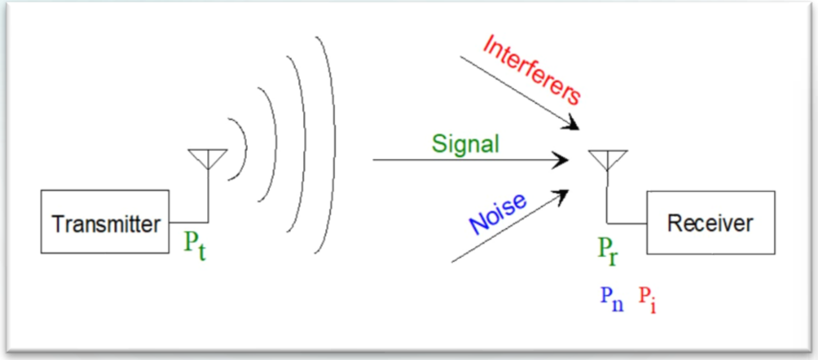
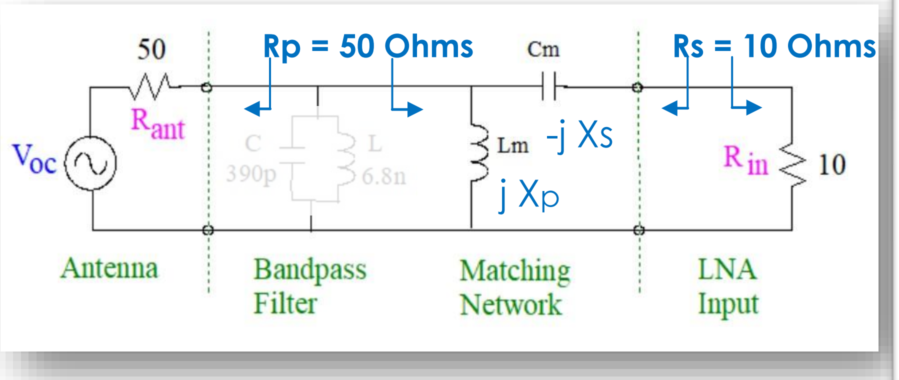
Radio Design 101
Episode 2 – Impedance Matching

Slides downloaded from: https://ecefiles.org/rf-design/
Companion videos at: https://www.youtube.com/watch?v=WXdGKErCjZw (part 1)
and: https://www.youtube.com/watch?v=ZWBem8GTzNs (part 2)

This episode starts with the "big picture" on why impedance matching is needed in RF circuits and then focuses on a design example using a low noise amplifier (LNA). The example uses L-type matching circuit architectures, but the material is general. The second part of this episode discusses alternative Pi, T, and LL networks as well as RF transformers and tapped LC designs. Part 2 also shows how these are used in actual radio / wireless products including a unique TR switch, LNA, and power amp combination in a UHF integrated circuit transceiver.





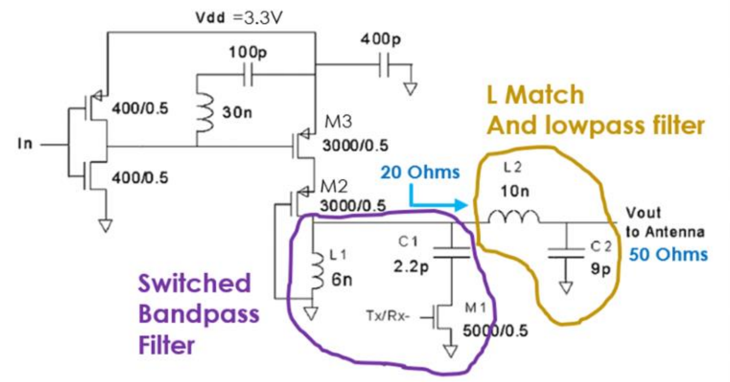


Fig. 14. Simplified schematic of 400-MHz PA. 100 mW (+20 dBm)

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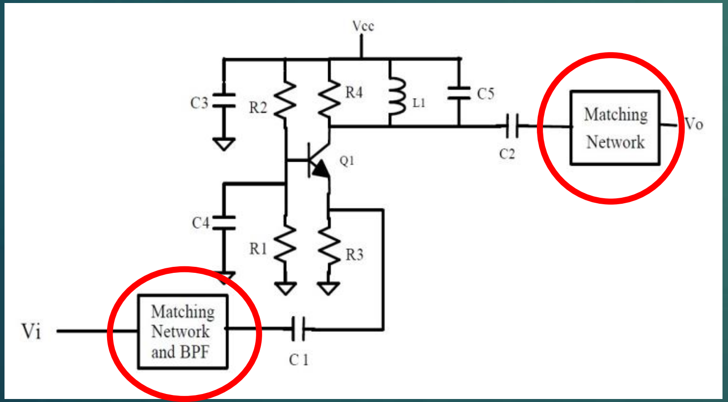
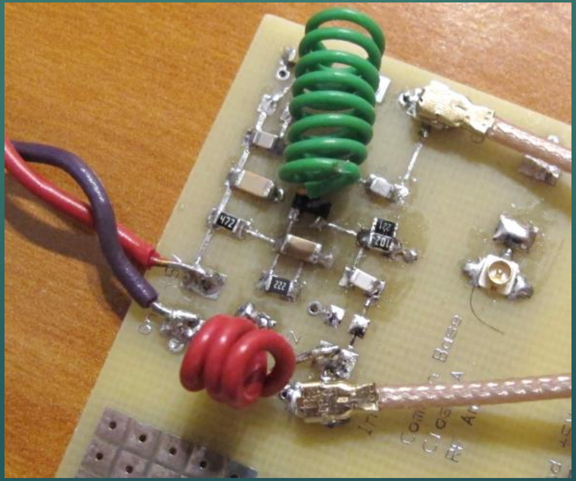
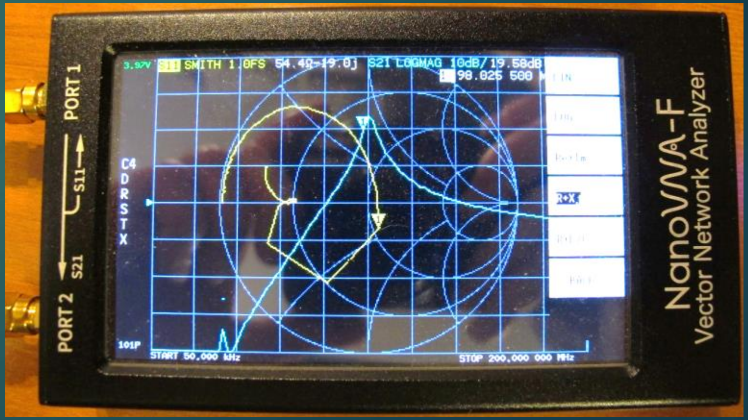
Impedance Matching







Topic Outline

- ***Why use matching networks ?***
- ***L Matching Network for Receiver Input***
- ***Using NanoVNA to validate design***
- ***Other MN circuit topologies***
- ***Examples in real-world applications***

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Part 2

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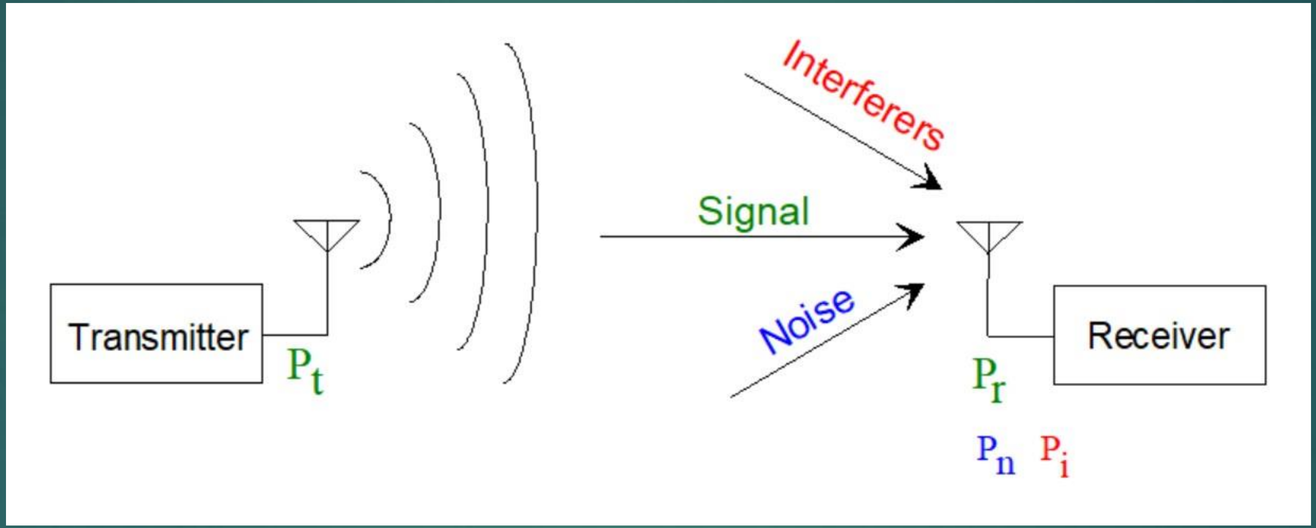
Impedance Matching
Part 2

Why Use Matching Networks ?

The Big Picture …



$$\mathrm{Pr} = \left[\frac{Pt}{4\pi R^2} Gt\right] Ae$$

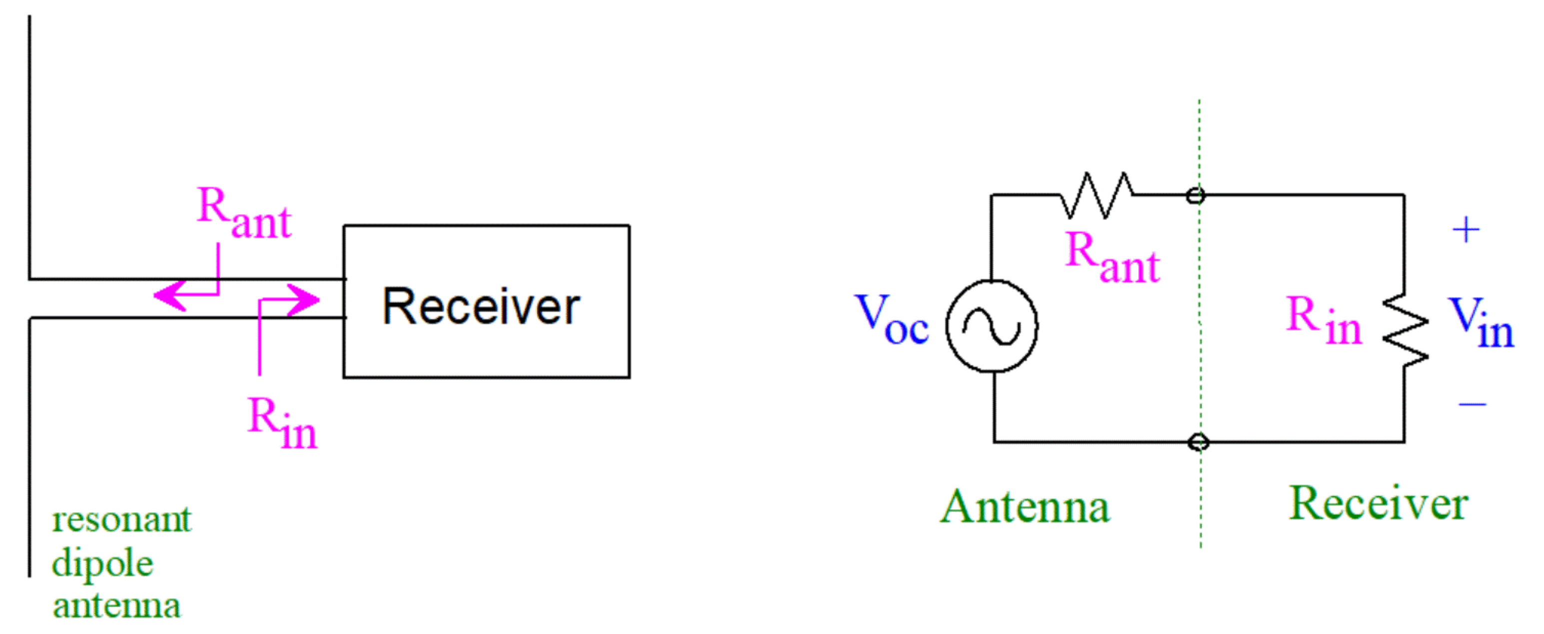
$$\mathrm{P}n = kTB$$

We usually need received power Pr greater than noise power Pn

For example, Pr = 10 Pn to 100 Pn (i.e. 10 to 20 dB SNR) or more

NOTE: "Path loss exponent is 2 for free-space only. Terrestrial propagation may use 3 to 5.
See "Propagation comparisons at VHF and UHF frequencies," 2009 IEEE Radio and Wireless Symposium

