Santa Clara IEEE EMC Chapter meeting

April 9, 2013

Dorothy we're not in Kansas any more, we are in Impedance land. Oh my!

Presented by

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Welcome to Impedance land

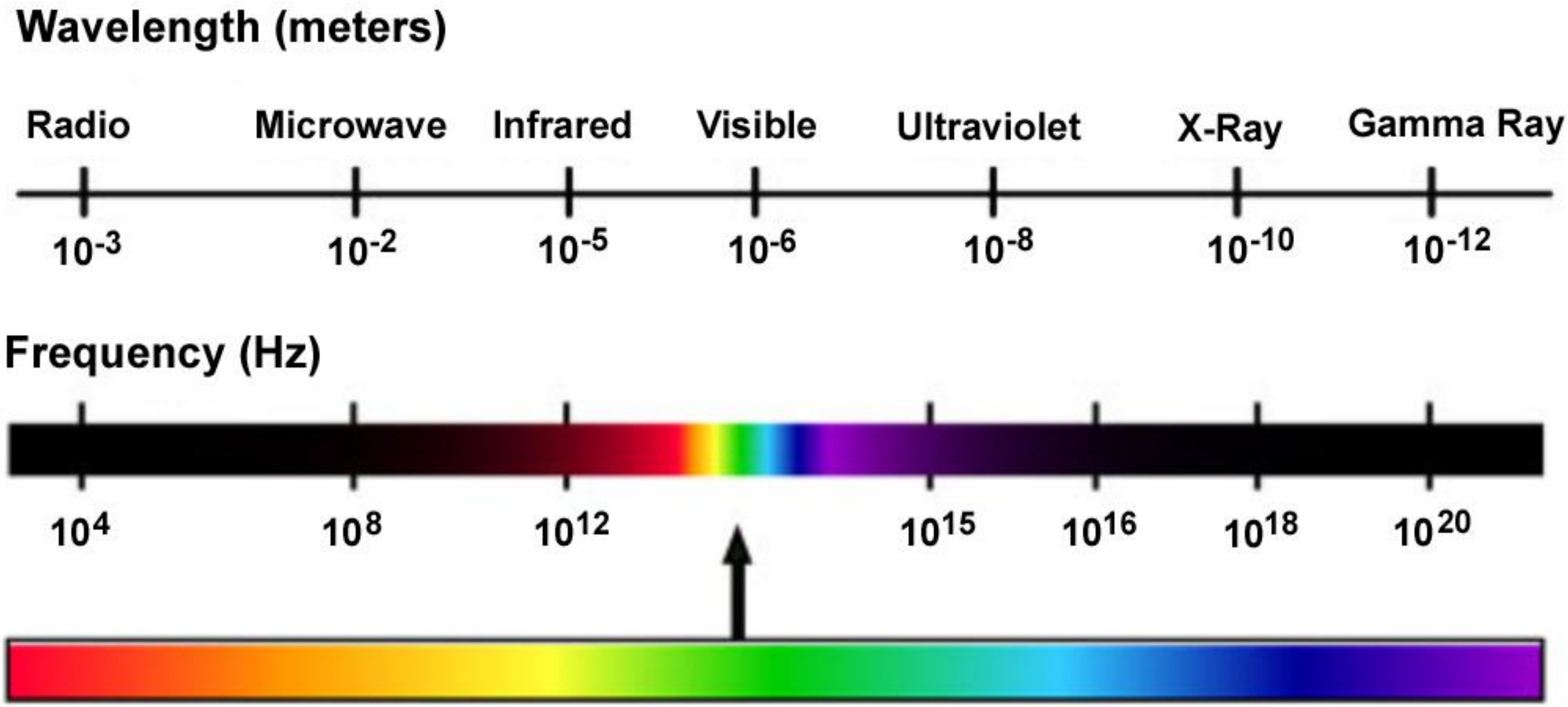
You don’t have to be crazy
to be into EMC.

Welcome to Impedance land

You don’t have to be crazy
to be into EMC.

We will train
you!

The Electromagnetic Spectrum



$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$

VISIBLE LIGHT

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

What is Wavelength?

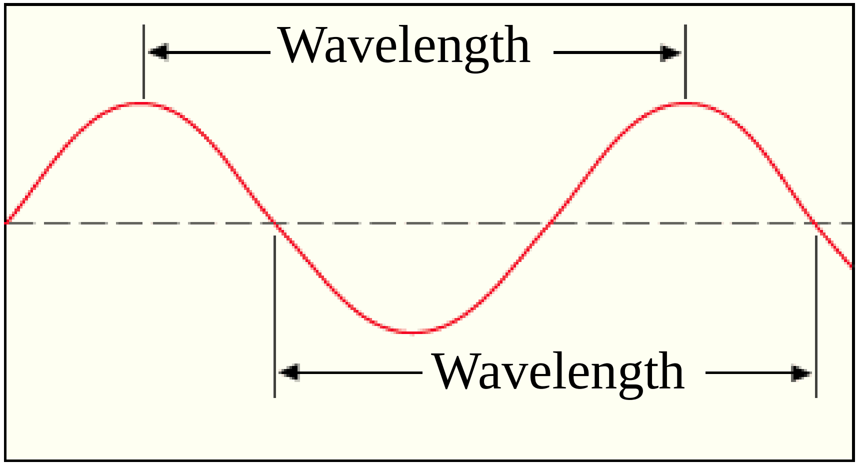
According to Wikipedia:

> “The distance over which the wave's shape repeats.”

To the RF and EMC engineer:

> It is the distance travelled by the propagating wave in one cycle.

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



When working an EMC issue, It's all the same stuff

Distance – Phase – Inductance

When working an EMC issue,
It’s all the same stuff

Distance – Phase – Inductance

The secret to understanding EMC is understanding wavelength as it relates to these three items.

Wavelength expressed in free space

$$c \approx 3x10^{8}\, meters / \sec = 300\, x10^{6}$$

$$\lambda = \frac{c}{f} \approx \frac{3x10^{11}\, mm / \sec}{f\ in\, GHz\, x10^{9}}$$

$$\approx \frac{300mm}{f(GHz)} \approx \frac{11.8\, inches}{f(GHz)}$$

We can also say the wave travels 11.8 inches in one nanosecond.

Wavelength expressed with stuff in the space

Permeability $$\mu = \mu_0 \mu_r \qquad \mu_0 = \frac{1}{4\pi} 10^{-7} \frac{H}{m}$$

Permittivity $$\varepsilon = \varepsilon_0 \varepsilon_r \qquad \varepsilon_0 = \frac{1}{36\pi} 10^{-9} \frac{F}{m}$$

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

$$\lambda_{not\,freespace} = \frac{v_{not\,freespace}}{f}$$

Wavelength expressed with FR4 PCB in the space

$$v_{FR4\ PCB} \approx 0.48c \approx 144\frac{mm}{n\sec} \approx 5.9\frac{inches}{n\sec}$$

$$\lambda_{FR4PCB} = \frac{v_{FR4PCB}}{f} \approx \frac{5.9\,inches\,/\,n\sec}{f\,(GHz)}$$

We can also say that in FR4 PCB material
the wave travels 5.9 inches in one nanosecond.

There is a lot to be learned from Figure 9-17

A dimensionally correct half wavelength Dipole is **not** resonant.

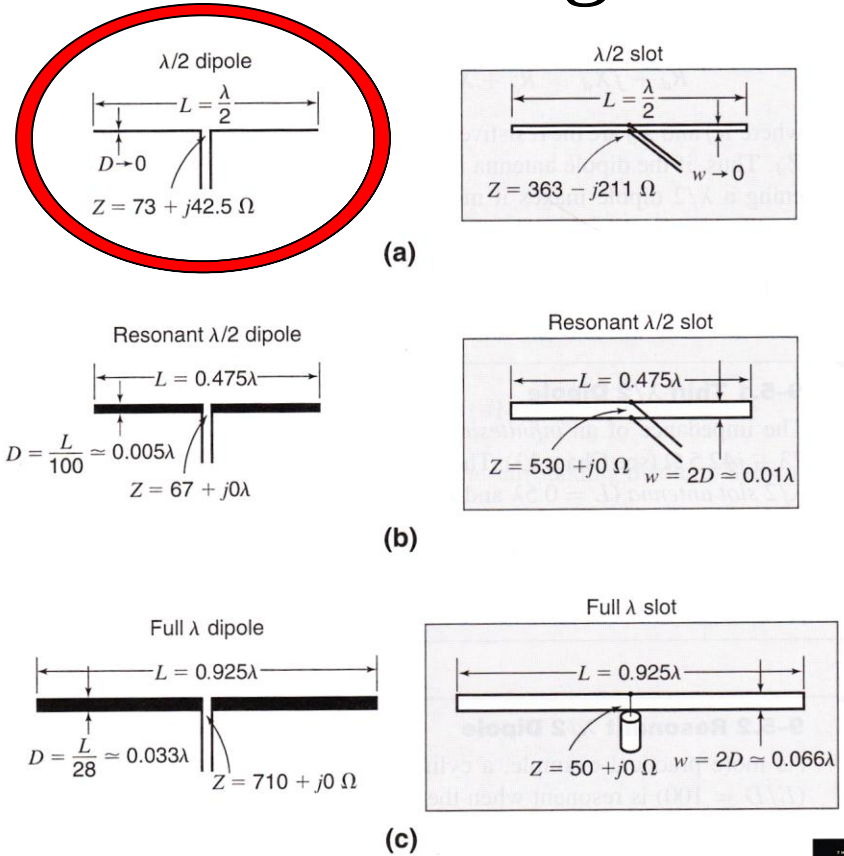
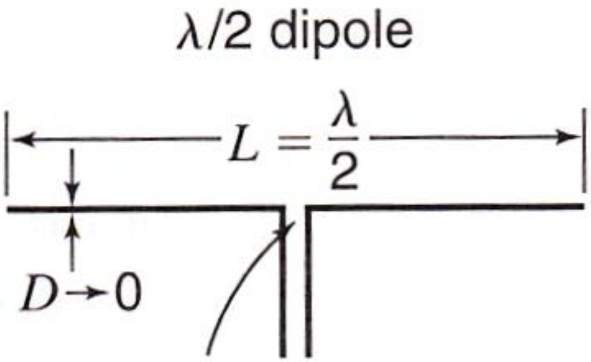


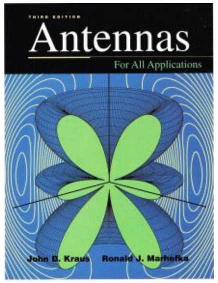
Figure 9–17
Comparison of impedances of cylindrical dipole antennas with complementary slot antennas. The slot in (*c*) matches directly to the 50 Ω coaxial line.



$$Z = 73 + j42.5\Omega$$

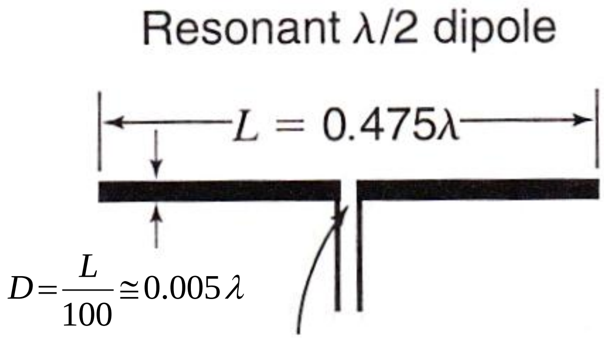
It is electrically too long.

From Antennas Third Edition by
Kraus & Marhefka, page 320



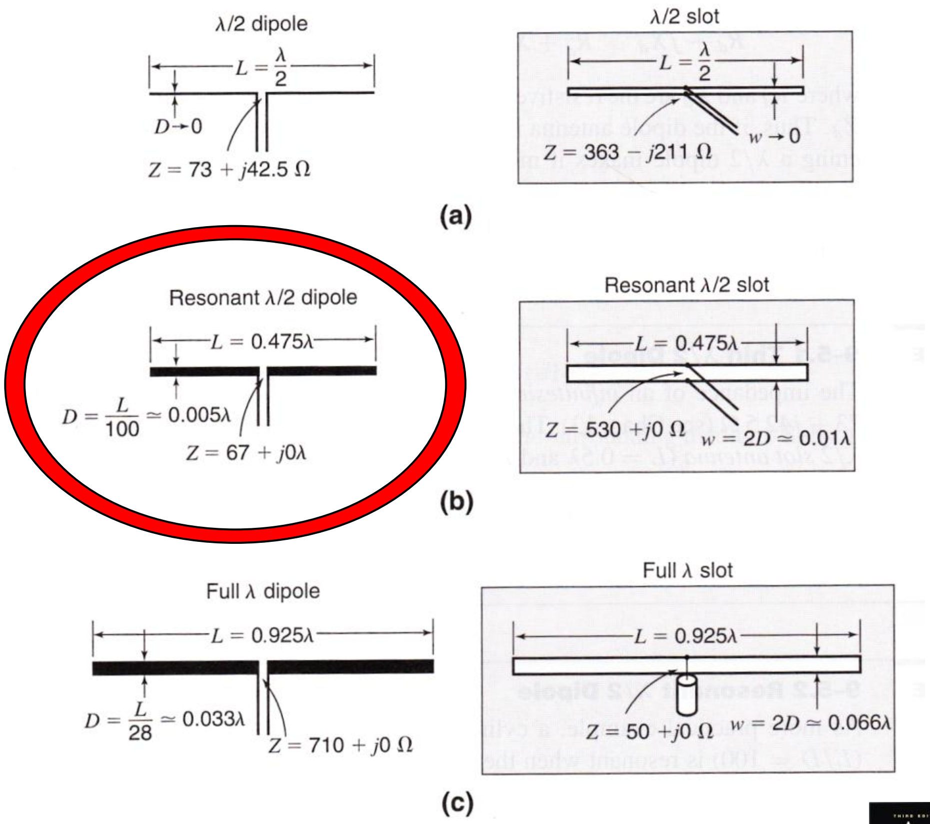
There is a lot to be learned from Figure 9-17

The length of a resonant dipole depends on the diameter of the conductors.



$$D=\frac{L}{100}\cong 0.005\lambda$$

$$Z=67+j0\Omega$$



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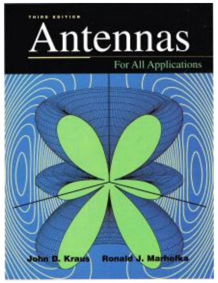
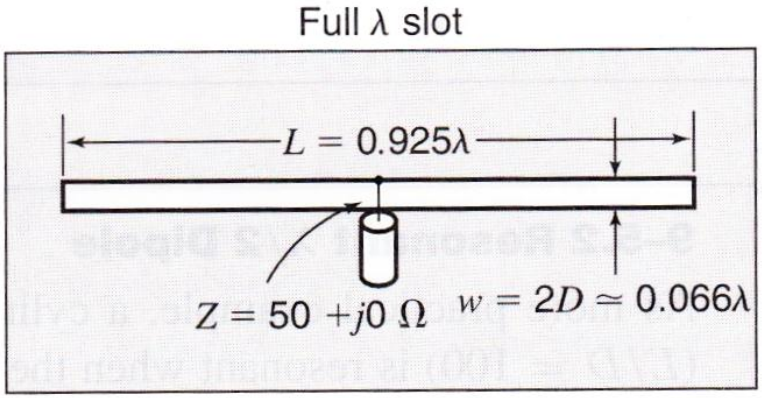
From Antennas Third Edition by Kraus & Marhefka, page 320



There is a lot to be learned from Figure 9-17

A hole in a conductor can also be a resonant antenna.



