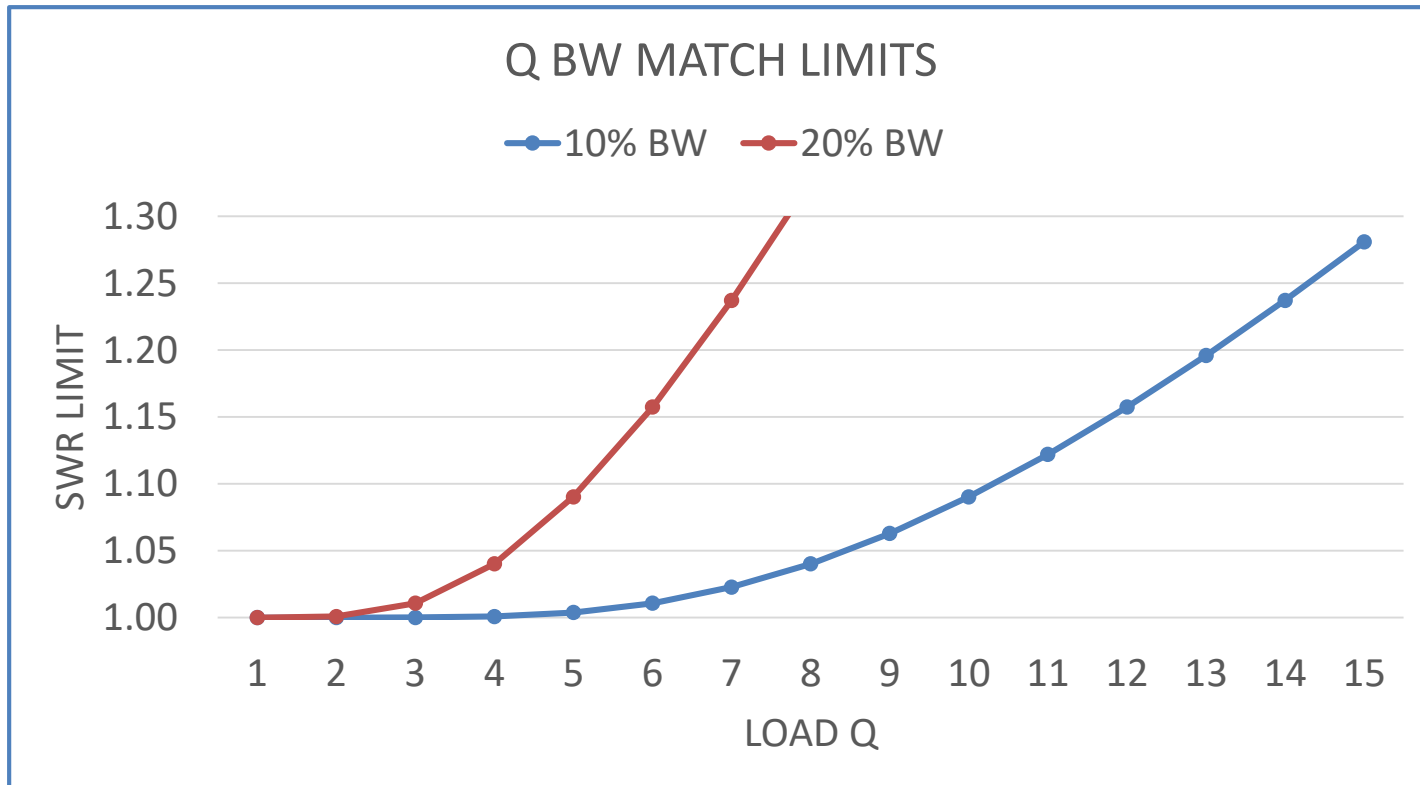


# IMPEDANCE MATCHING TECHNIQUES FOR RF & MICROWAVE CIRCUIT DESIGN

*2019 Microwave Update*

# ACHIEVABLE MATCH DEPENDS ON $Q_L$ AND BW%

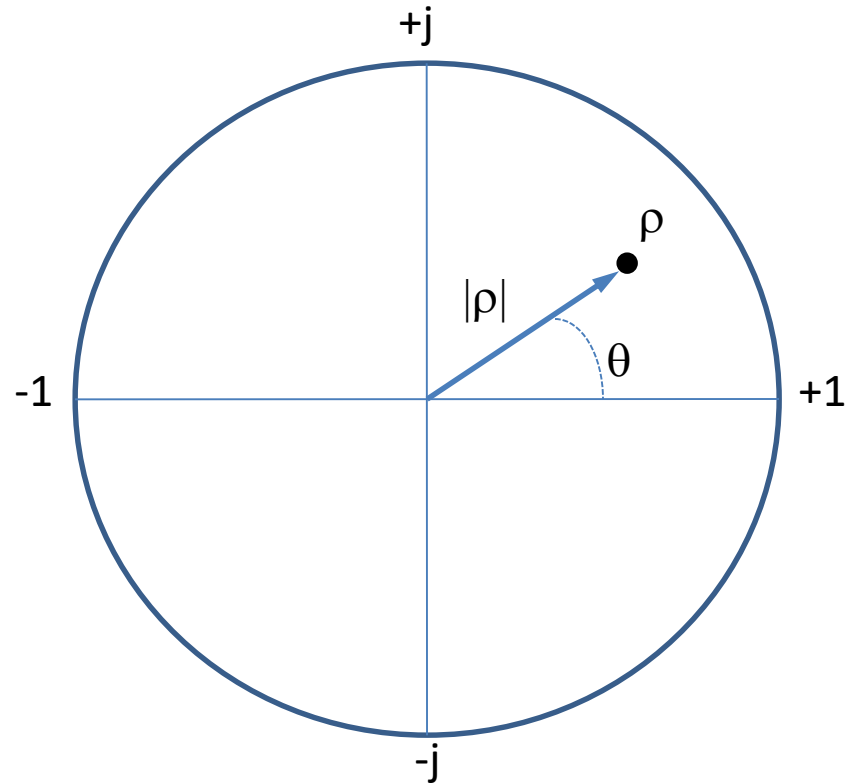
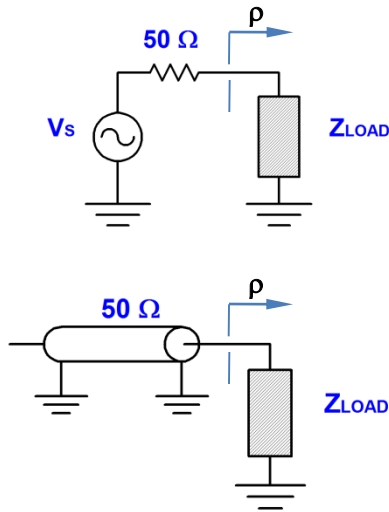


