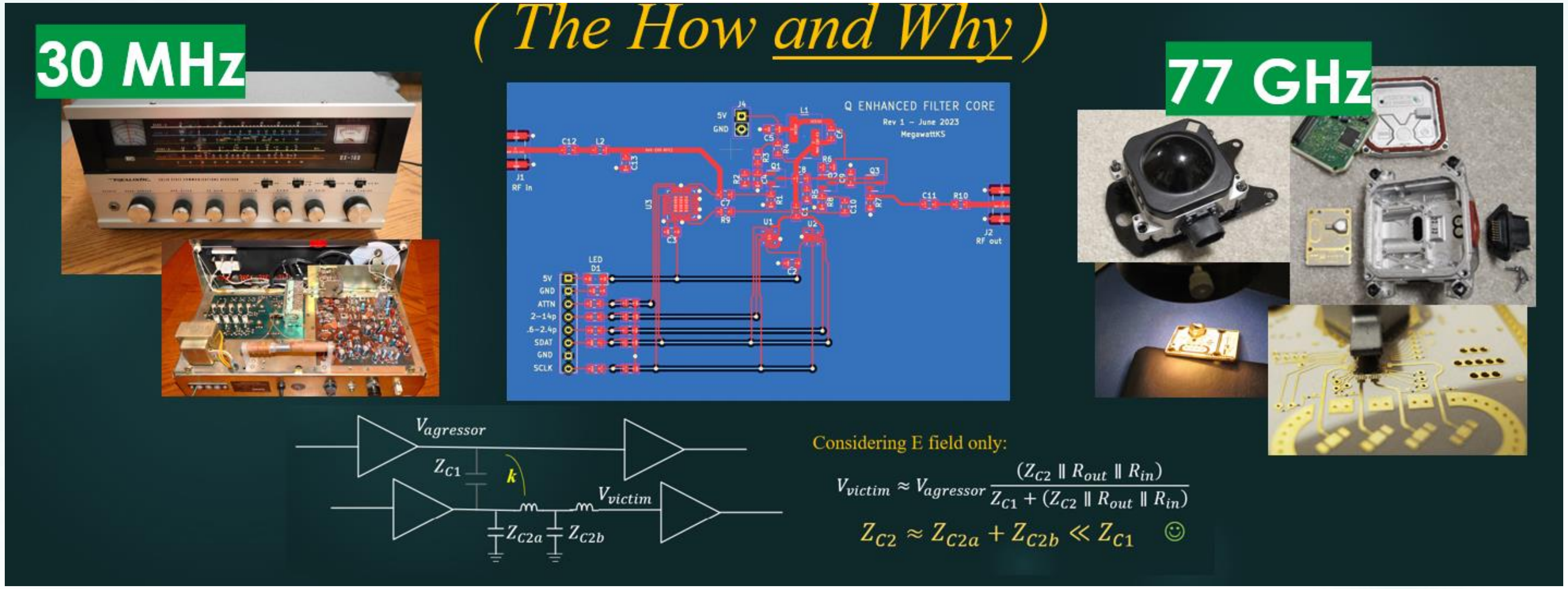
Radio Design 101
Appendix C - RF Circuit Construction & EMC

Slides downloaded from: https://ecefiles.org/rf-design/
Companion video at: https://www.youtube.com/watch?v=26fABQ9WOTQ

This video covers issues important in successful construction of radio frequency circuits. We concentrate on component parasitics and on coupling between circuits. While construction techniques are illustrated and example products are shown, the focus is on when and why the complexities of parasitics must be considered and how to address them.

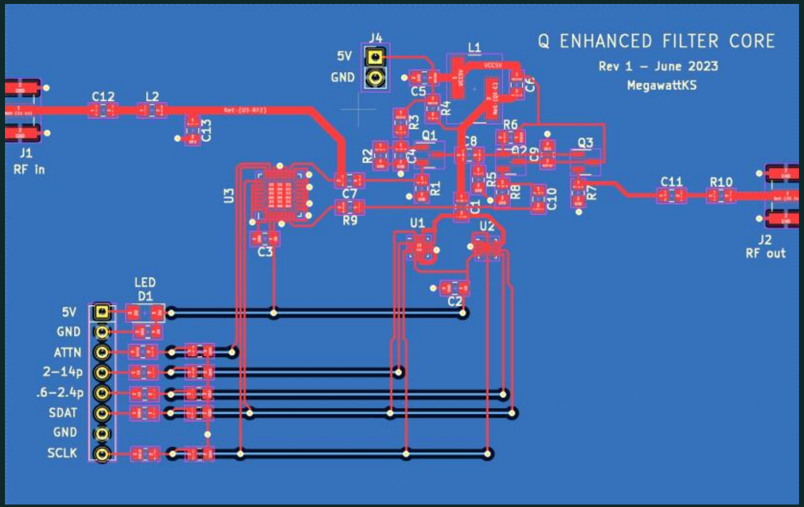


Radio Design 101
Appendix C

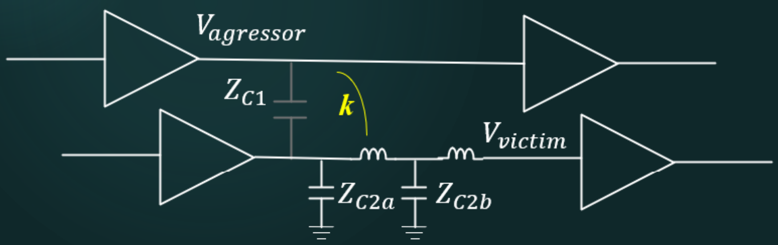
RF Circuit Construction & EMC

(The How and Why)

30 MHz



77 GHz



Considering E field only:

$$V_{victim} \approx V_{agressor} \frac{(Z_{C2} \parallel R_{out} \parallel R_{in})}{Z_{C1} + (Z_{C2} \parallel R_{out} \parallel R_{in})}$$

$$Z_{C2} \approx Z_{C2a} + Z_{C2b} \ll Z_{C1}$$ ☺

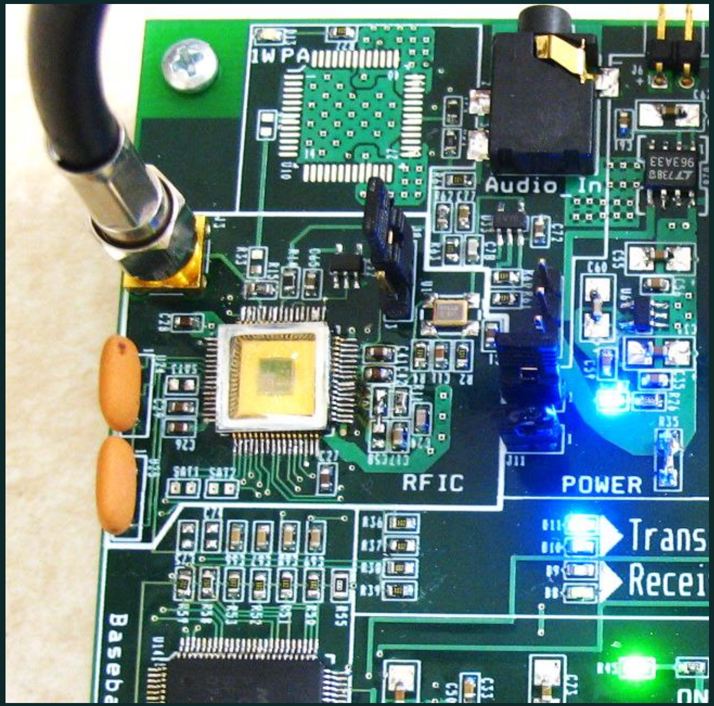
Key Issues

Mechanical / Thermal

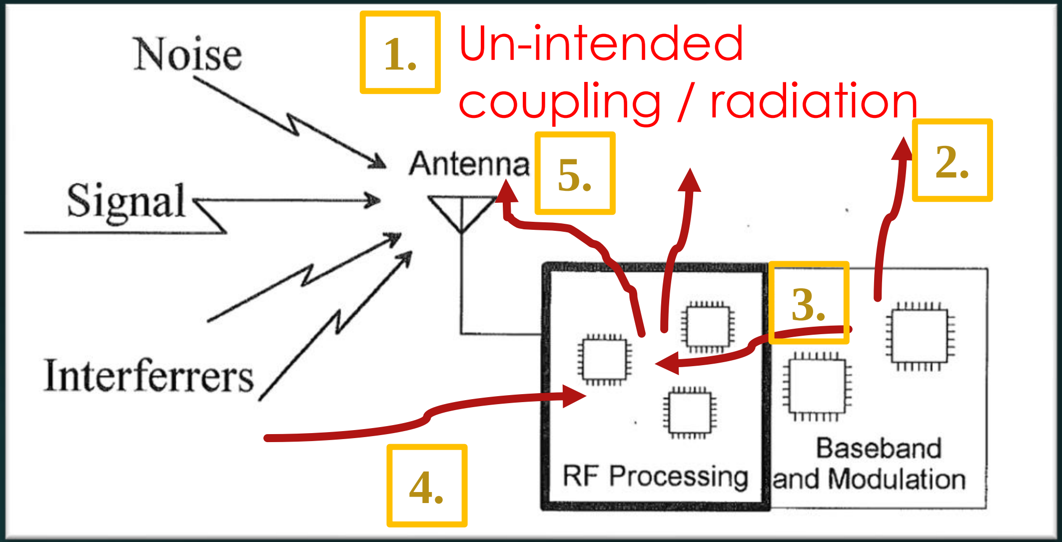
Application/Appearance, Form-Factor, Materials, Heat-Dissipation, …

Electrical

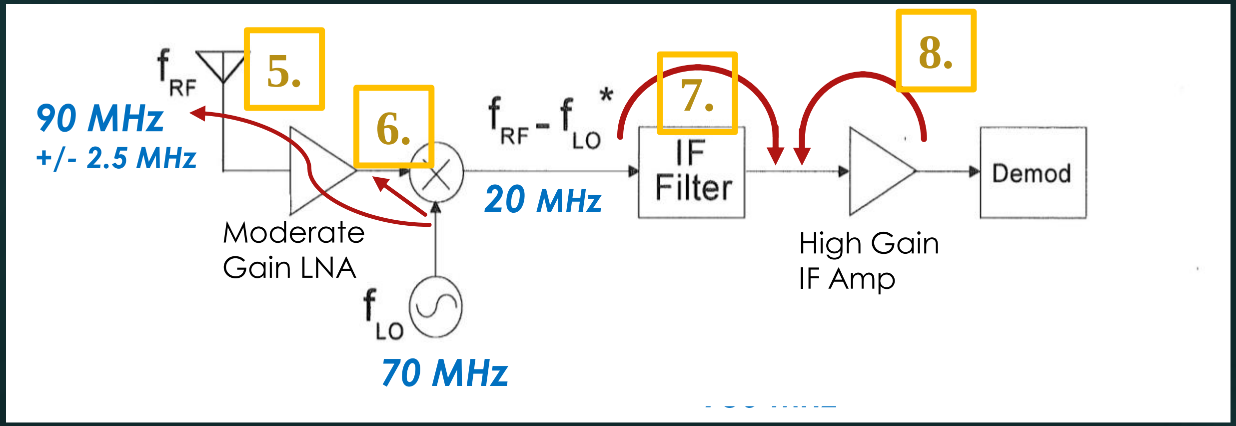
- Component placement and interconnection
- C and L parasitics
- Circuit/component size vs frequency
- PCB ground planes and Shielding (for EMC/SIPI)
- PCB traces, microstrip, CPW, twisted-pairs, coax, busses, …



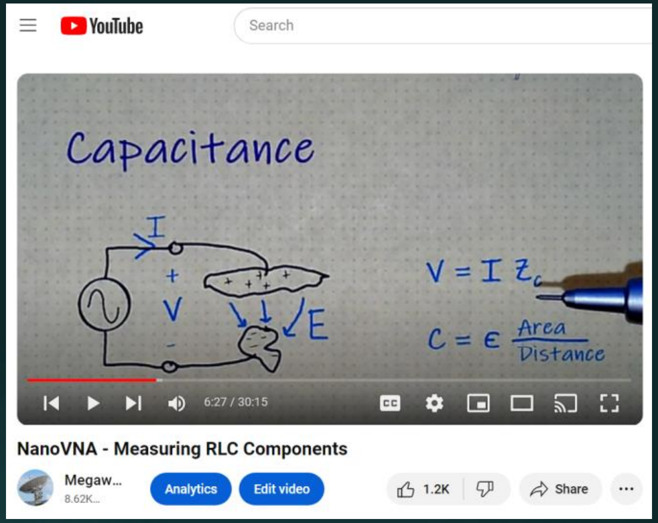
Why This Matters

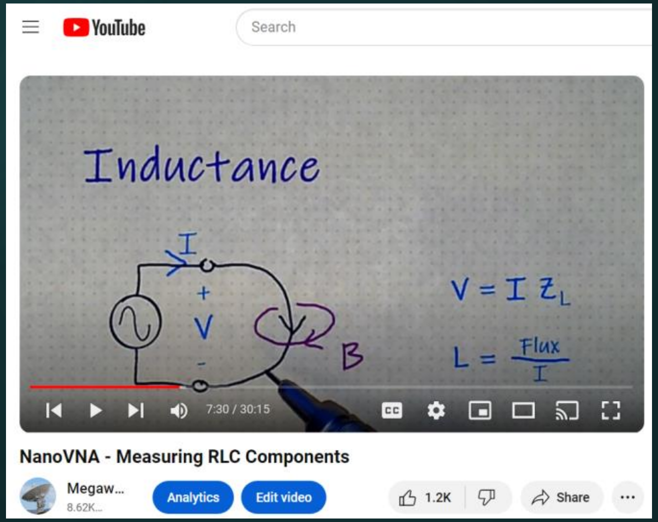


1. Electromagnetic Compatibility (EMC) issues
2. Digital signals can generate external RFI
3. Clock signals create spurious responses
4. Spurious reception from coils / etc.
5. LO Radiation
6. LO to RF port coupling -> DC offsets
7. Crosstalk and limited isolation
8. Instability and other circuit 'misbehavior'