Circuit Level View



$$V_{in} = V_{oc} \frac{R_{in}}{R_{in}+R_{ant}}$$

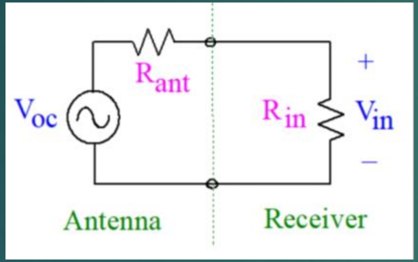
$$P_r = \frac{(V_{in})^2}{R_{in}}$$

$$P_r\ (dBm) = 10 \log\left(\frac{P_r}{1\ mW}\right)$$

Max Power Transfer

$Let\ \ V_{oc} = 1\ \mu V\ RMS \quad and\ \ R_{ant} = 50\ Ohms$

$Then\ \ \ldots$



Rin	Vin	Pr	Pr (dBm)
10	0.17 uV	2.8 fW	-116
50	0.50 uV	5.0 fW	-113
1K	0.95 uV	0.91 fW	-120

$P_r\ is\ maximized\ when\ R_{in} = \ R_{ant}$

Or $in\ general, when\ Z_{in} = \ {Z_{ant}}^*$

$V_{in}\ is\ maximized\ here, but\ P_r\ is\ low\ since\ R_{in} is\ big$

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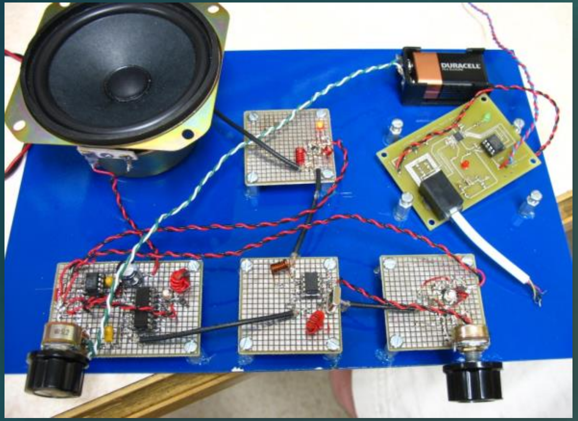
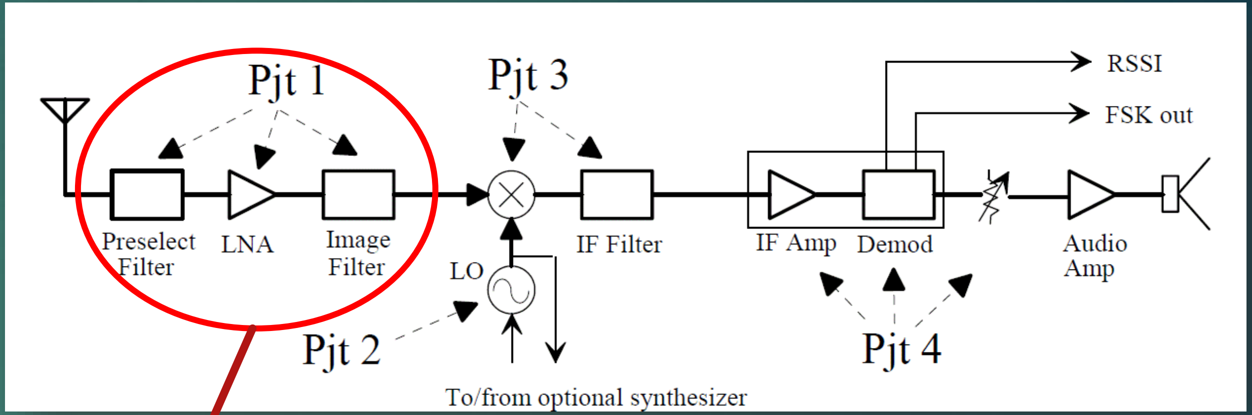
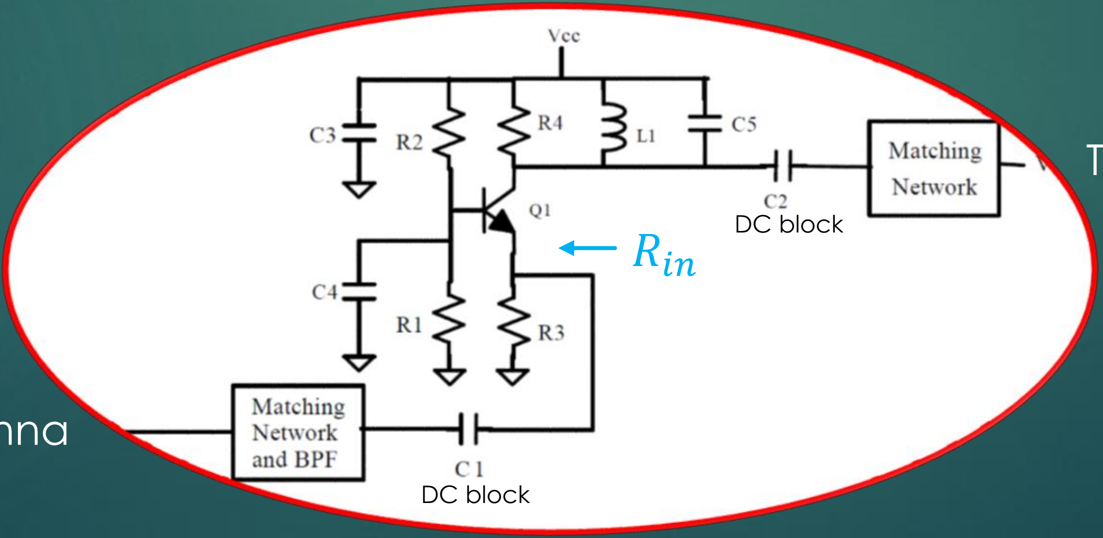
Project 1 – FM Receiver Front End





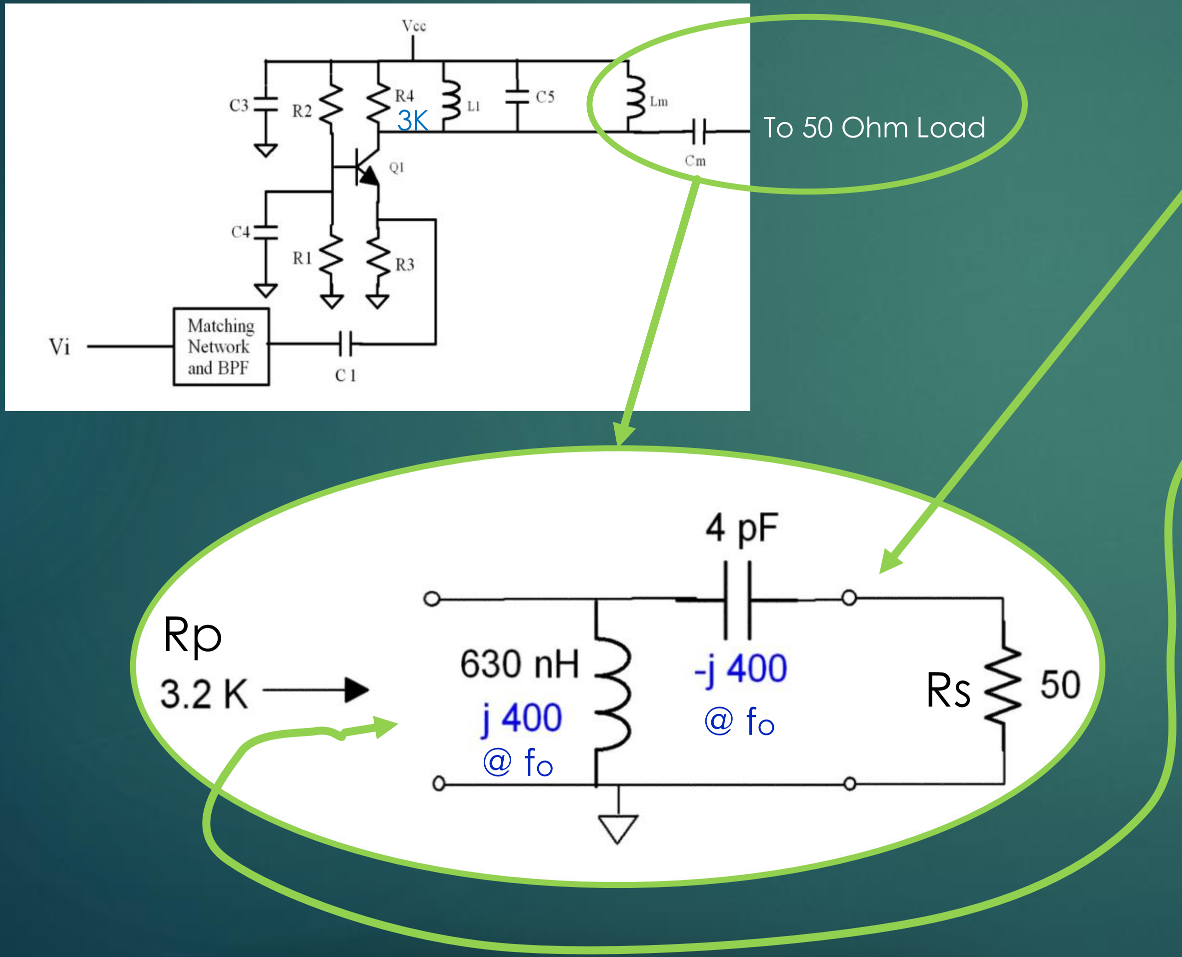


To 50 Ohm load (project 3 input)

From 50 Ohm antenna

Review (from Episode 1)

Output “L-type” matching network uses LC resonator to convert 50 Ohm load to 3.2K Ohms (with minimal power loss)



Viewed from load (series resonant circuit view):

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

Viewed from amplifier (parallel resonant circuit view):

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

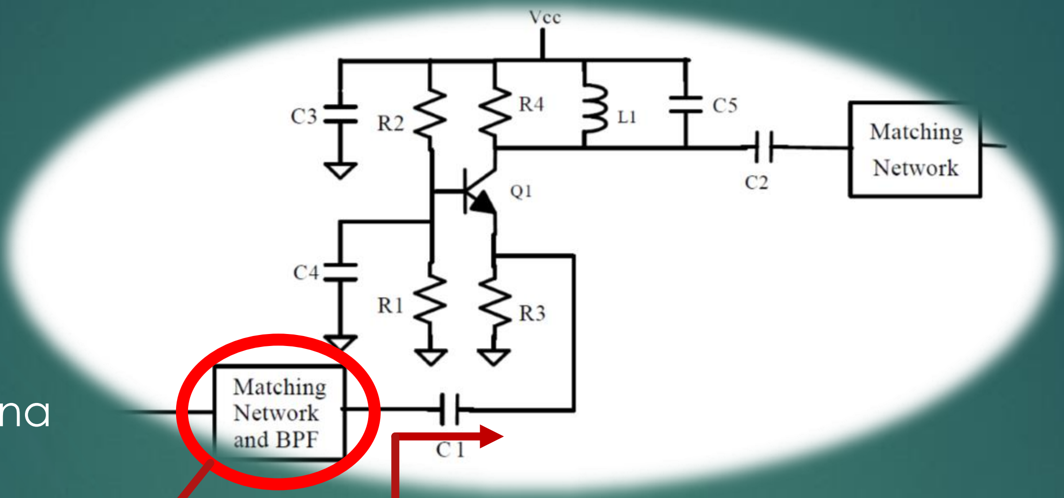
$$\Rightarrow \ Rp = Q \ Xo \ = Q^2 \ Rs = 3.2 \text{ K Ohms}$$

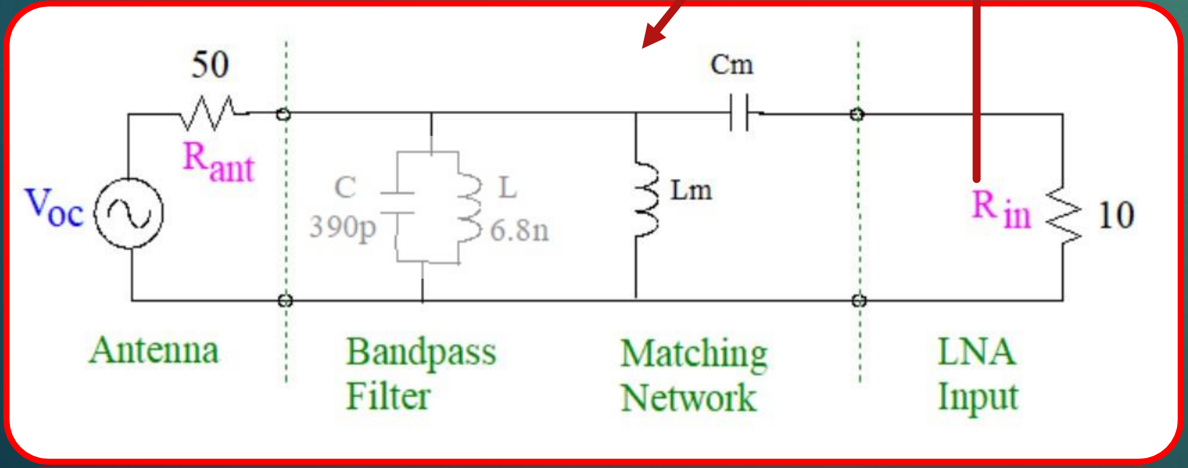
$NOTE: \ Above\ is\ approximately\ true\ at\ for\ high\ Q\ case.$

