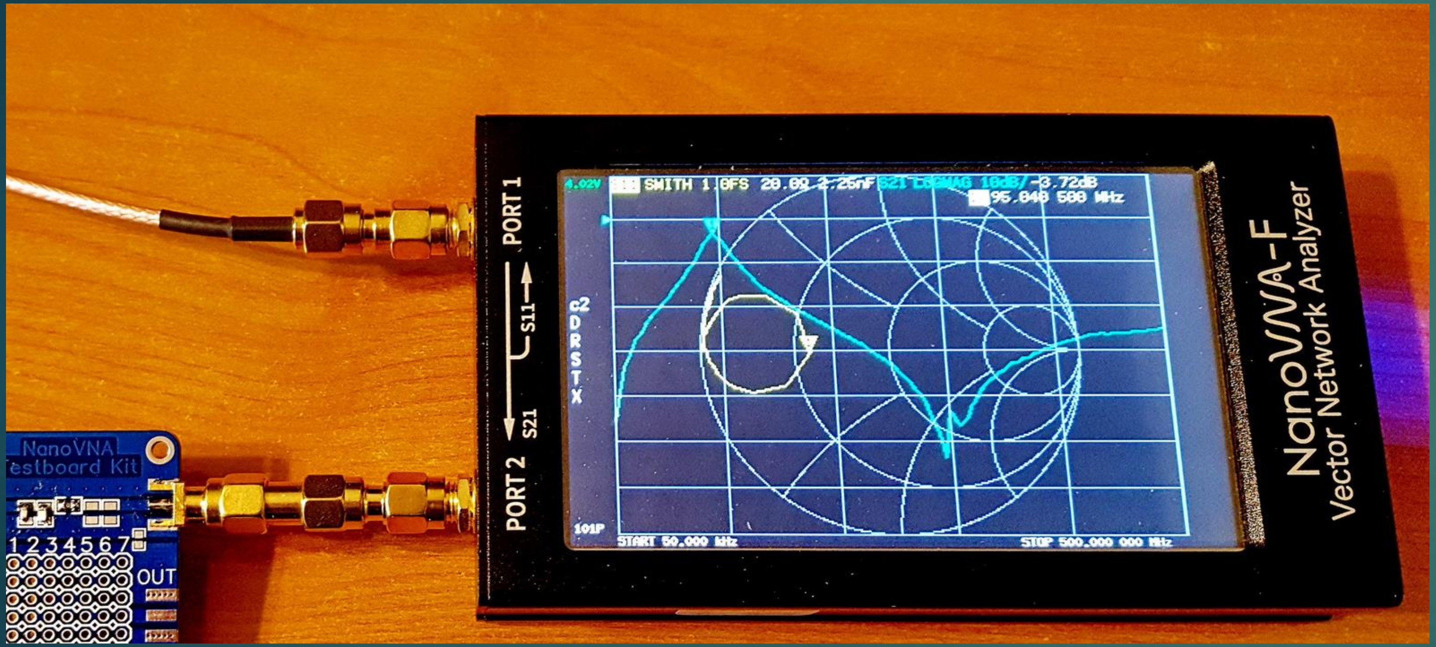
$$Q_{inductor} = \frac{4.12\ Ohms}{0.406\ Ohms} = 10$$

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

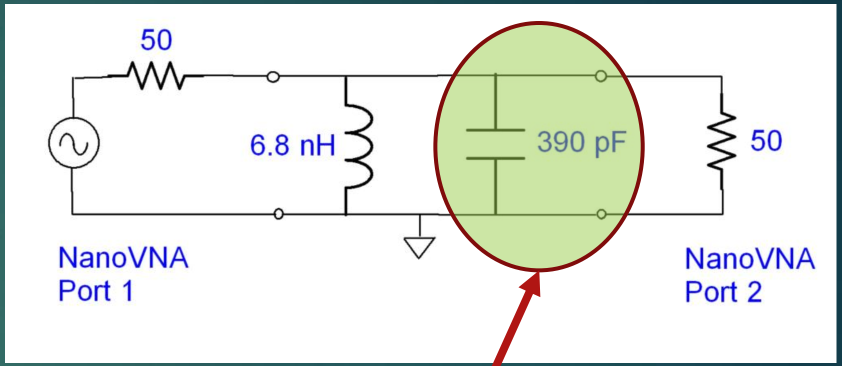
Not the ideal values of infinity !