$$\rho \geq e^{\left(\frac{-\pi}{Q*BW}\right)}$$

$$SWR = (1 + \rho)/(1 - \rho)$$

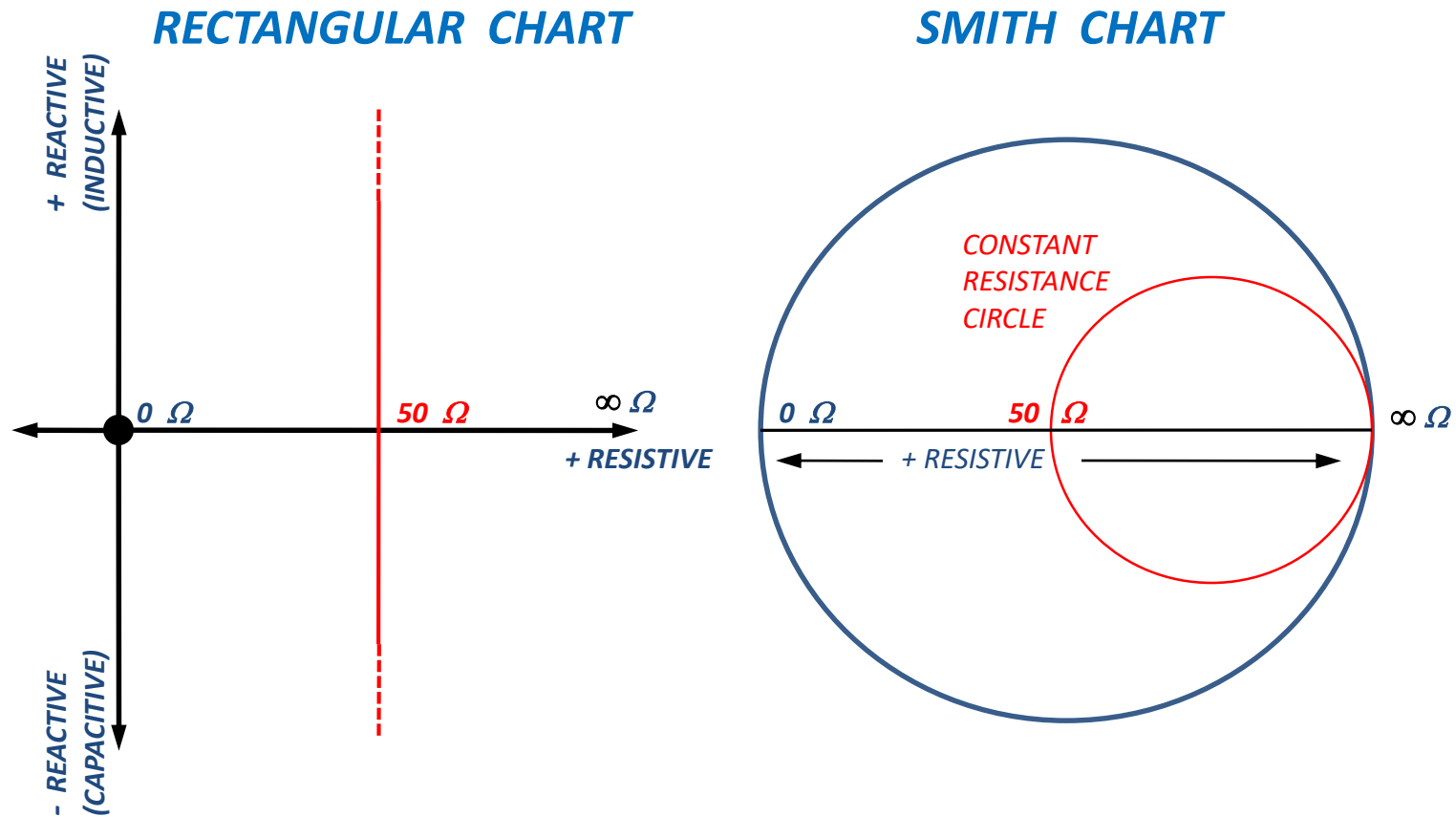
# ORIGIN OF THE SMITH CHART

REFLECTION COEFFICIENT:  $\rho$



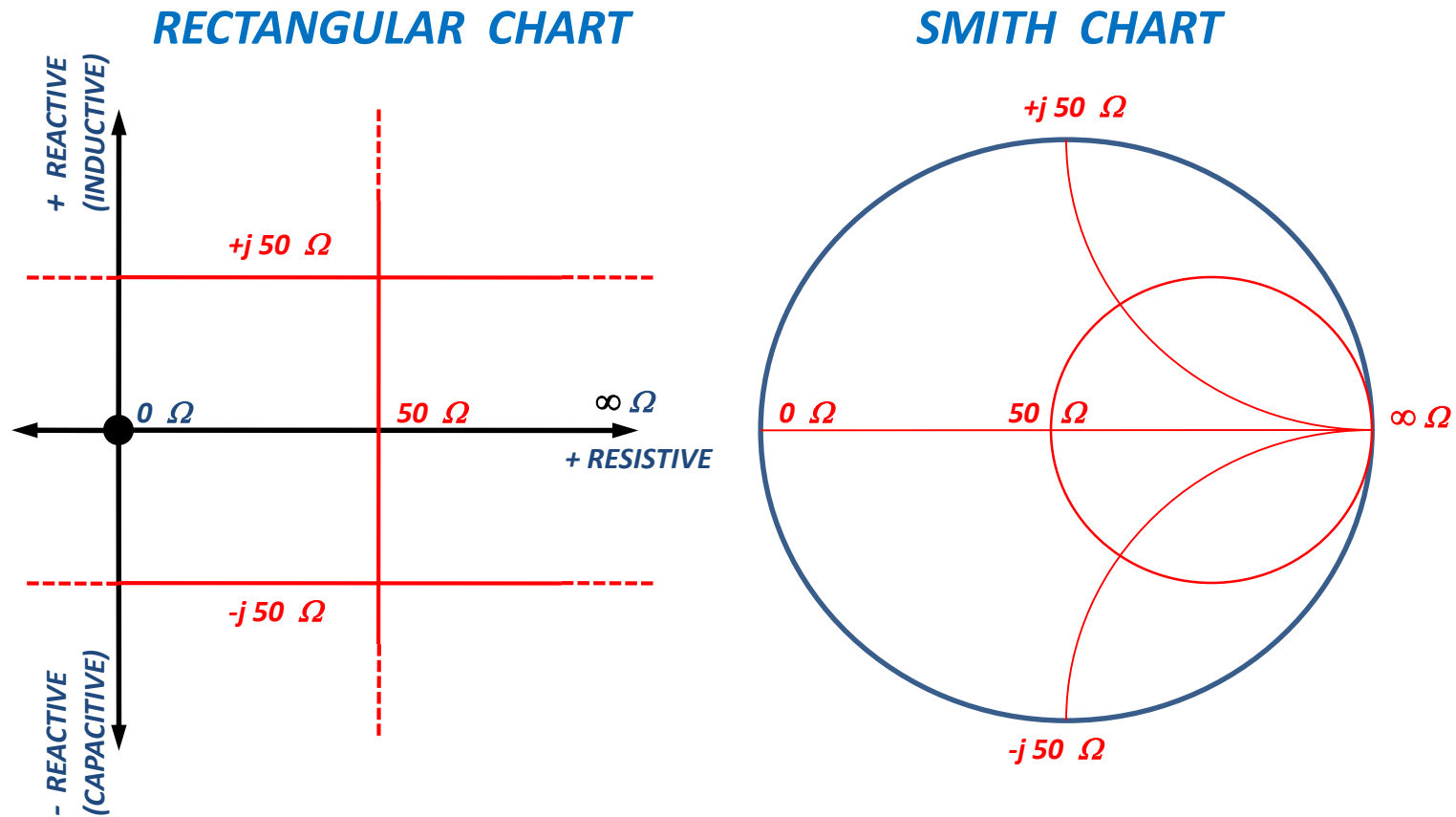
- $\rho$  IS RATIO OF REFLECTED TO FORWARD VOLTAGE AT LOAD
- $\rho$  IS COMPLEX NUMBER: (REAL, IMAGINARY) or (MAGNITUDE, ANGLE)
- $|\rho| = 1.0$  IS MAXIMUM POSSIBLE WITH PASSIVE LOAD (TOTAL REFLECTION)
- $|\rho| = 1.0$  CIRCLE IS OUTER BOUNDARY OF STANDARD SMITH CHART

# IMPEDANCE VIEW – CONSTANT RESISTANCE



- $Z = R + jX$
- IMPEDANCE HAS A **REAL PART** AND AN **IMAGINARY PART**
- IMPEDANCE REPRESENTS A SERIES CONNECTION
- CONSTANT **REAL LINES** BECOME **CIRCLES** ON SMITH CHART

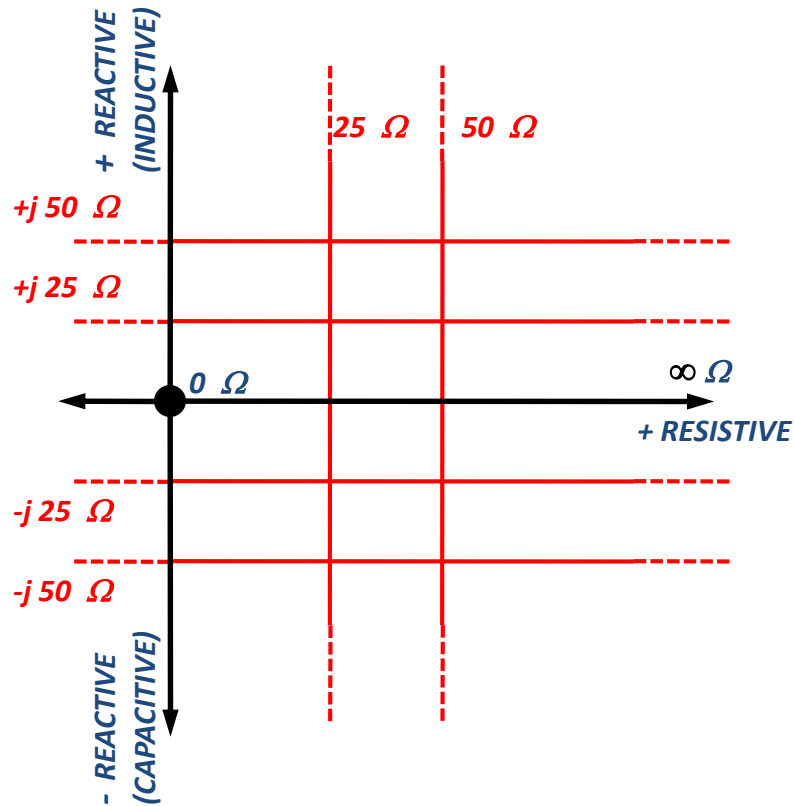
# IMPEDANCE VIEW – CONSTANT REACTANCE



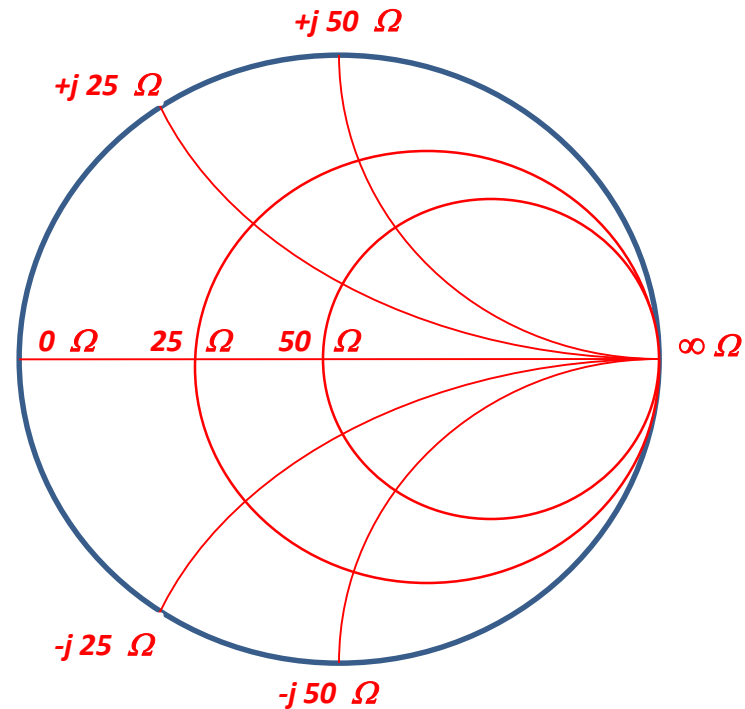
- CONSTANT **REACTANCE LINES** BECOME **ARCS** ON SMITH CHART
- UPPER HALF IS INDUCTIVE
- LOWER HALF IS CAPACITIVE
- POSITIVE REAL IS **INSIDE** THE SMITH UNIT CIRCLE