In general: $\boxed{Rp \ = (1+Q^2) \ Rs}$

Solution for Input MN and Filter

From 50 Ohm antenna



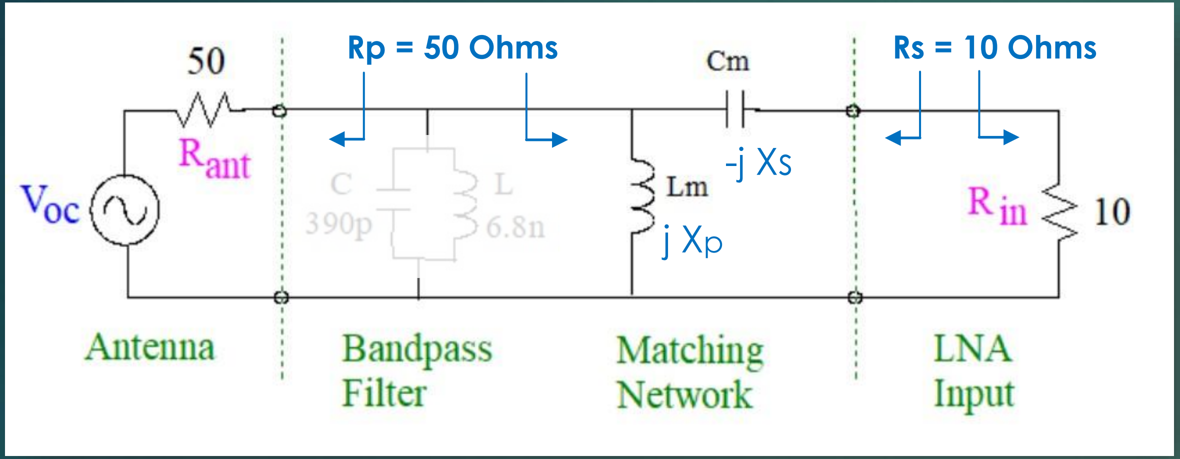


Bandpass Filter designed in Episode 1

Parallel LC filter becomes open circuit at f_o

For matching network, need to convert 10 Ohms to 50 Ohms

Solution for MN Components



Analysis Formulas:

$$R_p = (1+Q^2)\ R_s$$

$$Q = \frac{R_p}{X_p} \qquad Q = \frac{X_s}{R_s}$$

$$X_p = 2\pi f L_m \qquad X_s = \frac{1}{2\pi f C_m}$$

Design Formulas:

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

$$X_p = \frac{R_p}{Q} \qquad X_s = R_s\ Q$$

$$L_m = \frac{X_p}{2\pi f} \qquad C_m = \frac{1}{2\pi f X_s}$$

With Rp = 50 and Rs = 10:

$$Q = \sqrt{\frac{50}{10} - 1} = 2$$

$$X_p = \frac{50}{2} = 25\ Ohms$$

$$X_s = (10)(2) = 20\ Ohms$$

$$L_m = \frac{25}{2\pi 100MHz} = 39.8\ nH$$

$$C_m = \frac{1}{2\pi(100MHz)(20)} = 79.6\ pF$$

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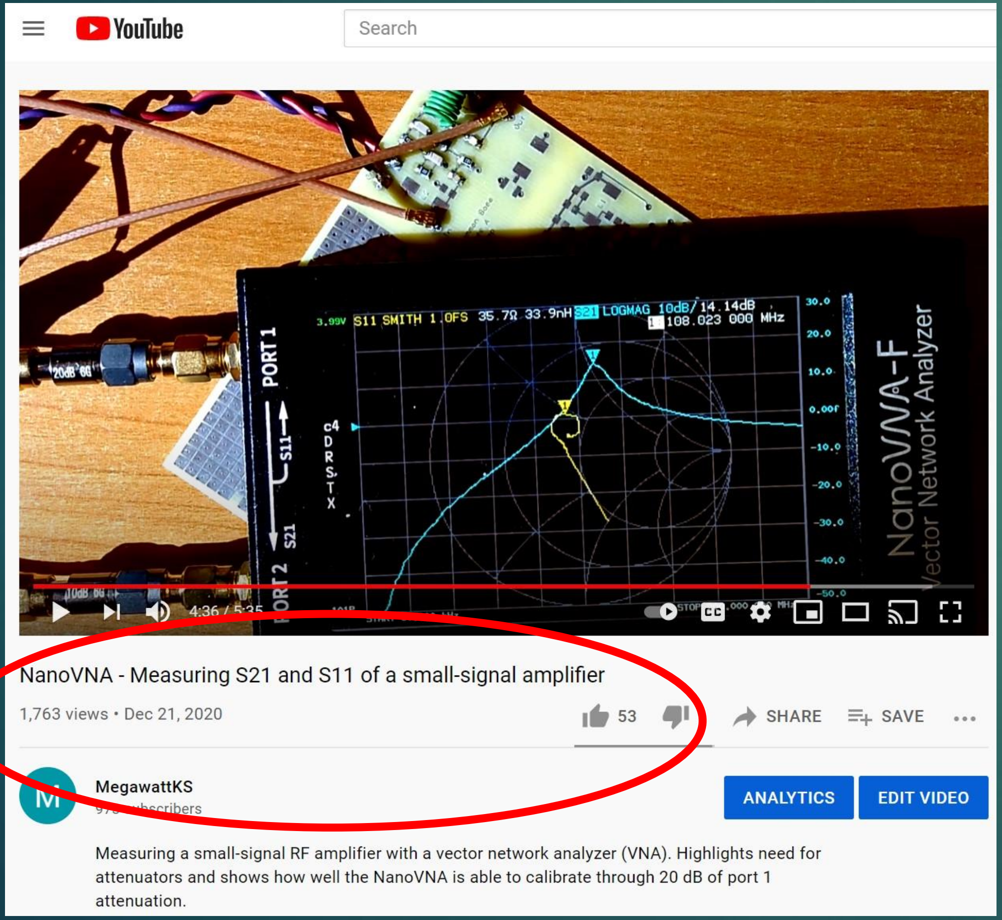
Testing amplifiers with NanoVNA

In previous video from the NanoVNA series…



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

1,763 views • Dec 21, 2020

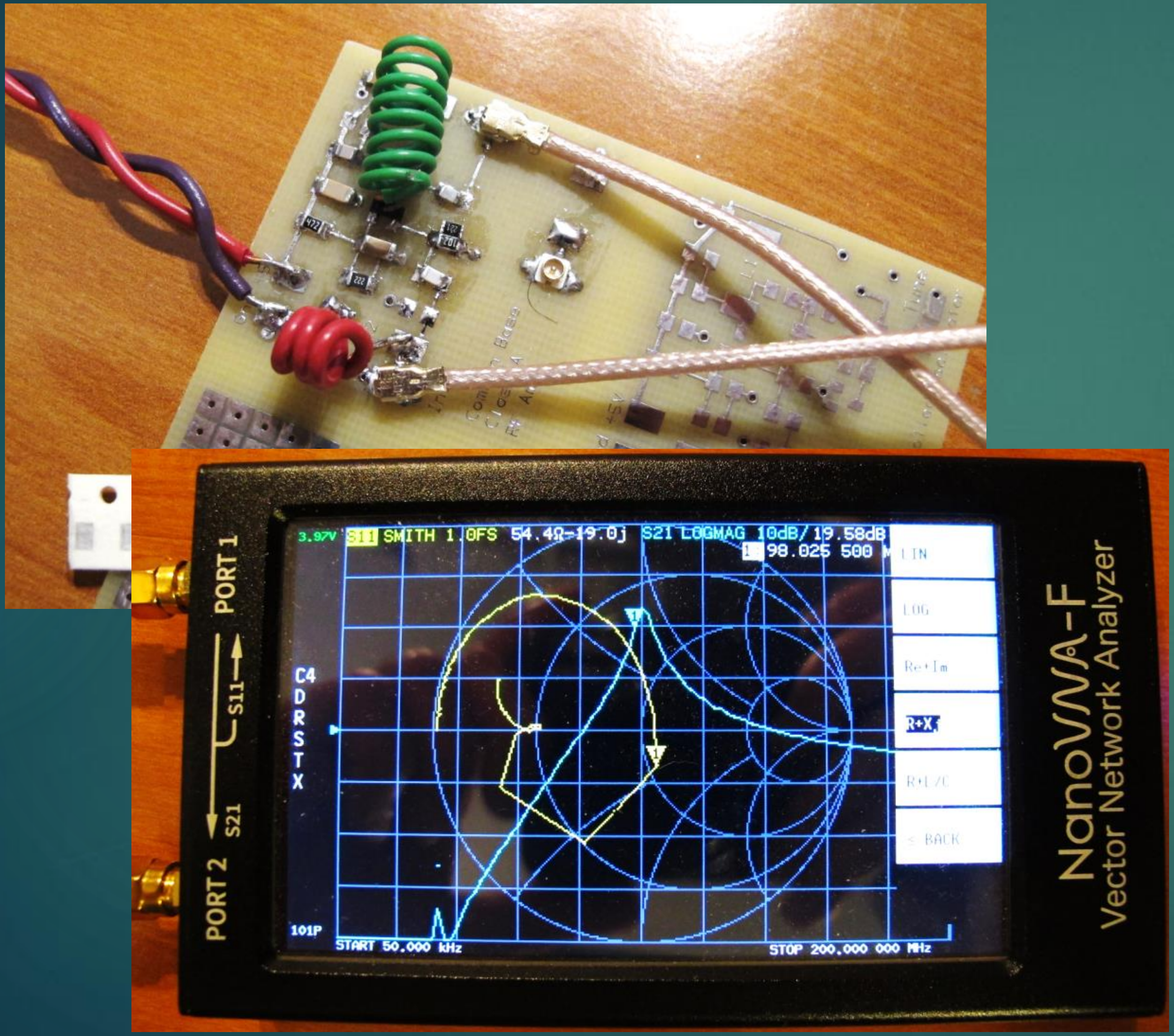
MegawattKS

97[illegible] subscribers

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.

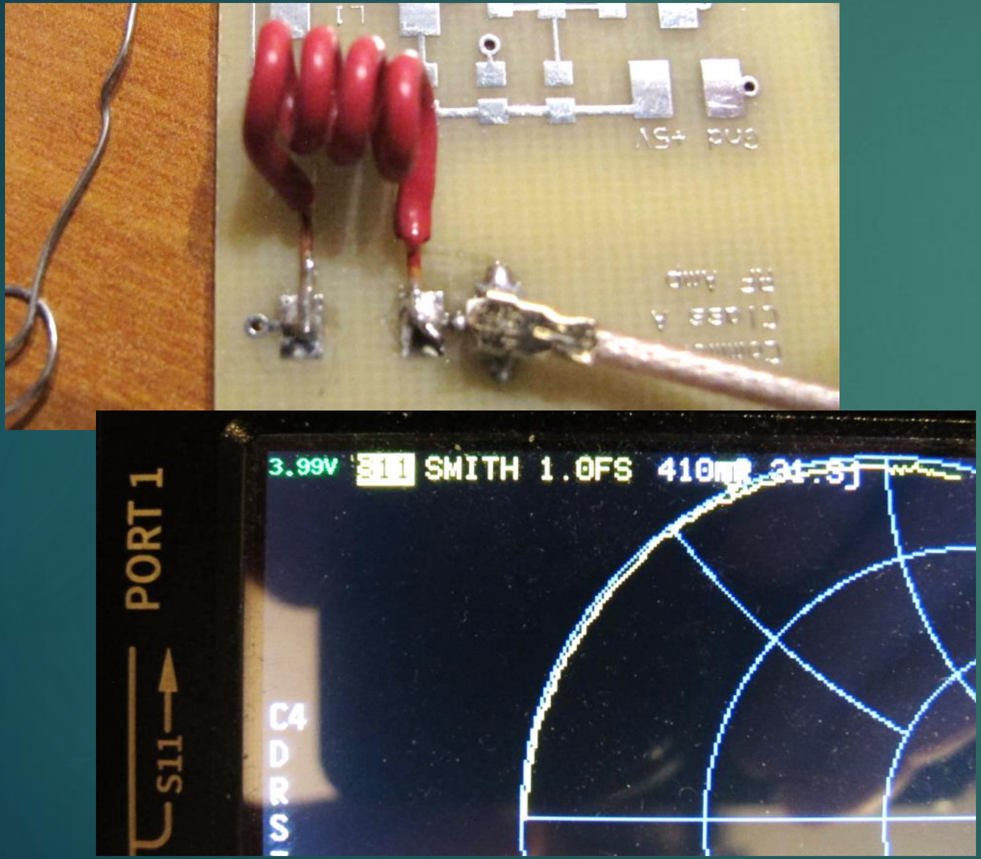
- Transistor was originally biased at 0.9 mA to give 50 Ohm R_{in}, so no input matching was used.
- Measured power gain S21 was 14 dB.