$$Z = 50 + j0\Omega$$

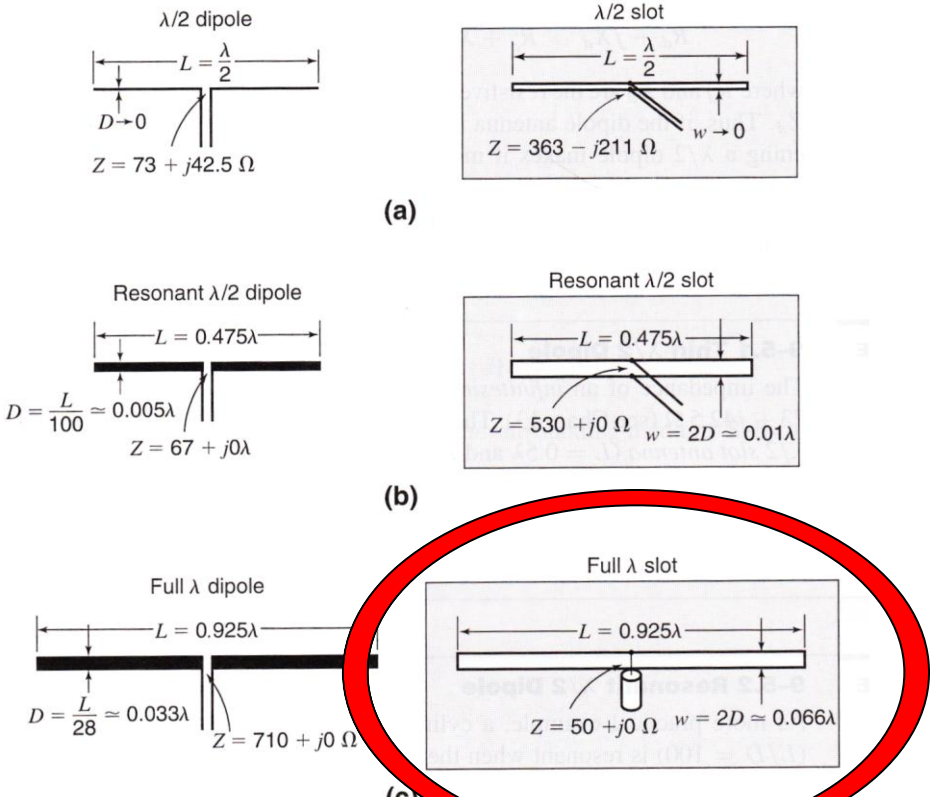
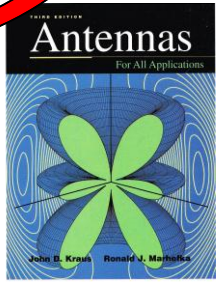


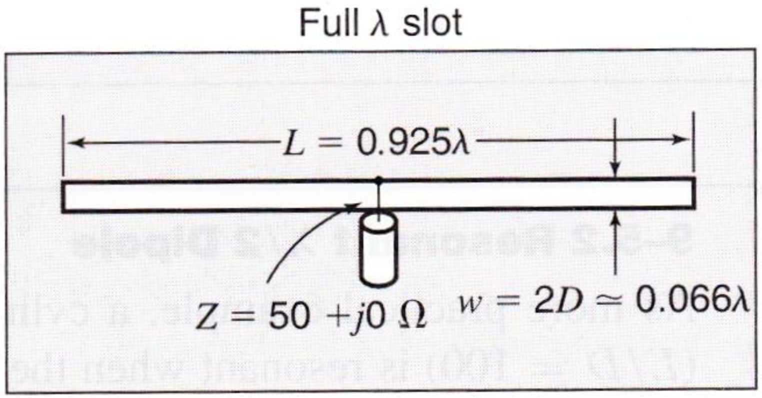
Figure 9–17
Comparison of impedances of cylindrical dipole antennas with complementary slot antennas. The slot in (c) matches directly to the 50 Ω coaxial line.

From Antennas Third Edition by Kraus & Marhefka, page 320



There is a lot to be learned from Figure 9-17

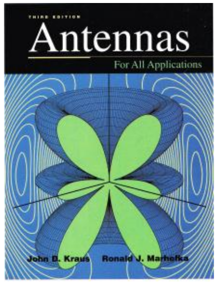
To get this hole in a sheet of conductor to resonate at 500 MHz, the slot would need to be 555 mm wide and have a width of 40 mm.



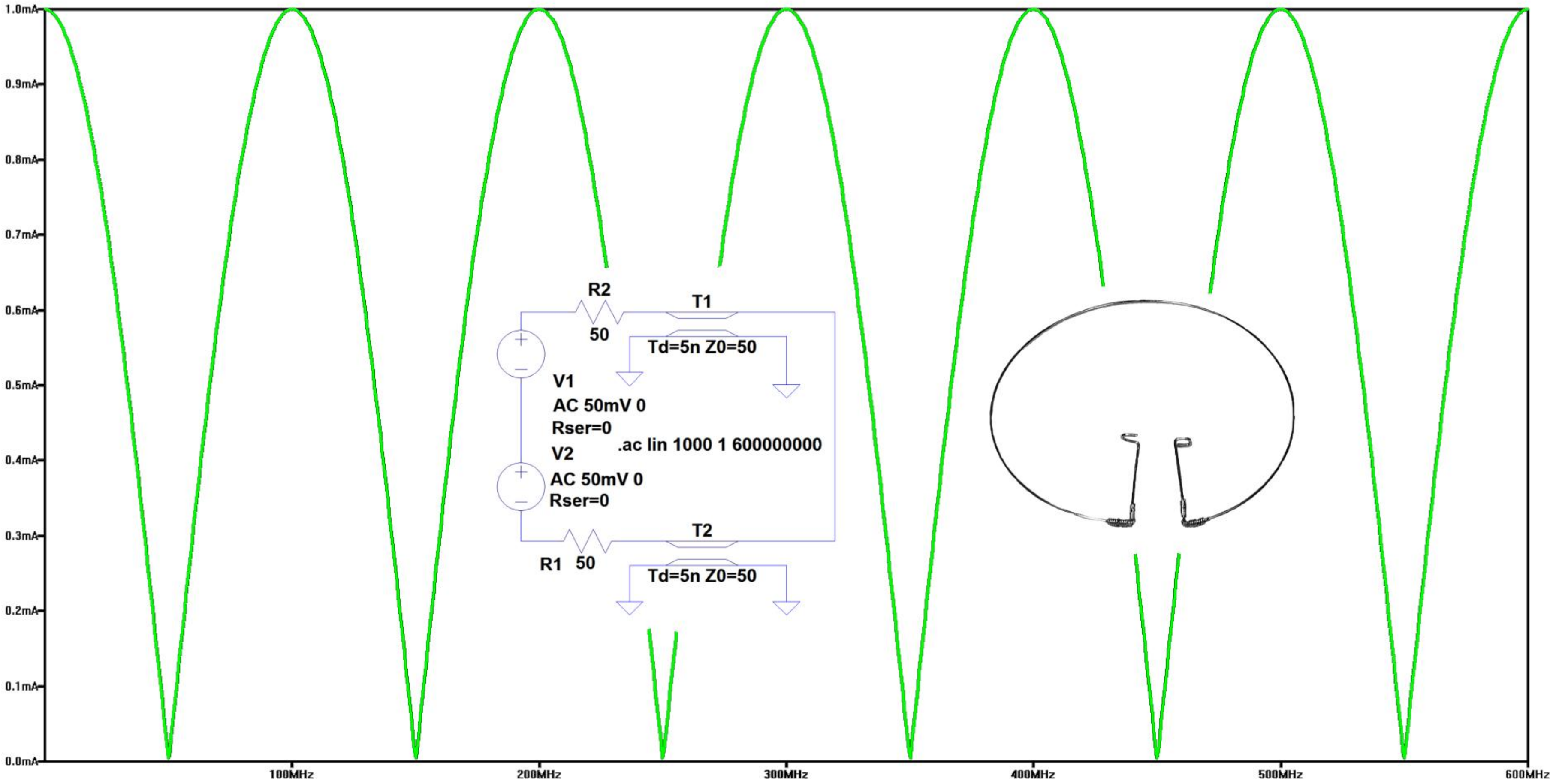
$$L = 0.925 * \frac{3}{5}\, Meters = 555\, mm$$

$$w \approx 0.066 * \frac{3}{5}\, Meters \approx 40\, mm$$

From Antennas Third Edition by
Kraus & Marhefka, page 320

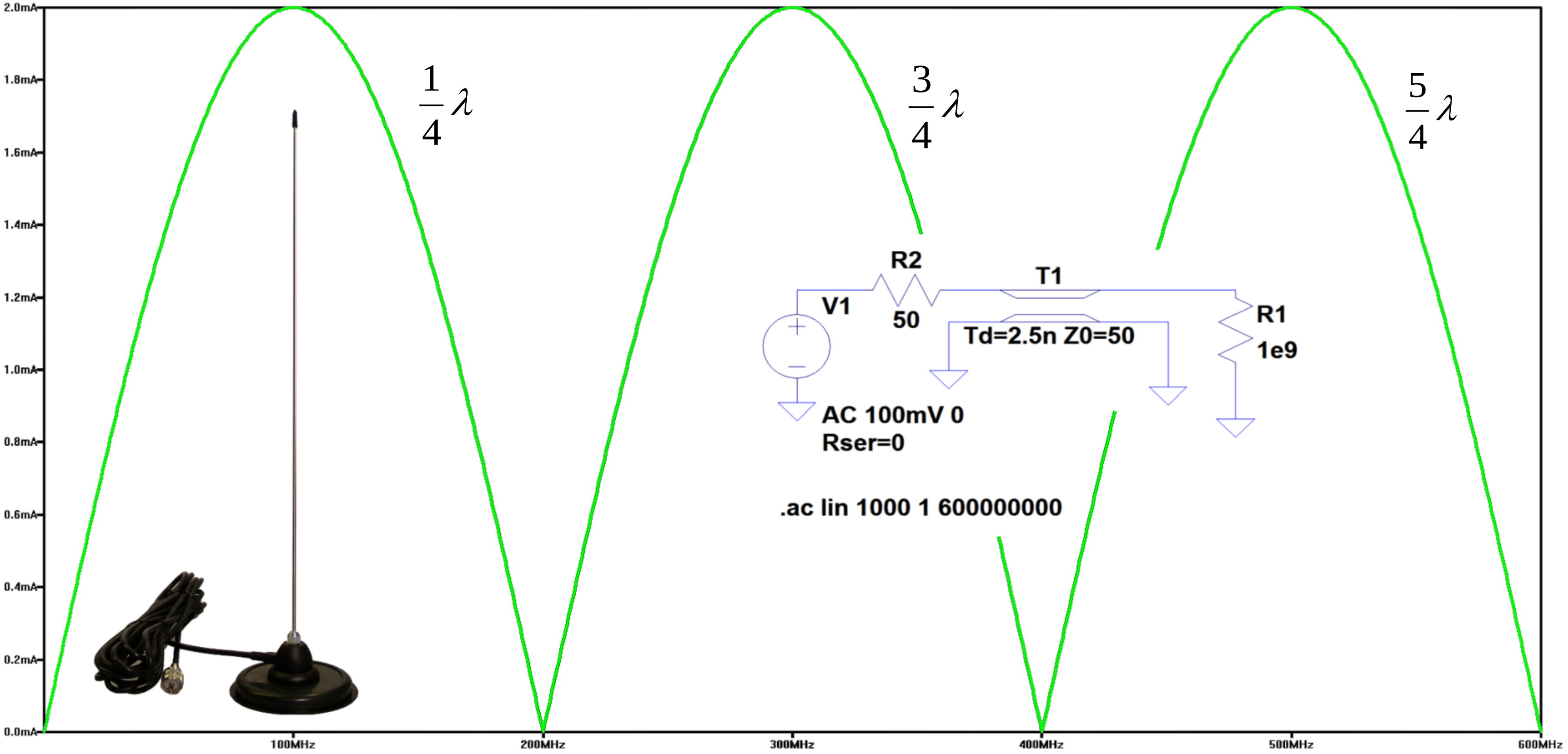


SPICE simulation of a loop



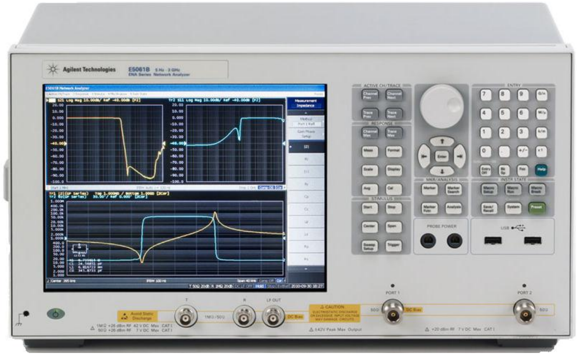
DC $3\,Meters$ $\frac{3}{2}Meters$ $1\,Meters$ $\frac{3}{4}Meters$ $3\,Meters$ $\frac{3}{6}Meters$

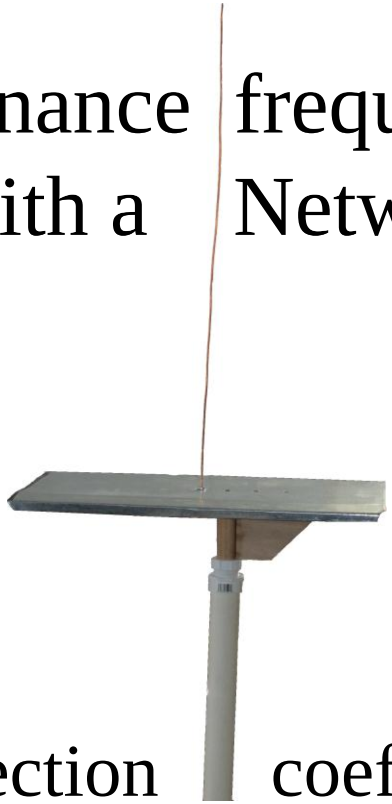
SPICE simulation of a Monopole



$\lambda_{100MHz} = 3\,Meters$ $\lambda_{300MHz} = 1\,Meters$ $\lambda_{500MHz} = 3/5\,Meters$

We measure the resonance frequency of a Monopole antenna with a Network Analyzer

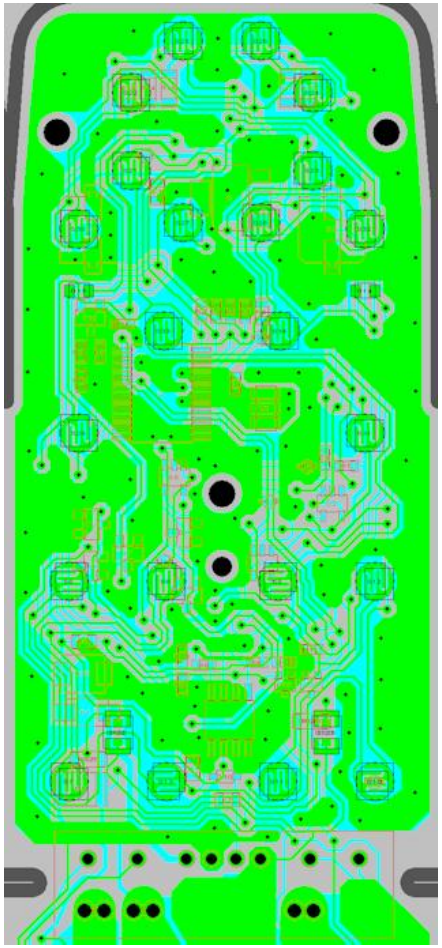




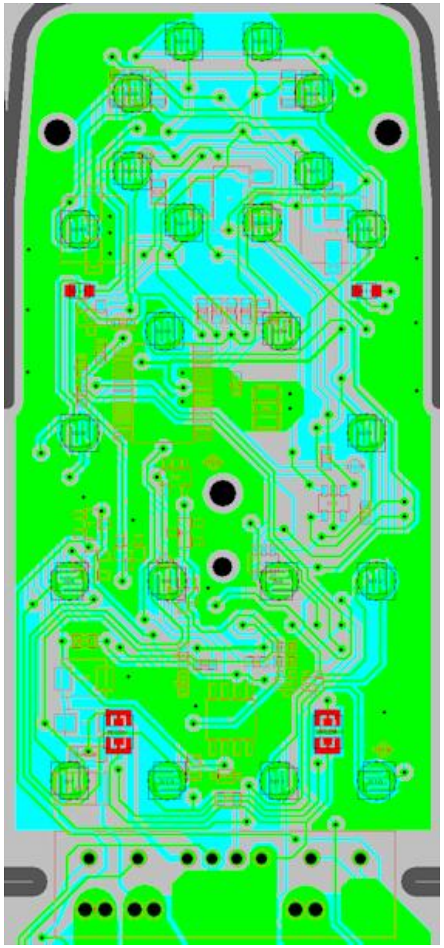
We measure the S11, reflection coefficient, of a 100 MHz monopole antenna. The reflection coefficient is a measure of the amount of energy that leaves the antenna verses the energy that is reflected back to the analyzer. As various materials are presented to the antenna, we watch how the S11 changes.

The Good, the Bad and the Ugly.