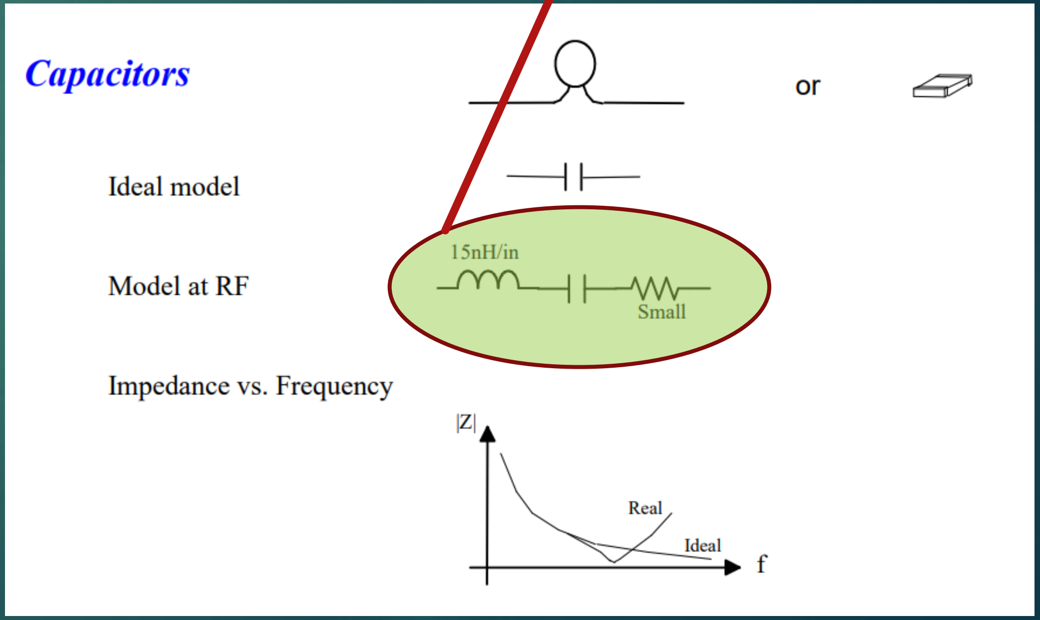
Capacitor Parasitics

- **Why does response go back up at high frequencies ?**



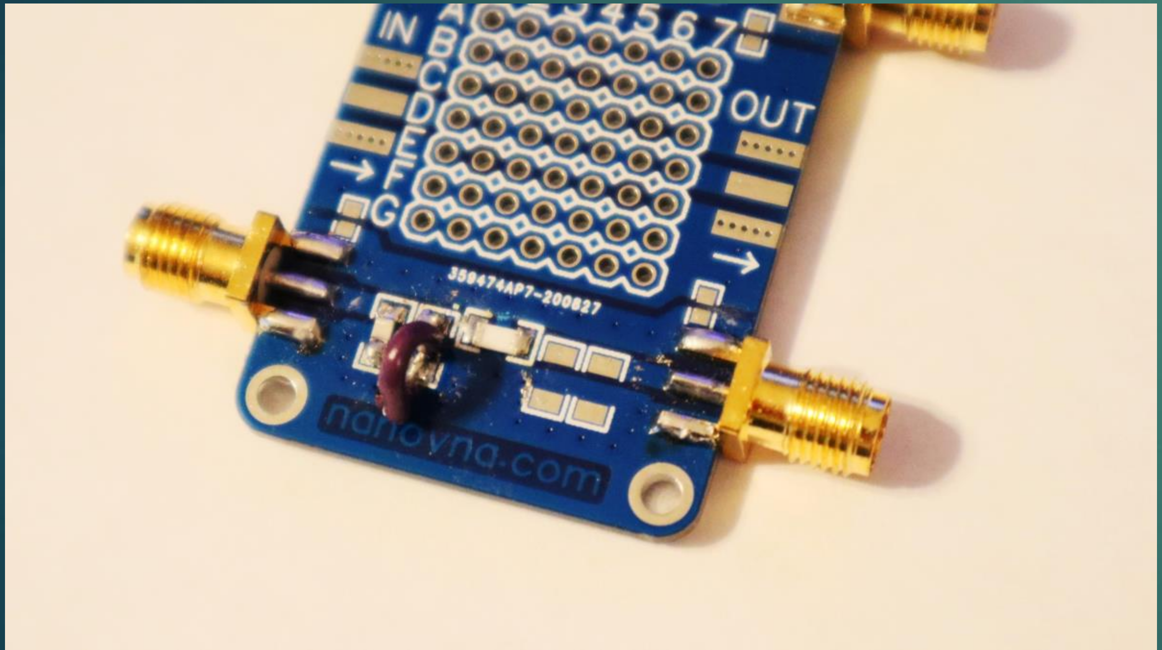
50 kHz to 500 MHz

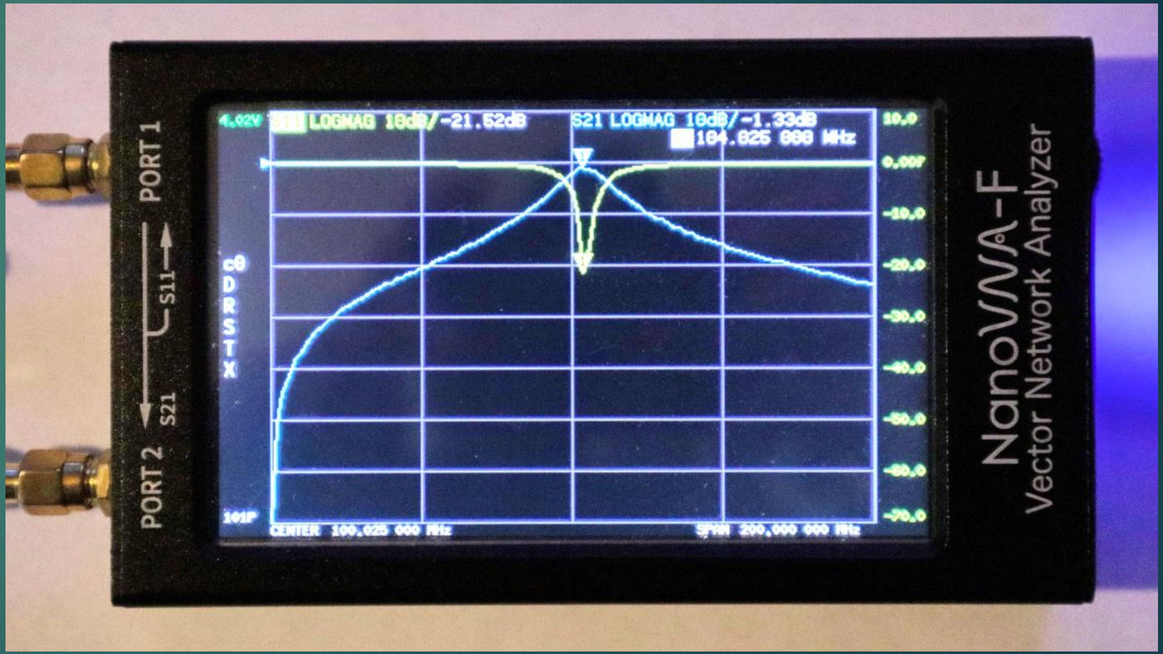




Filter Improvement

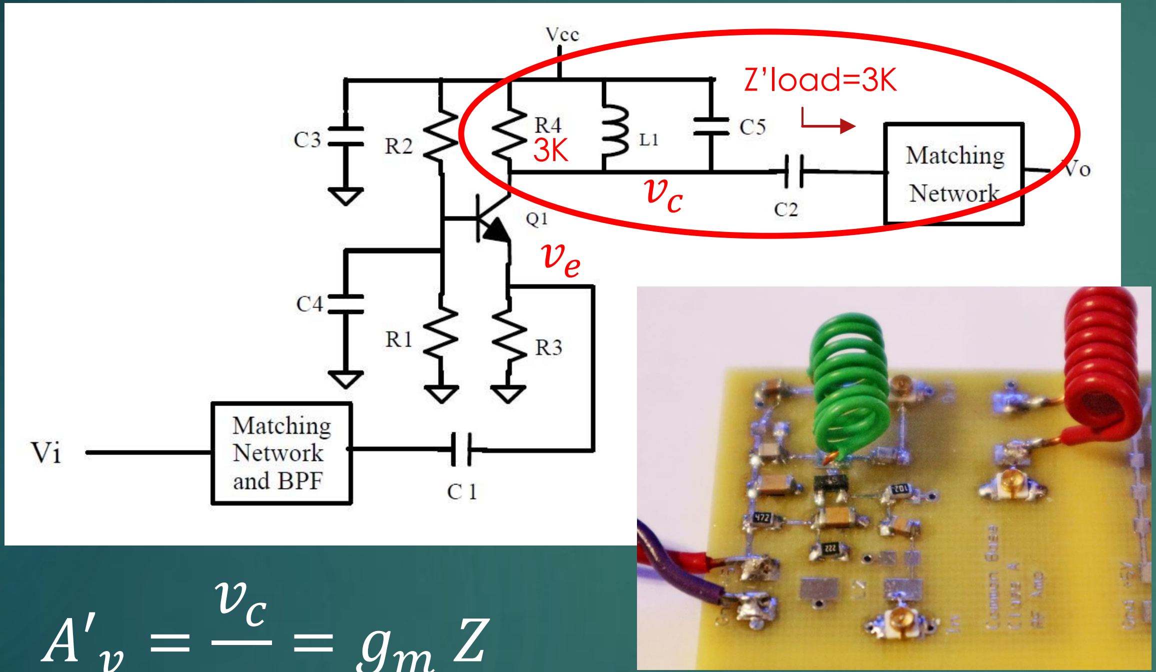
Use higher-Q inductor !





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



