

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>

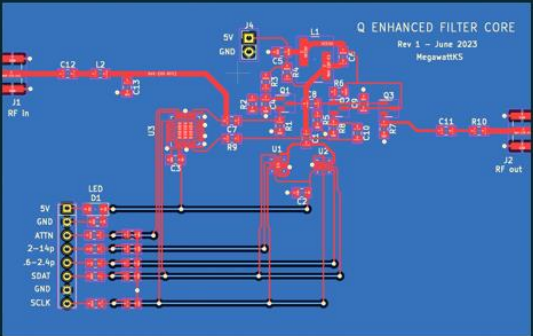
This material is **provided by ecefiles.org for educational use only.**

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.


30 MHz



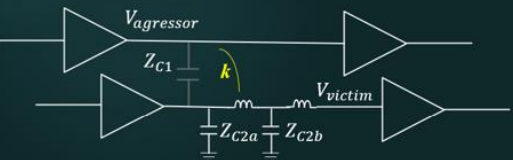
(The How and Why)



77 GHz



Considering E field only:

$$V_{victim} \approx V_{agressor} \frac{(Z_{C2} \parallel R_{out} \parallel R_{in})}{Z_{C1} + (Z_{C2} \parallel R_{out} \parallel R_{in})}$$
$$Z_{C2} \approx Z_{C2a} + Z_{C2b} \ll Z_{C1} \quad \text{☺}$$


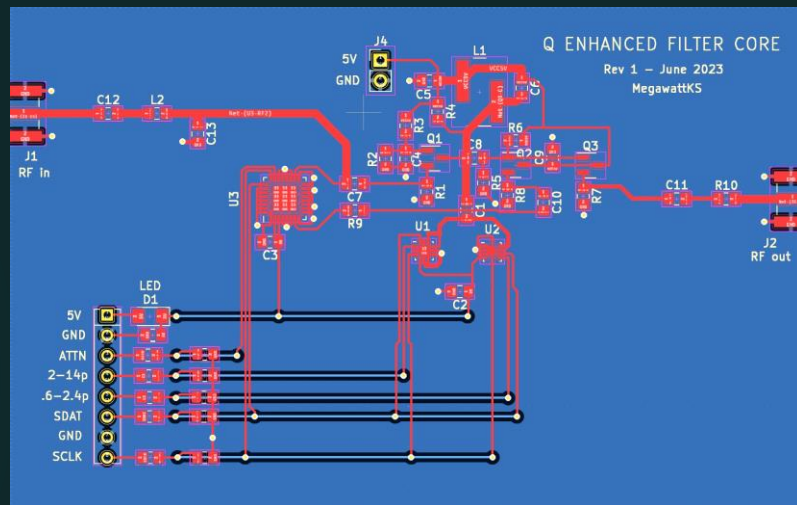
Radio Design 101

Appendix C

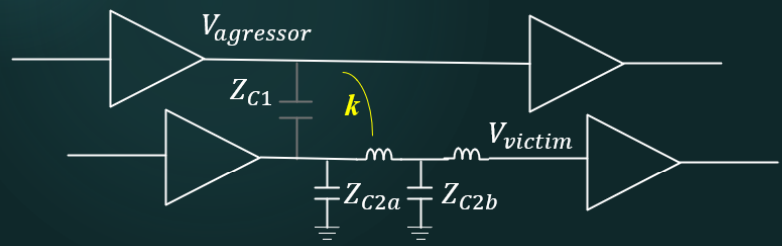
RF Circuit Construction & EMC

(*The How and Why*)

30 MHz



77 GHz



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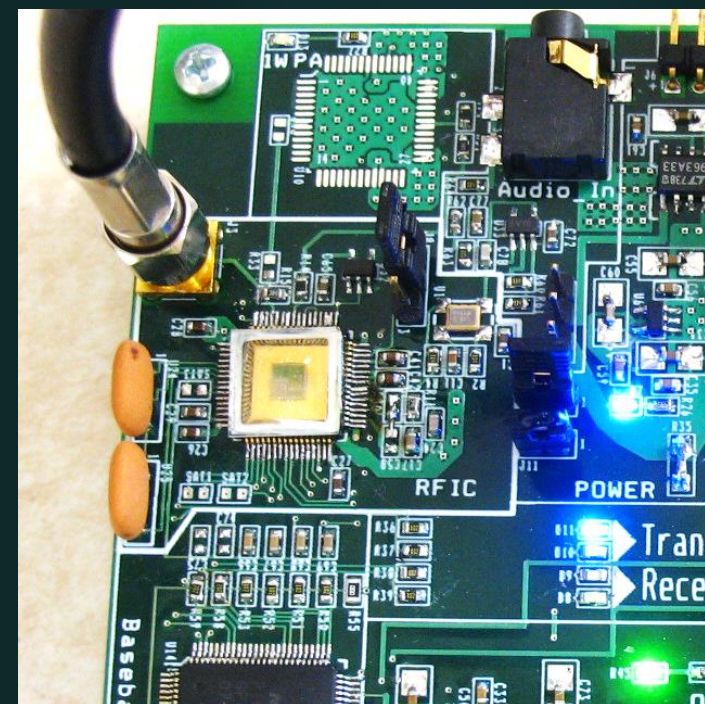
Key Issues

Mechanical / Thermal

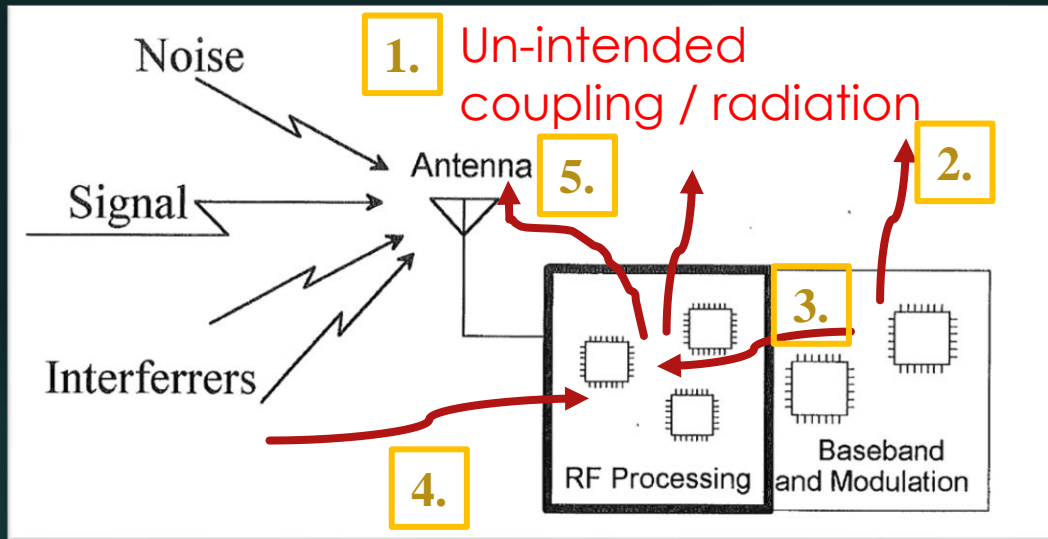
Application/Appearance, Form-Factor, Materials, Heat-Dissipation, ...

Electrical

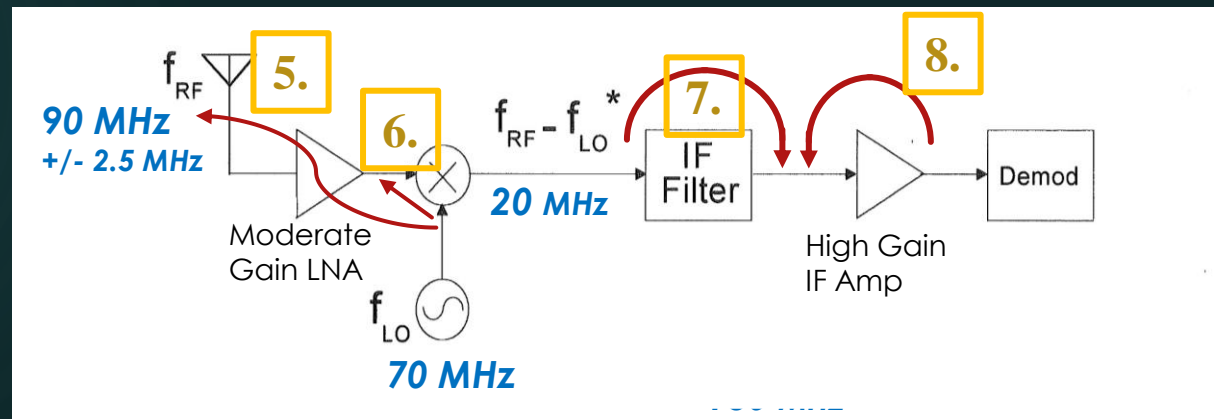
- Component placement and interconnection
- C and L parasitics
- Circuit/component size vs frequency
- PCB ground planes and Shielding (for EMC/SIPI)
- PCB traces, microstrip, CPW, twisted-pairs, coax, busses, ...



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

Capacitance

$V = I Z_C$
 $C = \epsilon \frac{\text{Area}}{\text{Distance}}$

NanoVNA - Measuring RLC Components

Megaw... 8.62K... Analytics Edit video 1.2K Share

$$Z = -jX_C$$

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

|Z| Values vs Frequency

1 pF at 1 MHz: $X_C = 159 \text{ K Ohms}$ 😊

1 pF at 1 GHz: $X_C = 159 \text{ Ohms}$ 😞

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

Inductance

$V = I Z_L$
 $L = \frac{\text{Flux}}{I}$

NanoVNA - Measuring RLC Components

Megaw... 8.62K... Analytics Edit video 1.2K Share

$$Z = jX_L$$

$$X_L = 2\pi f L$$

10 nH at 1 MHz: $X_L = 0.063 \text{ Ohms}$ 😊

10 nH at 1 GHz: $X_L = 63 \text{ Ohms}$ 😞

Estimating L and C Values

6

YouTube Search

Capacitance

$V = I Z_C$
 $C = \epsilon \frac{\text{Area}}{\text{Distance}}$

NanoVNA - Measuring RLC Components
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YouTube Search

Inductance

$V = I Z_L$
 $L = \frac{\text{Flux}}{I}$

NanoVNA - Measuring RLC Components
 Megaw... 8.62K...
 Analytics Edit video 1.2K Share

$$\begin{array}{l} \text{C} \\ Z = -jX_C \\ X_C = \frac{1}{2\pi fC} \end{array}$$



1960s DTL Logic



C between adjacent traces

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

L along traces

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

$$\begin{array}{l} \text{L} \\ Z = jX_L \\ X_L = 2\pi fL \end{array}$$

L and C on Multilayer PCBs

Capacitance

$V = I Z_C$
 $C = \epsilon \frac{\text{Area}}{\text{Distance}}$

NanoVNA - Measuring RLC Components

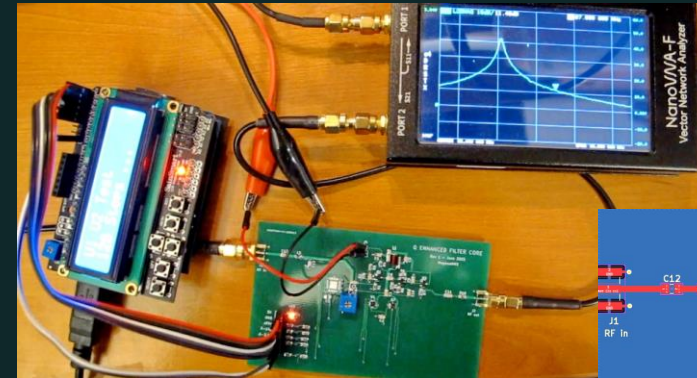
$Z = -jX_C$
 $X_C = \frac{1}{2\pi fC}$

Inductance

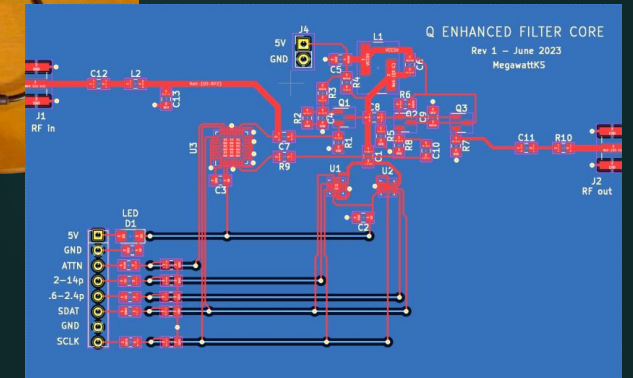
$V = I Z_L$
 $L = \frac{\text{Flux}}{I}$