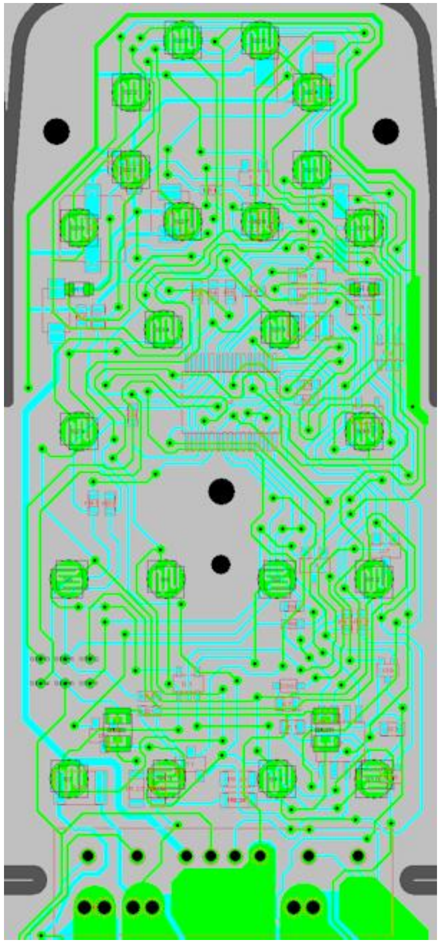
Good Ground.



Bad Ground
Holes in the ground.



Ugly Ground
Daisy-chained.



The Good, the Bad and the Ugly.

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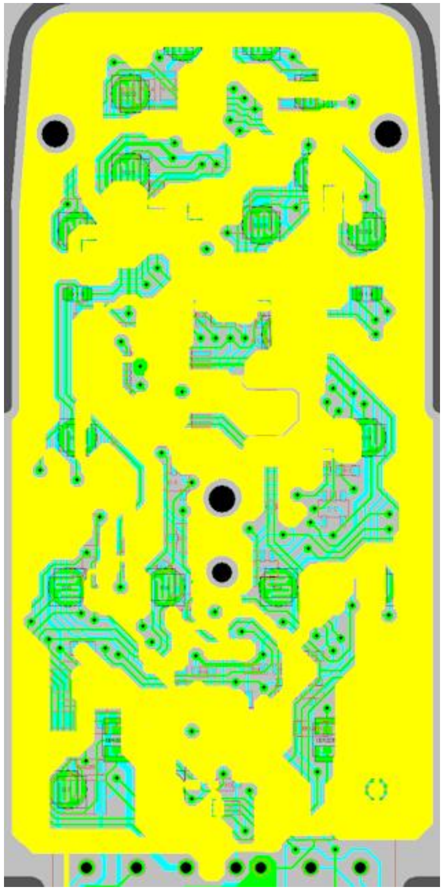

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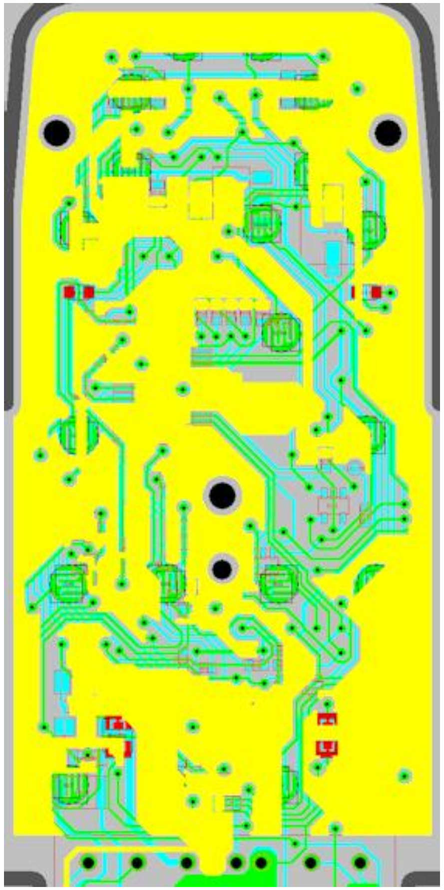

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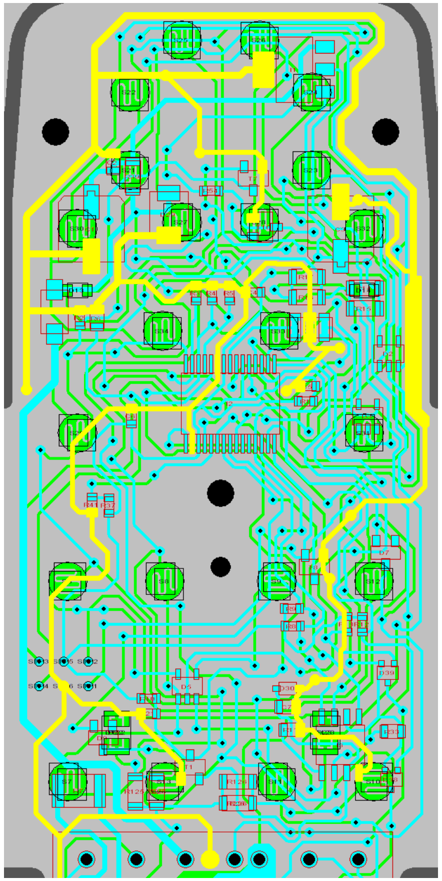
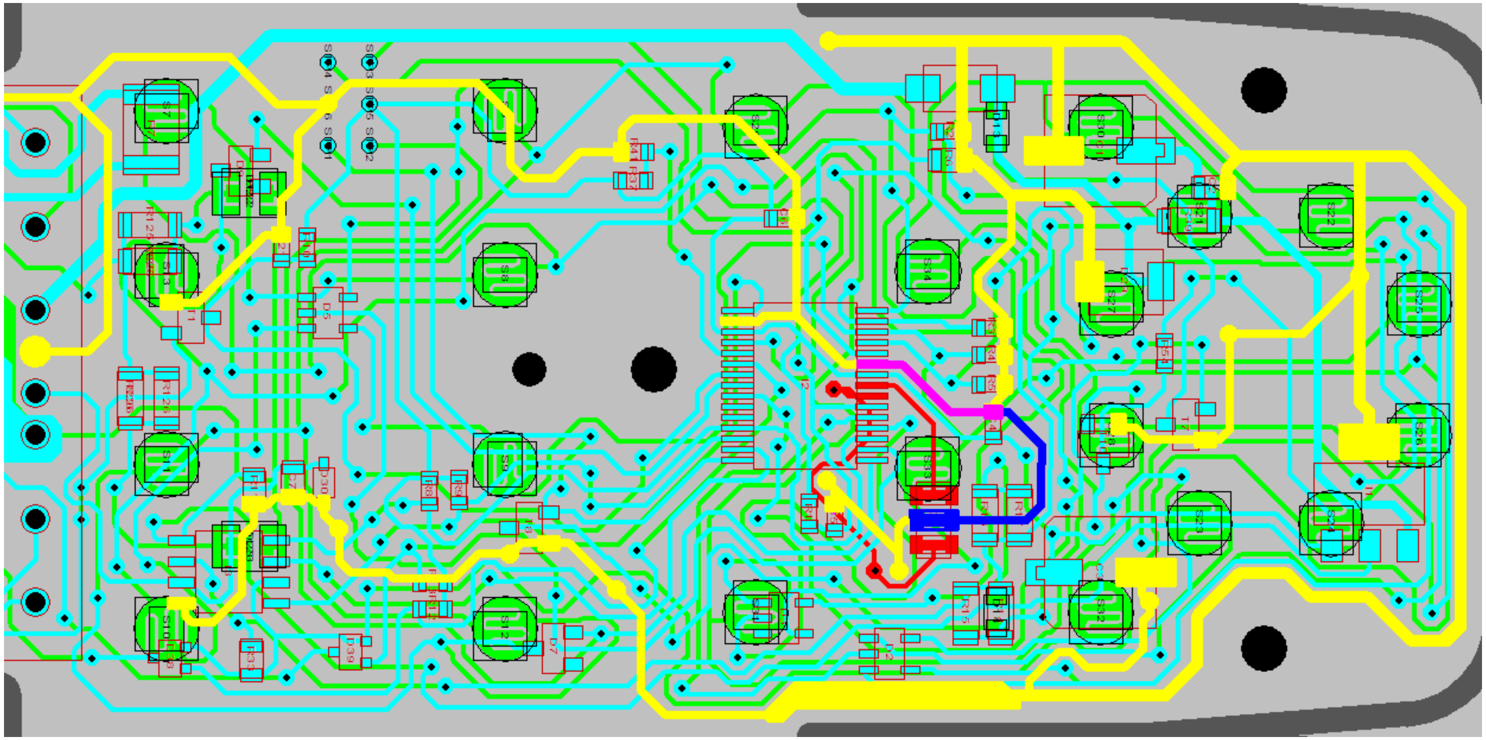


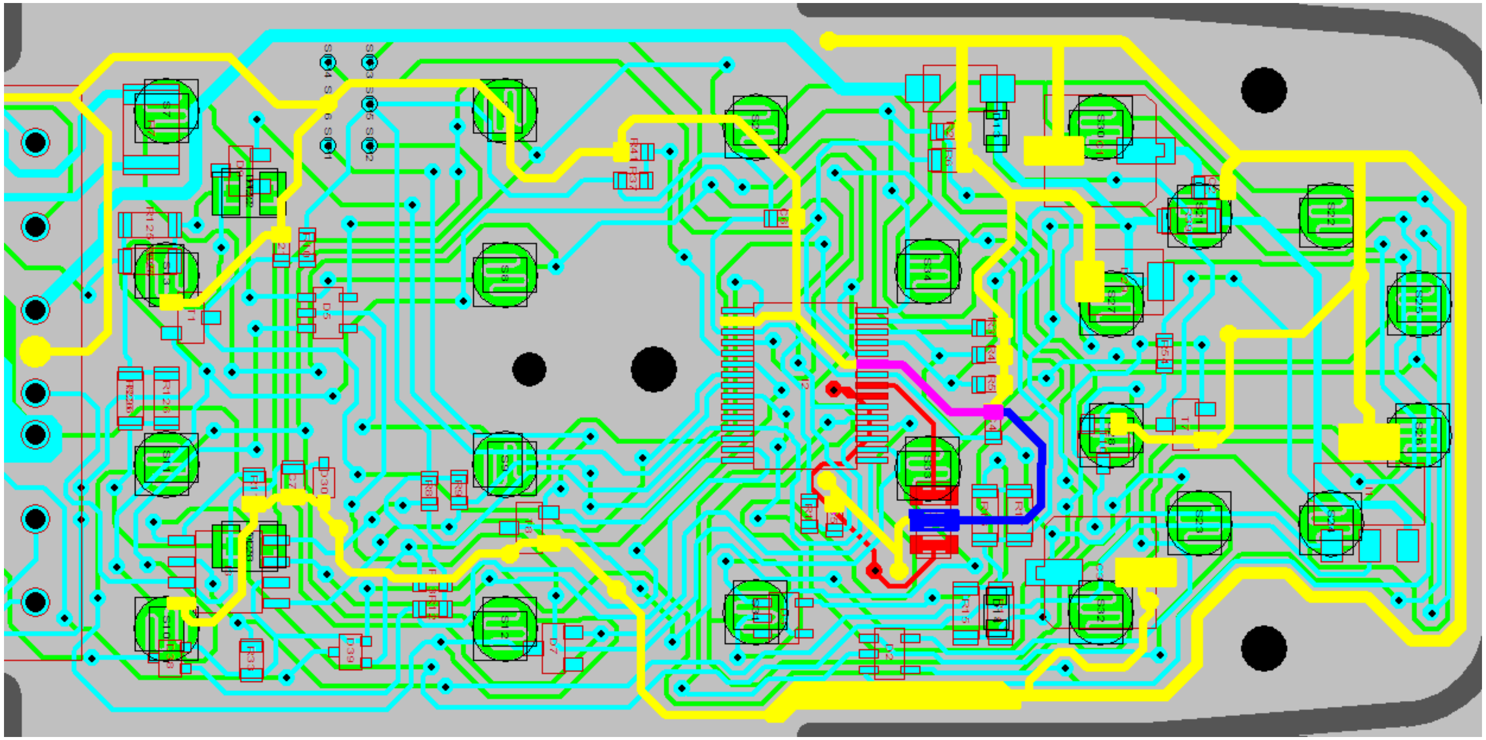
The Good, the Bad and the Ugly.

The Daisy-chained ground trace, shown in yellow, has a common mode impedance with the clock shown in purple. The microcontroller clock trace is shown in red. The load capacitors provide the offending common mode current shown in blue.



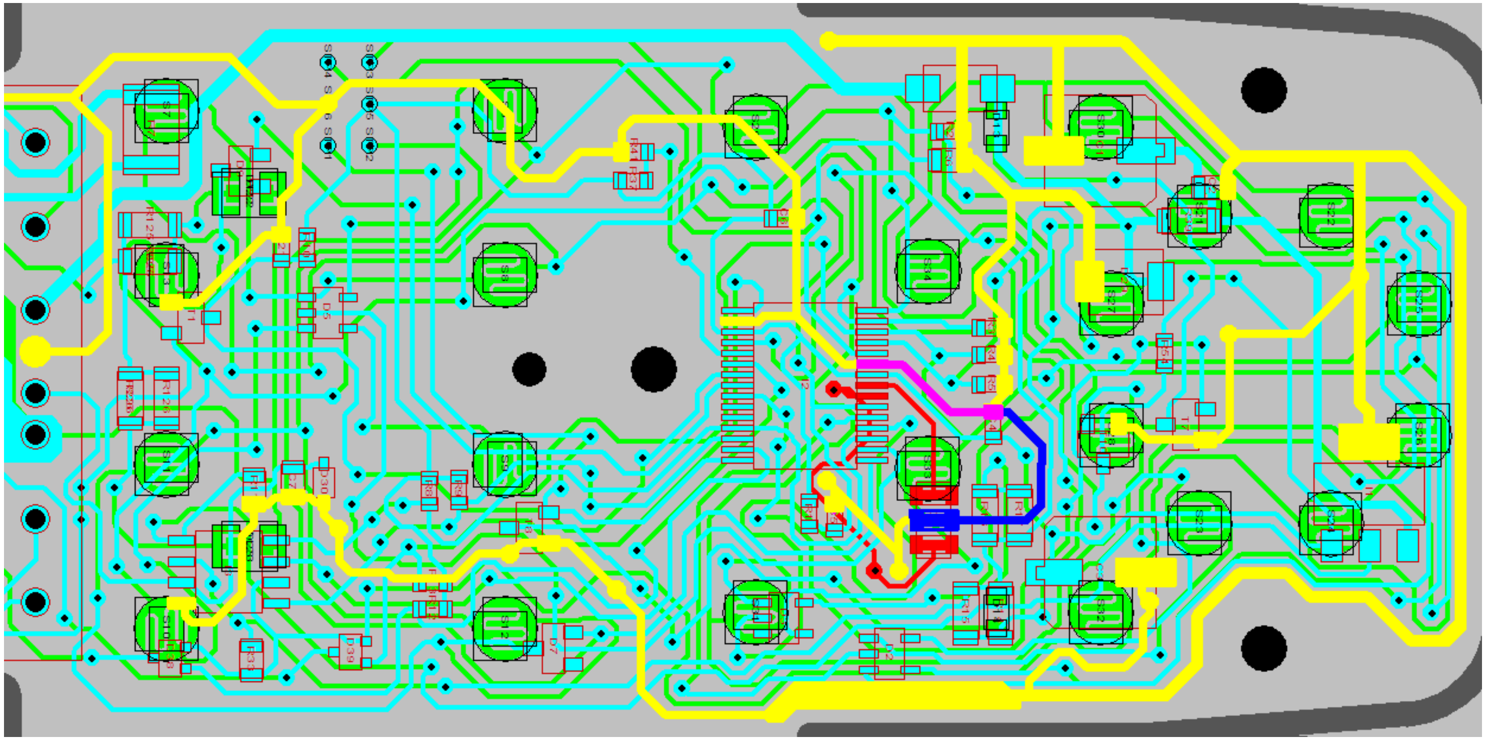
The Good, the Bad and the Ugly.

The Daisy-chained ground trace, shown in yellow, forms an asymmetric dipole antenna feed by the common mode impedance of the clock.