# IMPEDANCE VIEW

## RECTANGULAR CHART



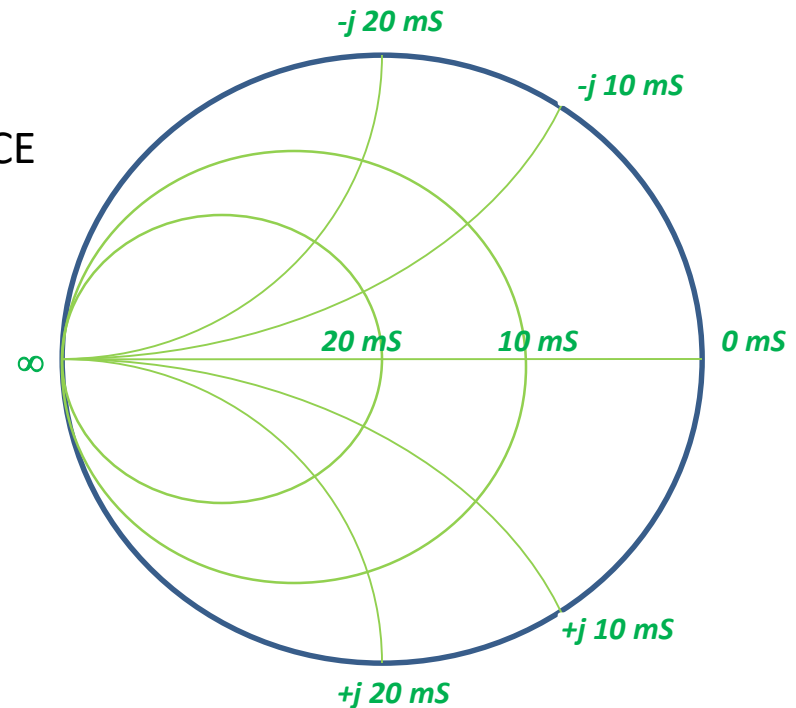
## SMITH CHART



- IMPEDANCE REPRESENTATION OF THE SMITH CHART
- USUALLY IN RED
- LOWER HALF IS CAPACITIVE
- POSITIVE REAL IS **INSIDE** THE SMITH UNIT CIRCLE

# ADMITTANCE VIEW

- $Y = 1/Z = G + jB$
- ADMITTANCE IS RECIPROCAL IMPEDANCE
- ADMITTANCE REPRESENTS A PARALLEL CONNECTION

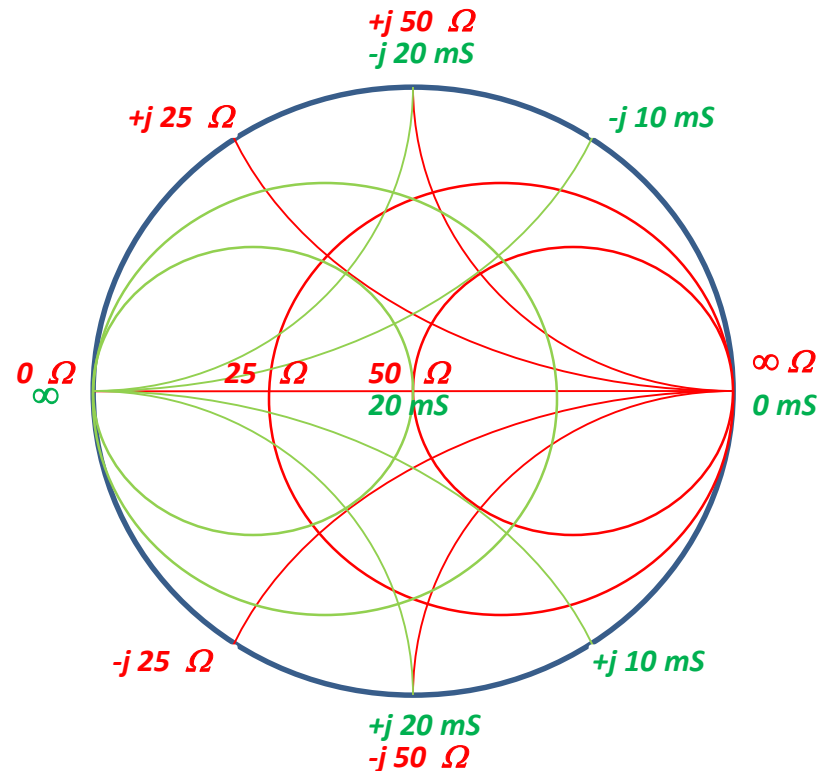


- ADMITTANCE HAS A REAL PART (CONDUCTANCE) AND AN IMAGINARY PART (SUSCEPTANCE)
- CONSTANT CONDUCTANCE IS A CIRCLE ON SMITH CHART
- CONSTANT SUSCEPTANCE IS AN ARC ON SMITH CHART

# OVERLAY SMITH CHART

- BOTH IMPEDANCE AND ADMITTANCE VIEWS OF SAME POINT
- SIMULTANEOUS VIEW OF **SERIES IMPEDANCE** OR **PARALLEL ADMITTANCE**
- THIS VIEW PROVIDES A CONVENIENT WAY TO DESIGN LUMPED ELEMENT MATCHING NETWORKS
- DOWNLOAD A NORMALIZED CHART:

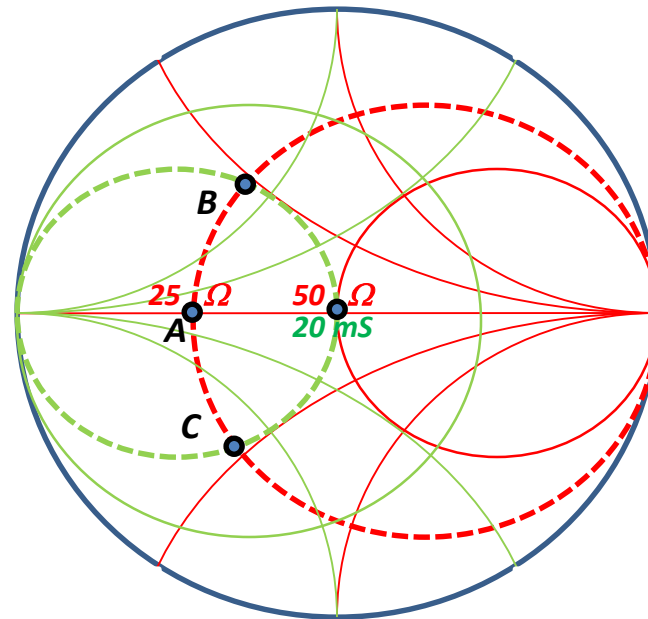
[http://k5tra.net/TechFiles/smith\\_color.pdf](http://k5tra.net/TechFiles/smith_color.pdf)





# LUMPED ELEMENT Z-MATCHING

- A SIMPLE EXAMPLE IS TO MATCH BETWEEN  $25 \Omega$  AND  $50 \Omega$
- FROM THE  $25 \Omega$  POINT (**A**) WE FIRST USE THE IMPEDANCE VIEW TO MOVE TO EITHER POINT **B** OR **C**
- **A**, **B**, and **C** ARE ALL ON THE CONSTANT  $25 \Omega$  CIRCLE
- THE (+) REACTIVE SHIFT FROM **A** TO **B** REPRESENTS A SERIES INDUCTOR
- THE (-) REACTIVE SHIFT FROM **A** TO **C** REPRESENTS A SERIES CAPACITOR
- NOTE THAT BOTH **B** and **C** ARE ON THE  $20 \text{ mS}$  CIRCLE. THIS ALLOWS US TO REACH  $50 \Omega$  WITH A SHUNT ELEMENT



- THROUGH **B** REQUIRES SERIES INDUCTOR AND SHUNT CAPACITOR
- THROUGH **C** REQUIRES SERIES CAPACITOR AND SHUNT INDUCTOR

# L OR C VALUES FROM CHART

- SERIES L OR C ELEMENT VALUES ARE CALCULATED FROM REACTANCE SHIFTS ALONG A CONSTANT RESISTANCE CIRCLE:

- $L_S = \frac{|X_L|}{2\pi F}$  and  $C_S = \frac{1000}{2\pi F |X_C|}$ ,

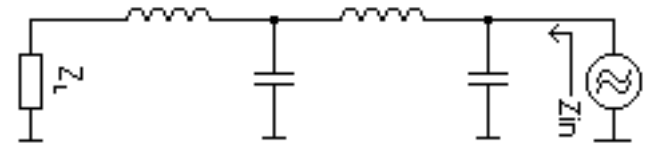
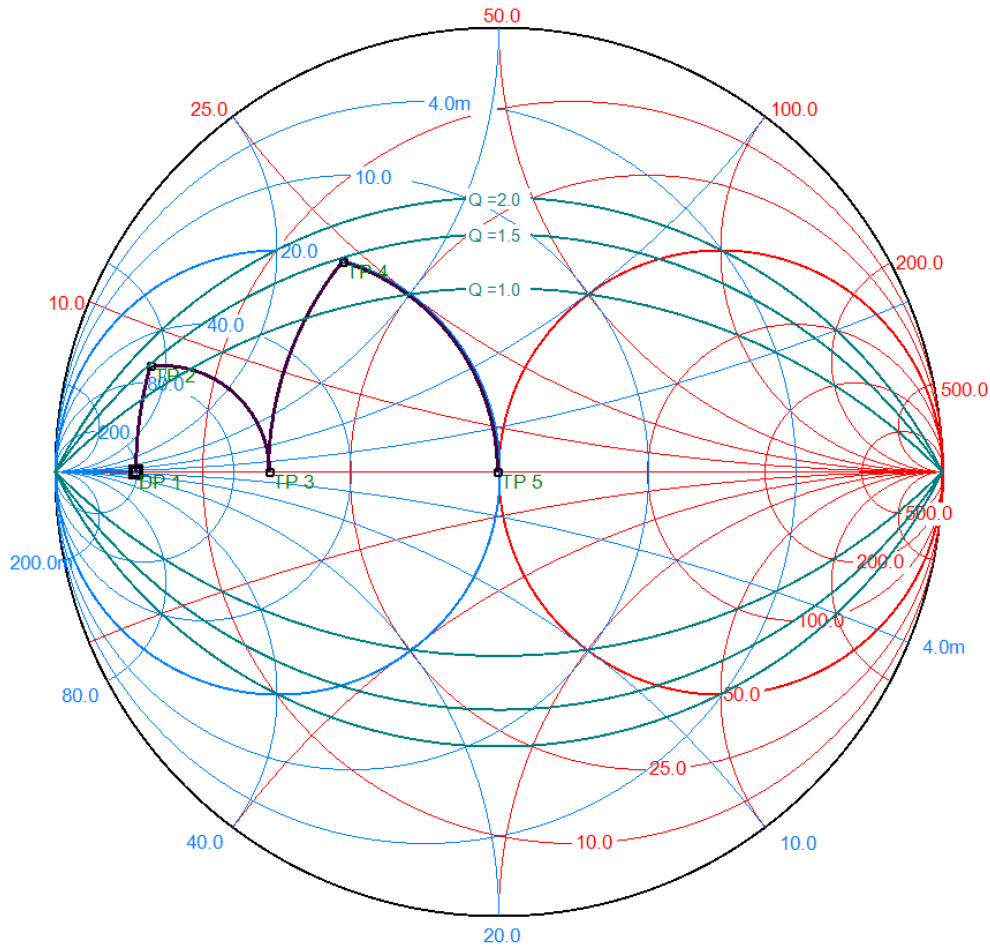
units are L(nH), C(pF), X( $\Omega$ ) and F(GHz).