Why it Happens





C

$Z = -jX_C$

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

L

$Z = jX_L$

$$X_L = 2\pi f L$$

|Z| Values vs Frequency

1 pF at 1 MHz: Xc = 159 K Ohms ☺

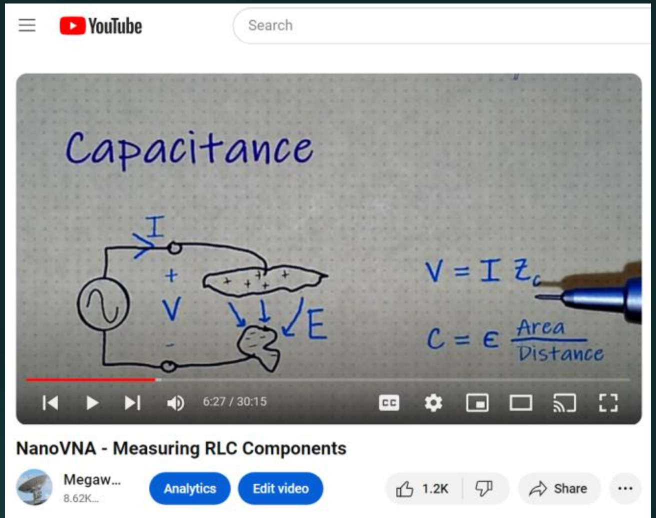
1 pF at 1 GHz: Xc = 159 Ohms ☹

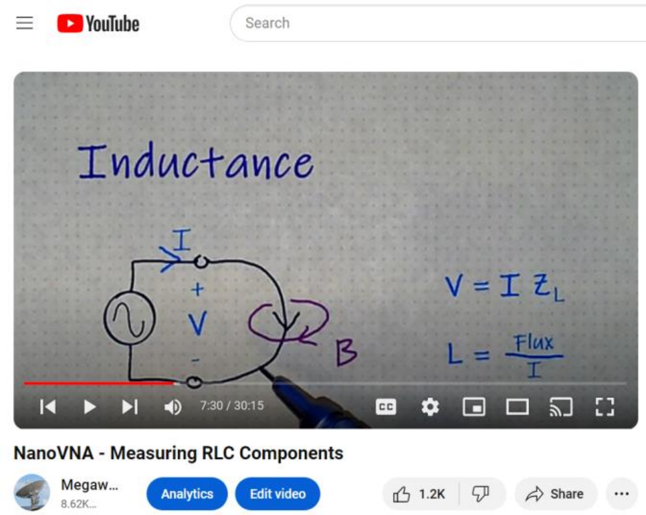
Compare with typical subcircuit node and I/O impedances of 10 to 10K Ohms

10 nH at 1 MHz: X_L = 0.063 Ohms ☺

10 nH at 1 GHz: X_L = 63 Ohms ☹

Estimating L and C Values





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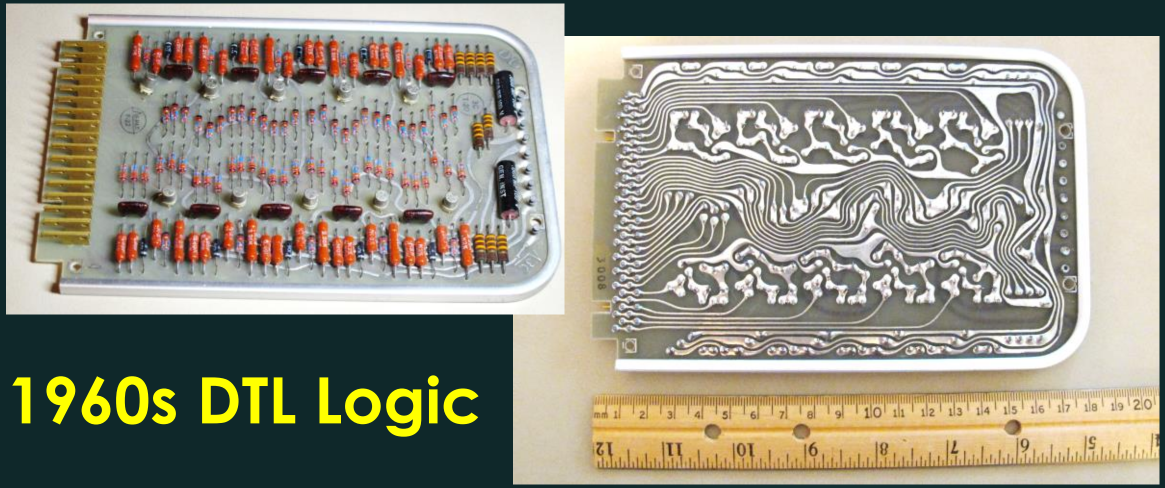


1960s DTL Logic

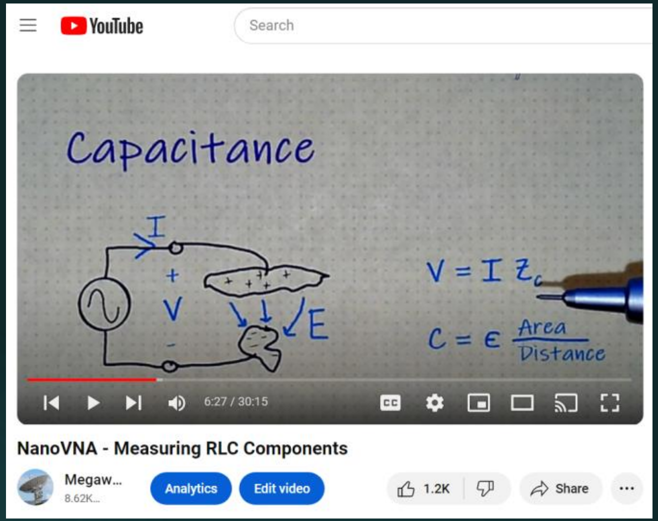
C between adjacent traces

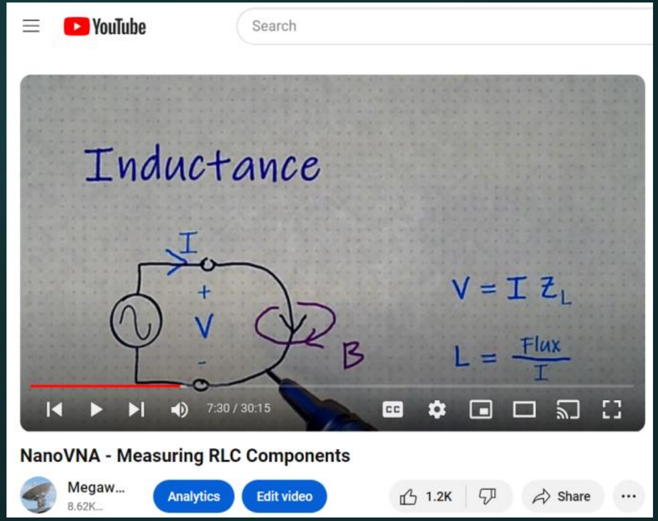
$$C \approx \frac{\epsilon_{eff}(width)(length)}{separation} \approx \frac{(8.85\ pF/m)(2mm)(0.2m)}{(2mm)} \approx 2pF$$

L along traces

$$L \approx (1\ nH/mm)(200\ mm) = 200\ nH$$

L and C on Multilayer PCBs



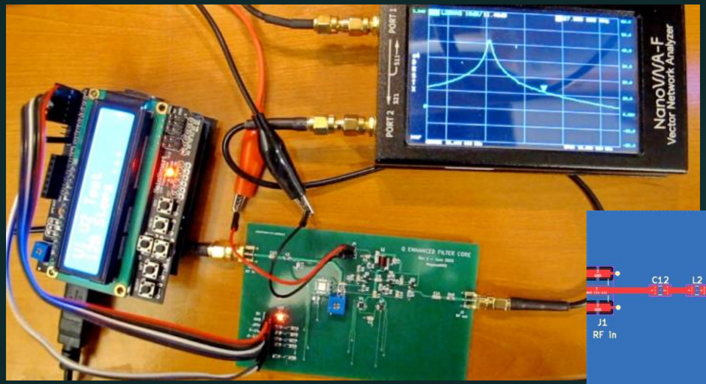


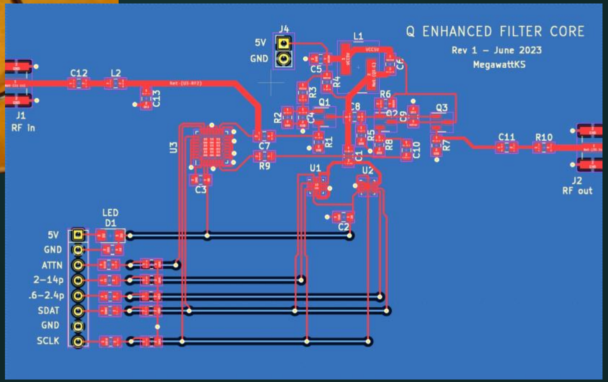
$$Z = -jX_C$$

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

$$Z = jX_L$$

$$X_L = 2\pi f L$$



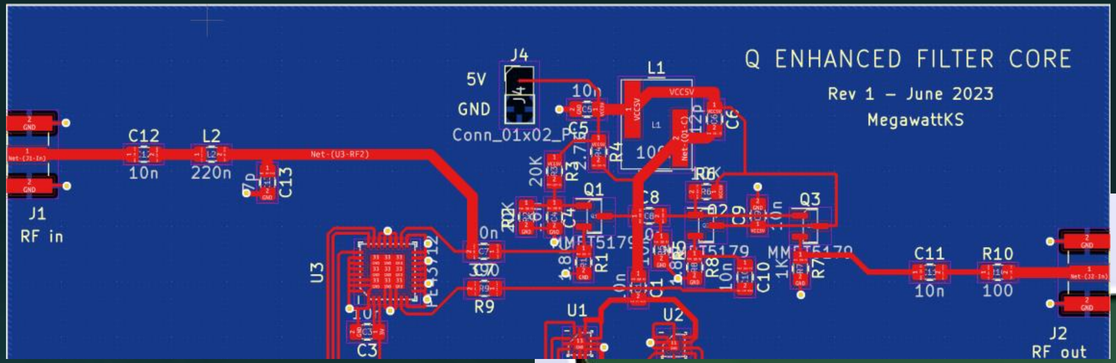


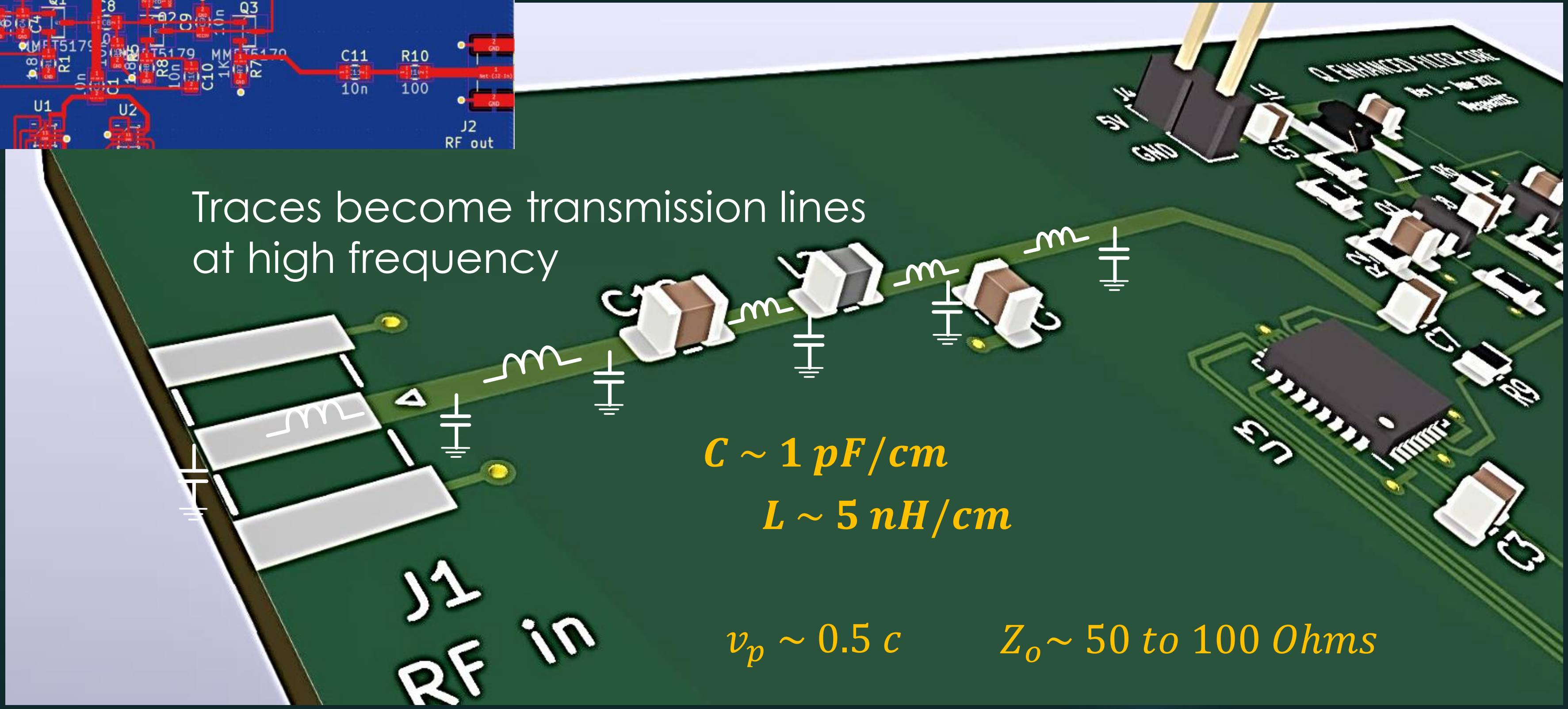
2023 VHF Bandpass Filter

- Put ground plane below traces !
- *Ground plane reduces E and B field coupling and L per unit length ☺*
- Must consider L and C per unit length and apply transmission-line theory in general…

PCB Traces above Ground Plane

(“Microstrip” Traces)