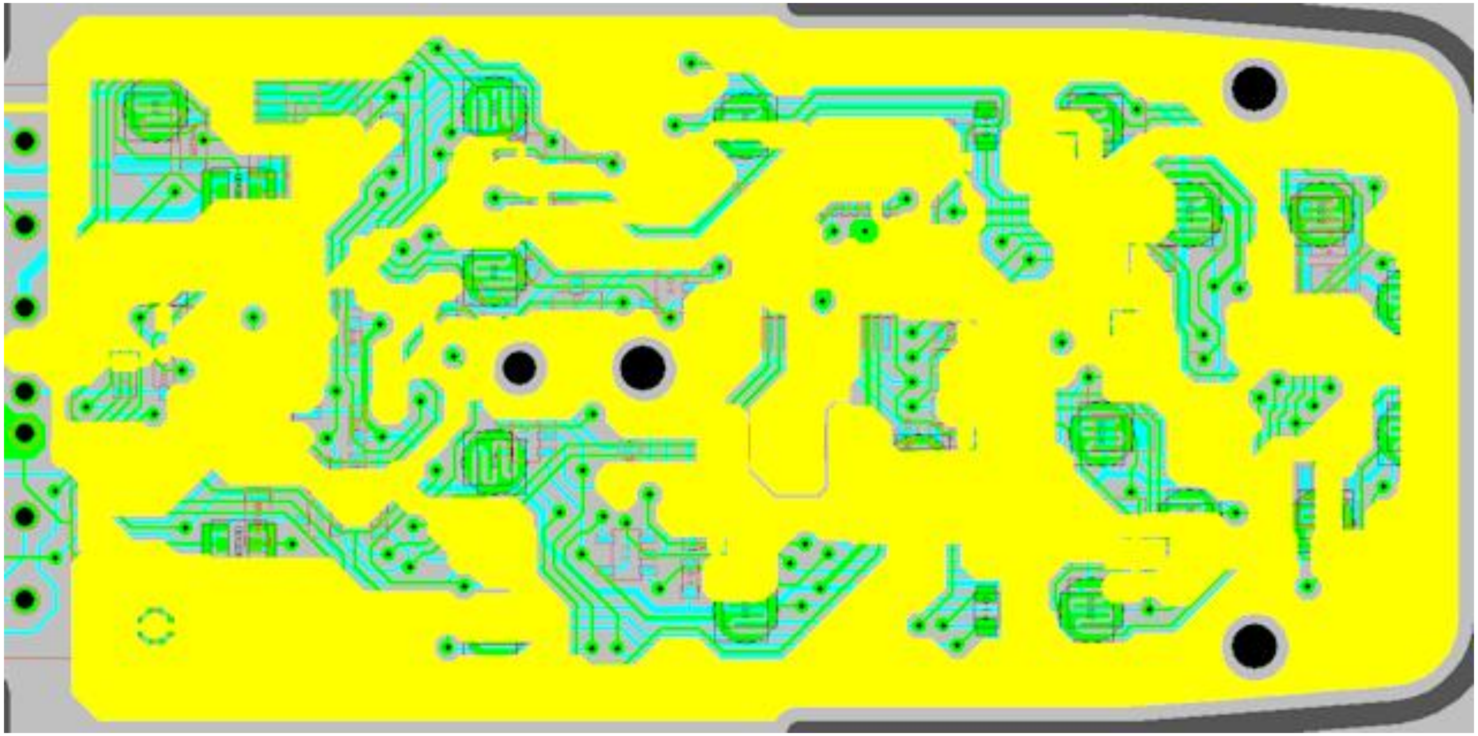
The Good, the Bad and the Ugly.

We break the antenna by removing the Daisy-chained ground trace and replacing it with a ground plane.



The Good, the Bad and the Ugly.

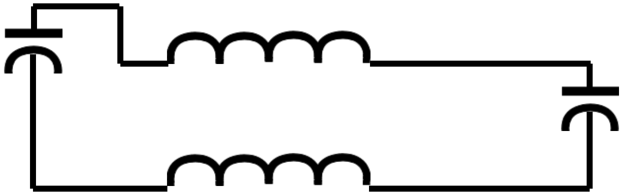
Yes a full ground plane was implemented in only two layers. The ground is stitched from top to bottom forming a sheet of ground with small holes.



Lots of people have the paradigm that adding capacitors is a good thing. But adding capacitors often

adds to your troubles by adding new resonances. You end up playing a game of Capacitor Whack-a-Mole.

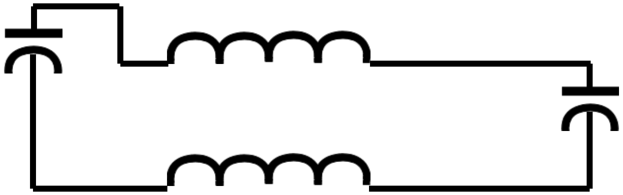
Let’s take a look at two capacitors and the distances between them.



Let’s take a look at two capacitors and the distances between them.

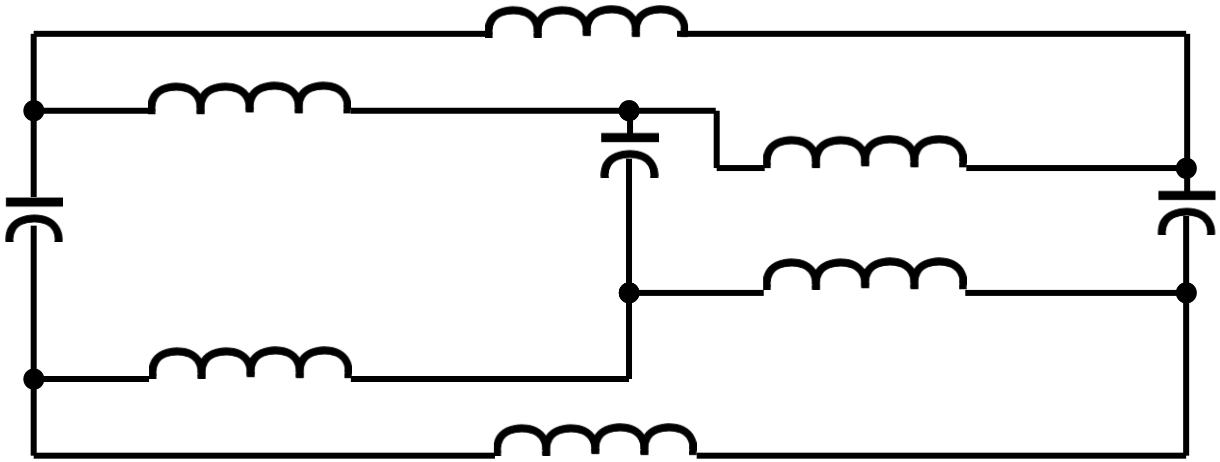
$$Frequency = \frac{1}{2\pi\sqrt{L_T\,C_T}}$$

There is one resonance and one loop of current.



$$L_{FR4\ PCB} \approx 15\frac{nH}{inch}$$

Now let's take a look at an array of three capacitors and the distances between them.



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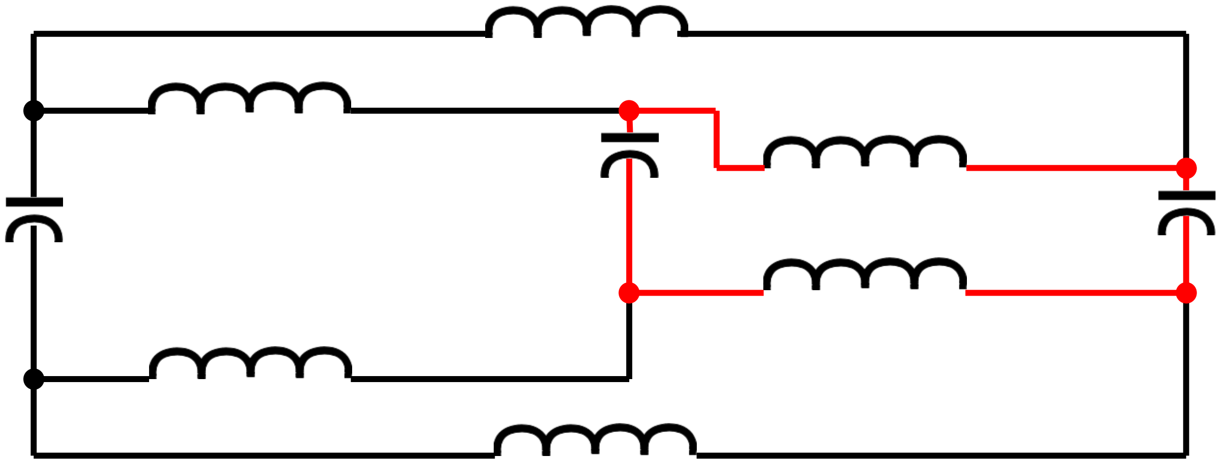

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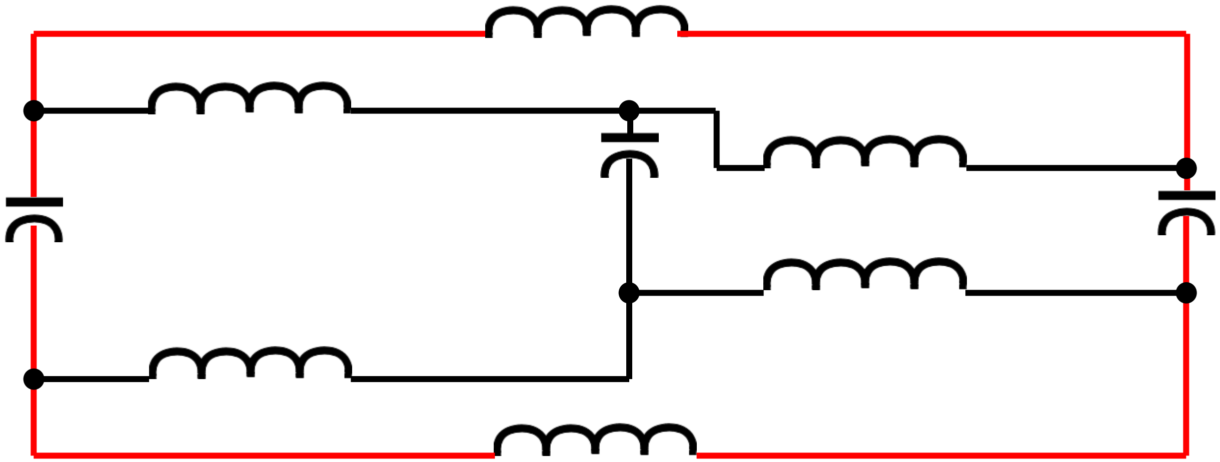

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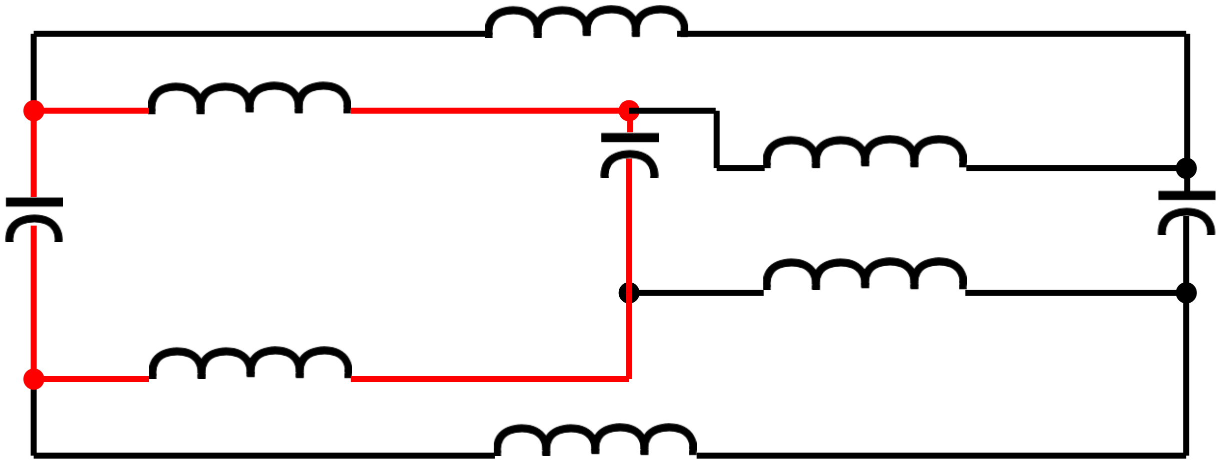

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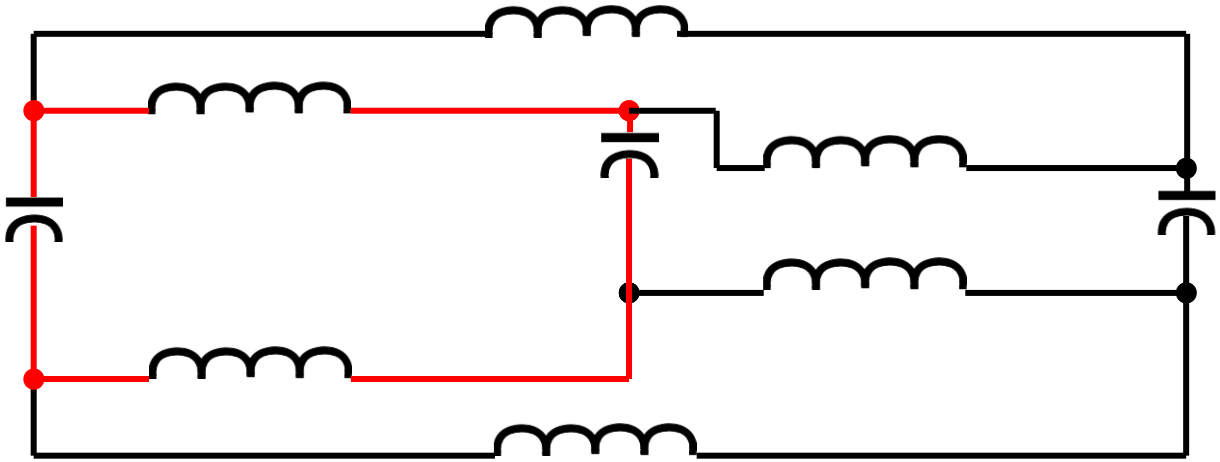
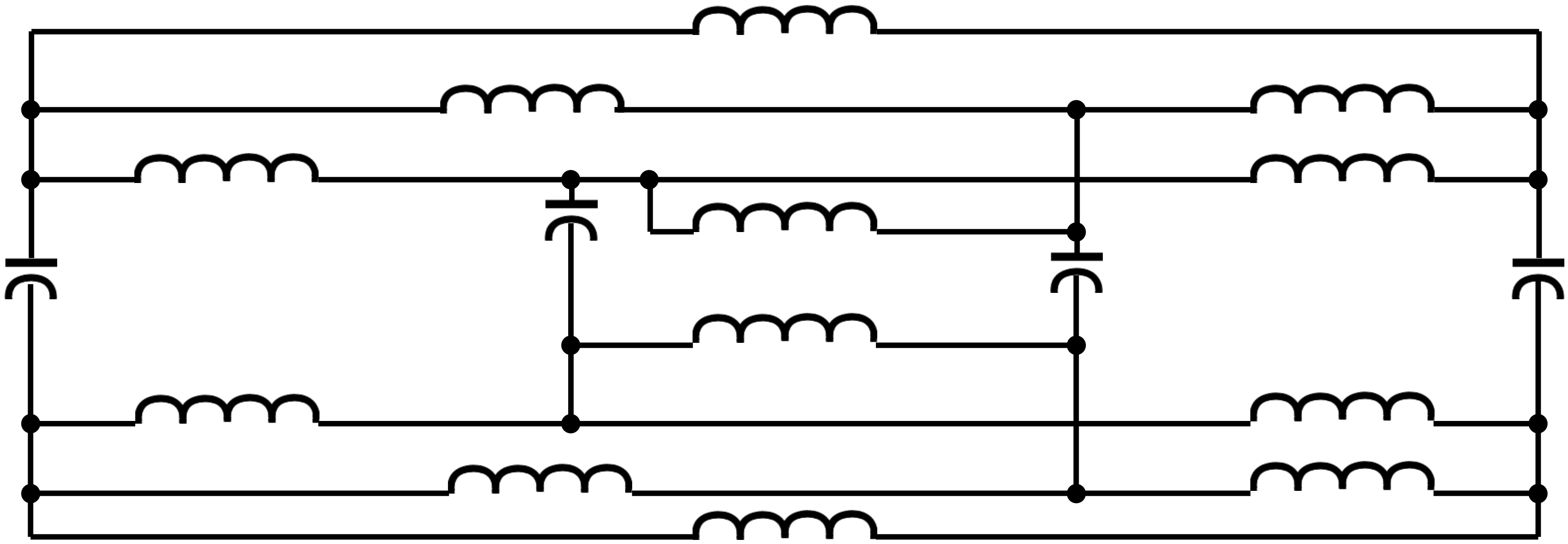
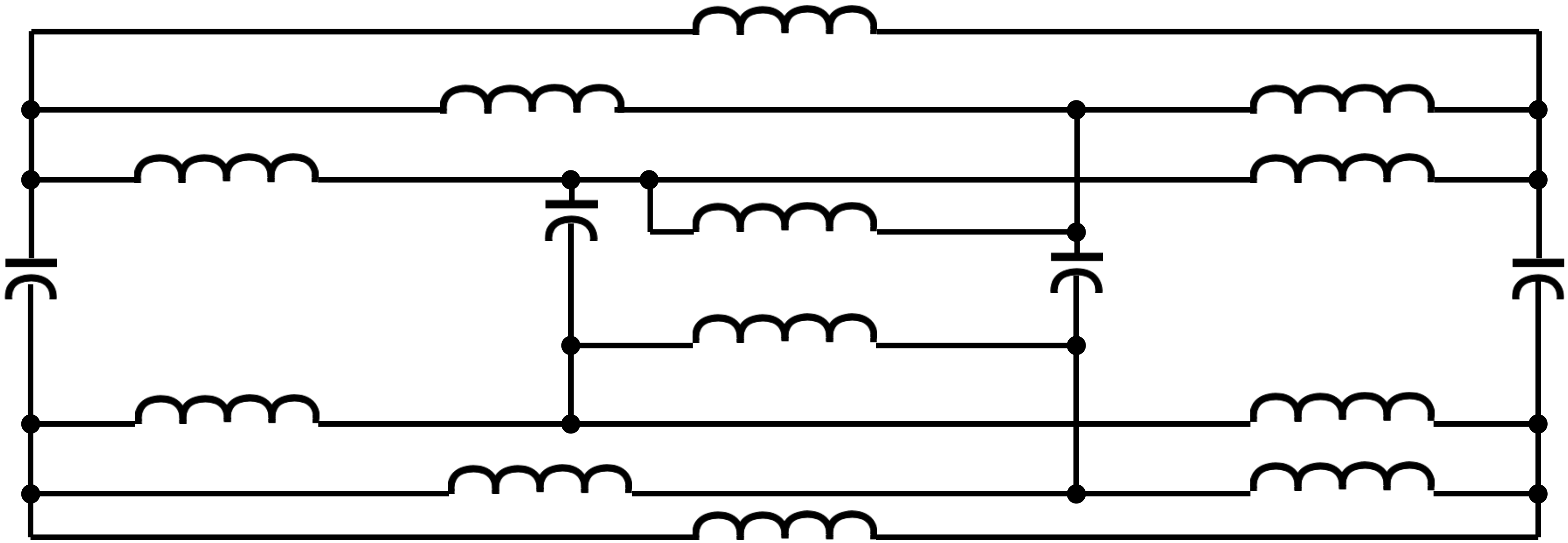


We now have three resonances.

