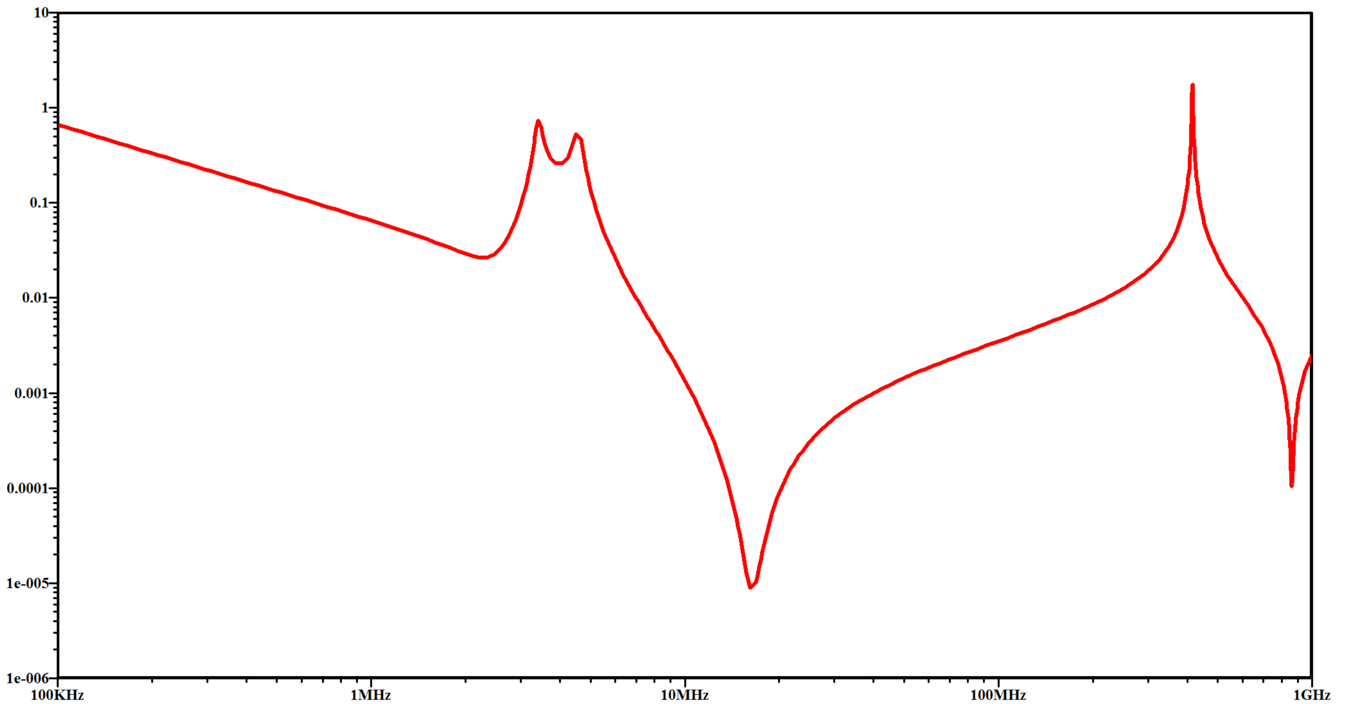
How Resonant Structures Affect Power Distribution Networks and Create Emissions.



Presented by Joanna McLellan
April 16, 2019
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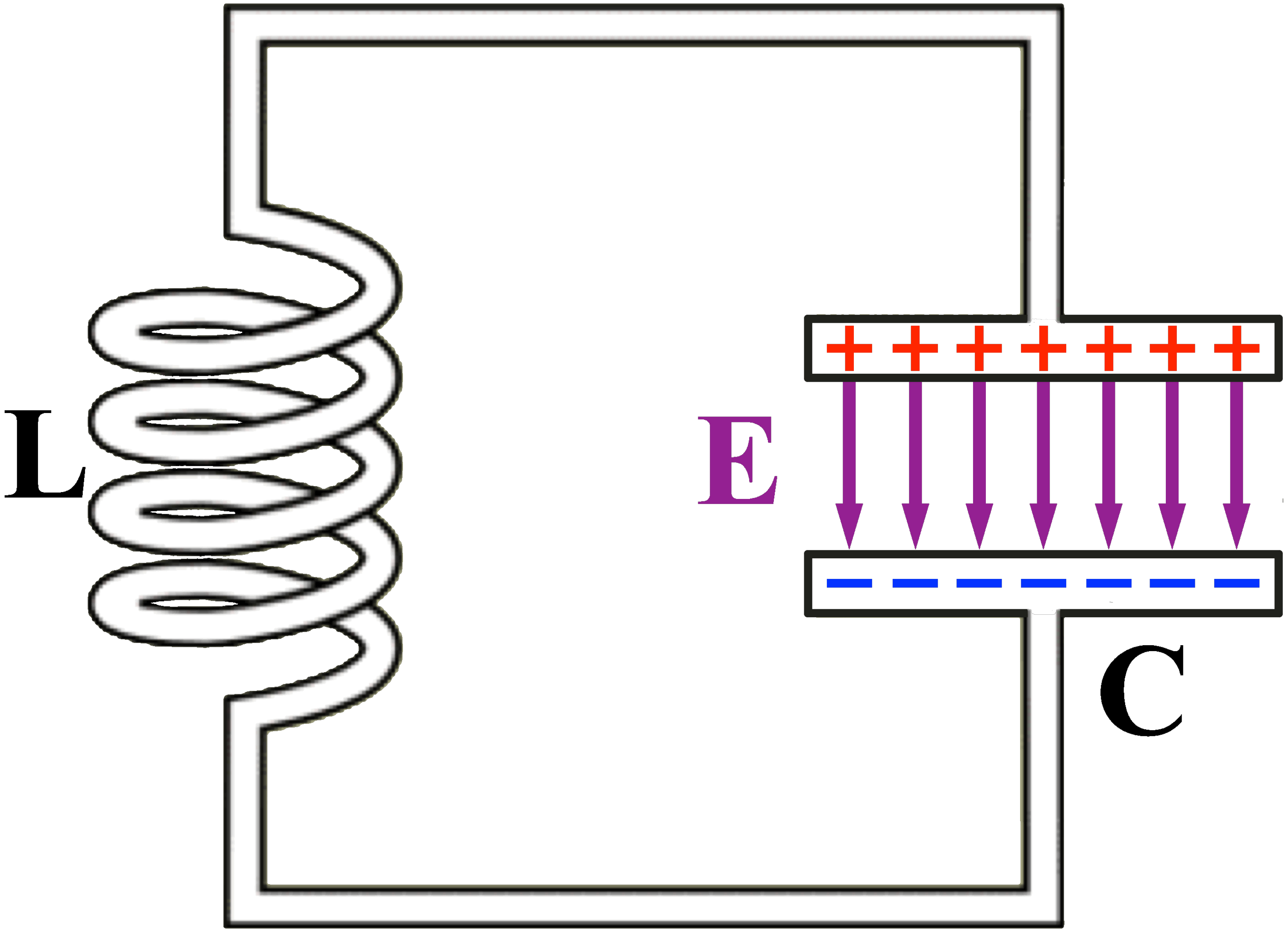
Lots of people have the paradigm that adding capacitors is the “Go-to” solution for all EMC and Power Integrity problems. But mindlessly adding capacitors often adds to your troubles. The reason you might ask? They create new resonance structures.

PDF copies of the presentation do not show the animations.

Where does the energy go?

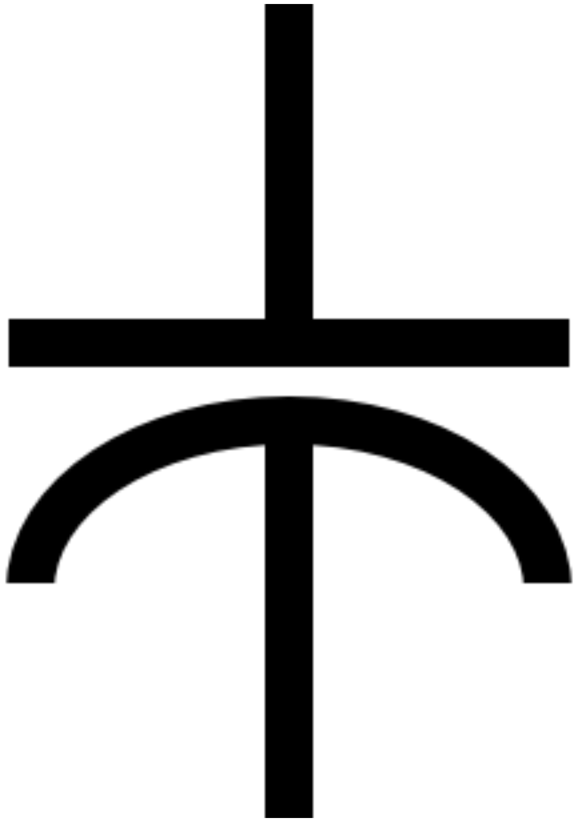


The energy moves back and forth as a current.

PDF copies of the presentation do not show the animations.

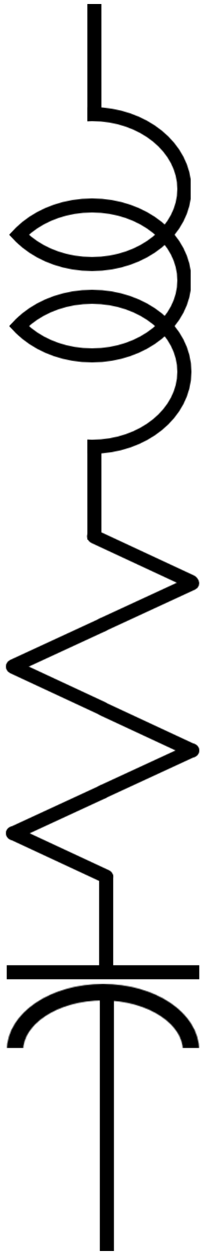
Frequencies changes the Impedance

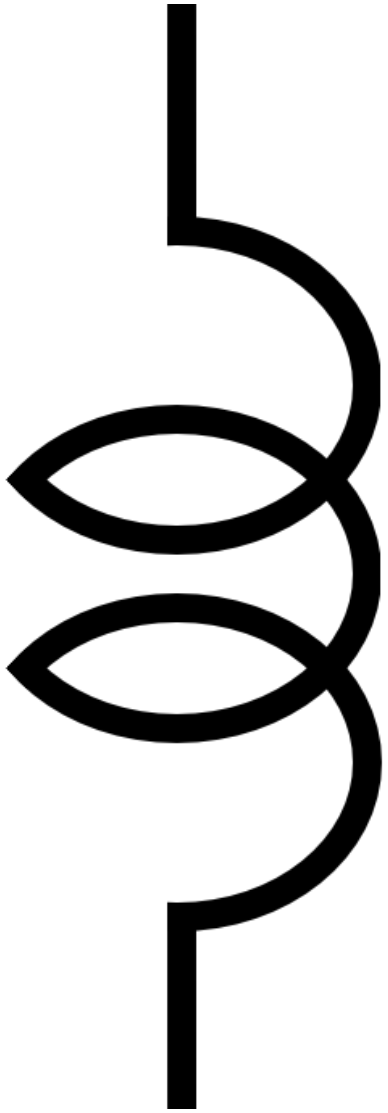
At low frequencies



At high frequencies

100 KHz < f < Fractional λ



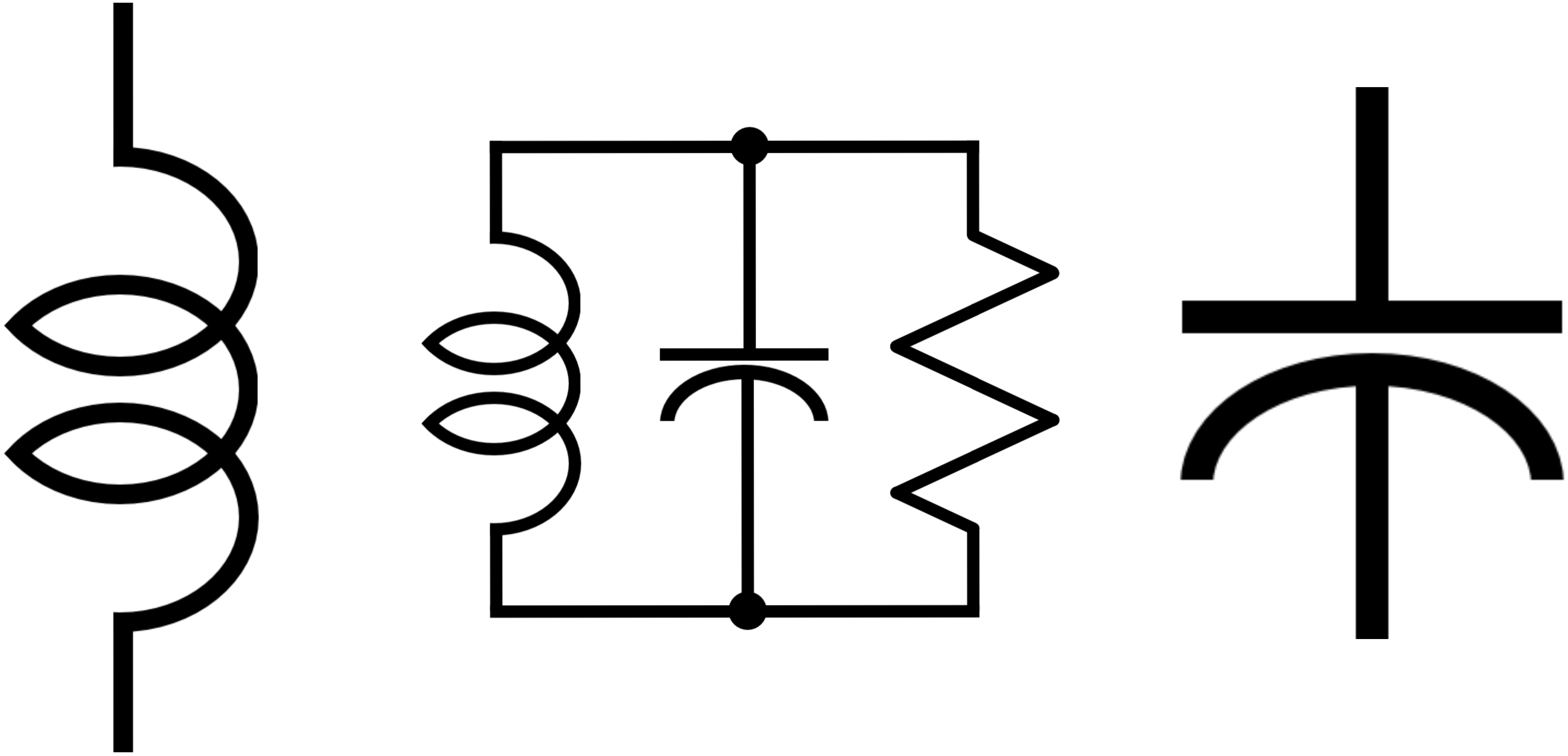


Frequencies changes the Impedance

At low frequencies

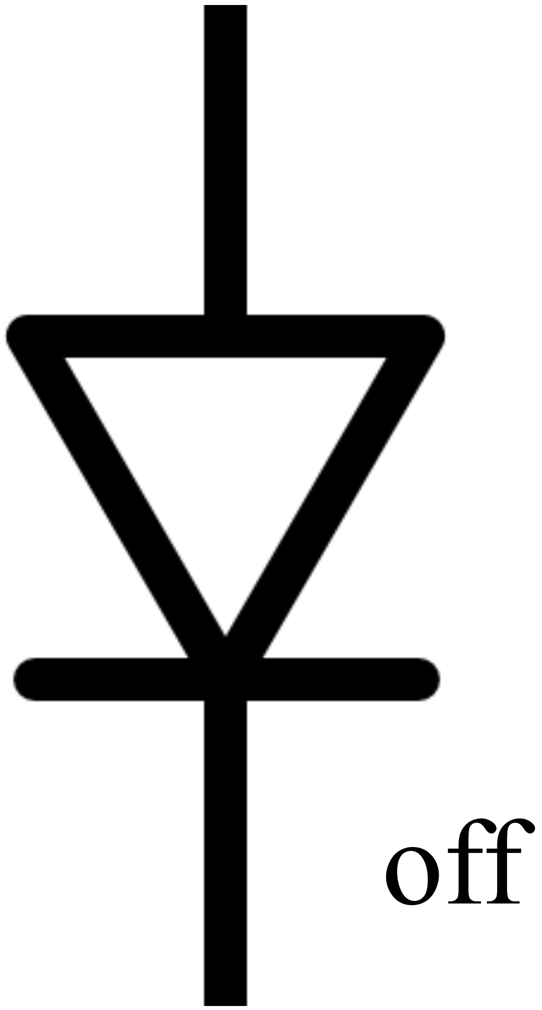
At high frequencies

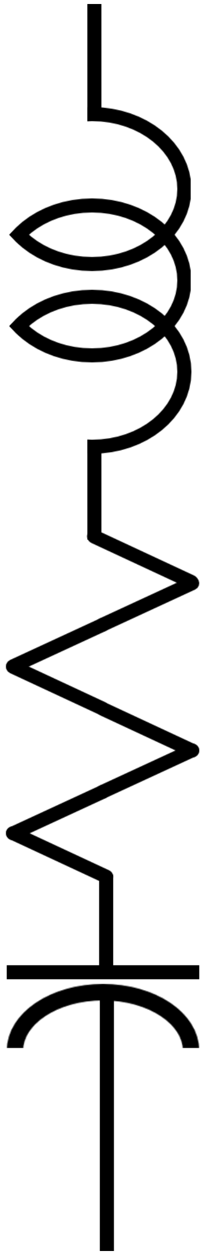
100 KHz < f < Fractional λ



Frequencies changes the Impedance

At low frequencies





At high frequencies

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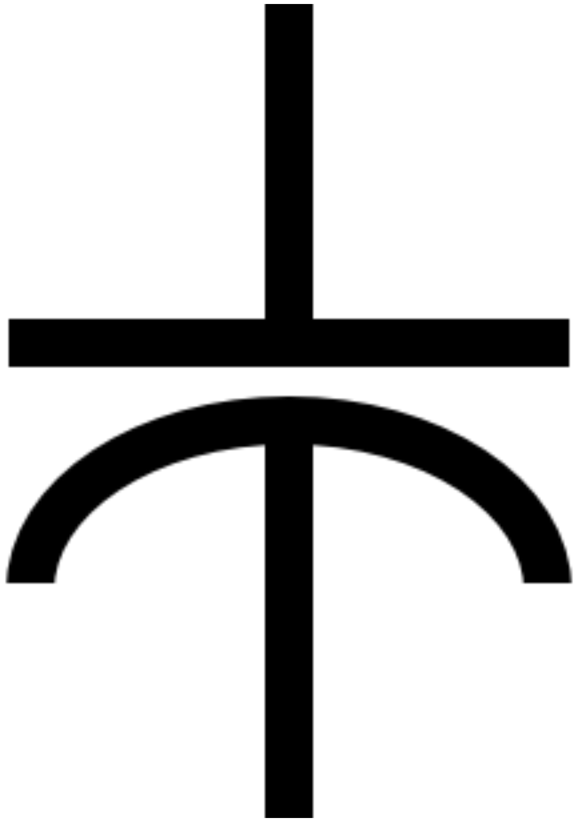

Frequencies changes the Impedance

At low frequencies

At high frequencies

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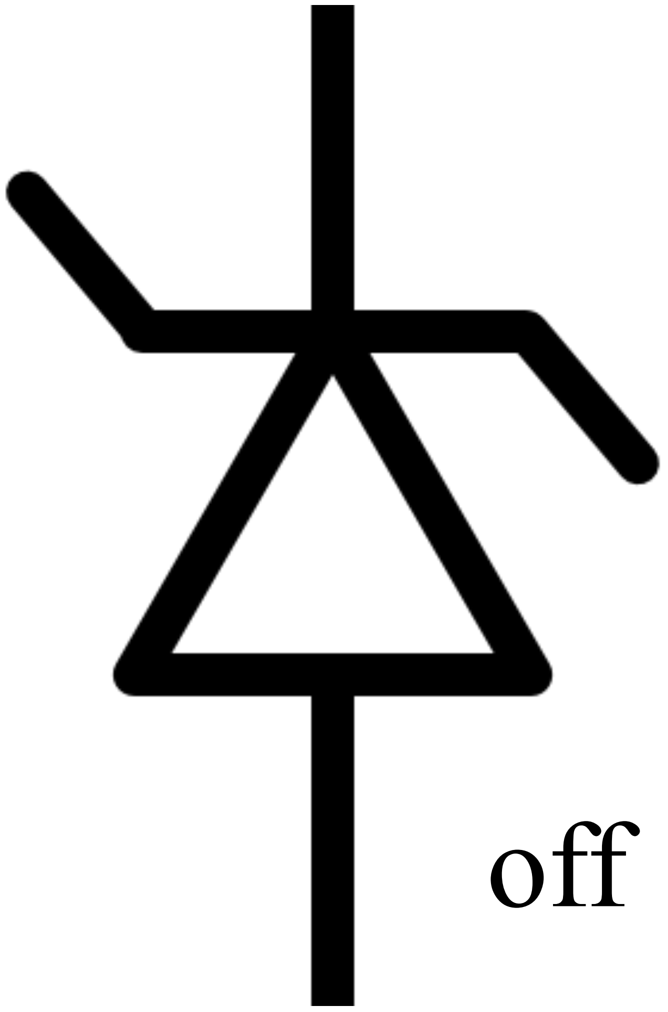
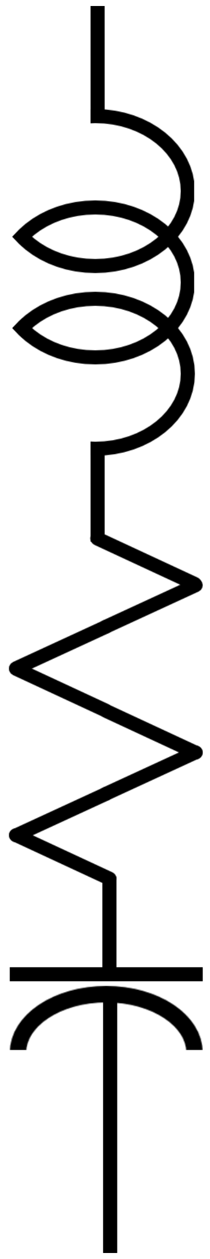
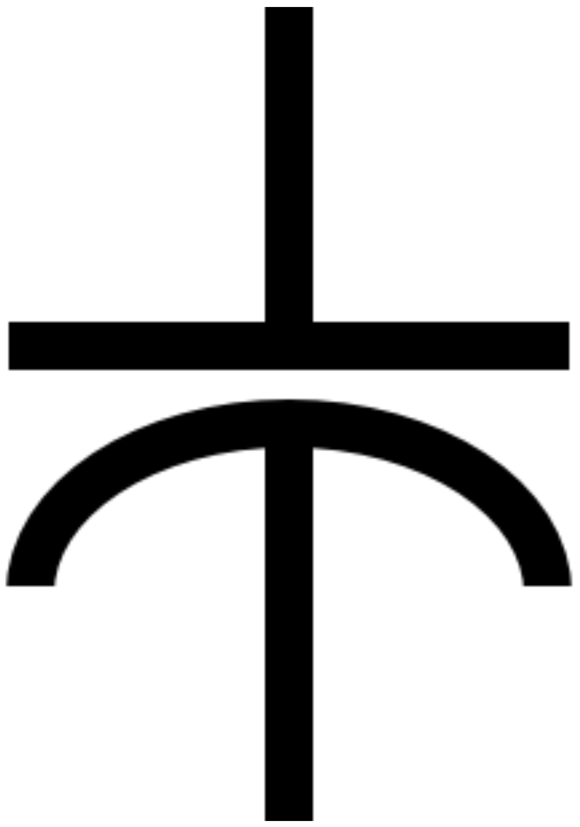


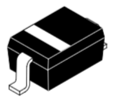




Voltage changes the Capacitance

ON Semiconductor®

http://onsemi.com



SOD−323
CASE 477
STYLE 1

MM3ZxxxT1G Series, SZMM3ZxxxT1G Series

Zener Voltage Regulators

300 mW SOD−323 Surface Mount

This series of Zener diodes is packaged in a SOD−323 surface mount package that has a power dissipation of 300 mW. They are designed to provide voltage regulation protection and are especially attractive in situations where space is at a premium. They are well suited for applications such as cellular phones, hand held portables, and high density PC boards.