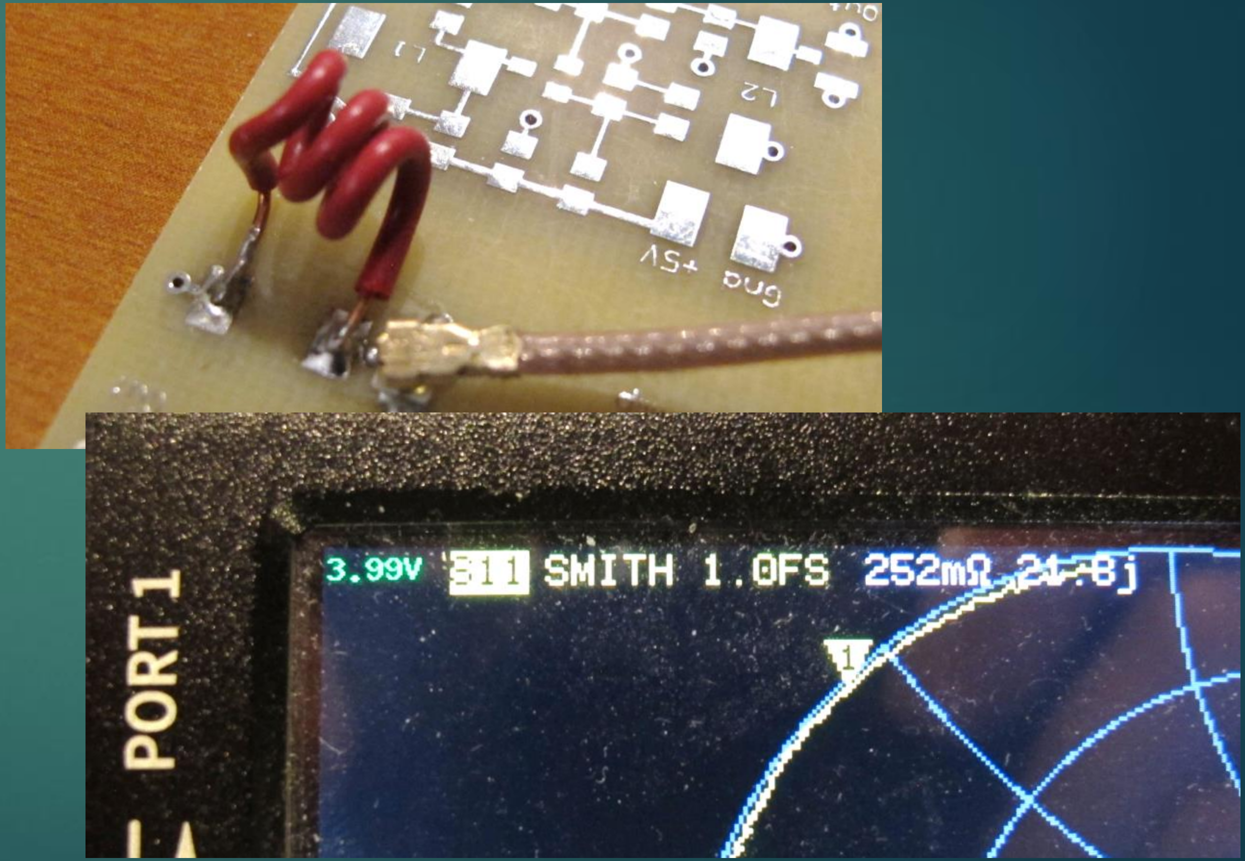
Testing Upgraded Amp



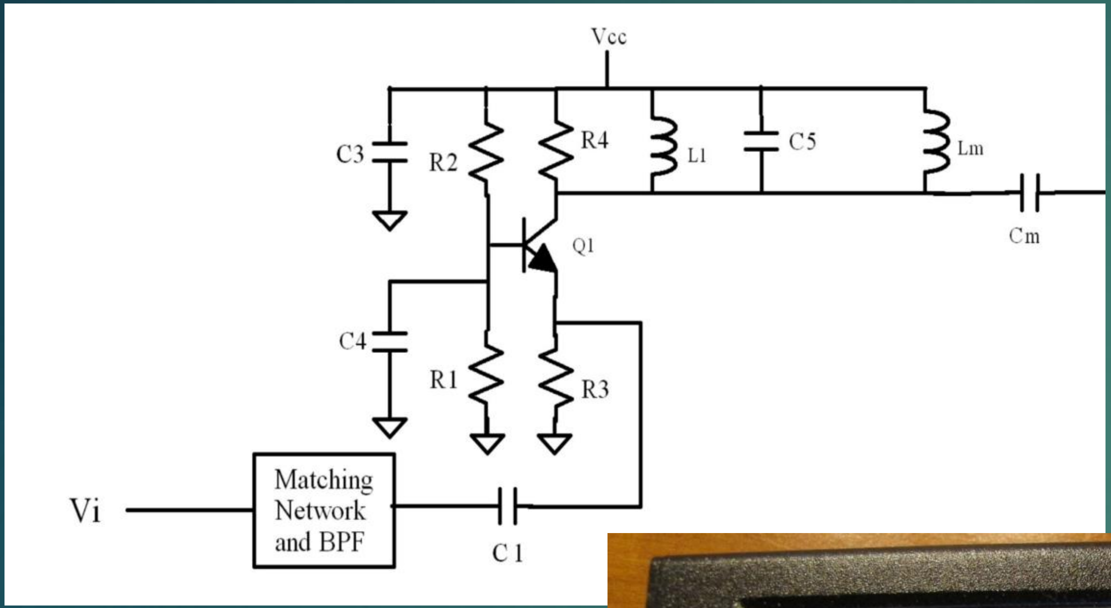
- Here, amplifier is re-biased at 4.5 mA to increase power gain by 5X.
- Input MN added.
- Measured power gain S21 increased from 14 dB to 22 dB.
- Measured input Z is 54 – j19, so MN is working ☺
- Still needs a little tweeking maybe…