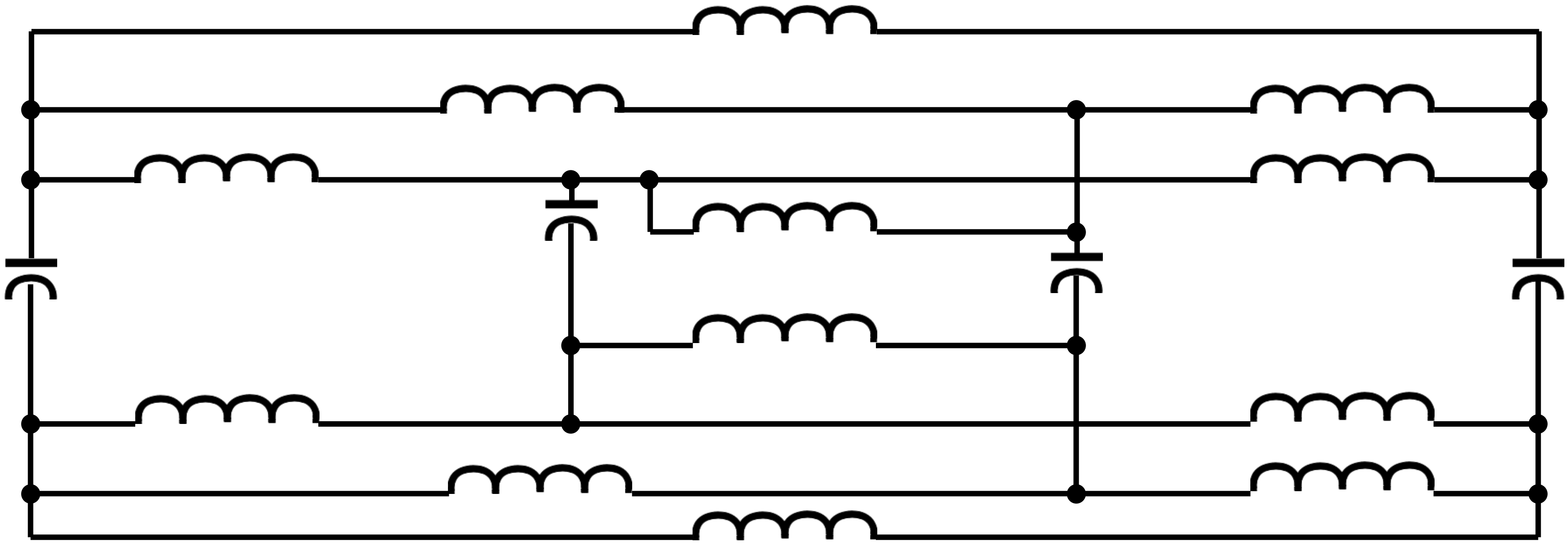
But what happens as we add a fourth capacitor?



We get ten different resonance frequencies.



And we get twelve common mode paths of resonance current.



Hence adding lots of capacitors is not the answer to EMC problem mitigation.

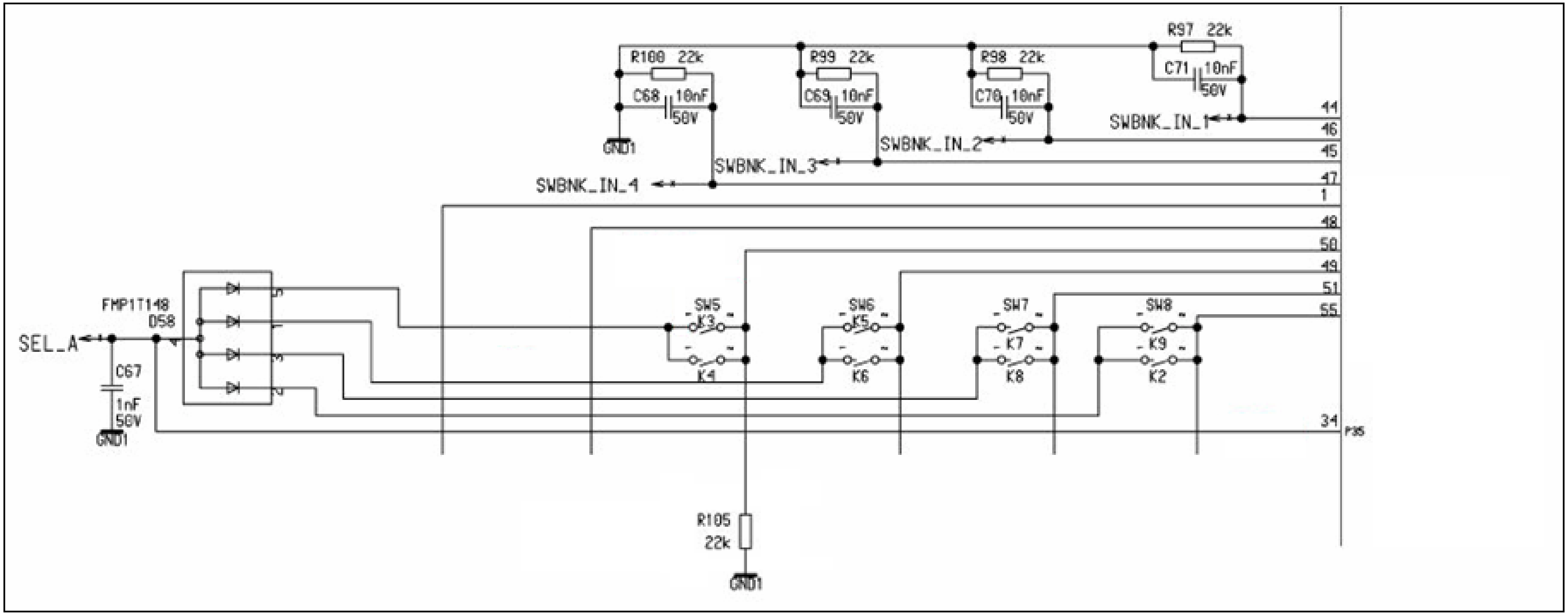
Because as capacitors are added you end up playing a game of Capacitor Whack-a-Mole.

Hence adding lots of capacitors is not the answer to EMC problem mitigation.

So what do we do?

We find and break the loop antennas.

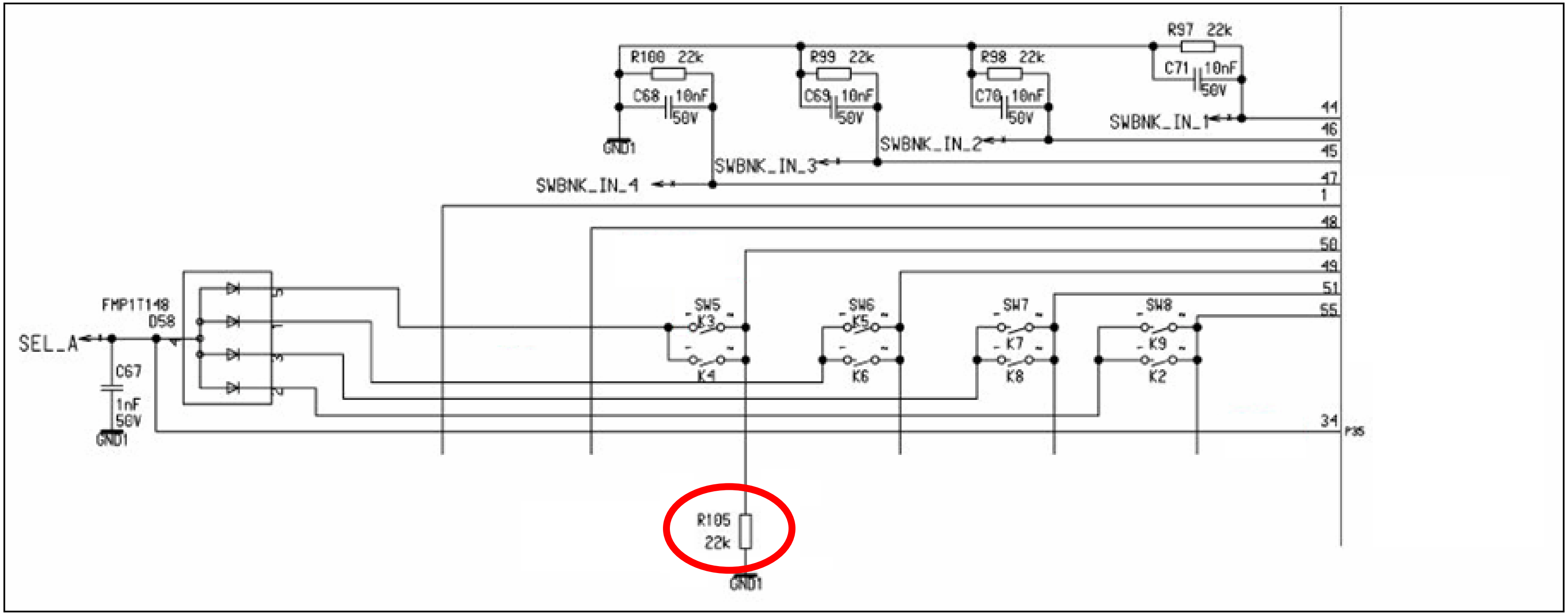
Pin the tail on the tank circuit.



Switch matrix inputs are very common.

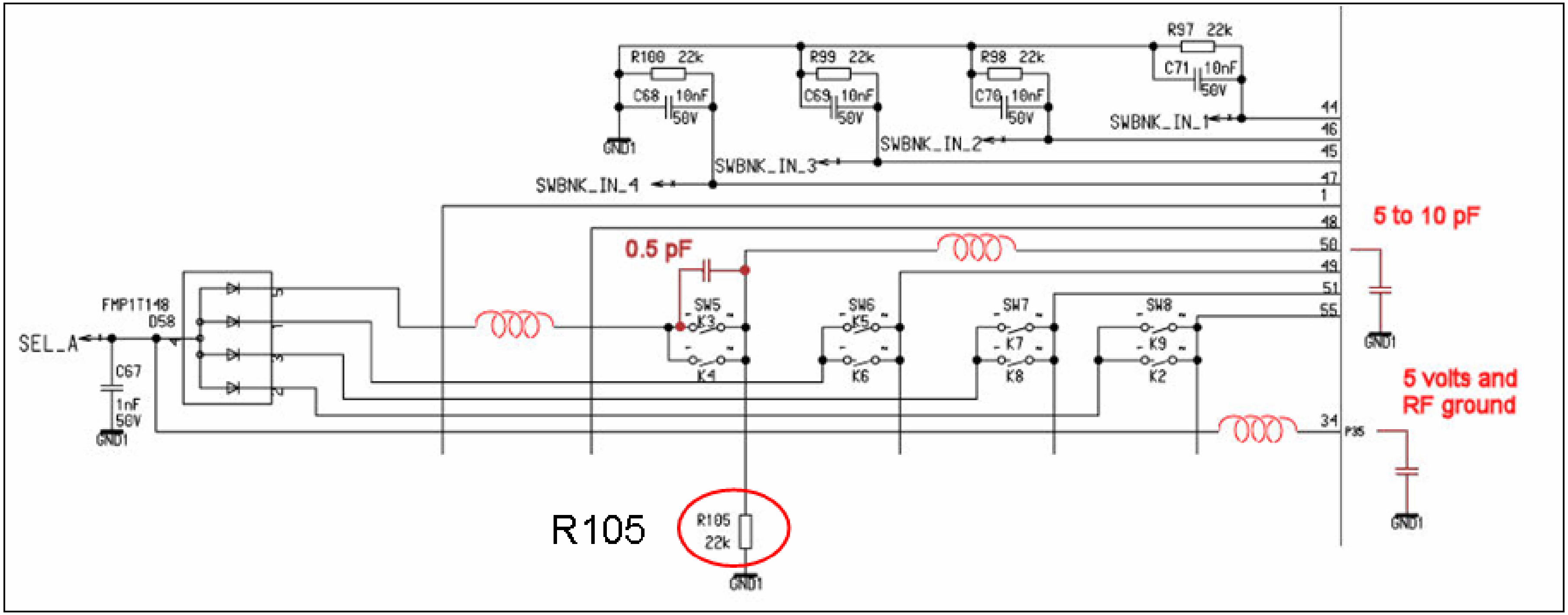
Can you find the tank circuit?

Pin the tail on the tank circuit.



Here’s a hint: with a higher value of R105 the EMC performance got worse.

Let’s find the components.



0.5 pF

5 to 10 pF

5 volts and RF ground

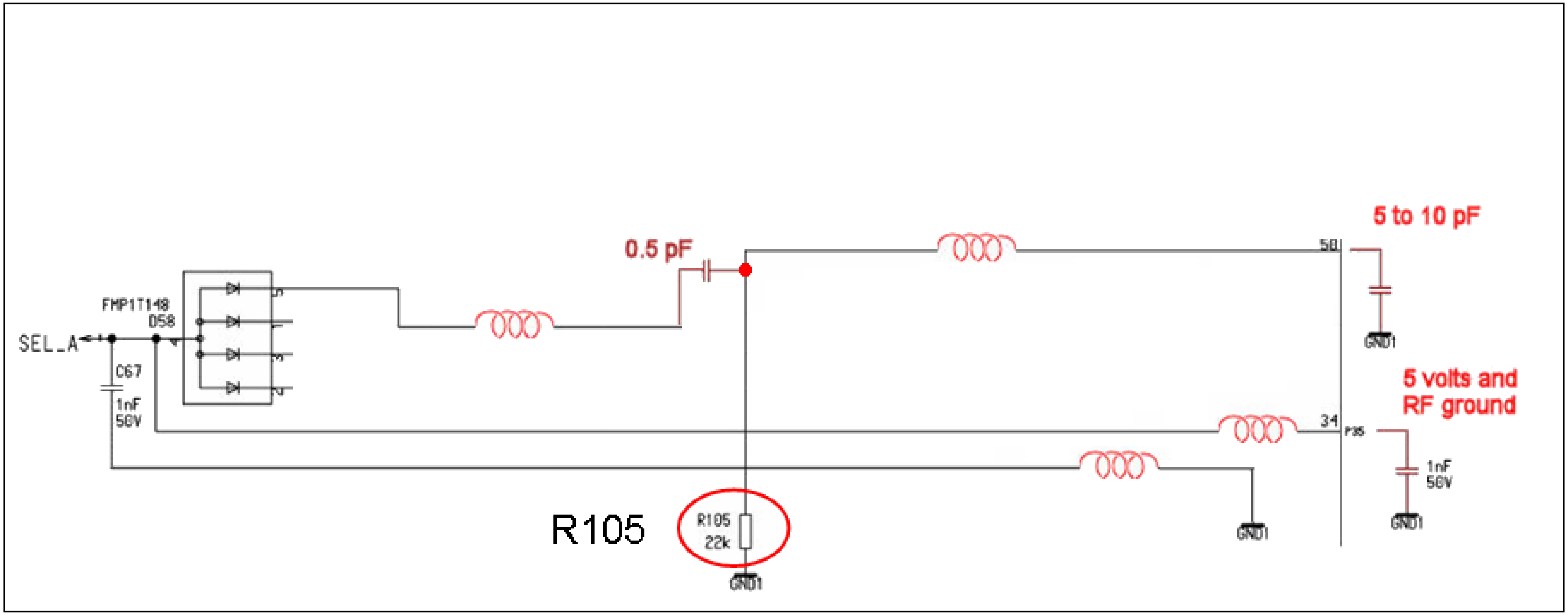
R105

The traces are the inductors. The open switch is a capacitor.