Specification Features:

- Standard Zener Breakdown Voltage Range – 2.4 V to 75 V
- Steady State Power Rating of 300 mW
- Small Body Outline Dimensions: 0.067” x 0.049” (1.7 mm x 1.25 mm)
- Low Body Height: 0.035” (0.9 mm)
- Package Weight: 4.507 mg/Unit
- ESD Rating of Class 3 (> 16 kV) per Human Body Model
- SZ Prefix for Automotive and Other Applications Requiring Unique Site and Control Change Requirements; AEC−Q101 Qualified and PPAP Capable
- These are Pb−Free Devices*

MM3ZxxxT1G Series, SZMM3ZxxxT1G Series

TYPICAL CHARACTERISTICS

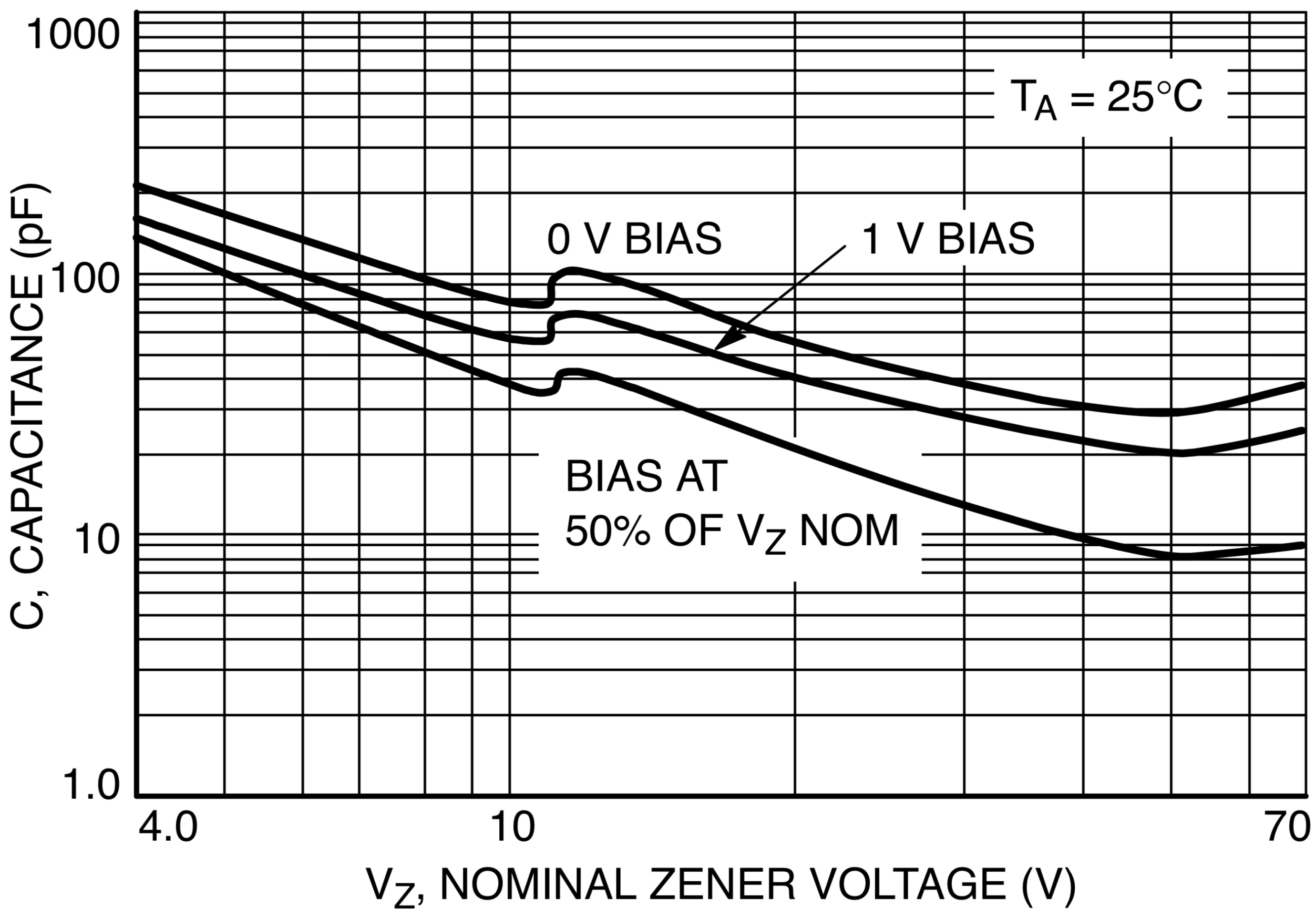
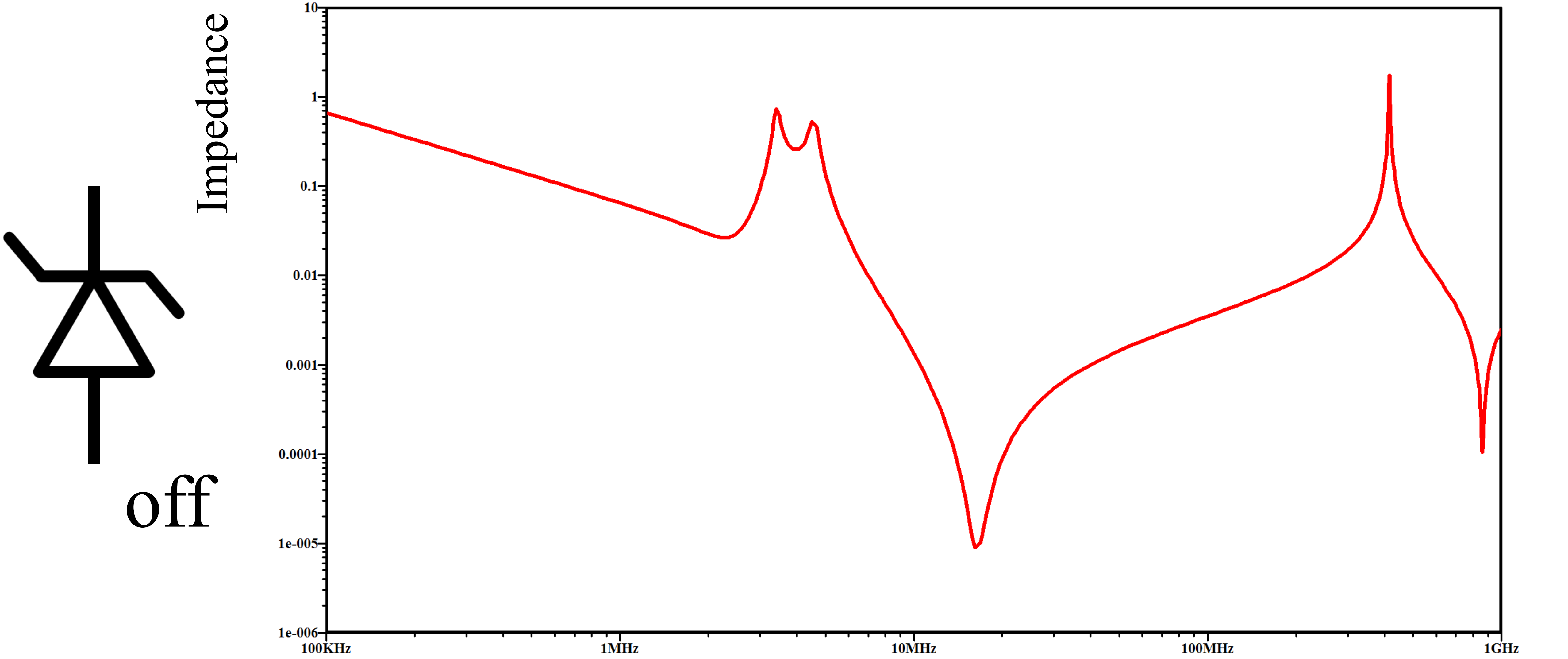


Figure 3. Typical Capacitance

Voltage changes the Capacitance

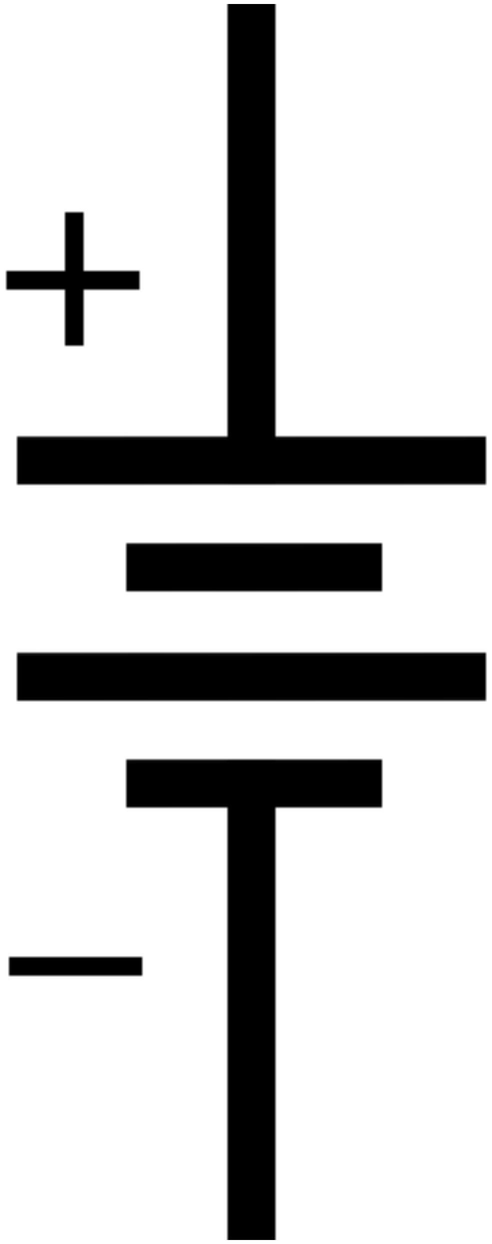


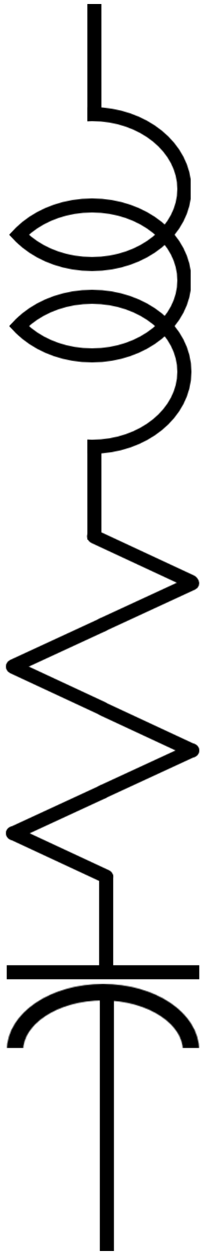
Output impedance of a current switch mode power supply with a zener in the circuit. Note the movement of the resonance and antiresonance as the DC voltage changes.

PDF copies of the presentation do not show the animations.

Frequencies changes the Impedance

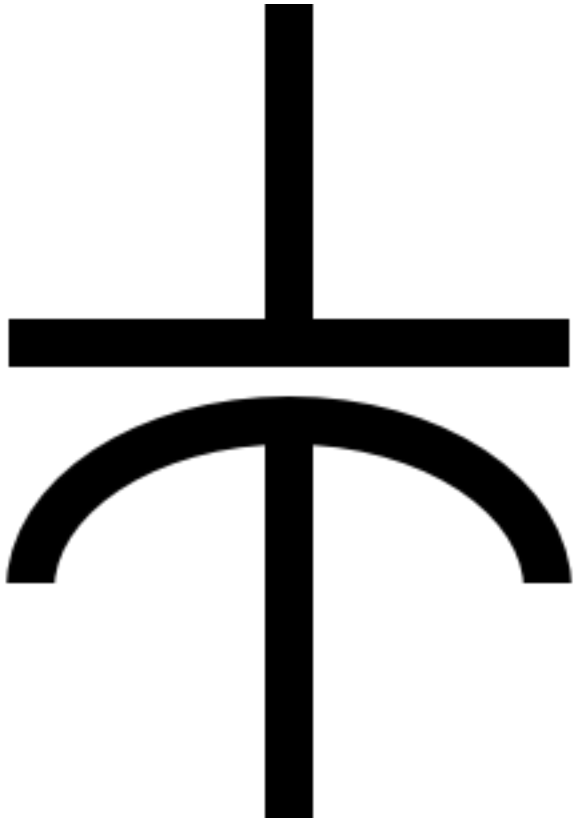
At low frequencies



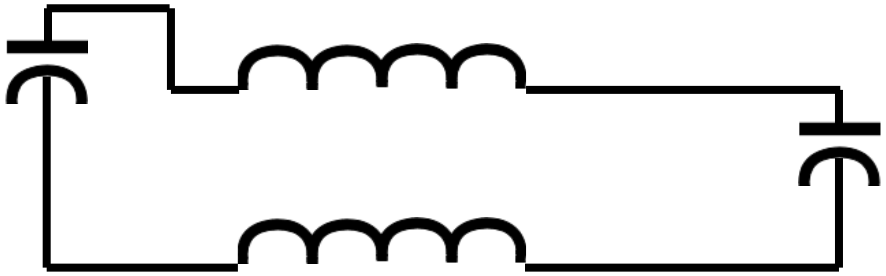


At high frequencies

100 KHz < f < Fractional λ



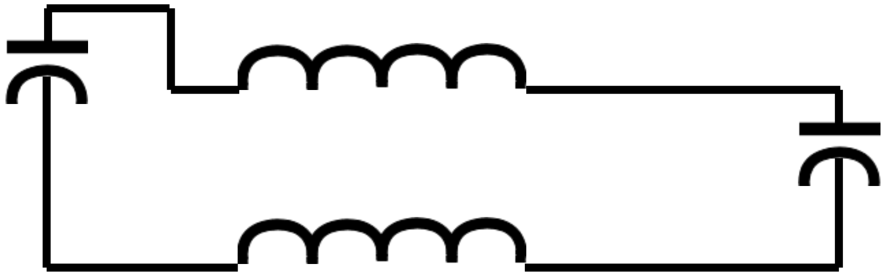
Let’s take a look at two capacitors and the distances between them.



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

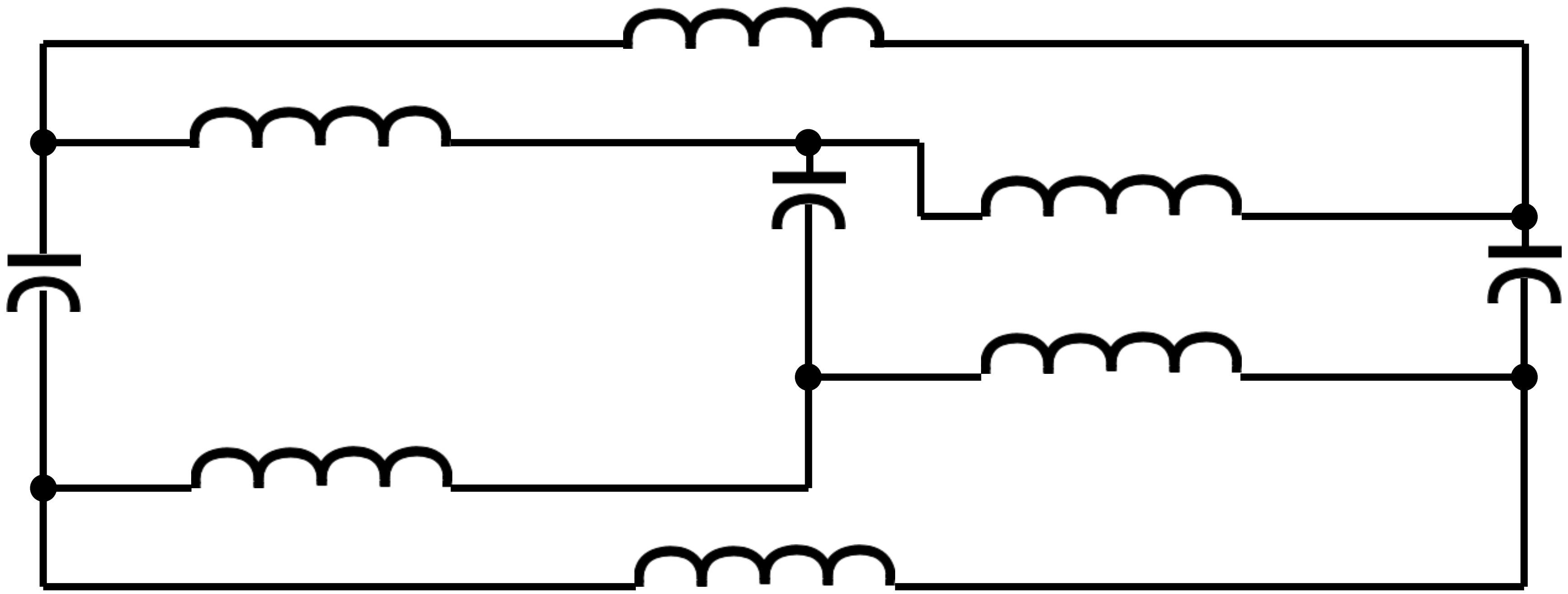
$$Frequency = \frac{1}{2\pi\sqrt{L_T C_T}}$$

There is one resonance and one loop of current.



$$L_{FR4\,PCB} \approx 10\frac{nH}{inch} \approx 400\frac{nH}{meter} \qquad L_{wire} \approx 15\frac{nH}{inch} \approx 600\frac{nH}{meter}$$

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



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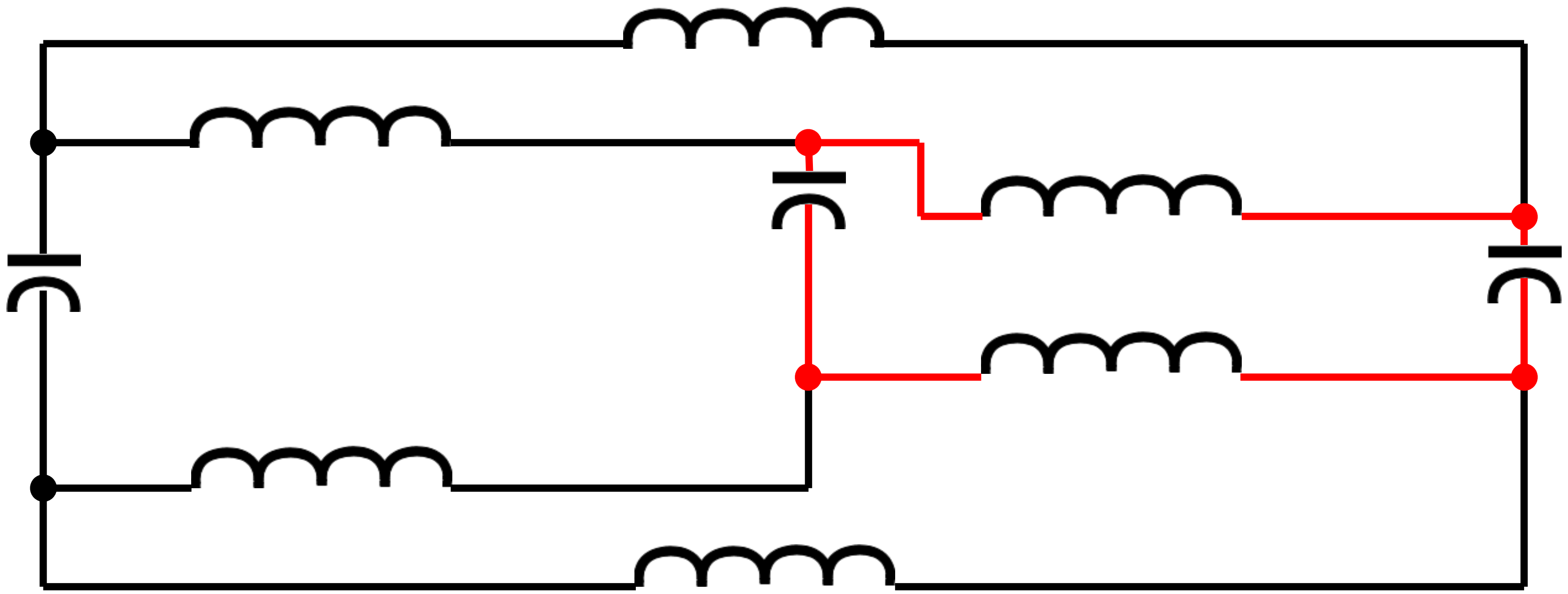
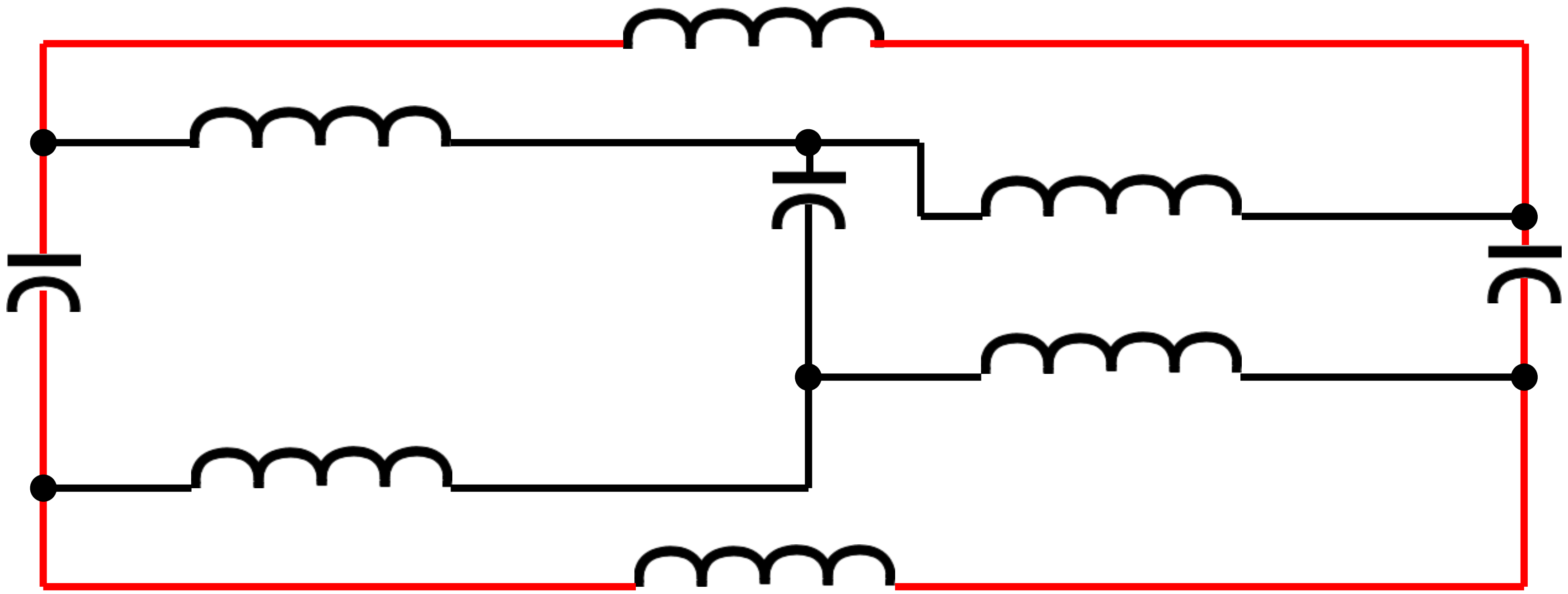


Now let’s take a look at an array of three capacitors and the distances between them.