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

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

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

L = 160 nH C = 16 pF

$f_o = 100MHz \qquad X @ 100\ MHz = 100$

$R = 1.5K$ So Q = 1500/100 = 15

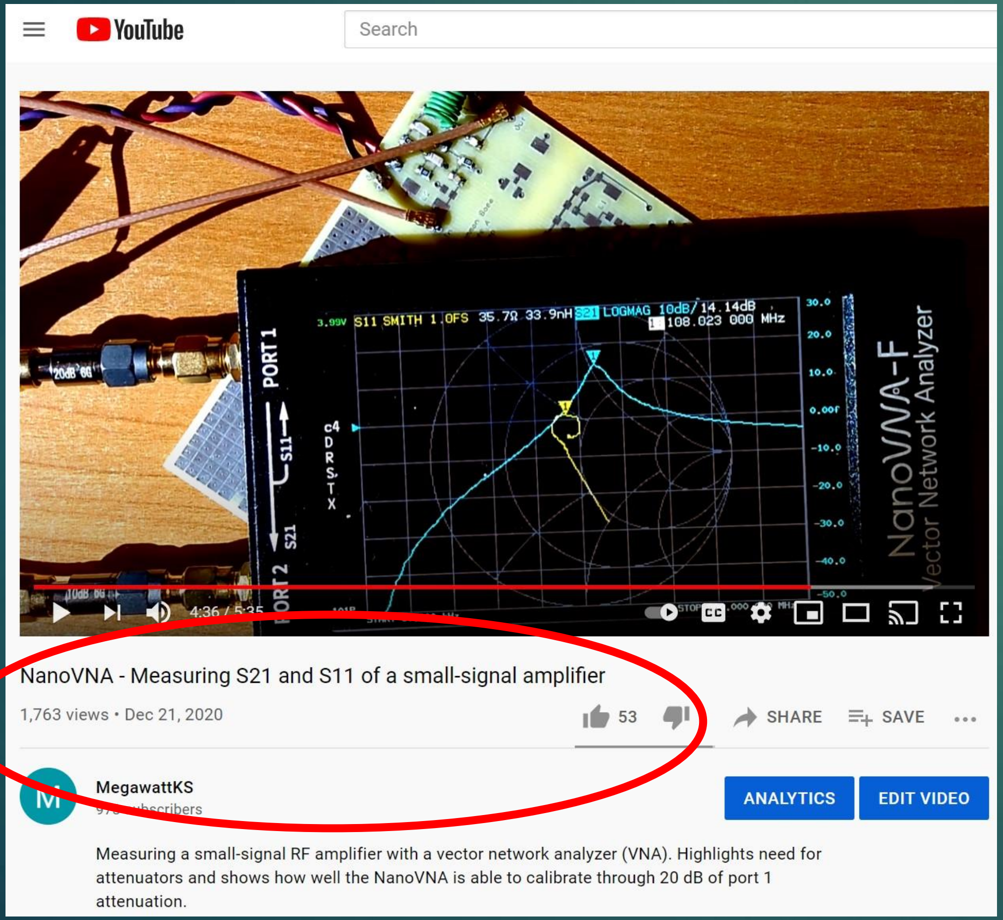
$So \ldots \quad B = \frac{100\ MHz}{15}$ = 6.7 MHz