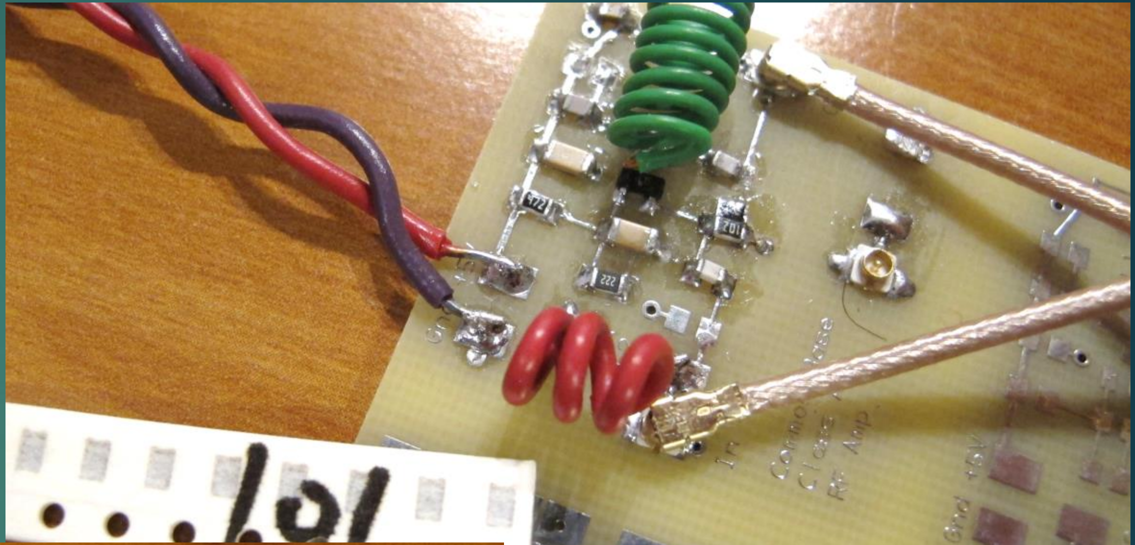
Inductor Measurements

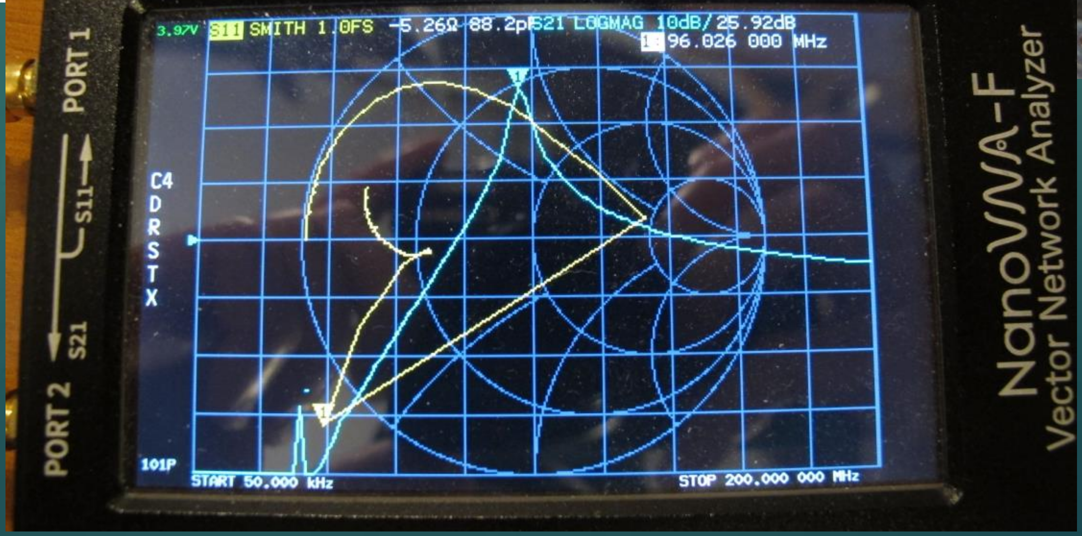




Initial Tuning / Stability Issues





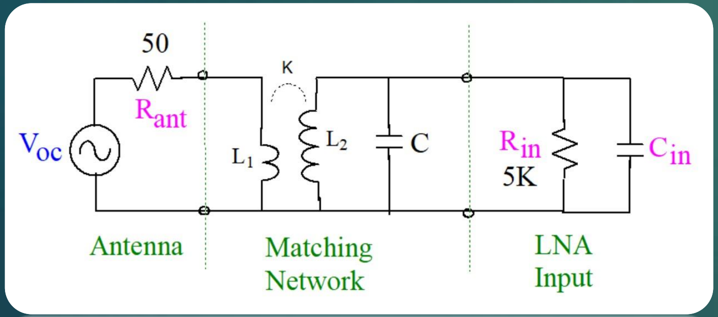


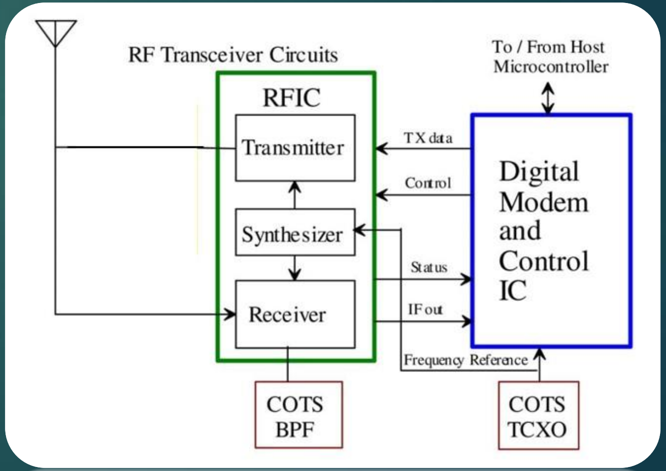
Radio Design 101

Episode 2

Impedance Matching

Part 2





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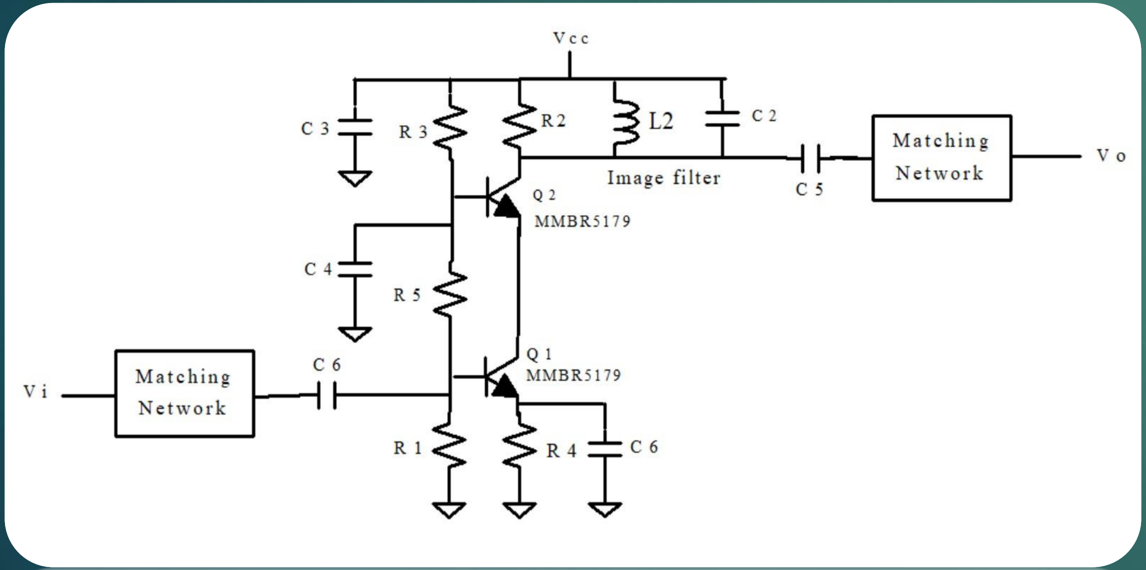
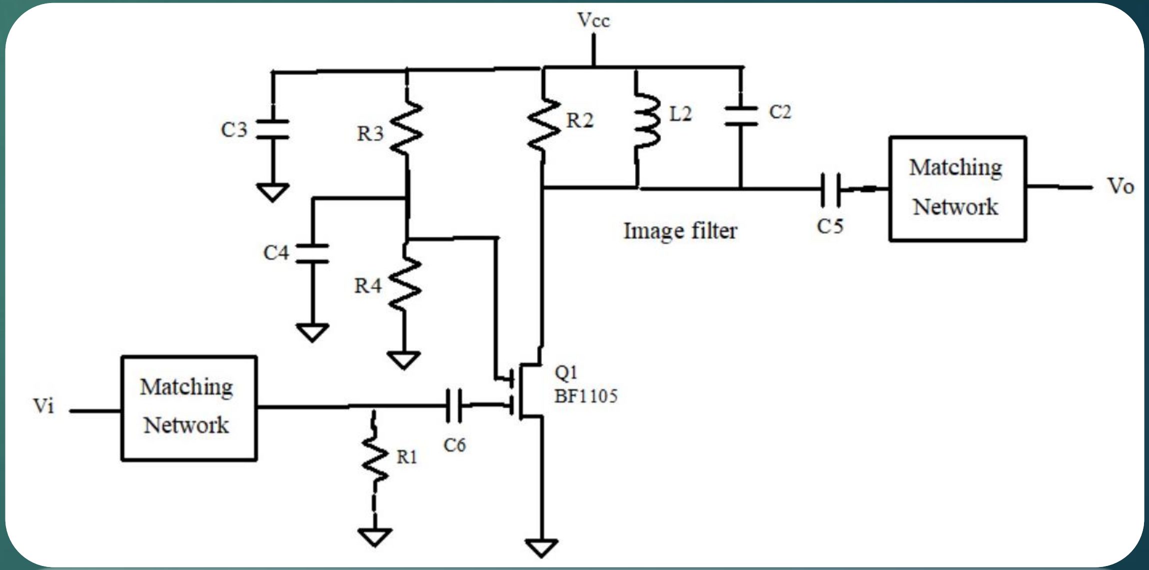
Converting from Low Z to High Z

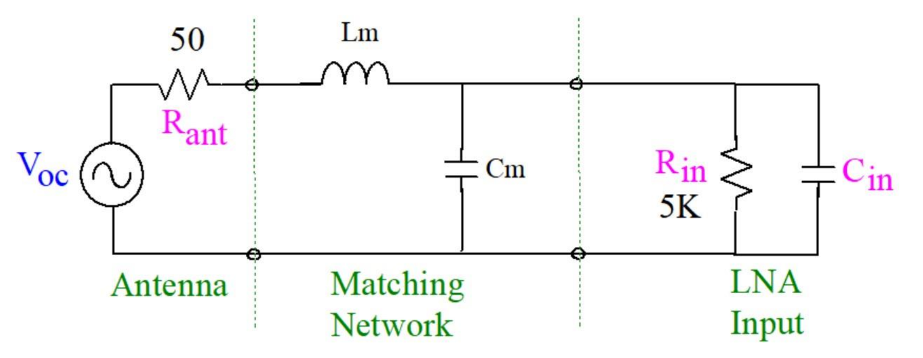
Cascode amps with high (and capacitive) Z_{in} :





Converting from Low Z to High Z

L-match network …

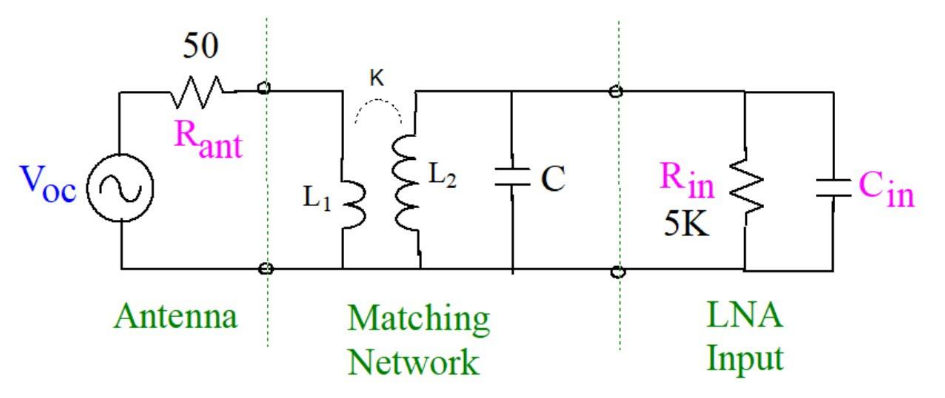


Design Procedure

- Same as before, except
  - Series and parallel sides are reversed
  - C and L are swapped.
- Adjust formulas as appropriate…
- Subtract C_{in} from C_m value

Tuned RF Transformers

Classic transformer design:



Design Procedure

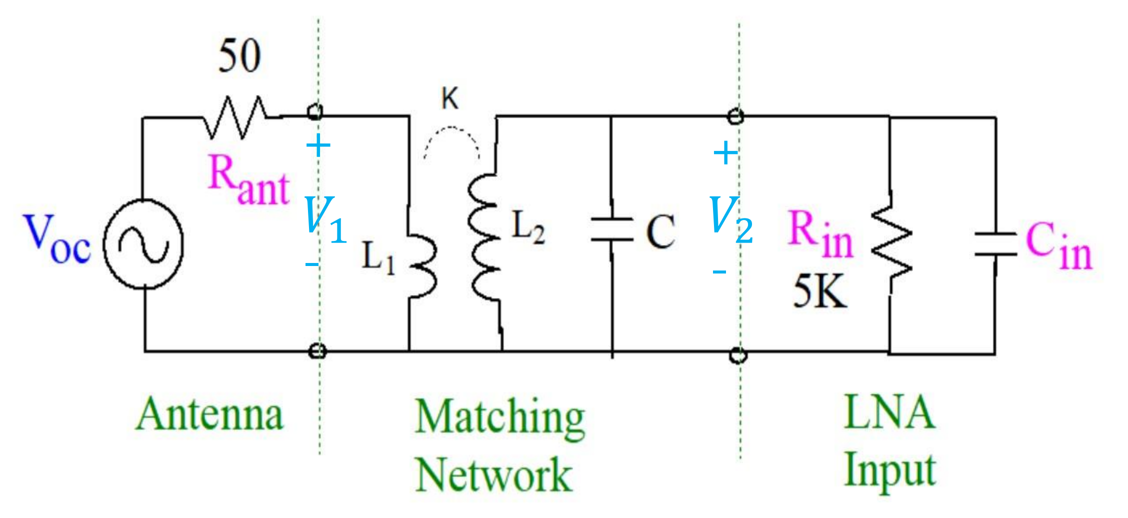
- L_2 and C form a bandpass filter. Design as in Episode 1
- After determining number of turns N_2 for L_2, estimate number of turns N_1 for L_1 from:

$$\frac{R_{in}}{R_{ant}} = \frac{L_2}{L_1} = \left(\frac{N_2}{N_1}\right)^2 \qquad *$$

- Wind coils so that coupling coefficient K > 1/Q

* Assumes K = 1

Impedance and Voltage Transformation

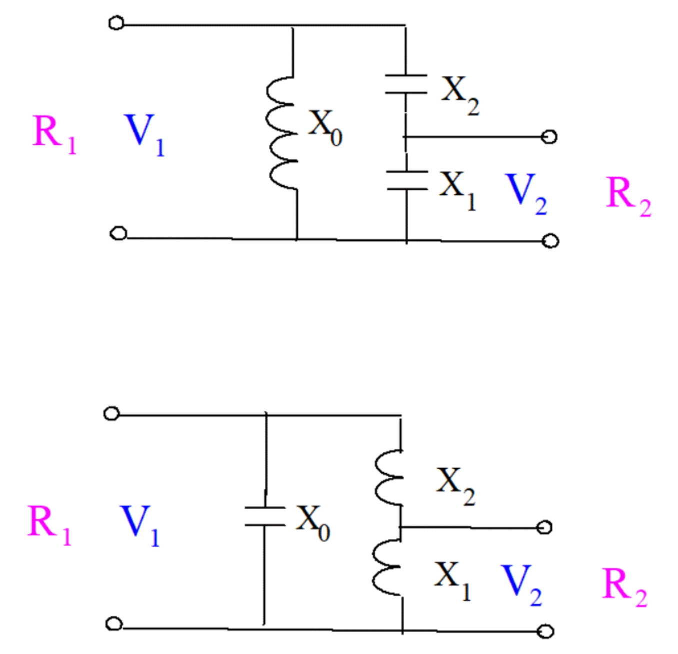


NOTE: Impedance step-up is associated with a voltage gain: ☺

$$\boxed{\frac{V_2}{V_1} = \sqrt{\frac{R_{in}}{R_{ant}}}}$$

← This is true in general for lossless matching, not just in this design !

Tapped LC Resonators



- Shunt L and C form a bandpass filter. Design as in Episode 1

$$Q = \frac{f_o}{B} \qquad X_0 = \frac{R_p}{Q} \qquad X_1 + X_2 = X_0$$

- Create L or C voltage divider using voltage and impedance relationship from previous slide and V divider

$$\frac{V_2}{V_1} = \sqrt{\frac{R_2}{R_1}} \quad \text{and} \quad \frac{V_2}{V_1} = \frac{X_1}{X_1 + X_2}$$

- Solve for L and C values

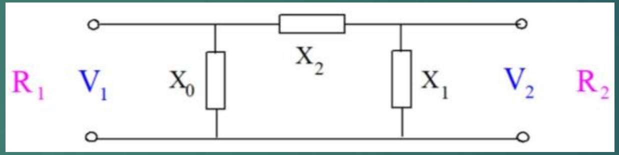
NOTES:

- Can use in either direction, to convert up or down
- When finding Rp, need to know if source/load resistances will exist on one side or both…
- If both, then Q is "loaded Q" found from $R_p = R_1$ / 2, else $R_p = R_1$

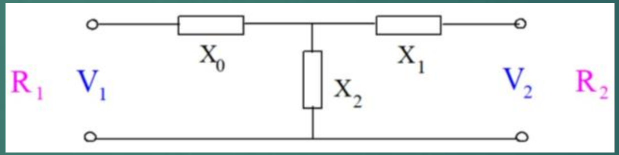
Additional Options…

To get narrower or wider bandwidths, more realizable L or C values, and to work better in face of component and PC board parasitics, also consider:

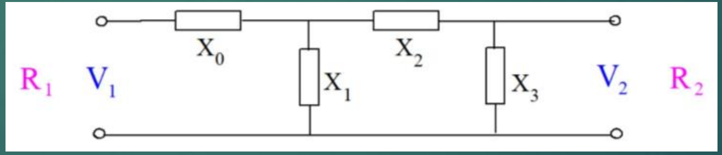
- Pi Networks



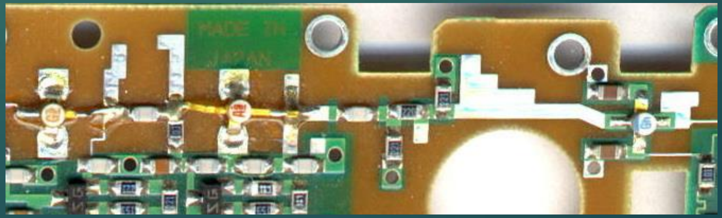
- T Networks



- LL Networks

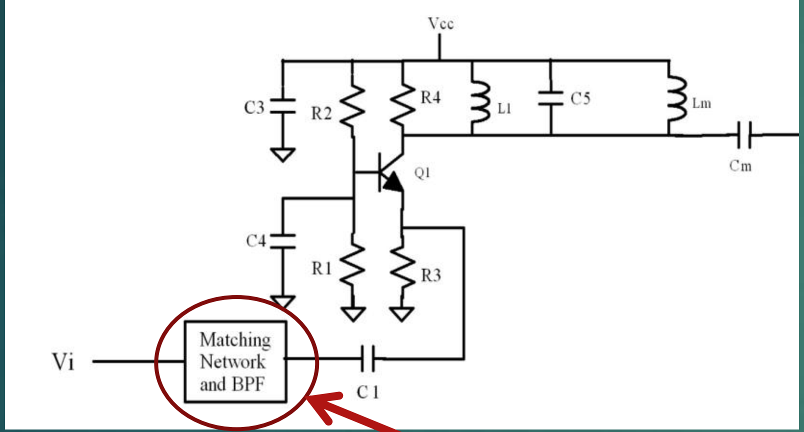


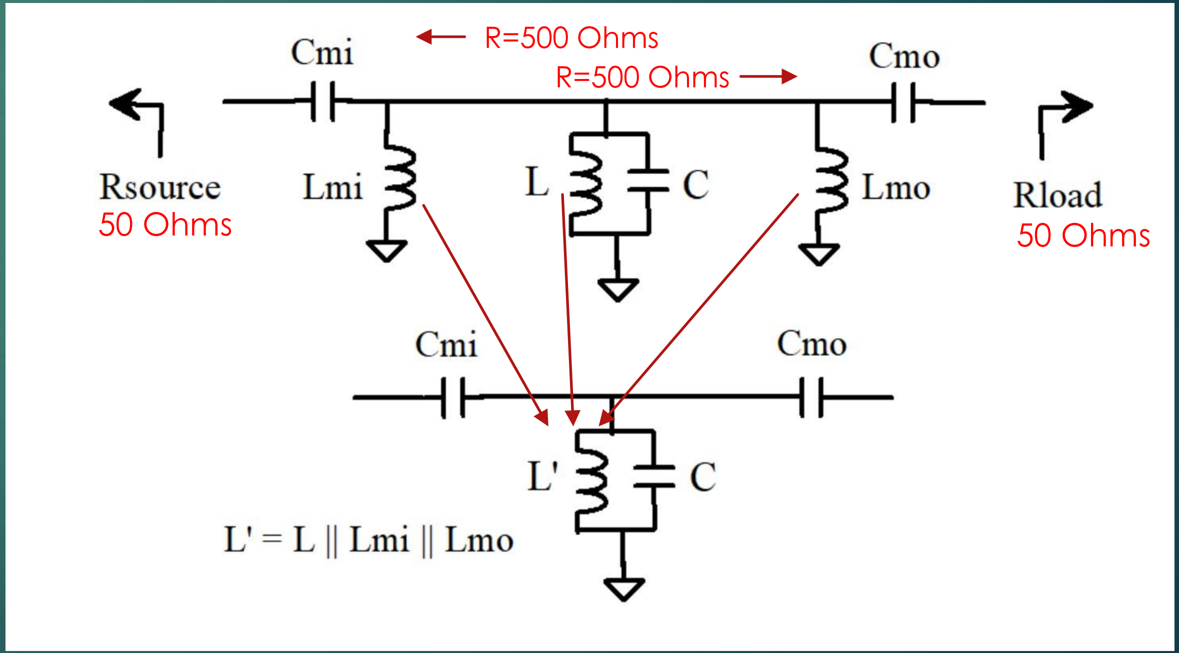
- Microstrip



T Matching Network + Filter

Use matching networks to make filters more “realizable”