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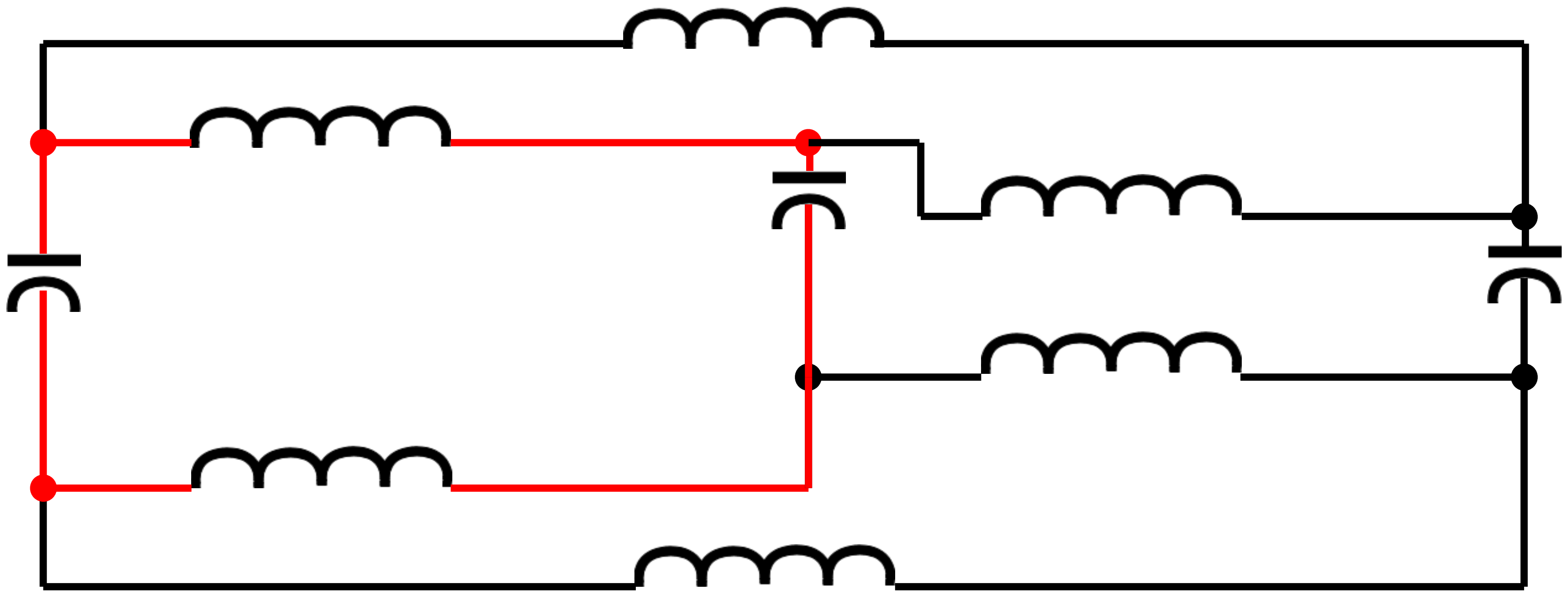
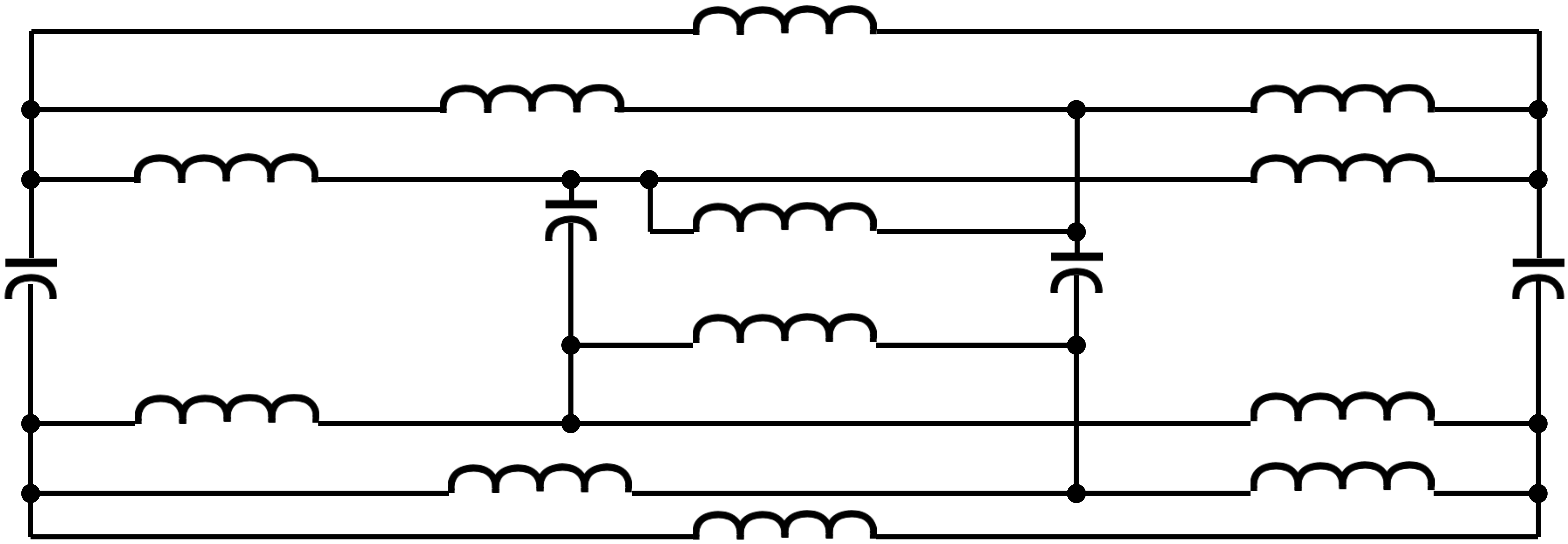
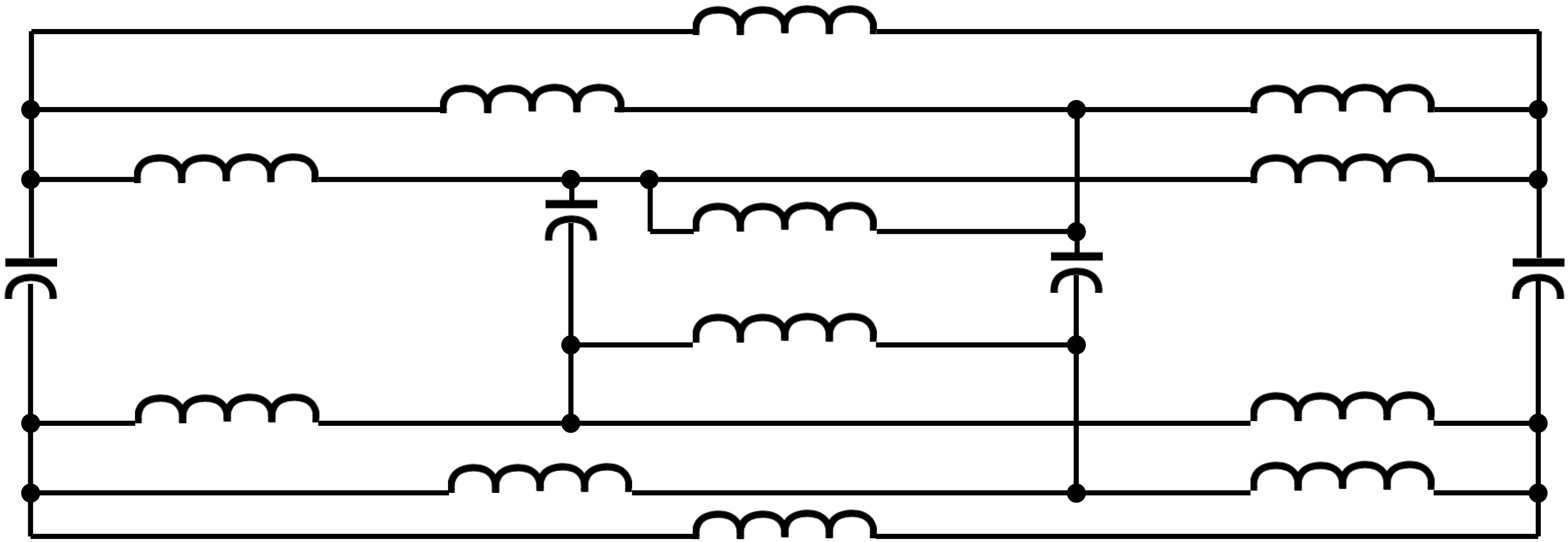


We now have three resonances.

But what happens as we add a fourth capacitor?



We get ten different resonant frequencies.



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.

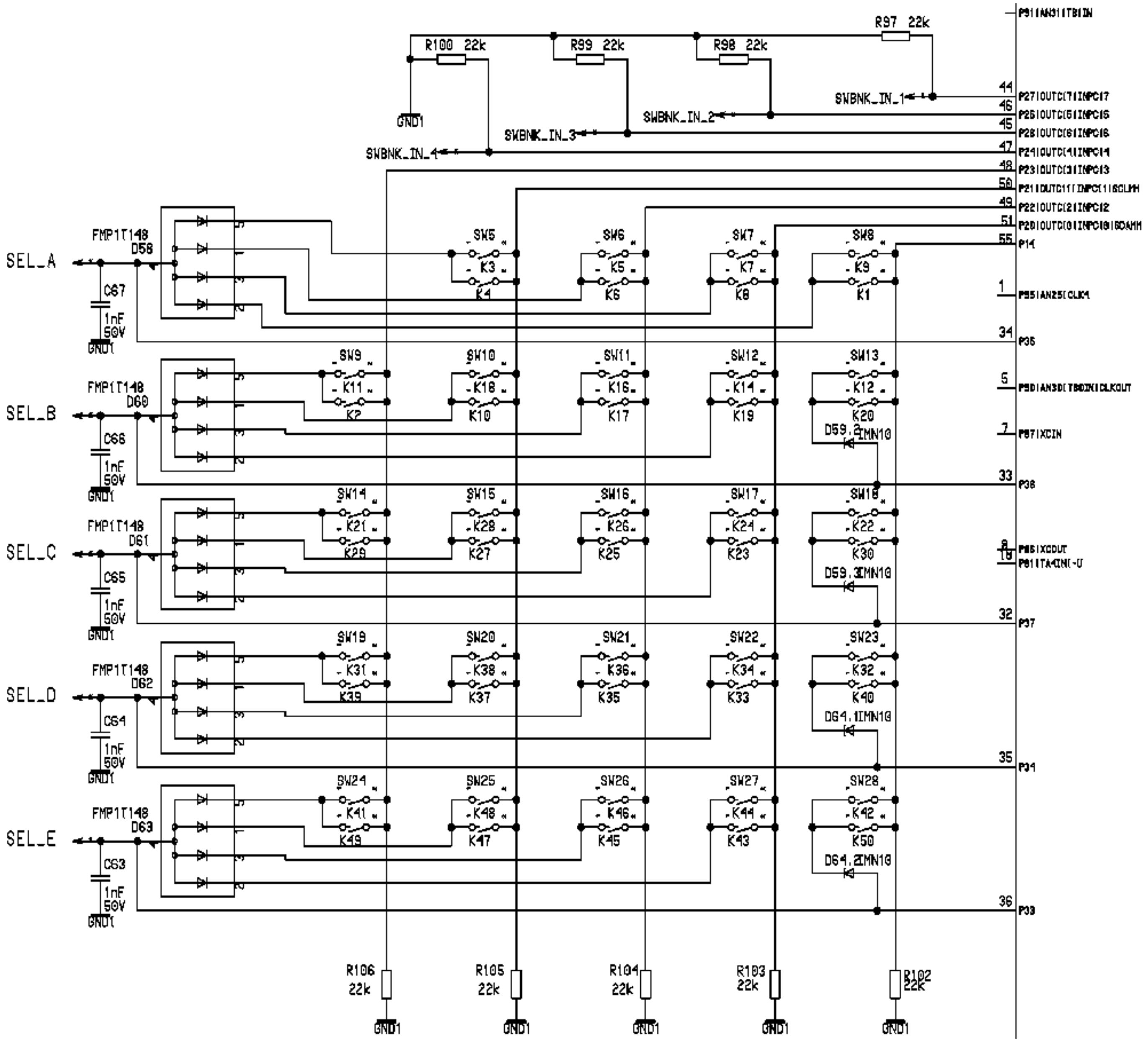
So what do we do?

We find and break the loop antennas.

This Switch Matrix failed EMC Testing

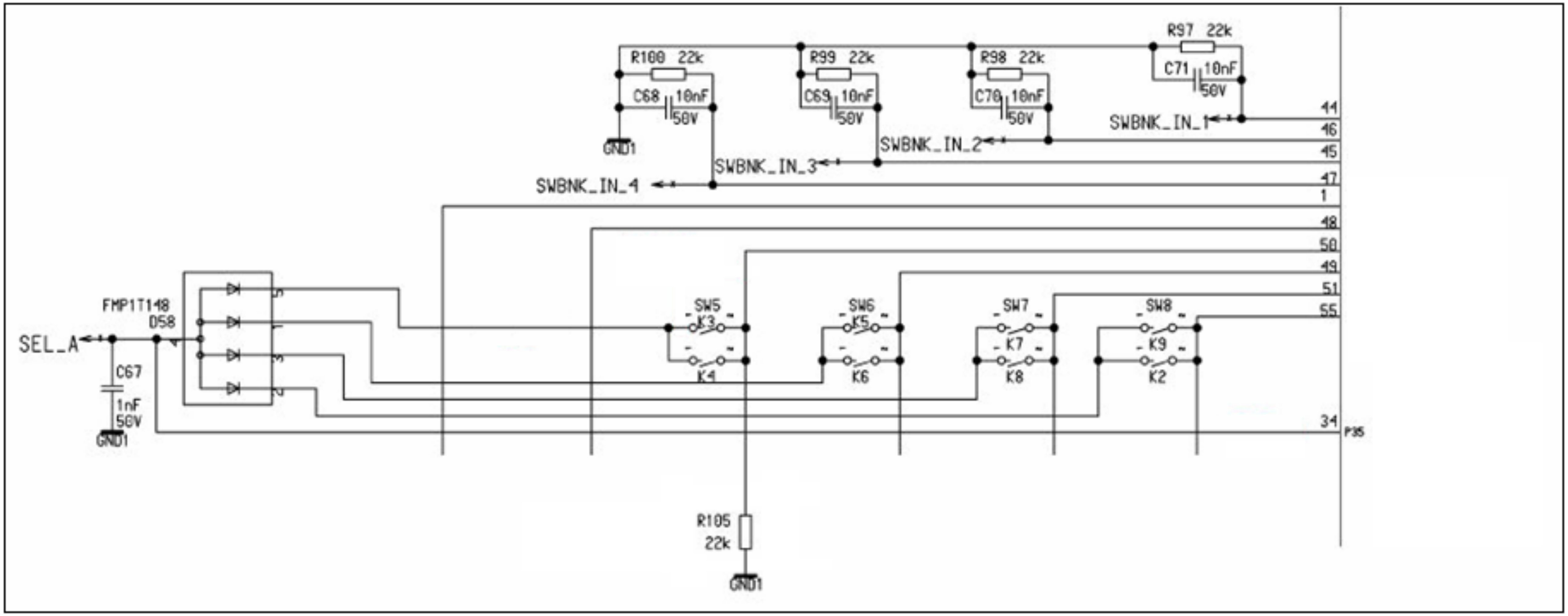
Switch matrix inputs are very common.

The microcontroller scans the rows and columns of the matrix to determine if a switch has been depressed.



This product detected a switch depression due to RF excitation at 220 MHz.

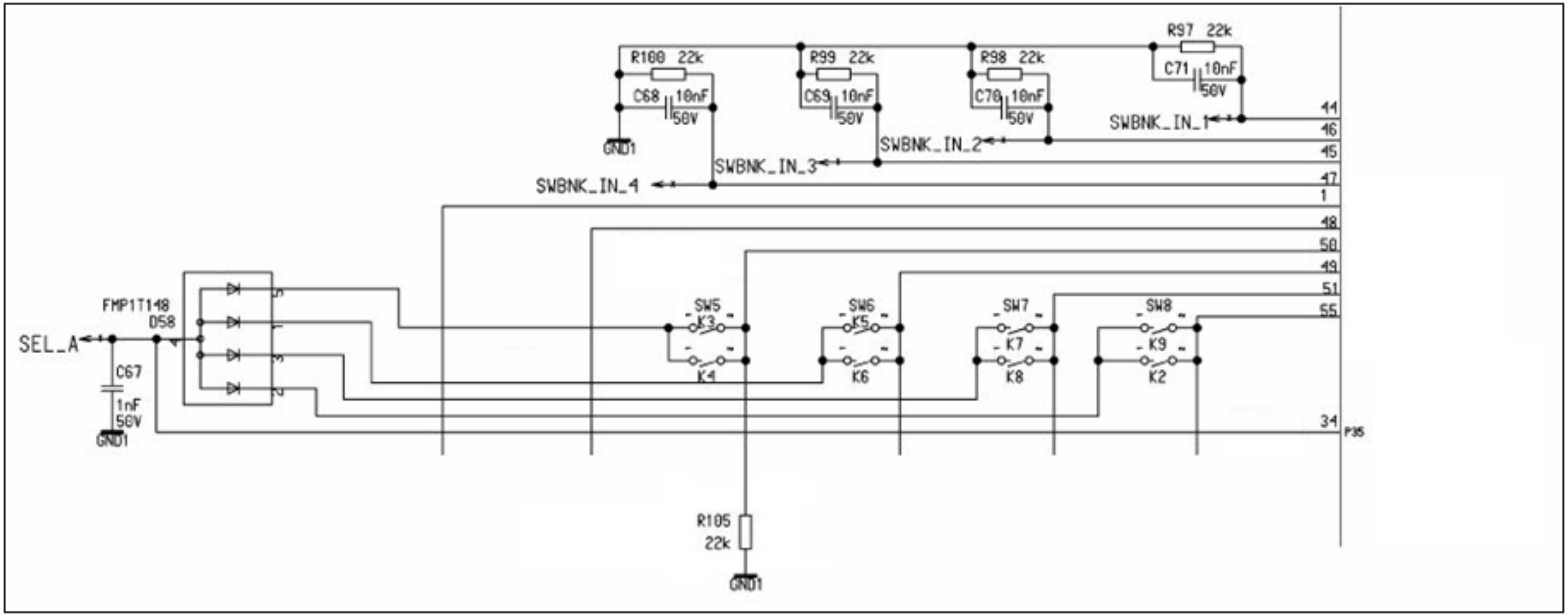
Pin the tail on the resonant circuit.



Here is a single row of the switch matrix.

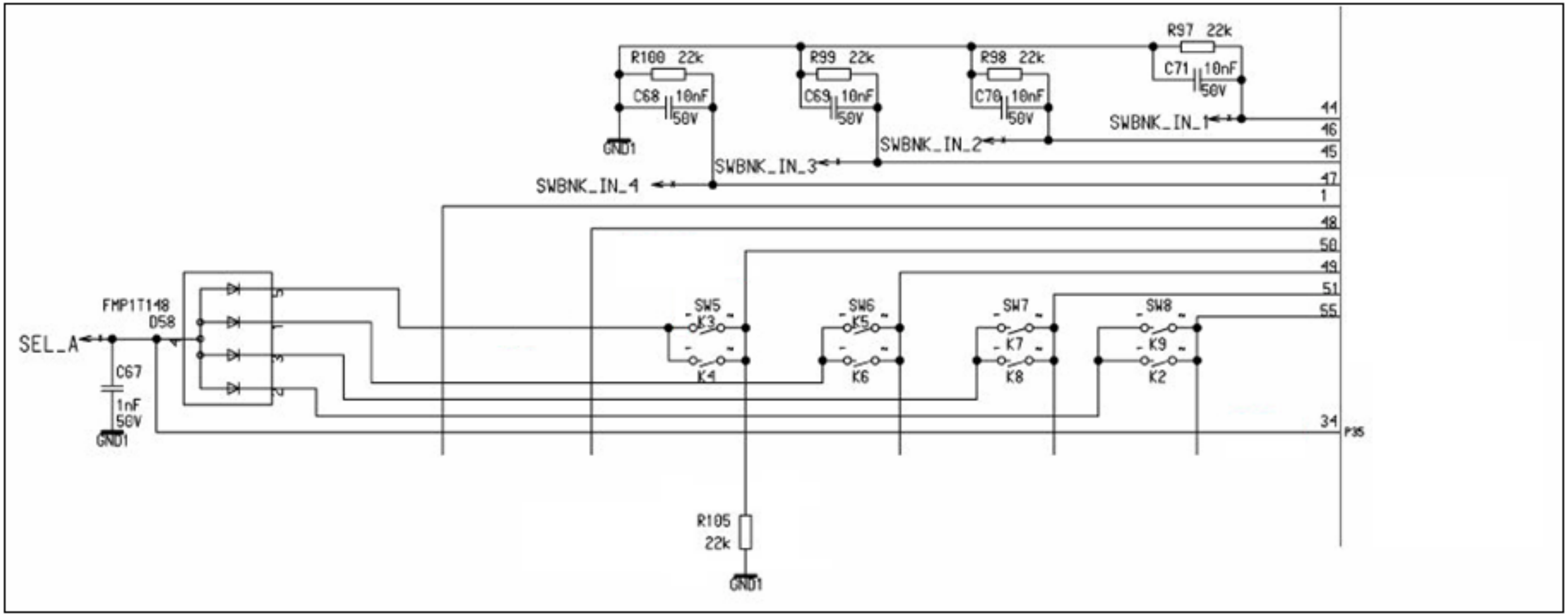
Can you find the 220 MHz resonant circuit?

Pin the tail on the resonant circuit.



Here's a hint: The distance to the switches is 10 inches.

