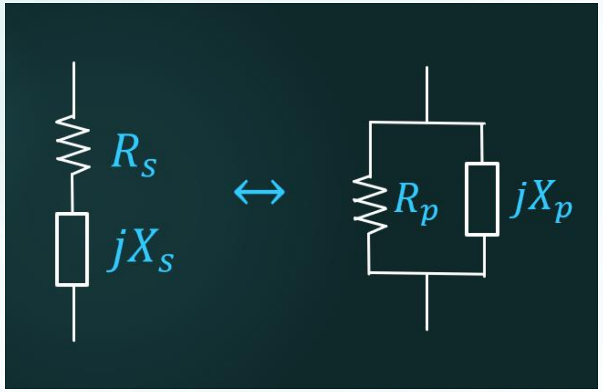
Radio Design 101
Appendix B - RF Impedance Conversions

Slides downloaded from: https://ecefiles.org/rf-design/
Companion video at: https://www.youtube.com/watch?v=vO-AJjIX7a4

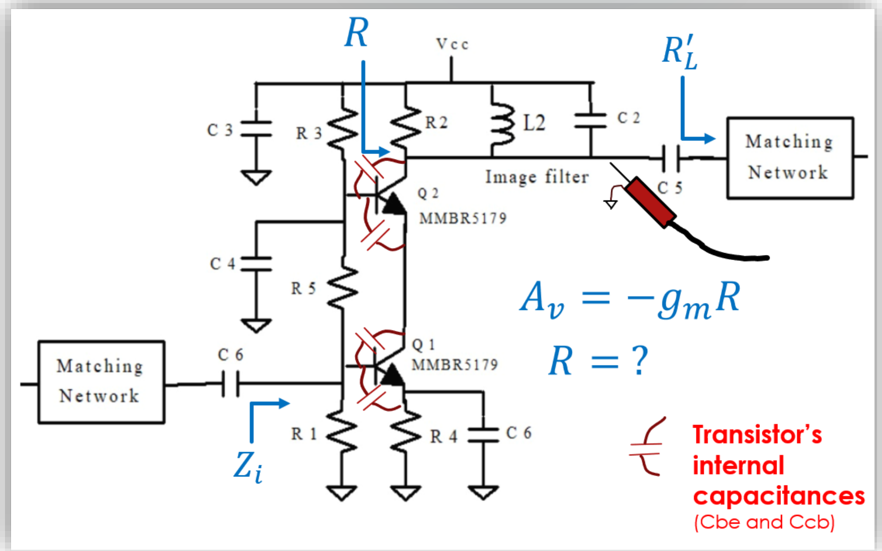
This video covers series to parallel impedance conversion, its use in matching networks, and in designing and measuring practical RF circuits. Example applications include understanding impedance values shown by RF test equipment and circuit simulations. In addition, an RF cascode amplifier is used to illustrate issues with real-world inductors, oscilloscope probes, and matching to complex impedance values.



$$R_p = (1 + q^2)R_s$$

$$X_p = \left(1 + \frac{1}{q^2}\right)X_s$$

$$\text{where} \quad q = \frac{X_s}{R_s} = \frac{R_p}{X_p}$$



$A_v = -g_m R$

$R = ?$

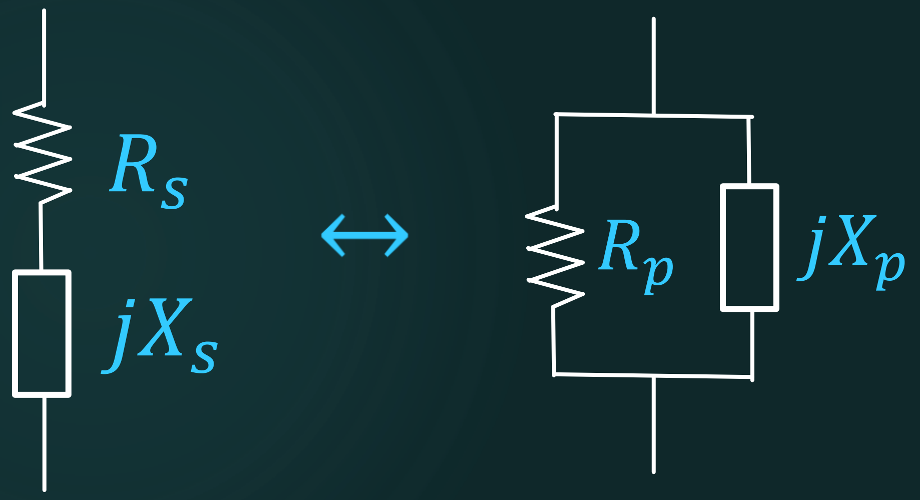
Transistor's internal capacitances (Cbe and Ccb)