NanoVNA - Measuring RLC Components

$Z = jX_L$
 $X_L = 2\pi fL$

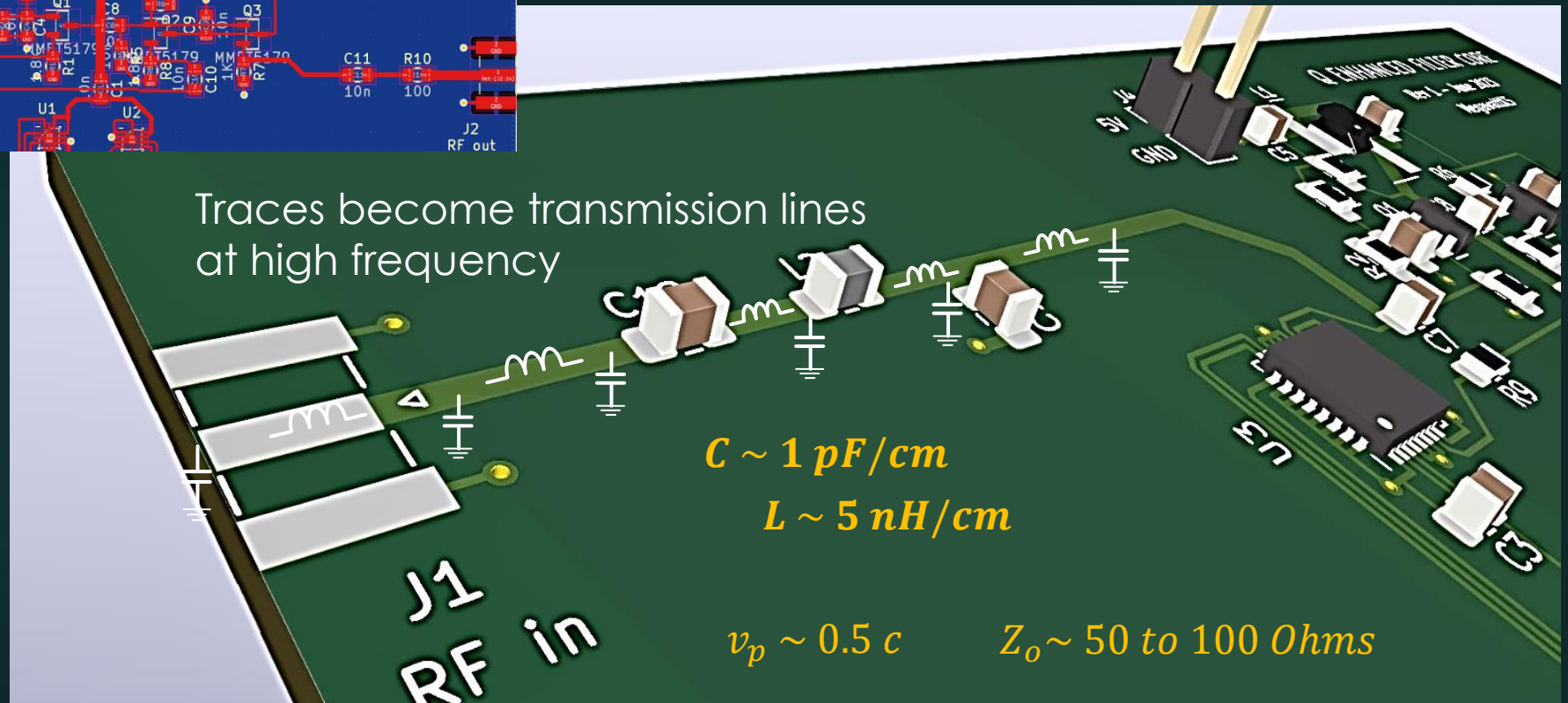
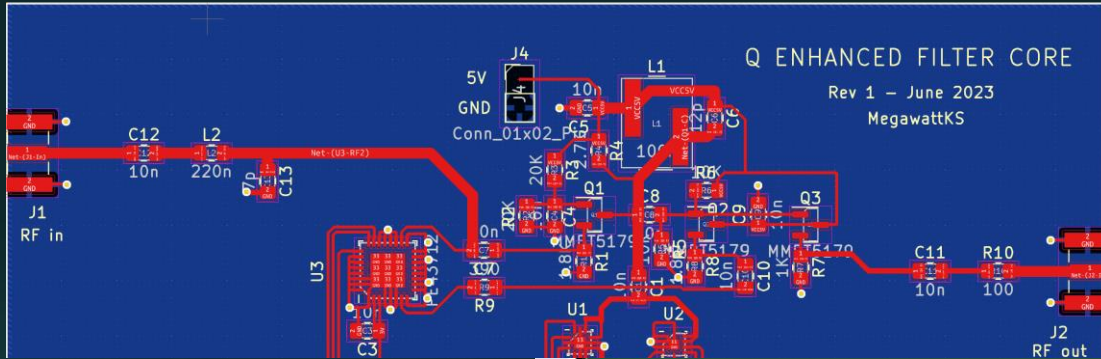


2023 VHF Bandpass Filter



- 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)



Traces become transmission lines
at high frequency

$$C \sim 1 \text{ pF/cm}$$

$$L \sim 5 \text{ nH/cm}$$

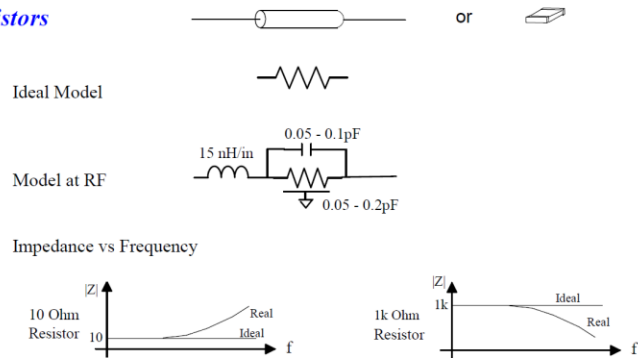
$$v_p \sim 0.5 c$$

$$Z_o \sim 50 \text{ to } 100 \text{ Ohms}$$

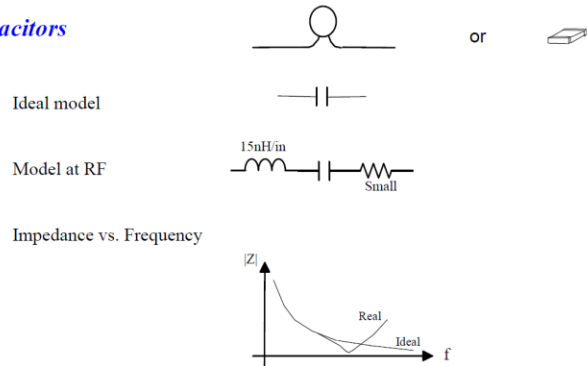
Class Handout on Parasitics

Component Parasitics at RF

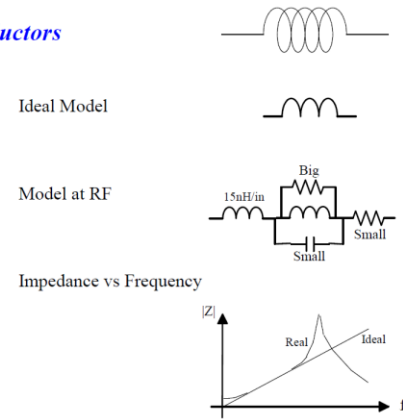
Resistors



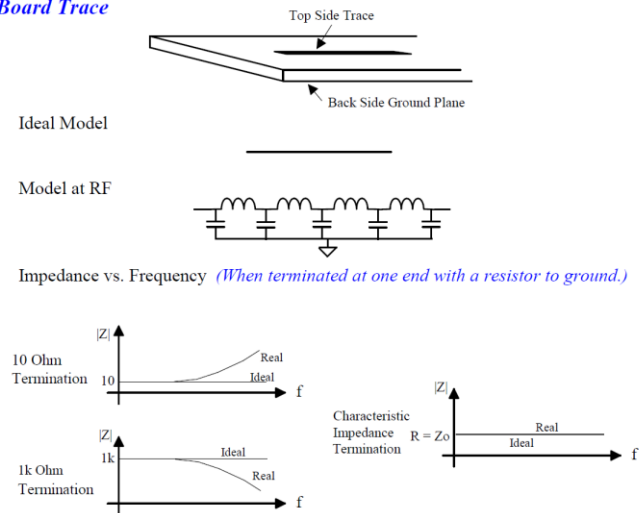
Capacitors



Inductors



PC Board Trace



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

Important if length is $> 1/10$ wavelength

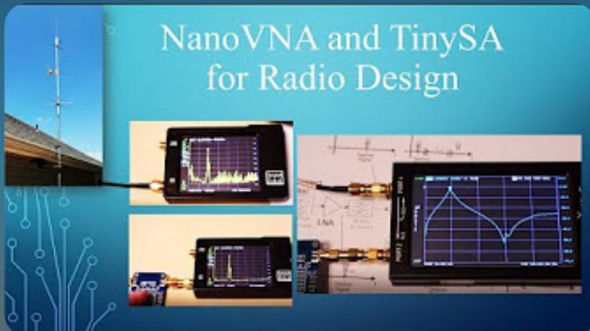
$$\lambda = \frac{c}{f} v_r$$

$$v_r \sim 0.5$$

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

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

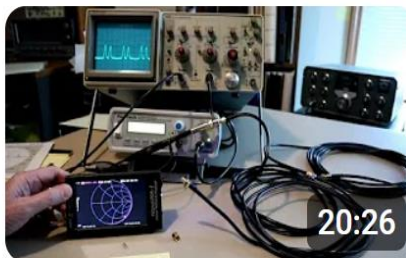


▶ Play all

↻ 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

20:26

4



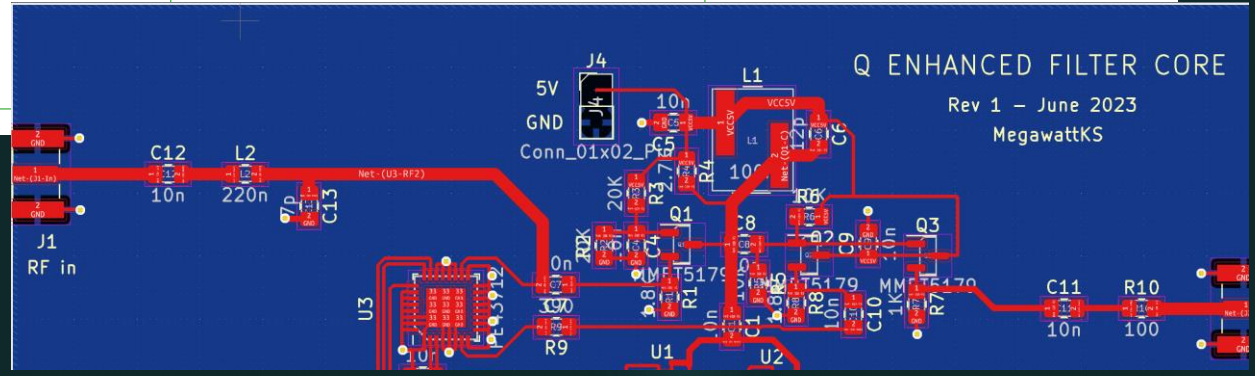
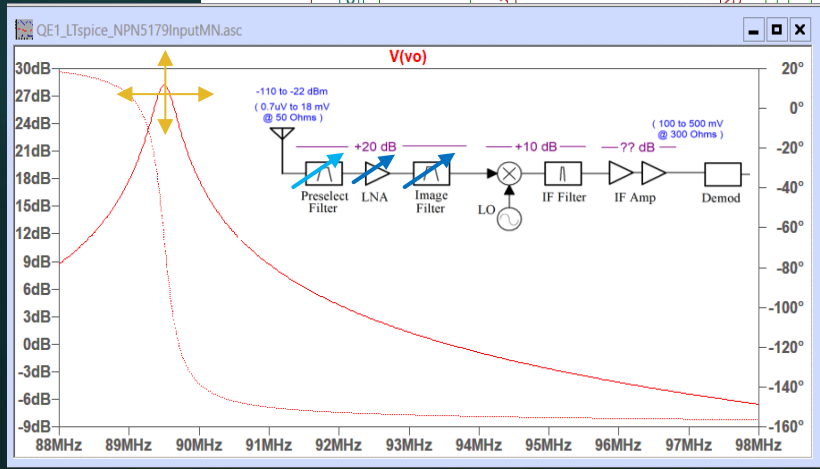
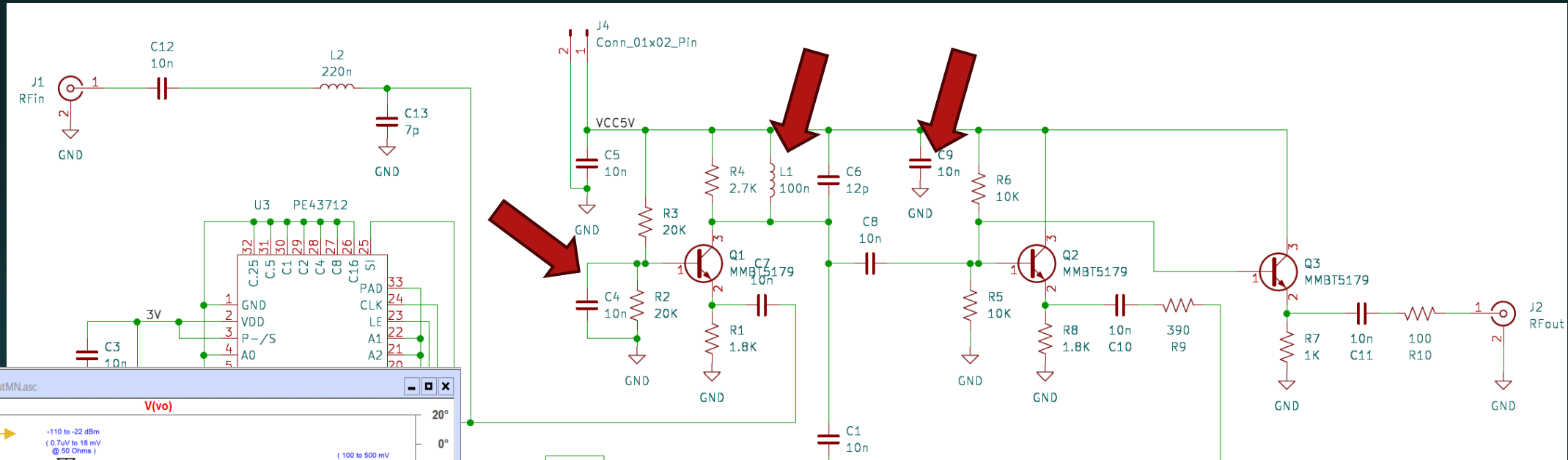
NanoVNA - Measuring RLC Components