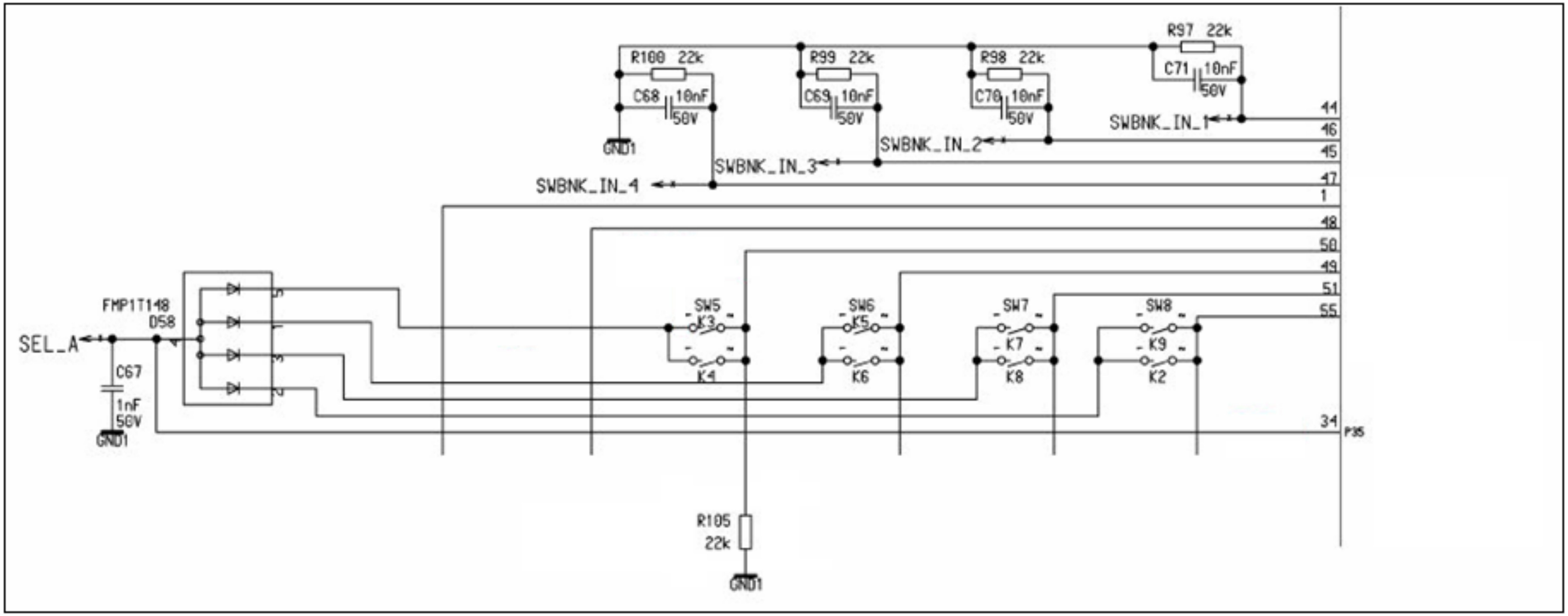
Pin the tail on the resonant circuit.



Here's a hint: The distance to the switches is 10 inches.

$$L_T = 10\ \frac{nH}{inch}\ 2\ 10\ inches = 200\ nH$$

Pin the tail on the resonant circuit.



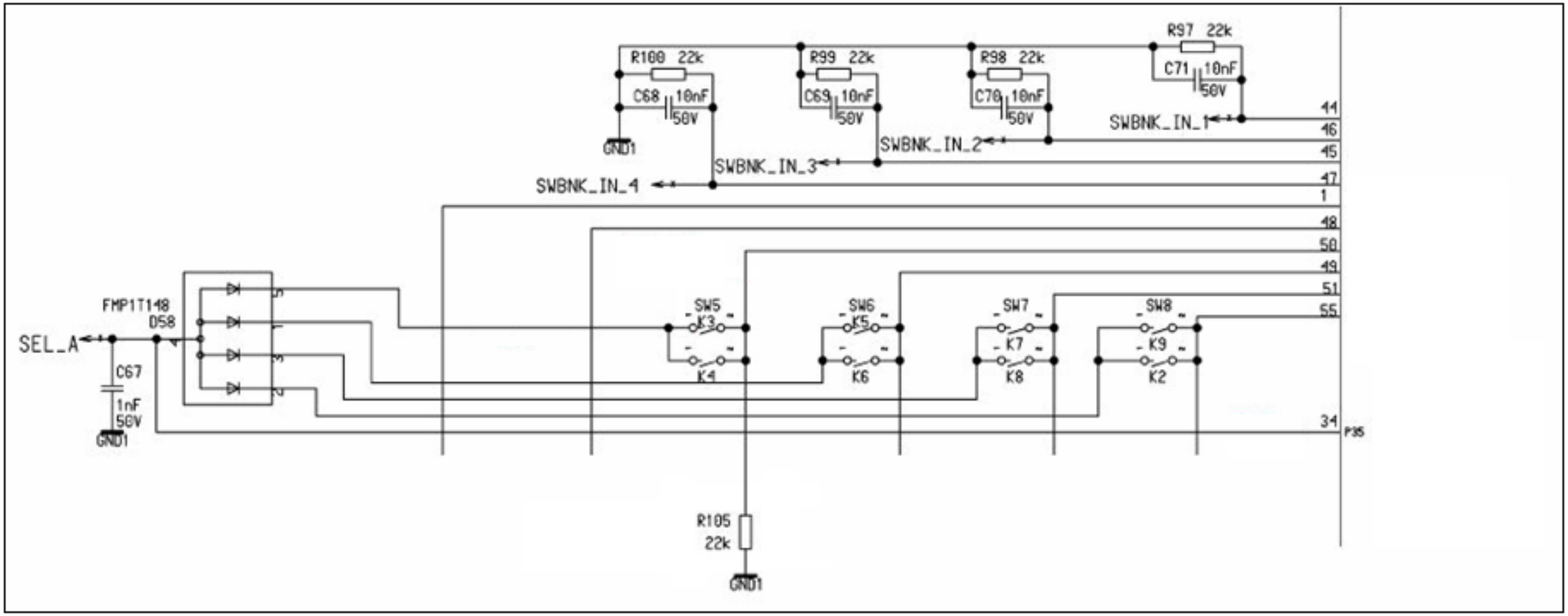
Here's a hint: The distance to the switches is 10 inches.

$$L_T = 10\,\frac{nH}{inch}\;2\;10\;inches = 200\;nH$$

$$C_T = \frac{1}{(2\pi\,Freq)^2\,L_T}$$

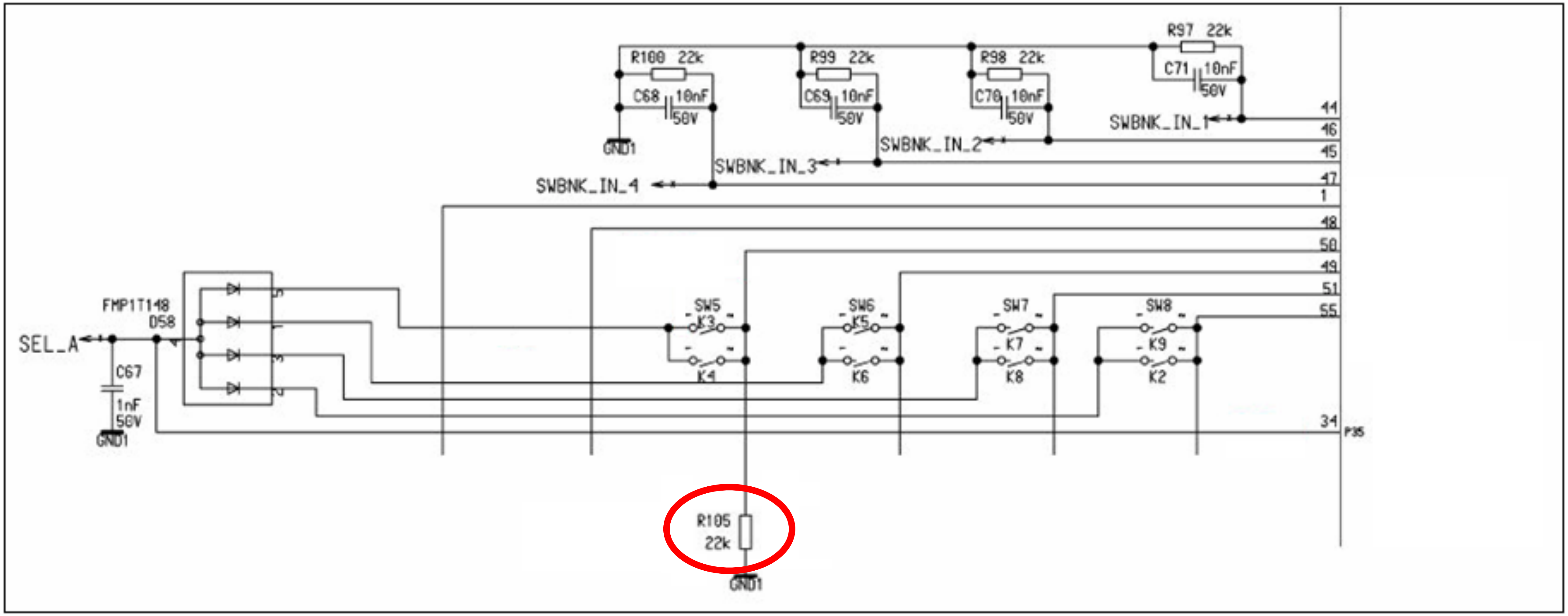
$$C_T = \frac{1}{\left(2\pi\;220\;10^6\right)^2\,200\;10^{-9}} = 2.6\;pF$$

Pin the tail on the resonant circuit.



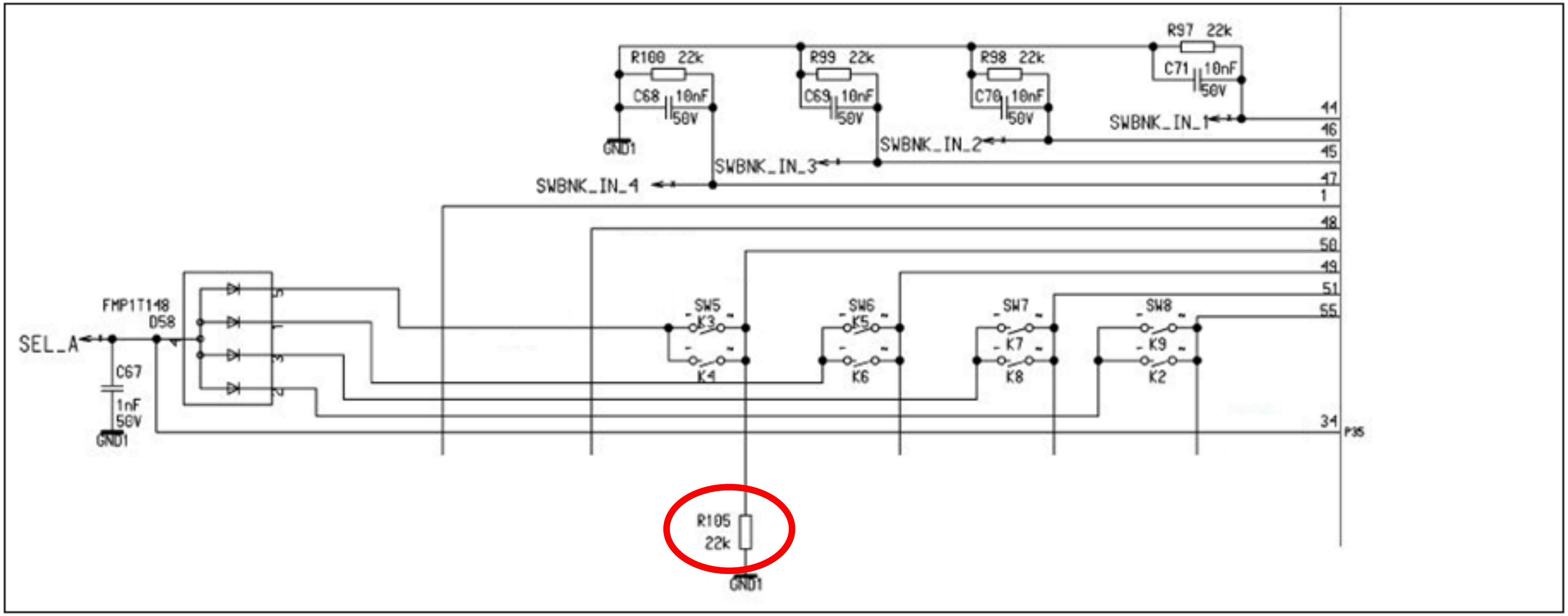
Where are we going to find a 2.6 pF capacitor?

Pin the tail on the resonant circuit.



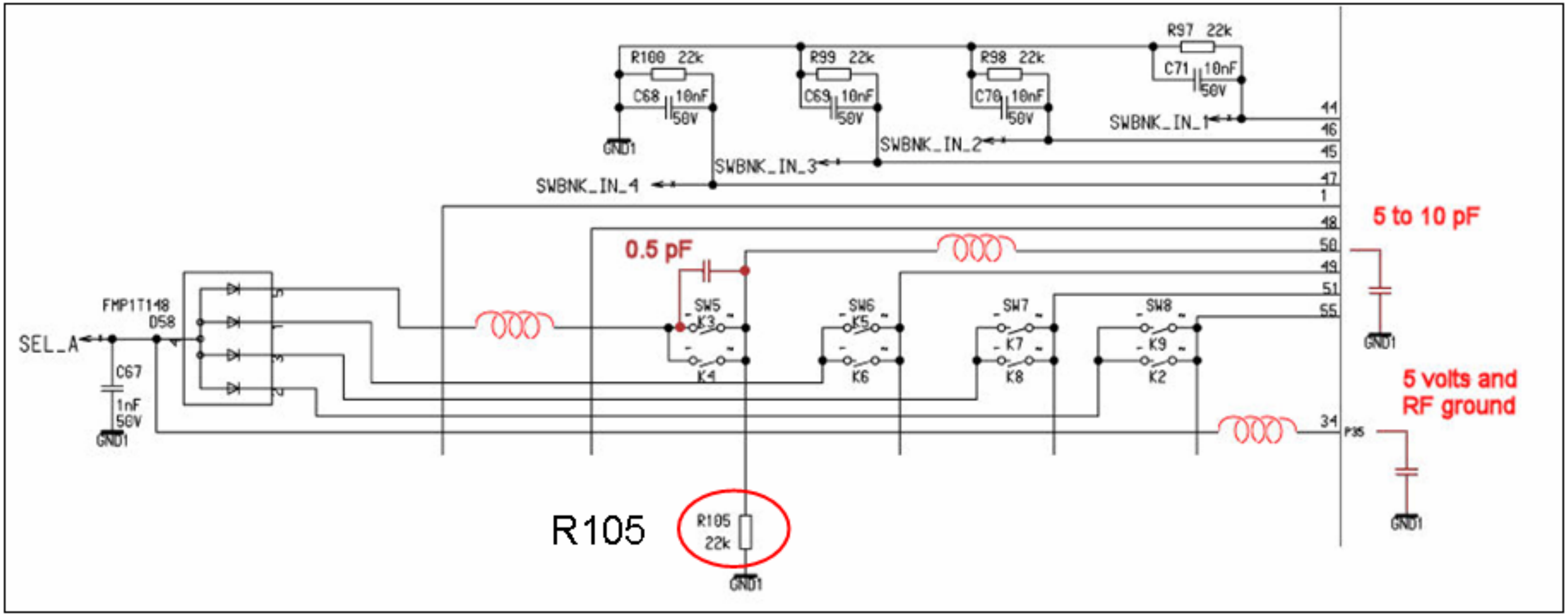
Here’s another hint: with an increased value of R105 the EMC performance got worse.

Pin the tail on the resonant circuit.



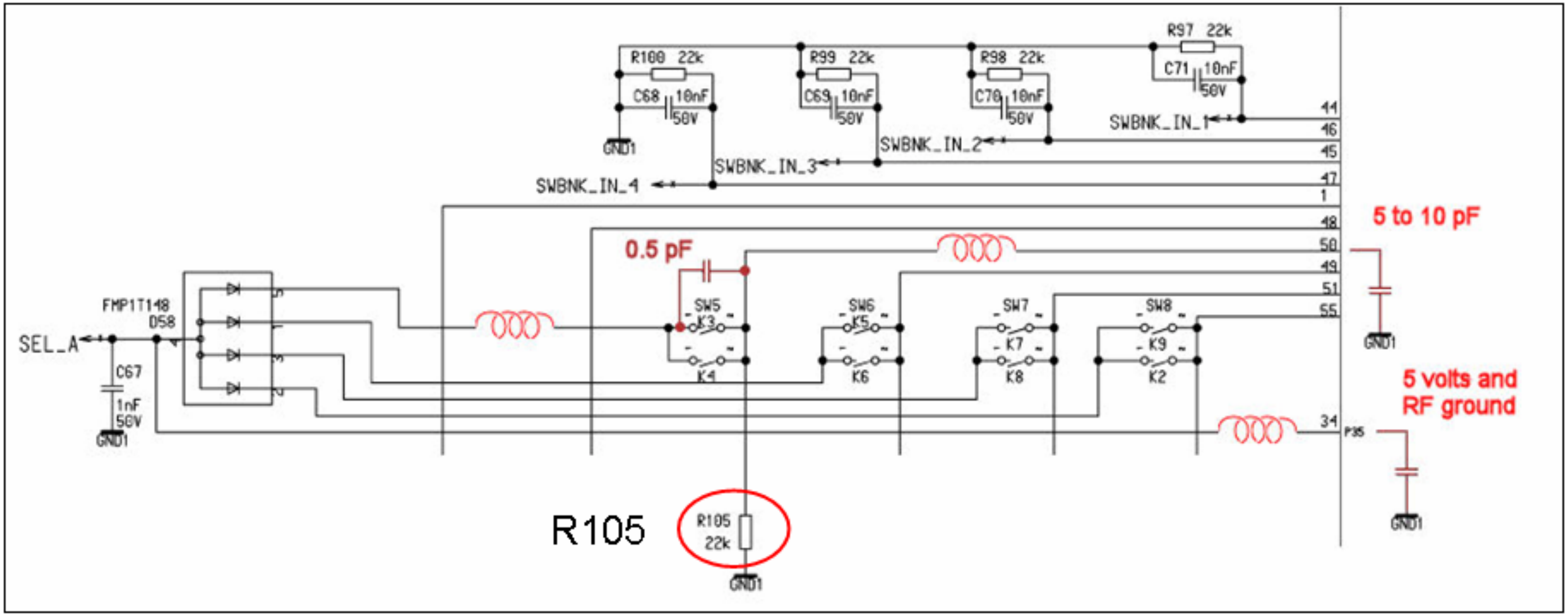
Resistor R105 is in a parallel resonant circuit.

Pin the tail on the resonant circuit.



The traces are inductors, the open switch is a capacitor. The microcontroller input is also a capacitor and so are the off diodes.

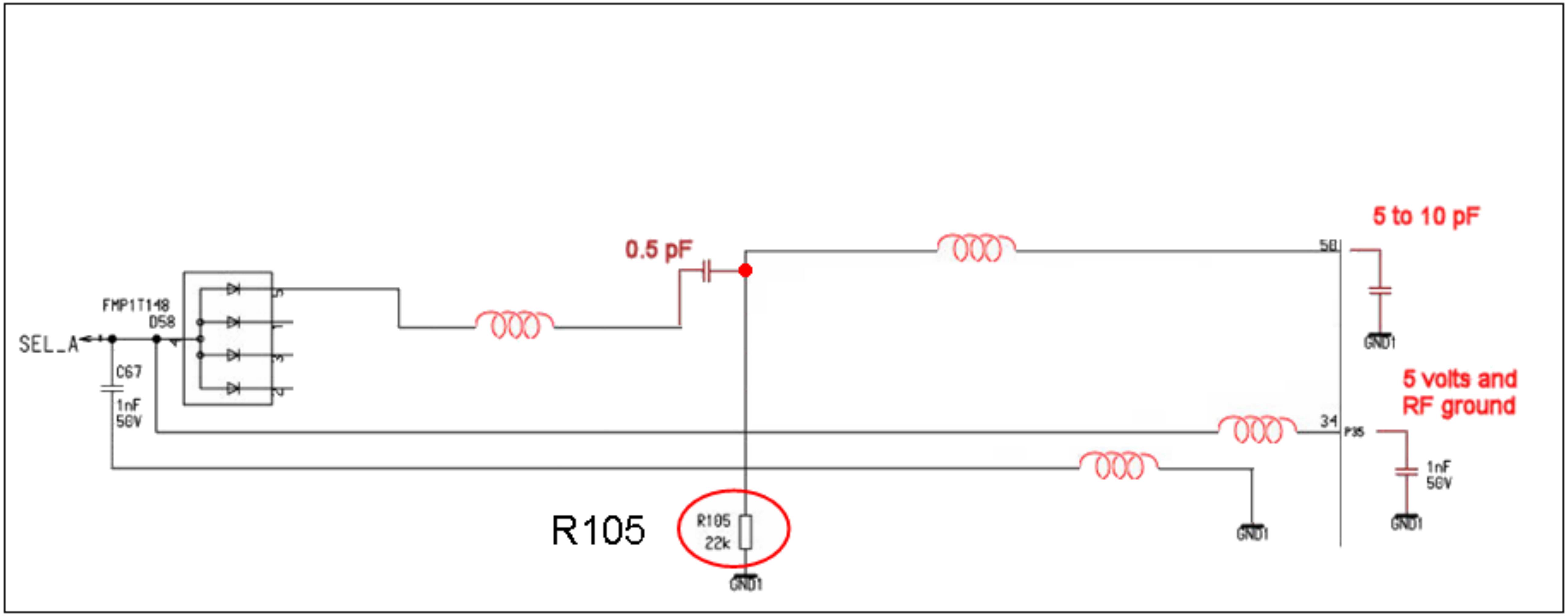
Pin the tail on the resonant circuit.



How do we make sure this is the right resonant circuit?

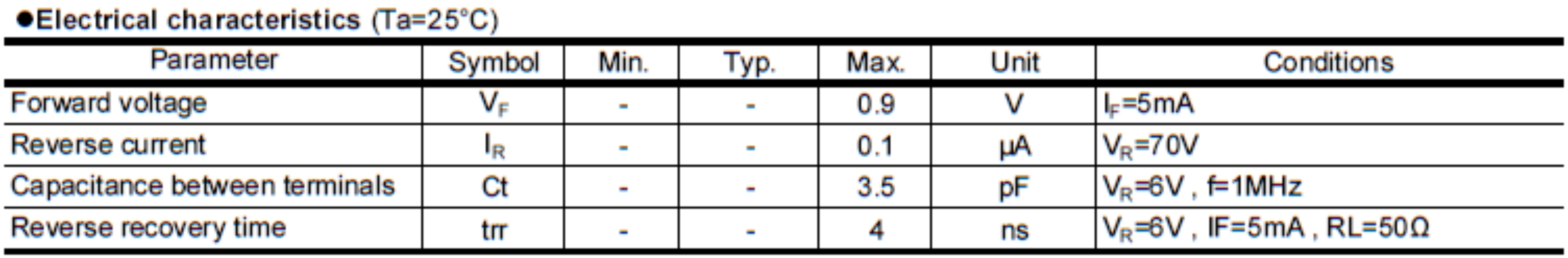
We calculate the resonant frequency.