Radio Design 101

Appendix B

RF Impedance Conversions

for Matching, Amplifiers, Simulation, and Measurements

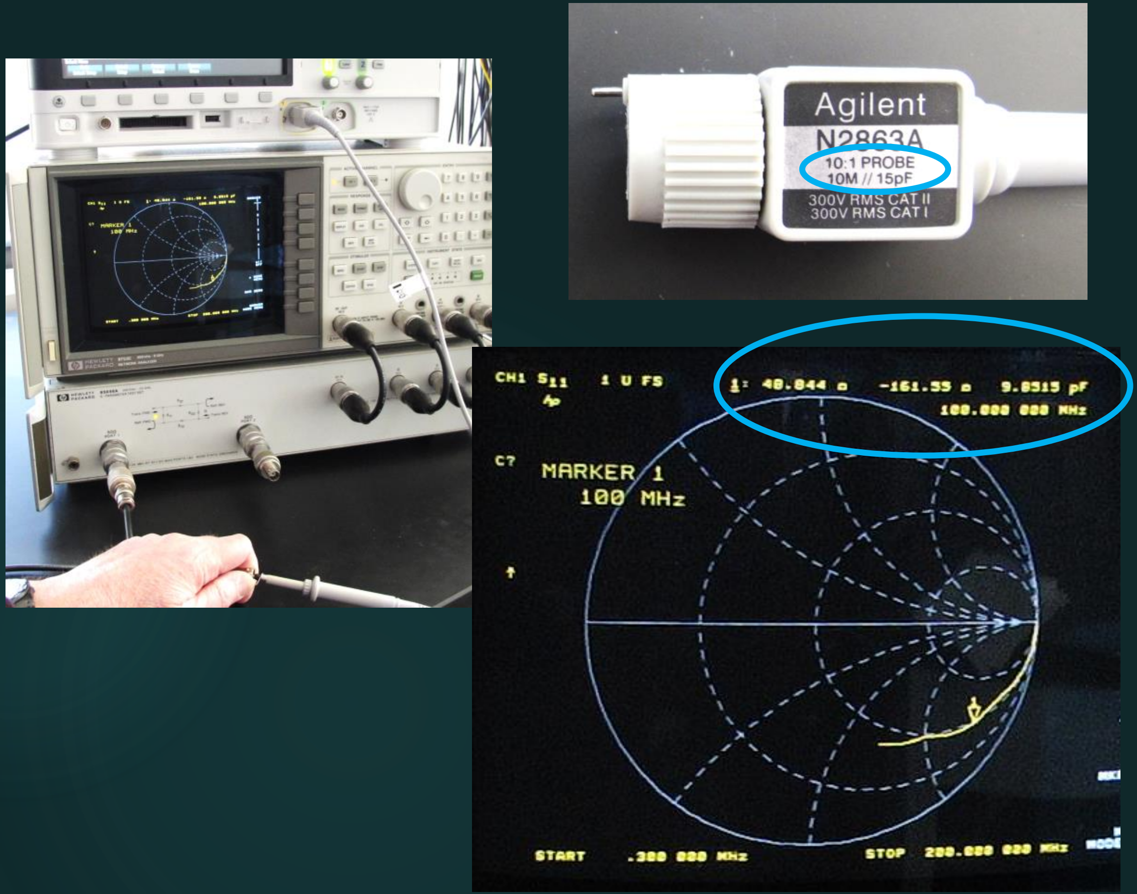


$$\boldsymbol{R_p = \left(1 + q^2\right) R_s}$$

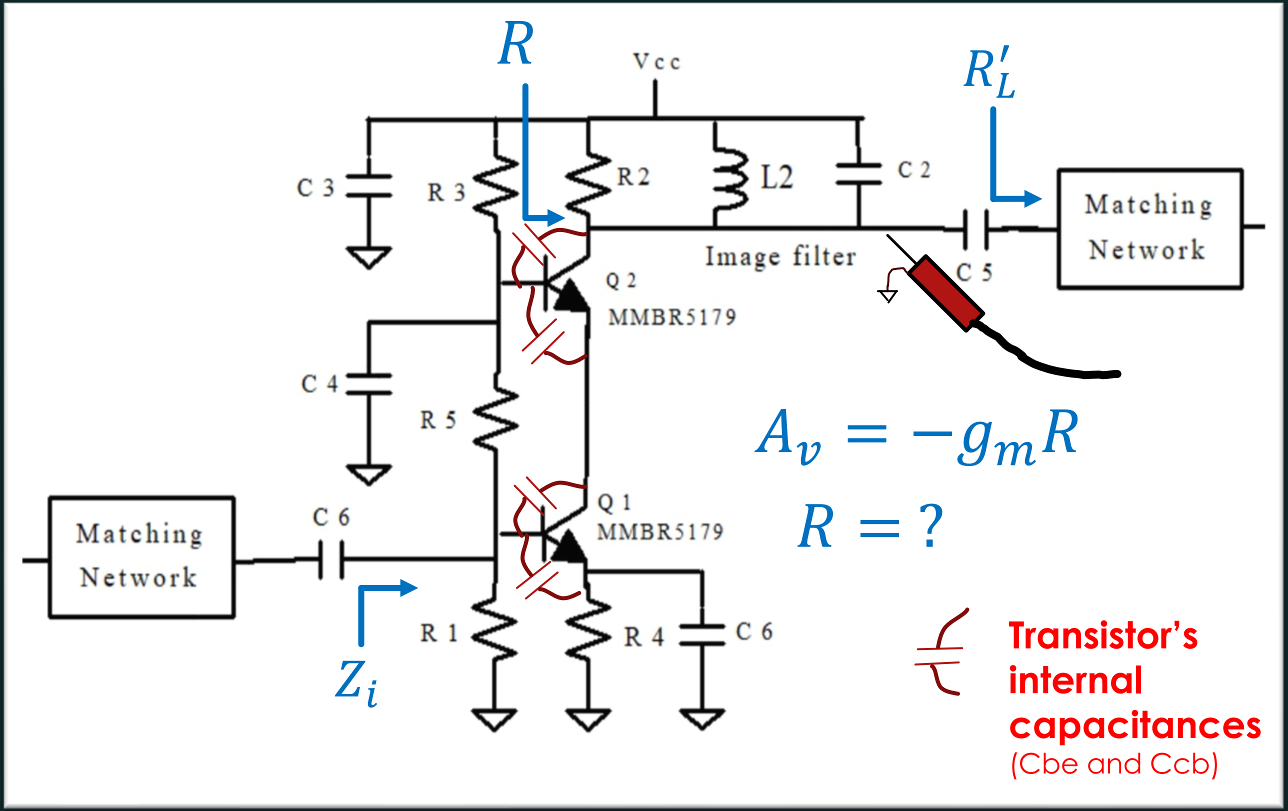
$$\boldsymbol{X_p = \left(1 + \frac{1}{q^2}\right) X_s}$$

where $q = \frac{X_s}{R_s} = \frac{R_p}{X_p}$

Applications



Series to Parallel Impedance Conversion



$$A_v = -g_m R$$

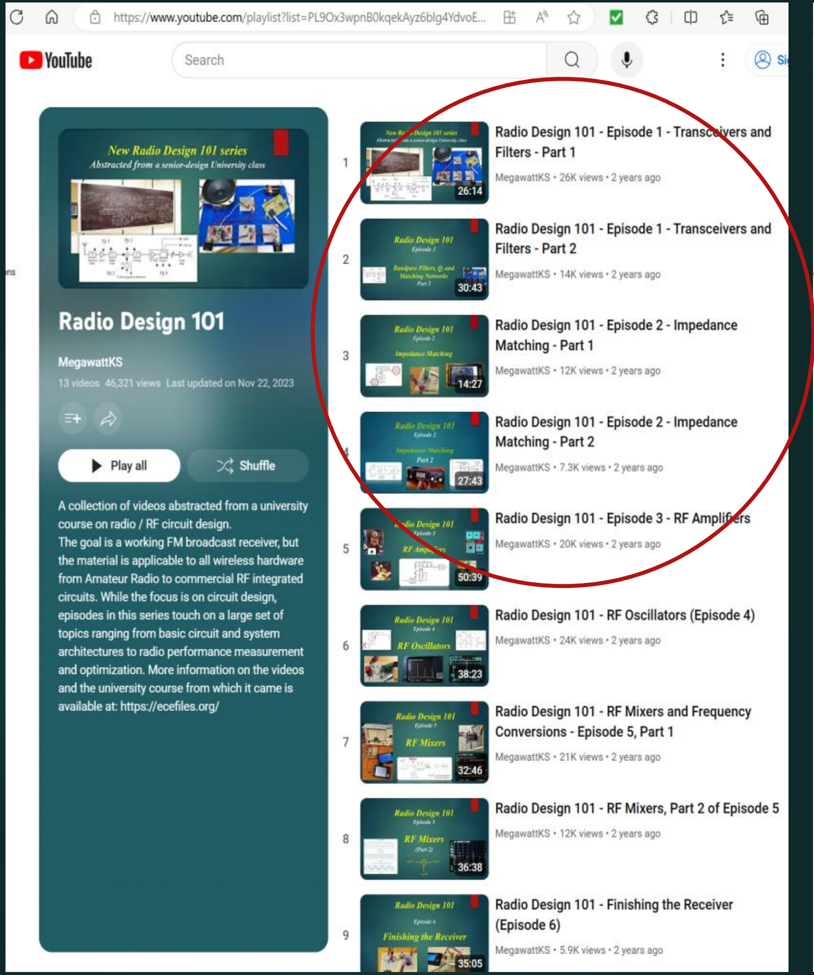
$$R = ?$$

Transistor's internal capacitances
(Cbe and Ccb)

Matching Networks & Amplifier Design

Lots more !

Background



Radio Design 101

MegawattKS

13 videos 46,321 views Last updated on Nov 22, 2023

A collection of videos abstracted from a university course on radio / RF circuit design.
The goal is a working FM broadcast receiver, but the material is applicable to all wireless hardware from Amateur Radio to commercial RF integrated circuits. While the focus is on circuit design, episodes in this series touch on a large set of topics ranging from basic circuit and system architectures to radio performance measurement and optimization. More information on the videos and the university course from which it came is available at: https://ecefiles.org/

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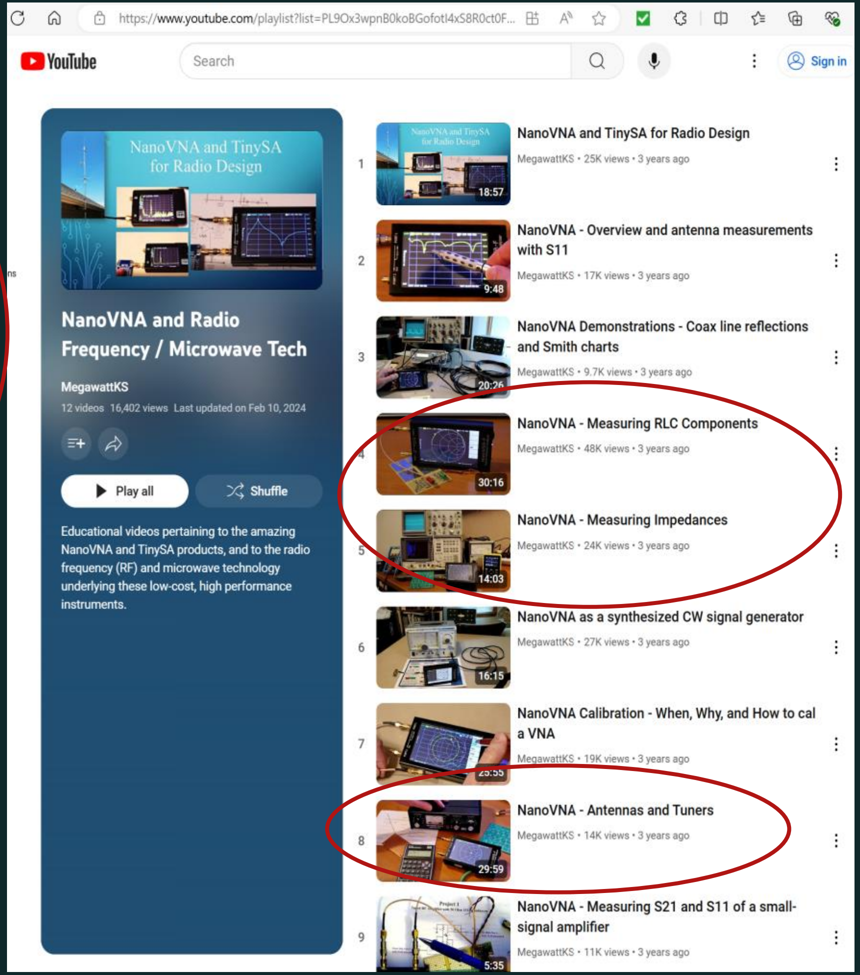

NanoVNA and Radio Frequency / Microwave Tech

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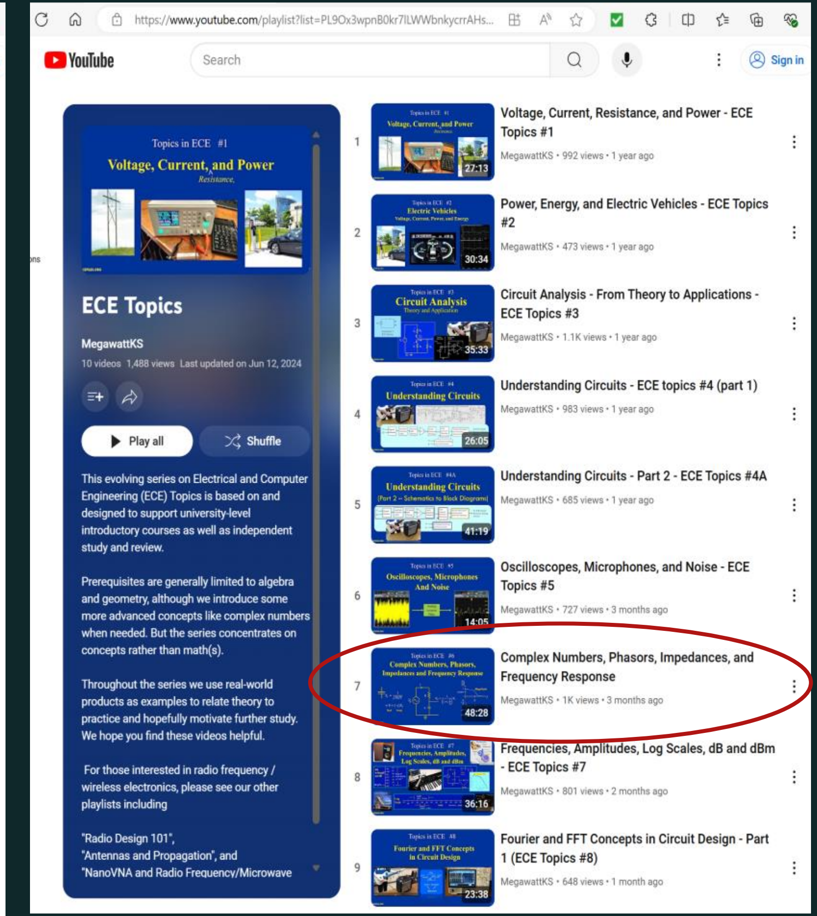

ECE Topics

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This evolving series on Electrical and Computer Engineering (ECE) Topics is based on and designed to support university-level introductory courses as well as independent study and review.