The microcontroller input is also a capacitor.

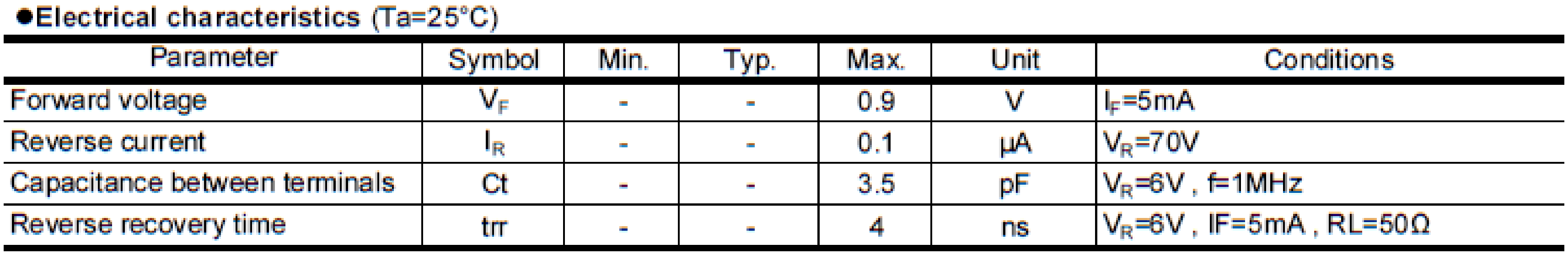
And if the diode is off, it is also a capacitor.

Pin the tail on the tank circuit.



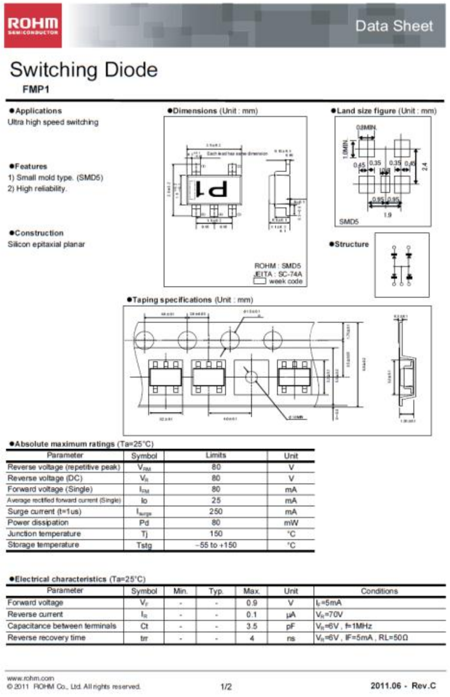
First we need to know the capacitance of the Diode.

The Rohm Data sheet



●Electrical characteristics (Ta=25°C)

Parameter	Symbol	Min.	Typ.	Max.	Unit	Conditions
Forward voltage	V_F	-	-	0.9	V	I_F=5mA
Reverse current	I_R	-	-	0.1	µA	V_R=70V
Capacitance between terminals	Ct	-	-	3.5	pF	V_R=6V , f=1MHz
Reverse recovery time	trr	-	-	4	ns	V_R=6V , IF=5mA , RL=50Ω



ROHM SEMICONDUCTOR

Data Sheet

Switching Diode

FMP1

●Applications
Ultra high speed switching

●Features
1) Small mold type. (SMD5)
2) High reliability.

●Construction
Silicon epitaxial planar

●Dimensions (Unit : mm)

●Land size figure (Unit : mm)

●Structure

●Taping specifications (Unit : mm)

●Absolute maximum ratings (Ta=25°C)

Parameter	Symbol	Limits	Unit
Reverse voltage (repetitive peak)	V_{RM}	80	V
Reverse voltage (DC)	V_R	80	V
Forward voltage (Single)	I_{FM}	80	mA
Average rectified forward current (Single)	Io	25	mA
Surge current (t=1us)	I_{surge}	250	mA
Power dissipation	Pd	80	mW
Junction temperature	Tj	150	°C
Storage temperature	Tstg	−55 to +150	°C

●Electrical characteristics (Ta=25°C)

Parameter	Symbol	Min.	Typ.	Max.	Unit	Conditions
Forward voltage	V_F	-	-	0.9	V	I_F=5mA
Reverse current	I_R	-	-	0.1	µA	V_R=70V
Capacitance between terminals	Ct	-	-	3.5	pF	V_R=6V , f=1MHz
Reverse recovery time	trr	-	-	4	ns	V_R=6V , IF=5mA , RL=50Ω

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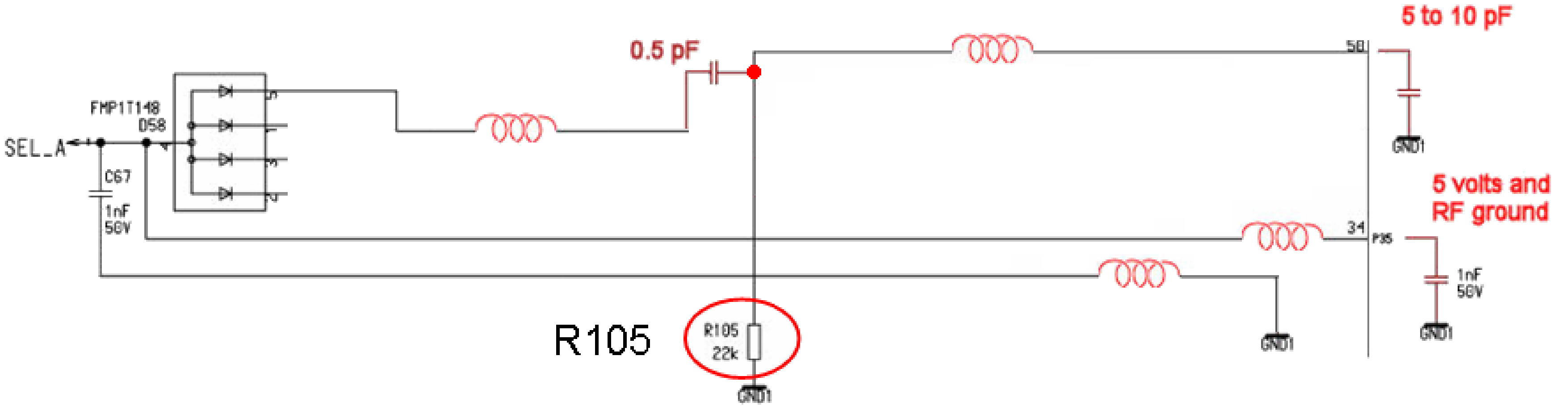
1/2
2011.06 - Rev.C

With the diode off the maximum capacitance is 3.5 pF.

The Tank’s resonant frequency

The total length to the switch through cables and PCB then back again is 20 inches.



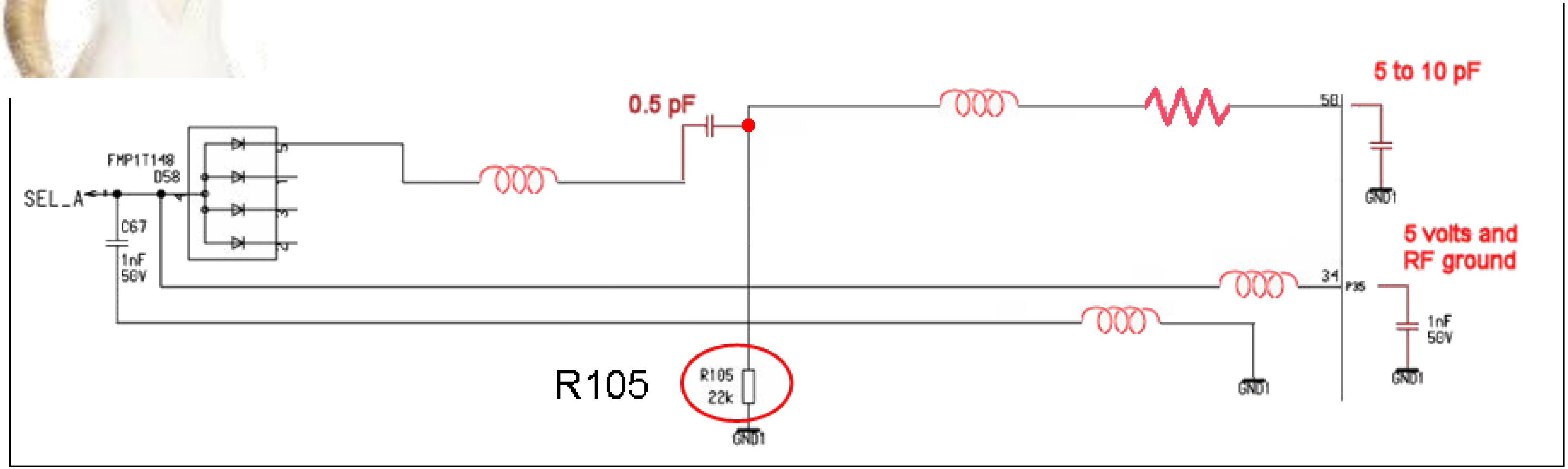
$$\frac{1}{C_T} = \frac{1}{0.5\,pF} + \frac{1}{7\,pF} + \frac{1}{3.5\,pF}$$

$$L_T \approx \frac{15\,nH}{Inch} * 20\,Inches = 300\,nH$$

$$C_T = 2.4\,pF$$

$$Frequency_{center} = \frac{1}{2\pi\sqrt{300\,nH\;2.4\,pH}} \approx 188\,MHz$$

I like to be a good witch by adding a resistor



The only DC current in the resistors is the input leakage current. The High Q tank is now a low Q tank and the emissions have been reduced by a substantial amount.

Presented with respect for those of the Wiccan Faith.

When the wavelength of the emission is physically much larger than the dimensions of the radiating element, the emitted field strength of a known current can be estimated using the Schelkunoff equations.

The emission of a small loop of current I can be estimated of a loop in the X Y plane of Area, at an angle down from the Z axis of σ, and measured at a distance d.

$$\left|E_{Small\,Loop}\right| = \frac{120\,\pi^2\,\mathrm{freq}^2\,\mathrm{Area}\,\mathrm{I}}{c^2\,d}\sqrt{1+\left(\frac{c}{2\,\pi\;freq\,d}\right)^2}\;\sin\sigma$$

The emission of a short wire of current I can be estimated of a small conductor area in Z axis, at an angle down from the Z axis of σ, and measured at a distance d.

$$\left|E_{ShortWire}\right| = \frac{120\,\pi\;freq\;I\;Length}{2\,c\,d}\sqrt{1+\left(\frac{c}{2\,\pi\;freq\;d}\right)^2+\left(\frac{c}{2\,\pi\;freq\;d}\right)^4}\;\sin\sigma$$

Derived from equations found in *Controlling Radiated Emission by Design* second edition by Michel Mardiguian and *Applied Electromagnetics and Electromagnetic Compatibility* by Sengupta and Liepa.

Here is an approximation of the Schelkunoff small loop equation

This is a first order approximation of the Schelkunoff equation shown in *Electrometric Compatibility Engineering* by Henry Ott of and equation 12-1 on page 466 of an equation found in *Controlling Radiated Emission by Design* second edition by Kraus and Marhefka, 2002 page 199, equation 8. It uses 300 * 10^6 for the speed of light.

$$\left|E_{SmallLoop}\right| = \frac{131.6 * 10^{-16}\ \mathrm{freq}^2\ \mathrm{Area}\ \mathrm{I}}{d} \sin\sigma$$

First order approximations of the Schelkunoff short wire equation are not useful except in the clearly far field.

What can we learn from the Schelkunoff short wire equation?

$$\left|E_{ShortWire}\right| = \frac{120\pi\ freq\ I\ Length}{2\,c\,d}\sqrt{1+\left(\frac{c}{2\,\pi\ freq\ d}\right)^2+\left(\frac{c}{2\,\pi\ freq\ d}\right)^4}\ \sin\sigma$$

$$20\ Log\frac{E_{radiated1}}{E_{radiated2}} = 20\,Log\ \frac{R_2}{R_1}$$

Change the Q of the tank
and add a resistor.

$$20\ Log\frac{E_{radiated1}}{E_{radiated2}} = 20\,Log\ \frac{Length_1}{Length_2}$$

Changing the area of the tank.
But will the center frequency of
the tank change as well?

What can we learn from the Schelkunoff small loop equation?

$$\left|E_{Small\,Loop}\right| = \frac{120\,\pi^2\ \mathrm{freq}^2\ \mathrm{Area\,I}}{c^2\,d}\sqrt{1+\left(\frac{c}{2\,\pi\ freq\,d}\right)^2}\ \sin\sigma$$

$$20\ Log\,\frac{E_{radiated1}}{E_{radiated2}} = 20\,Log\ \frac{R_2}{R_1}$$

Change the Q of the tank

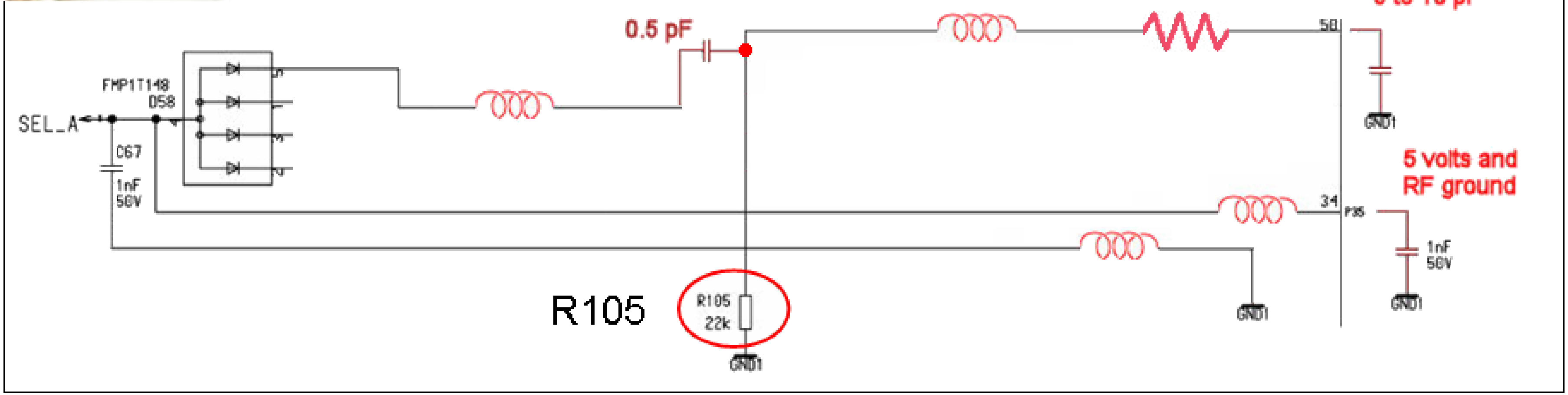
$$20\ Log\,\frac{E_{radiated1}}{E_{radiated2}} = 20\,Log\ \frac{Area_1}{Area_2}$$

Changing the area of the tank.

$$20\ Log\,\frac{E_{radiated1}}{E_{radiated2}} \approx 20\,Log\ \frac{Freq_1^2}{Freq_2^2} = 40\,Log\,\frac{Freq_1}{Freq_2}$$

Using a first order approximation and changing the resonance frequency of the tank also has a big effect.

We can calculate the amount of resistance required to pass the EMC requirement.