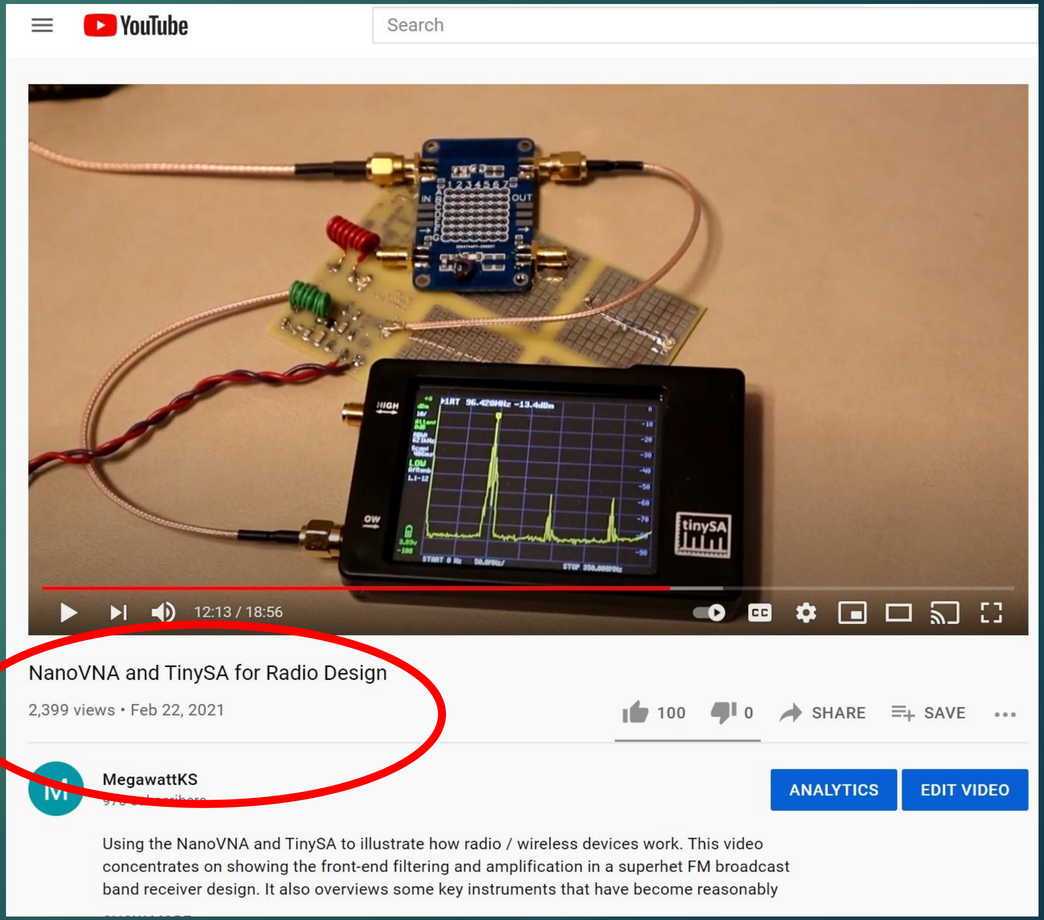
Take home assignment: ☺

Redesign for 98 MHz center
And 20 MHz bandwidth.
(How realizable is required inductor ?)

System Level Testing

Videos from the NanoVNA series…





Outline of This Video

Part 1

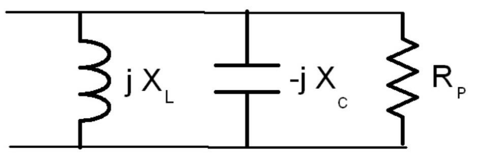
- *Transmitters and Receivers*
- *Impedances, Ohms Law, and Voltage dividers*
- *1-pole Filters (Lowpass and Bandpass)*

Part 2

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

Parallel vs Series Resonators

Parallel LC circuit

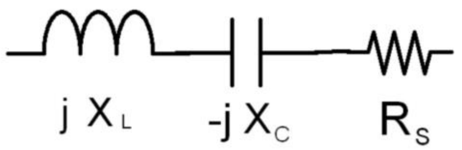


$$Z \rightarrow R_P \; @ \; f = f_o$$

$$Z \rightarrow 0 \quad for \quad f \rightarrow 0$$
$$Z \rightarrow 0 \quad for \quad f \rightarrow \infty$$

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

Series LC circuit



$$Z \rightarrow R_S \; @ \; f = f_o$$

$$Z \rightarrow \infty \quad for \quad f \rightarrow 0$$
$$Z \rightarrow \infty \quad for \quad f \rightarrow \infty$$

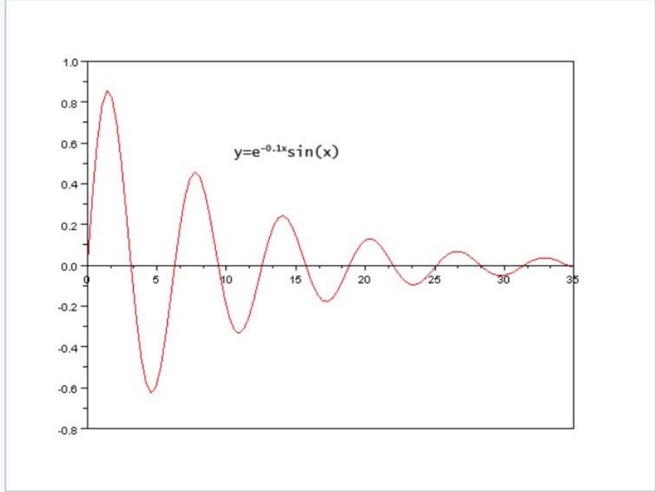
$$Q = \frac{X_o}{R_s}$$

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]

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

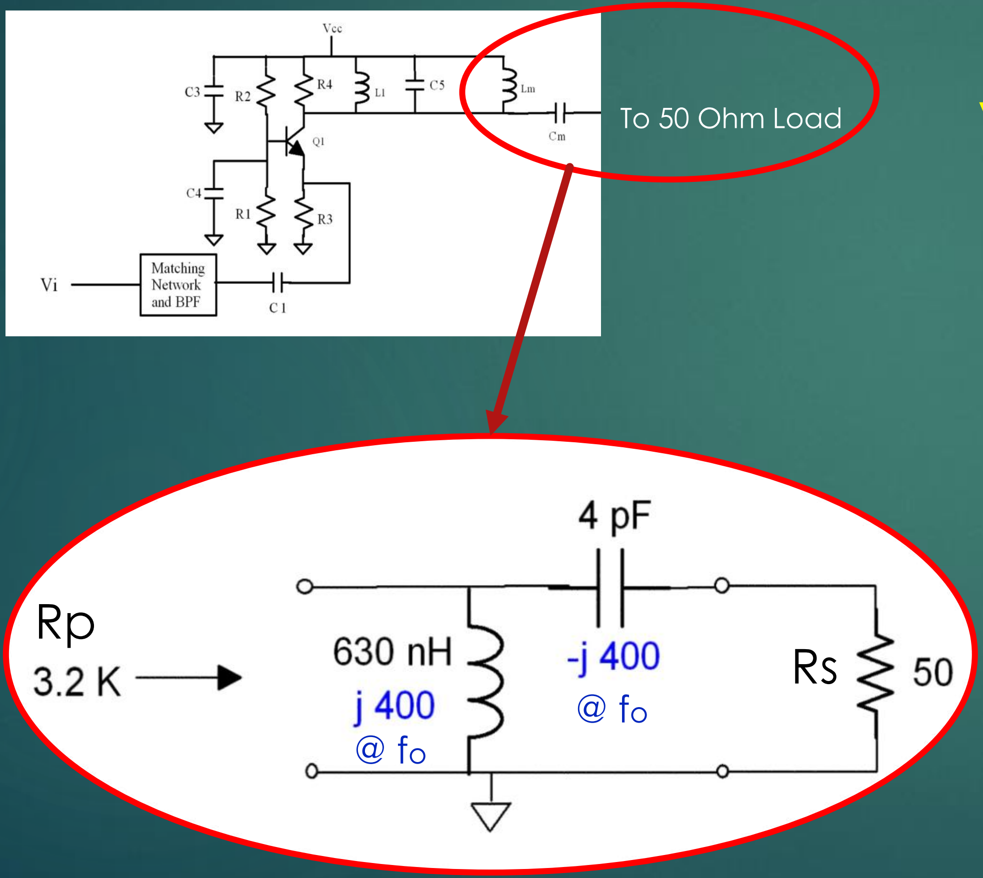


A damped oscillation. A low Q factor – about 5 here – means the oscillation dies out rapidly.