MegawattKS • 50K views • 3 years ago

30:16

30:16

Effects at Schematic Level ('Add in' parasitics for correct design/simulation)



Radio Construction Examples

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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**

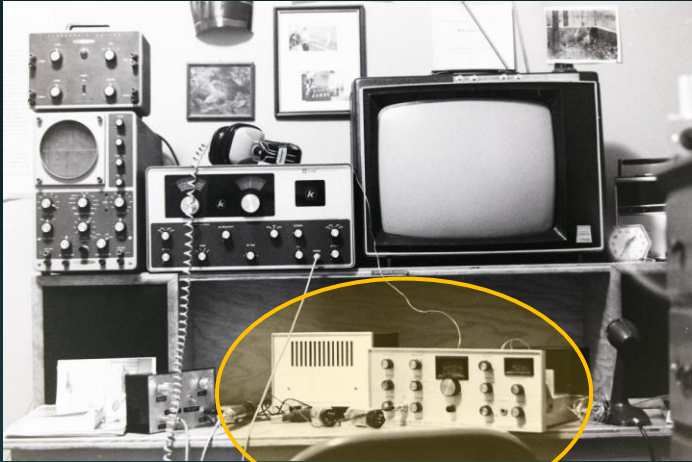
UHF: 430 – 450 MHz

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

Microwave / Millimeter Wave: 2.4 to 77 GHz

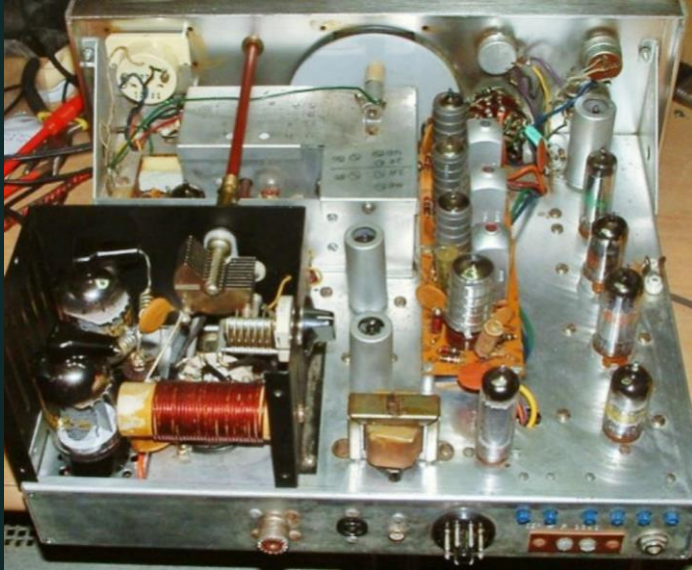
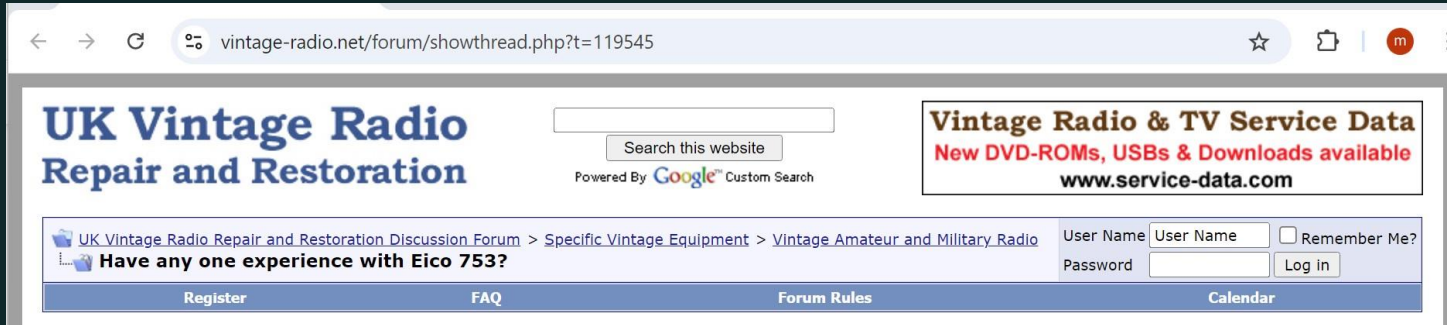
- Commercial Automotive FMCW Radar (fully packaged, teardown)

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

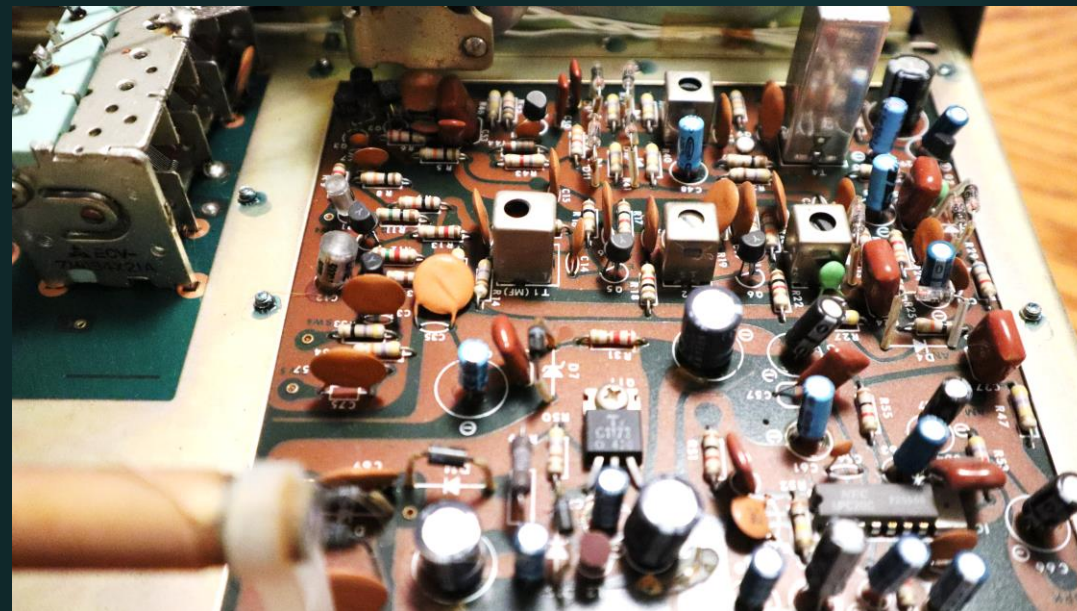
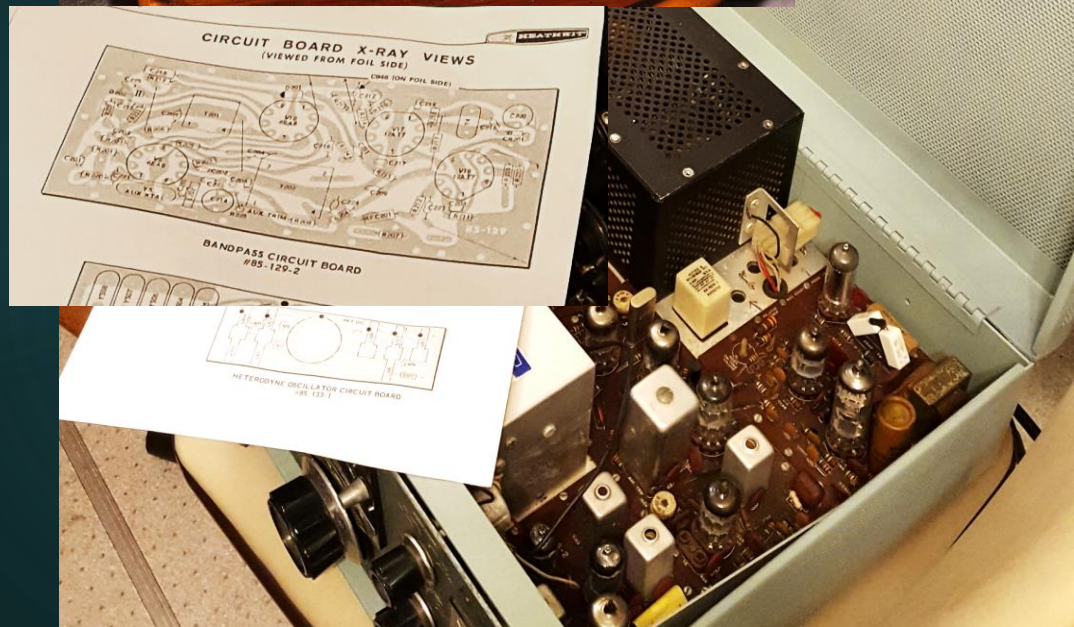
HF Radios with Early PCBs

14

1967

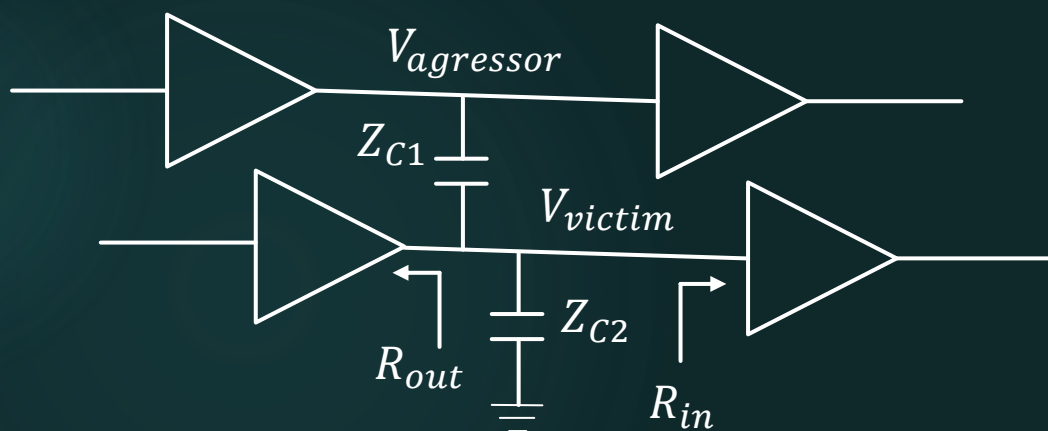
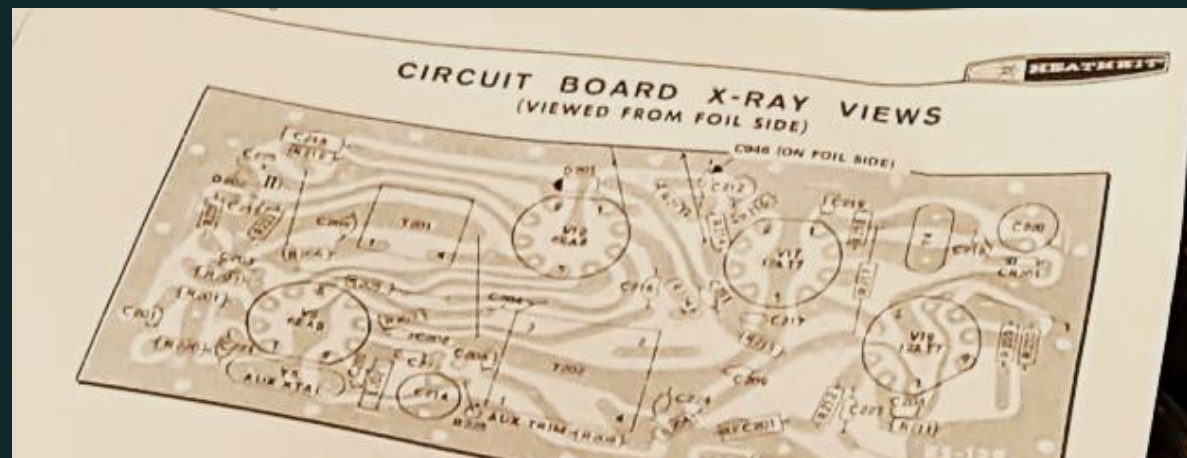


1975 ...