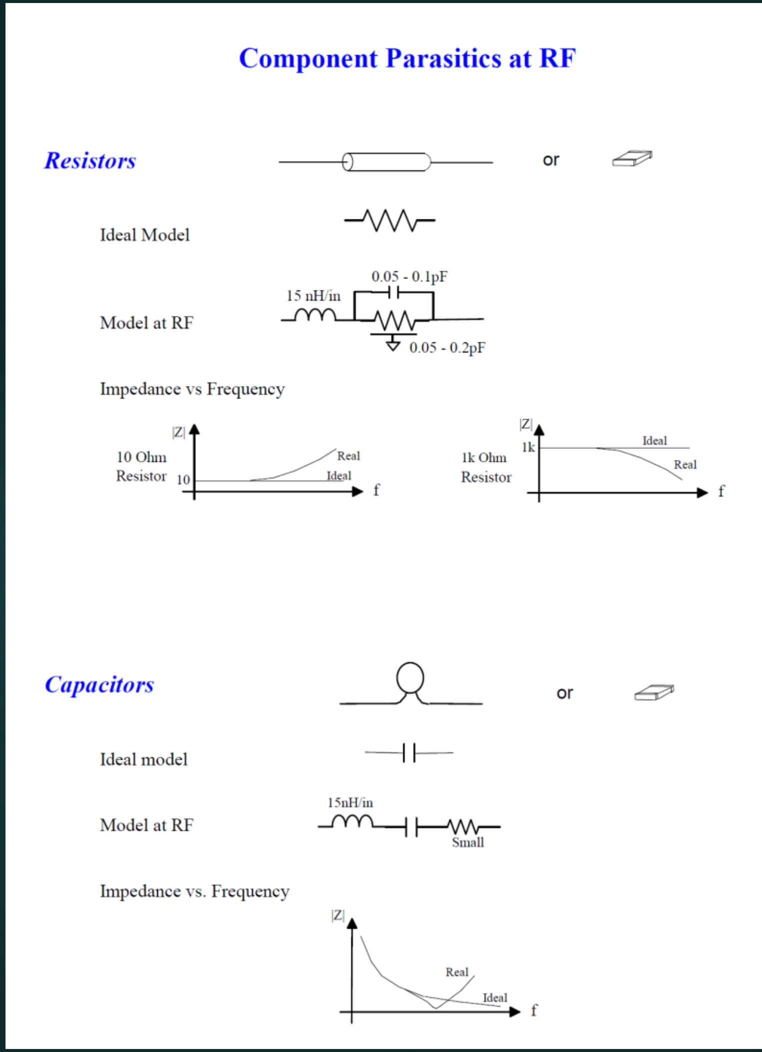


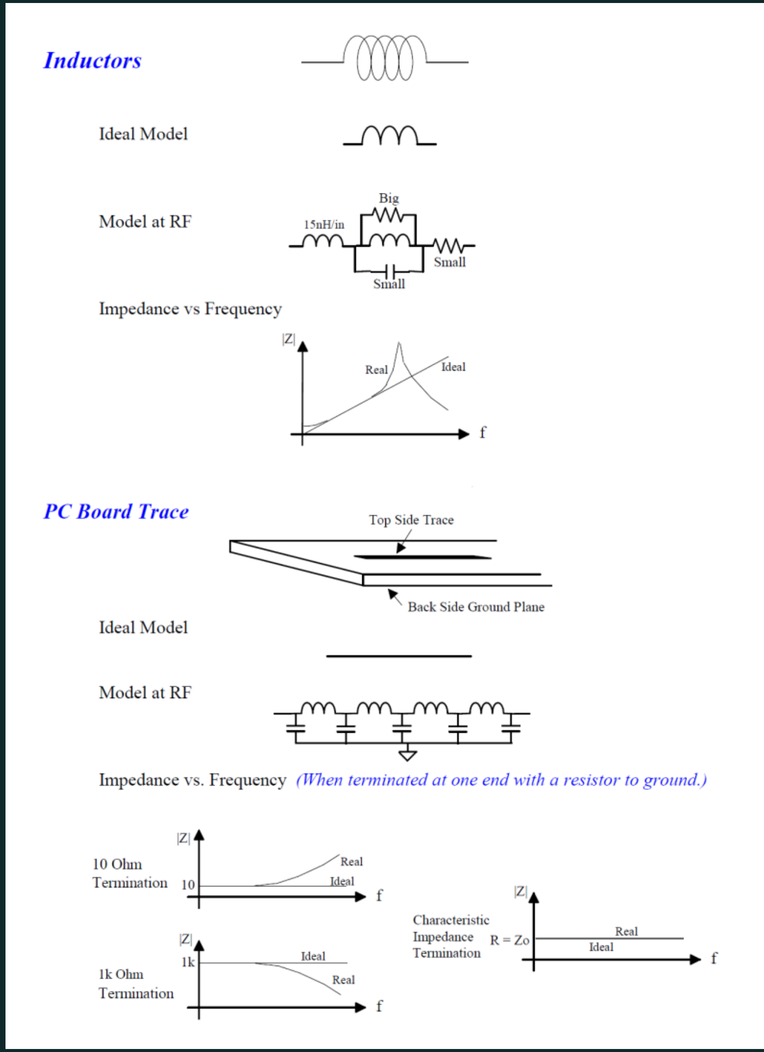
$C \sim 1\, pF/cm$

$L \sim 5\, nH/cm$

$v_p \sim 0.5\, c$ $\quad$ $Z_o \sim 50\ to\ 100\ Ohms$

Class Handout on Parasitics





PCB traces, wires, etc are *transmission lines* at "high frequency".

Important if length is > 1/10 wavelength

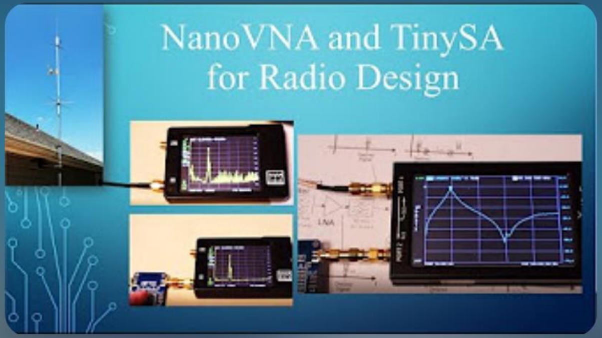
$$\lambda = \frac{c}{f} v_r$$

$$v_r \sim 0.5$$

$$\Rightarrow \frac{\lambda}{10} \approx 1.5\ cm\ at\ 1\ GHz$$

L, C, and characteristic impedance varies with trace width and board interlayer thickness

Videos on These Topics



NanoVNA and Radio Frequency / Microwave Tech

MegawattKS

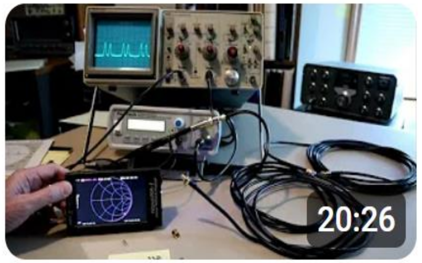
12 videos 17,167 views Last updated on Feb 10, 2024

Play all

Shuffle

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.

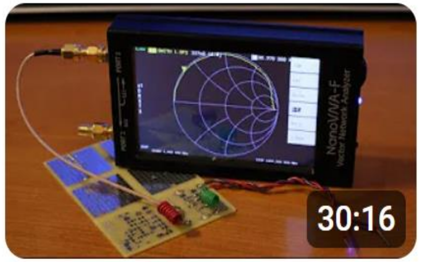
3



NanoVNA Demonstrations - Coax line reflections and Smith charts

MegawattKS • 10K views • 3 years ago

4

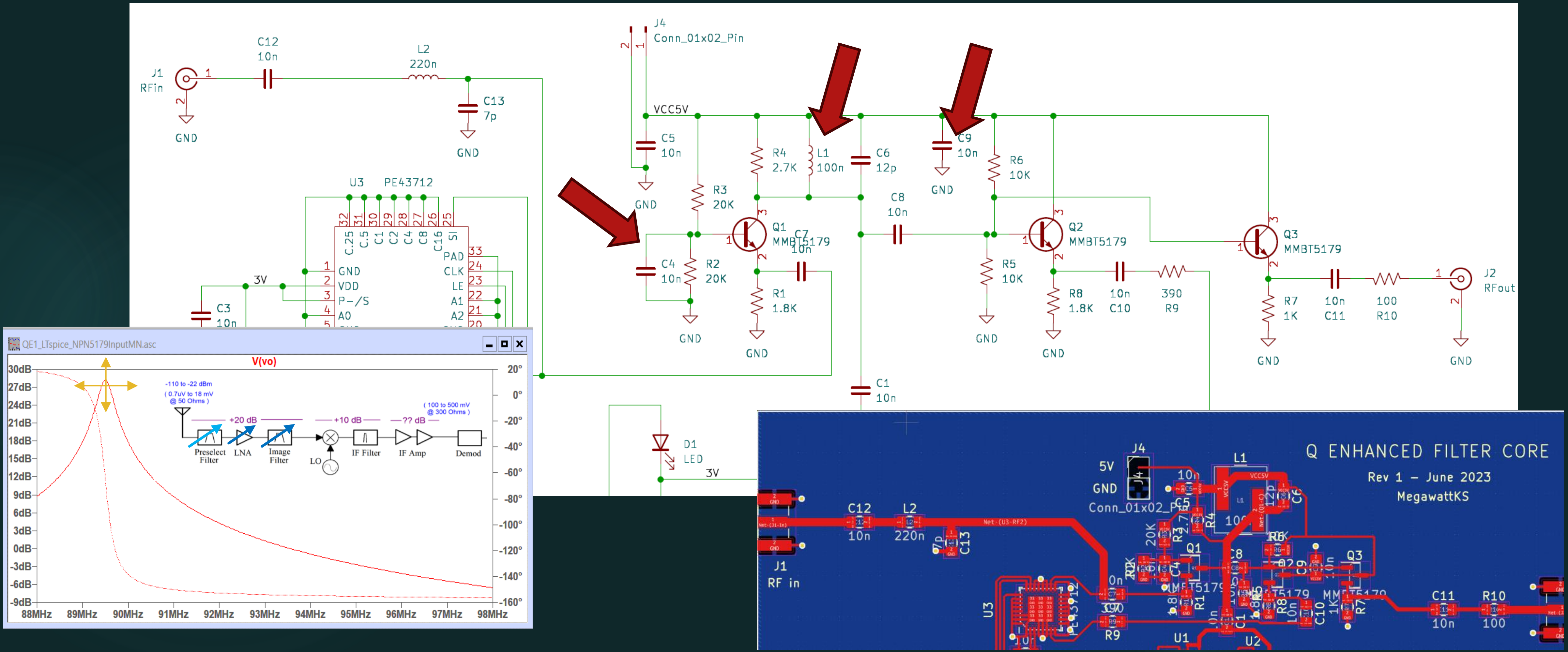


NanoVNA - Measuring RLC Components

MegawattKS • 50K views • 3 years ago

Effects at Schematic Level

(‘Add in’ parasitics for correct design/simulation)



Radio Construction Examples

HF: 0.1 – 30 MHz

- 1966 Eico 753 HF Transceiver with point-to-point wiring
- 1967 Heathkit SB101 Amateur Radio Transceiver with early PCBs
- 1975 Realistic DX160 Shortwave Receiver (Solid State)
- Homebrew 80m Transceiver teardown with unique 1-layer RF protoboards

VHF: 100 MHz

- Radio Design 101 YouTube series FM Receivers with unique 2-layer RF protoboards
- Q-enhanced bandpass filters on protoboard, 2-layer PCB, and 4-layer PCB

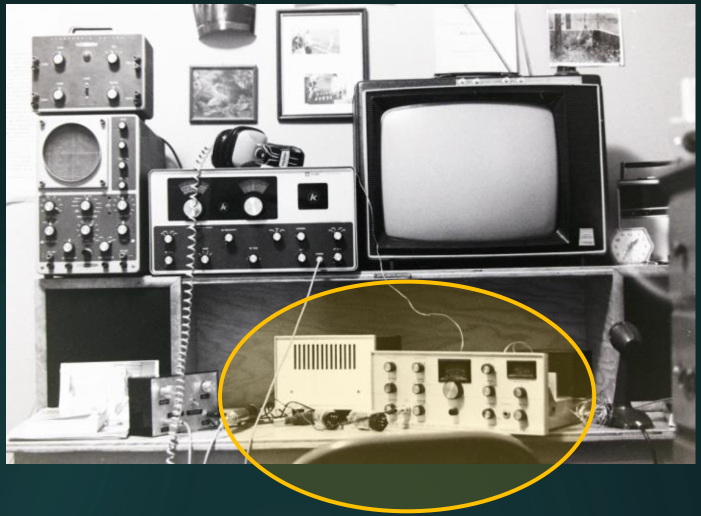
UHF: 430 – 450 MHz

- Fully-integrated QPSK transceiver IC with on-chip ground-plane and counter-wound inductors

Microwave / Millimeter Wave: 2.4 to 77 GHz

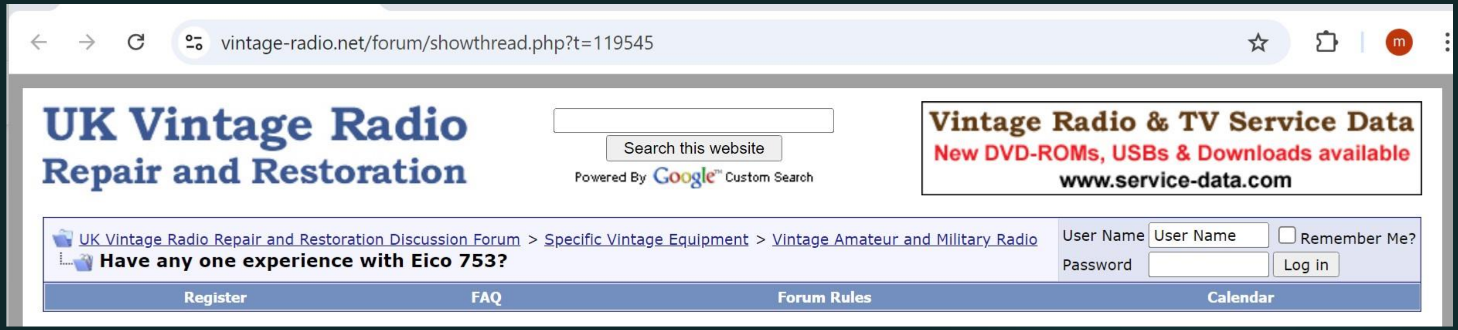
- Commercial Automotive FMCW Radar (fully packaged, teardown)

Early HF Radio Construction



B&W photo of my amateur radio 'shack' around 1970

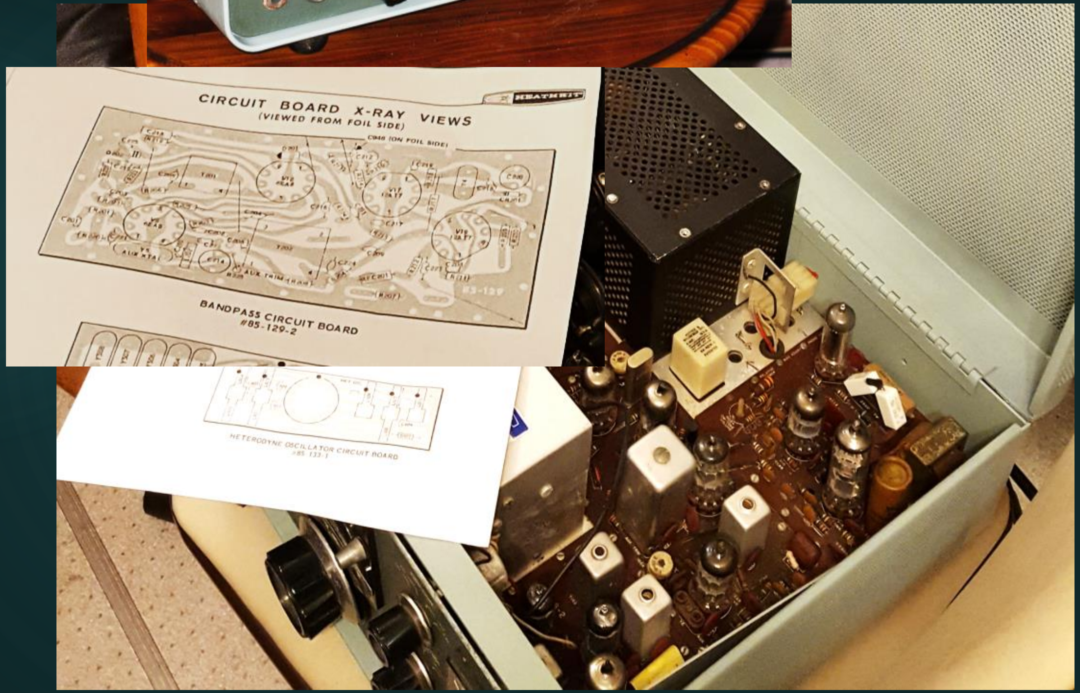
1966 vintage Eico 753 radio at bottom center