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):

$$Q = \frac{Xo}{Rs} = \frac{400}{50} = 8$$

Viewed from amplifier (parallel resonant circuit view):

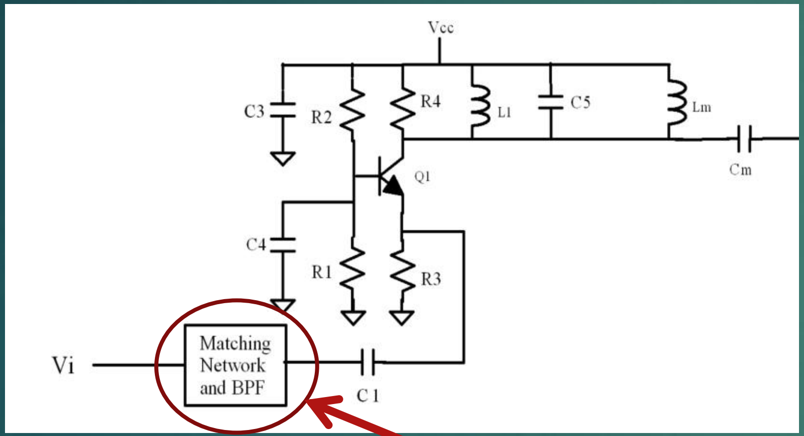
$$Q = 8 \quad and \quad Q = \frac{Rp}{Xo}$$

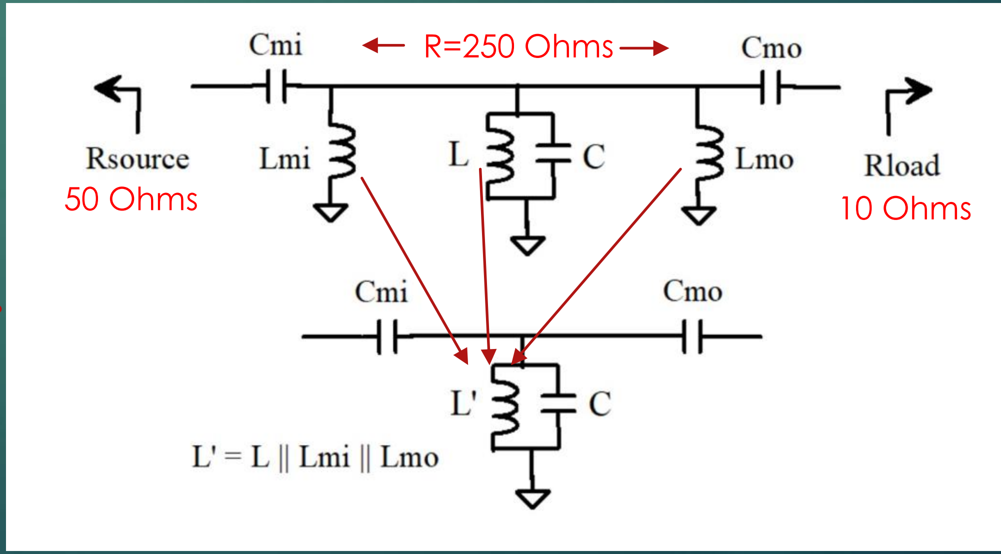
$$\Rightarrow \; Rp = Q\ Xo\ = Q^2\ Rs = 3.2\text{ K Ohms}$$

NOTES: This is approximate. In general: $Rp\ = (1+Q^2)\ Rs$
Only works well near resonant frequency fo

Matching Networks in Filters

Use matching networks to make filters more "realizable" and compatible with different source/load impedances…