Pin the tail on the resonant circuit.



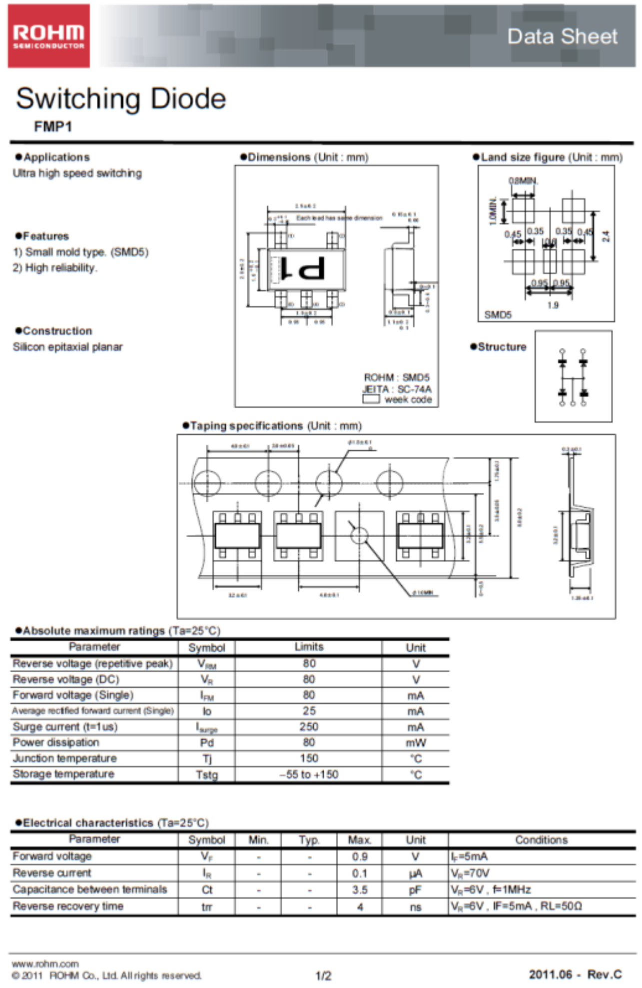
First we need to know the capacitance of the off diode.

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

www.rohm.com

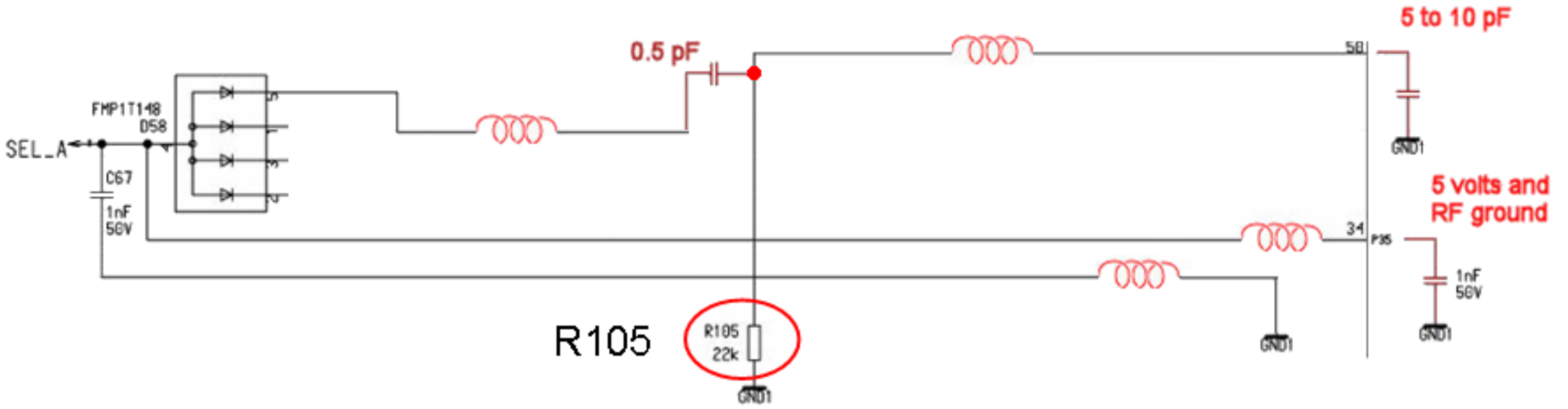
1/2

2011.06 - Rev.C

With the diode off the maximum capacitance is 3.5 pF.

The resonant frequency

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



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

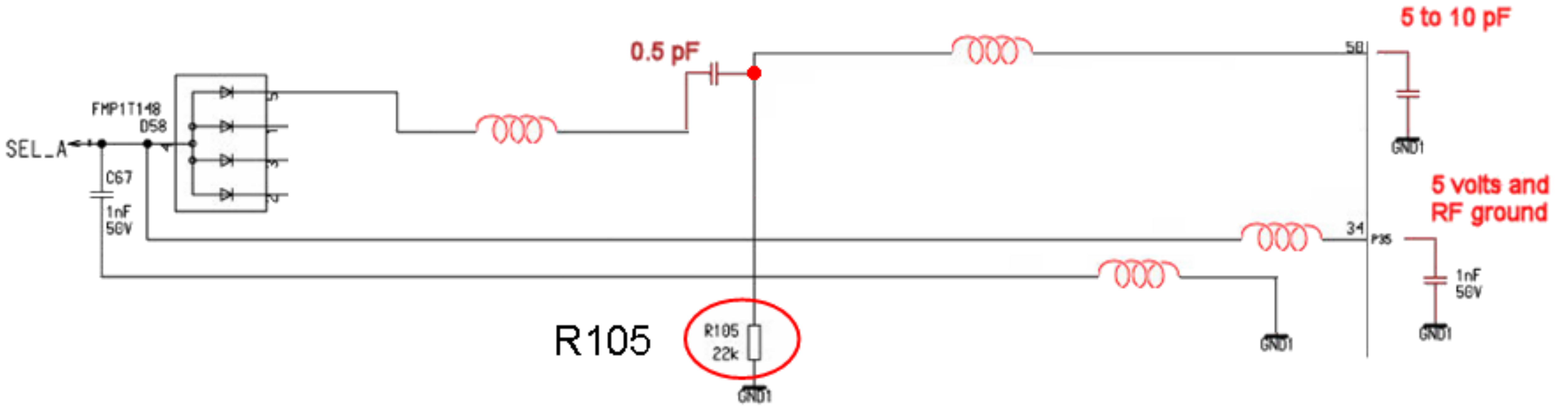
$$L_T = \frac{10\,nH}{inch} 20\,inches = 200\,nH$$

$$C_T = 2.4\,pF$$

$$Frequency_{center} = \frac{1}{2\pi\sqrt{200\,nH \cdot 2.4\,pF}} \approx 230\,MHz$$

The resonant frequency

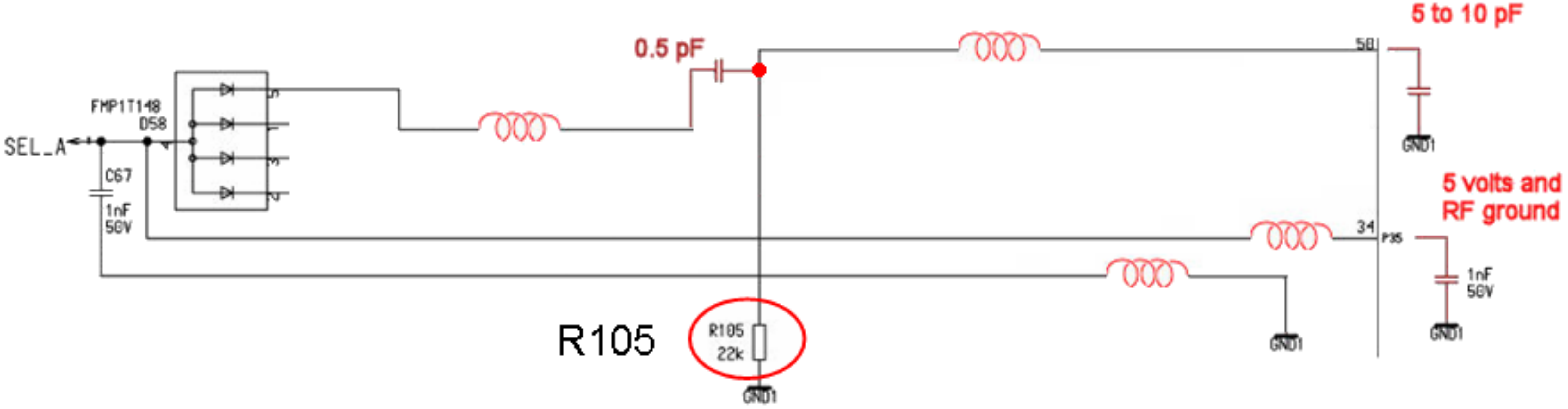
The total length to the switch through cables and PCB then back again is 20 inches.



Now that we have determined the offending circuit, how do we fix it?

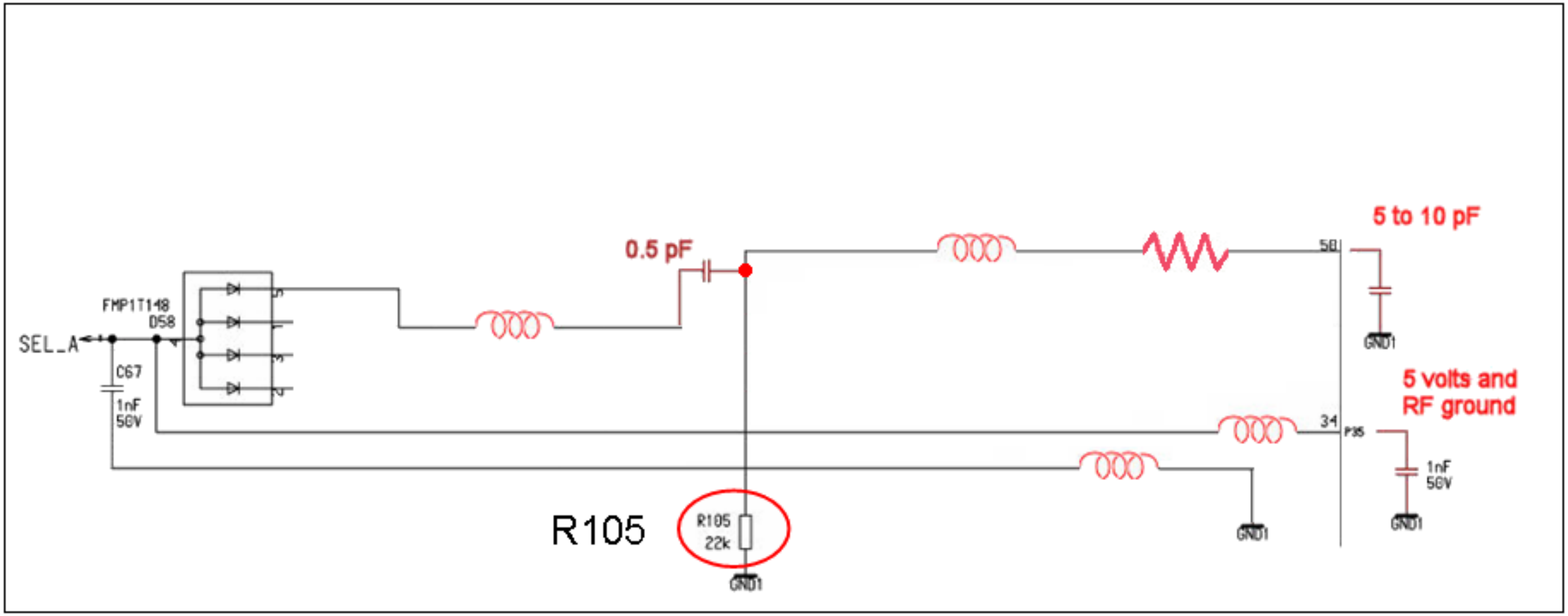
The resonant frequency

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



We add a series resistor.

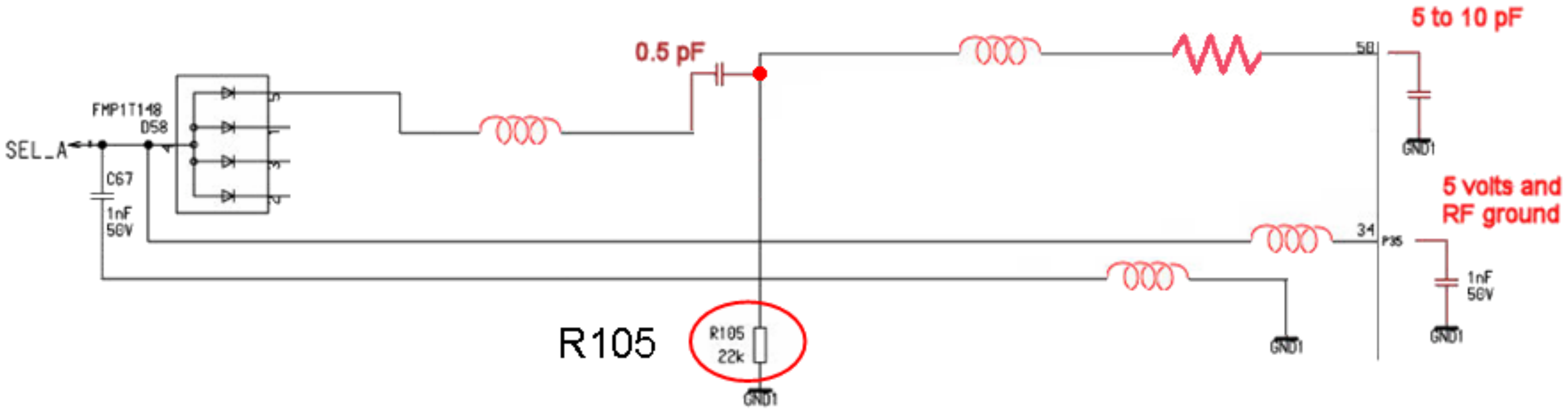
Resistor are very Broadband



The only DC current in the resistor is the input leakage current. With a series resistor the Q of the resonance is lowered and the circuit susceptibility have been reduced by a substantial amount.

But how much resistance do we need to pass?

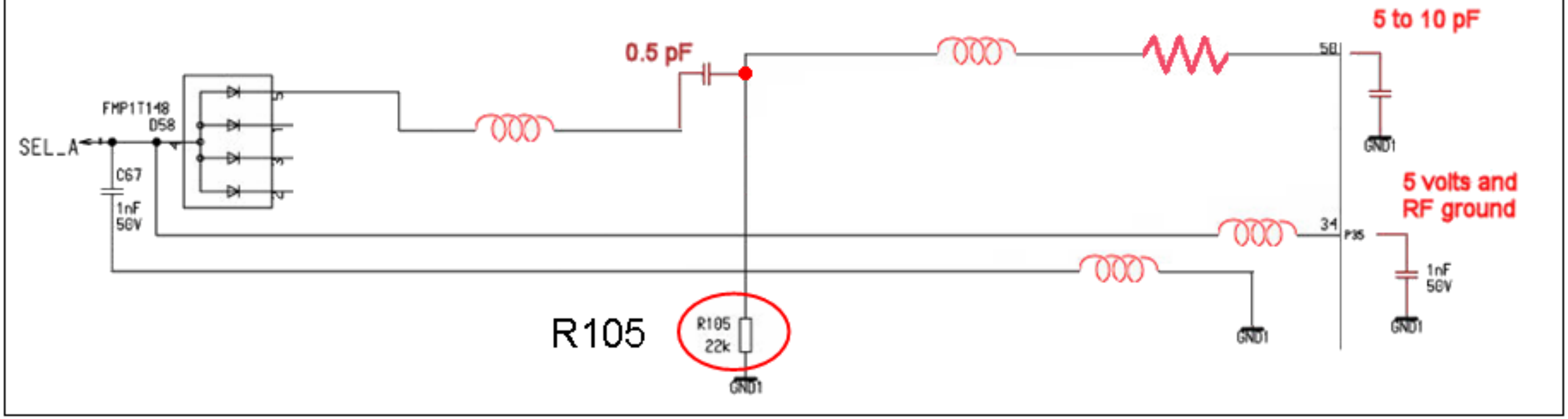
We can calculate the amount of resistance required to pass the EMC requirement.



The Schelkunoff small loop equation tells us:

$$20\,Log\,\frac{E_{radiated\,1}}{E_{radiated\,2}} \approx 20\,Log\,\frac{R_2}{R_1} \approx 20\,Log\,\frac{100}{100\,m\Omega} \approx 60\,dB$$

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



In the words of Henry Ott, “kill it dead”

$$20\,Log\frac{E_{radiated\,1}}{E_{radiated\,2}} \approx 20\,Log\frac{R_2}{R_1} \approx 20\,Log\frac{100}{100\,m\Omega} \approx 60\,dB$$

Do you add resistors or capacitors?

It is better to lower the Q with a resistor.

Adding capacitors makes more resonances.

Changing a capacitor value moves the center frequency.

Let's not play hide and seek with the emissions and circuit susceptibilities.

Use resistors to fix EMC issues.

Decoupling Circuits

Decoupling is a Bucket Brigade of charge from slow big buckets to fast small buckets.

The Bucket List

Power supply bulk charge well.

Discreet decoupling capacitors.

Interlayer sheet capacitance in the PCB.

Discreet capacitance on the interposer.

Interlayer sheet capacitance of the interposer.

White space (unused) space on the die.

Sizing the Buckets

The size of each bucket is determined by the

Current demand,

Rate of charge drain,

Voltage ripple requirements, and

Electrical length to where the charge is needed.

Sizing the Buckets

Each capacitor of the Bucket Brigade can form a resonant loop with another capacitor in the Bucket Brigade.

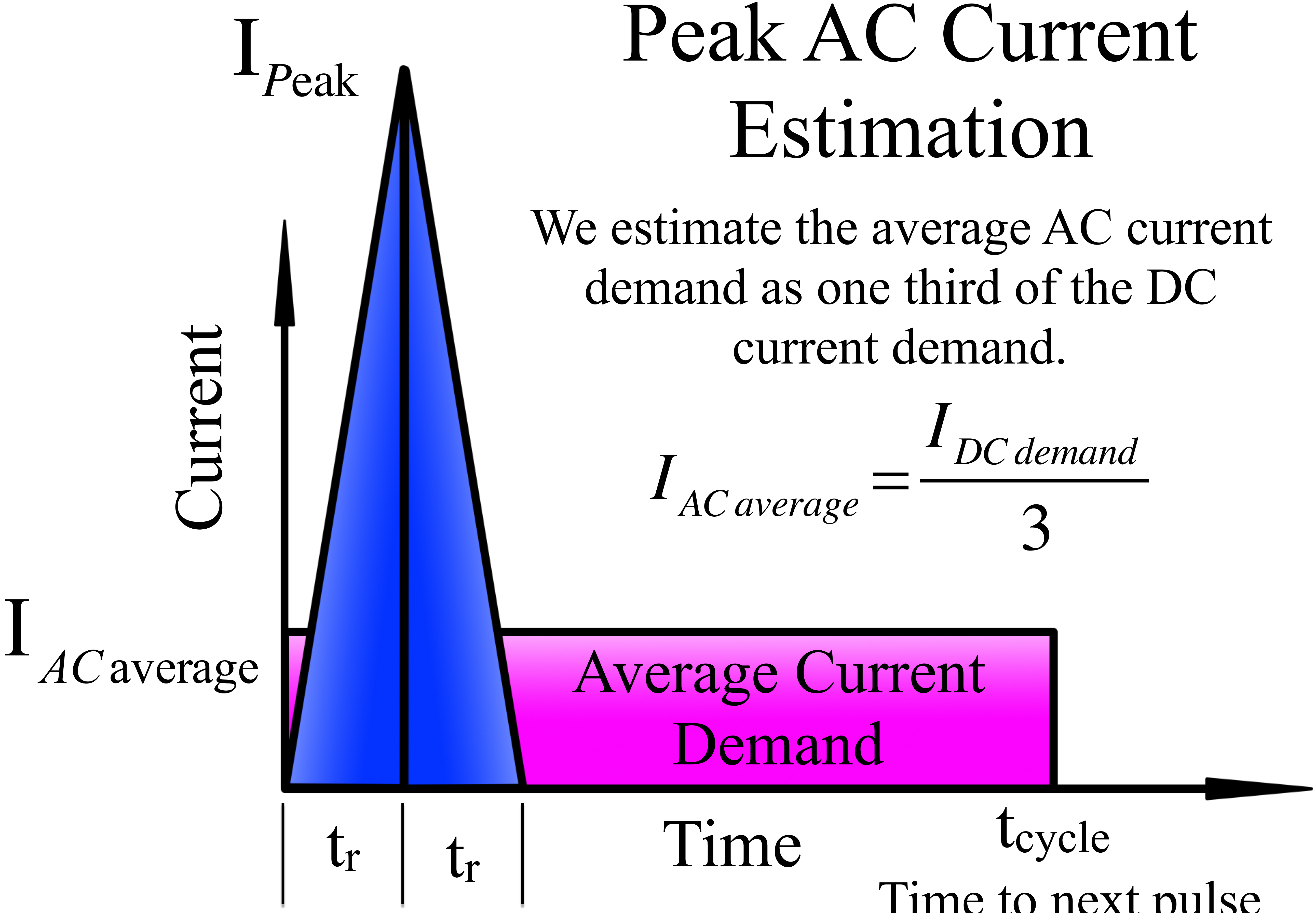
This will cause ringing on the two resonating capacitors.

The off-board communication bus drivers decoupling capacitors should be checked for ringing due to this issue. As again, we are playing Capacitor Whack-a-Mole.

Peak AC Current Estimation

We estimate the average AC current demand as one third of the DC current demand.

$$I_{AC\,average} = \frac{I_{DC\,demand}}{3}$$



This estimate is from the work of Bruce Archambeault.