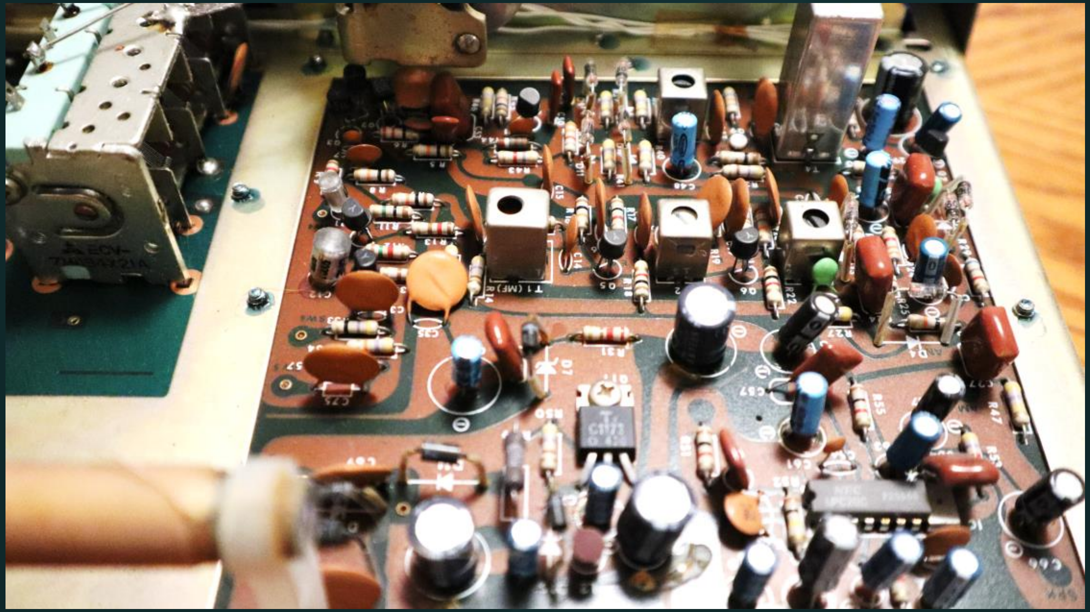
Pictures of 753 internals from 2006 post by 6AL5W-Martin, Germany

HF Radios with Early PCBs

1967

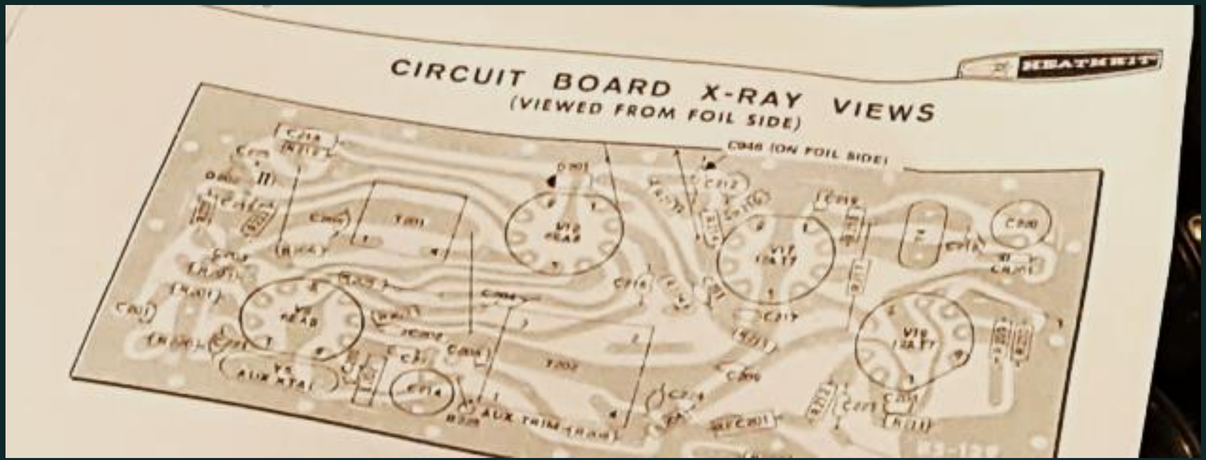


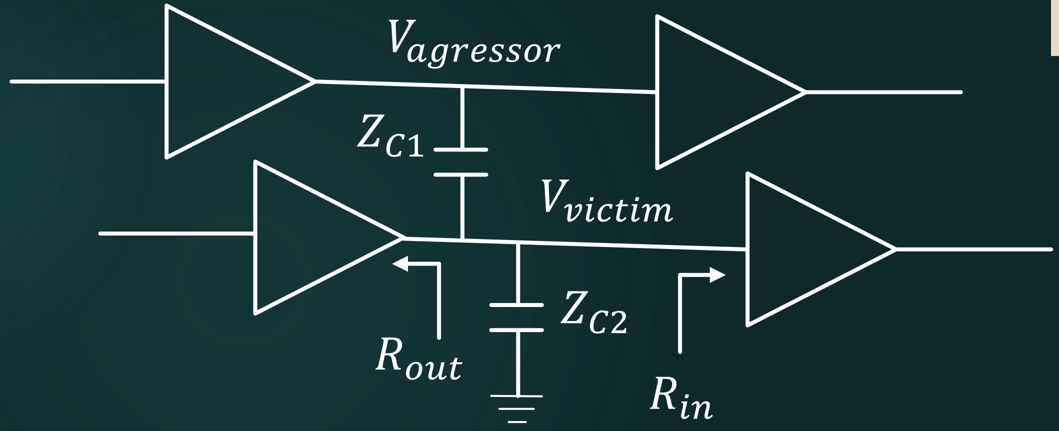
1975 …



Problems with 1-Layer PCBs

- Routing Limitations
- Coupling and crosstalk !
- Works OK thru HF: 0 - 30 MHz …





$$V_{victim} = V_{agressor} \frac{(Z_{C2} \parallel R_{out} \parallel R_{in})}{Z_{C1} + (Z_{C2} \parallel R_{out} \parallel R_{in})}$$

Here, typically we may have

$$Z_{C2} \geq Z_{C1}$$ ☹

But in low frequency regime, hopefully

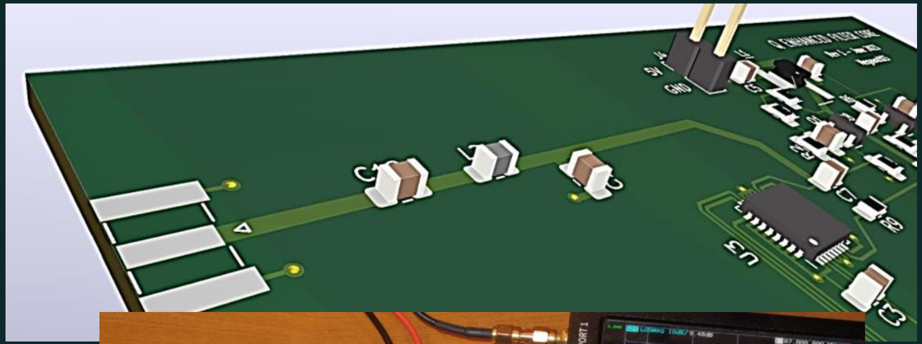
$$Z_{C1} \gg R_{out} \parallel R_{in}$$ ☺

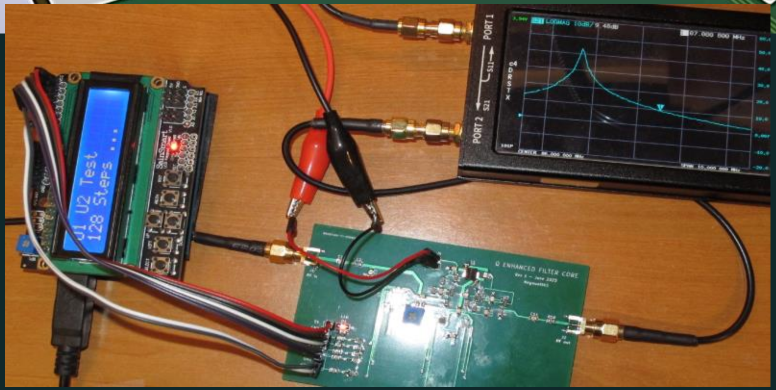
So this can be OK depending on circuits

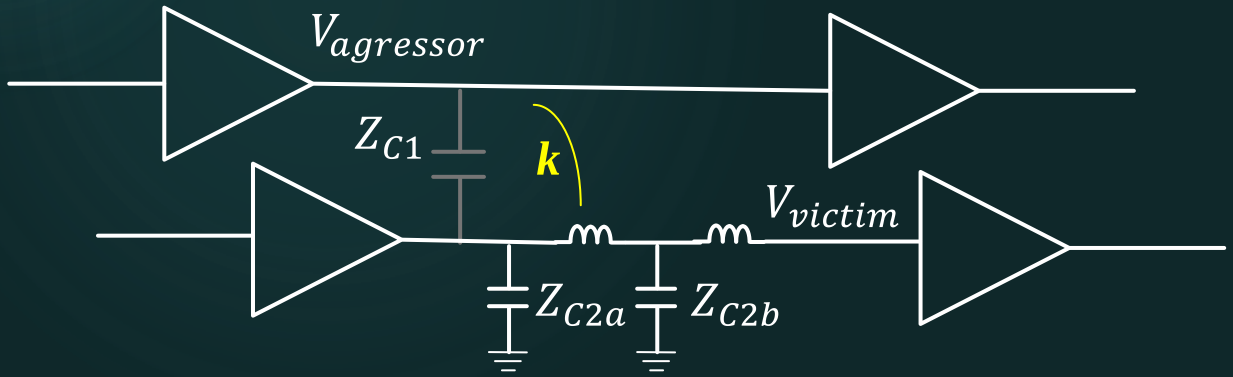
Need to consider B field couplings too !!

Benefits of 2^+ Layer PCBs

- Ground plane below traces makes Z_{C2} << Z_{C1} if trace spacing is >> board/layer thickness
- Distance to ground is typically about 62 mils (1.5mm) for 2-layer. 6 mils (0.15 mm) for 4-layer board !
- Ground plane also results in image-currents below trace that help mitigate magnetic coupling
- ***At high frequencies, need transmission-line theory …***







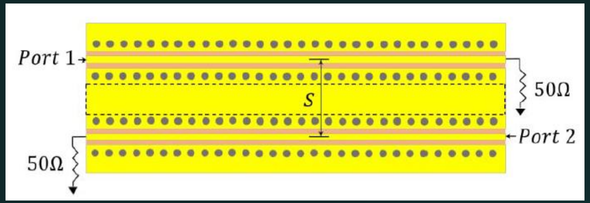
Considering E field only:

$$V_{victim} \approx V_{agressor} \frac{(Z_{C2} \parallel R_{out} \parallel R_{in})}{Z_{C1} + (Z_{C2} \parallel R_{out} \parallel R_{in})}$$

$$Z_{C2} \approx Z_{C2a} + Z_{C2b} \ll Z_{C1}$$ ☺

*Coupling Between Parallel Lines**

- Parallel 3.3 cm (1300 mil) 50 Ohm lines
- Microstrip was 10 mils above ground
- Tested pairs separated by 75 to 300 mils
- Nominal coupling around - 40 dB (40 dB isolation)
- Coupling **decreases** 10 dB per separation doubling
- Coupling increases 6 dB per length doubling
- GB-CPW lines achieve about 10 dB better isolation
- Stripline to CPW was best: 70 to 100 dB (below 6 GHz ☺)



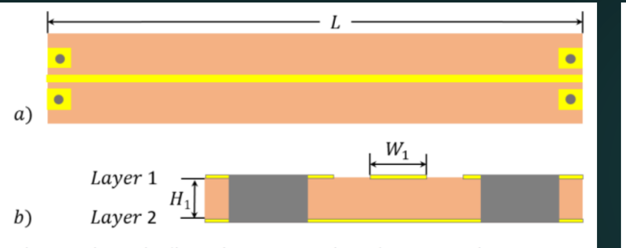


Fig. 1. Microstrip dimensions. (a) top view. (b) cross section.

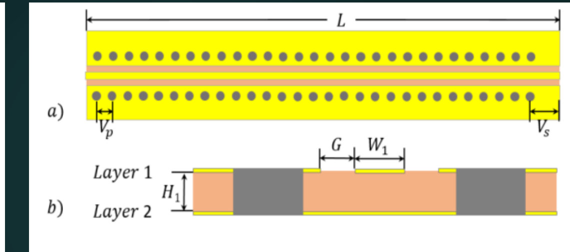
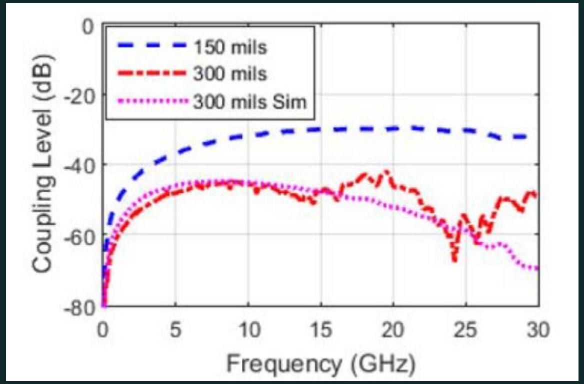
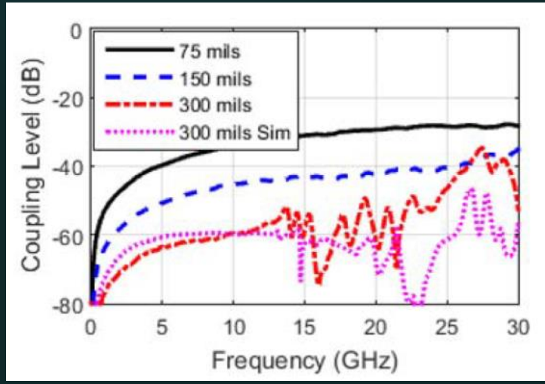


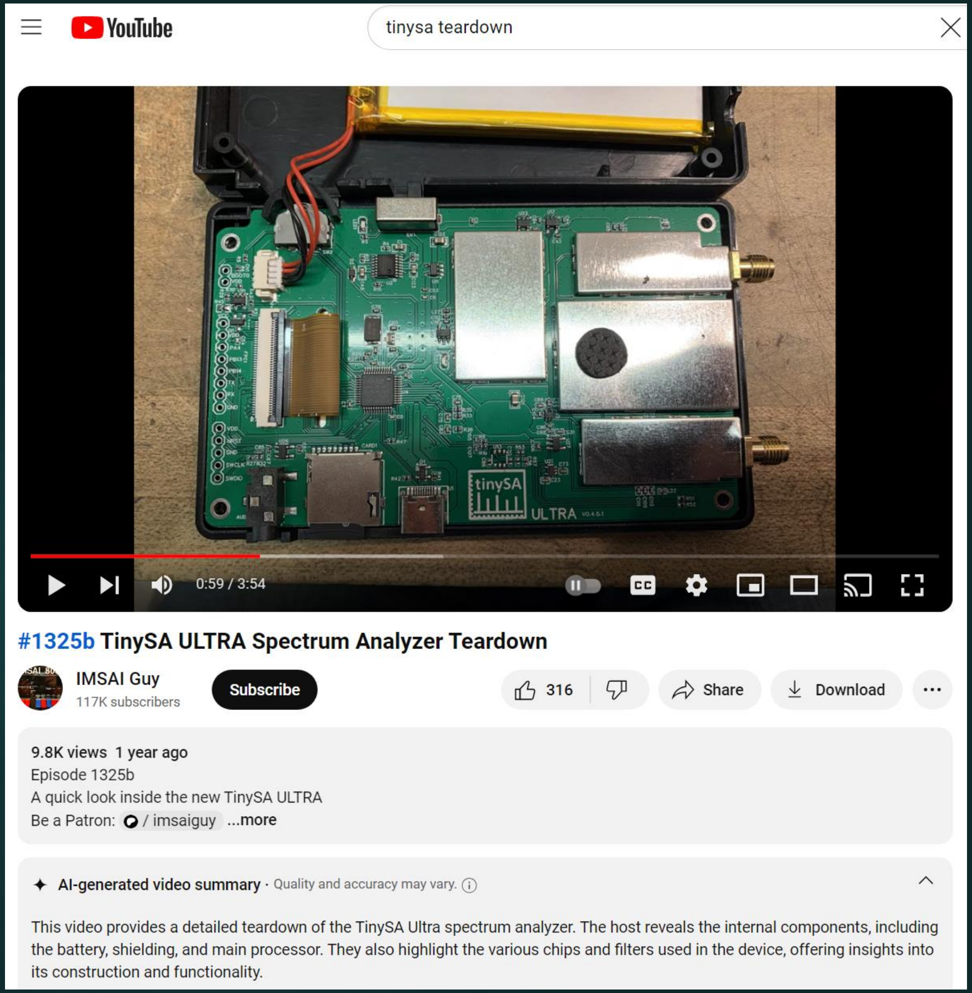
Fig. 2. GBCPW dimensions. (a) top view. (b) cross section.