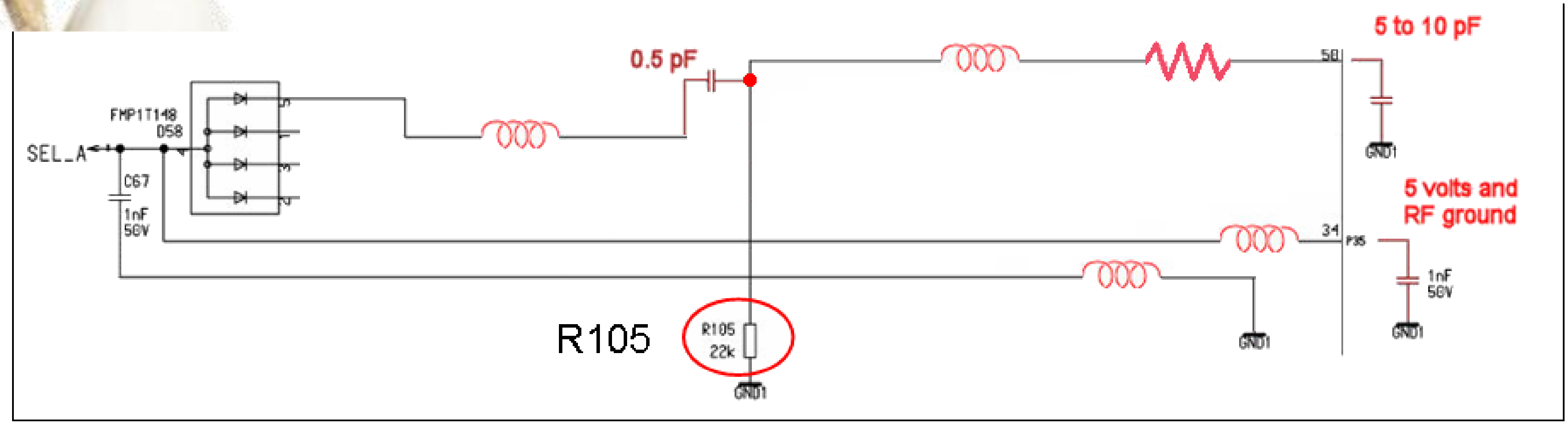


The Schelkunoff small loop equation tells us:

$$20\ Log\frac{E_{radiated1}}{E_{radiated2}} = 20\,Log\ \frac{R_2}{R_1} = 20\,Log\ \frac{100}{100\,m\Omega} = 60\,dB$$

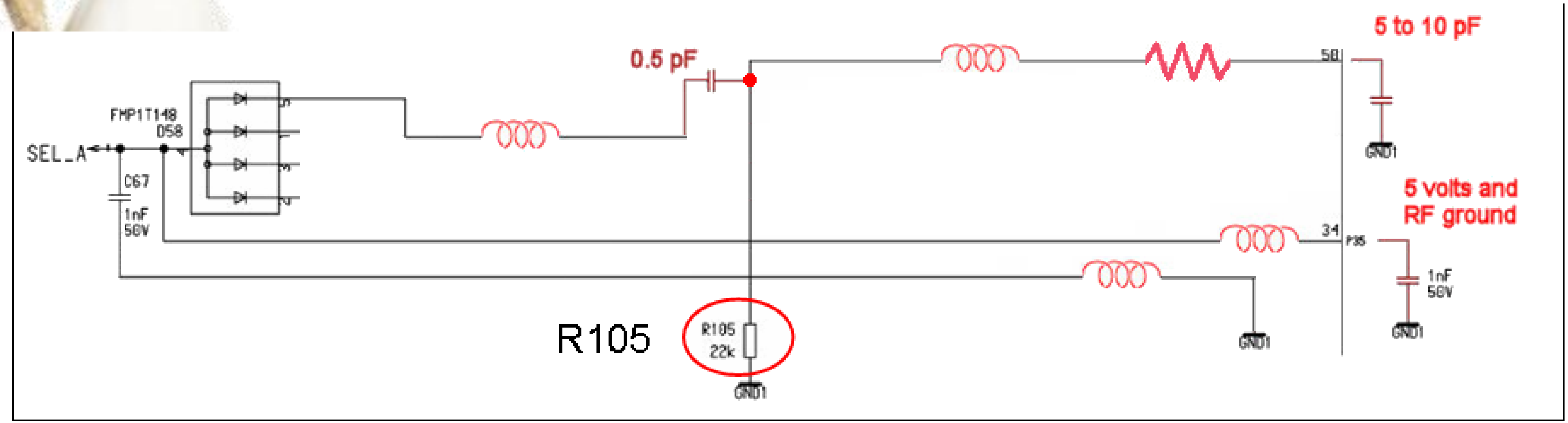
Presented with respect for those of the Wiccan Faith.

Now for extra credit, can you find a second tank circuit?



Presented with respect for those of the Wiccan Faith.

Now for extra credit, can you find a second tank circuit?

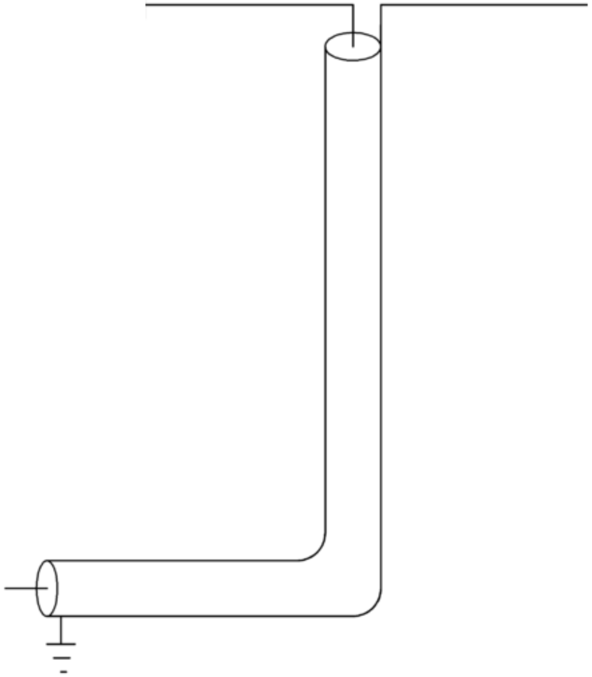


The tank circuit is formed by the trace from pin 34 to the capacitor C67 and back to the microcontroller decoupling capacitors (1nF) show in red.

Presented with respect for those of the Wiccan Faith.

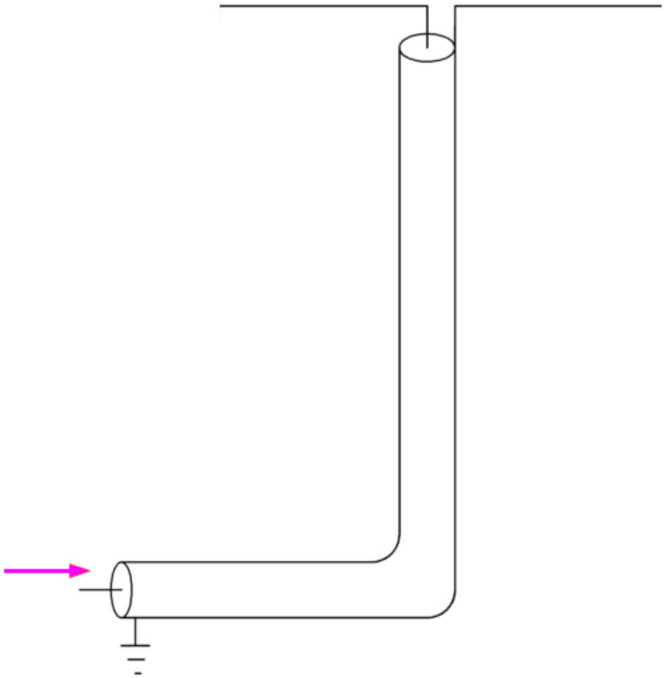
Were does the current go?

To the right we have a Dipole antenna without a Balun



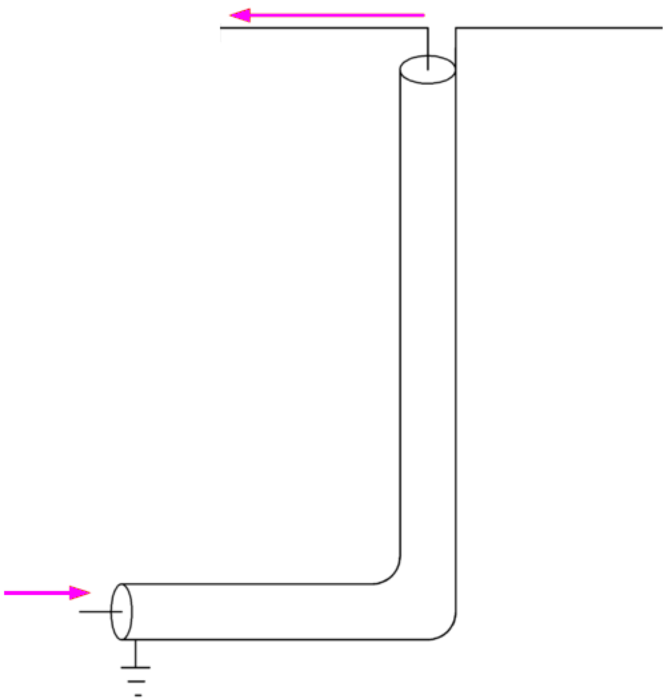
Were does the current go?

We put current into the coax.



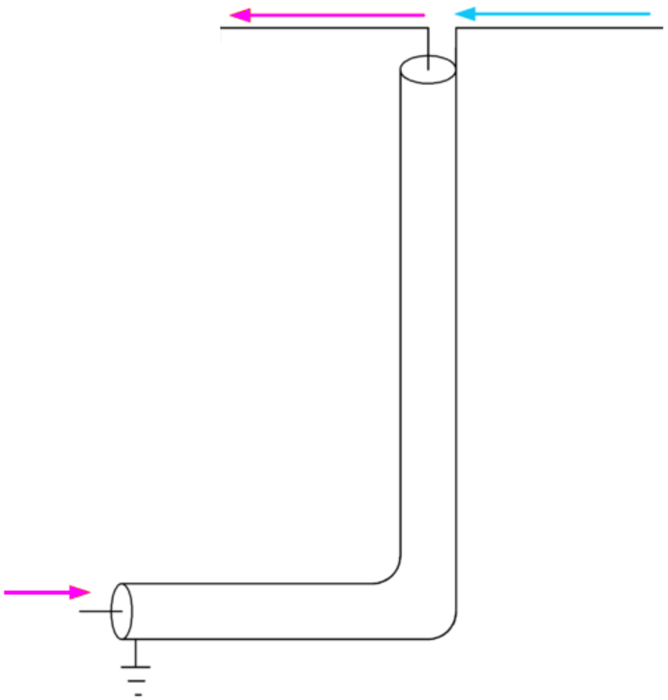
Were does the current go?

And it comes out the
hot side of the dipole.



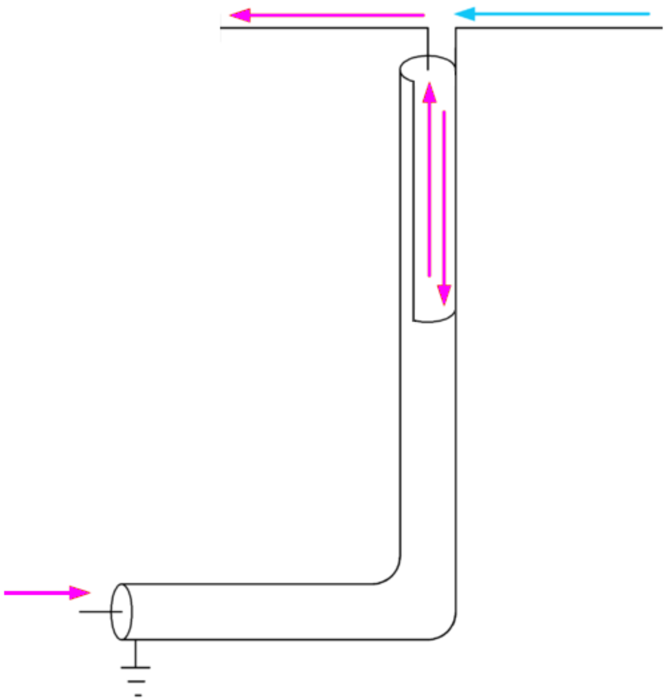
Were does the current go?

- Some but not all of the current is received by the cold side of the Dipole antenna.
- Some of the current finds other paths back to the source.



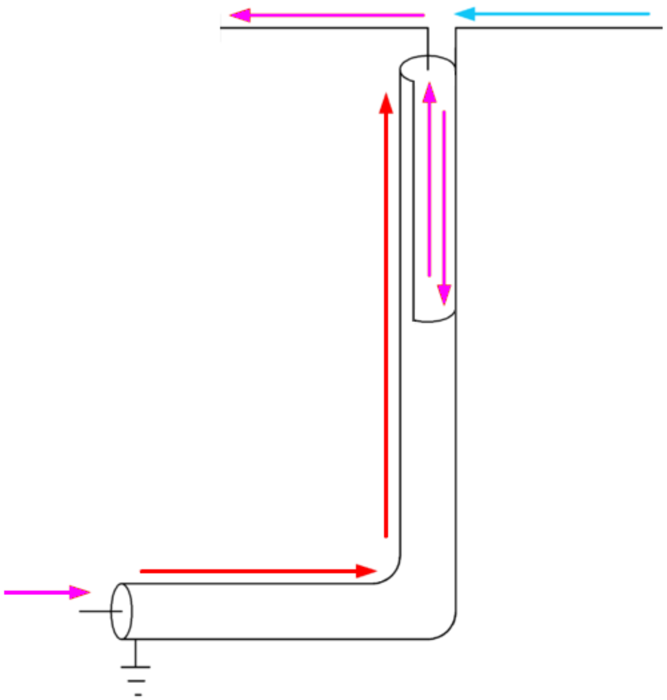
Were does the current go?

- Inside the coax the current in the center conductor forces an equal and opposite current on the inside of the shield.



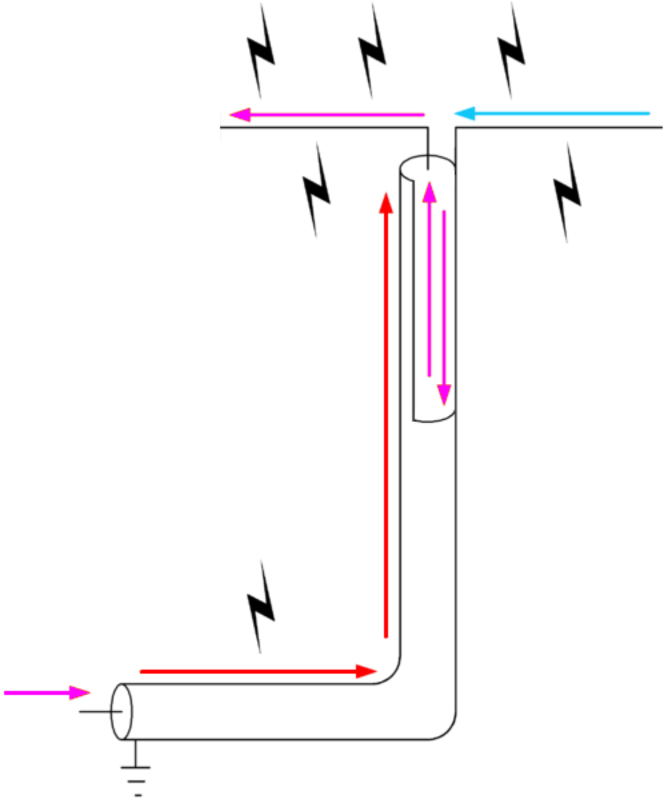
Were does the current go?

But the current returning from the antenna element is not a much as the current on the inside of the coax. The difference is sucked in from the outside of the shield. Shown in Red.