- SHUNT L OR C ELEMENT VALUES ARE CALCULATED FROM SUSCEPTANCE SHIFT ALONG A CONSTANT CONDUCTANCE CIRCLE:

- $C_P = \frac{|B_C|}{2\pi F}$  and  $L_P = \frac{1000}{2\pi F |B_L|}$ ,

units are L(nH), C(pF), B(mS) and F(GHz).

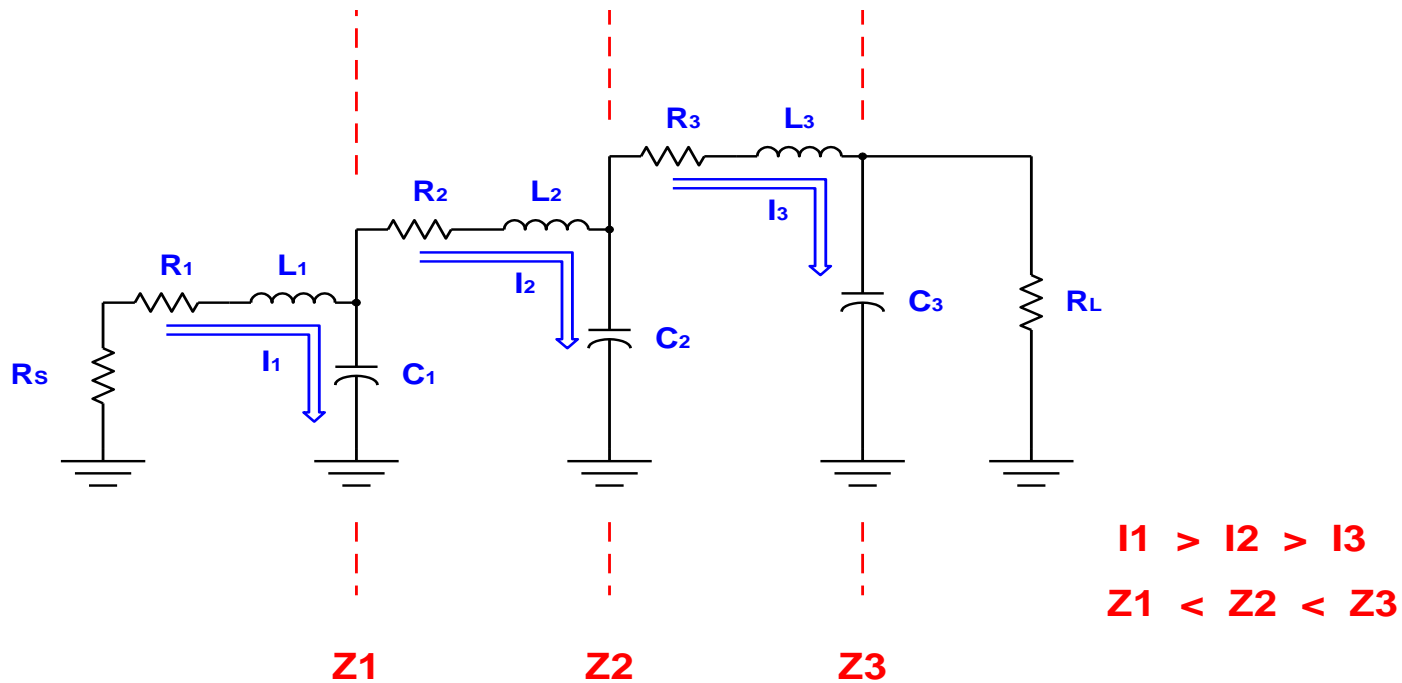
# Ls Cp Ls Cp LOWPASS MATCH



$(5.00 + j0.00) \Omega @ 1.3 \text{ GHz}$   
 900.0pH  
 11.5pF  
 2.9nH  
 3.6pF

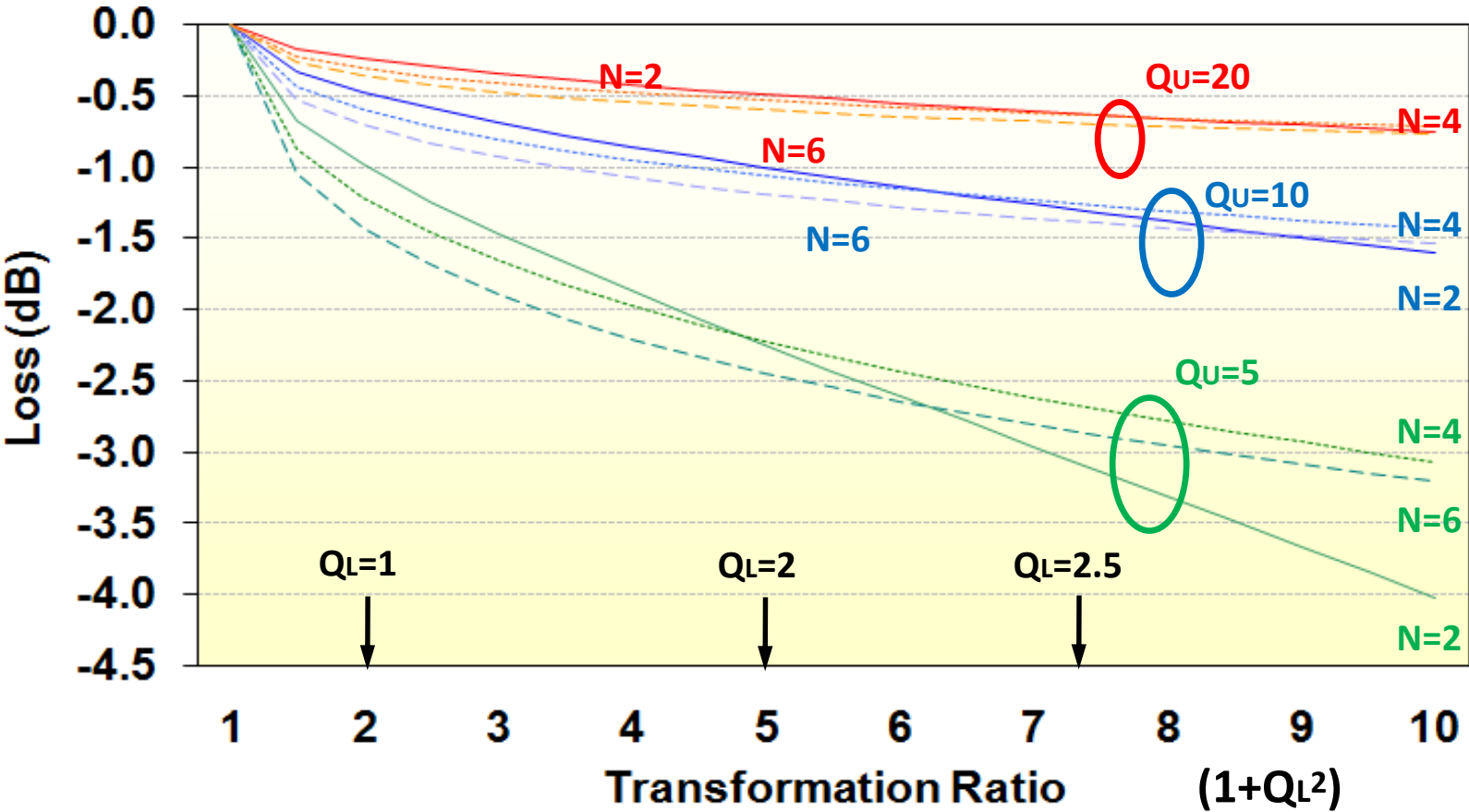


# LOSS CONSIDERATIONS



- POWER TRANSFER OF EACH SECTION IS:  $(Q_U - Q_L) / Q_U$
- $I^2 R$  LOSSES (PRIMARILY IN INDUCTORS) PRODUCE INSERTION LOSS
- Z TRANSFORMATION PER SECTION IS:  $1 + Q_L^2$
- IMPEDANCE TRANSFORMATION REQUIRES:  $Q_L > 1$