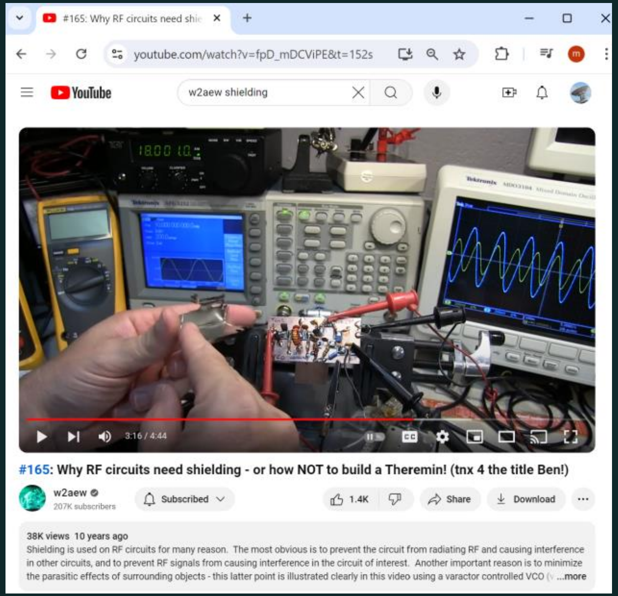


*Measurements From: "Crosstalk and EMI in mixed-signal/microwave multi-layer pc boards"
2017 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI)

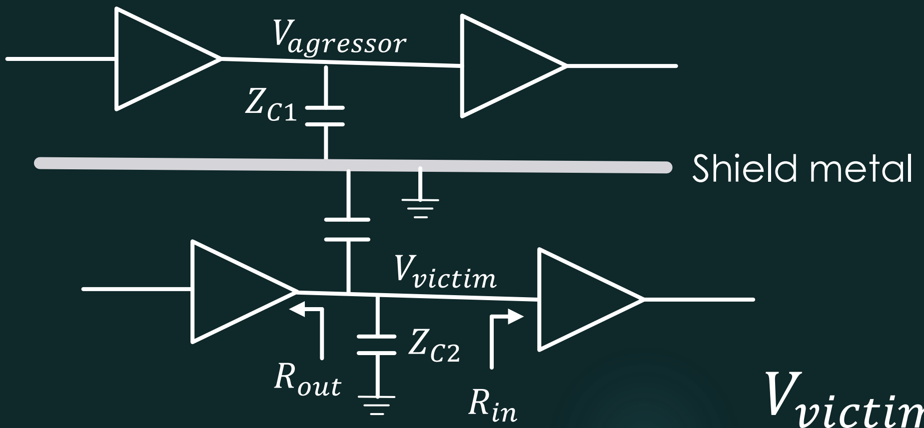
E-Field Shielding and Why it Works



https://www.youtube.com/watch?v=EGRvL2gy21I

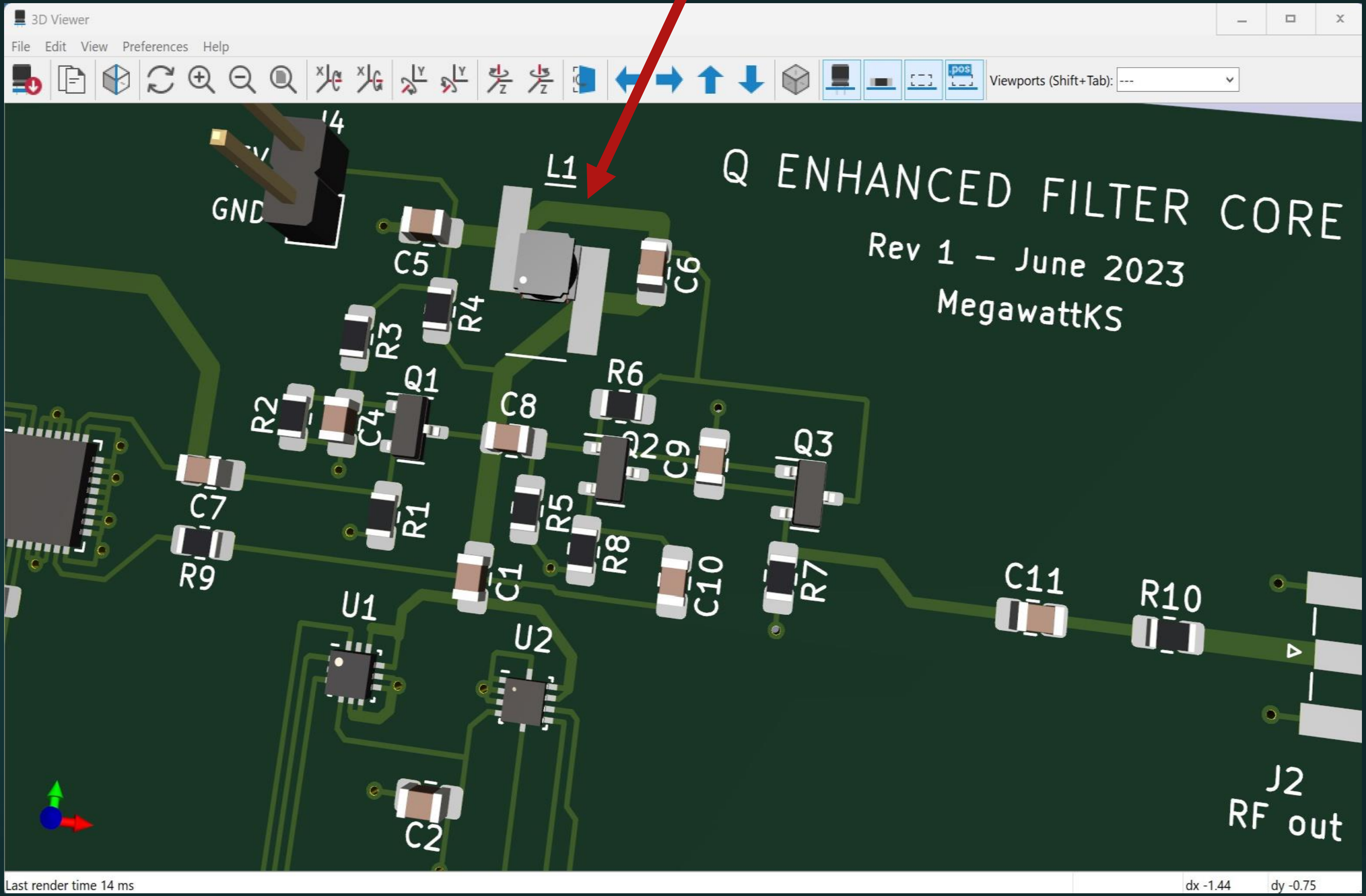


https://www.youtube.com/watch?v=fpD_mDCViPE



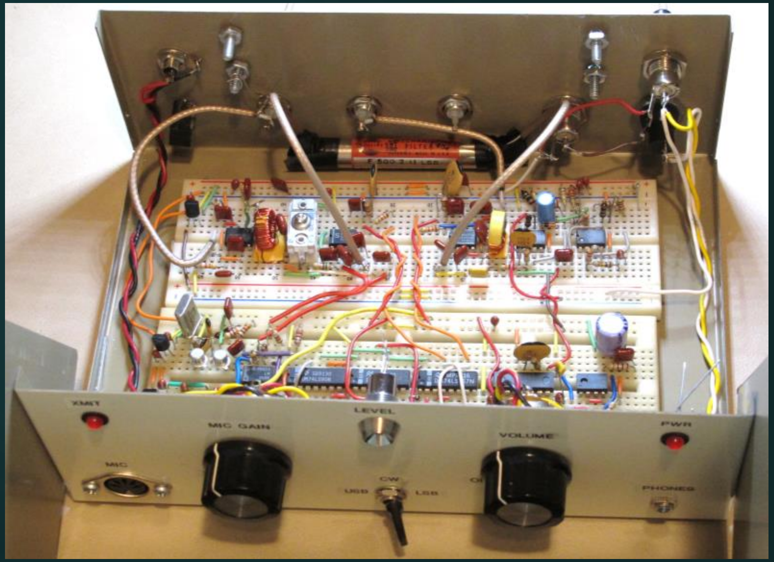
$$V_{victim} \approx 0$$

Watch Out for B-Field Coupling Too

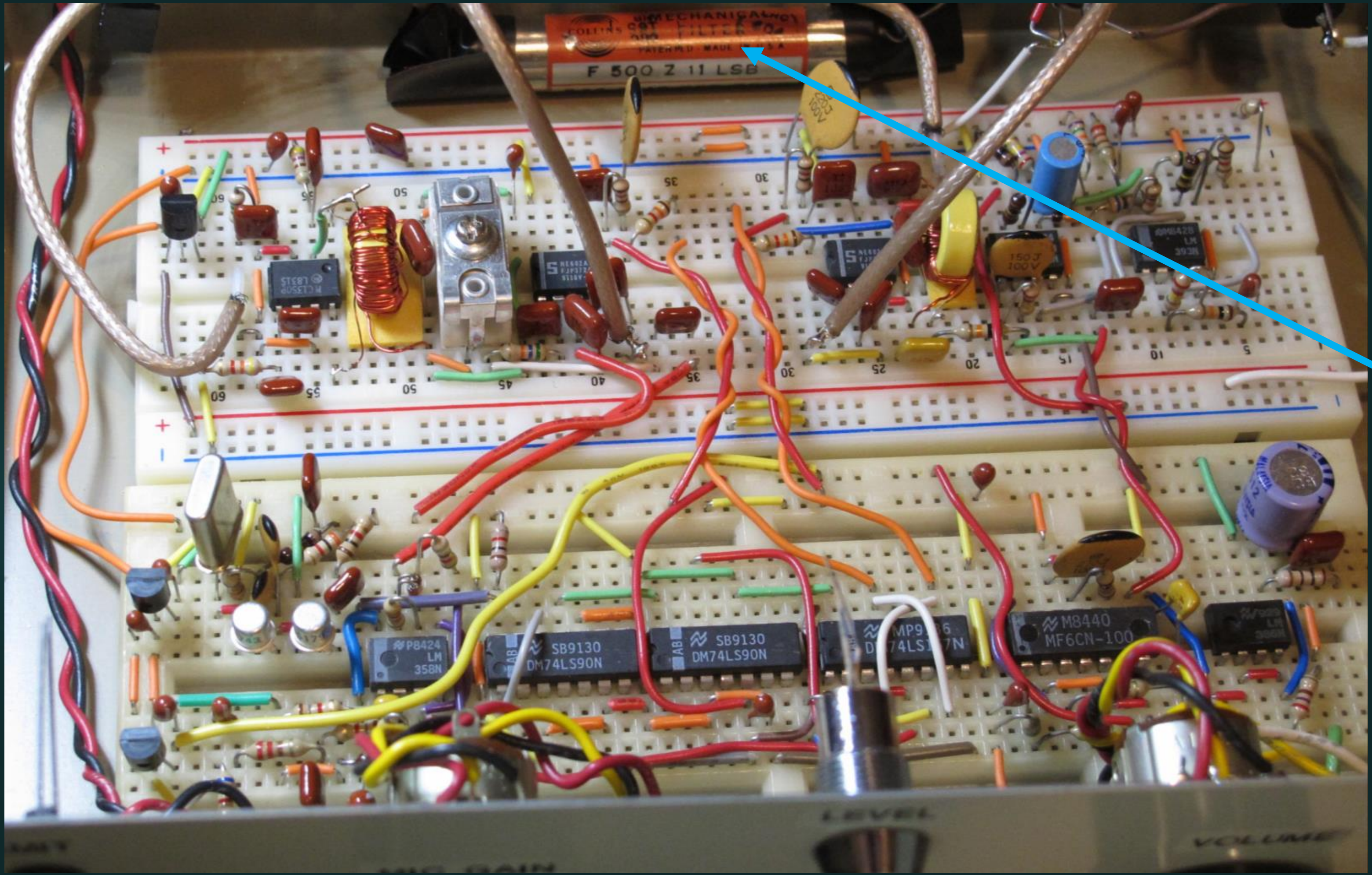


Construction on Protoboards

80-meter (3.5 to 4 MHz) SSB/CW Transceiver "teardown"