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

$$Z_{C2} \geq Z_{C1} \text{ ☹}$$

But in low frequency regime, hopefully

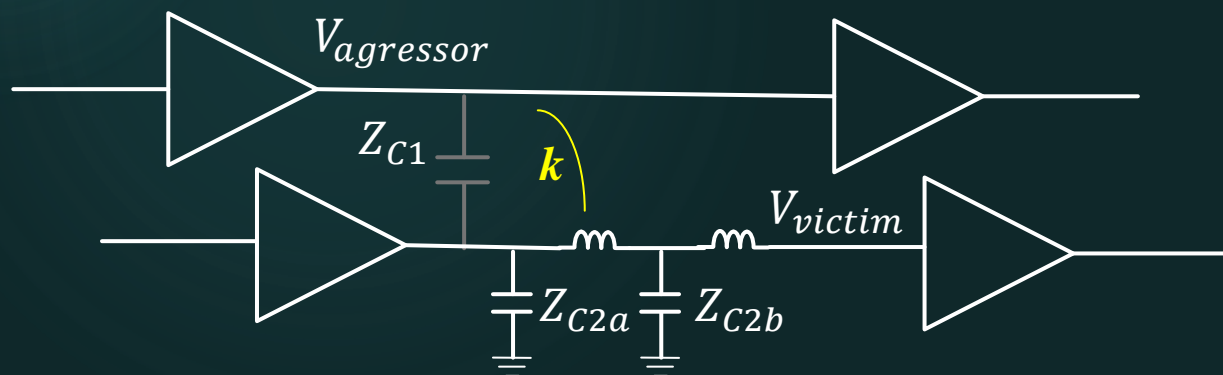
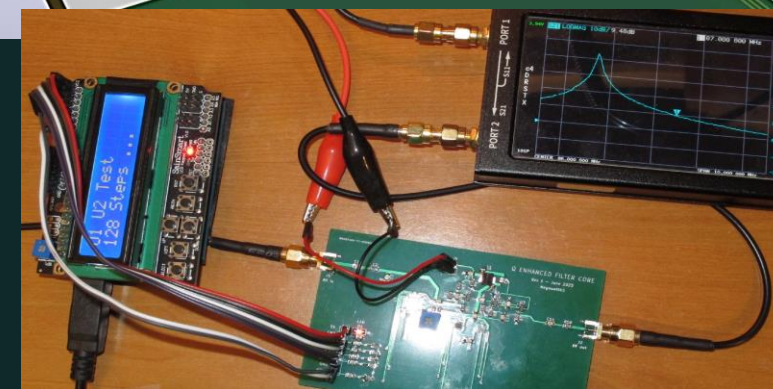
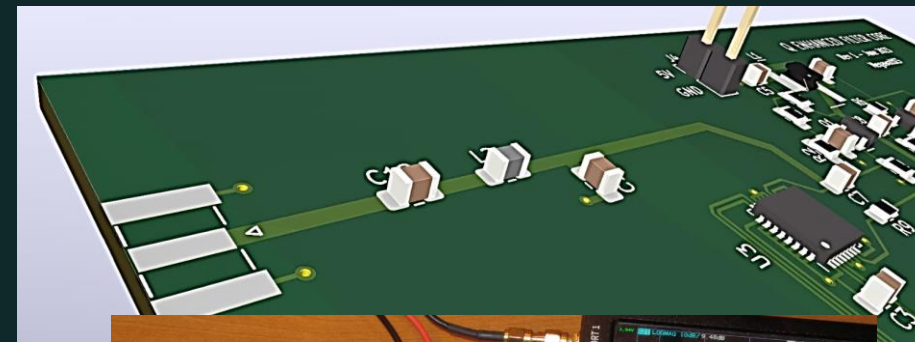
$$Z_{C1} \gg R_{out} \parallel R_{in} \text{ ☺}$$

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 $Z_{C2} \ll Z_{C1}$ if trace spacing is \gg 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:

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

$$Z_{C2} \approx Z_{C2a} + Z_{C2b} \ll Z_{C1} \quad \text{😊}$$

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 😊)

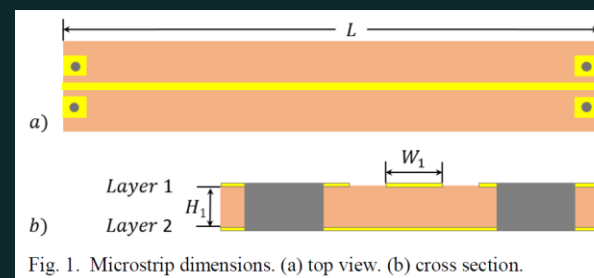
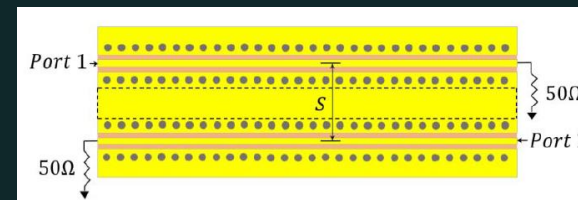


Fig. 1. Microstrip dimensions. (a) top view. (b) cross section.

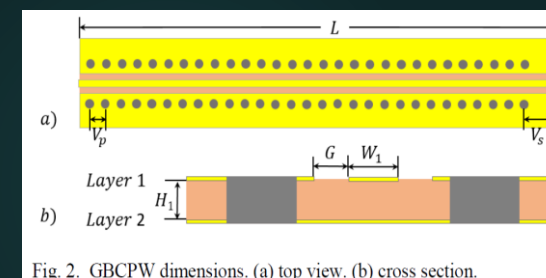
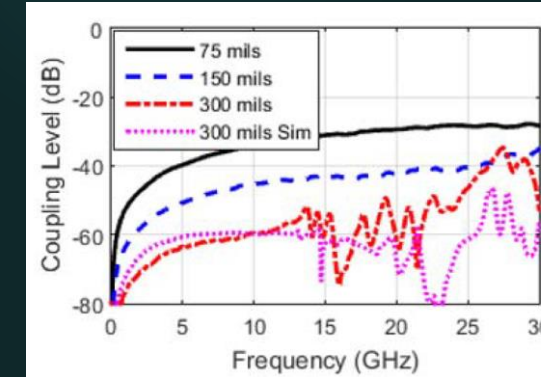
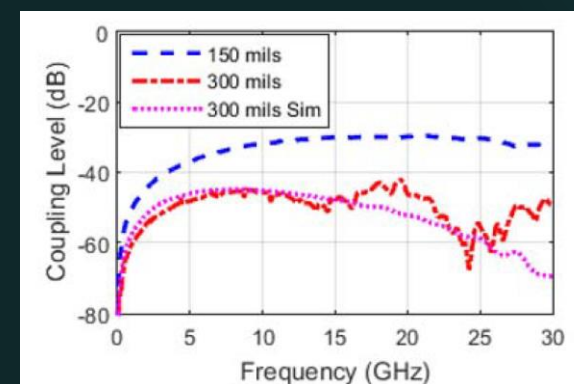


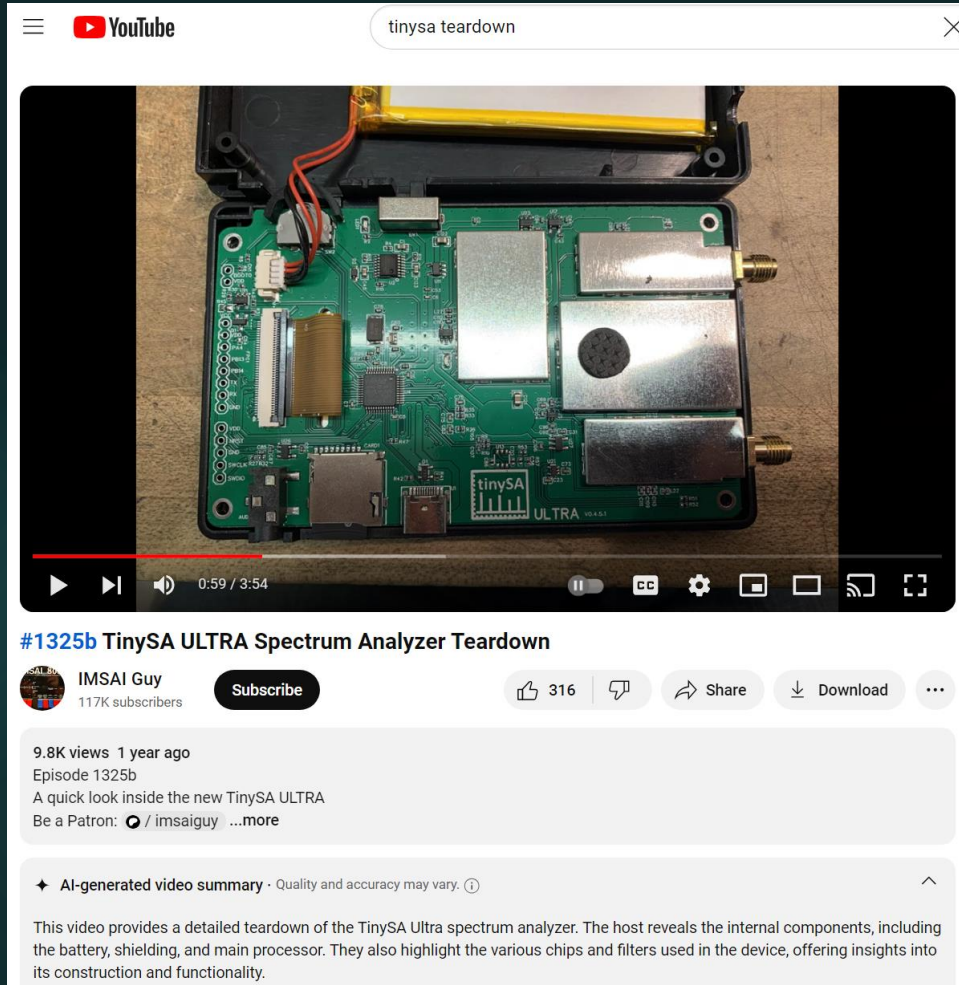
Fig. 2. GB-CPW dimensions. (a) top view. (b) cross section.



*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

18



#1325b TinySA ULTRA Spectrum Analyzer Teardown

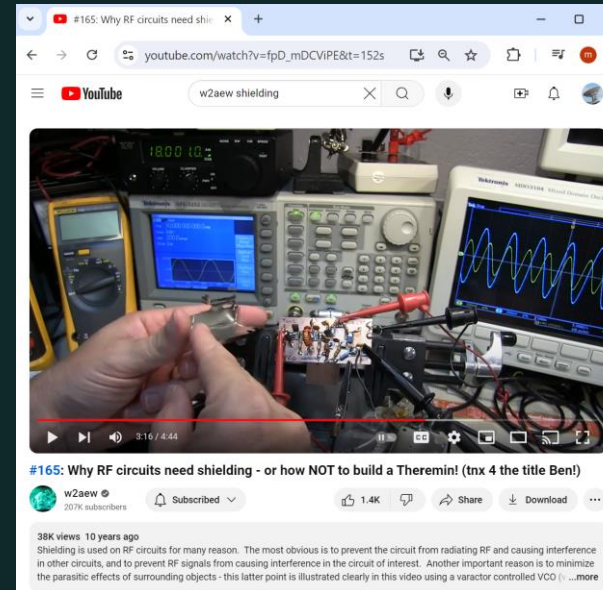
IMSAI Guy
117K subscribers

9.8K views 1 year ago
Episode 1325b
A quick look inside the new TinySA ULTRA
Be a Patron: /imsaiguymore

AI-generated video summary · Quality and accuracy may vary.