Take-home assignment:

Combine with (impedance scaled) filter from Episode 1 and build, test ☺

Answer check: L’ should come out to 33 nH

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Simple “Crystal” Radio

FIGURE 1. This restored crystal radio kit from Allied Radio in Chicago cost $2.50 in the 1950s and ‘60s.

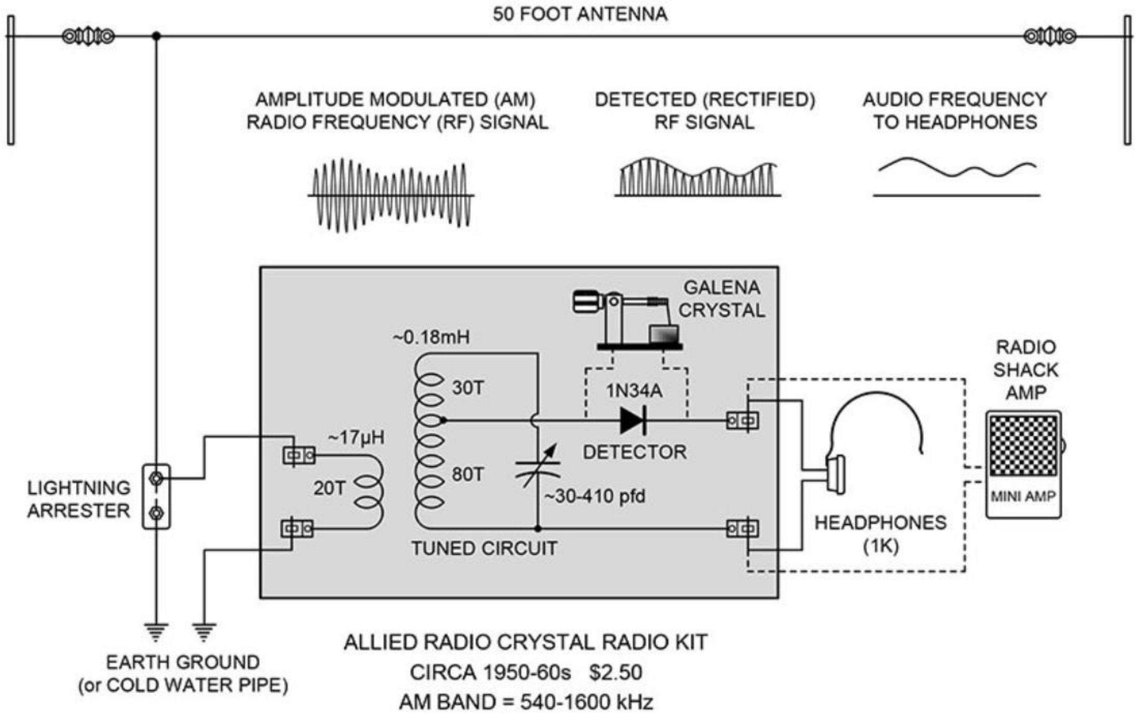
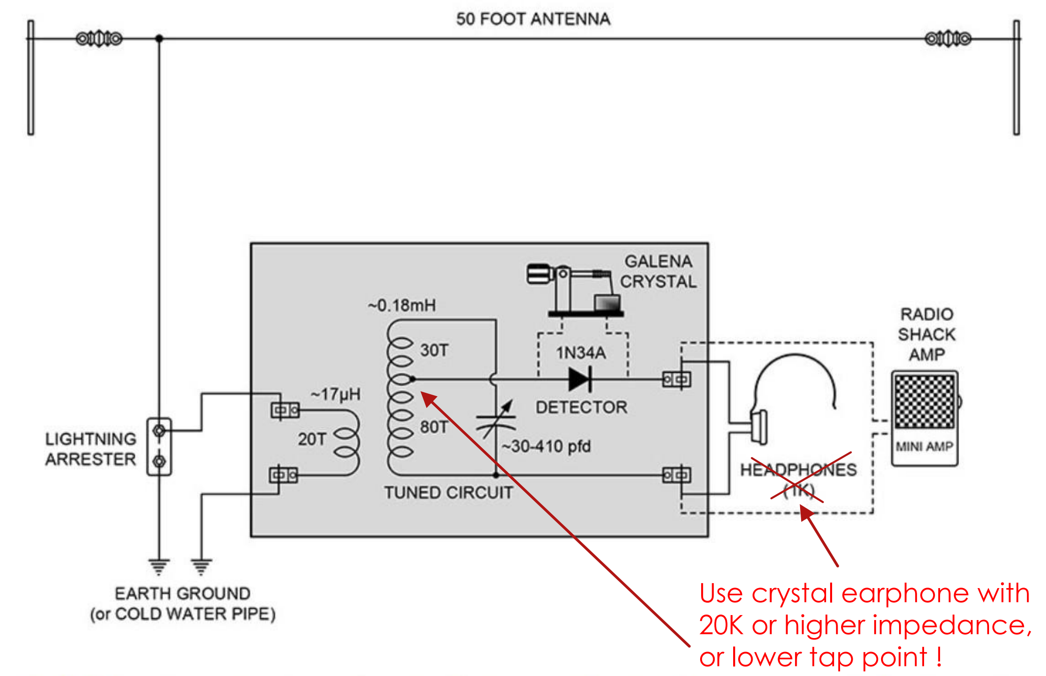


FIGURE 3. Early crystal radios used a natural galena crystal instead of a germanium diode to detect the audio modulation.

From: https://www.nutsvolts.com/magazine/article/remembering-the-crystal-radio

Hidden Complexities

(doing more with less)



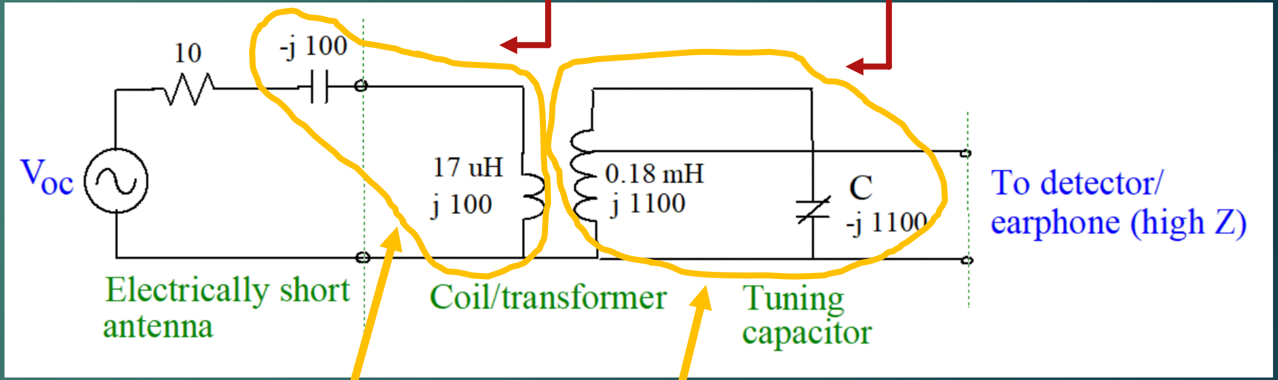
Use crystal earphone with 20K or higher impedance, or lower tap point !

FIGURE 3. Early crystal radios used a natural galena crystal instead of a germanium diode to detect the audio modulation.

From: https://www.nutsvolts.com/magazine/article/remembering-the-crystal-radio

R = 1 K
V = 10 V_{oc}

R = 11 K
V = 33 V_{oc}

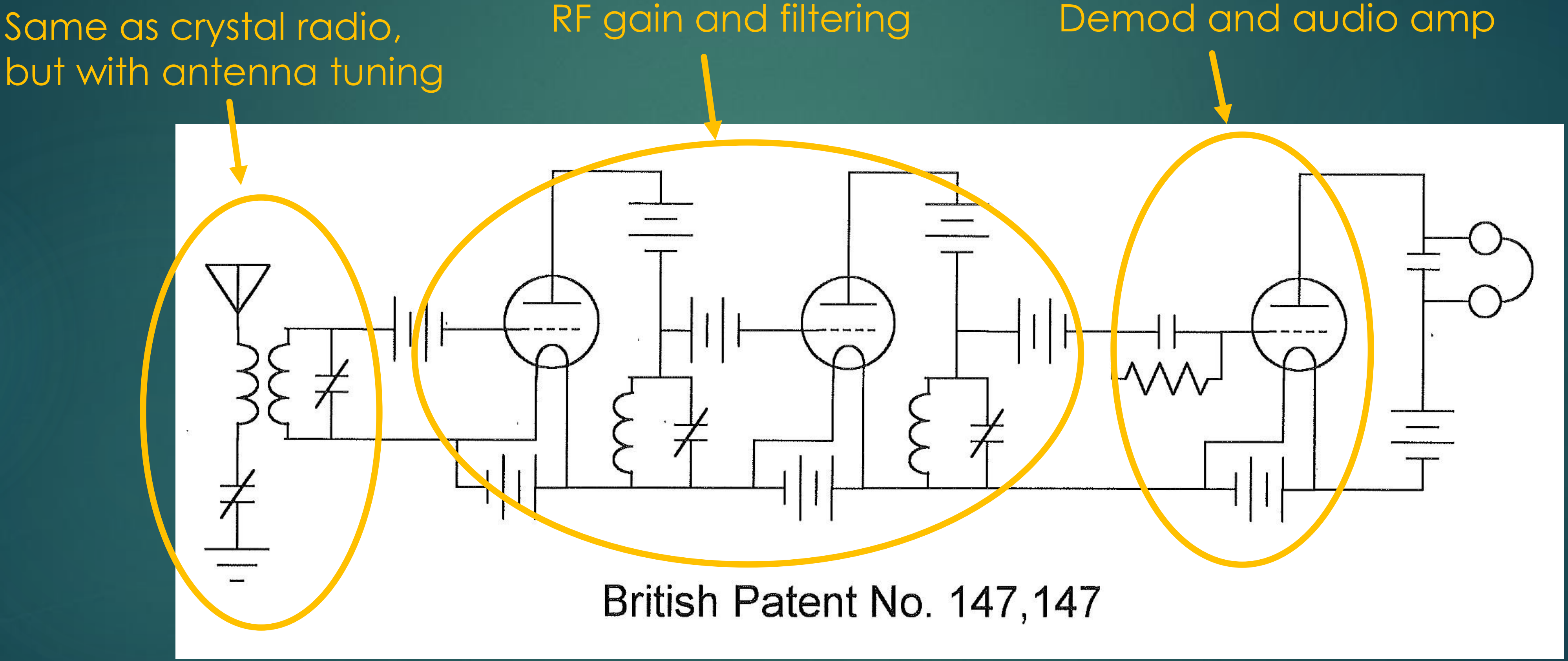


Impedance and voltage step-up, plus (untuned) bandpass filtering

More bandpass filtering
$Q = R_p/X_o = 10$
$BW = f_o/Q = 100$ kHz

Tuned RF Receiver

(doing more with more)



Same as crystal radio, but with antenna tuning

RF gain and filtering

Demod and audio amp

British Patent No. 147,147

Multi-band Shortwave Receiver

A World of Listening Enjoyment!

