Application Derived Inductor and Transformer

University of Washington

Ka - Wo Pang (Fred)

Outline

- Background and Motivation: Inductor
- Transformer design methodology
  - Structures
  - Layout technique
- Transformer example: LNA
  - Design
  - Layout
  - result
- Future work and conclusion

Motivation

- Key components for RF circuits
- Hard for beginners
  – How to construct the structure for specific inductance and quality factor
  – Matlab program
- Provide design technique for different applications
  – How parameters affect the results
    - LNA: gain, noise figure
    - PA: DC current handling

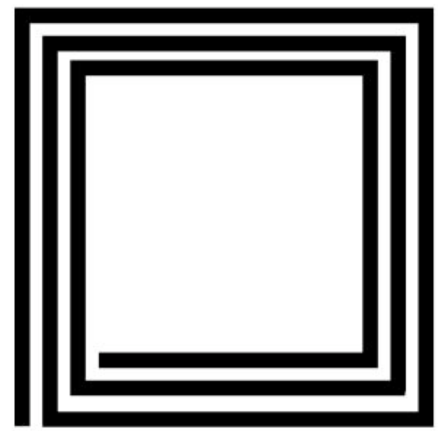
Inductor

- **What is it?**
  - An element stores magnetic energy
  - Amount of stored energy called Henry
  - Lossless ideally
- **Applications**
  - Passive filter
  - Matching network
  - LC tuning
  - VCO, PA, LNA
  - Etc.

Integrated spiral inductor

- Inductance
  - Greenhouse (1974)

$$L = \sum_{i=1}^{n} L_i + 2 \sum_{i=1}^{n-1} \sum_{i=2}^{n} M_{i,j}$$



Grover (1964):

Line inductance (micro-henry):

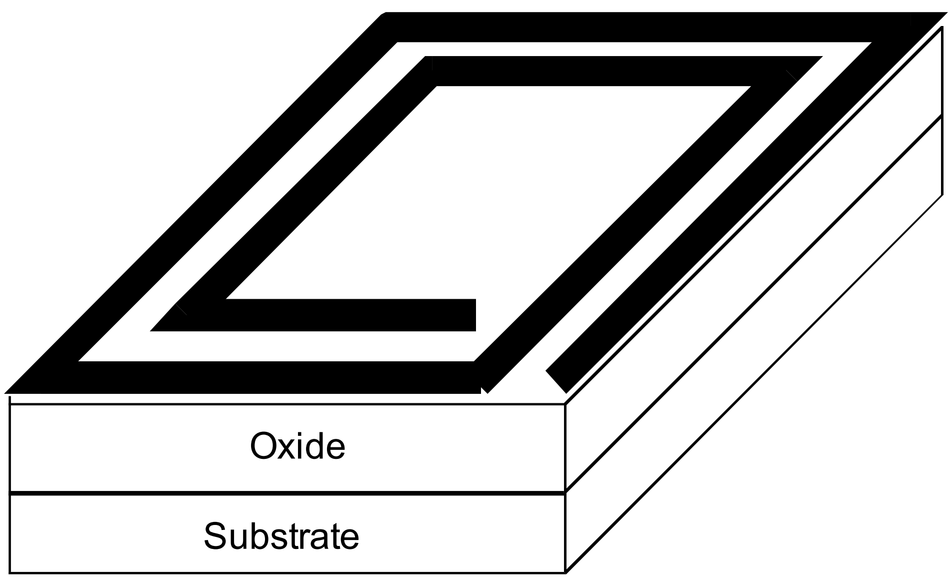
L = 0.002l{ln[2l/0.2232(w+t)]-1.25+[(w+t)/3l]+(u/4)T}