Prerequisites are generally limited to algebra and geometry, although we introduce some more advanced concepts like complex numbers when needed. But the series concentrates on concepts rather than math(s).

Throughout the series we use real-world products as examples to relate theory to practice and hopefully motivate further study. We hope you find these videos helpful.

For those interested in radio frequency / wireless electronics, please see our other playlists including

"Radio Design 101",
"Antennas and Propagation", and
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Associated website: https://ecefiles.org/

R L C Impedances

$Z = R$

$Z = jX_L$

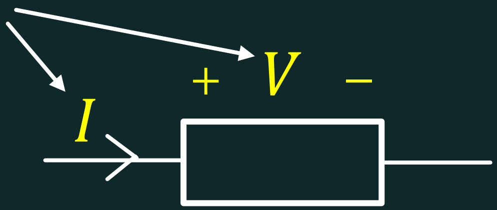
$$X_L = 2\pi f L$$

$Z = -jX_C$

$$X_C = \frac{1}{2\pi f C}$$

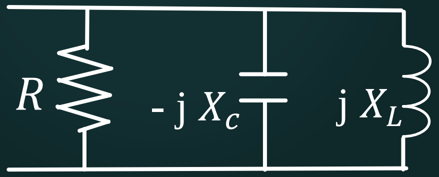
$$\boldsymbol{Z = R + jX}$$

Phasors



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

$Z = R - jX_C + \mathrm{j}\,X_L$



$Z = R \parallel -jX_C \parallel \mathrm{j}\,X_L$

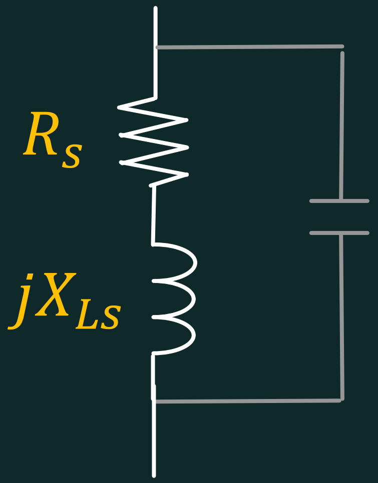
$$f_o = \frac{1}{2\pi\sqrt{LC}} \qquad BW = \frac{f_o}{Q}$$

$$Q_s = \frac{X_s}{R_s} \qquad Q_p = \frac{R_p}{X_p}$$

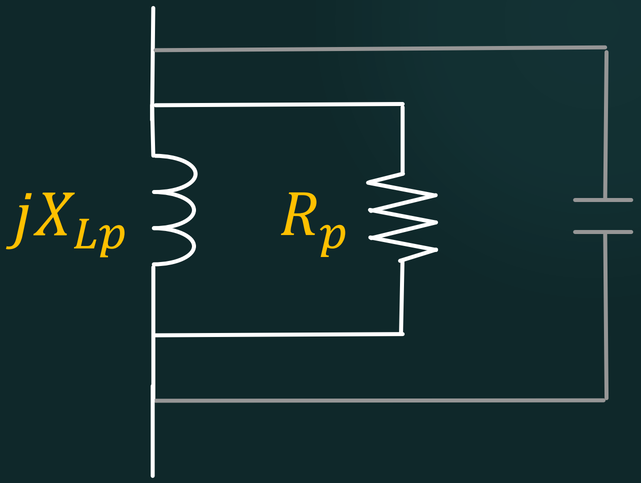
Real-World Components at RF

Ideal

Real-World (Simplified Models)



Series
Loss Resistance

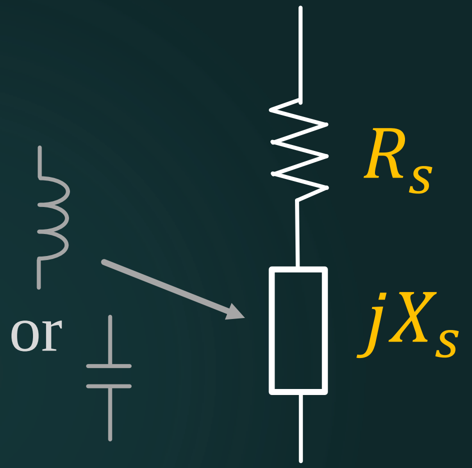


Parallel
Loss Resistance

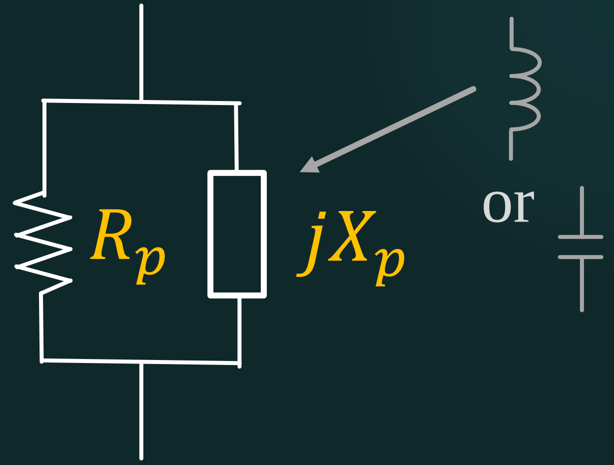
Theorem

At a specific frequency, an impedance $Z = R + jX$ can be realized in a series form or a parallel form:

Series form:



Parallel form:



NOTE: At the specific frequency (say f_o), these two realizations are *equivalent* – they will yield the same circuit behavior and can be swapped to make circuit analysis/design/production easier/cheaper …

(Constructive) **Proof**

Series form is trivial: $R + jX = R_s + jX_s$

Parallel form is ***messy***: $R + jX = R_p \parallel jX_p$

$$R_p \parallel jX_p = \frac{(R_p)(jX_p)}{(R_p+jX_p)} = \frac{(R_p)(jX_p)}{(R_p+jX_p)}\frac{(R_p-jX_p)}{(R_p-jX_p)} = \frac{R_p^2(jX_p) + R_p(X_p^2)}{R_p^2 + X_p^2} = R_p\frac{X_p^2}{R_p^2+X_p^2} + jX_p\frac{R_p^2}{R_p^2+X_p^2}$$

So, $R + jX = R_s + jX_s = R_p\frac{X_p^2}{R_p^2+X_p^2} + jX_p\frac{R_p^2}{R_p^2+X_p^2}$

And, hence…

$$R_s = R_p\frac{X_p^2}{R_p^2+X_p^2} \qquad X_s = X_p\frac{R_p^2}{R_p^2+X_p^2}$$

Cleaning up *(and solving for* R_p, X_p *)*

Define a quality factor $\boldsymbol{q} = {}^{\boldsymbol{R_p}}\!/\!_{\boldsymbol{X_p}}$

Then

$$R_s = R_p \frac{X_p^2}{R_p^2 + X_p^2} \left(\frac{{}^{1}\!/\!_{X_p^2}}{{}^{1}\!/\!_{X_p^2}} \right) = R_p \frac{1}{q^2+1}$$

And

$$X_s = X_p \frac{R_p^2}{R_p^2 + X_p^2} \left(\frac{{}^{1}\!/\!_{X_p^2}}{{}^{1}\!/\!_{X_p^2}} \right) = X_p \frac{q^2}{q^2+1}$$

Re-arranging yields …

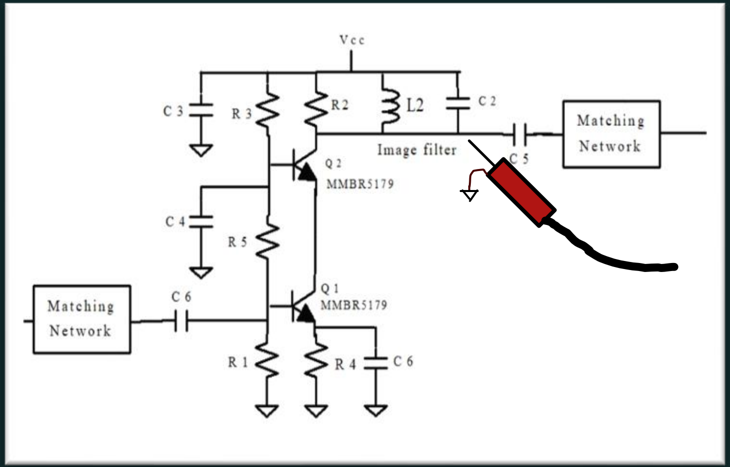
$$\boldsymbol{R_p = (1 + q^2) R_s}$$

$$\boldsymbol{X_p = \frac{q^2 + 1}{q^2} X_s = \left(1 + \frac{1}{q^2}\right) X_s}$$