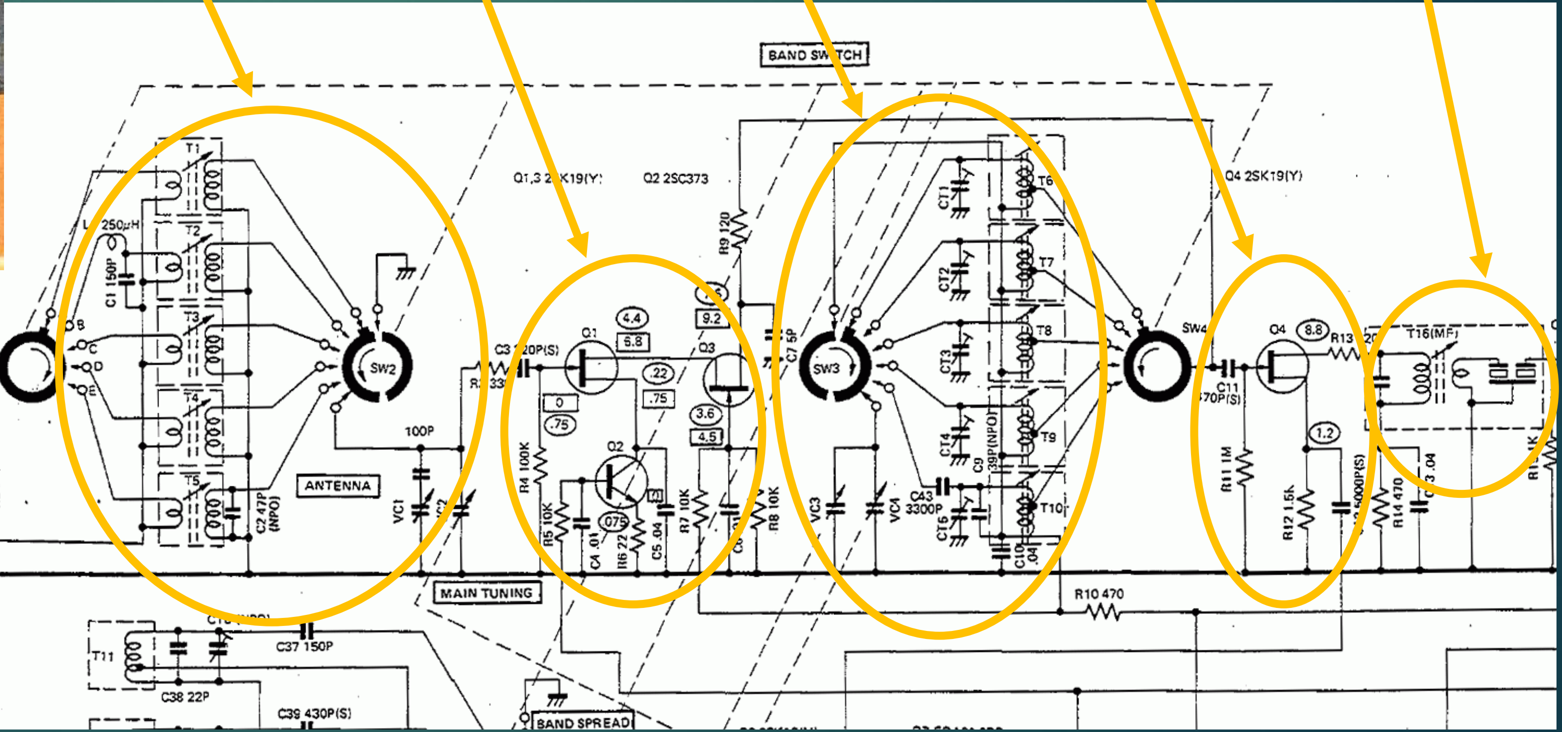
159⁹⁵

Exciting 5-Band Coverage

150 to 400 kHz Longwave
535 to 1600 kHz AM Band
1.5 to 4.5 MHz Shortwave
4.5 to 13 MHz Shortwave
13 to 30 MHz Ham and CB

Realistic® DX-160 HAM/SWL SSB/CB Receiver

Big, exciting, professional—a "hot" performer! Hear marine/aviation weather and more on longwave; English-language shortwave programs and news from every major city around the globe; Hams and Citizens Band operators, ships at sea, Voice of America, WWV time signals plus AM stations—full coverage from 150 kHz to 30 MHz. A product detector and variable BFO assure superior SSB and CW reception, too. There are 11 front panel controls including electrical bandspread tuning for 160-10 meter Ham and CB bands, and there's shortwave conversion data in the manual. FET's in all critical stages, Zener stabilization, noise limiting in IF and audio stages, illuminated "S" meter, logging scale and a headphone jack. Receiver, 6½x14¼x9¼". Matching speaker, 7x3½x5⅛". For 120 VAC or 12 VDC neg. gnd. U.L. listed. 20-152 .... 159.95



Preselect Filters

Cascode LNA

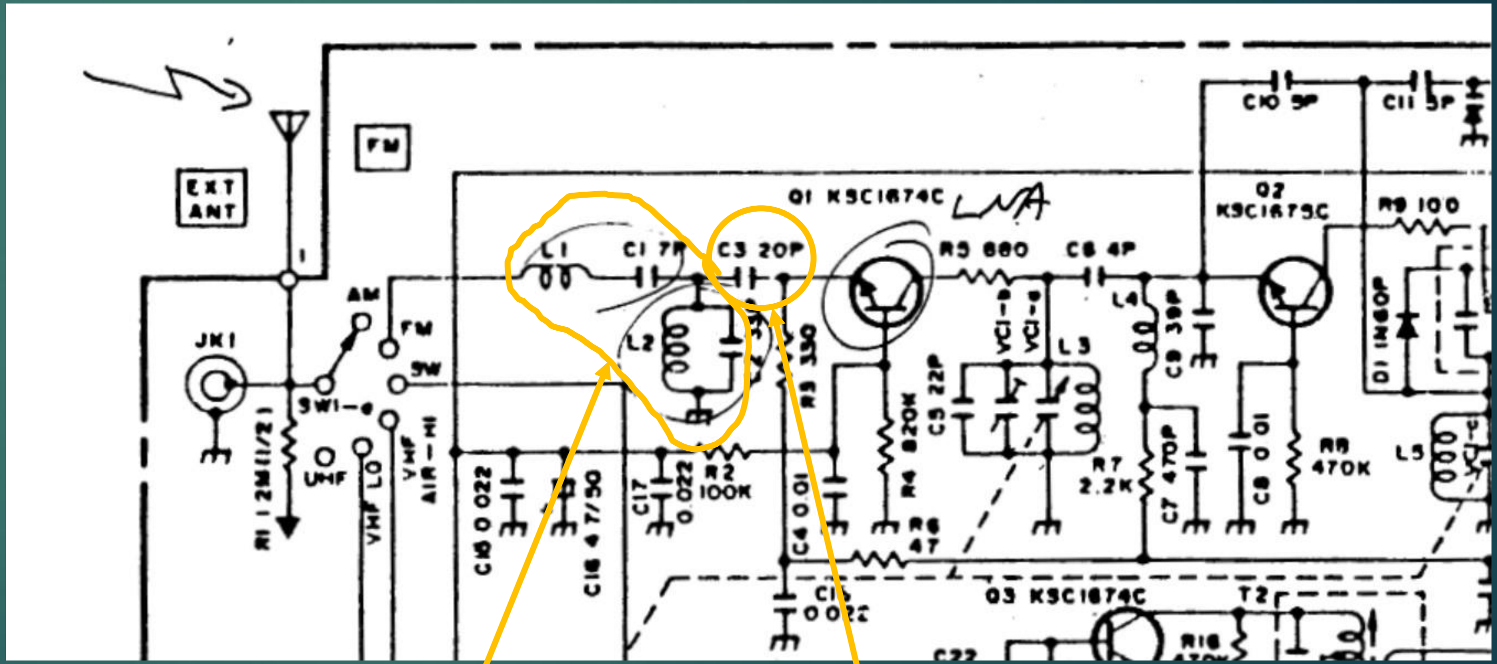
Image Filters

JFET mixer

IF filter

Antenna Input

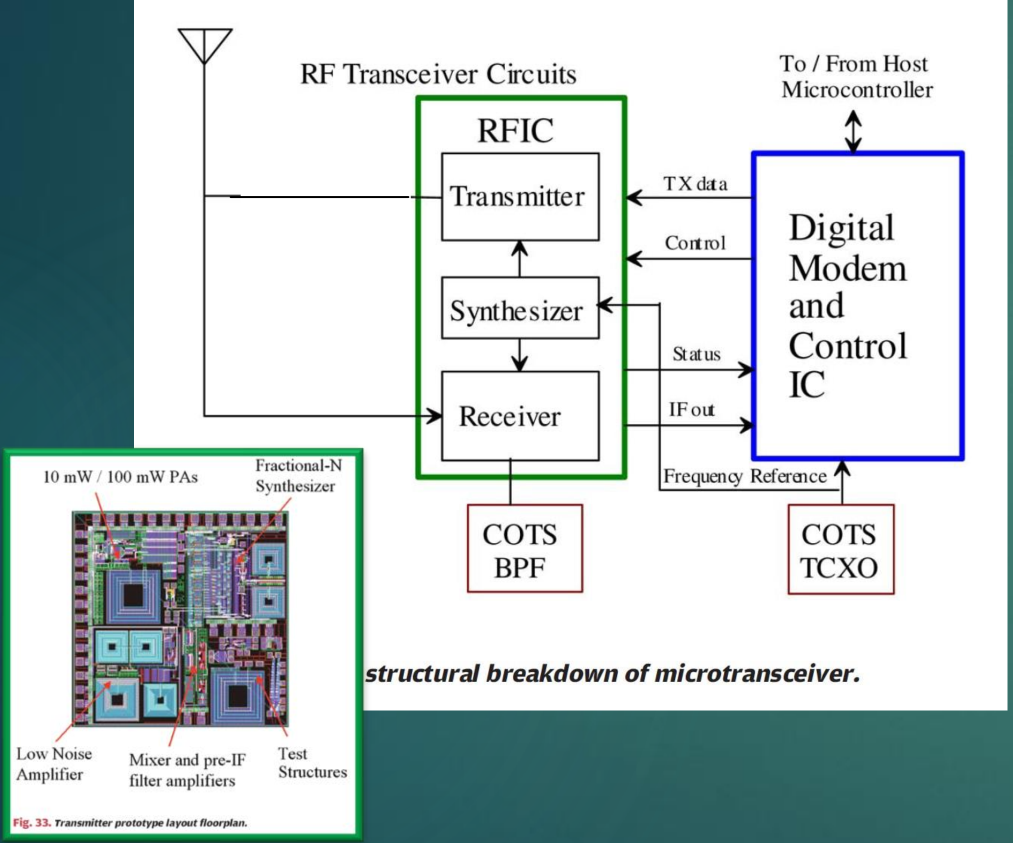
Multi-band VHF/UHF Radio



2-pole preselect BPF

C3 = 20 pF => -j 80 Ohms
So P/O matching – not just DC block

UHF Transceiver with Resonant TR Switch



structural breakdown of microtransceiver.

Fig. 33. *Transmitter prototype layout floorplan.*

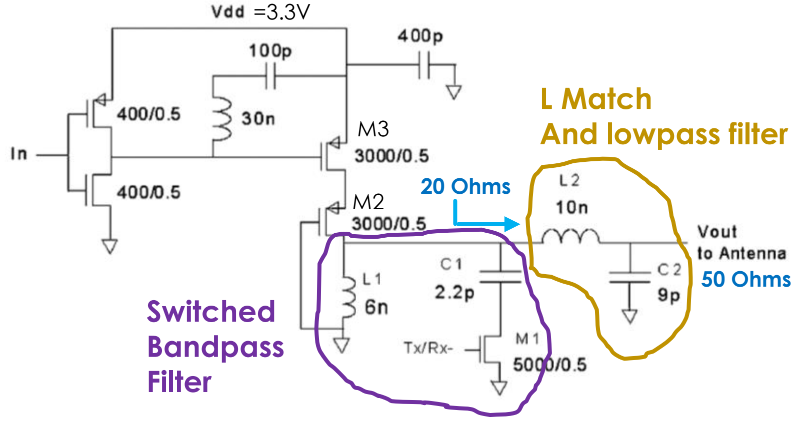


Fig. 14. Simplified schematic of 400-MHz PA. **100 mW (+20 dBm)**

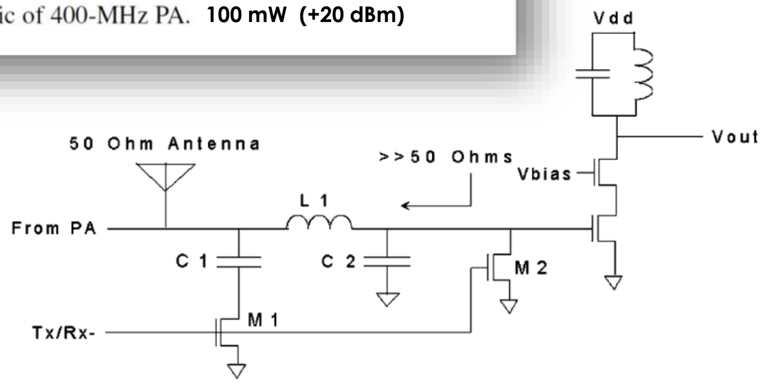


Fig. 5. Proposed switch connected to representative LNA circuit (optional source inductor not shown).