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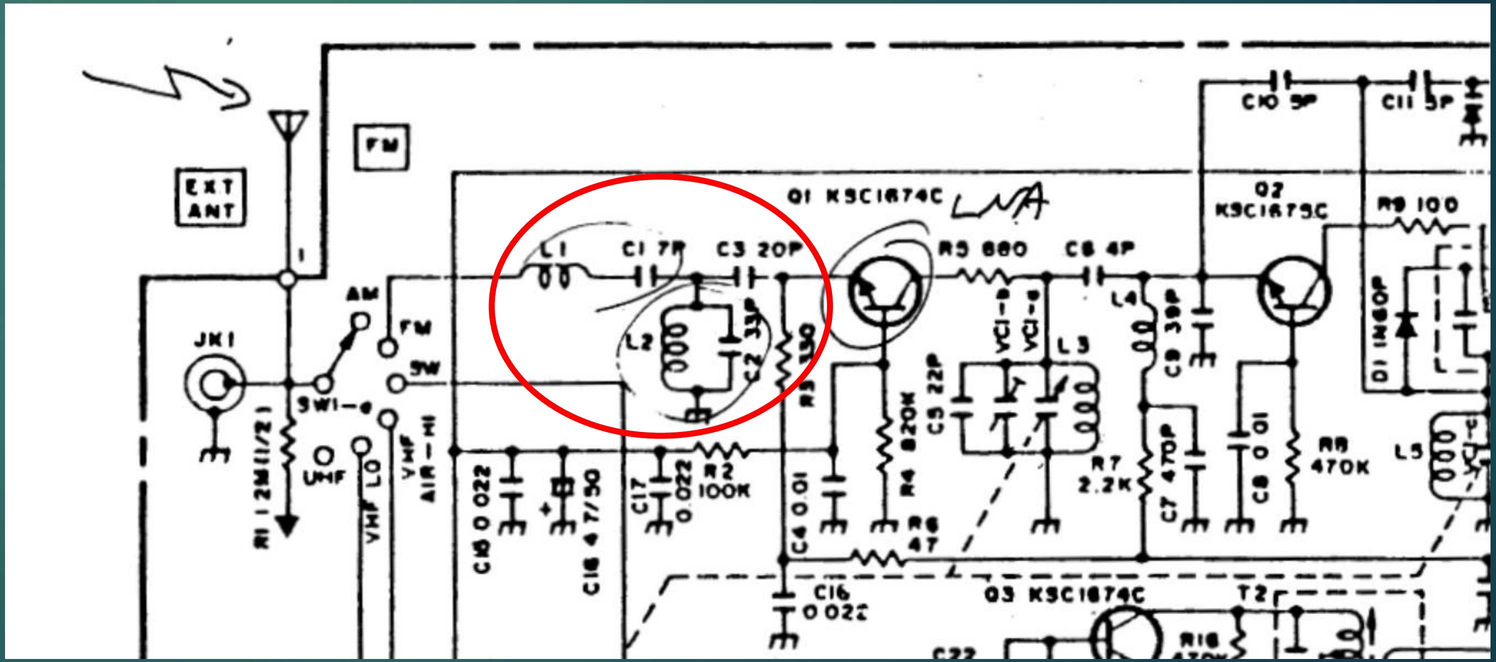
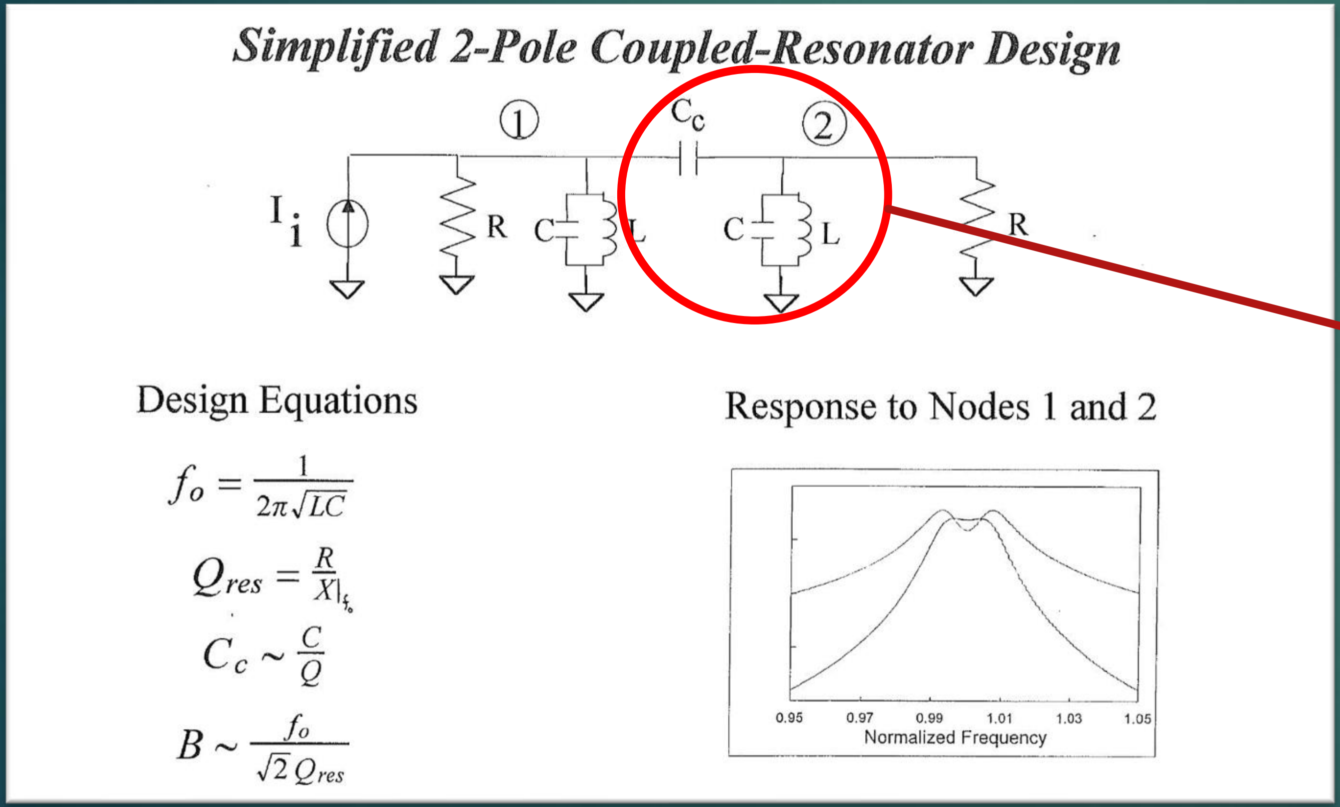
More Bandpass Filter Examples