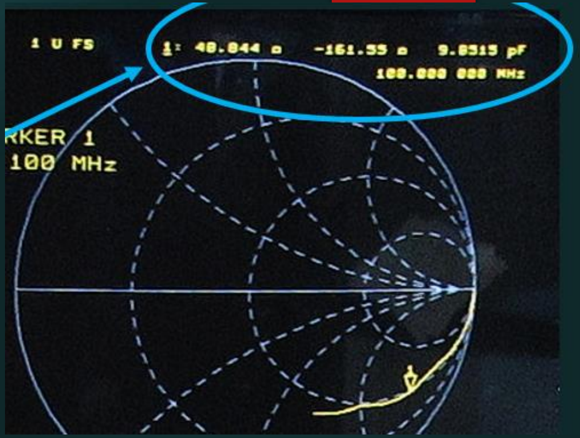
NOTE: It can also be shown that

$$q = {}^{X_s}\!/\!_{R_s}$$

The proof is left as an exercise for the reader ;-)

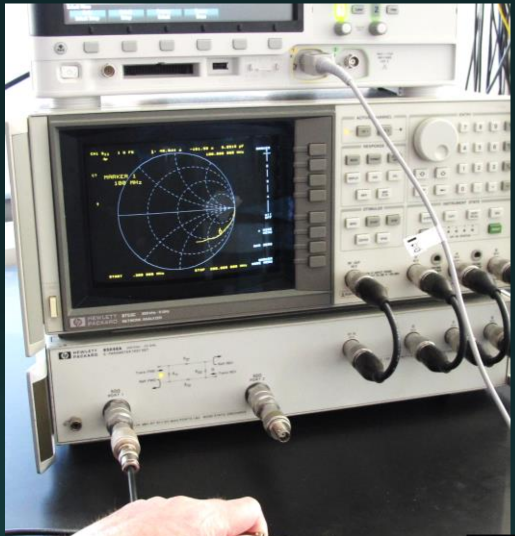


Applications



1. Convert series-form simulation or measurement results to parallel form, to better understand effects on circuit
2. Derive / understand impedance matching networks
3. Quantify real-world inductor and capacitor parasitics
4. Design RF amplifiers !

Convert Series Z to Parallel Form



Measured loading of probe **at 100 MHz** in series form is:

$$Z_{meas} = 48 - j\,161$$

$$q = \frac{161}{48} = 3.35$$

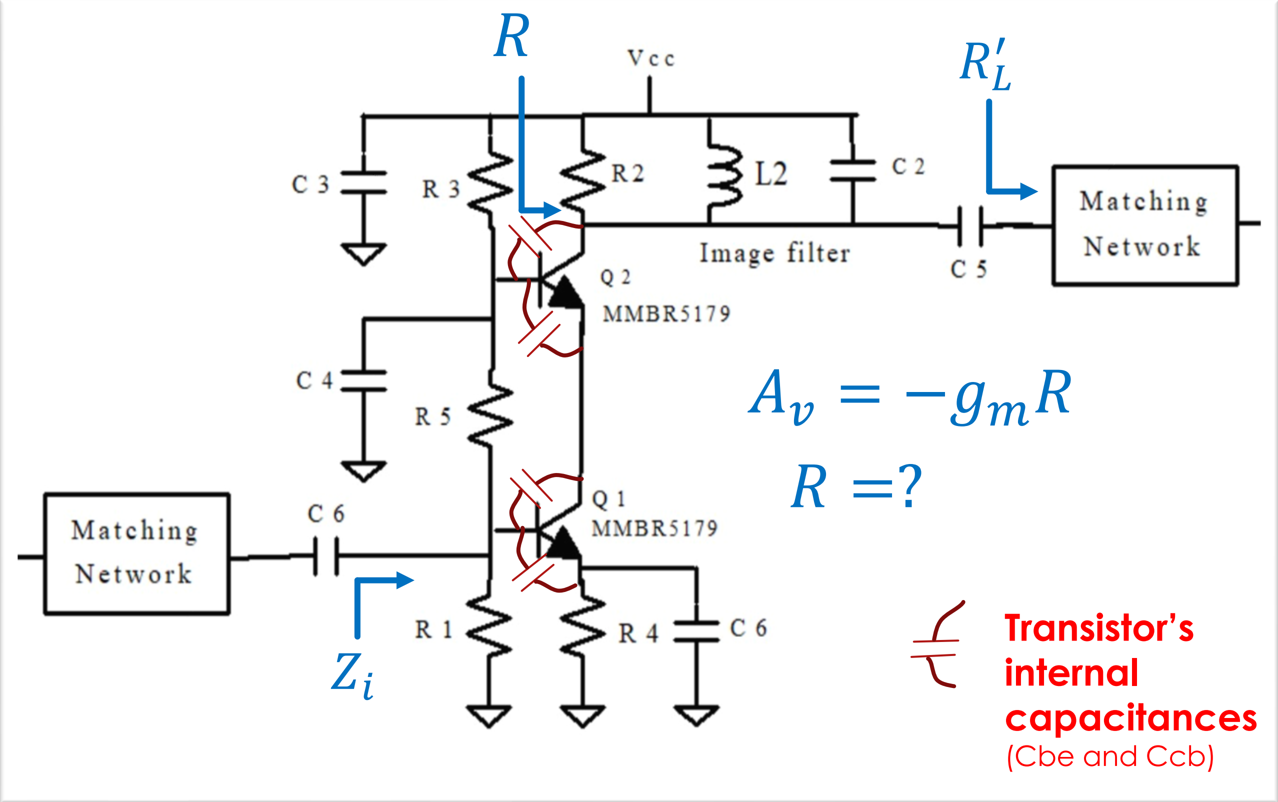
$$R_p = (1 + 3.35^2)48 = 588\,! \quad (not\ 10\ M)$$

$$X_p = \left(1 + \frac{1}{3.35^2}\right)161 = 175$$

$$C_p = \frac{1}{2\pi f X_p} = 9.1pF \quad (a\ bit\ less\ than\ 15p)$$

What is
48 – j 161
in parallel form ?

Real-World Inductors



$$A_v = -g_m R$$

$$R = ?$$

Transistor's internal capacitances
(Cbe and Ccb)

Assume L2, C2+C_{cb} resonate at 100 MHz,

Suppose R2 = 3K and gm=20mA/V

Then, for matched load ($R'_L = 3K$), we *should* have R = 1.5K and Av= -30 V/V (29.5 dB)
if L2 is ideal

Practical inductors have Q from 10 to 100, depending on size, construction.

Suppose L2 is 100 nH ($X_L = 63\ Ohms\ \ @\ 100\ MHz$)

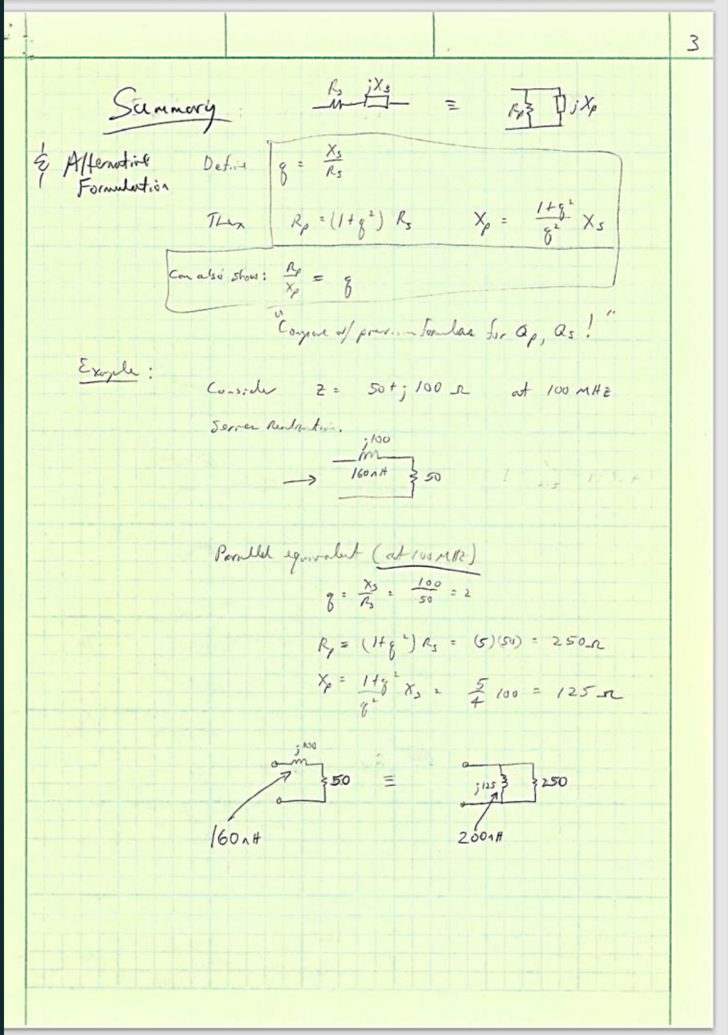
If Q of L2 is 10, then

$R_s = 6.3,$ and

$R_p = (1+10^2)6.3 = 636\ Ohms$

and R falls to 447 and Av falls to 8.9 V/V (19 dB) !

L Matching Network Design



3

Summary

$R_s + jX_s \equiv R_p \parallel jX_p$

& Alternative Formulation

Define $q = \frac{X_s}{R_s}$

Then $R_p = (1+q^2)\,R_s \qquad X_p = \frac{1+q^2}{q^2}\,X_s$

Can also show: $\frac{R_p}{X_p} = q$

"Compare w/ previous formulas for Q_p, Q_s!"