This video provides a detailed teardown of the TinySA Ultra spectrum analyzer. The host reveals the internal components, including the battery, shielding, and main processor. They also highlight the various chips and filters used in the device, offering insights into its construction and functionality.

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



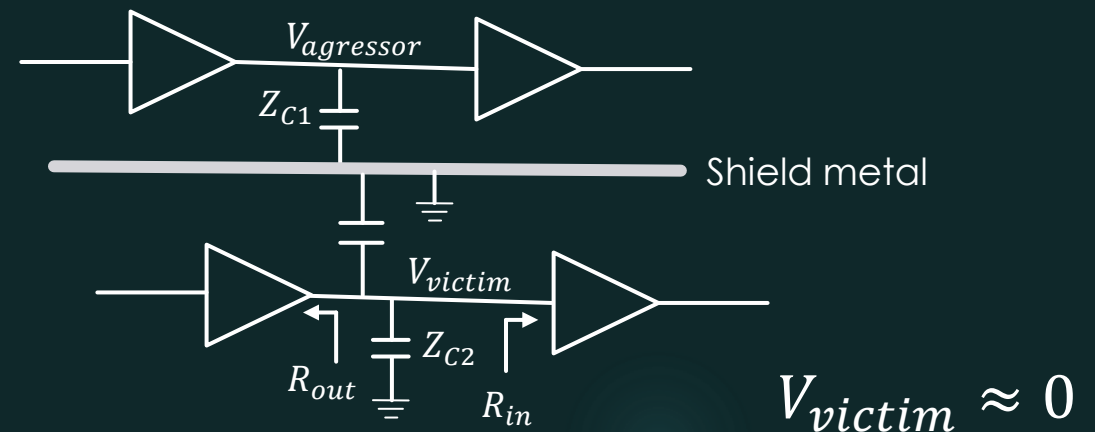
#165: Why RF circuits need shielding - or how NOT to build a Therman! (tx 4 the title Ben!)

w2aew
207K subscribers

38K views 10 years ago

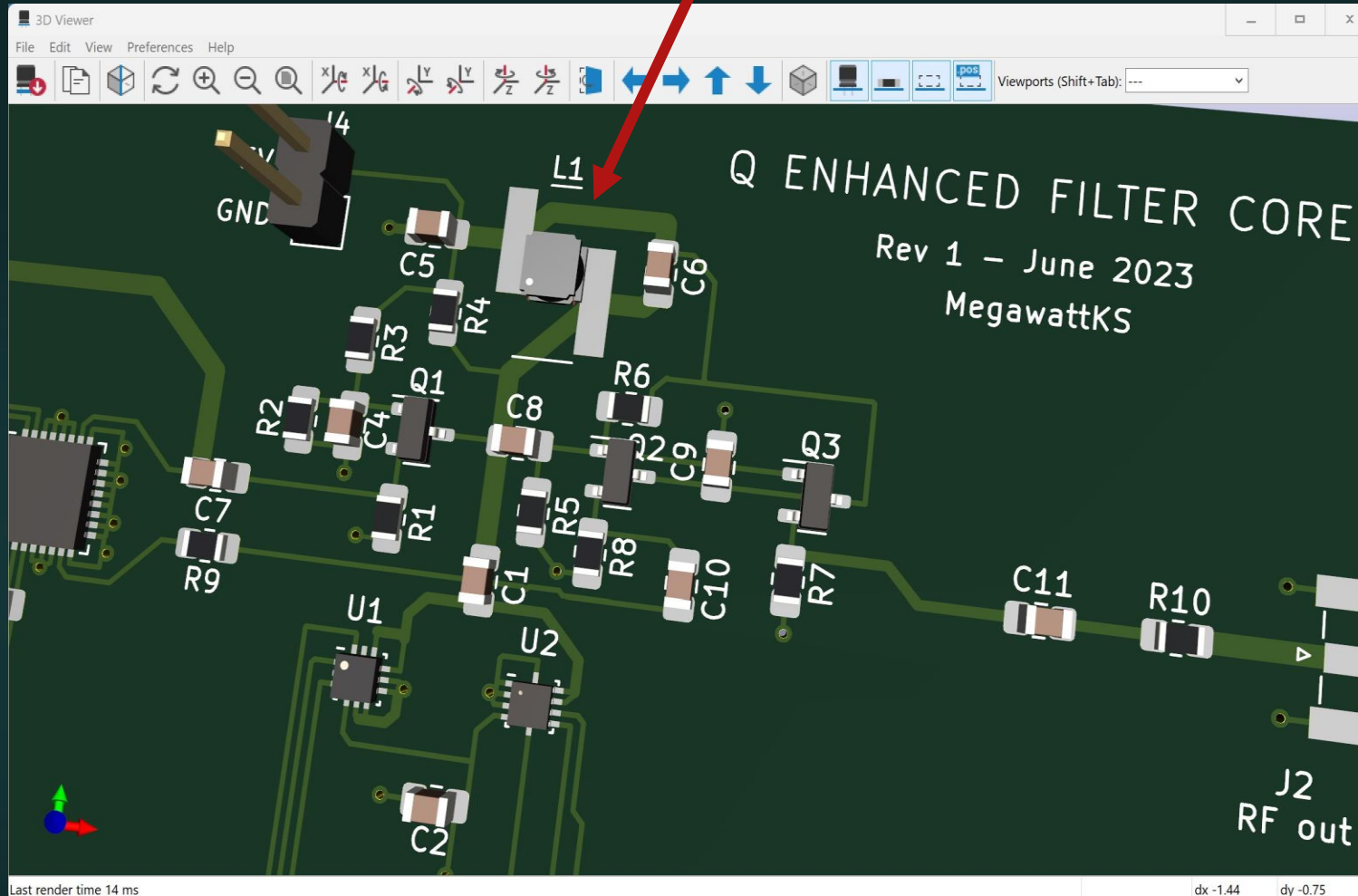
Shielding is used on RF circuits for many reasons. The most obvious is to prevent the circuit from radiating RF and causing interference in other circuits, and to prevent RF signals from causing interference in the circuit of interest. Another important reason is to minimize the parasitic effects of surrounding objects - this latter point is illustrated clearly in this video using a varactor controlled VCO in ...more

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



Watch Out for B-Field Coupling Too

19

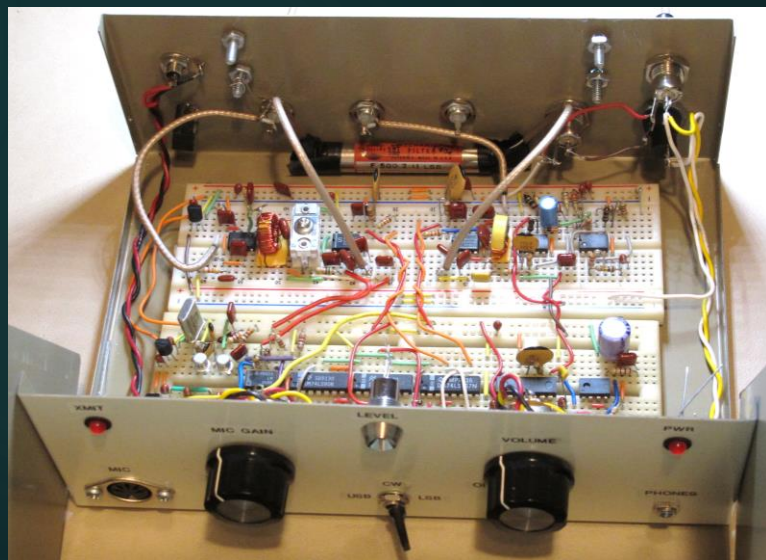


Construction on Protoboards

20

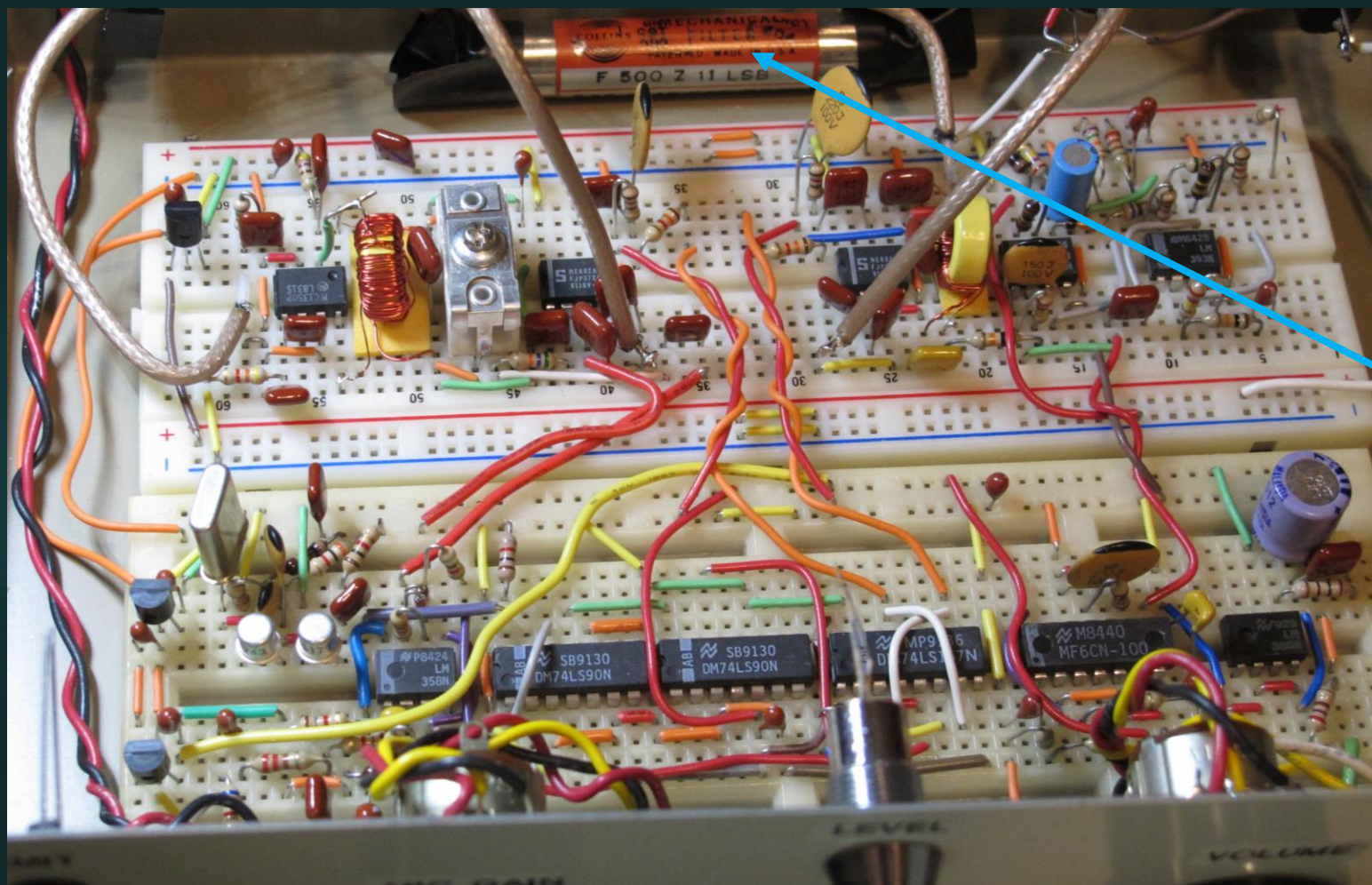


80-meter (3.5 to 4 MHz) SSB/CW Transceiver "teardown"