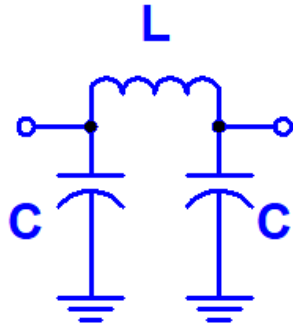
# NUMBER OF ELEMENTS - LOSS TRADE-OFF



# LUMPED DESIGN ON A CIRCUIT BOARD

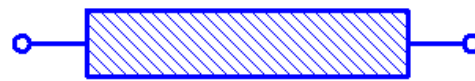
- THERE REALLY ARE NO LUMPED ELEMENTS
  - CHIP CAPACITORS HAVE SERIES INDUCTANCE (and LOSS)
  - CHIP INDUCTORS HAVE DISTRIBUTED CAPACITANCE (SELF RESONANCE)
  - CHIP RESISTORS HAVE SERIES INDUCTANCE AND SHUNT CAPACITANCE
- CIRCUIT BOARD TRACES OVER BACKSIDE GROUND ARE MICROSTRIP TRANSMISSION LINES.
- MICROSTRIP LINES ARE QUASI-TEM; SO THEY CAN BE REPRESENTED AS A SERIES OF INCREMENTAL SERIES L AND SHUNT C ELEMENTS.
- $Z_0 = \sqrt{\frac{L}{C}}$ , WHERE L AND C ARE INCREMENTAL (PER UNIT LENGTH)
- THIN TRACES:
  - HIGH  $Z_0$  TRACES HAVE HIGH L/C
  - USED FOR PRINTED INDUCTORS
- WIDE TRACES:
  - LOW  $Z_0$  TRACES HAVE MORE C
  - PROVIDE SHUNT C (AND SOME SERIES L)

# LC REPRESENTATION OF A SHORT LINE

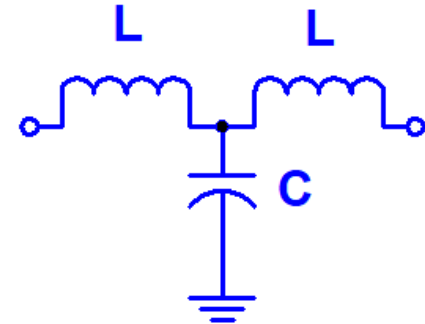


$$X_L = Z_0 \cdot \sin(\beta l)$$

$$X_C = Z_0 \cdot \cot(\beta l / 2)$$



$$Z_0, \quad \theta = \beta l$$



$$X_L = Z_0 \cdot \tan(\beta l / 2)$$

$$X_C = \frac{Z_0}{\sin(\beta l)}$$

- HIGH  $Z_0$  LINES USE THE  $\pi$  CIRCUIT FOR INDUCTOR REPRESENTATION
- THE END CAPACITANCES ARE SMALL WITH HIGH  $Z_0$  LINES
- LOW  $Z_0$  LINES USE THE T CIRCUIT FOR CAPACITOR REPRESENTATION
- THE END INDUCTANCES ARE SMALL WITH LOW  $Z_0$  LINES



# LUMPED EQUIVALENT CALCULATOR

MicroStrip Lumped Equivalent Circuits

Length 300 Analysis 20.00 Width

C(pF)-T 0.4304 Synth. T Synth. Pi 4.3345 L(nH)-Pi

L(nH)-T 2.2388  microns  mils 0.2299 C(pF)-Pi

ApelSoft

Solve Microstrip About

100.36	3.020	0.5755	20.59
Impedance	Effective Dielectric	Relative Velocity	Phase Length (degrees)
4.500	50.00	1.000	1.296
Dielectric Constant	Dielectric Thickness	Conductor Thickness	Frequency (GHz)

- MICROSTRIP ANALYSIS AND SYNTHESIS
- $\pi$  and T EQUIVALENT CIRCUIT CALCULATION
- SELECTABLE UNITS: MILS OR MICRONS

<http://k5tra.net/TechFiles/LumpEquiv.exe>

# SMD CHIP SERIES INDUCTANCE

## SMD SERIES INDUCTANCE

CHIP PKG	DIM (mil <sup>2</sup> )	L(nH)
0402	40x20	0.59
0603	60x30	0.77
0805	80x50	0.84
ATC 100A	55x55	0.55
ATC 100B	110x110	0.77

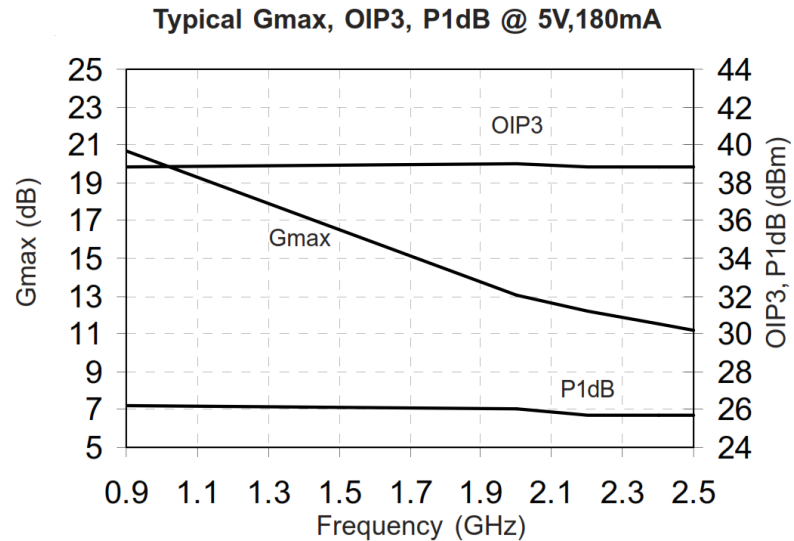
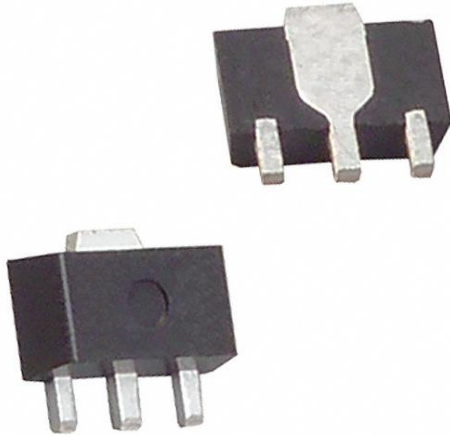
Series Trap

Freq (GHz)	1.296	Harmonics	Fo	2 Fo	3 Fo
Ls (nH)	0.77	Effective Value	1.30	2.59	3.89
Cs (pF)	3.0	Type	3.54 pF	7.75 pF	0.21 nH
			Cap	Cap	Ind
Calculate			Resonant Freq (GHz)	3.31	

<http://k5tra.net/TechFiles/SeriesTrap.exe>

- AN 0603 3 pF CAP ALSO HAS 0.77 nH SERIES INDUCTANCE
- SERIES RESONANT FREQUENCY IS 3.31 GHz
- EFFECTIVE CAPACITANCE IS 3.54 AT 1296 MHz
- EFFECTIVE CAPACITANCE IS 7.75 AT 2<sup>nd</sup> HARMONIC OF 1296 MHz
- EFFECTIVE INDUCTANCE IS 0.21 nH AT 3<sup>rd</sup> HARMONIC OF 1296 MHz

# DESIGN EXAMPLE: SGA-9189 PA DRIVER



- THE SGA-9189 IS A MEDIUM POWER SiGe TRANSISTOR
- > 25 dBm POWER OUTPUT AT  $V_{cc} = +5V$
- SOT-89 PACKAGE
- MANUFACTURER: RFMD

# SGA-9189 TARGET IMPEDANCES

- OPTIMUM EXTERNAL IMPEDANCES:

$$Z_{S\text{OPT}} = 7.1 - j 4.4 \Omega$$

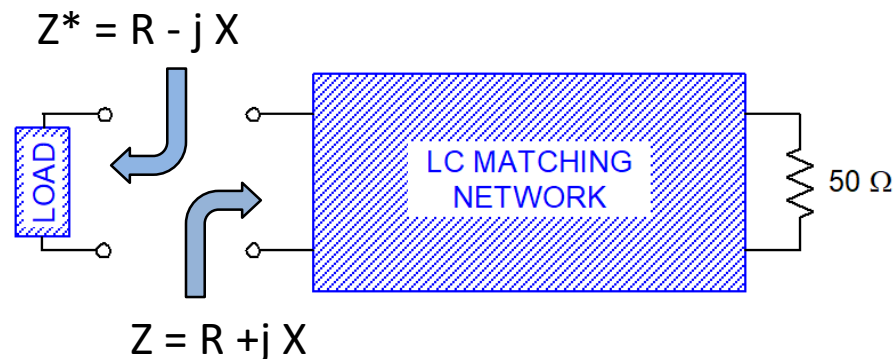
$$Z_{L\text{OPT}} = 18.4 + j 4.1 \Omega$$