500 kHz Low IF Section

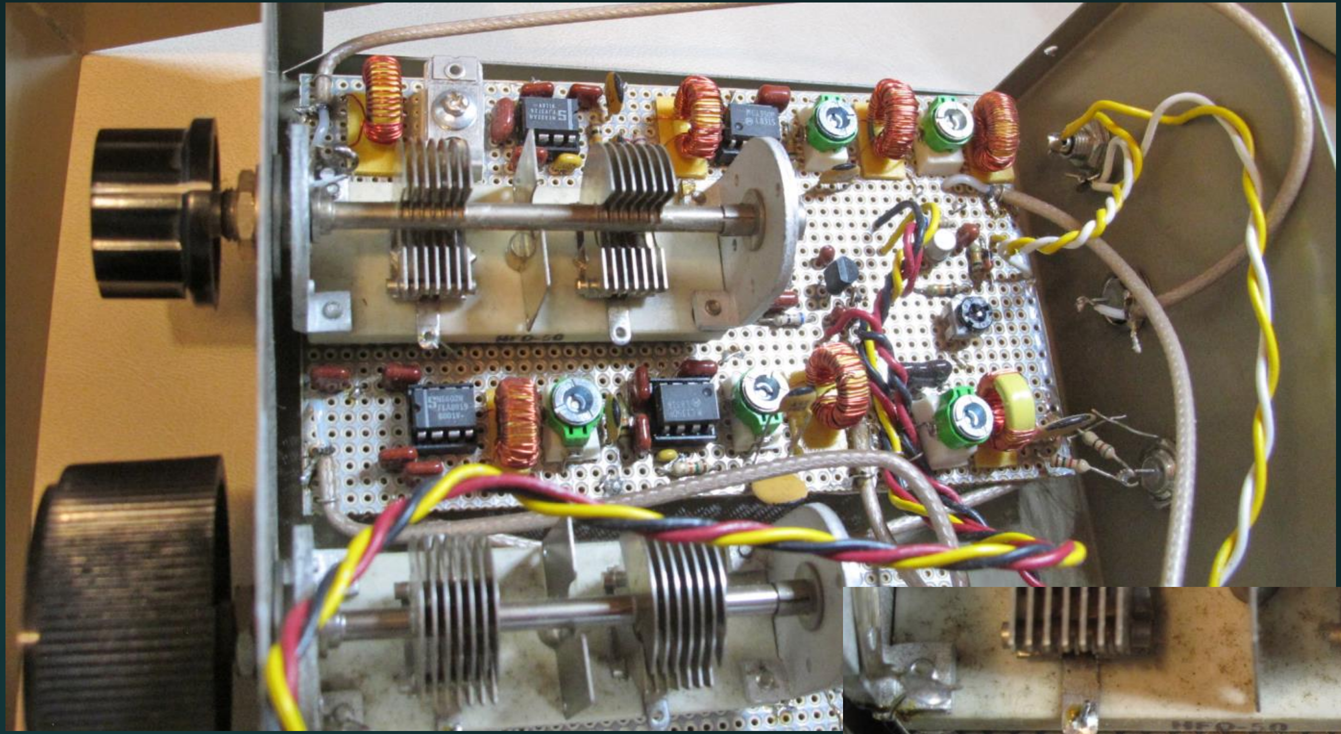


DSB-SC Modulator / Demodulator

500 kHz center, 2 kHz bandwidth BPF for LSB selection

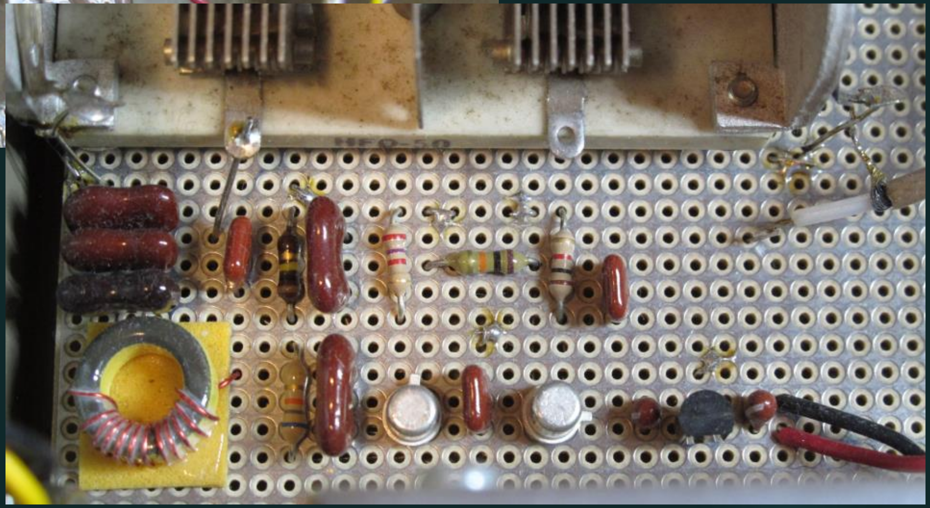
10 MHz osc with /20 for 500 kHz LO + SC LPF for receive audio

3.5 – 4 MHz RF Section



Preselected RF amp and downconverter

Upconverter and harmonic filtering



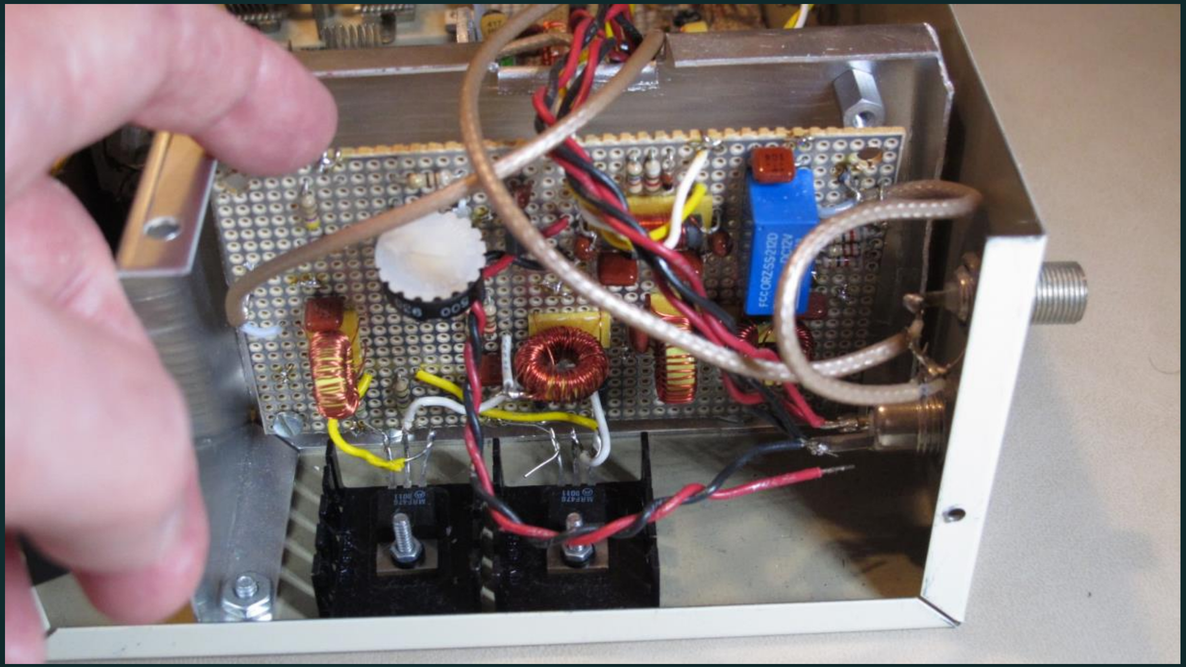
4 – 4.5 MHz VFO

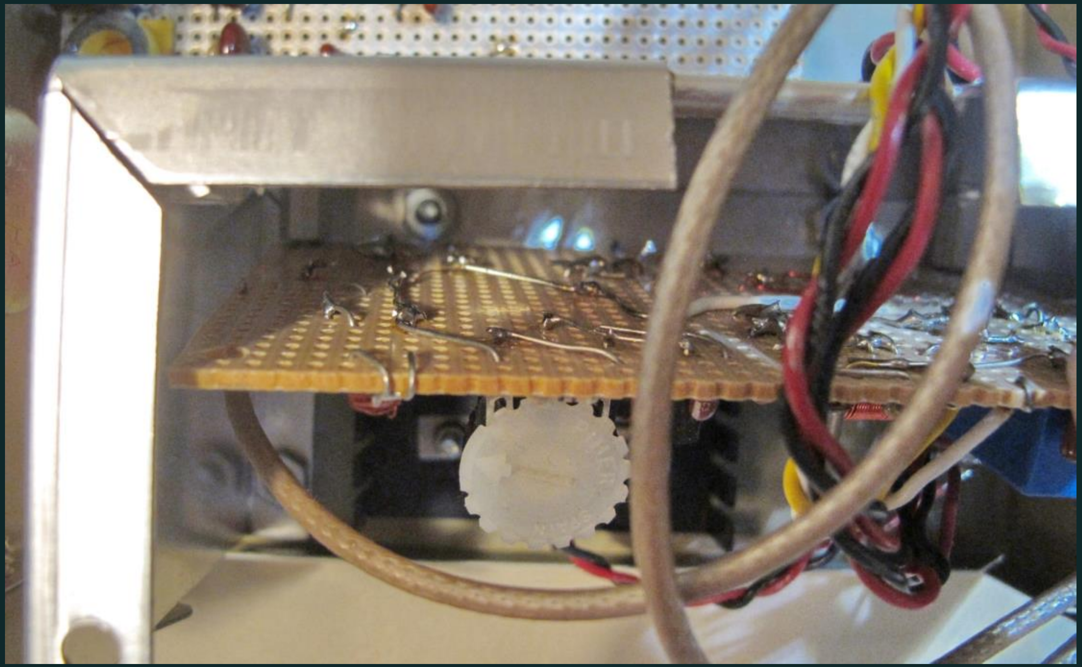
1-sided RF Perf-boards !