500 kHz Low IF Section

21

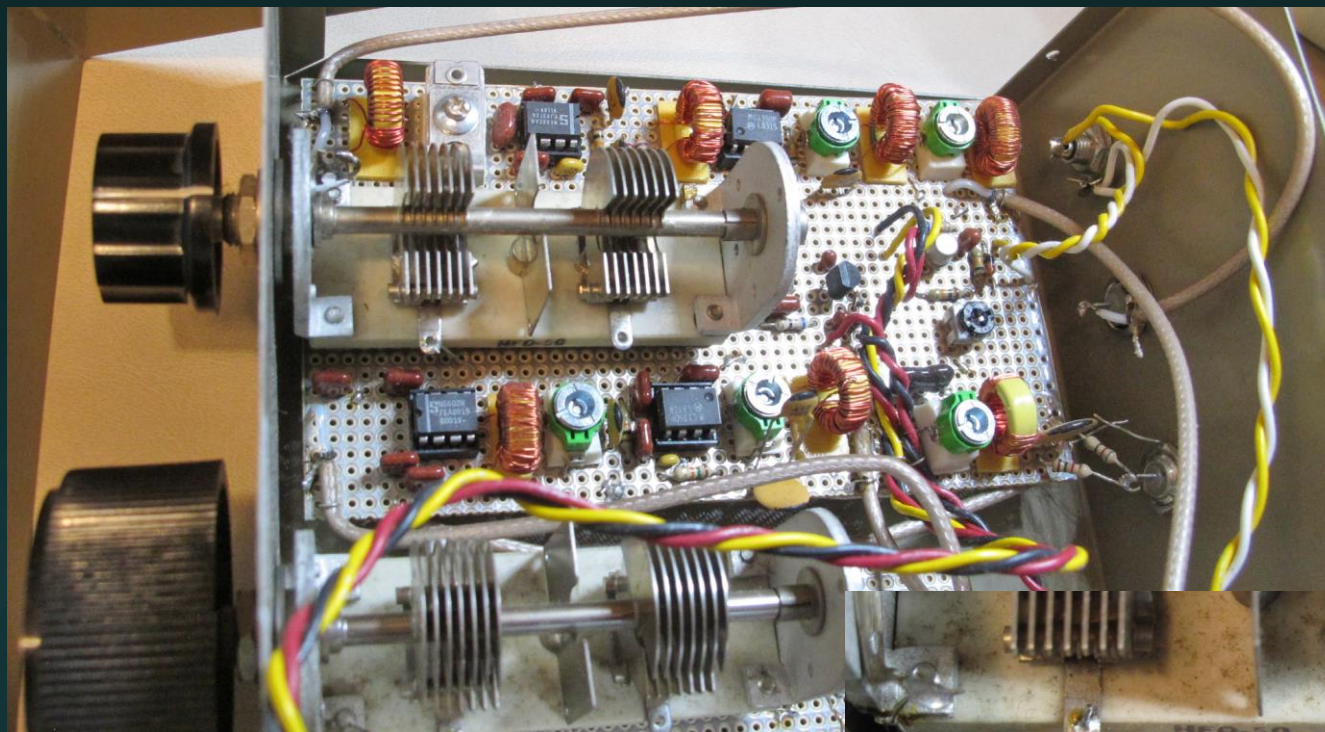


DSB-SC Modulator /
Demodulator

500 kHz center, 2 kHz
bandwidth BPF for LSB
selection

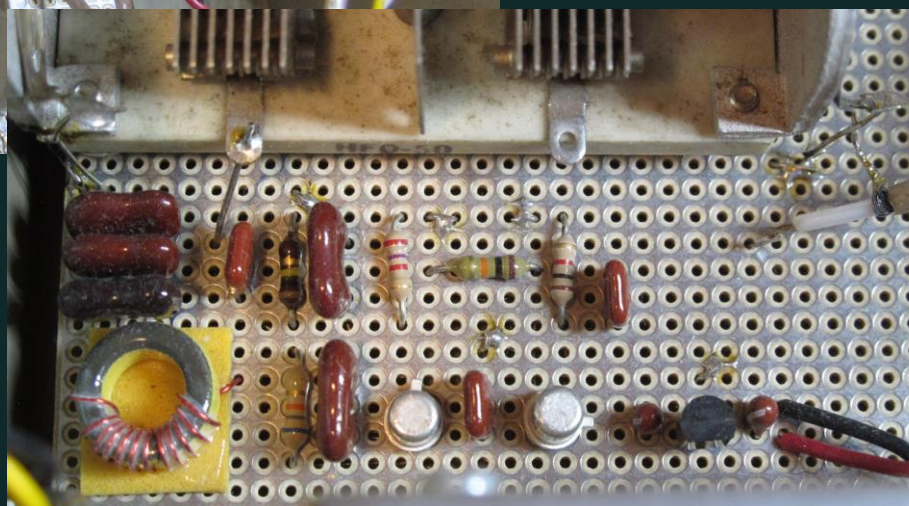
10 MHz osc with /20 for
500 kHz LO + SC LPF for
receive audio

3.5 – 4 MHz RF Section



Preselected RF amp
and downconverter

Upconverter and
harmonic filtering



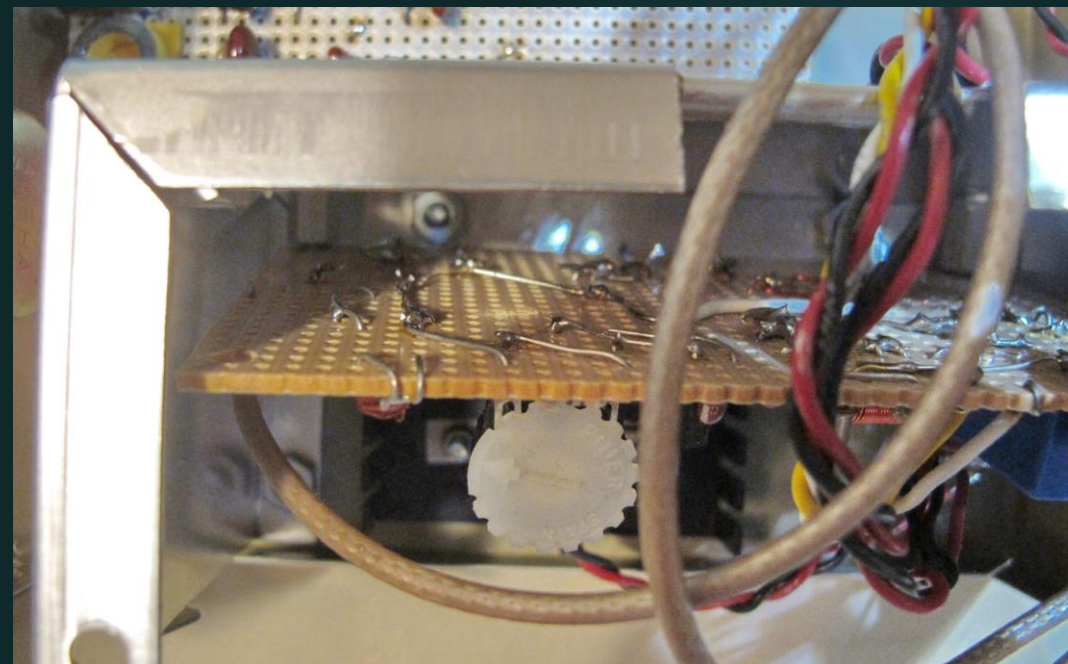
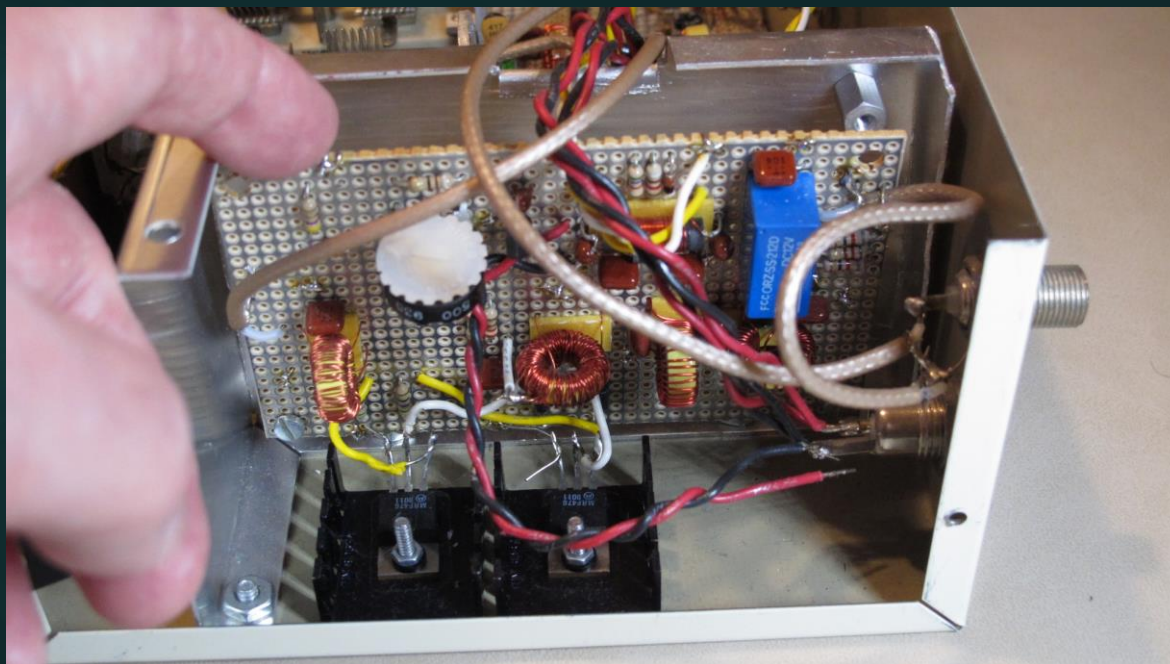
4 – 4.5 MHz
VFO

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 ☺

24

Amateur Radio Station				LOG	REPORT		TIME OFF	QTH	COMMENTS	QSL VIA		QSL	
AMERICAN RADIO RELAY LEAGUE NEWINGTON, CONNECTICUT, U.S.A.					SENT	REC'D				NAME	S	R	
CALL SIGN									Finished construction of homebrew rig. Measured approx 3w out. Antenna raised earlier is 80m dipole up - 25'				
							01:20		Unsuccessful - Too much static at his end (
2/1/92	—	—	—	01:30					Listened for Craig Unsuccessful - too much QRN				
2/2/92	3.820	PH	2W	22:30		59	57	23:00	After initial problem with feedback due to cover off, worked perfect after installing cover. Some VFO drift.				✓
2/2/92	3.740	CW	2W	01:45		219	519		Craig copied all of my TX. Could copy some of his. Lost contact at end when I bumped VFO off freq.				

UTZ
↓

Available Perf-boards

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

Google search results for "single-side RF perfboard".

Sponsored results:

Product Name	Price	Source	Lead Time	Category
SchmalzTech, LLC ST-PROTO-2-3	\$4.99	DigiKey	30-day returns	Breadboard
uxcell 3 Pcs Single Sided SMD Prototyp...	\$10.59	Amazon.com	30-day returns	PCB
SchmalzTech, LLC ST-PROTO-1-2	\$3.49	DigiKey	30-day returns	Breadboard
SchmalzTech, LLC ST-PERF-1-2	\$1.95	DigiKey	30-day returns	Breadboard
SchmalzTech, LLC ST-PERF-1-1	\$7.40	DigiKey	30-day returns	Breadboard
DIGIKEY STANDARD DKS-...	\$1.16	DigiKey	Get by 8/26	Breadboard
1" x 1" Perfboard Perfboard ...	\$1.49	SchmalzTech	Get by 8/29	Breadboard
SchmalzTech, LLC ST-PERF-3-3	\$5.99	DigiKey	30-day returns	Breadboard

Reddit · r/AskElectronics
9 comments · 5 years ago

Perfboard effects on RF circuits : r/AskElectronics ✓

Is it one sided?