- "A resonant switch for LNA protection in watt-level CMOS transceivers", IEEE Transactions on microwave theory and techniques, 2005.
- "A microtransceiver for UHF proximity links including Mars surface-to-orbit applications", Proceedings of the IEEE, 2007.

Commercial Transceiver IC

Chipcon Products from Texas Instruments

CC1000 is based on Chipcon's SmartRF® technology in 0.35 µm CMOS.

CC1000

Single Chip Very Low Power RF Transceiver

Applications

- *Very low power UHF wireless data transmitters and receivers*
- *315 / 433 / 868 and 915 MHz ISM/SRD band systems*
- *RKE – Two-way Remote Keyless Entry*
- *Home automation*
- *Wireless alarm and security systems*
- *AMR – Automatic Meter Reading*
- *Low power telemetry*
- *Game Controllers and advanced toys*

Item	315 MHz
C31	8.2 pF, 5%, C0G, 0402
C41	Not used
C42	4.7 pF, 5%, C0G, 0402
C171	18 pF, 5%, C0G, 0402
C181	18 pF, 5%, C0G, 0402
L32	39 nH, 5%, 0402 (Ceramic multilayer)
L41	22 nH, 5%, 0402 (Ceramic multilayer)

Chipcon Products from Texas Instruments ***CC1000***

5. Circuit Description

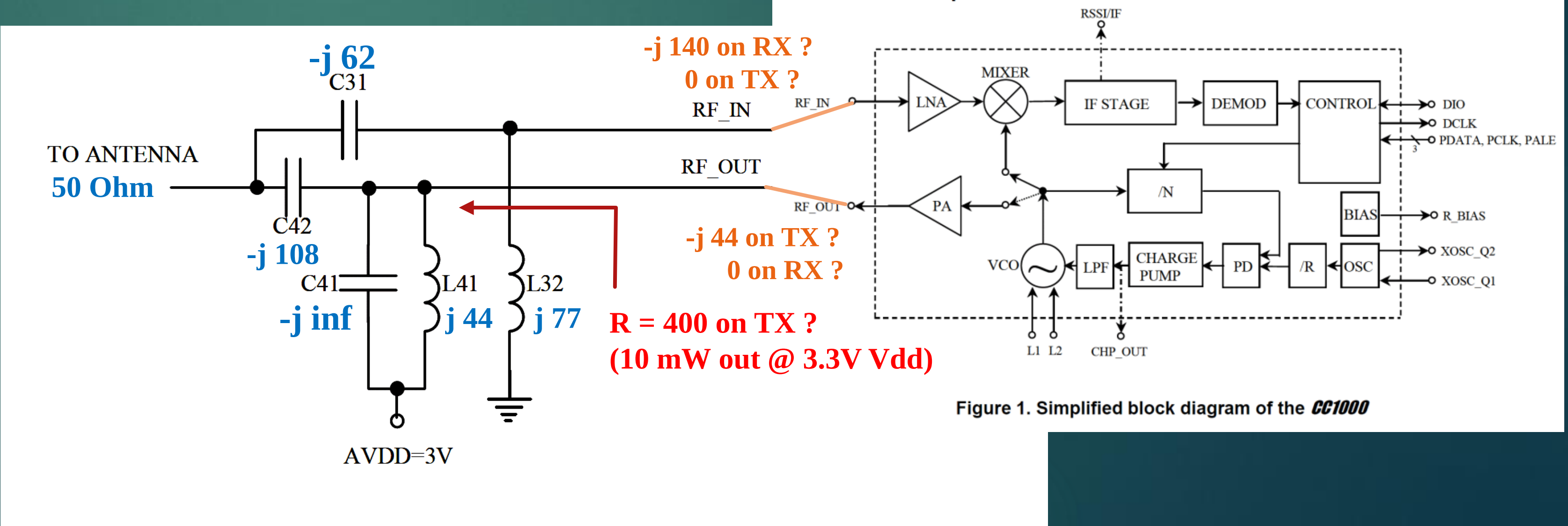


Figure 1. Simplified block diagram of the ***CC1000***

Figure 20. Input/output matching network

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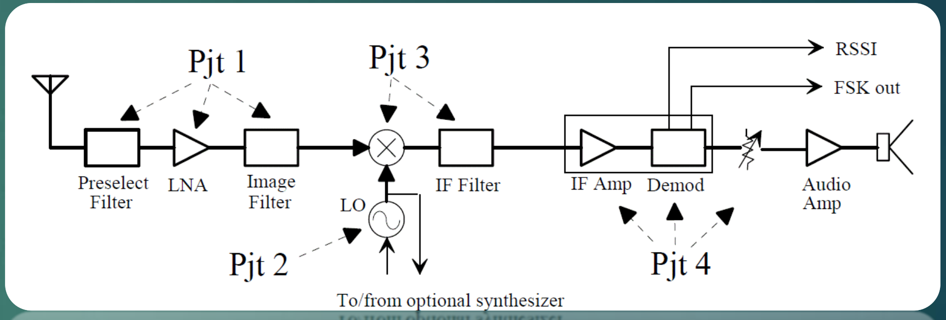
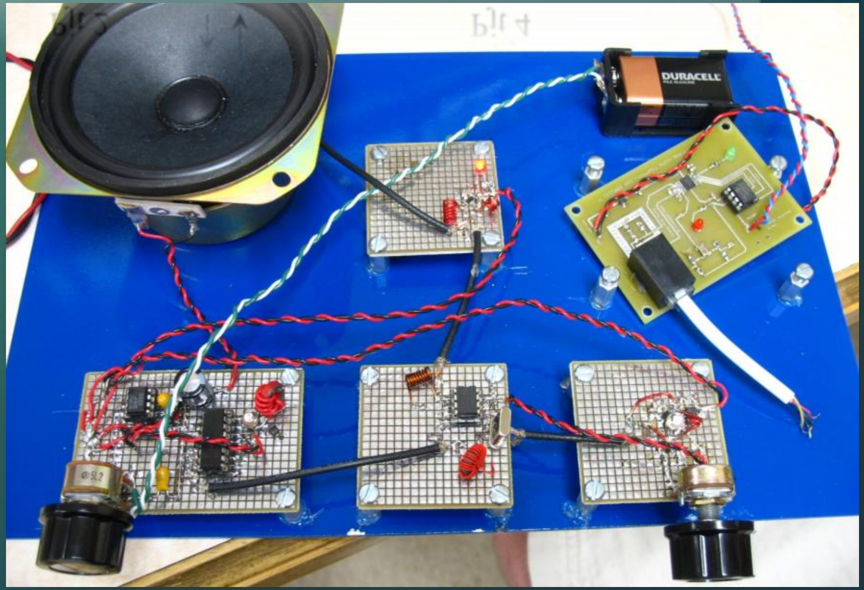
Future Videos

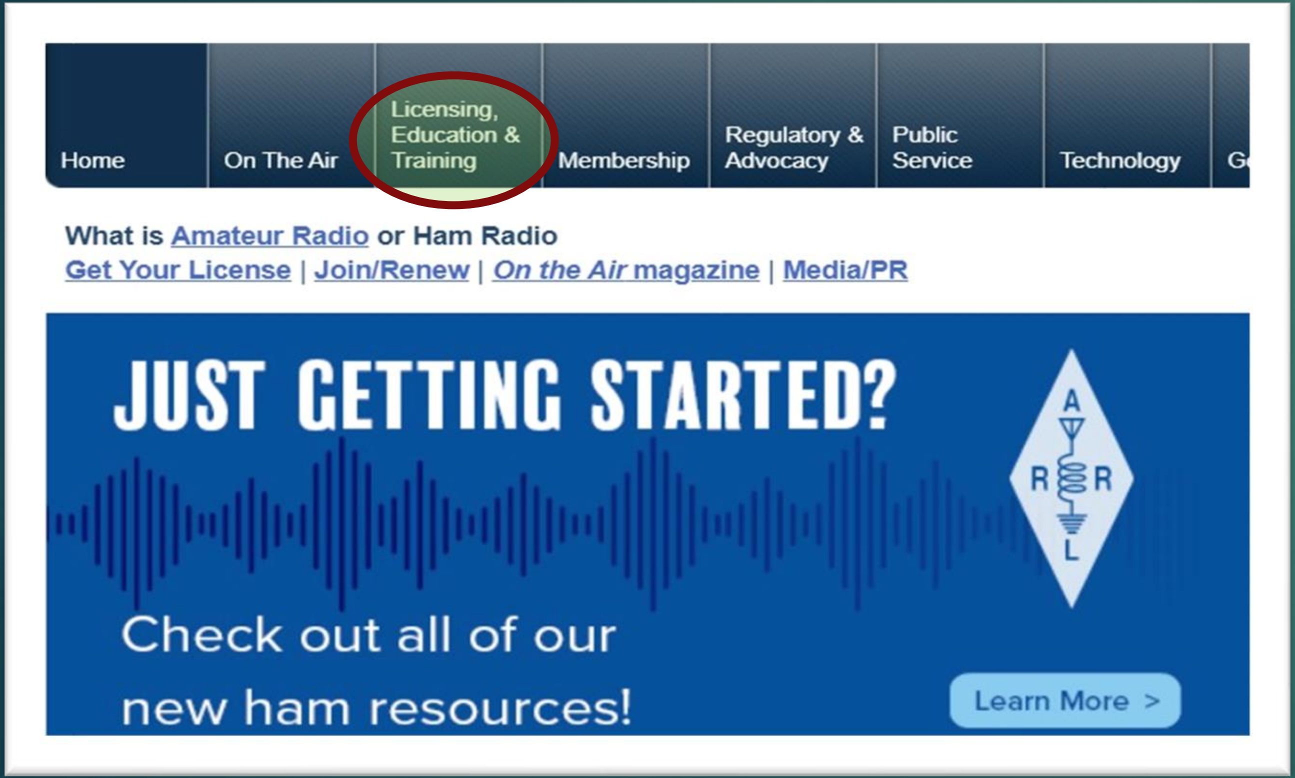
- ✓ ***Bandpass Filters and Q***
- ✓ ***Impedance Matching***
- ***Amplifiers***
- ***Local Oscillators***
- ***Mixers***
- ***IF Amps / Demodulators***
- ***Other** (e.g. antennas/synthesizers)*





Additional Resources

American Radio Relay League (ARRL)



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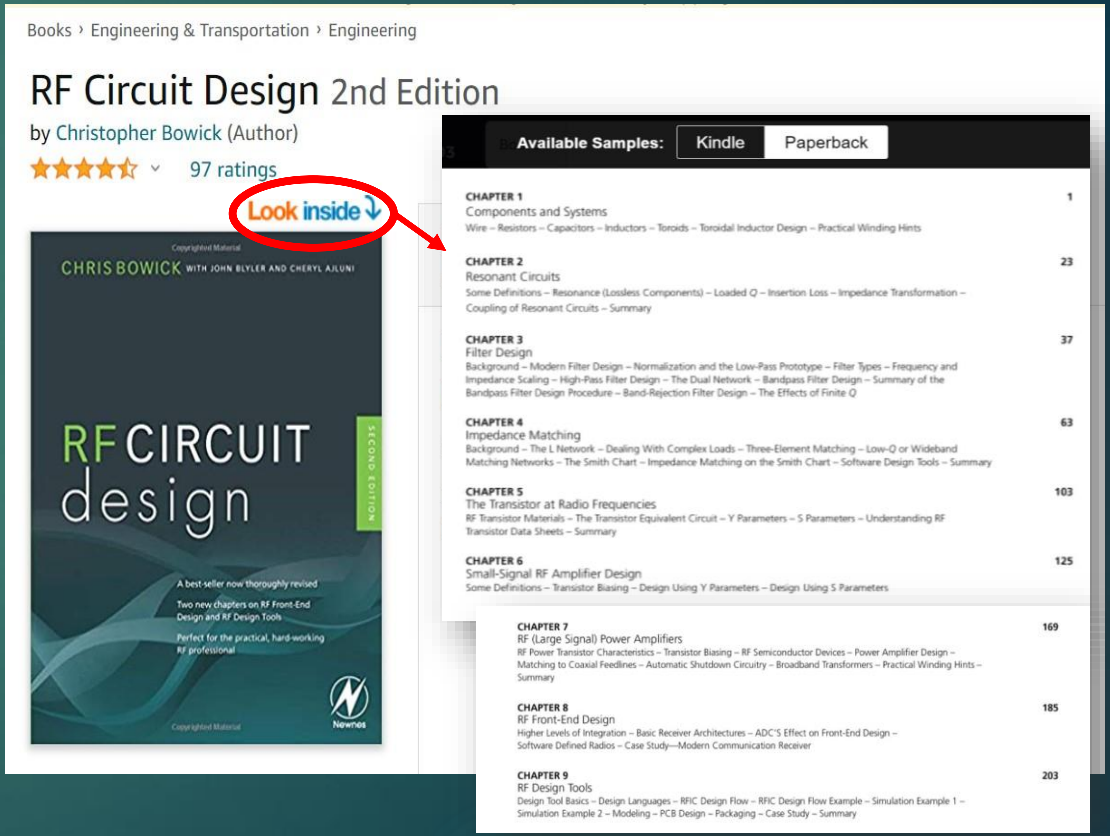
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Thanks For Watching !