Peak AC Current Estimation

By equating the charge of these two waveforms we can determine the peak current demand.

$$Q = \int_{t_1}^{t_2} I\,dt$$

$$Q_{Pulse} = \int_0^{t_r} I\,dt + \int_{t_r}^{2t_r} I\,dt$$

$$Q_{AC\,Average} = \int_0^{t_{Cycle}} I_{AC\,Average}\,dt$$

$$Q_{Pulse} = area_{Rise\,Right\,Angle\,Trangle} + area_{Fall\,Right\,Angle\,Trangle}$$

$$Q_{Pulse} = \frac{I_{Peak}\,t_r}{2} + \frac{I_{Peak}\,t_r}{2} = I_{Peak}\,t_r$$

$$Q_{AC\,Average} = area_{AC\,currrent\,demand\,rectangle} = I_{AC\,Average}\,t_{cycle}$$

$$I_{Peak}\,t_r = I_{AC\,Average}\,t_{cycle}$$

$$I_{AC\,average} = \frac{I_{DC\,demand}}{3}$$

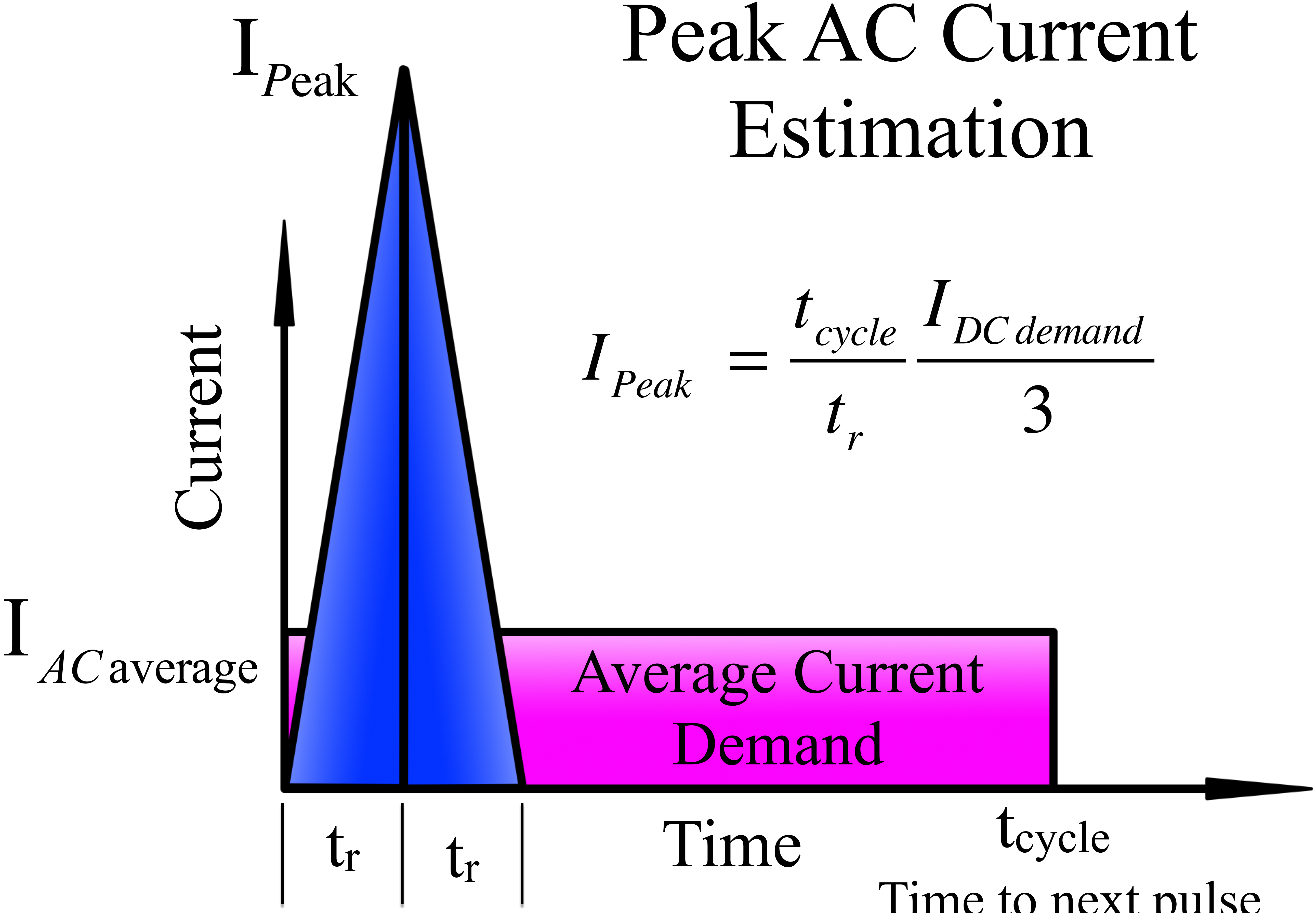
Reference:

https://en.wikipedia.org/wiki/Electric_charge

$$I_{Peak} = \frac{t_{cycle}}{t_r}\,\frac{I_{DC\,demand}}{3}$$

Peak AC Current Estimation

$$I_{Peak} = \frac{t_{cycle}}{t_r}\frac{I_{DC\,demand}}{3}$$



Peak AC Current Estimation

We consider the voltage noise on V_{DD}.

$$V(t)=\frac{1}{C}\int_0^t I(t)\,dt+V(0) \quad \text{then} \quad V(2t_r)=\frac{1}{C}\int_0^{2tr} I(t)\,dt+V(0)$$

with $Q_{Pulse}=\int_0^{t_r} I\,dt+\int_{t_r}^{2t_r} I\,dt=I_{Peak}\,t_r$, $I_{Peak}=\frac{t_{cycle}}{t_r}\frac{I_{DC\,demand}}{3}$

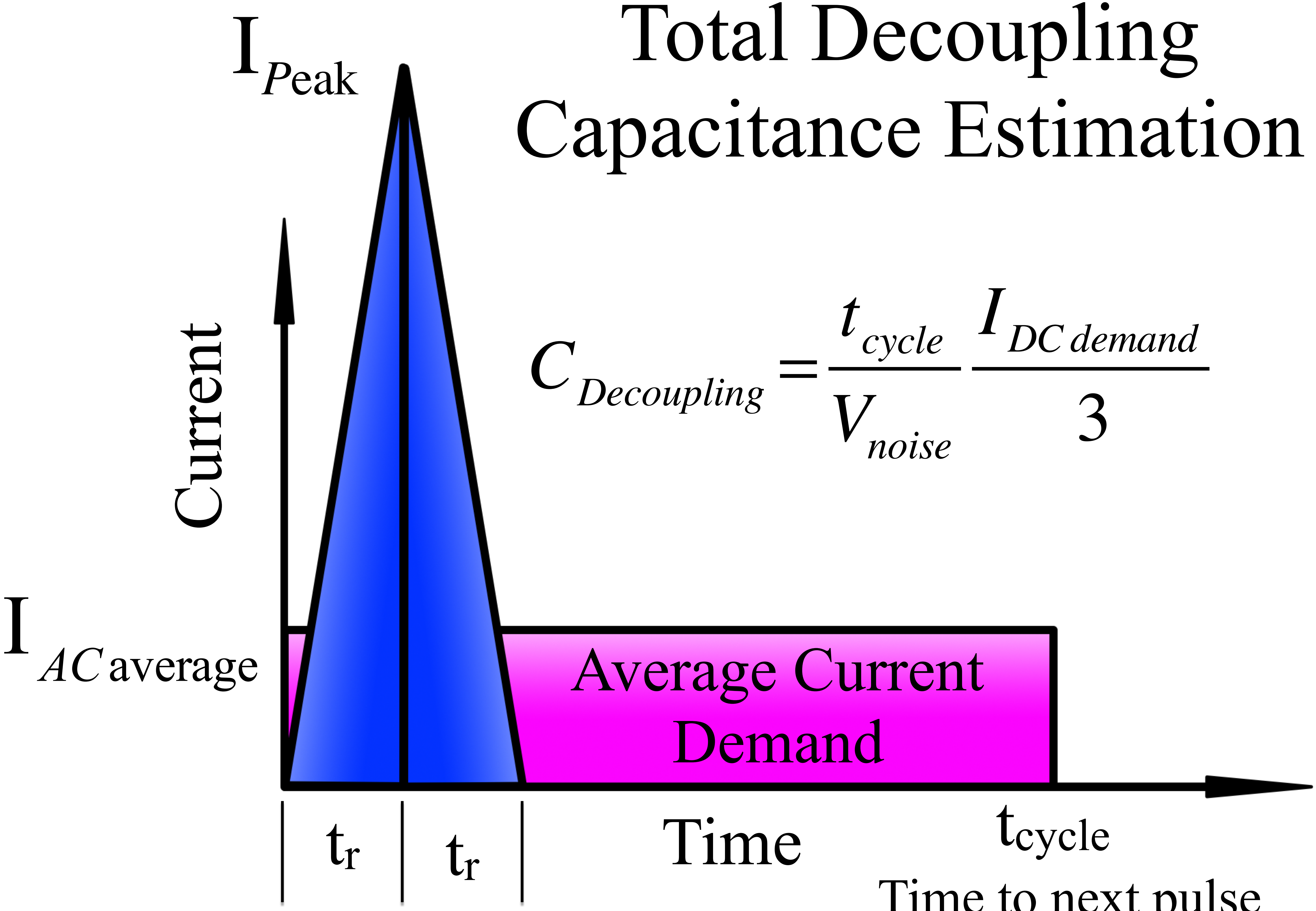
$V(2t_r)=V_{DD}-\mathrm{V}_{noise}$ and $V(0)=V_{DD}$ than $V_{DD}-\mathrm{V}_{noise}=\frac{-Q_{Pulse}}{C}+V_{DD}$

with V_{noise} specified by the requirements, than $\mathrm{V}_{noise}=\frac{Q_{Pulse}}{C}$

$$C_{Decoupling}=\frac{t_{cycle}}{V_{noise}}\frac{I_{DC\,demand}}{3}$$

Total Decoupling Capacitance Estimation

$$C_{Decoupling} = \frac{t_{cycle}}{V_{noise}} \frac{I_{DC\,demand}}{3}$$



Total Decoupling Capacitance Estimation

$$C_{Decoupling} = \frac{t_{cycle}}{V_{noise}} \frac{I_{DC\,demand}}{3}$$

If physical limits do not allow compliance with this value, change the design.

Distance to Decoupling Capacitance Estimation

We consider the pesky slow speed of light.

$$v = \frac{1}{\sqrt{\mu \varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \qquad t_{capacitor} = \frac{t_{cycle}}{20}$$

then $$d_{capacitor} = t_{capacitor}\, v = \frac{t_{capacitor}}{\sqrt{\mu \varepsilon}} = t_{capacitor} \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

$$d_{capacitor} = \frac{t_{cycle}}{20} \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

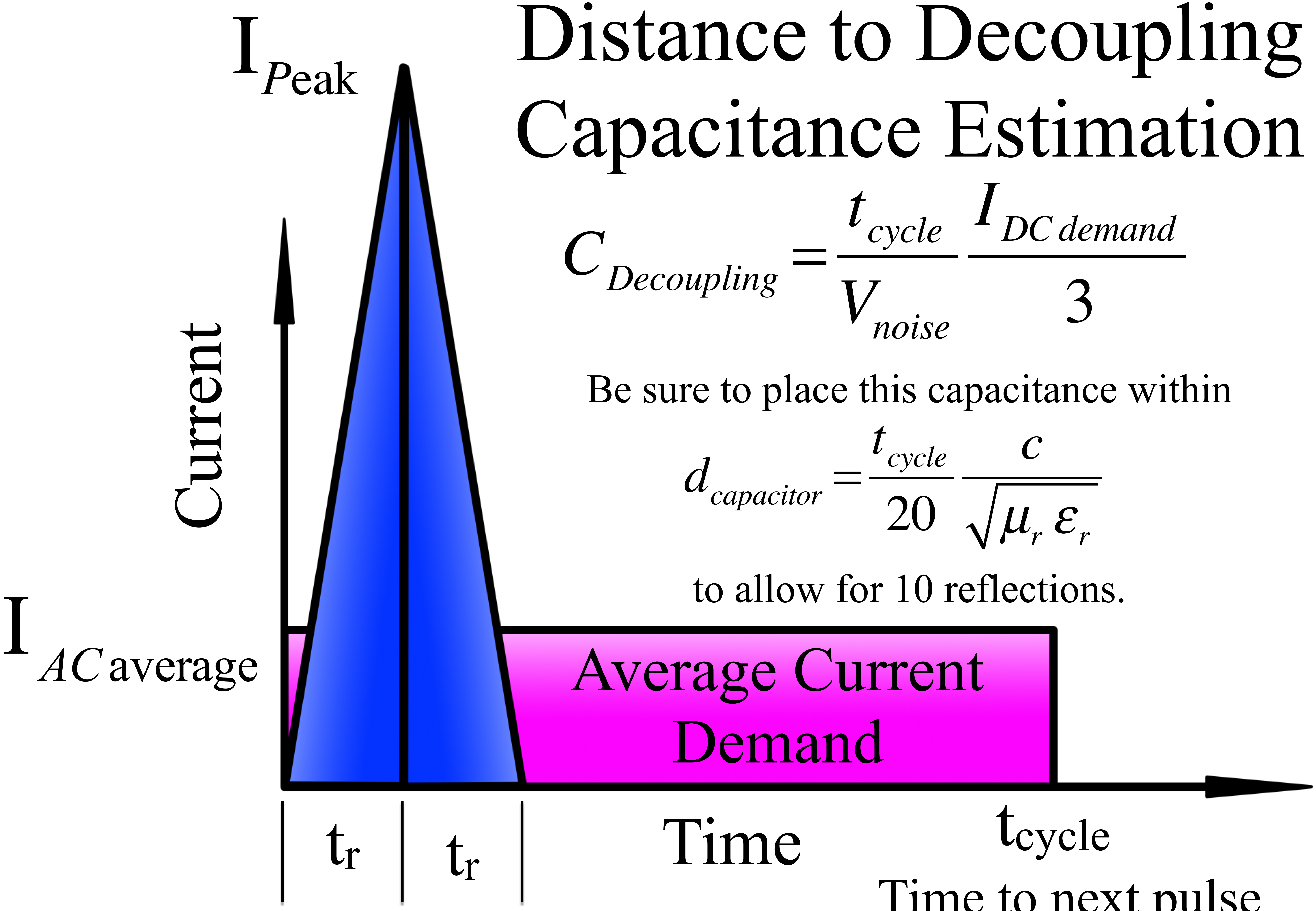
Distance to Decoupling Capacitance Estimation

$$C_{Decoupling} = \frac{t_{cycle}}{V_{noise}} \frac{I_{DC\,demand}}{3}$$

Be sure to place this capacitance within

$$d_{capacitor} = \frac{t_{cycle}}{20} \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

to allow for 10 reflections.



Distance to Decoupling Capacitance Estimation

Be sure to place this capacitance within

$$d_{capacitor} = \frac{t_{cycle}}{20} \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

If physical limits do not allow compliance with this value, change the design.

Sizing the Decoupling Capacitor

These equations will provide a minimum capacitance value at a maximum distance.

$$C_{Decoupling} = \frac{t_{cycle}}{V_{noise}} \frac{I_{DC\,demand}}{3}$$

But it is always best to use the biggest capacitor value available within the package size minus one step.

$$d_{capacitor} = \frac{t_{cycle}}{20} \frac{c}{\sqrt{\mu_r \varepsilon_r}}$$

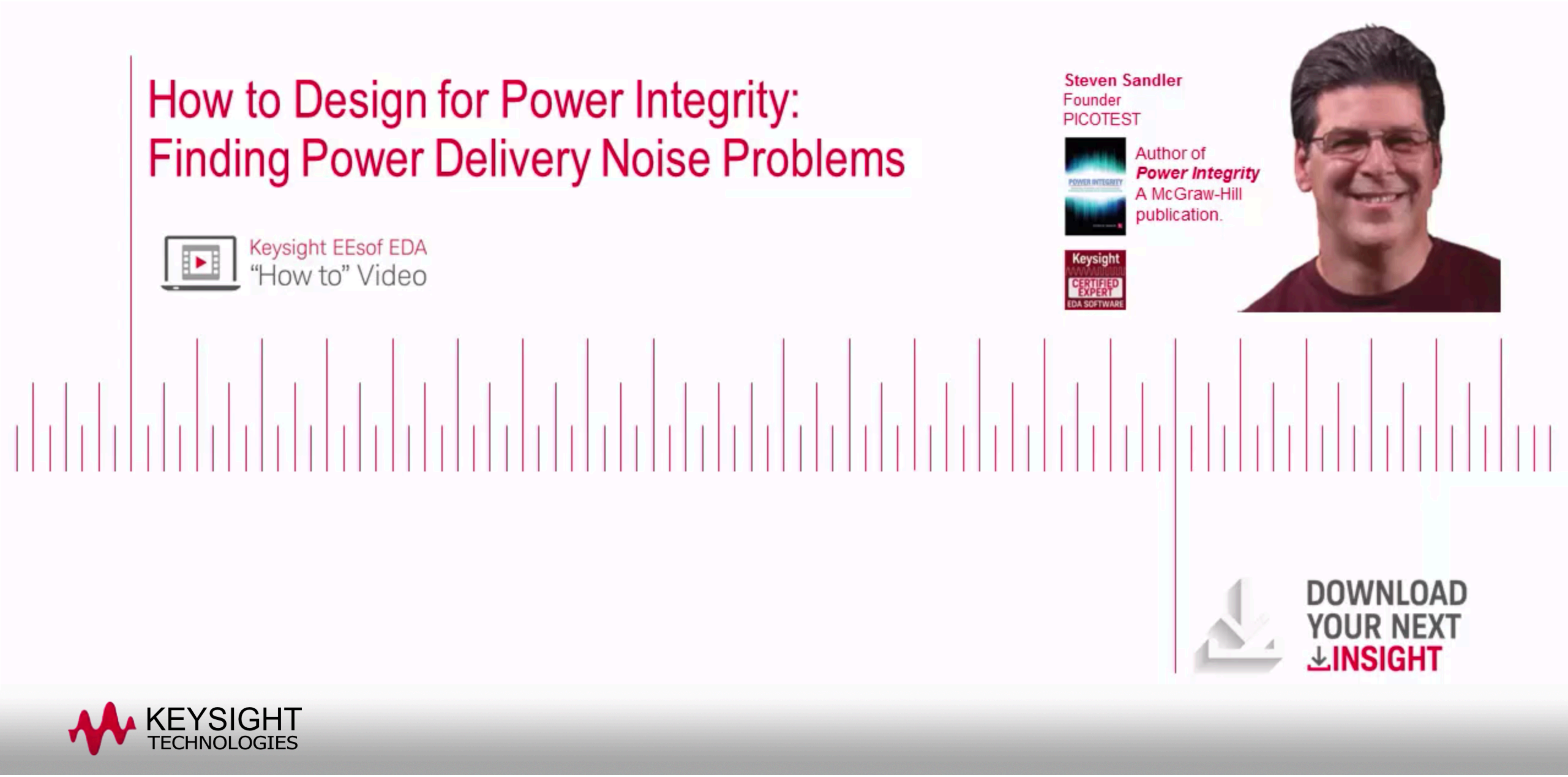
Sometime it Doesn't Work Out

There is inductance between decoupling capacitors and the other capacitors on the rail.

They will resonate at various frequencies.

If any of these frequencies are at a harmonic of the current demand, there will be voltage noise on the capacitors and also on the driven outputs.

Power Plane Target Impedance



How to Design for Power Integrity:
Finding Power Delivery Noise Problems

Keysight EEsof EDA
"How to" Video

Steven Sandler
Founder
PICOTEST

Author of
Power Integrity
A McGraw-Hill
publication.

For further information see Steve Sandler's YouTube Videos or his book:

https://www.youtube.com/watch?v=X_l-aJzVYq8&list=PLtq84kH8xZ9FNXAsf-odoGNe6h5A6D3in
https://www.amazon.com/Power-Integrity-Optimizing-Troubleshooting-Electronics/dp/0071830995/

Power Plane Target Impedance

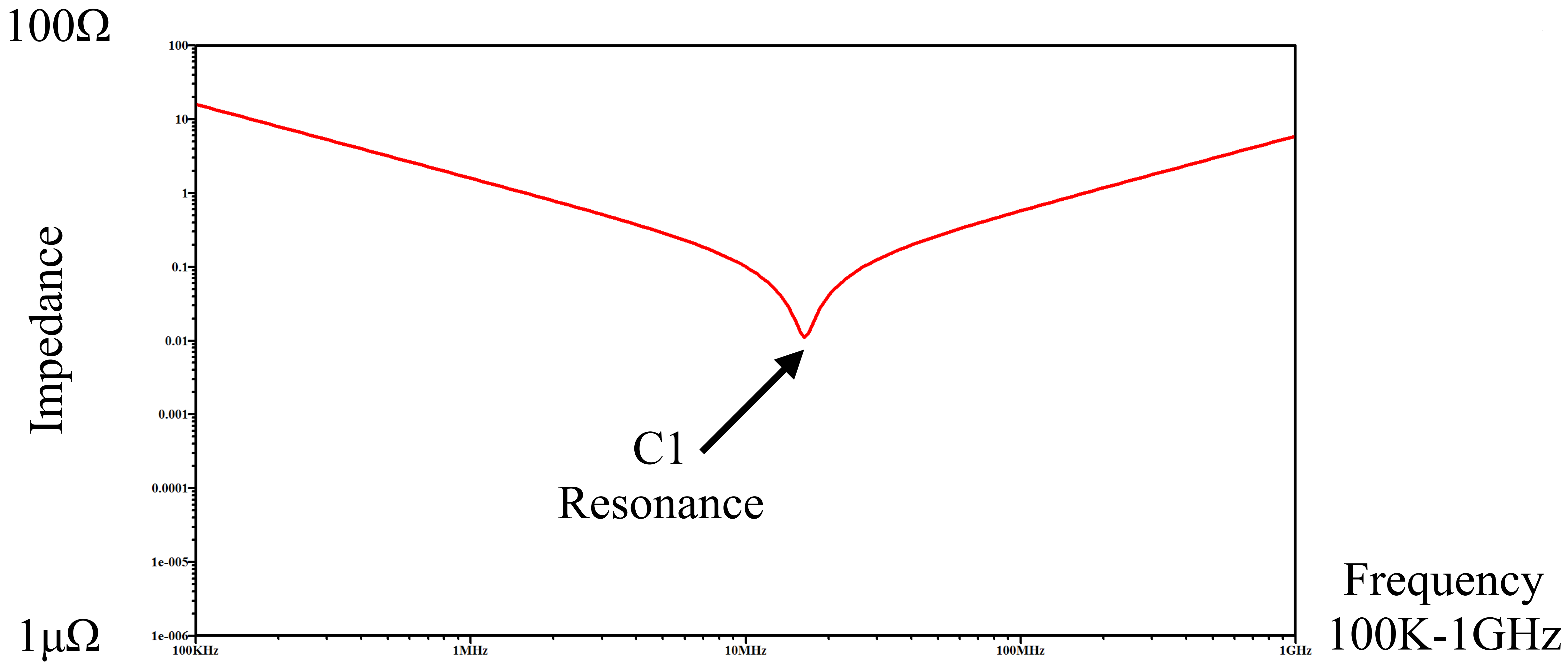
$$Z_{\text{target}} = \frac{\text{Allowed Voltage Ripple}}{\text{Dynamic Current}}$$

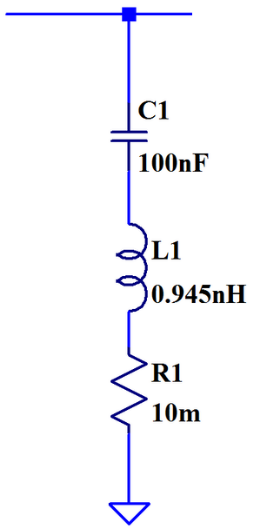
Often we do not know the dynamic current, but we can estimate it as half of the maximum current.

$$Z_{\text{target}} = \frac{\text{Nominal Voltage} \cdot \text{\% Allowed Ripple}}{\text{50\% Maximum Current}}$$

$$Z_{\text{target}} = \frac{5\text{V} \cdot 5\%}{1.5\text{A}\,50\%} = \frac{250\text{mV}}{750\text{mA}} = 333\text{m}\Omega$$

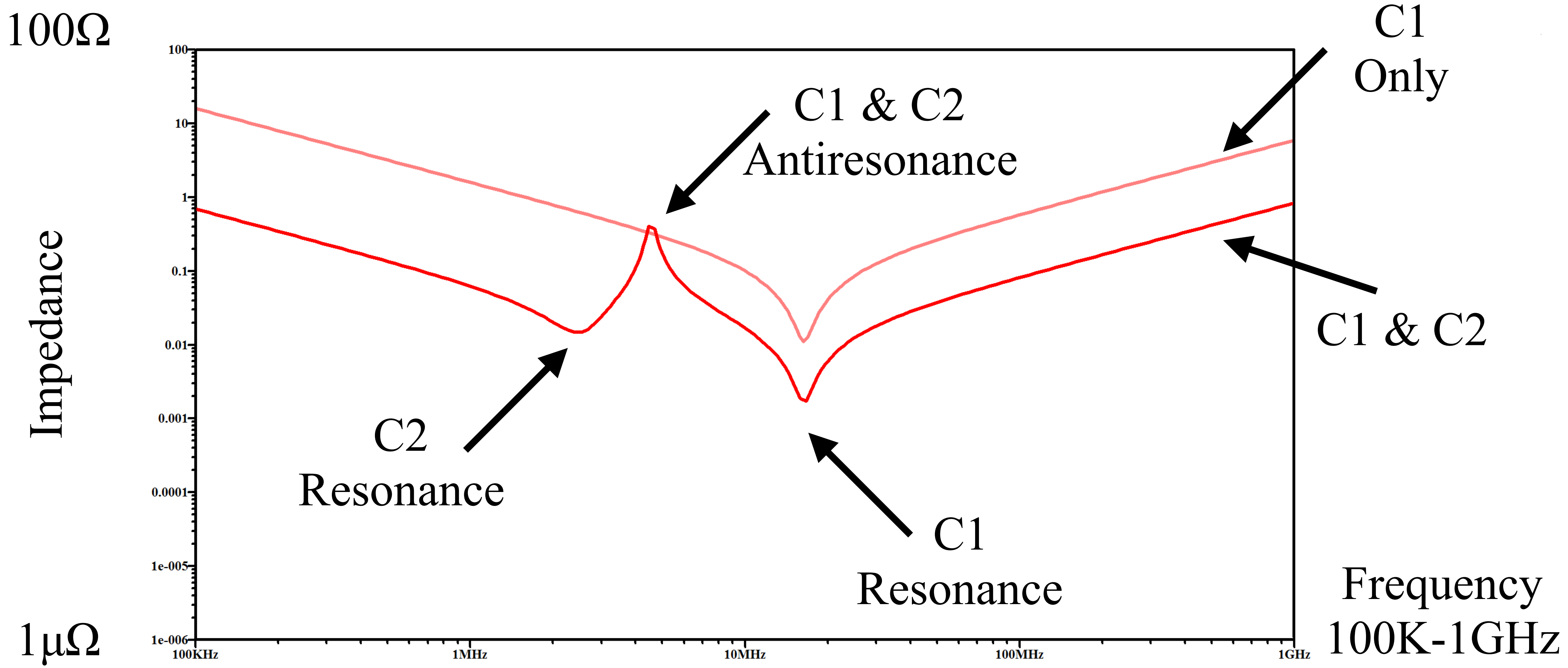
Decoupling Example





A single 100nF capacitor has a self resonance frequency (SRF) of 16.4MHz.