Example:

Consider $Z = 50 + j100\ \Omega$ at 100 MHz

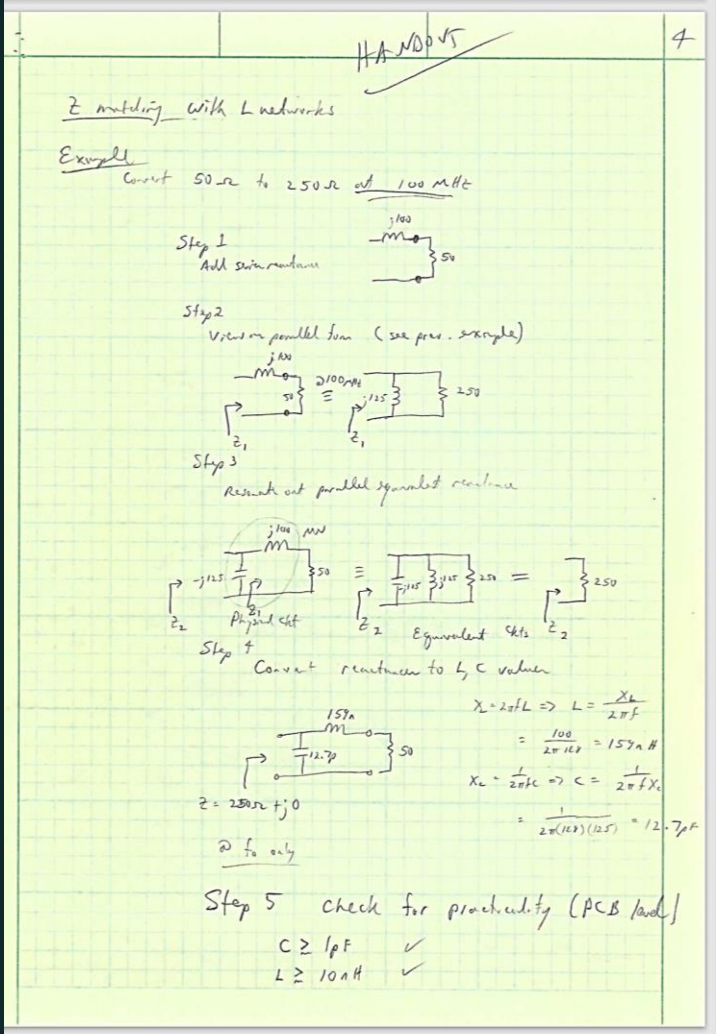
Series Realization.

Parallel equivalent (at 100 MHz)

$q = \frac{X_s}{R_s} = \frac{100}{50} = 2$

$R_p = (1+q^2)\,R_s = (5)(50) = 250\ \Omega$

$X_p = \frac{1+q^2}{q^2}\,X_s = \frac{5}{4}\,100 = 125\ \Omega$



4

HANDOUT

Z matching with L networks

Example

Convert 50 Ω to 250 Ω at 100 MHz

Step 1
Add series reactance

Step 2
View in parallel form (see prev. example)

Step 3
Resonate out parallel equivalent reactance

Physical ckt

Equivalent ckts

Step 4
Convert reactances to L, C values

$X_L = 2\pi f L \Rightarrow L = \frac{X_L}{2\pi f}$

$= \frac{100}{2\pi\, 1E8} = 159\,nH$

$X_C = \frac{1}{2\pi f C} \Rightarrow C = \frac{1}{2\pi f X_C}$

$= \frac{1}{2\pi (1E8)(125)} = 12.7\,pF$

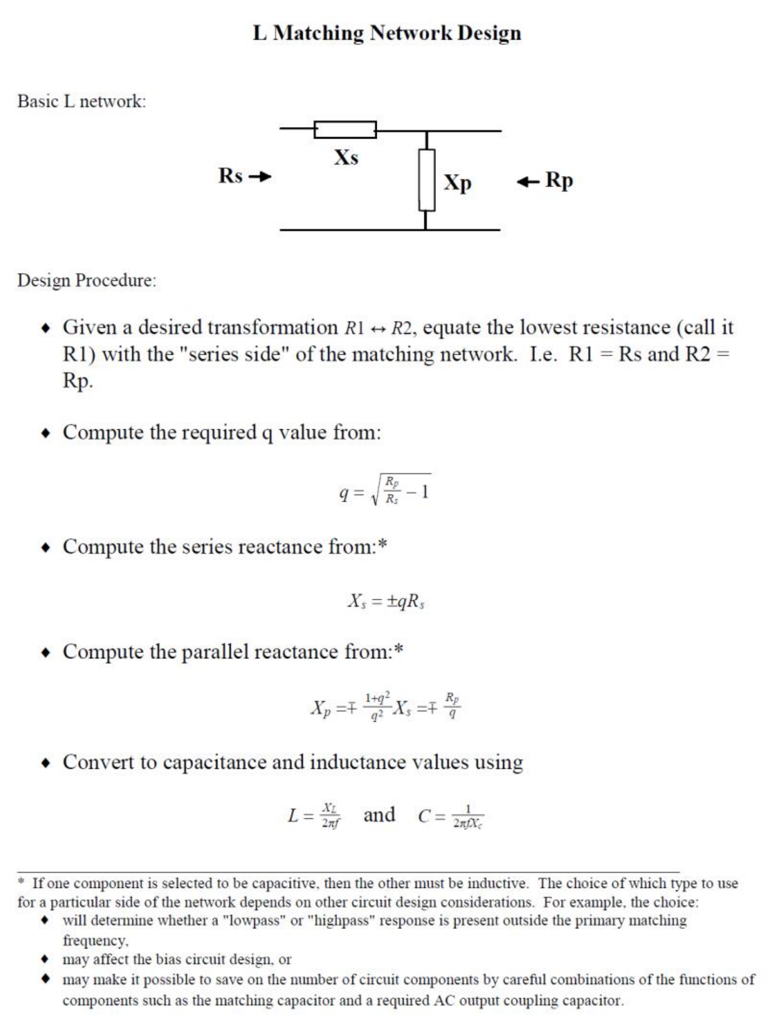
$Z = 250\ \Omega + j0$

@ f_0 only

Step 5 check for practicality (PCB level)

$C \gtrsim 1\,pF$ ✓

$L \gtrsim 10\,nH$ ✓



L Matching Network Design

Basic L network:

Design Procedure:

- Given a desired transformation $R1 \leftrightarrow R2$, equate the lowest resistance (call it R1) with the "series side" of the matching network. I.e. R1 = Rs and R2 = Rp.
- Compute the required q value from:

$$q = \sqrt{\frac{R_p}{R_s} - 1}$$

- Compute the series reactance from:*

$$X_s = \pm q R_s$$

- Compute the parallel reactance from:*

$$X_p = \mp \frac{1+q^2}{q^2} X_s = \mp \frac{R_p}{q}$$

- Convert to capacitance and inductance values using

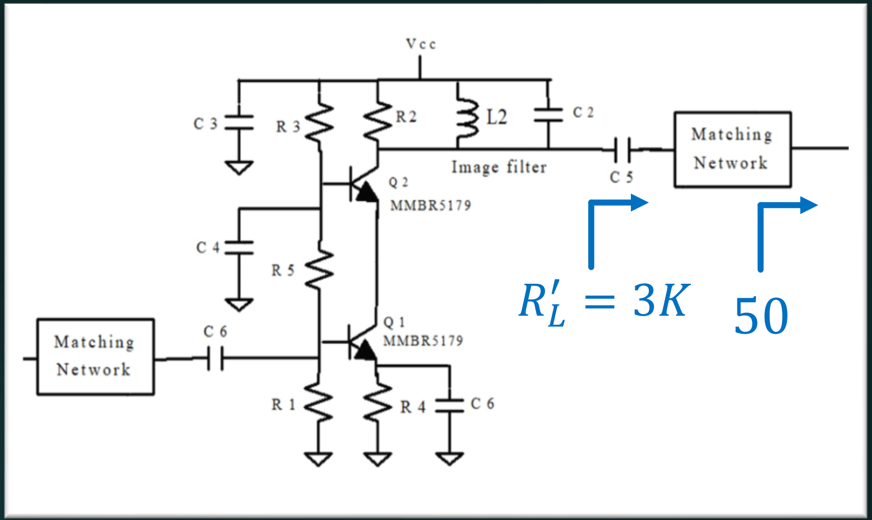
$$L = \frac{X_L}{2\pi f} \quad \text{and} \quad C = \frac{1}{2\pi f X_c}$$

---

* If one component is selected to be capacitive, then the other must be inductive. The choice of which type to use for a particular side of the network depends on other circuit design considerations. For example, the choice:

- will determine whether a "lowpass" or "highpass" response is present outside the primary matching frequency,
- may affect the bias circuit design, or
- may make it possible to save on the number of circuit components by careful combinations of the functions of components such as the matching capacitor and a required AC output coupling capacitor.

Matching Network Example

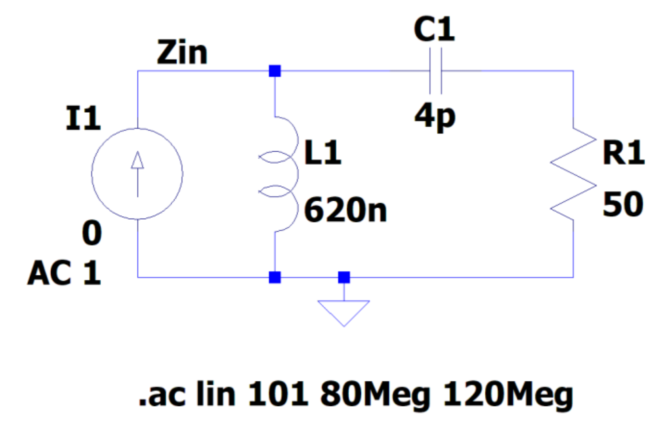


Design/verify output MN for converting 50 Ohm load to R'_L = 3K at 100 MHz

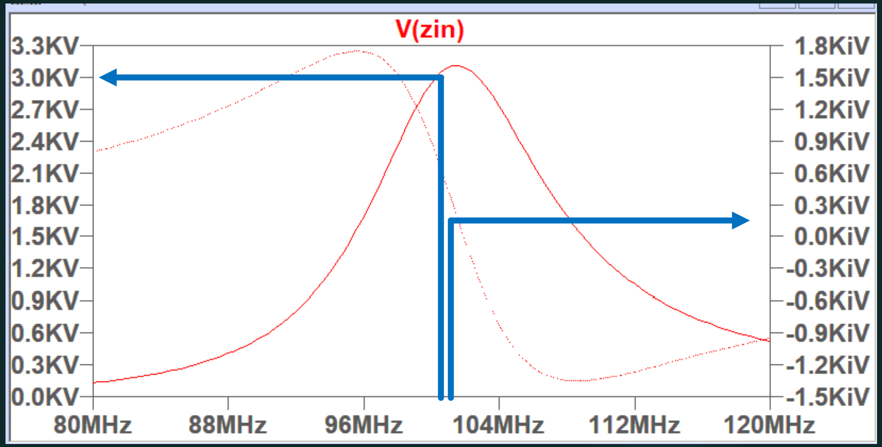
$$q = \sqrt{\frac{R_p}{R_s} - 1} = \sqrt{\frac{3K}{50} - 1} = 7.68$$

$$X_s = q(50) = 384 \quad \Rightarrow C_s = \frac{1}{2\pi(100E6)(384)} = 4.15pF$$