- OPTIMUM MATCHING NETWORKS WILL PROVIDE A MATCH TO LOADS THAT ARE COMPLEX CONJUGATE OF THE OPTIMUMS

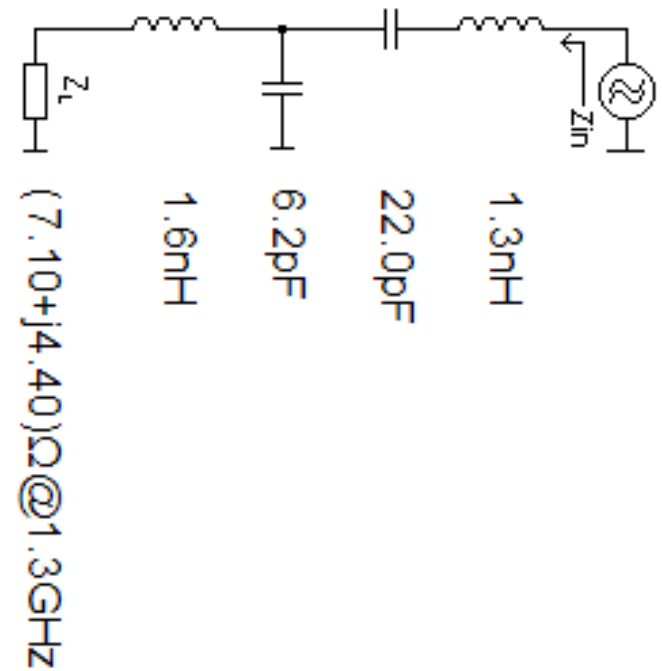
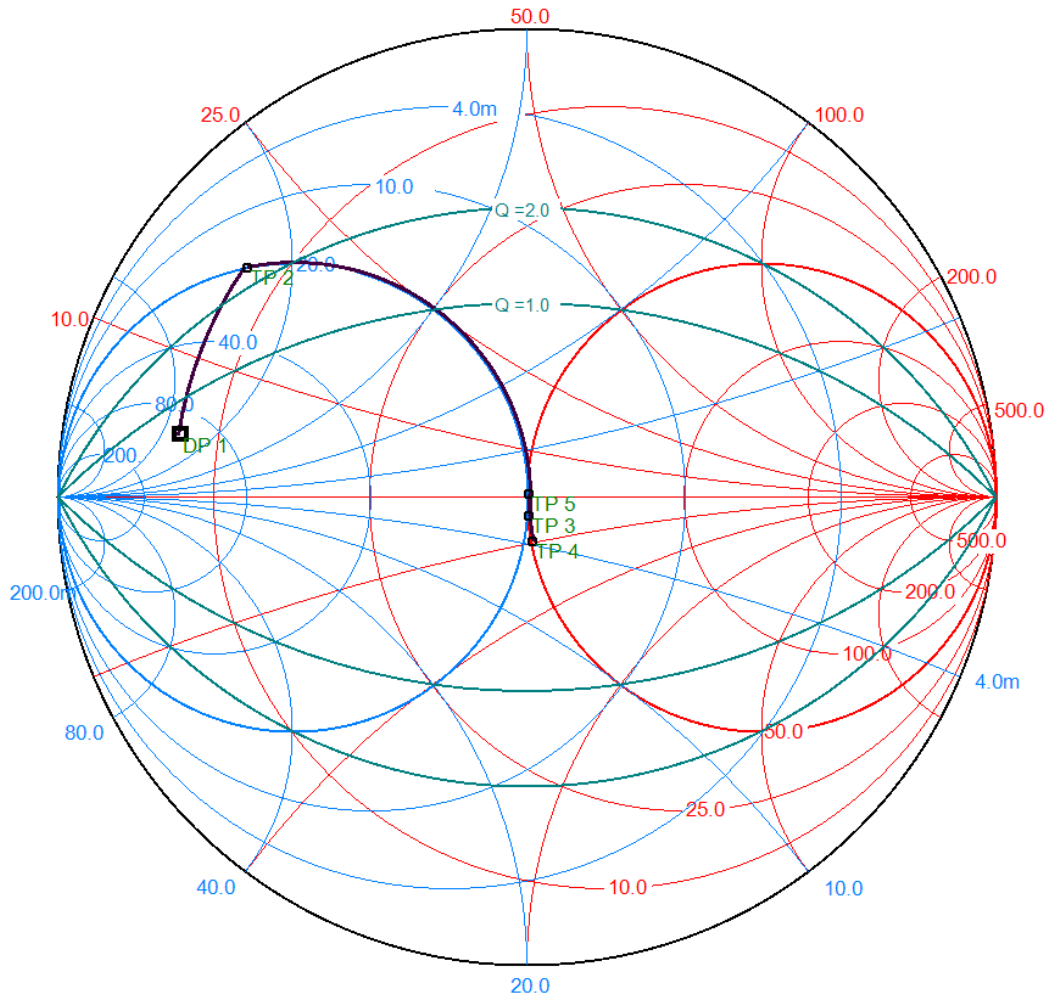
- SO, DESIGN MATCHING NETWORKS TERMINATED WITH:

$$Z_{S\text{OPT}}^* = 7.1 + j 4.4 \Omega$$

$$Z_{L\text{OPT}}^* = 18.4 - j 4.1 \Omega$$



# SGA-9189 LC INPUT MATCH



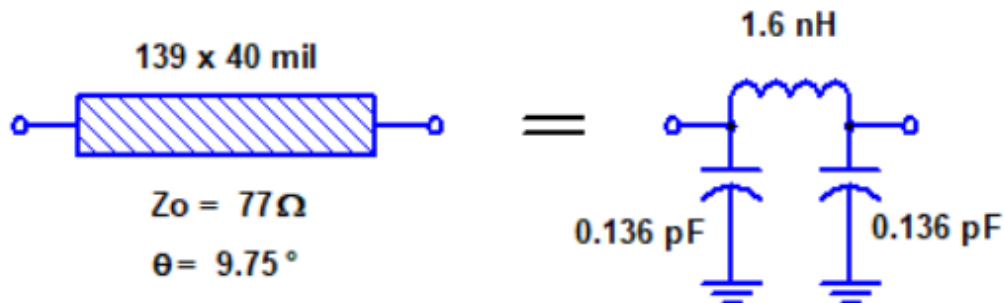
# 1.6 nH FROM 77 $\Omega$ MICROSTRIP

MicroStrip Lumped Equivalent Circuits

Length	139.19	Analysis	40.00	Width	
C(pF)-T	0.2703	Synth. T	Synth. Pi	1.6000	L(nH)-Pi
L(nH)-T	0.8058	<input type="radio"/> microns <input checked="" type="radio"/> mils	0.1361	C(pF)-Pi	

ApelSoft

Solve Microstrip	About		
76.94	3.144	0.5640	9.75
Impedance	Effective Dielectric	Relative Velocity	Phase Length (degrees)
4.500	50.00	1.000	1.296
Dielectric Constant	Dielectric Thickness	Conductor Thickness	Frequency (GHz)



# 6.2 pF SHUNT CAP

## SMD SERIES INDUCTANCE

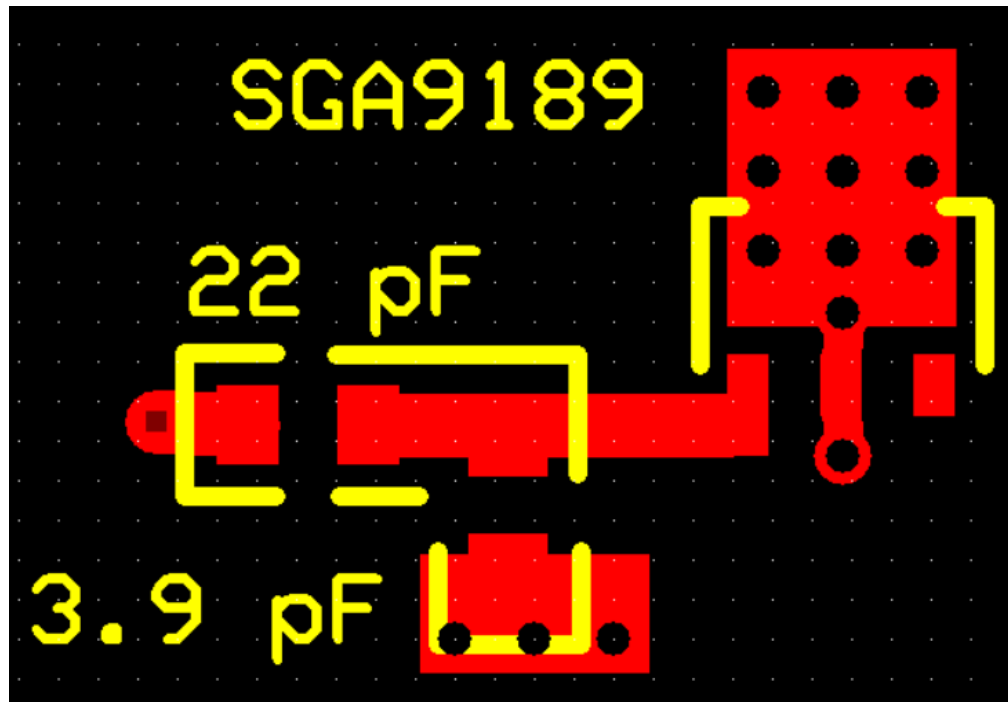
CHIP PKG	DIM (mil <sup>2</sup> )	L(nH)
0402	40x20	0.59
0603	60x30	0.77
0805	80x50	0.84
ATC 100A	55x55	0.55
ATC 100B	110x110	0.77

Series Trap

Freq (GHz)	1.296	Harmonics	Fo	2 Fo	3 Fo
Ls (nH)	1.4	Effective Value	1.30	2.59	3.89
Cs (pF)	3.9	Type	6.11 pF	0.43 nH	0.97 nH
			Cap	Ind	Ind
Calculate		Resonant Freq (GHz)			2.15