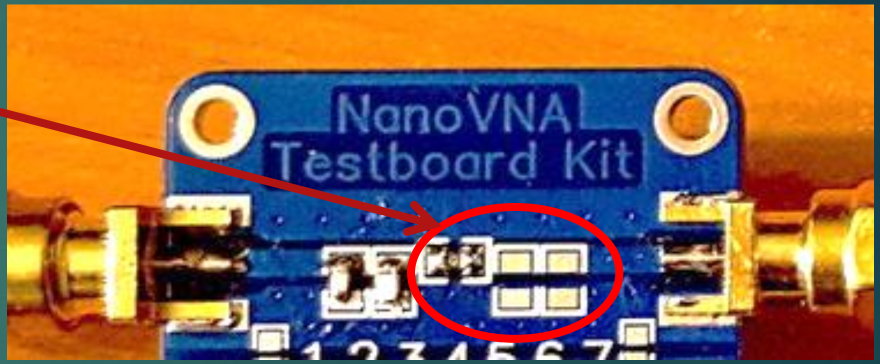
2-pole preselect BPF, plus matching



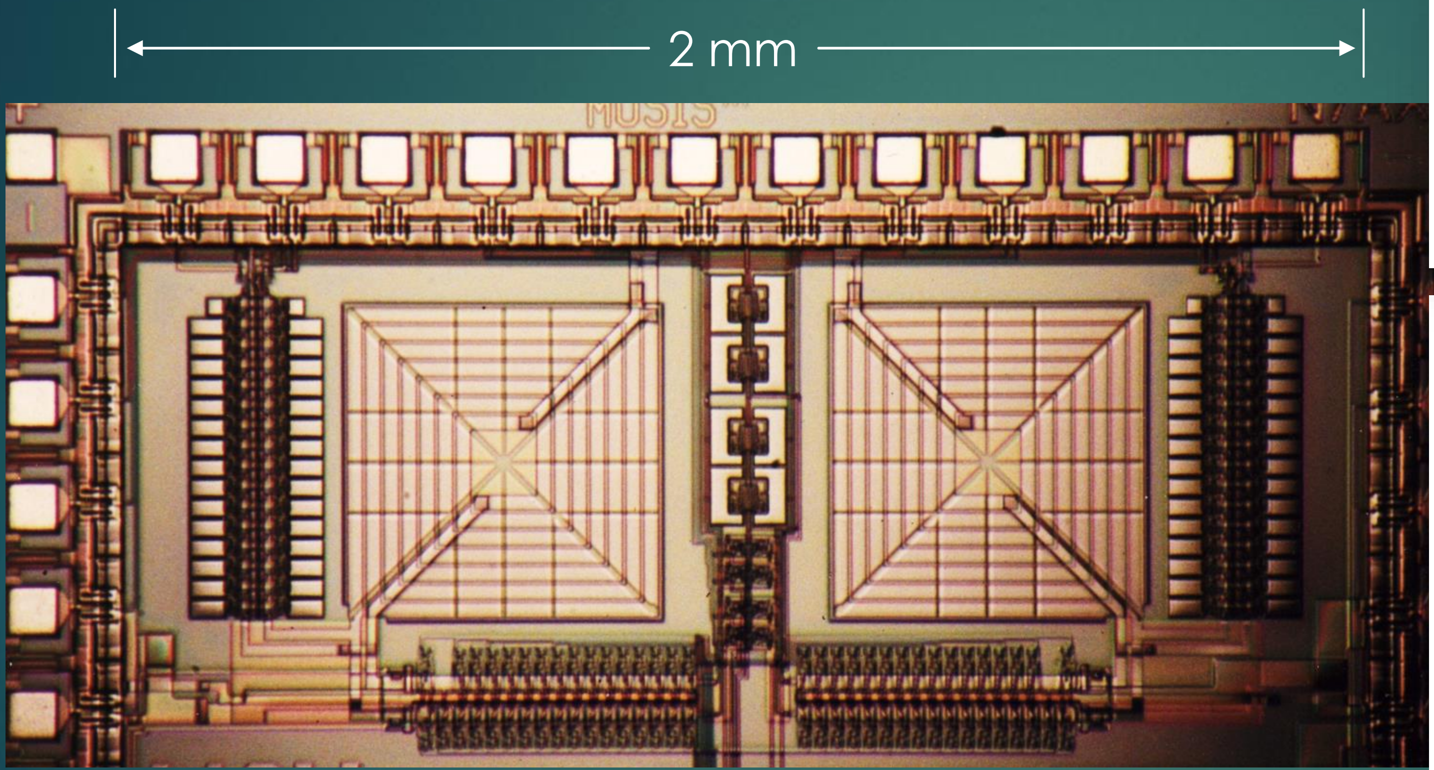
Coupled Resonator Designs



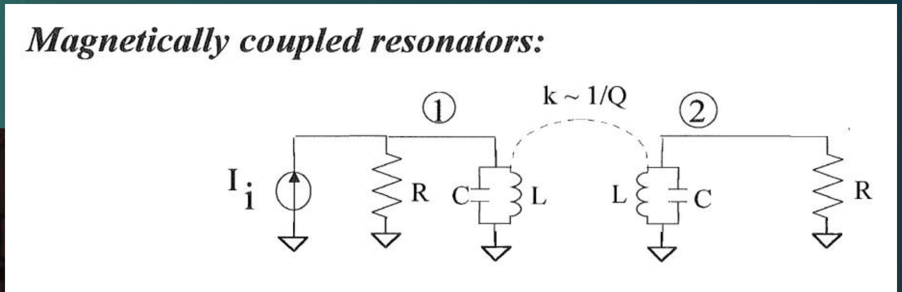
Just add a second identical LC resonator and swap 0 Ohm resistor with a small capacitor C_c



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



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



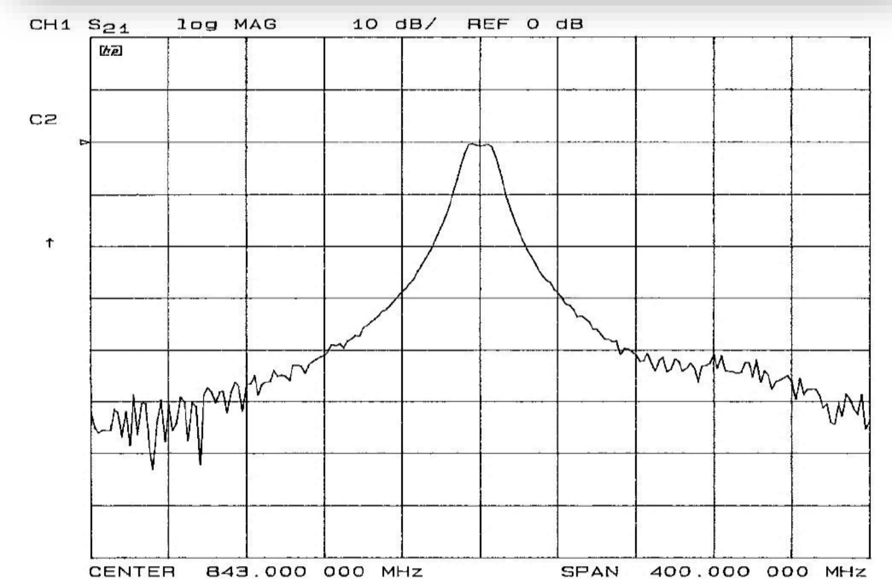
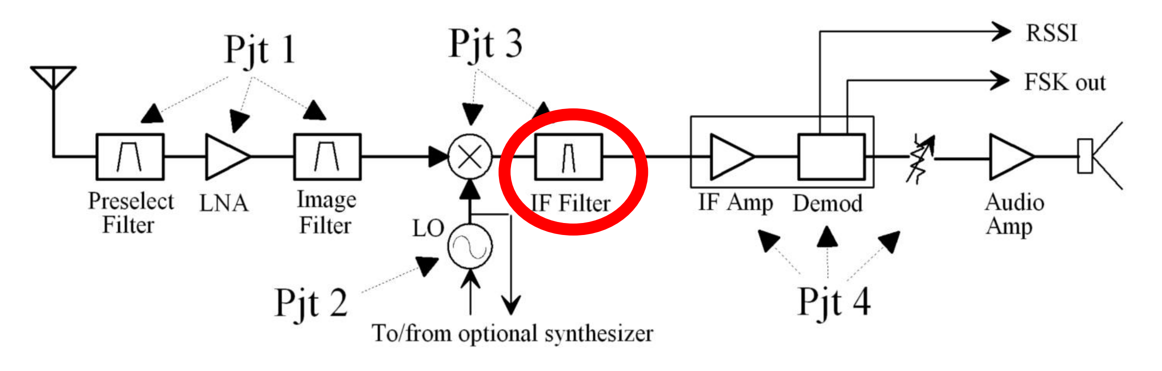
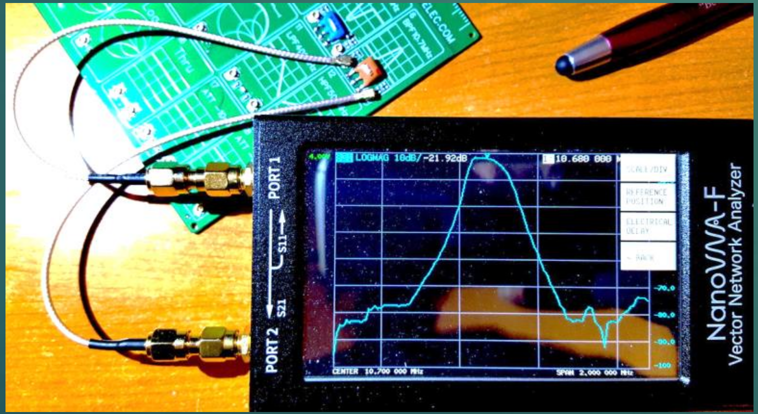