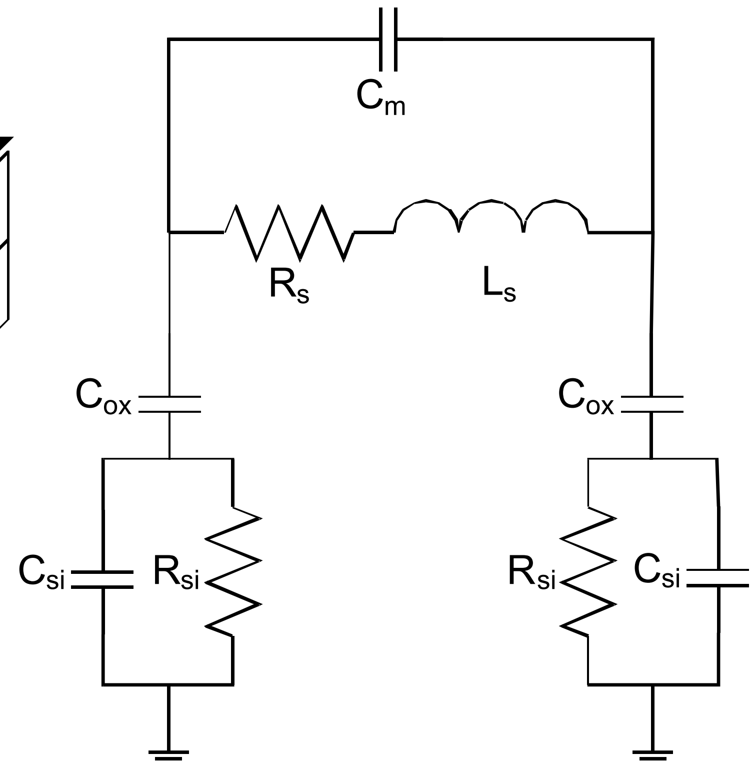
Parallel mutual inductance (nano-henry):

$M = 2l \ln\{ (l/GMD) + [1+(l^2/GMD^2)]^{0.5}\} – [1 + (GMD^2/l^2)]^{0.5} + (GMD/l)]$

$GMD = de^k$

Spiral Inductor Model



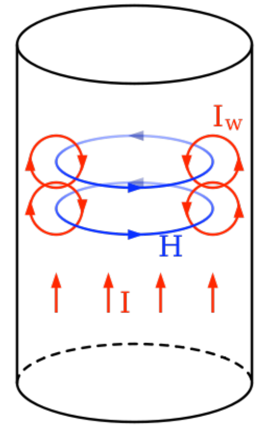


Standard PI model

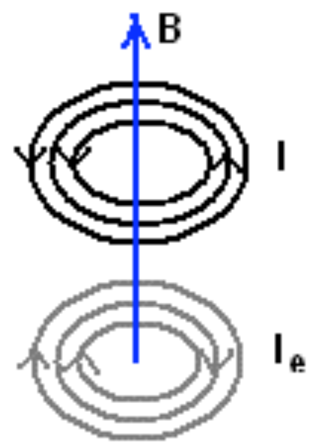
High frequency Loss for Spiral Inductor

- Resistive loss
  - Skin effect
- Substrate loss
  - Proximity effect
- Self resonant frequency

$$w = \frac{1}{\sqrt{LC}}$$

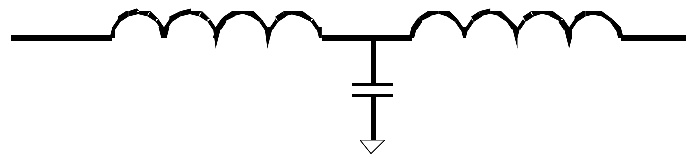


Wikipedia.com

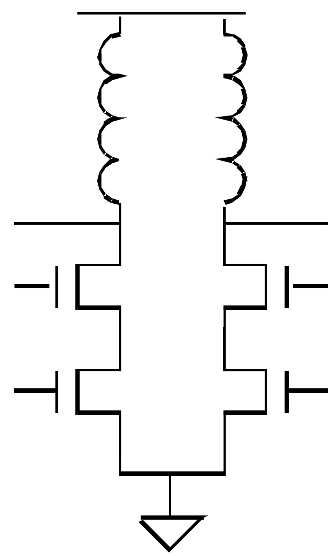


Applications

- **LC matching network**
  - Minimize the loss
  - Self resonant frequency

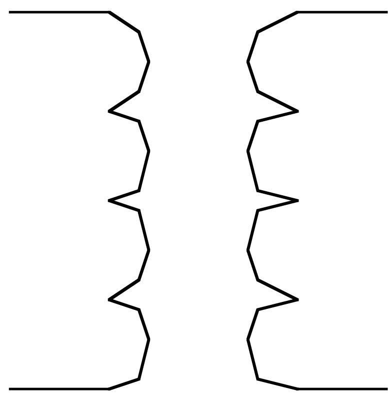


- **Power amplifier**
  - Bias current handling
    - Metal current density



Transformer

- What is it?
  - AC couple between two inductors
- Applications
  - Energy transfer
  - Balun
  - Wideband circuits
  - Matching networks
  - Feedback circuits