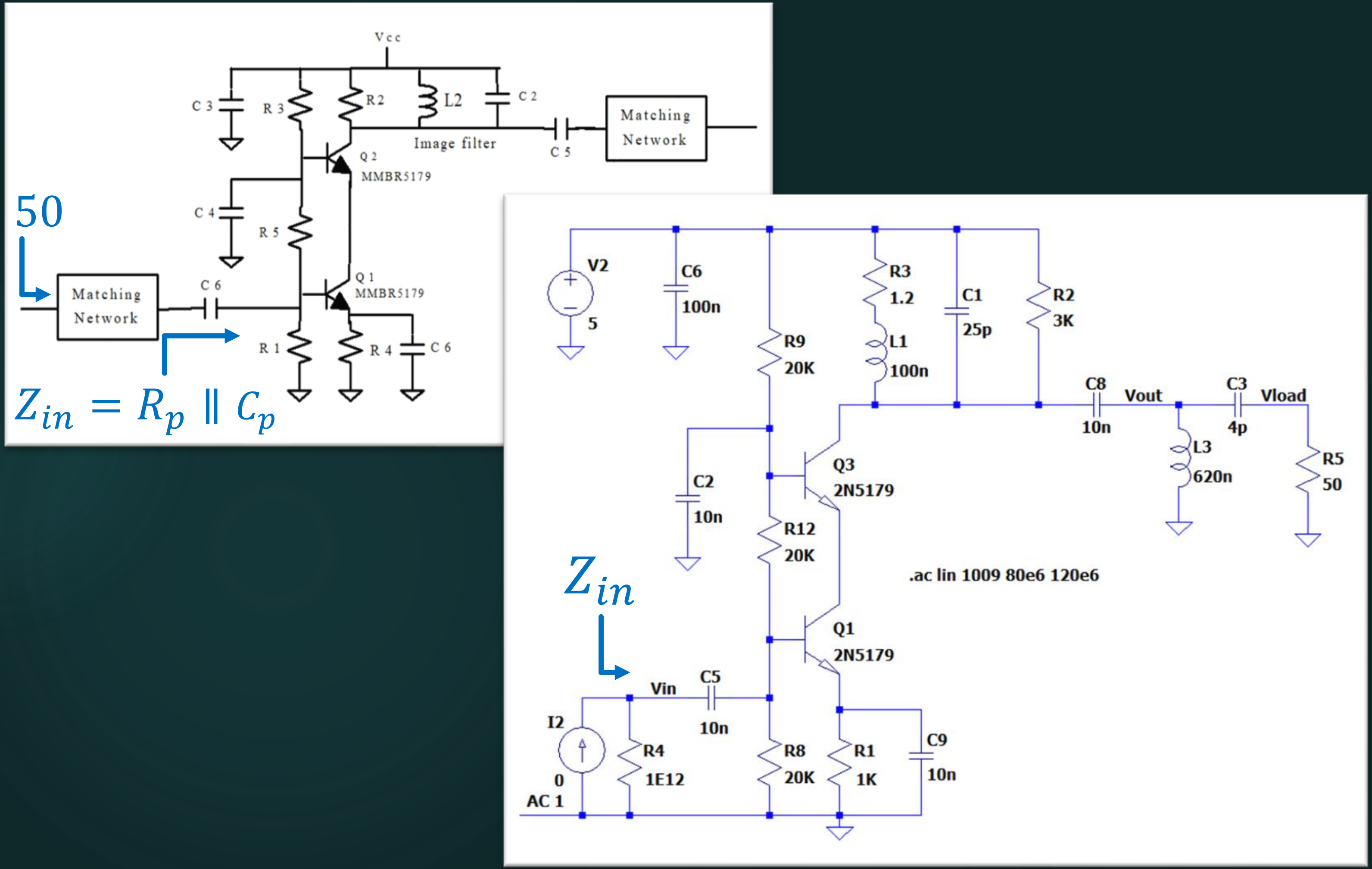
$$X_p = (3K)/q = 391 \quad \Rightarrow L_p = \frac{391}{2\pi(100E6)} = 622nH$$