What do you think of double sided single hole perfboard? Jul 5, 2018

to what frequency is typical perfboard soldering become not ... Nov 18, 2022

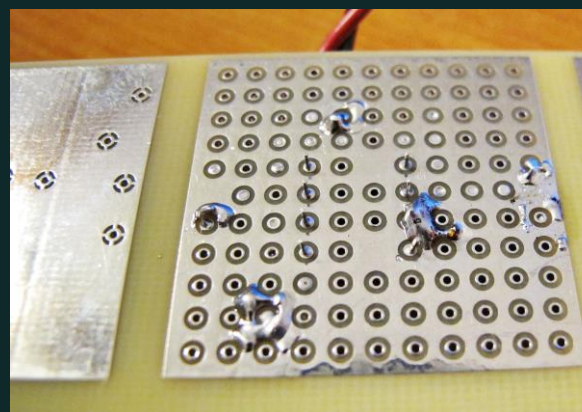
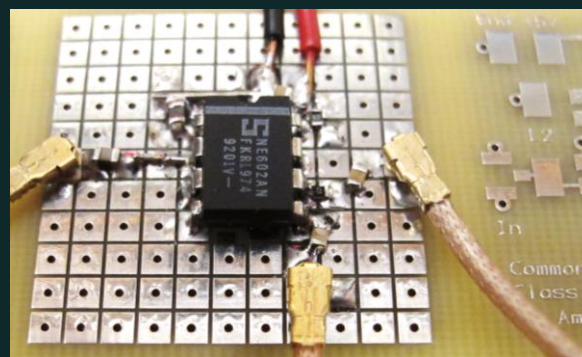
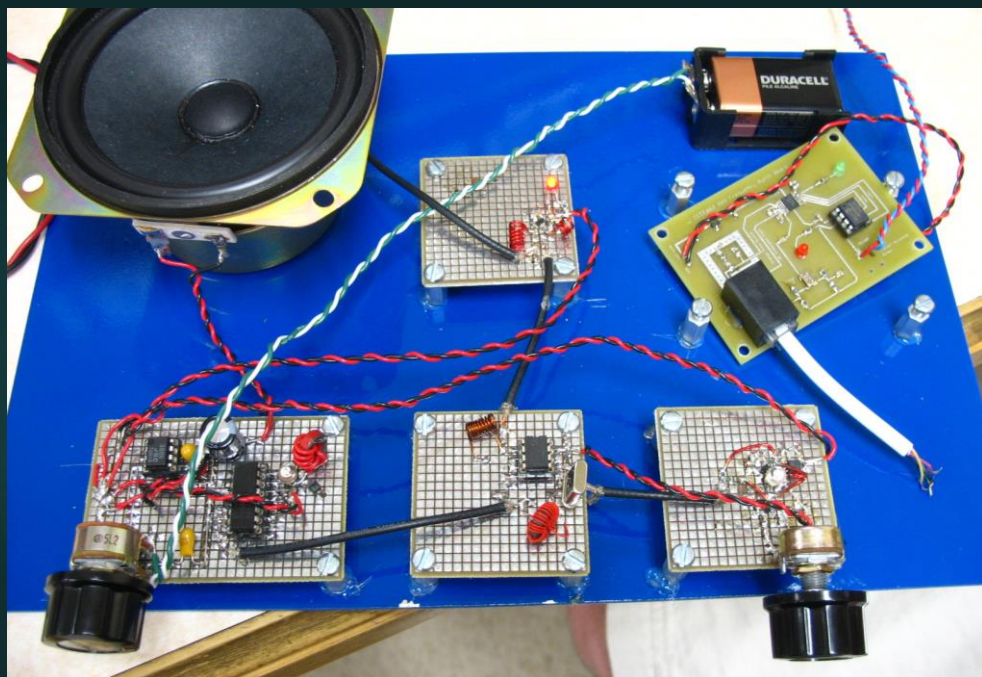
Does anyone know what kind of perfboard this is and ... - Reddit Nov 3, 2016

Can I solder a perfboard like this? First time working on one ... Mar 8, 2023

More results from www.reddit.com

VHF RD101 Construction

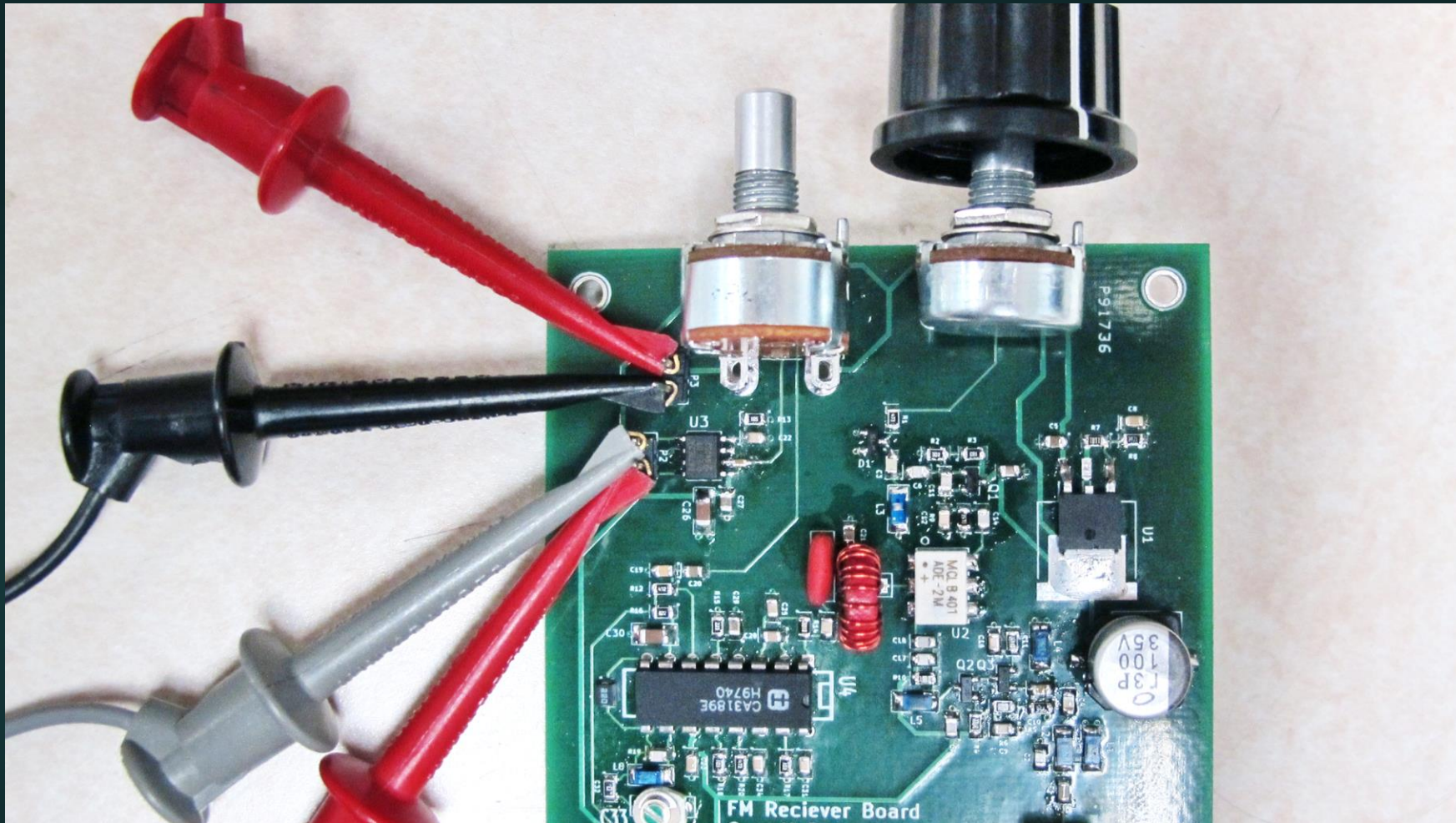
Back-side Ground Plane and top-side "Sorta - Microstrip"



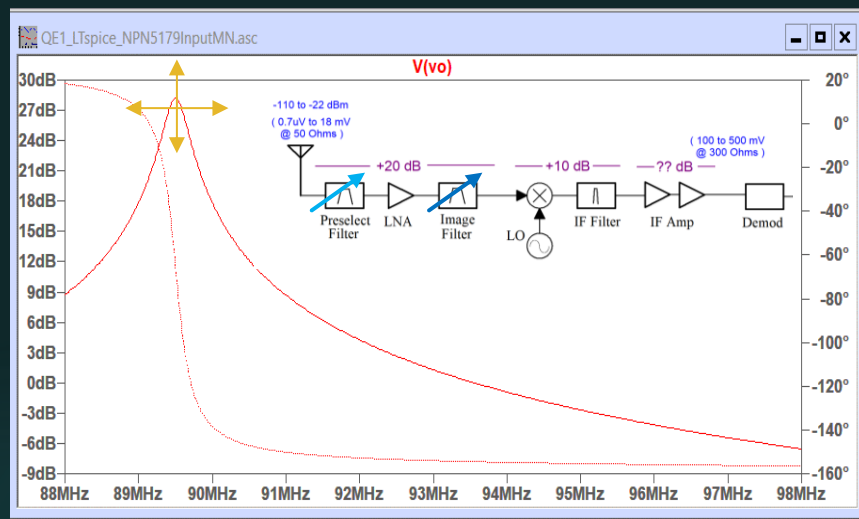
See: <https://ecefiles.org/rf-circuit-prototyping/>

VHF Receiver on PCB

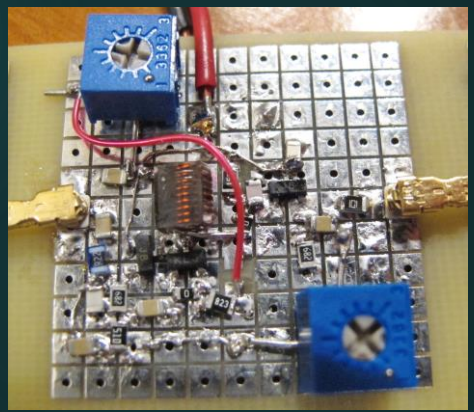
27



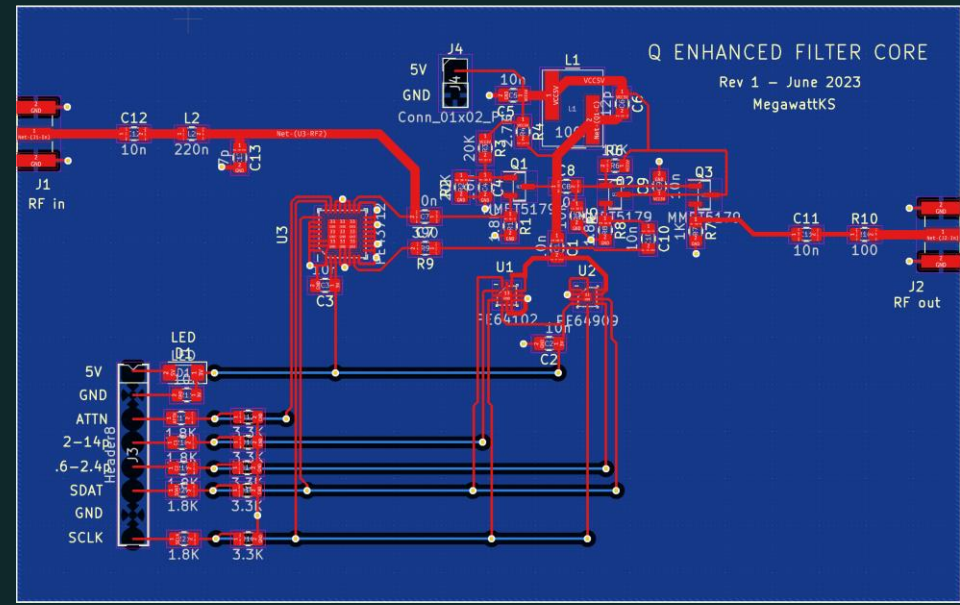
More on RF Prototyping



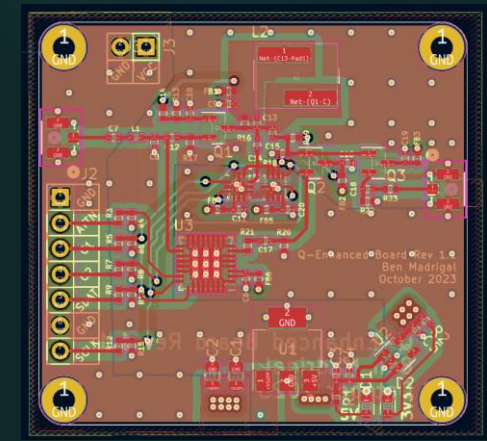
Q-Enhanced bandpass filter
 See Radio Design 101 – Final Epilogue (Epilogue 3) video