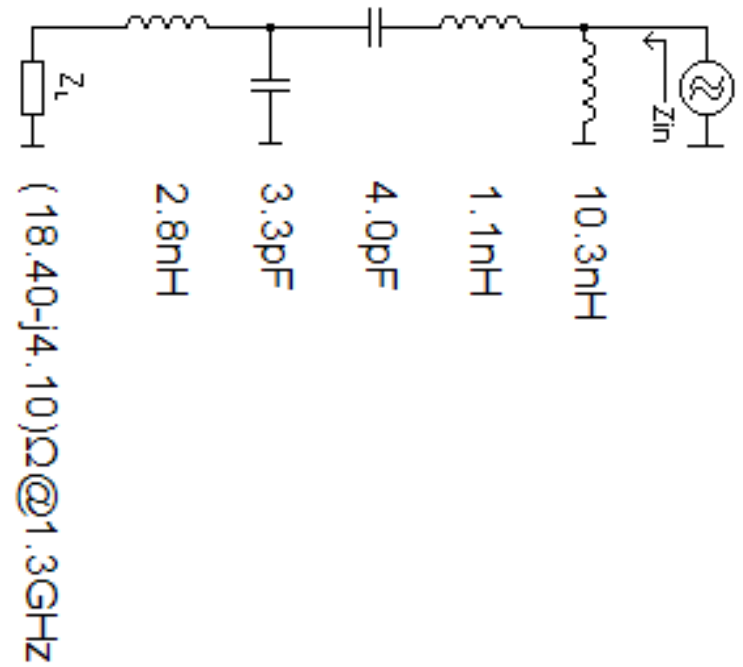
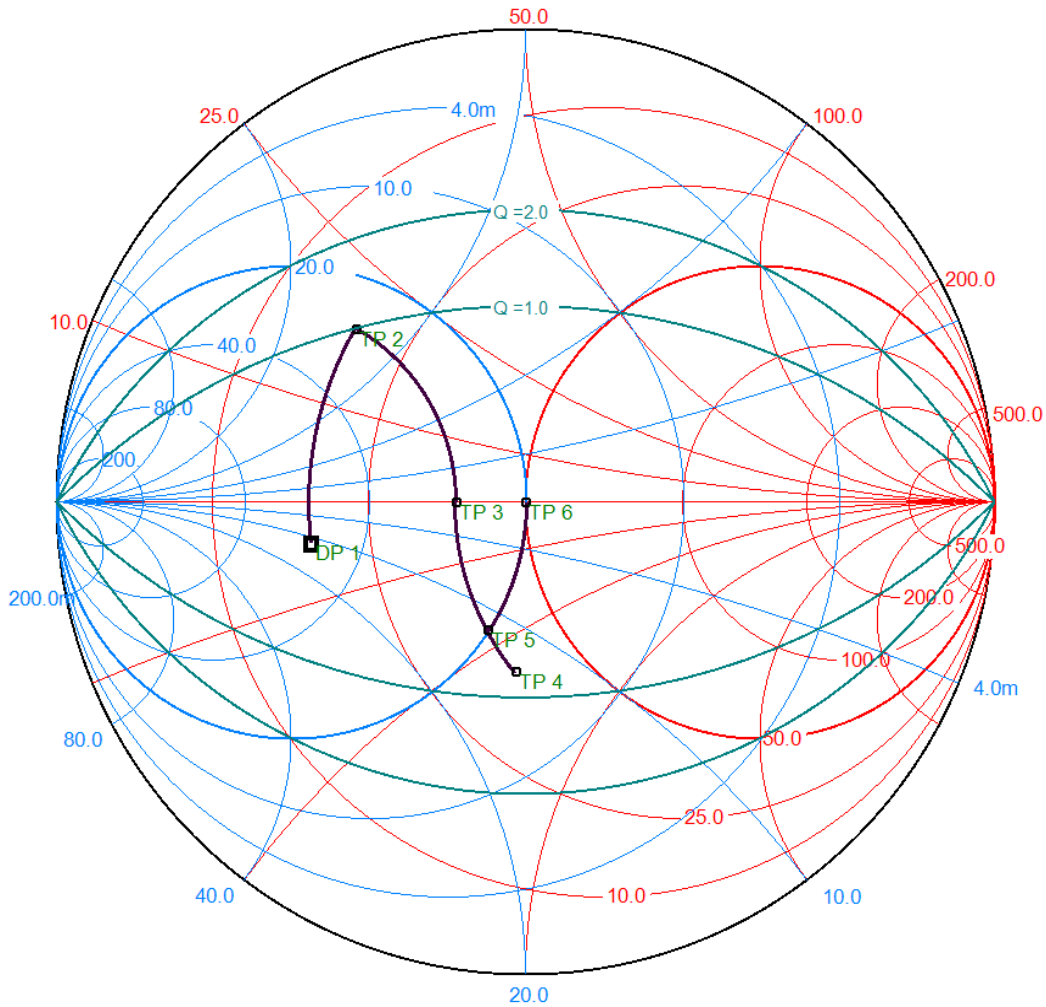
- 0805 SMD 3.9 pF CHIP HAS 0.84 nH IN SERIES
- THE PATH TO GROUND IS A 0.035 DIAMETER VIA = 0.52 nH
- THE TOTAL SERIES INDUCTANCE IS 1.4 nH (= 0.84 + 0.52 nH)
- EFFECTIVE CAPACITANCE IS 6.1 pF AT 1296 MHz
- THE TOTAL SHUNT C IS 6.23 pF (= 6.1 + 0.13 pF)

# INPUT MATCH ON 50 MIL FR4

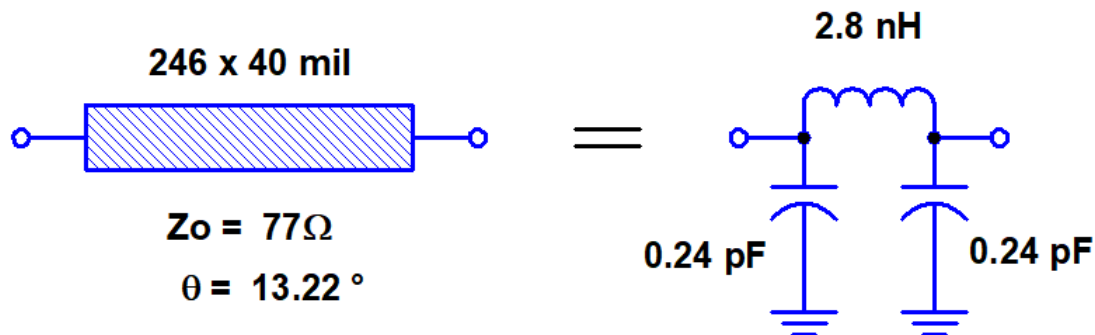
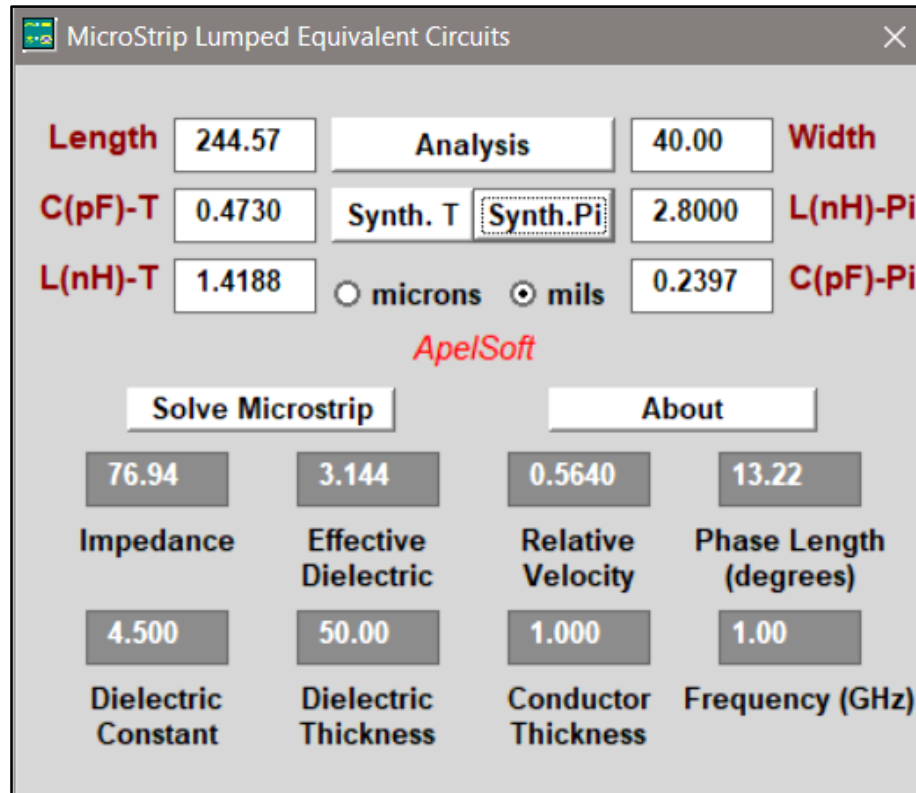




# SGA-9189 LC OUTPUT MATCH



# 2.8 nH FROM 77 $\Omega$ MICROSTRIP



# 3.3 pF SHUNT CAP

## SMD SERIES INDUCTANCE

CHIP PKG	DIM (mil <sup>2</sup> )	L(nH)
0402	40x20	0.59
0603	60x30	0.77
0805	80x50	0.84
ATC 100A	55x55	0.55
ATC 100B	110x110	0.77

Series Trap

Freq (GHz)	1.296	Harmonics	Fo	2 Fo	3 Fo
Ls (nH)	1.4	Effective Value	1.30	2.59	3.89
Cs (pF)	2.4	Type	3.09 pF	22.06 pF	0.70 nH
			Cap	Cap	Ind
Calculate			Resonant Freq (GHz)	2.75	

- 0805 SMD 2.4 pF CHIP HAS 0.84 nH IN SERIES
- THE PATH TO GROUND IS A 0.035 DIAMETER VIA = 0.52 nH
- THE TOTAL SERIES INDUCTANCE IS 1.4 nH (= 0.84 + 0.52 nH)
- EFFECTIVE CAPACITANCE IS 3.09 pF AT 1296 MHz
- THE TOTAL SHUNT C IS 3.3 pF (= 3.09 + 0.24 pF)

# 4.0 pF SERIES CAP

## SMD SERIES INDUCTANCE

CHIP PKG	DIM (mil <sup>2</sup> )	L(nH)
0402	40x20	0.59
0603	60x30	0.77
0805	80x50	0.84
ATC 100A	55x55	0.55
ATC 100B	110x110	0.77

MicroStrip Lumped Equivalent Circuits

Length: 22.51    Analysis    Width: 40.00

C(pF)-T: 0.0439    Synth. T    Synth. Pi    L(nH)-Pi: 0.2600

L(nH)-T: 0.1300     microns     mils    C(pF)-Pi: 0.0220

ApelSoft

Solve Microstrip    About

76.94    3.144    0.5640    1.22

Impedance    Effective Dielectric    Relative Velocity    Phase Length (degrees)

4.500    50.00    1.000    1.00

Dielectric Constant    Dielectric Thickness    Conductor Thickness    Frequency (GHz)