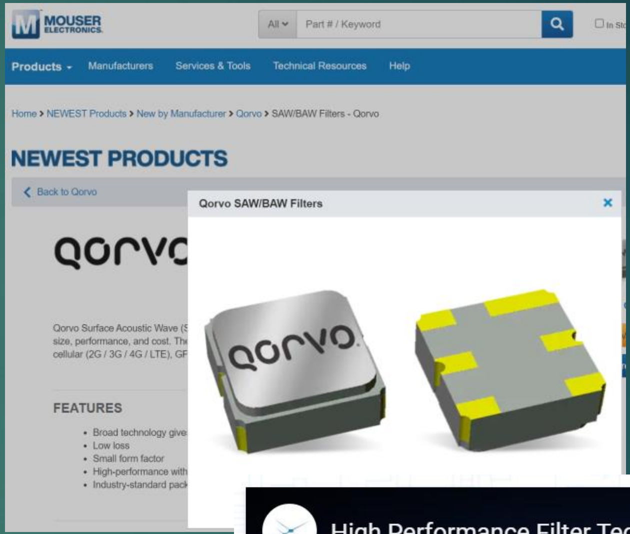
Fig. 9. Measured filter response: 843 MHz center, 10 dB/div vertical, 40 MHz/div horizontal.

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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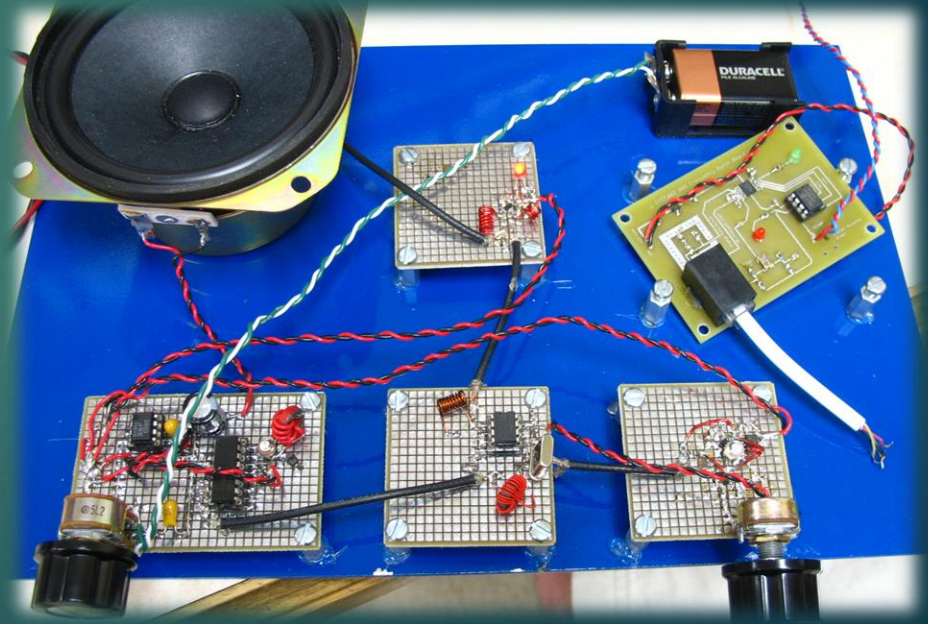
Possible Radio Design 101
Future Videos

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



Book Recommended in Class

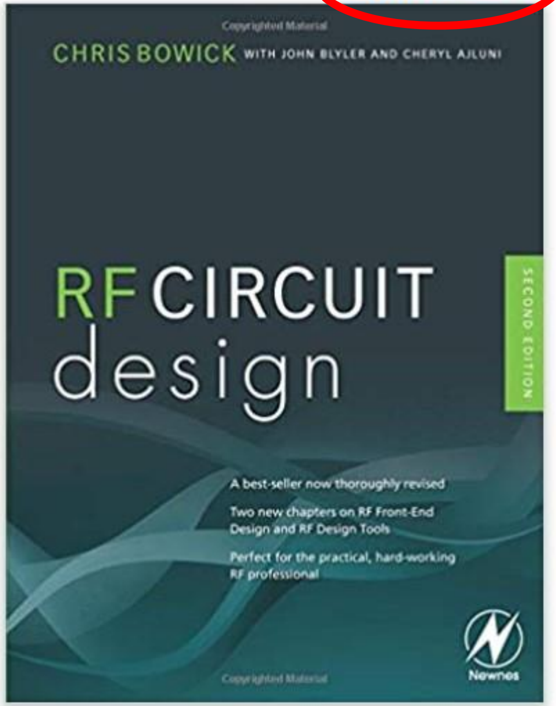
Books › Engineering & Transportation › Engineering

RF Circuit Design 2nd Edition

by Christopher Bowick (Author)

97 ratings

Look inside



Available Samples: Kindle | Paperback

Thanks For Watching !