- For construction with through-hole components
- Pretty good through VHF ☺

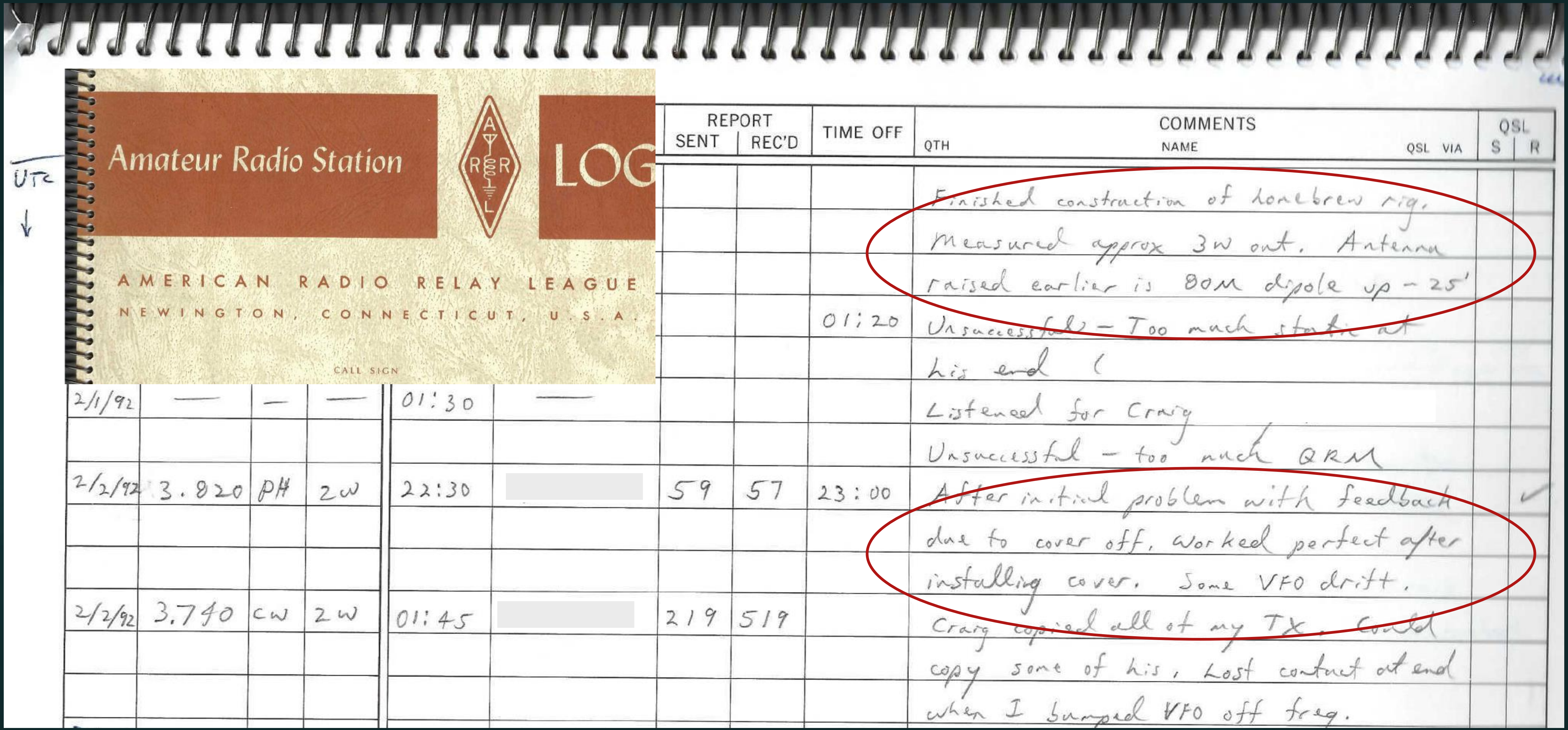
Shielded PA Section

1-sided RF Perf-board provides top-side Ground Plane and back-side Microstrip



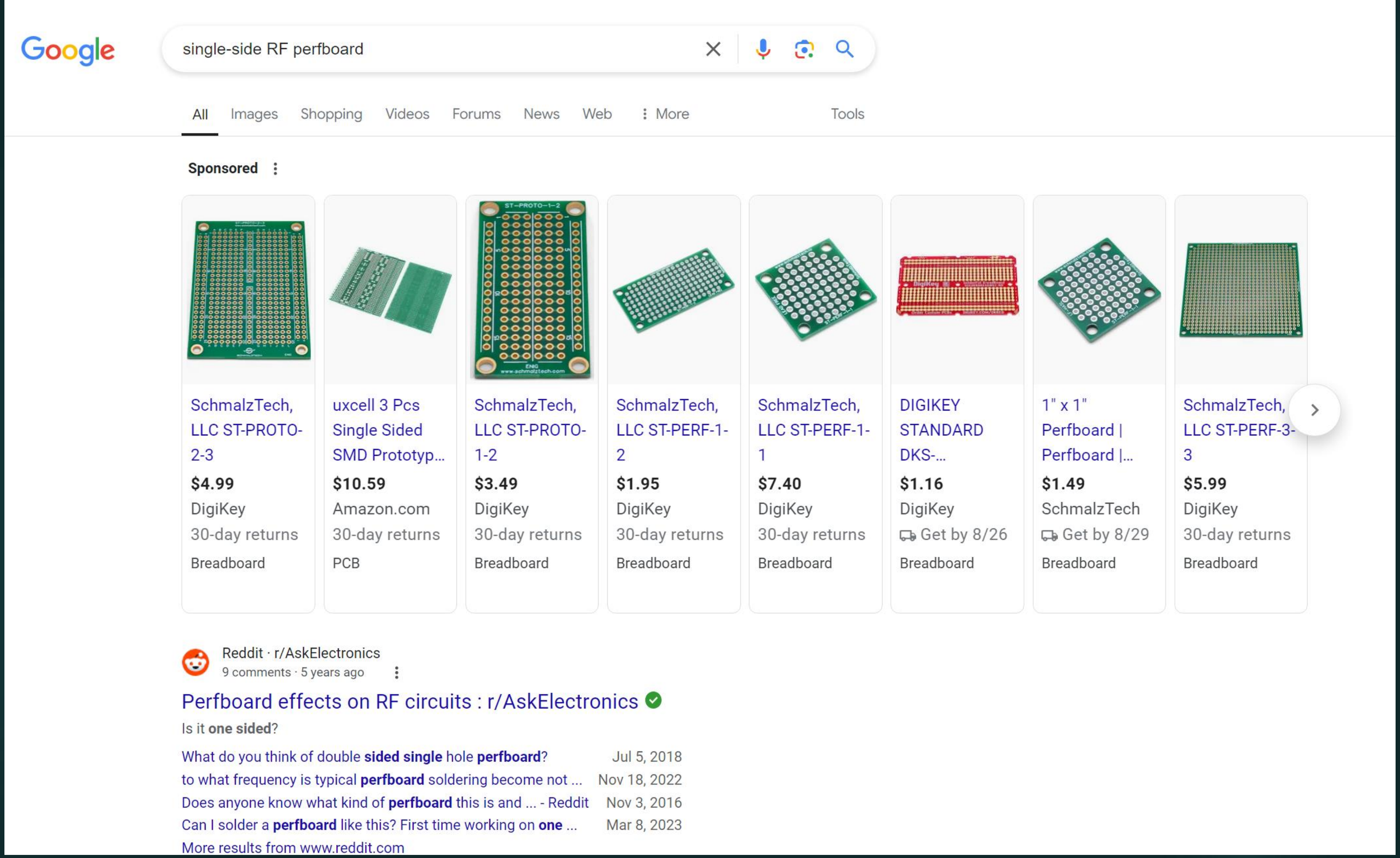


HF Homebrew Rig Testing ☺



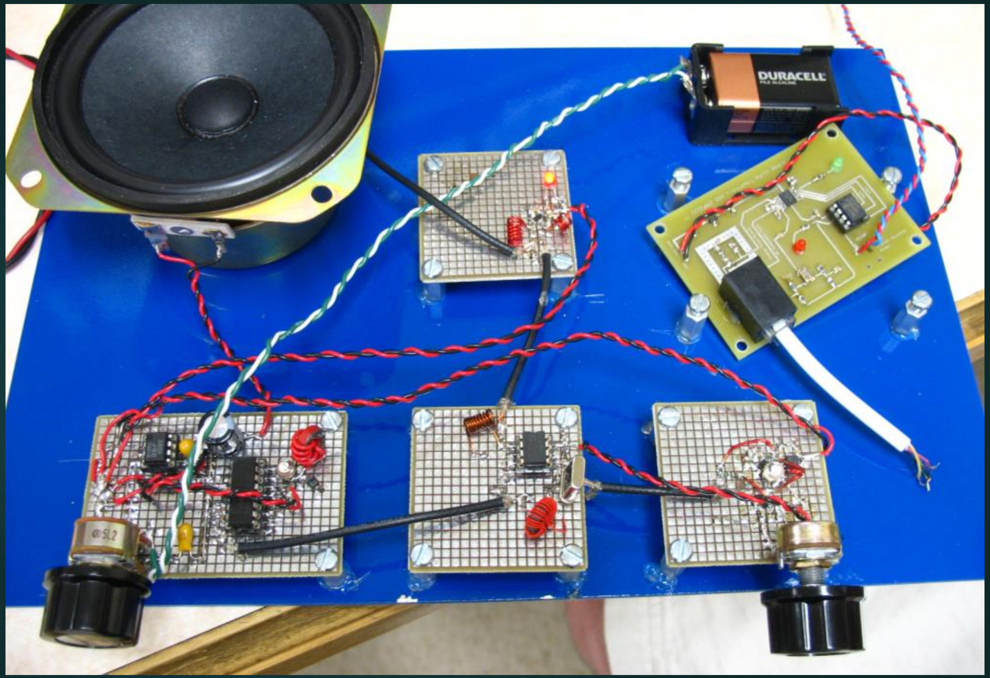
Available Perf-boards

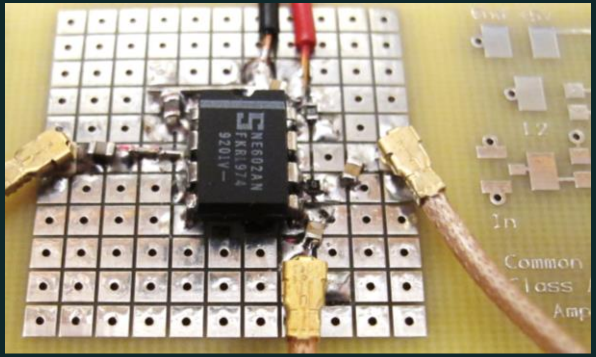
Why can't we buy RF perf-boards anymore ?

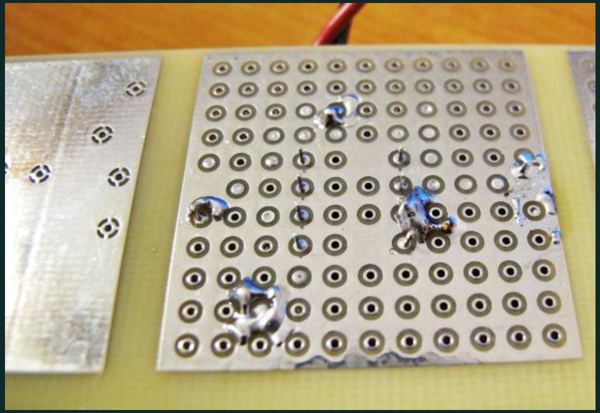


VHF RD101 Construction

Back-side Ground Plane and top-side "Sorta - Microstrip"

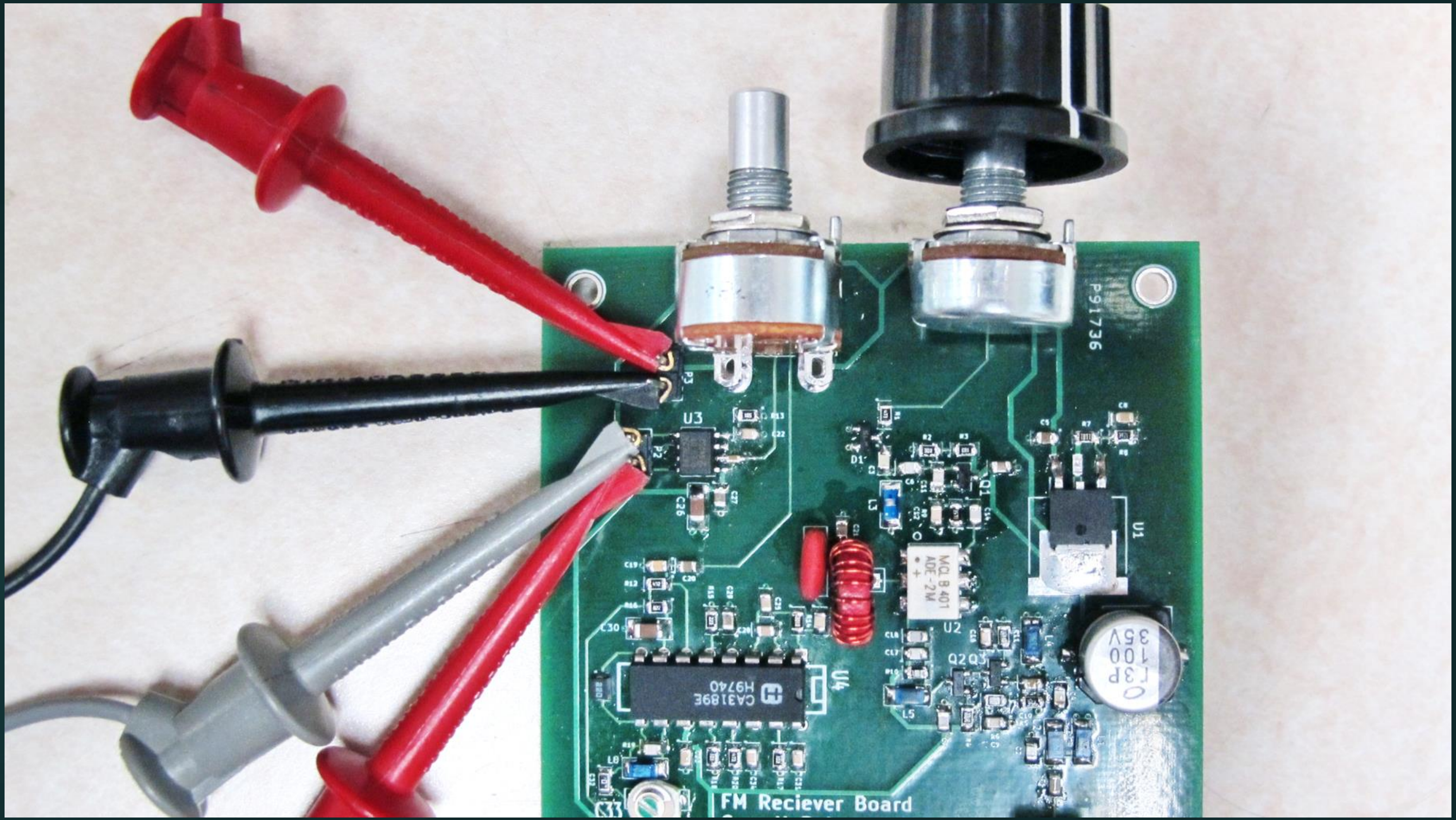




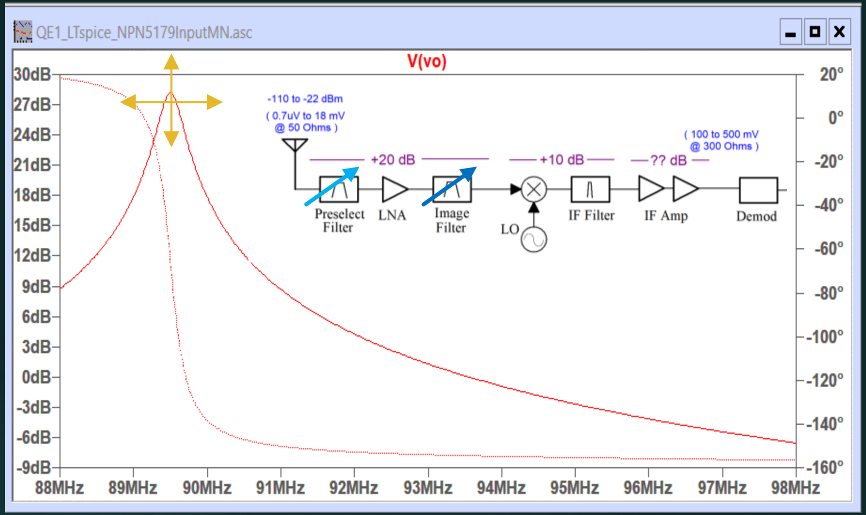


See: https://ecefiles.org/rf-circuit-prototyping/

VHF Receiver on PCB

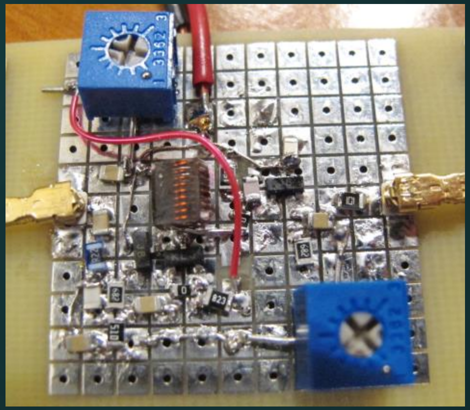


More on RF Prototyping

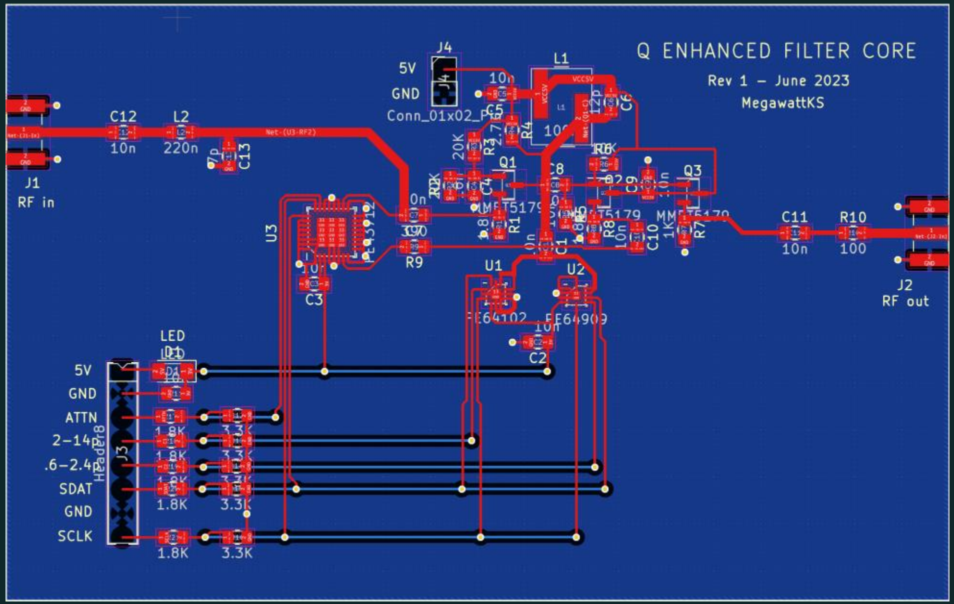


Q-Enhanced bandpass filter

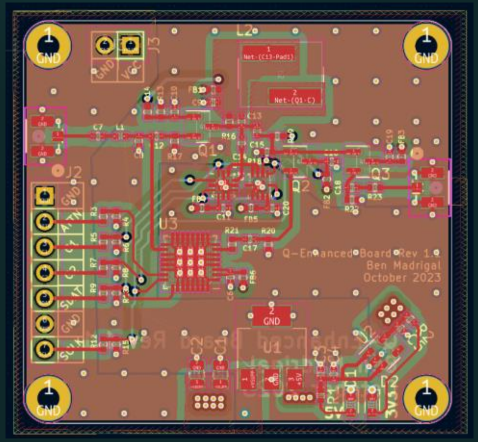
See Radio Design 101 – Final Epilogue (Epilogue 3) video