.ac lin 101 80Meg 120Meg



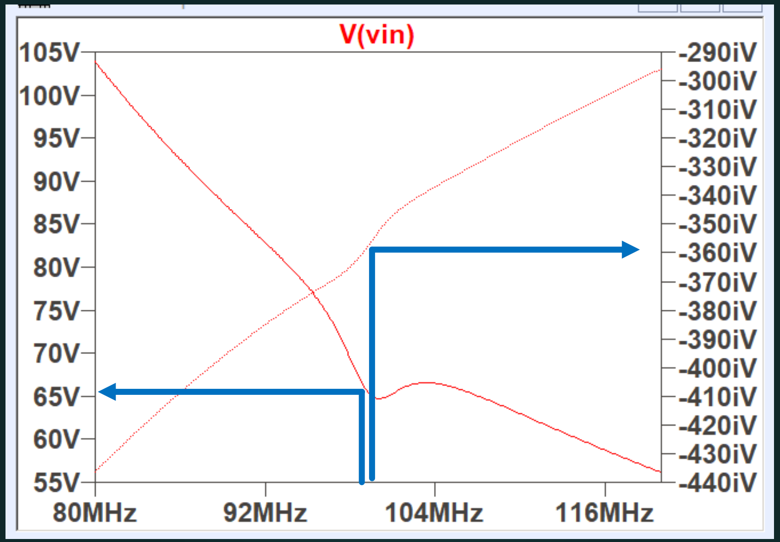
Matching to Complex Zin



50

$Z_{in} = R_p \parallel C_p$

Z_{in}



At 100 MHz,

$Z_{in} = R_s + j\,X_s = 65 - j\,360$

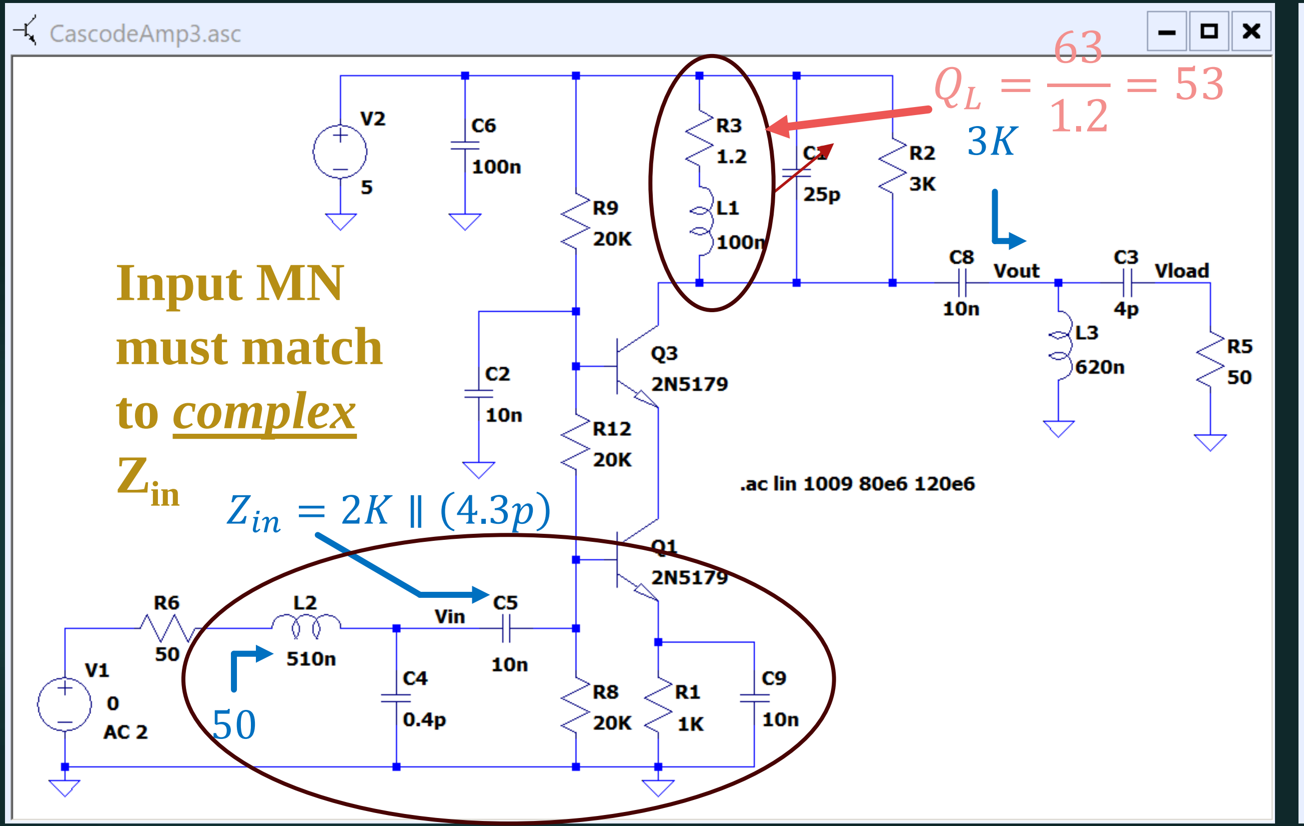
$$q = \frac{360}{65} = 5.54$$

$$R_p = (1 + q^2)\, R_s = 2.06K$$

$$X_p = \frac{(1+q^2)}{q^2}\, X_s = 372$$

$$C_p = \frac{1}{2\pi(100E6)372} = 4.28\ \text{pF}$$

Full RF Amp Simulation ☺



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.ac lin 1009 80e6 120e6
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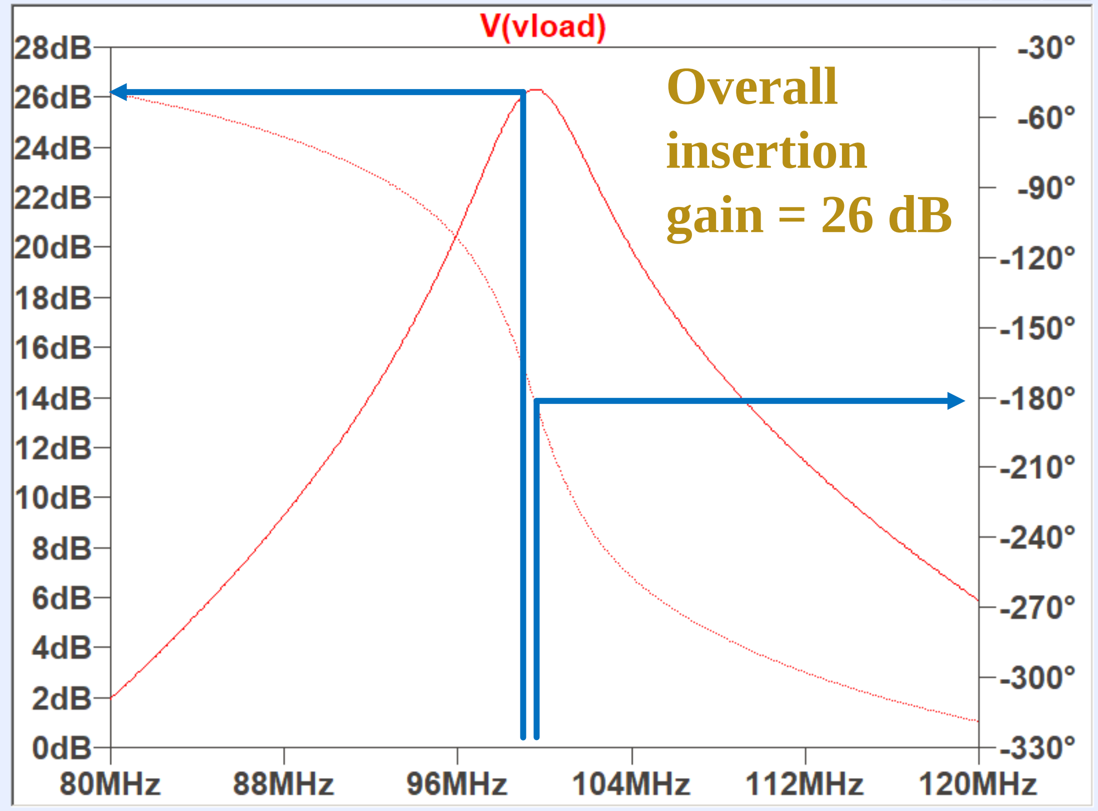
$Q_L = \frac{63}{1.2} = 53$

$3K$

Input MN must match to ***complex*** Z_{in}

$Z_{in} = 2K \parallel (4.3p)$

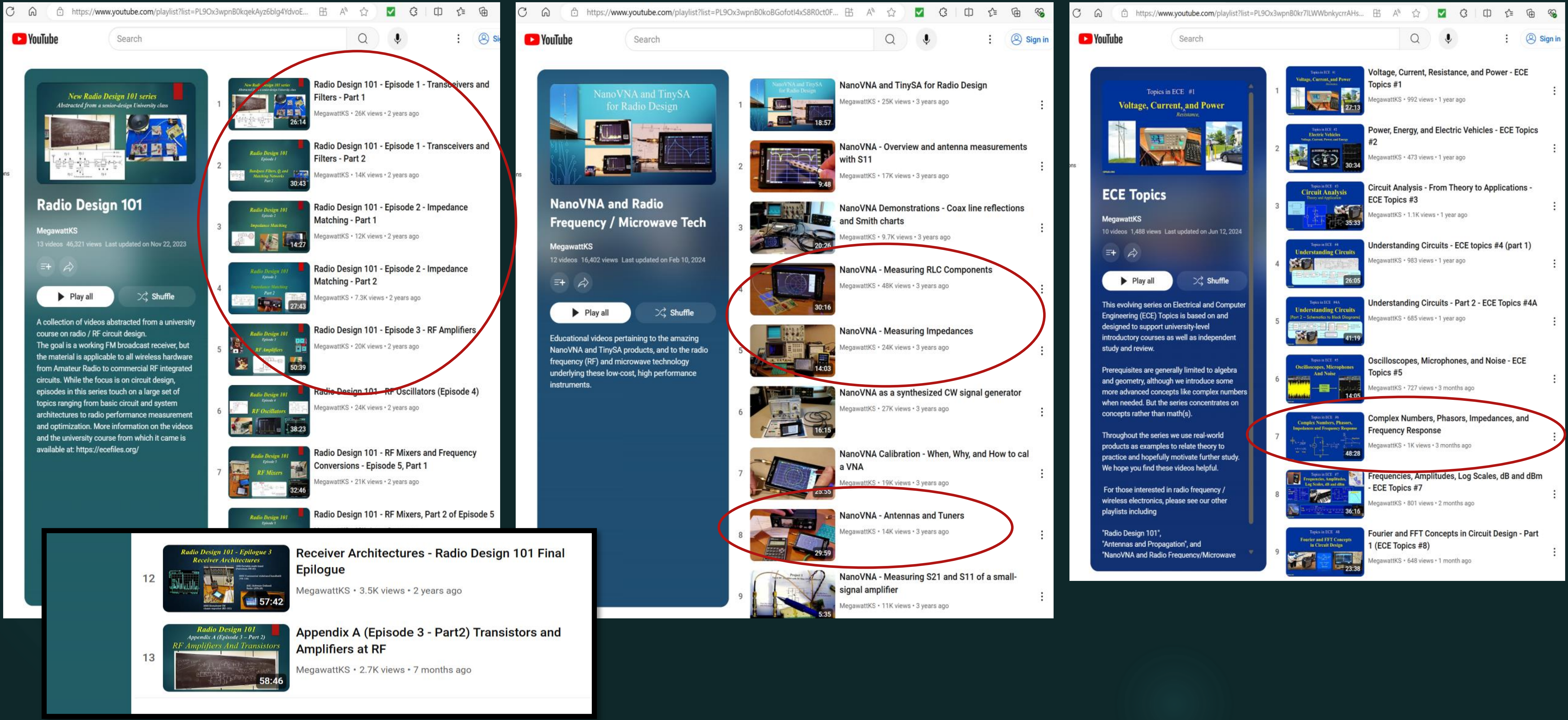
50



Overall insertion gain = 26 dB

NOTE: We should probably delete R2 here. Why ?

For More Information



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13 Appendix A (Episode 3 - Part2) Transistors and Amplifiers at RF — 58:46 — MegawattKS • 2.7K views • 7 months ago

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NanoVNA and Radio Frequency / Microwave Tech

MegawattKS

12 videos 16,402 views Last updated on Feb 10, 2024

Educational videos pertaining to the amazing NanoVNA and TinySA products, and to the radio frequency (RF) and microwave technology underlying these low-cost, high performance instruments.

1 NanoVNA and TinySA for Radio Design — 18:57 — MegawattKS • 25K views • 3 years ago
2 NanoVNA - Overview and antenna measurements with S11 — 9:48 — MegawattKS • 17K views • 3 years ago
3 NanoVNA Demonstrations - Coax line reflections and Smith charts — 20:26 — MegawattKS • 9.7K views • 3 years ago
4 NanoVNA - Measuring RLC Components — 30:16 — MegawattKS • 48K views • 3 years ago
5 NanoVNA - Measuring Impedances — 14:03 — MegawattKS • 24K views • 3 years ago
6 NanoVNA as a synthesized CW signal generator — 16:15 — MegawattKS • 27K views • 3 years ago
7 NanoVNA Calibration - When, Why, and How to cal a VNA — 25:55 — MegawattKS • 19K views • 3 years ago
8 NanoVNA - Antennas and Tuners — 29:59 — MegawattKS • 14K views • 3 years ago
9 NanoVNA - Measuring S21 and S11 of a small-signal amplifier — 5:35 — MegawattKS • 11K views • 3 years ago

https://www.youtube.com/playlist?list=PL9Ox3wpnB0kr7lLWWbnkycrrAHs...

ECE Topics

MegawattKS

10 videos 1,488 views Last updated on Jun 12, 2024

This evolving series on Electrical and Computer Engineering (ECE) Topics is based on and designed to support university-level introductory courses as well as independent study and review.

Prerequisites are generally limited to algebra and geometry, although we introduce some more advanced concepts like complex numbers when needed. But the series concentrates on concepts rather than math(s).

Throughout the series we use real-world products as examples to relate theory to practice and hopefully motivate further study. We hope you find these videos helpful.