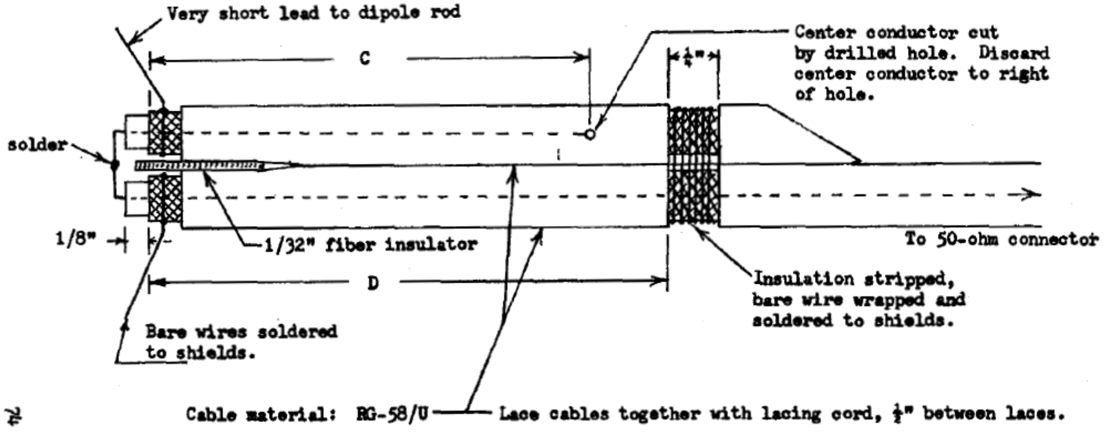


Were does the current go?

Hence we have radiation from the Dipole elements and from the outside of the shield.



The Roberts Balun



Frequency range Megahertz	Length C inches	Length D inches
20 - 65	43.3	43.3
65 - 180	14.2	16.25
180 - 400	6.125	7.5
400 - 1000	2.7	3.0
220 - 450	5.5	6.625

Figure 7. CONSTRUCTION OF BALUNS FOR FIELD STRENGTH MEASURING DIPOLE ANTENNAS, AS DEVELOPED BY W. K. ROBERTS

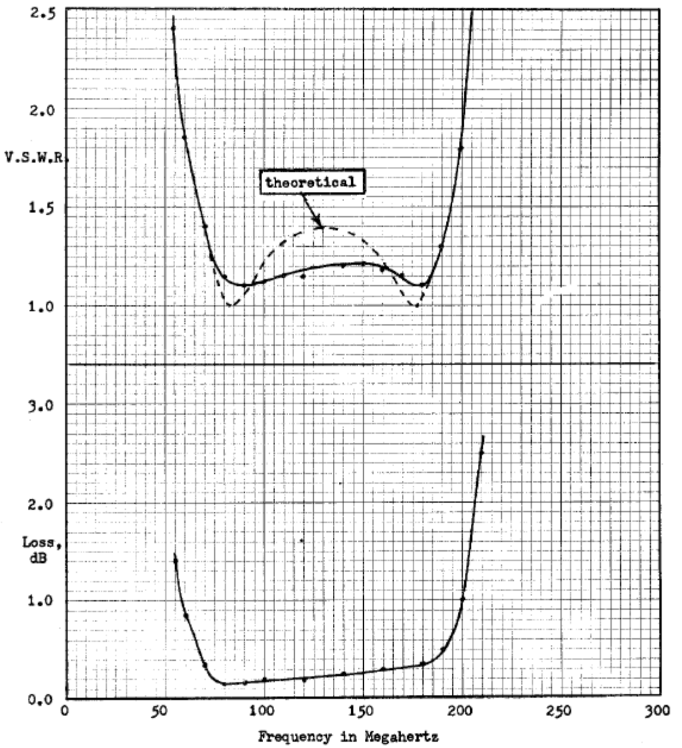


Figure 9. Voltage standing-wave ratio and loss of typical Roberts balun. VSWR relative to 50 ohms was measured with a 70-ohm resistor connected to balanced end. Loss was measured as one-half the loss of identical baluns connected together at their balanced ends.

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“In 1957, W. K. Roberts, who was then a member of the staff of the FCC Laboratory, measured the voltage standing-wave ratio of the dipole antennas supplied with certain commercial models of field strength meters. He found that the VSWR values were high enough to lead to some uncertainties in the calibrations of these instruments. This was because the measuring sets also had high VSWR's on their most sensitive ranges; the combination of mismatches at both ends of the antenna transmission line would cause the indicated field strength to vary cyclically with varying frequency. The scale factor of the cyclic variation would depend upon the precise length of the cable.”

The Roberts
Extra Wide Band Balun

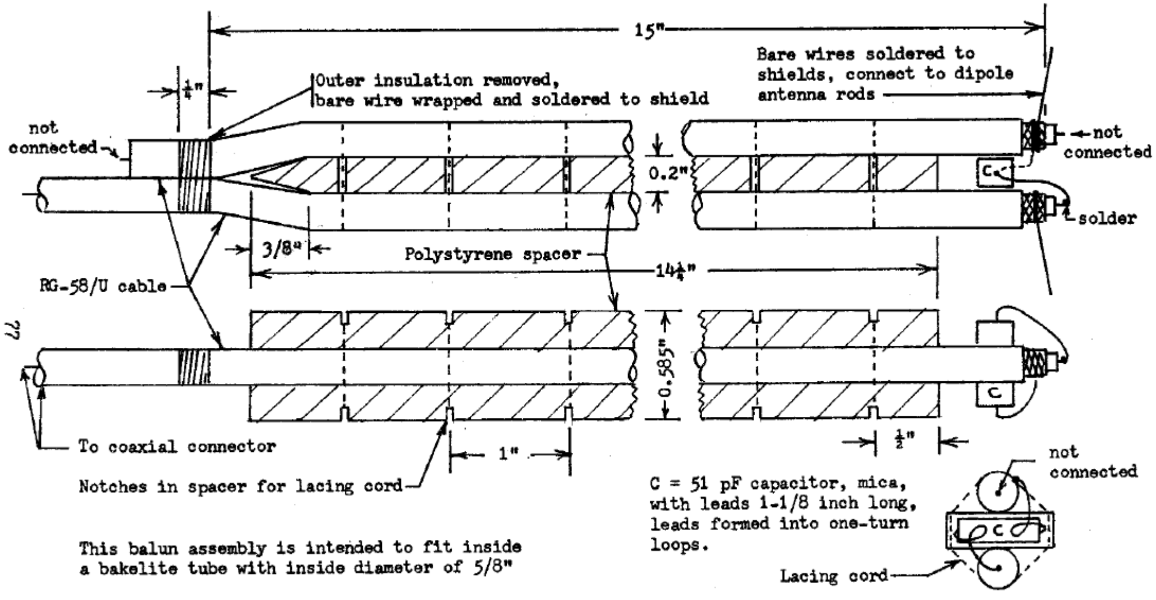

Figure 10. CONSTRUCTION OF EXTRA-WIDE-BAND BALUN (50 - 220 MHz)
Designed for the FCC by W. K. Roberts, built by Glenn Stephens

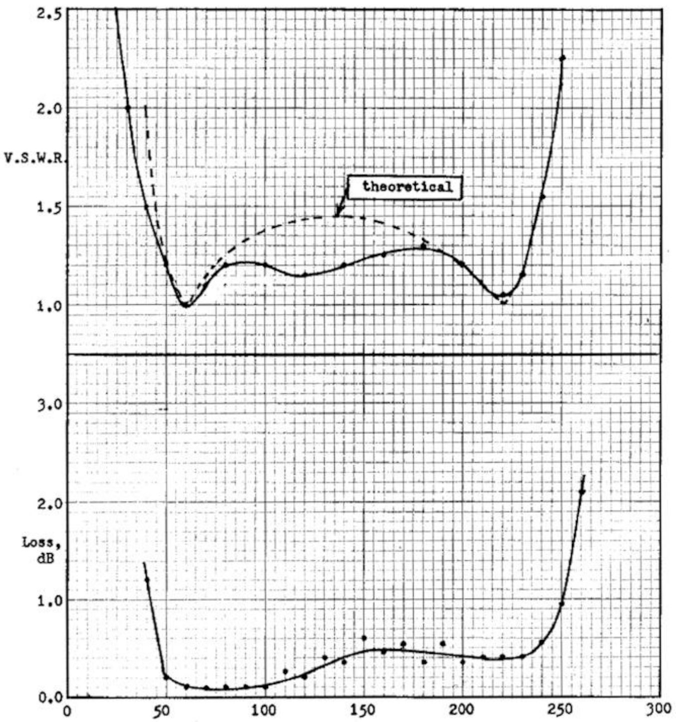

Figure 11. Voltage standing-wave ratio and loss of Roberts extra-wide-band balun. VSWR relative to 50 ohms was measured with a 70-ohm resistor connected to balanced end. Loss was measured as one-half the loss of identical baluns connected together at their balanced ends.

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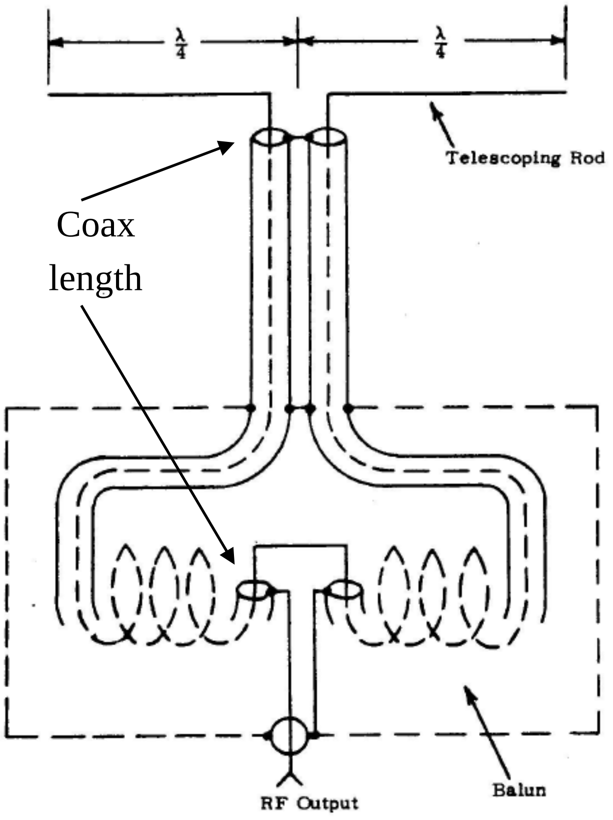
“Also in 1957, Roberts developed a wide-band balun suitable for matching the 70-ohm dipole impedance at resonance to the 50-ohm line impedance which is common in U. S. field strength meters and spectrum analyzers. The word "balun" also indicates that the device is a transformer between the balanced Impedance of the dipole and the unbalanced impedance of the line. A paper describing the operation of the new balun was published: "A New Wide Band Balun," by Willmar K. Roberts, Proceedings of the IRE, December, 1957, page 1628.”

A Balun from possibly 1954

To the right is a dipole antenna and Balun from an Empire (Singer Metrics Division) Noise and Field Intensity Meter model NF-105.

What length of coax do we need left and right for a 100 MHz Antenna?

Is it λ/8, λ/4, λ/2, or λ?



Coax length

Figure 8-1. Dipole Antenna and Broadband Balun Schematic,

Two ¼ wavelength rods with to ½ wavelengths of coax

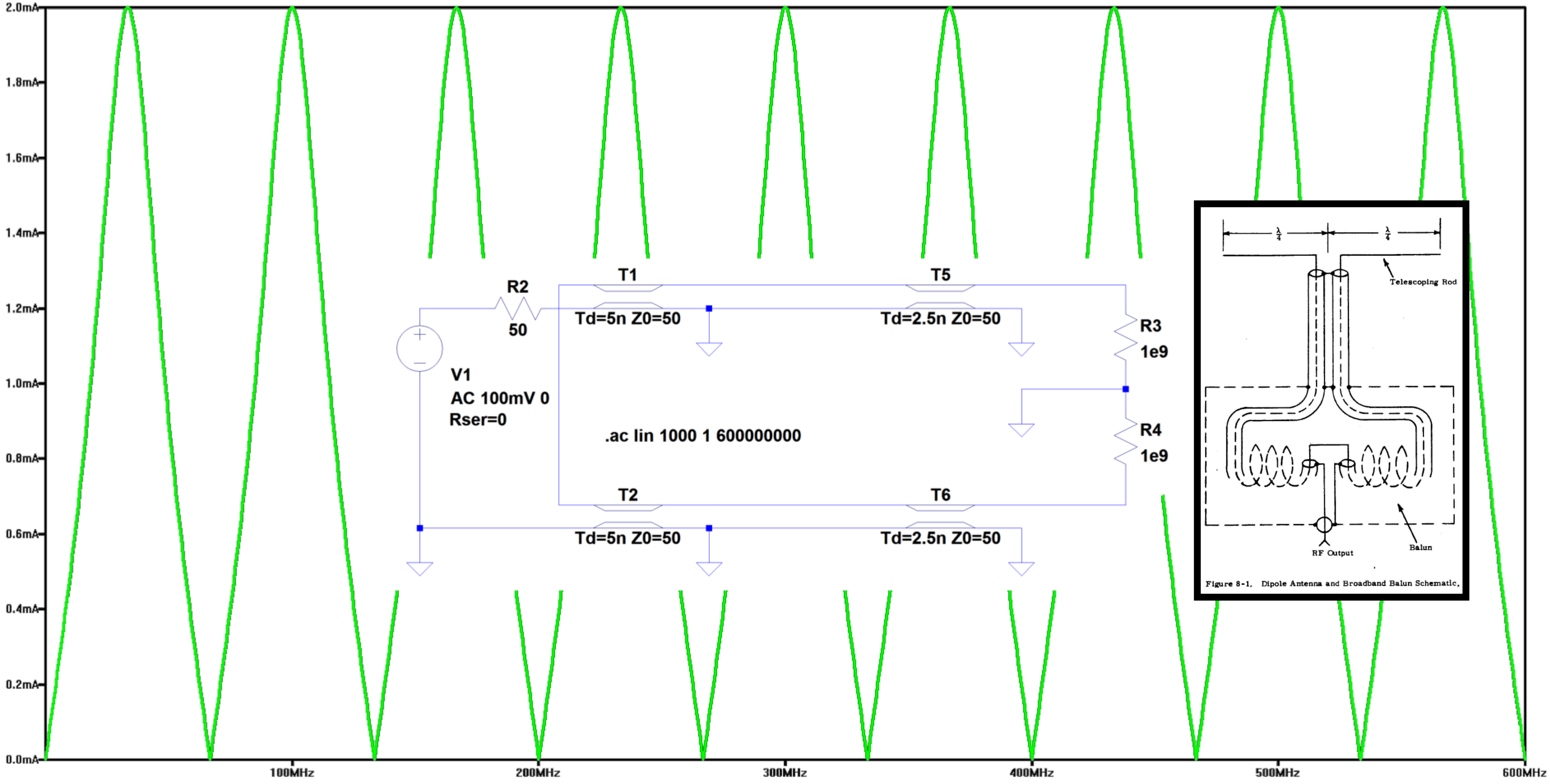


Figure 8-1. Dipole Antenna and Broadband Balun Schematic,

A Balun from possibly 1954

To the right is a dipole antenna and Balun from an Empire (Singer Metrics Division) Noise and Field Intensity Meter model NF-105.

What length of coax do we need left and right for a 100 MHz Antenna?

The correct length is λ/2.

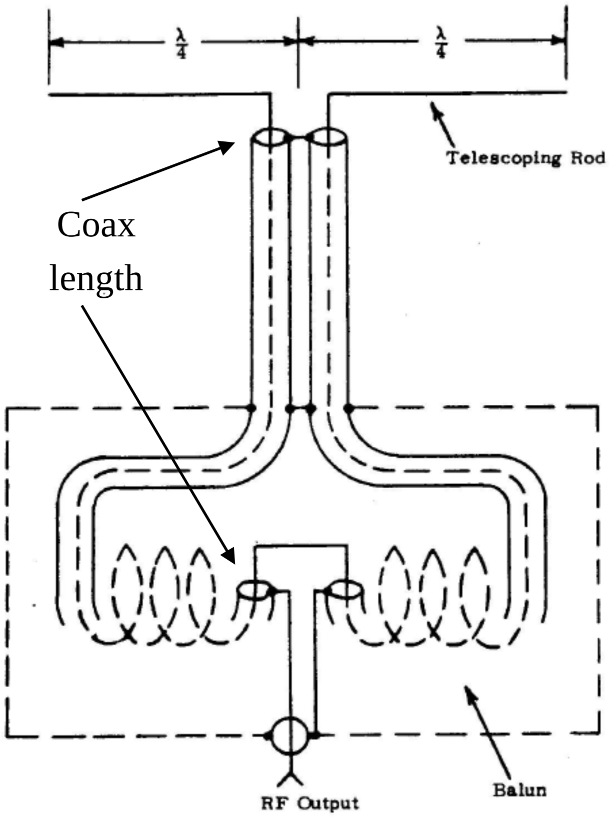


Figure 8-1. Dipole Antenna and Broadband Balun Schematic,

Thank you

for allowing me to share this information about impedance land with you

Joanna Hill jhill28590@comcast.net 248-765-3599