First build on protoboard



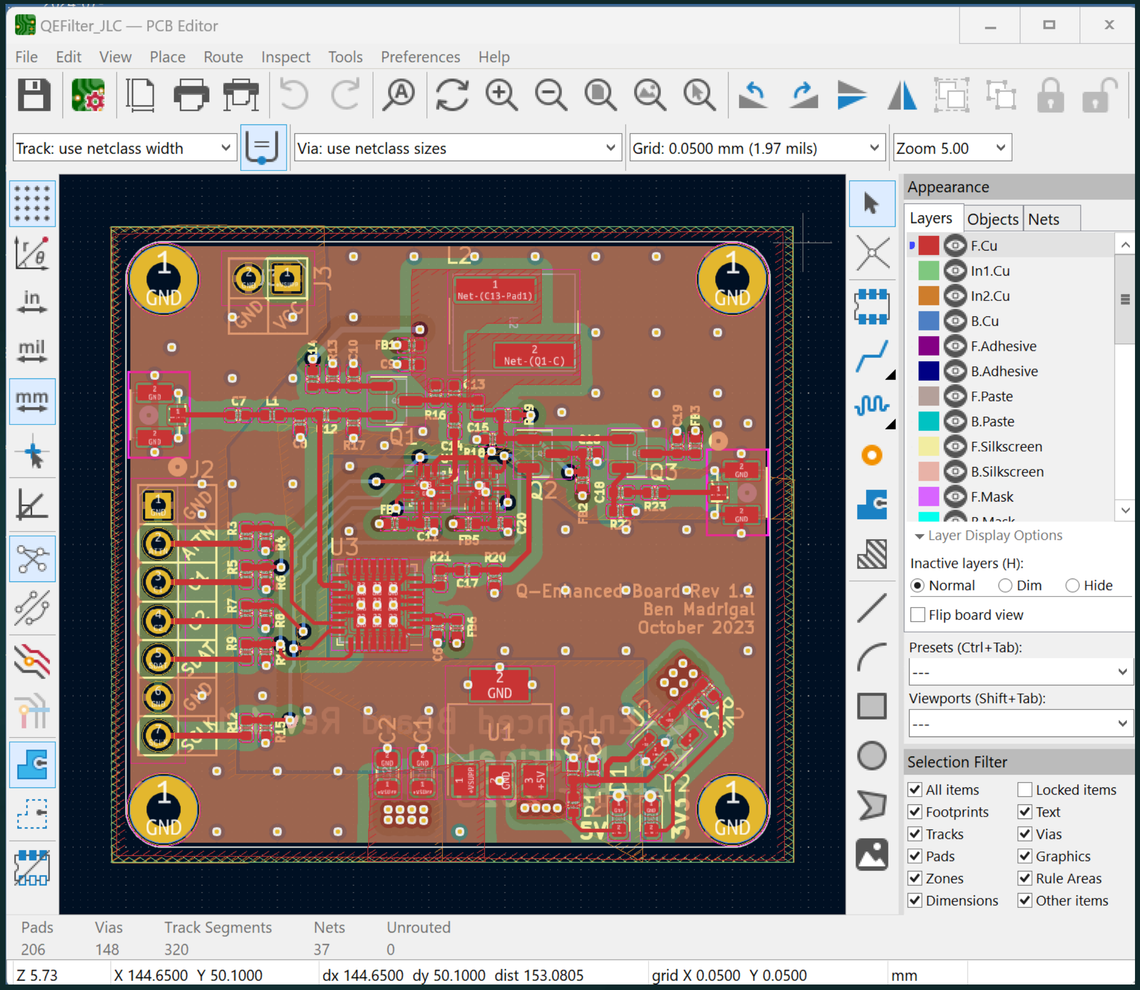
Second build on 2-layer PCB



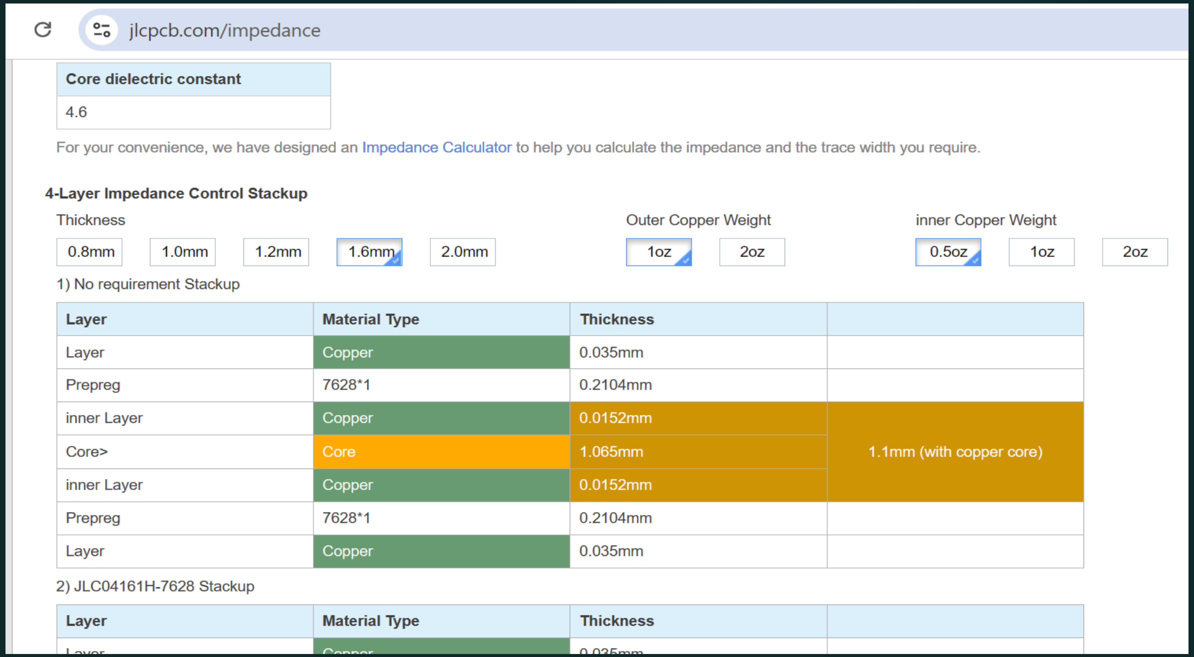
Third build on 4-layer PCB

4-Layer board, KiCad & JLCPCB

1. Top (front) layer for components, interconnect
2. Internal layer 1 typically used for ground plane
3. Internal layer 2 typically used for power
4. Bottom (backside) layer may be used for components, interconnect



Layout in KiCad



jlcpcb.com/impedance

Core dielectric constant

4.6

For your convenience, we have designed an Impedance Calculator to help you calculate the impedance and the trace width you require.

4-Layer Impedance Control Stackup

Thickness: 0.8mm | 1.0mm | 1.2mm | 1.6mm | 2.0mm

Outer Copper Weight: 1oz | 2oz

inner Copper Weight: 0.5oz | 1oz | 2oz

1) No requirement Stackup

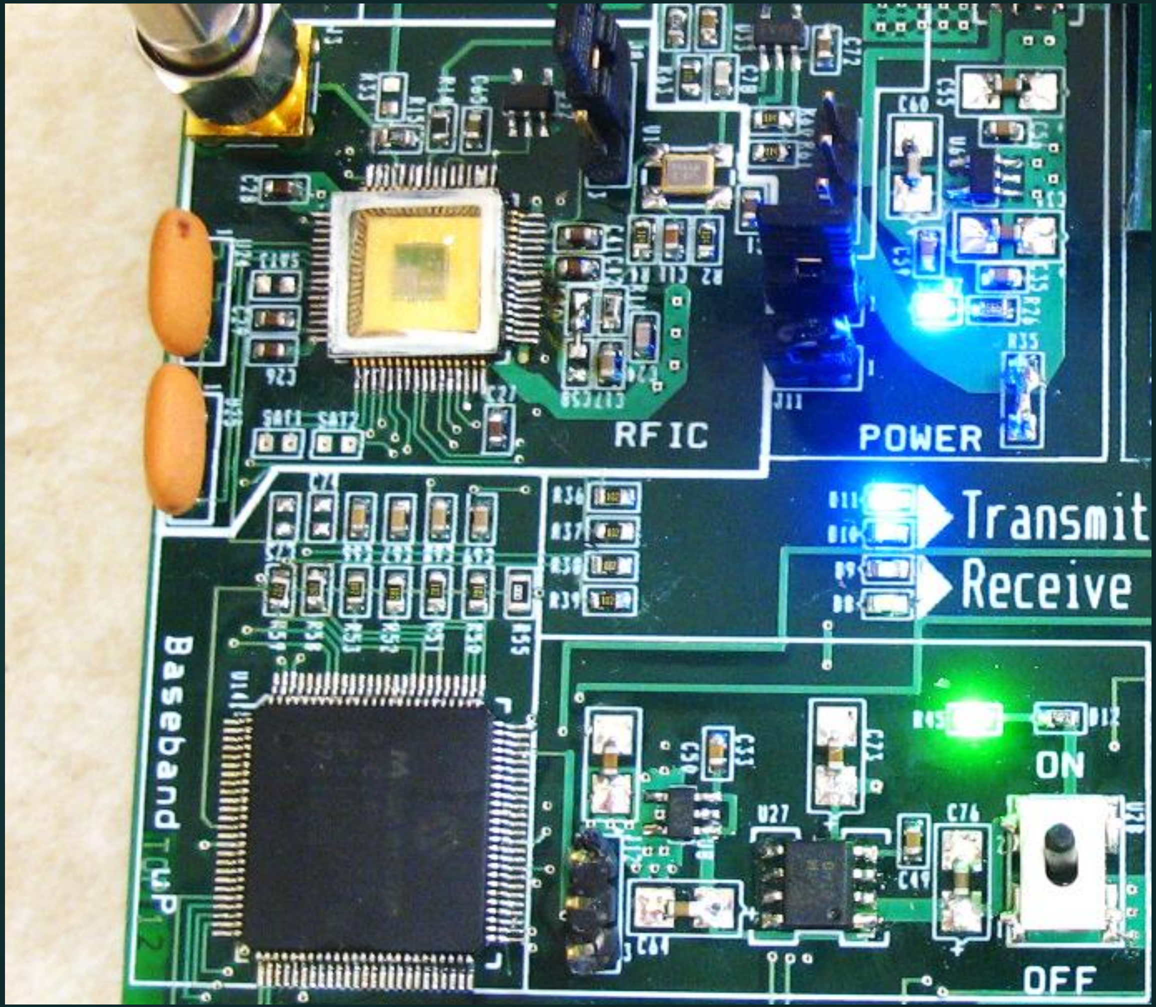
Layer	Material Type	Thickness	
Layer	Copper	0.035mm	
Prepreg	7628*1	0.2104mm	
inner Layer	Copper	0.0152mm	1.1mm (with copper core)
Core>	Core	1.065mm	
inner Layer	Copper	0.0152mm	
Prepreg	7628*1	0.2104mm	
Layer	Copper	0.035mm	

2) JLC04161H-7628 Stackup

Layer	Material Type	Thickness	

Example Stackup from JLCPCB

UHF Fully Integrated Radio



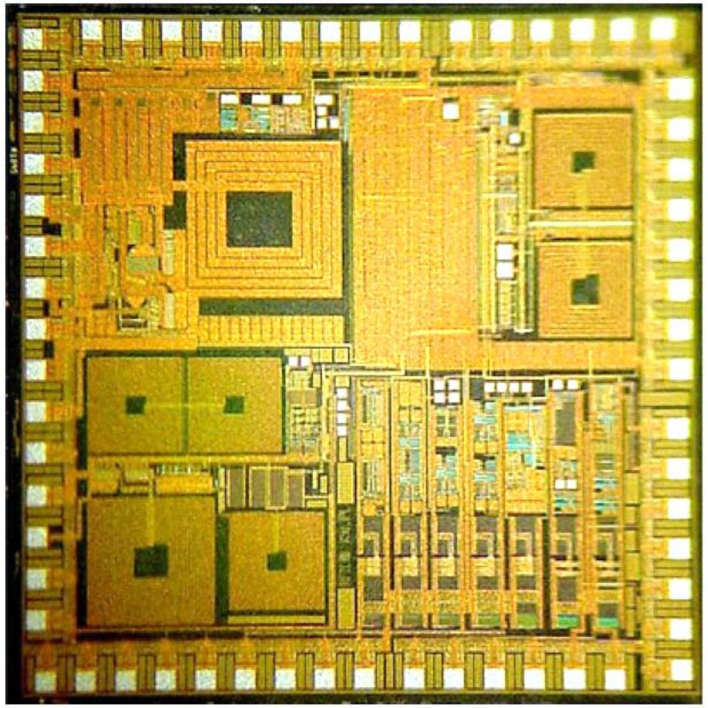
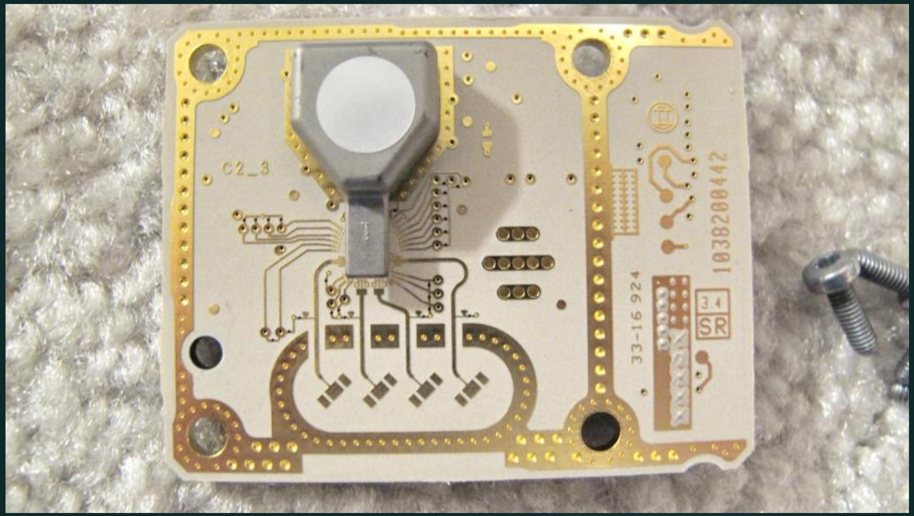
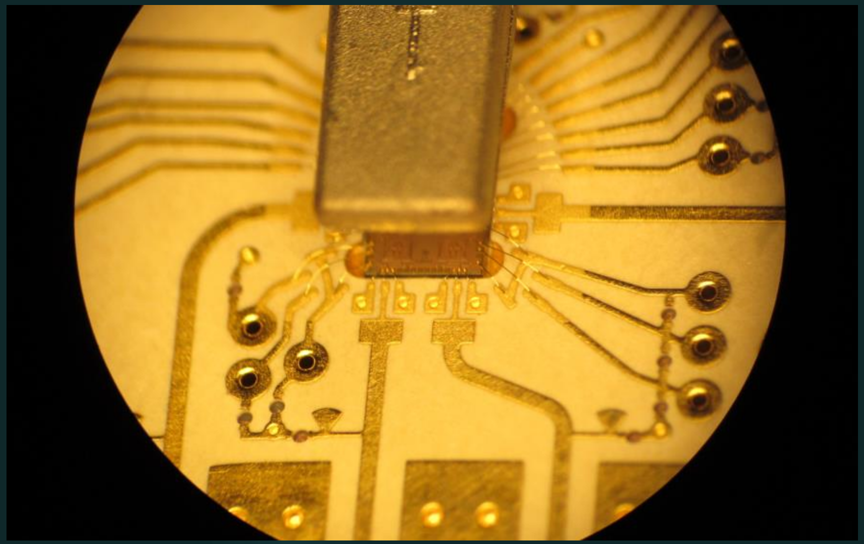


Fig. 39. *Die photo of fully integrated single-chip 100-mW transceiver.*

77 GHz Automotive Radar





Possible Future Videos

- Transmission Lines

  The math v_p, Z_o, Γ, S_{ij}, etc ...

  Coax, Microstrip, Coplanar Waveguide, Stripline,

- Crosstalk Measurements and Shielding
- Planar Microwave Circuits

Thanks For Watching !