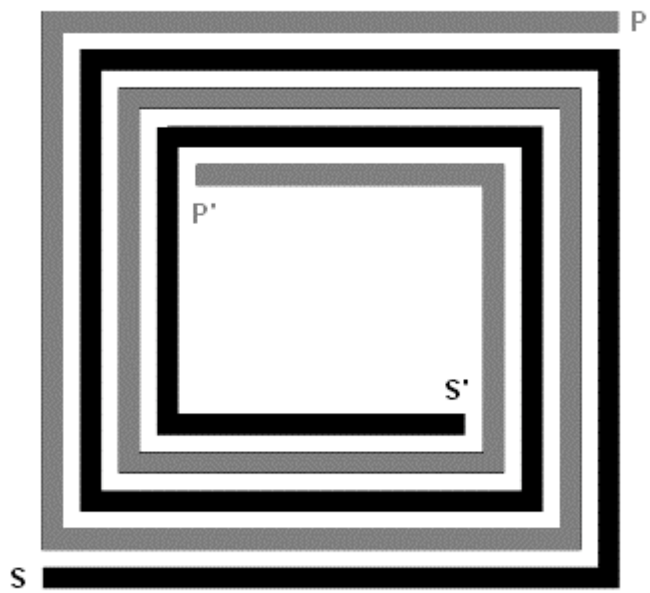


Transformer Parameter

- Quality Factor: $Q = wL_s/R_s$
- Coupling Factor: $K = M/\sqrt{(L_sL_p)}$
- Number of Turns or ratio: $n = \sqrt{(L_s/L_p)}$
- Self Resonant Frequency:

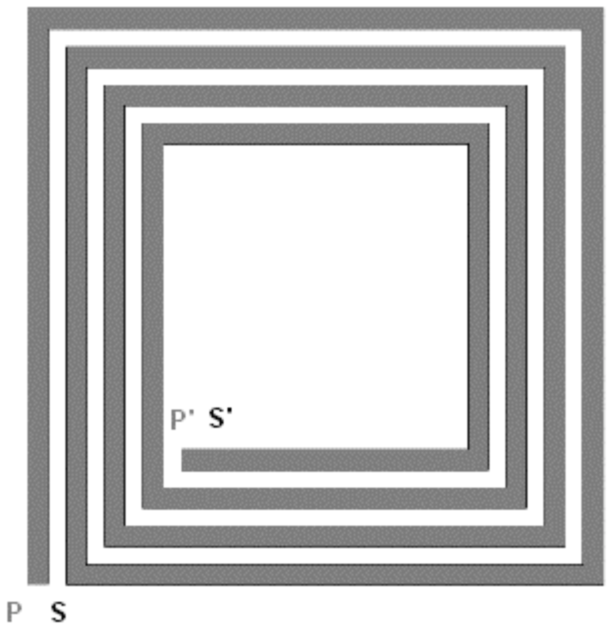
  $W_0 = 1/\sqrt{(L_sC_{tot})}$

Structure: Frlan Transformer



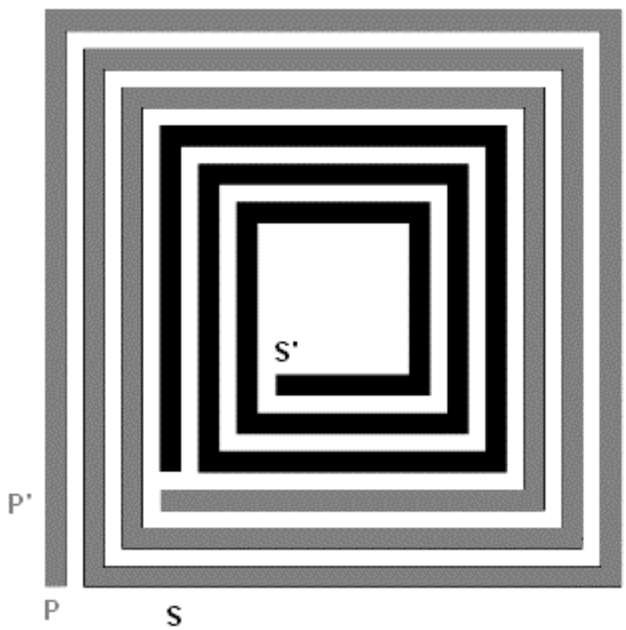
- Same layer
- primary and secondary parallel with each other
- 180 degree different
- Non-inverting (current flows in the same direction)