Decoupling Example



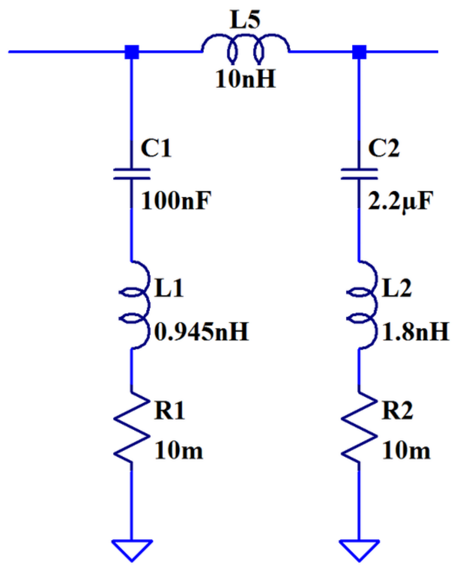
C1 & C2
Antiresonance

C1
Only

C1 & C2

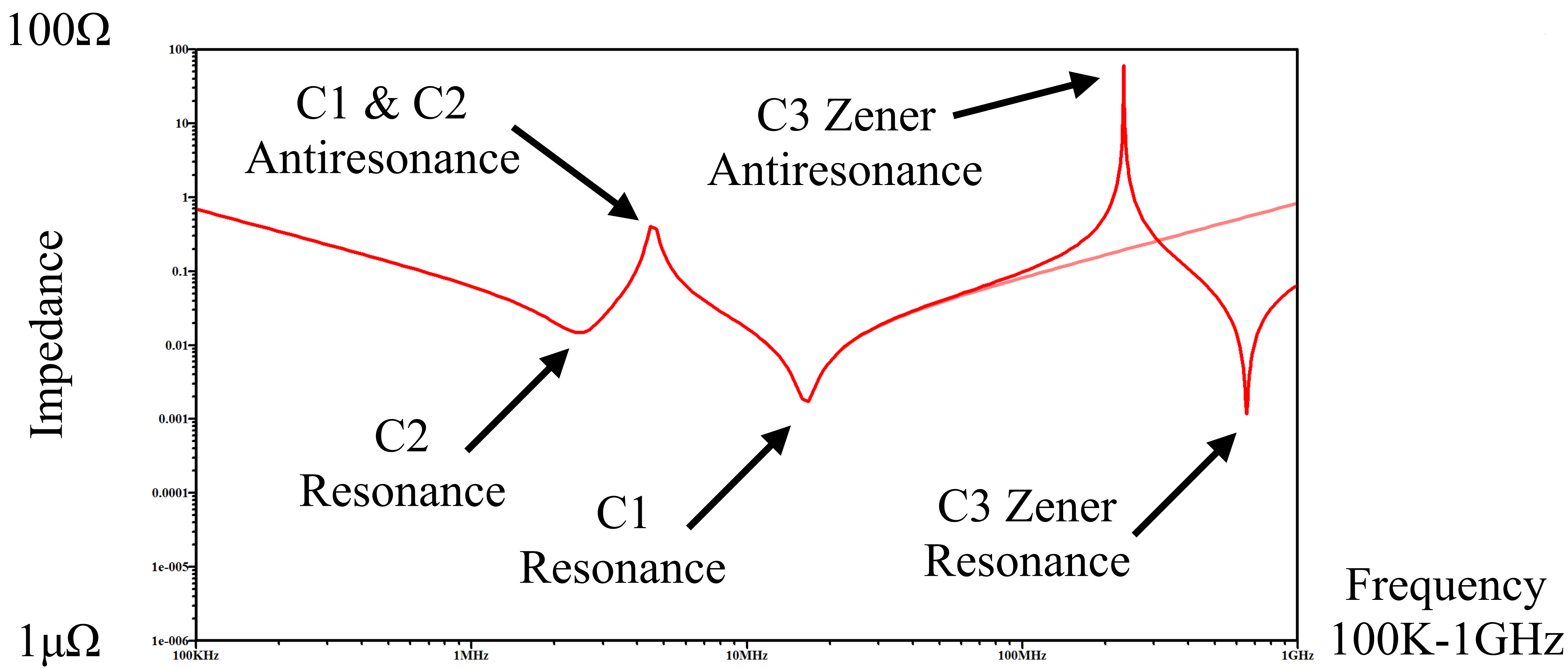
C2
Resonance

C1
Resonance



By adding a 2.2μF capacitor we get a new resonance at 2.5MHz and an antiresonance at 4.5MHz

Decoupling Example



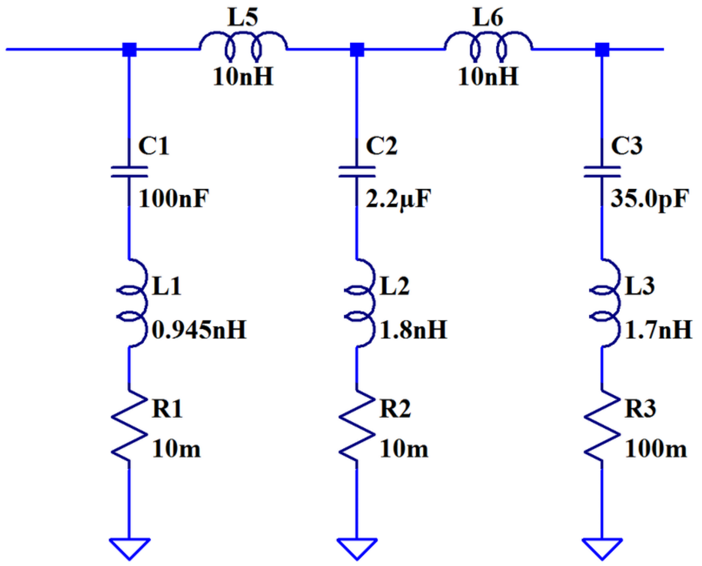
C1 & C2 Antiresonance

C3 Zener Antiresonance

C2 Resonance

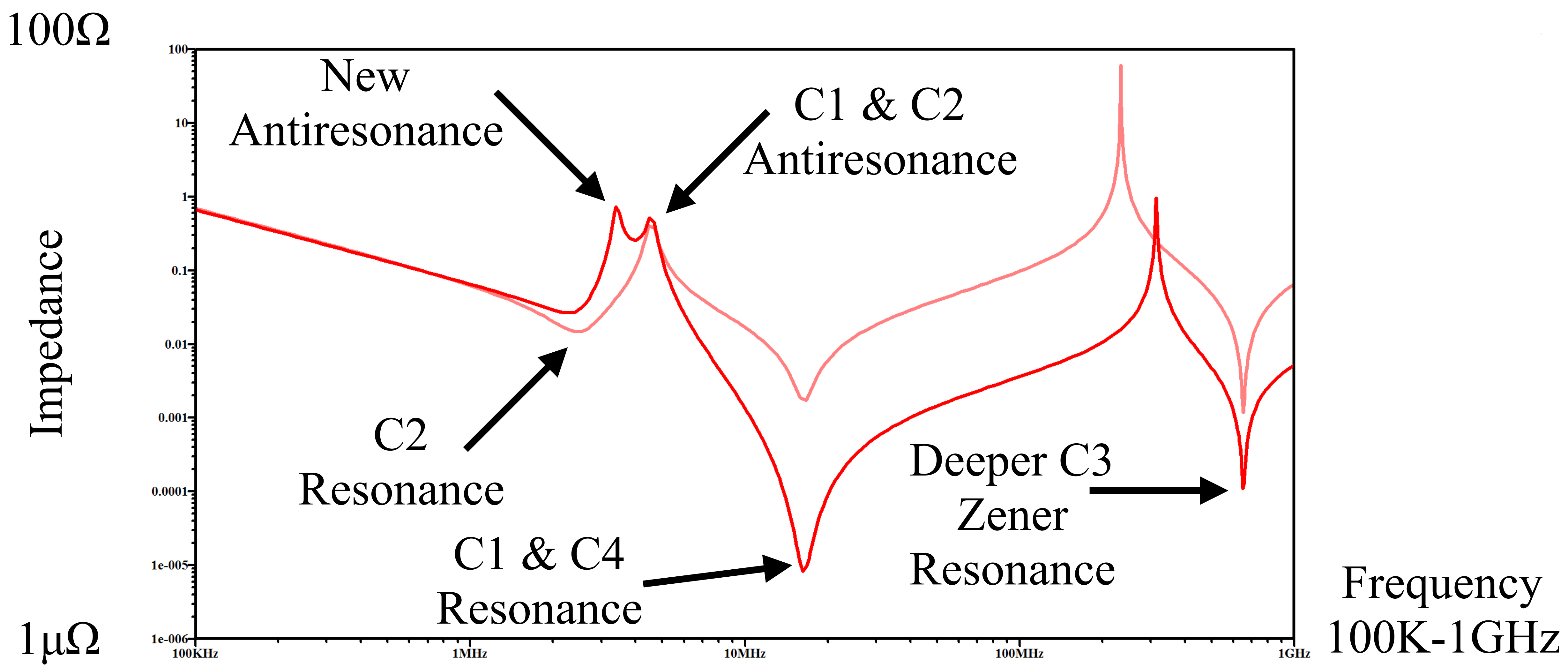
C1 Resonance

C3 Zener Resonance



By adding and an off zener diode we get a new resonance at 652MHz and an antiresonance at 234MHz.

Decoupling Example



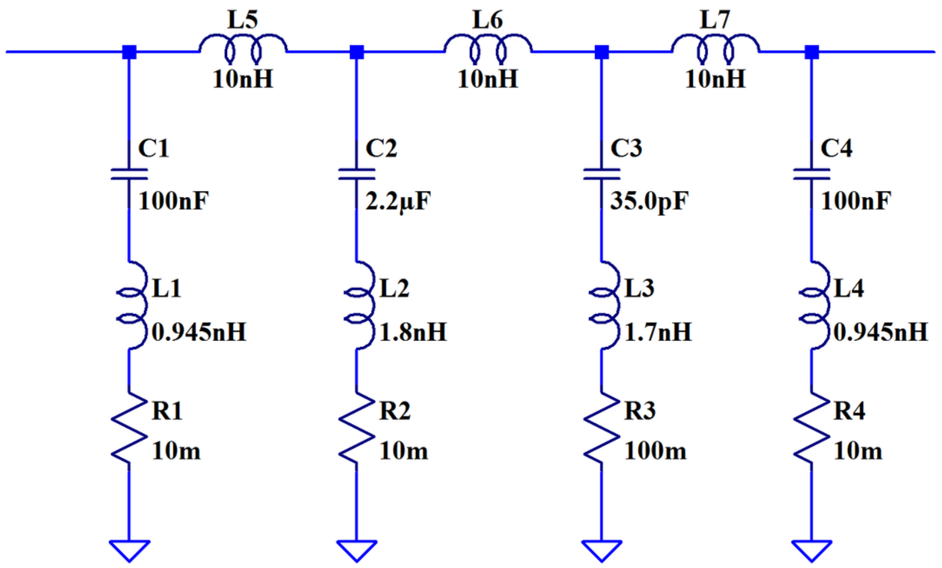
New Antiresonance

C1 & C2 Antiresonance

C2 Resonance

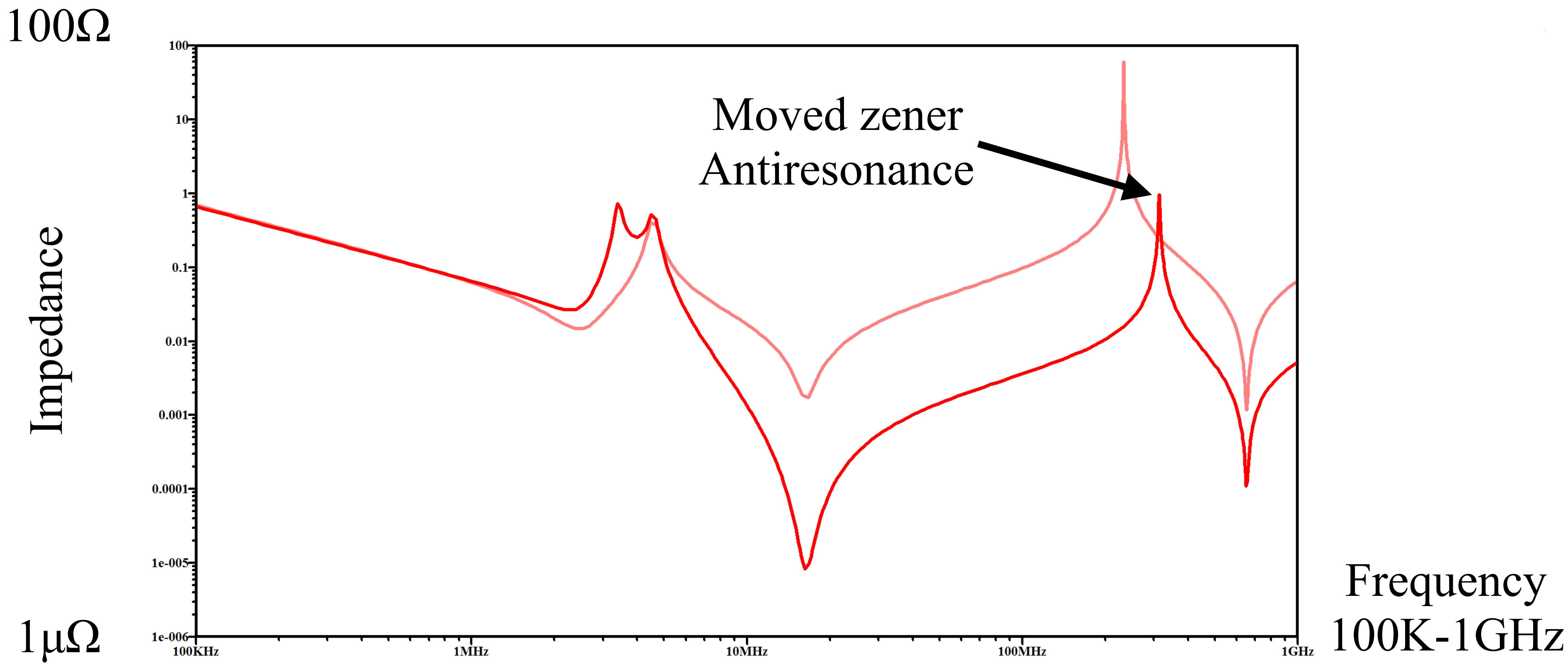
C1 & C4 Resonance

Deeper C3 Zener Resonance

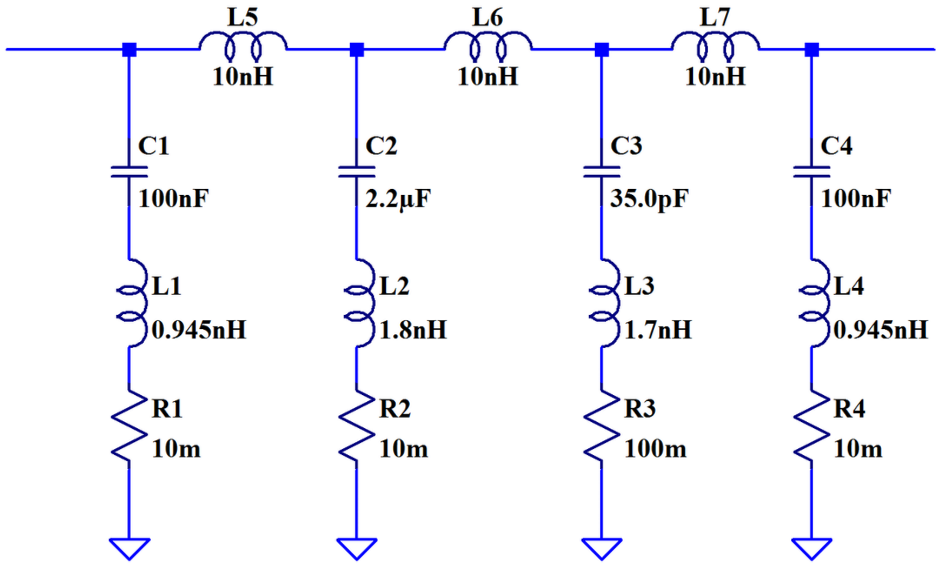


By adding a second 100nF capacitor we get a deeper resonance at 16.4MHz and 652MHz.

Decoupling Example

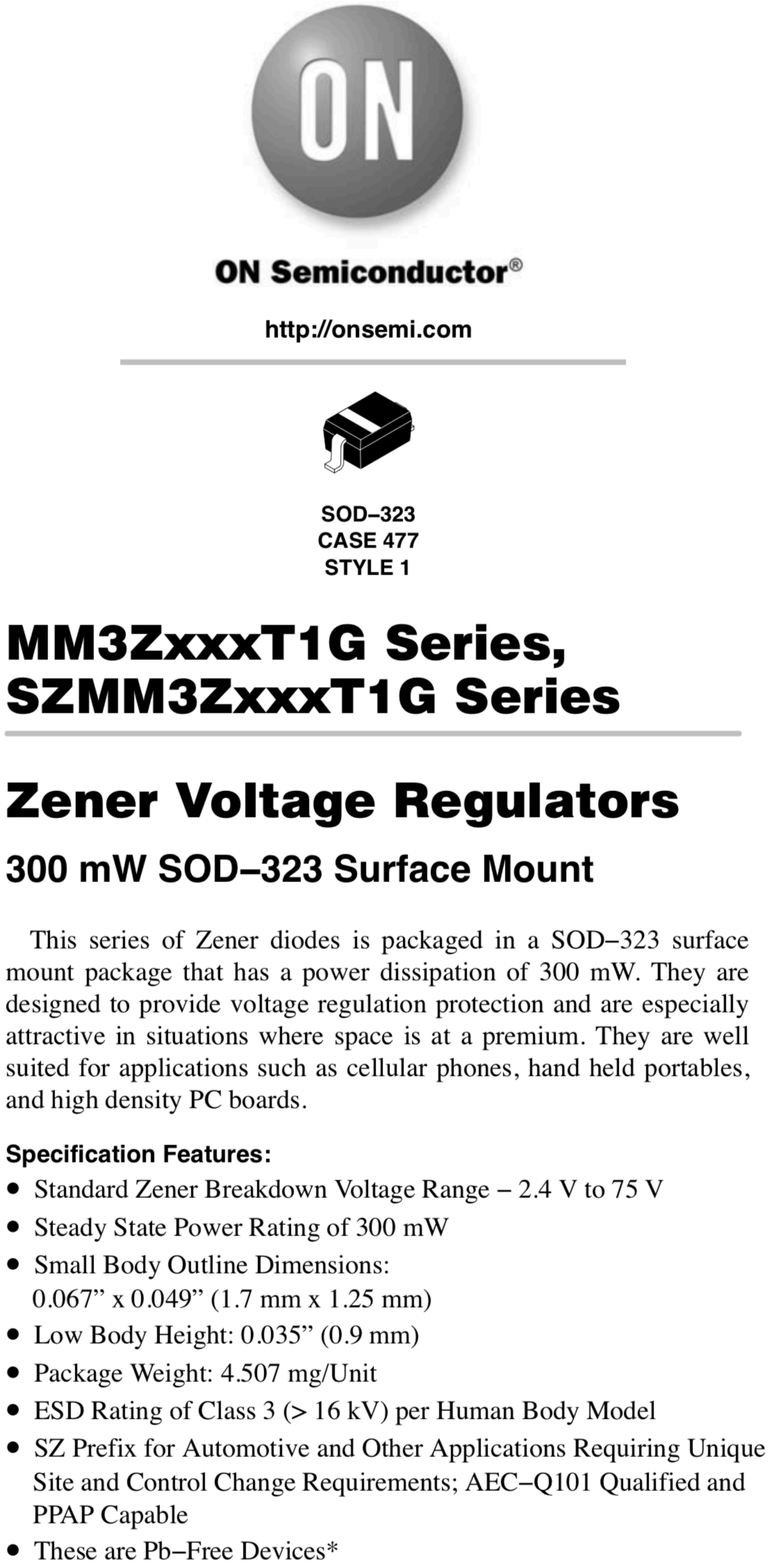


Moved zener Antiresonance



The second 100nF capacitor also moved the zener's antiresonance to 314.5MHz.