- 0805 SMD 4 pF CHIP HAS 0.84 nH IN SERIES
- THE LUMPED DESIGN HAS PROVIDED 1.1 nH IN SERIES WITH 4 pF
- THE EXCESS 0.26 nH (=1.1 – 0.84 nH) REPRESENTS 22 MILS of 77 Ω LINE

# 10.3 nH SHUNT INDUCTOR

MicroStrip Lumped Equivalent Circuits

Length: 470.57    Analysis: 10.00    Width: **Width**

C(pF)-T: 0.5356    Synth. T: Synth.Pi    L(nH)-Pi: 8.1500

L(nH)-T: 4.2675     microns     mils    C(pF)-Pi: 0.2804


*ApelSoft*

Solve Microstrip    About

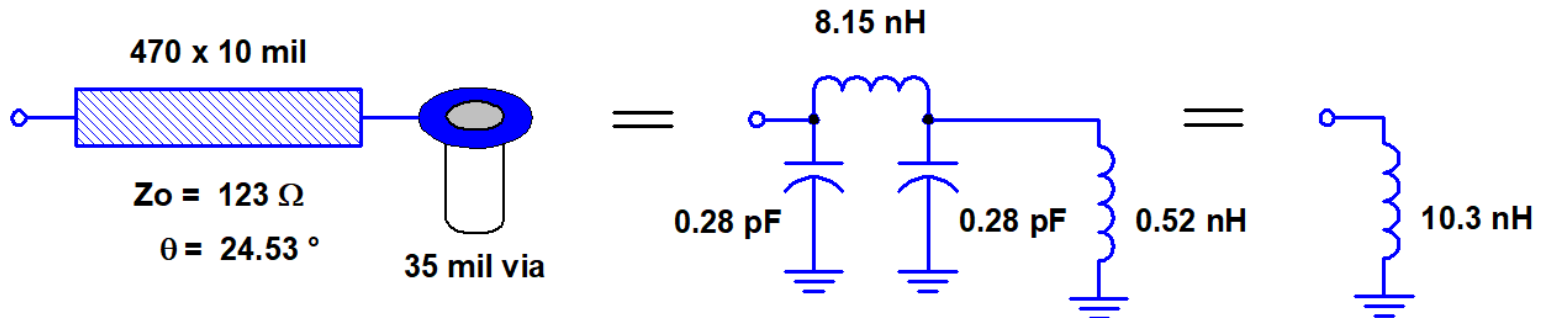
123.36	2.924	0.5848	24.53
Impedance	Effective Dielectric	Relative Velocity	Phase Length (degrees)
4.500	50.00	1.000	1.00
Dielectric Constant	Dielectric Thickness	Conductor Thickness	Frequency (GHz)

Shunt Trap

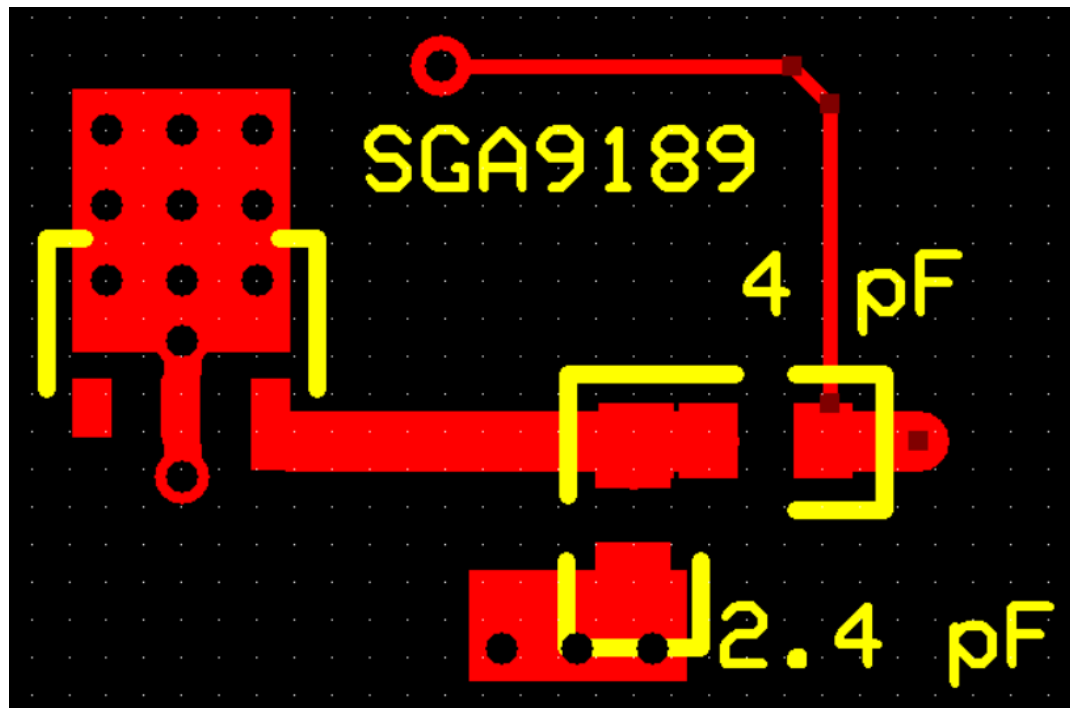
	Fo	2 Fo	3 Fo
Freq (GHz)	1.296	2.59	3.89
Lp (nH)	8.67	24.3 nH	0.09 pF
Cp (pF)	0.28	Ind	Cap
Effective Value	10.3 nH	Ind	Ind
Type	Ind	Ind	Cap
Resonant Freq (GHz)	3.23		

Calculate 

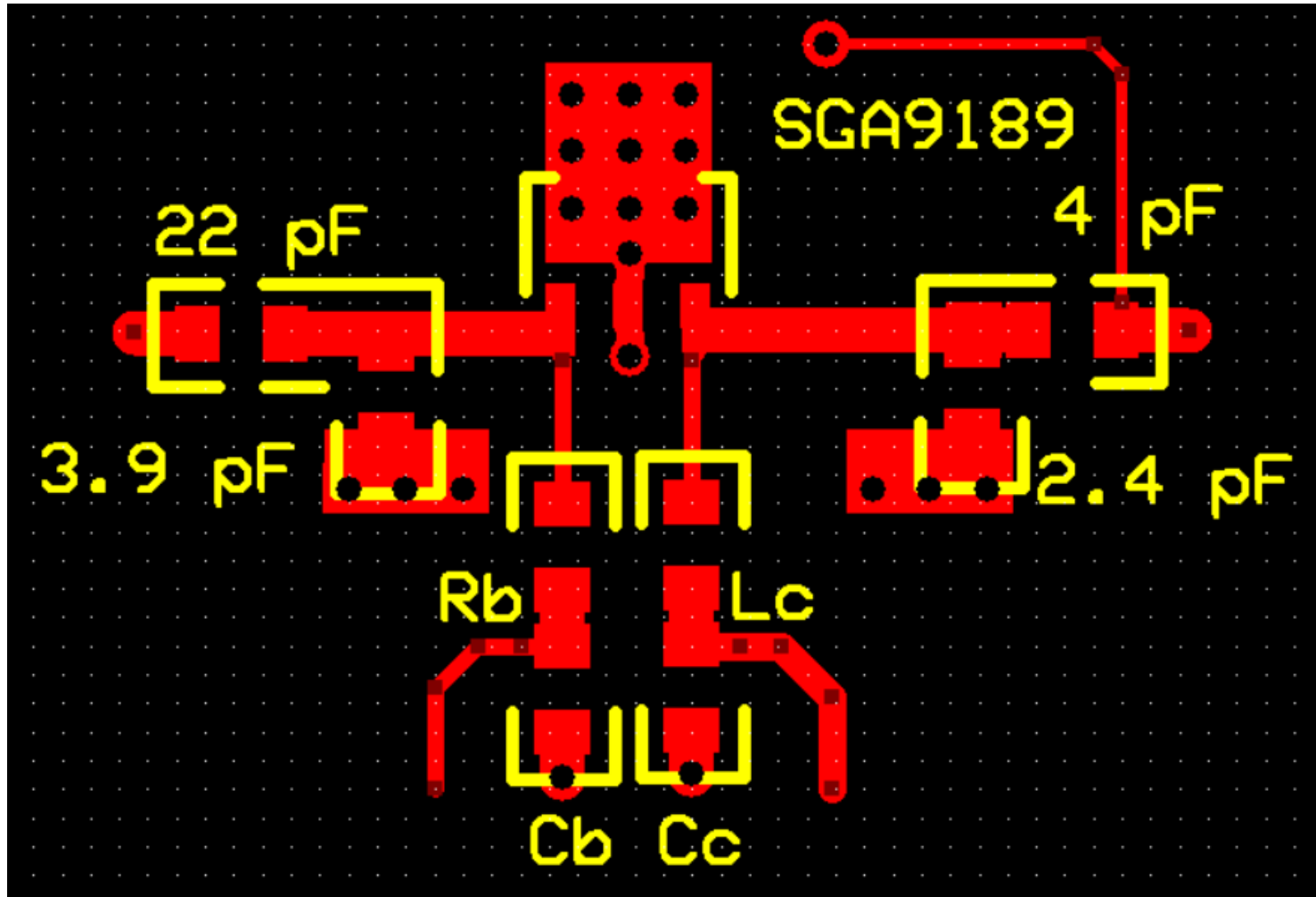
- SHUNT INDUCTOR
- PARALLEL LC EQUIVALENT
- EFFECTIVE INDUCTNCE = 10.3 nH



# OUTPUT MATCH ON 50 MIL FR4



# 1296 MHz DRIVER LAYOUT WITH BIAS FEEDS



# SOFTWARE TOOLS

- SMITH:

<http://www.fritz.dellsperger.net/smith.html>

- MICROSTRIP LUMPED EQUIVALENT:

<http://k5tra.net/TechFiles/LumpEquiv.exe>

- SERIES TRAP:

<http://k5tra.net/TechFiles/SeriesTrap.exe>

- SHUNT TRAP:

<http://k5tra.net/TechFiles/ShuntTrap.exe>