First build on protoboard

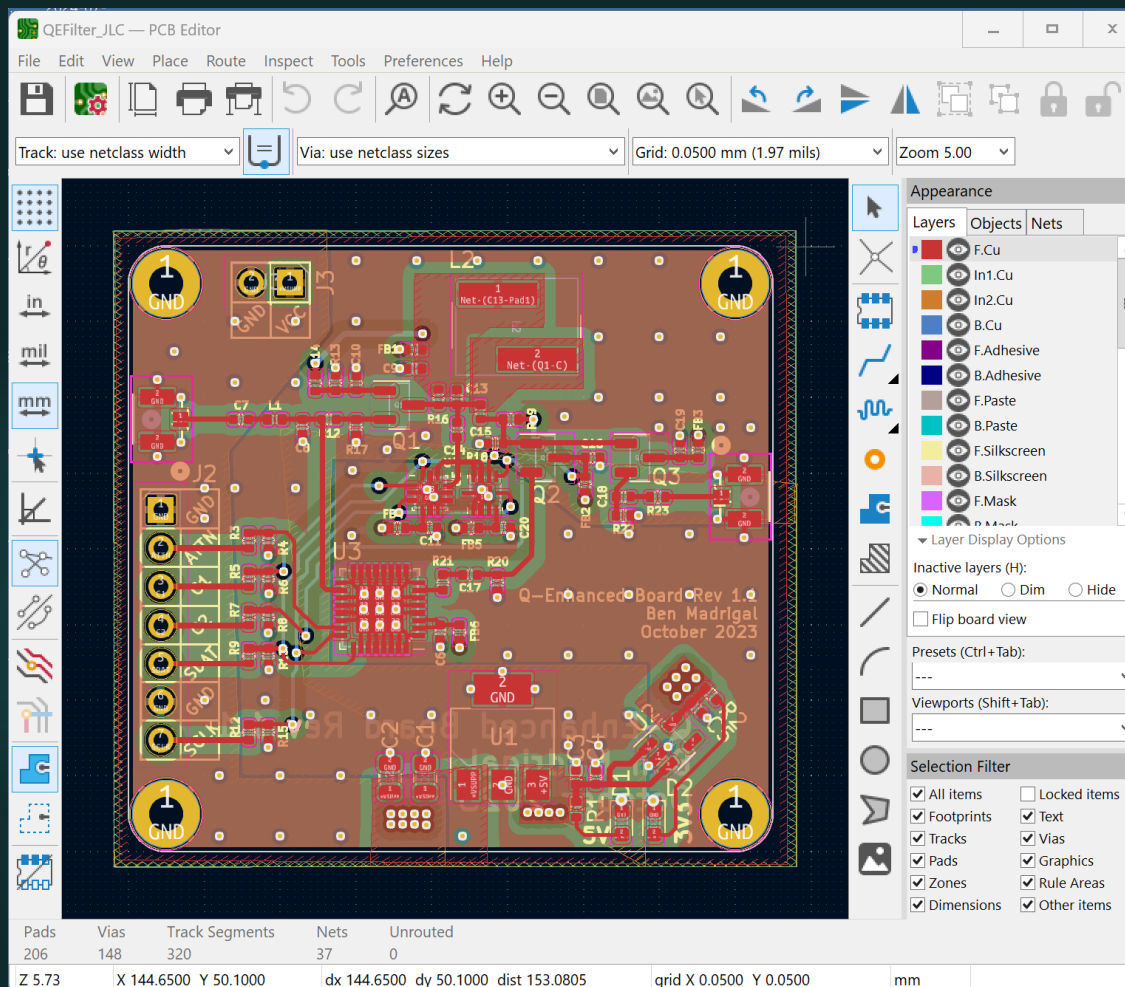


Second build on 2-layer PCB



Third build on 4-layer PCB

4-Layer board, KiCad & JLCPCB



Layout in KiCad

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

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	
Layer	Copper	0.035mm	

Example Stackup from JLCPCB

UHF Fully Integrated Radio

30

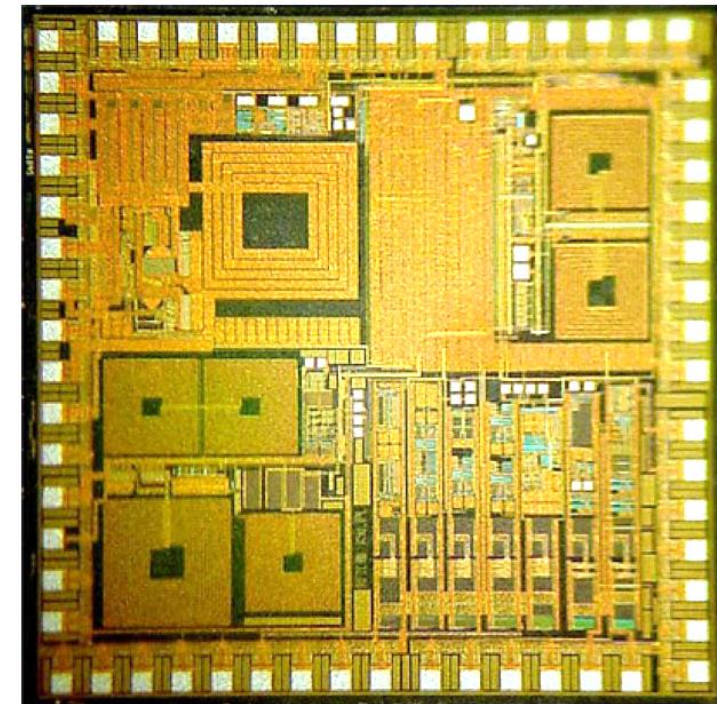
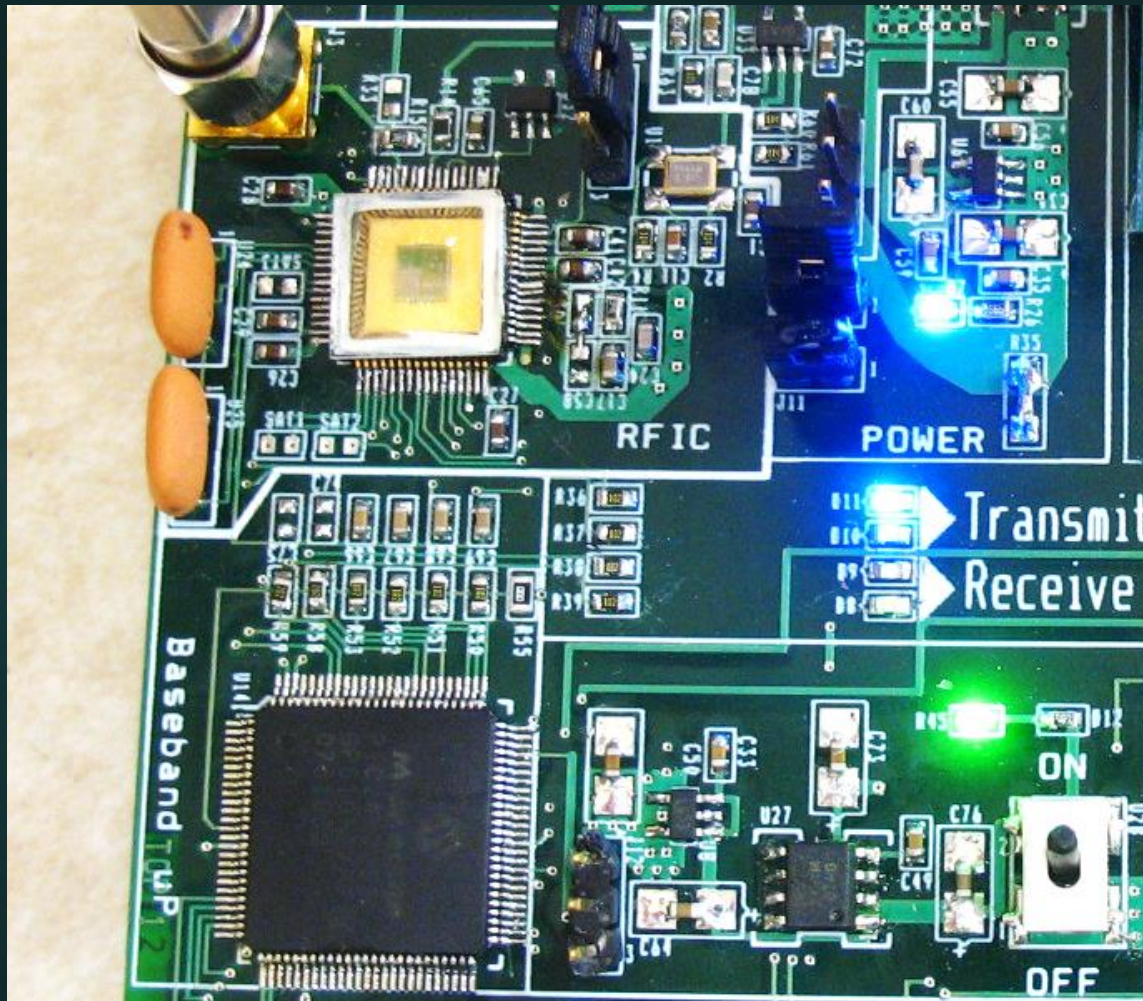
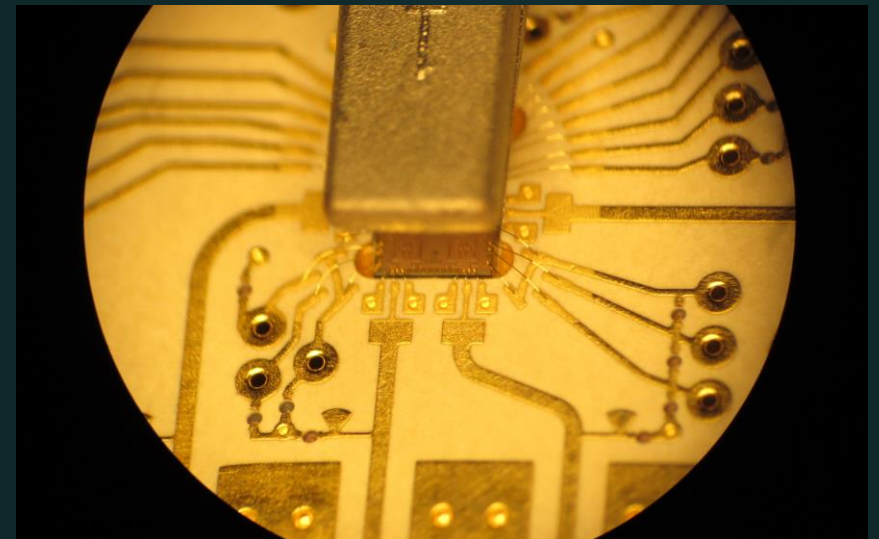
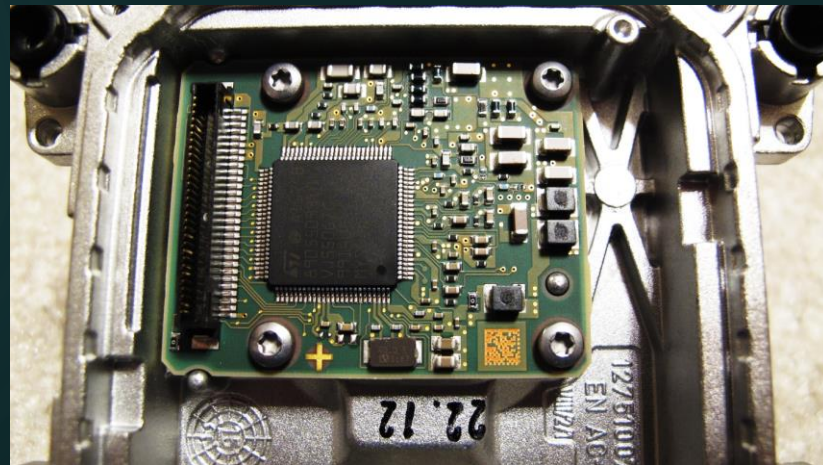
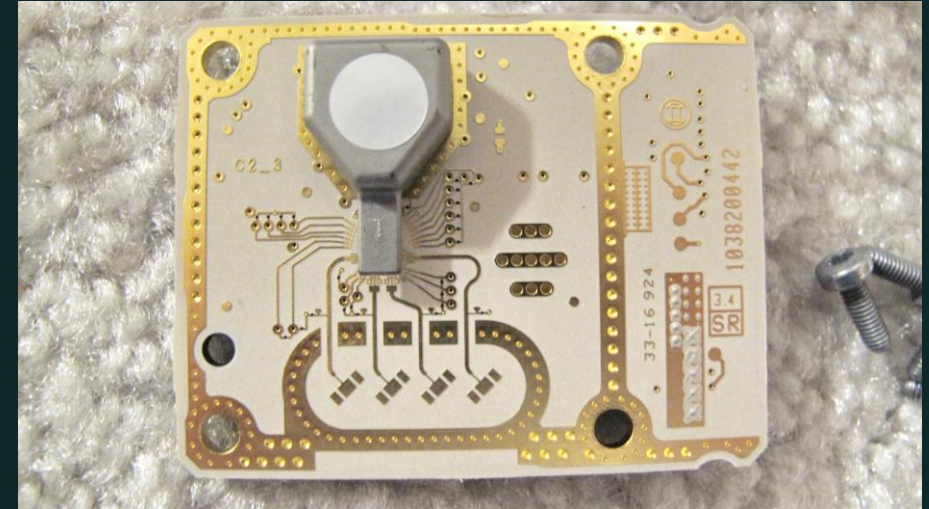


Fig. 39. Die photo of fully integrated single-chip 100-mW transceiver.

77 GHz Automotive Radar



Possible Future Videos

- Transmission Lines

The math v_p , Z_0 , Γ , S_{ij} , etc ...

Coax, Microstrip, Coplanar Waveguide, Stripline,

- Crosstalk Measurements and Shielding

- Planar Microwave Circuits

*Thanks For
Watching !*