Frequencies changes the Impedance



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SOD–323
CASE 477
STYLE 1

MM3ZxxxT1G Series, SZMM3ZxxxT1G Series

Zener Voltage Regulators

300 mW SOD–323 Surface Mount

This series of Zener diodes is packaged in a SOD–323 surface mount package that has a power dissipation of 300 mW. They are designed to provide voltage regulation protection and are especially attractive in situations where space is at a premium. They are well suited for applications such as cellular phones, hand held portables, and high density PC boards.

Specification Features:

- Standard Zener Breakdown Voltage Range – 2.4 V to 75 V
- Steady State Power Rating of 300 mW
- Small Body Outline Dimensions: 0.067” x 0.049” (1.7 mm x 1.25 mm)
- Low Body Height: 0.035” (0.9 mm)
- Package Weight: 4.507 mg/Unit
- ESD Rating of Class 3 (> 16 kV) per Human Body Model
- SZ Prefix for Automotive and Other Applications Requiring Unique Site and Control Change Requirements; AEC−Q101 Qualified and PPAP Capable
- These are Pb−Free Devices*

MM3ZxxxT1G Series, SZMM3ZxxxT1G Series

TYPICAL CHARACTERISTICS

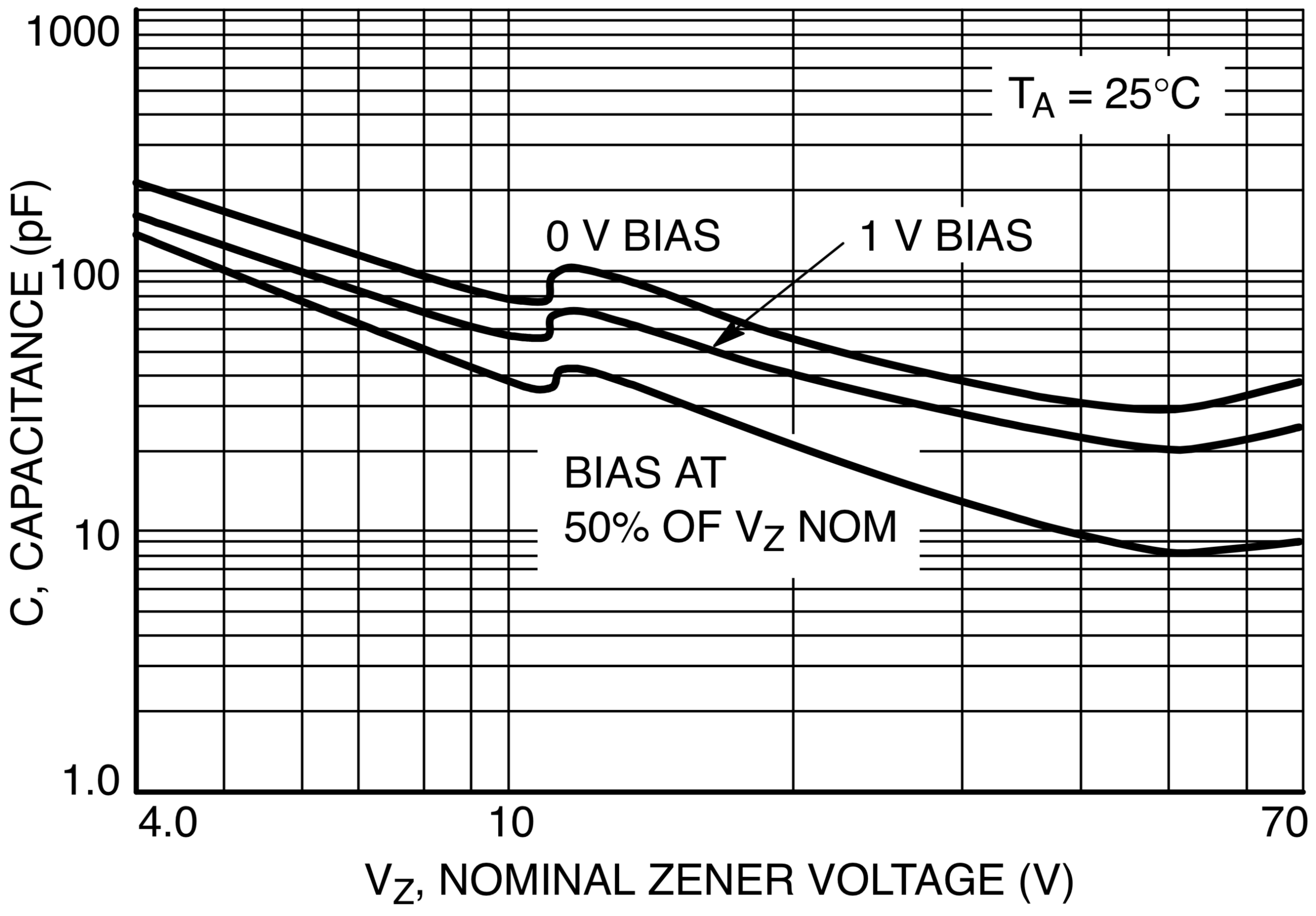
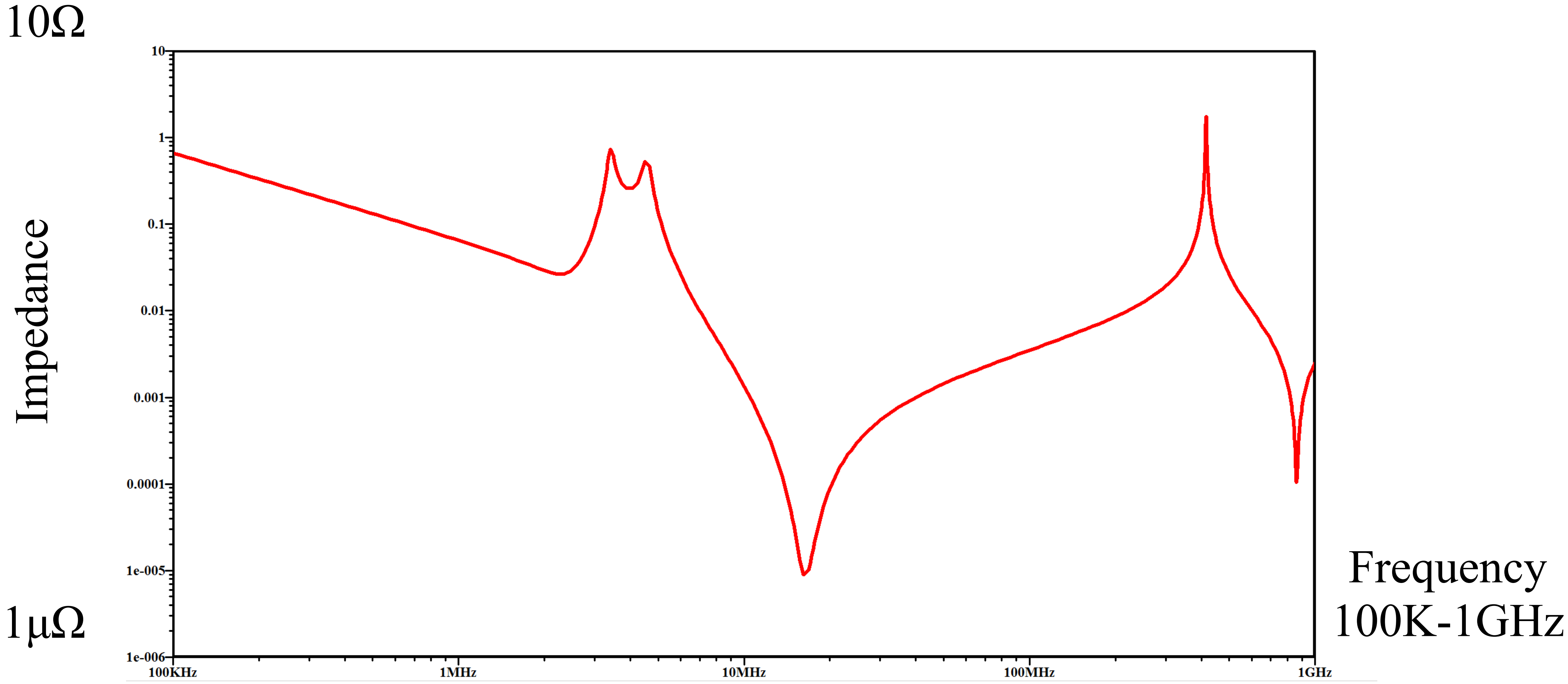


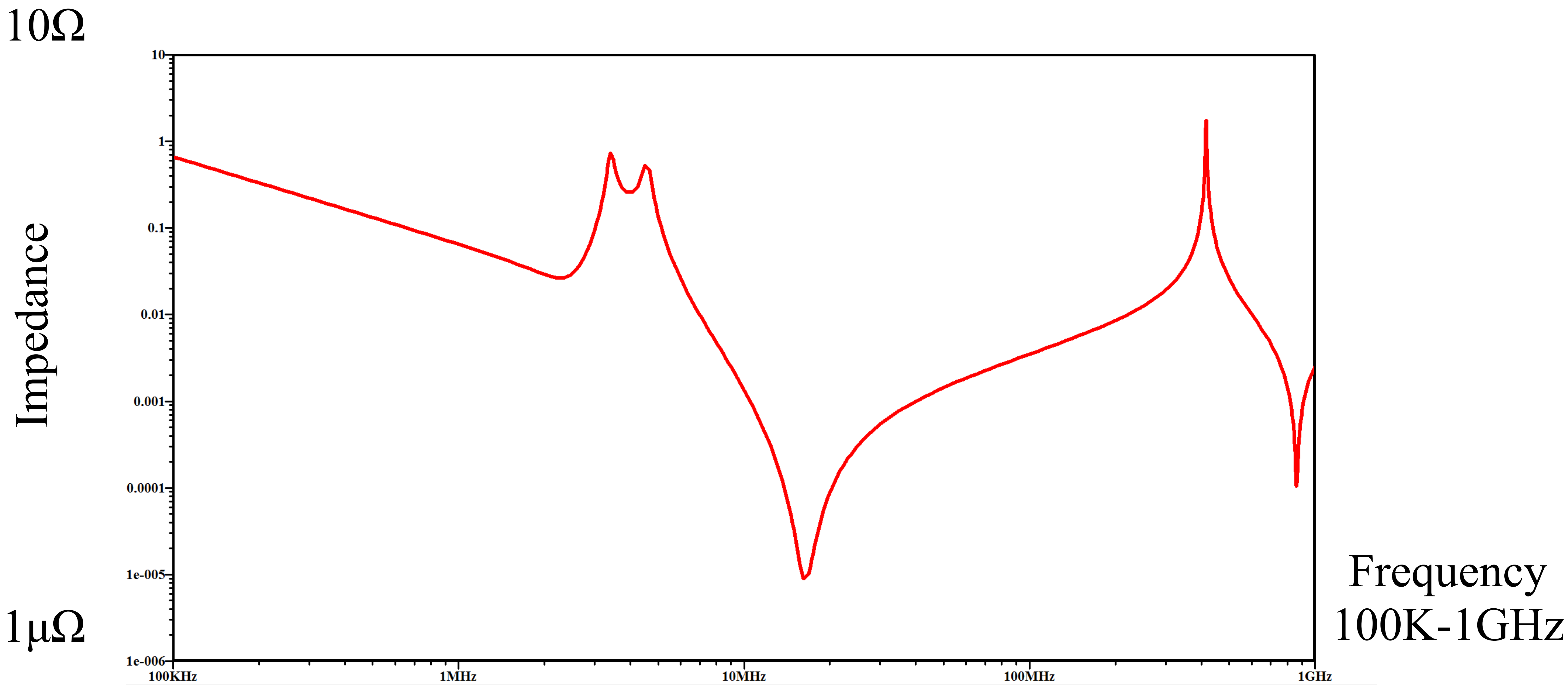
Figure 3. Typical Capacitance

Decoupling Example



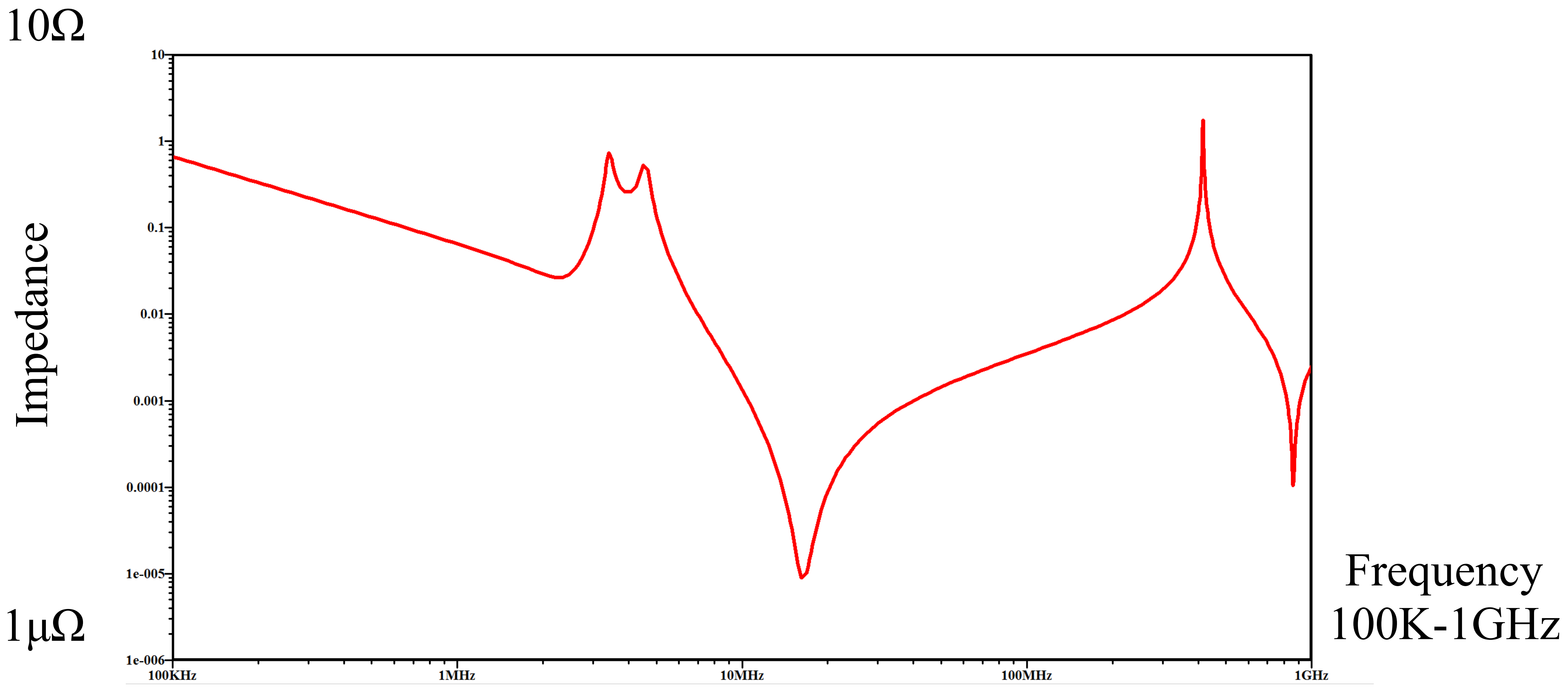
If the zener voltage is changing, the capacitance of the junction will change. This changes the frequency of the zener's antiresonance from 314MHz (off, 35pF) to 416MHz (on, 20pF).

Decoupling Example

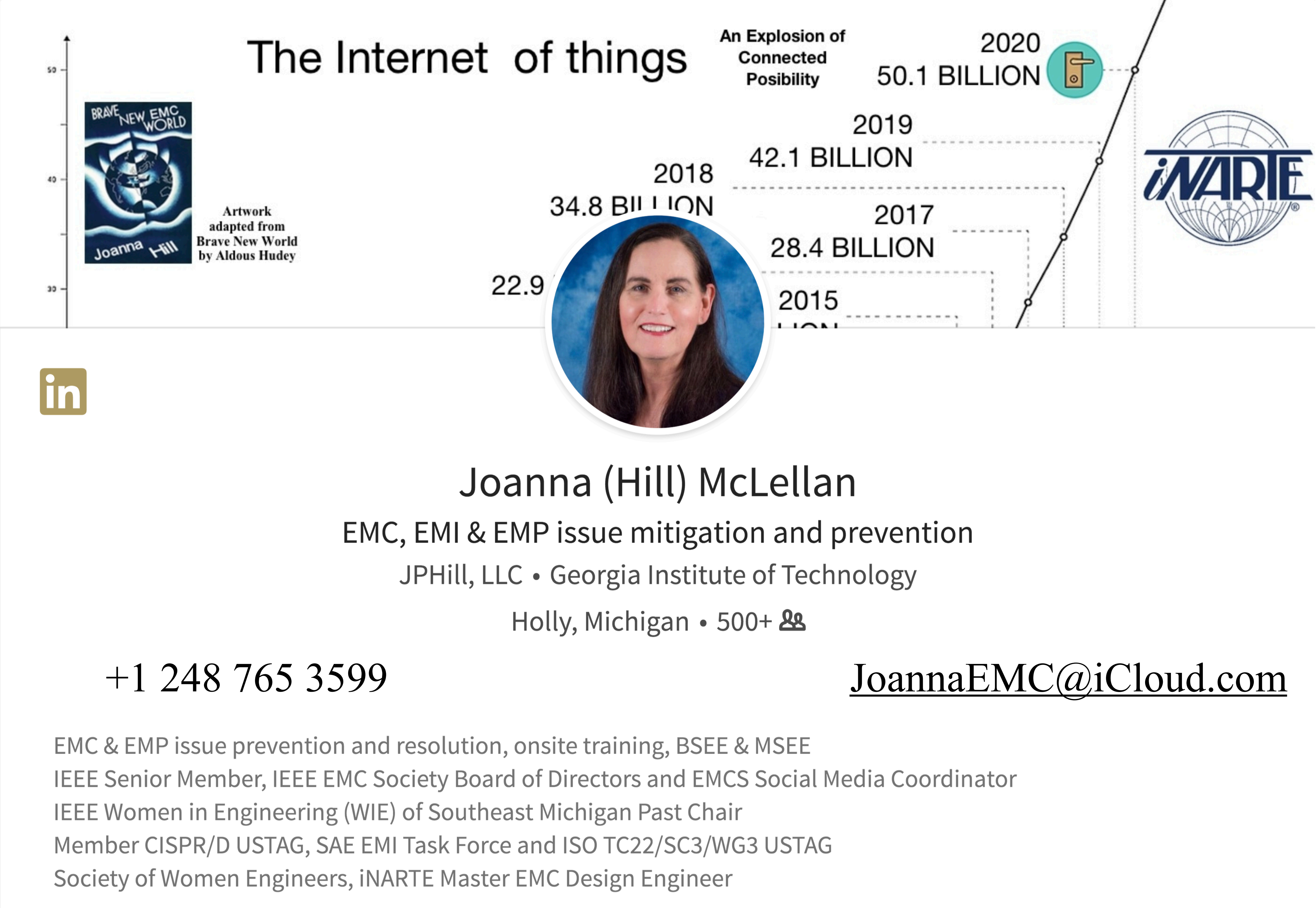


If load current has frequency content at a antiresonance, large voltage ringing will result. This ringing has been known to exceed maximum allowed voltages causing a microprocessor reset. It is also known as rogue waves.

Decoupling Example



If an external RF excitation is applied at an antiresonance frequency, the energy will be absorbed by the circuit and again rogue waves are created.



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Society of Women Engineers, iNARTE Master EMC Design Engineer

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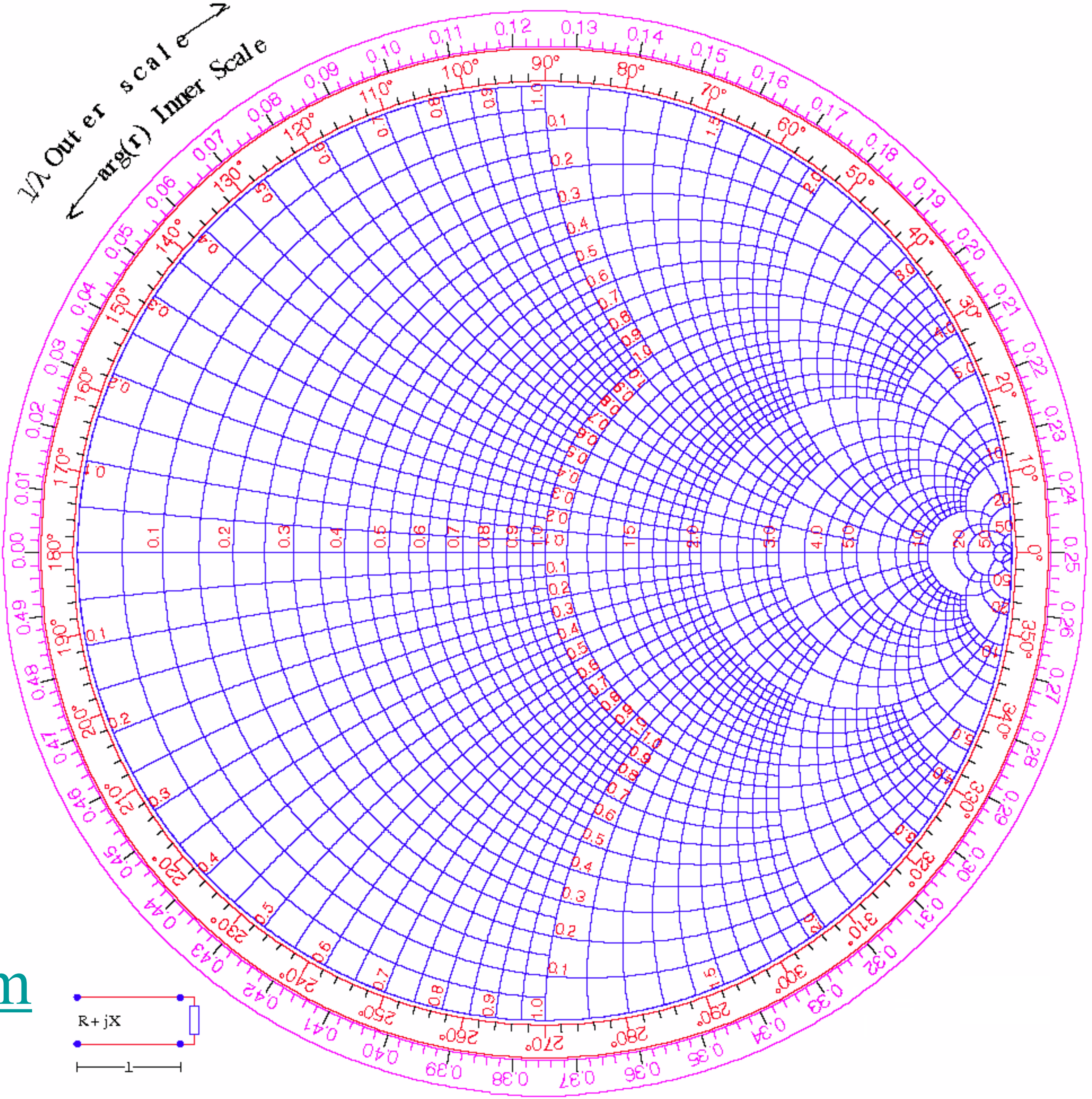

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