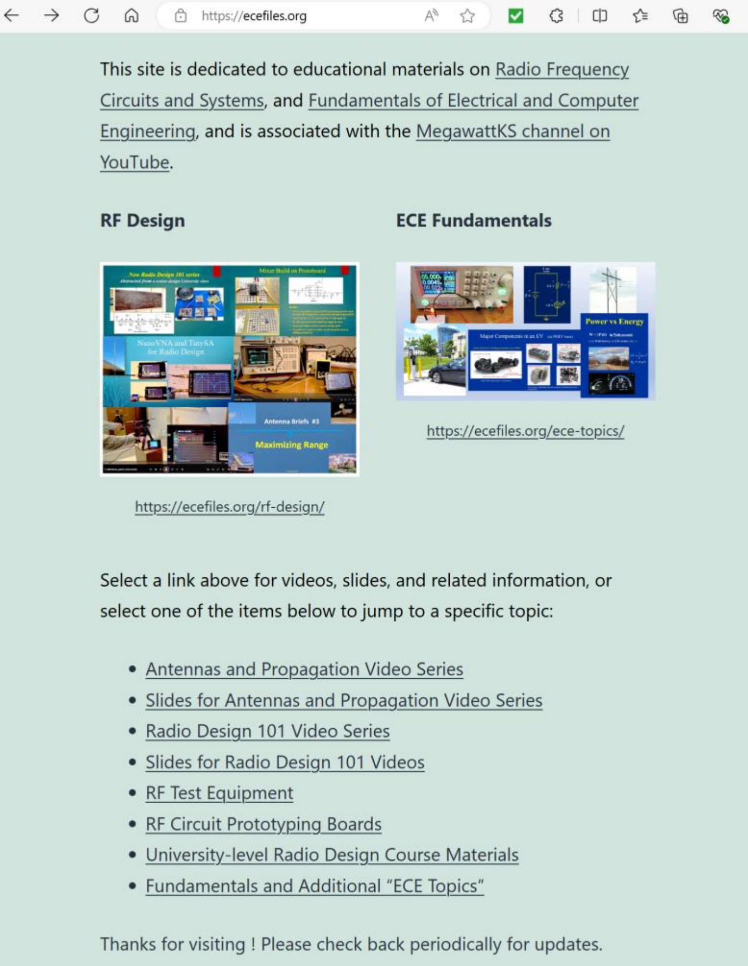
For those interested in radio frequency / wireless electronics, please see our other playlists including

"Radio Design 101",
"Antennas and Propagation", and
"NanoVNA and Radio Frequency/Microwave

1 Voltage, Current, Resistance, and Power - ECE Topics #1 — 27:13 — MegawattKS • 992 views • 1 year ago
2 Power, Energy, and Electric Vehicles - ECE Topics #2 — 30:34 — MegawattKS • 473 views • 1 year ago
3 Circuit Analysis - From Theory to Applications - ECE Topics #3 — 35:33 — MegawattKS • 1.1K views • 1 year ago
4 Understanding Circuits - ECE topics #4 (part 1) — 26:05 — MegawattKS • 983 views • 1 year ago
5 Understanding Circuits - Part 2 - ECE Topics #4A — 41:19 — MegawattKS • 685 views • 1 year ago
6 Oscilloscopes, Microphones, and Noise - ECE Topics #5 — 14:05 — MegawattKS • 727 views • 3 months ago
7 Complex Numbers, Phasors, Impedances, and Frequency Response — 48:28 — MegawattKS • 1K views • 3 months ago
8 Frequencies, Amplitudes, Log Scales, dB and dBm - ECE Topics #7 — 36:16 — MegawattKS • 801 views • 2 months ago
9 Fourier and FFT Concepts in Circuit Design - Part 1 (ECE Topics #8) — 23:38 — MegawattKS • 648 views • 1 month ago

For Even More Information

https://ecefiles.org



This site is dedicated to educational materials on Radio Frequency Circuits and Systems, and Fundamentals of Electrical and Computer Engineering, and is associated with the MegawattKS channel on YouTube.

RF Design

https://ecefiles.org/rf-design/

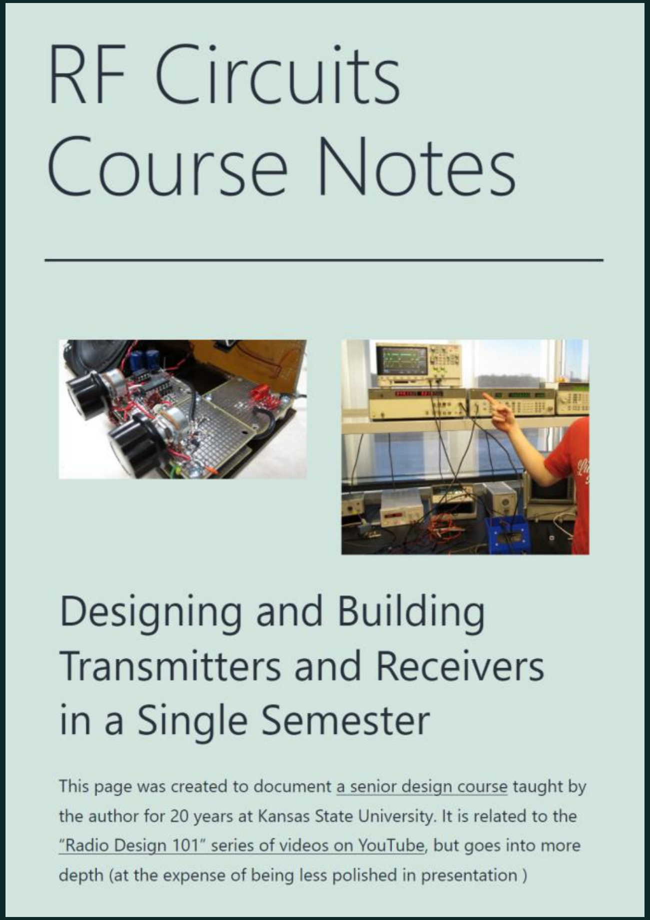
ECE Fundamentals

https://ecefiles.org/ece-topics/

Select a link above for videos, slides, and related information, or select one of the items below to jump to a specific topic:

- Antennas and Propagation Video Series
- Slides for Antennas and Propagation Video Series
- Radio Design 101 Video Series
- Slides for Radio Design 101 Videos
- RF Test Equipment
- RF Circuit Prototyping Boards
- University-level Radio Design Course Materials
- Fundamentals and Additional "ECE Topics"

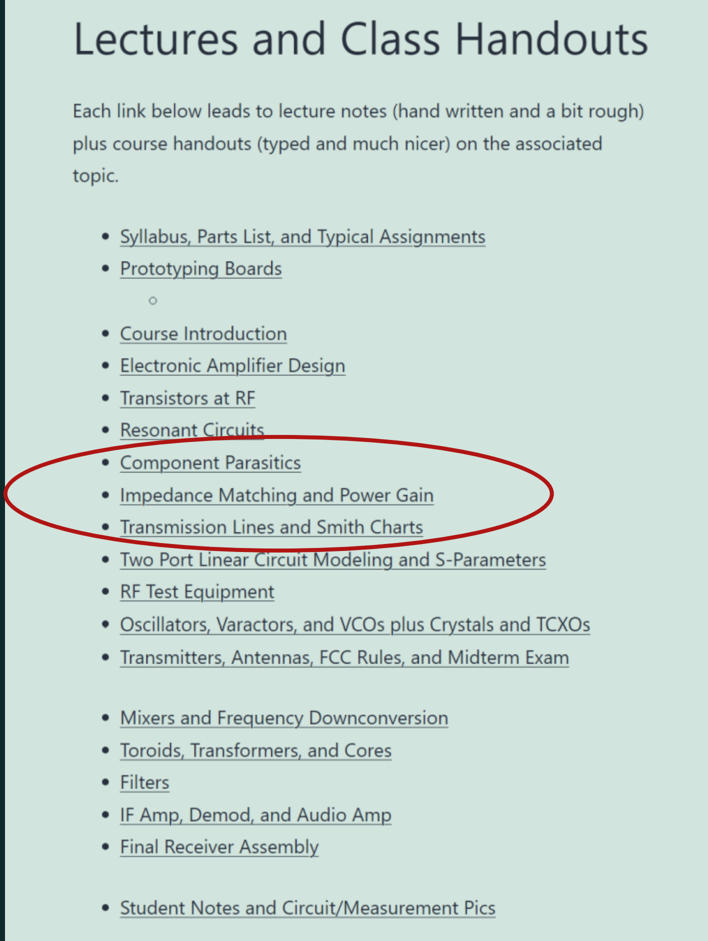
Thanks for visiting ! Please check back periodically for updates.



RF Circuits Course Notes

Designing and Building Transmitters and Receivers in a Single Semester

This page was created to document a senior design course taught by the author for 20 years at Kansas State University. It is related to the "Radio Design 101" series of videos on YouTube, but goes into more depth (at the expense of being less polished in presentation)



Lectures and Class Handouts

Each link below leads to lecture notes (hand written and a bit rough) plus course handouts (typed and much nicer) on the associated topic.

- Syllabus, Parts List, and Typical Assignments
- Prototyping Boards
    - ○
- Course Introduction
- Electronic Amplifier Design
- Transistors at RF
- Resonant Circuits
- Component Parasitics
- Impedance Matching and Power Gain
- Transmission Lines and Smith Charts
- Two Port Linear Circuit Modeling and S-Parameters
- RF Test Equipment
- Oscillators, Varactors, and VCOs plus Crystals and TCXOs
- Transmitters, Antennas, FCC Rules, and Midterm Exam

- Mixers and Frequency Downconversion
- Toroids, Transformers, and Cores
- Filters
- IF Amp, Demod, and Audio Amp
- Final Receiver Assembly

- Student Notes and Circuit/Measurement Pics

Thanks For Watching !