Overlay Transformer



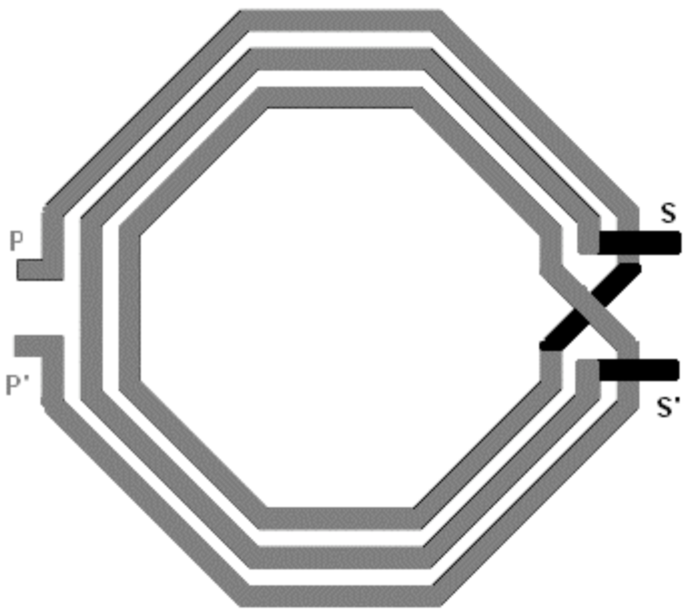
- Primary and secondary in different layer
- Non-inverting

Concentric Transformer



- Same layer
- Inside and outside configuration
- Various structures

Nested Transformer



- require transitional layer
- Inverting

Structure Comparison

	Frlan	Overlay	concentric	Nested
Coupling (k)	med	high	low	med
Self - Resonant	med	low	med	med
Inductance	med	high	high	med
Type	Non-symmetric	Depends	Depends	symmetric

Layout technique

- Minimize no. of Vias (for inductance)
- Maximize no. of Vias (for Quality factor)
- Use the top layers
- 45 degree for angles
- Use minimal separate distance
- Quality Factor: Reduce R_s
  - Increase metal width or thickness (typically 10u - 20u)
- K and Self resonant frequency:
  - depends on Structure

Simulation tools

- Asitic
  - Fast
  - less Accuracy (20% off)
  - Good starting step
- ADS
  - Slow
  - High Accuracy
  - Final verification
  - Layout and model comparison

Asitic Setup

- Download the Unix setup from http://rfic.eecs.berkeley.edu/~niknejad/asitic.html
- Follow the installing instructions
- To start the program: ./asitic_linux
- Build technology file .tek
- Tutorial on the website

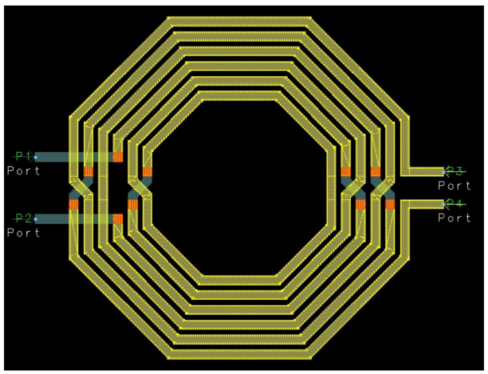
Asitic: symmetric inductor results

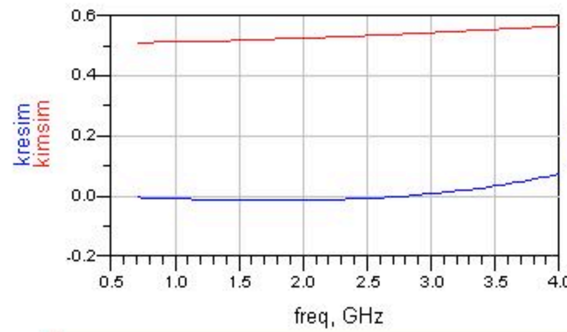
R	W	S	Gap	Side	N	Q1	L	R	C1	C2	R1	R2	SRF
100	10	10	15	8	3	4.98	1.56	1.38	33.7	34.1	131.	46.8	27.7
100	10	5	15	8	3	5.61	1.88	1.47	32.3	32.5	123.	53.1	23.7
100	5	10	15	8	3	2.81	2.12	3.31	29.3	29.1	220.	48.4	35.3
100	10	10	20	8	3	5.07	1.60	1.39	34.5	34.8	129.	47.0	26.7
200	10	10	15	8	3	8.20	5.11	2.71	76.8	76.9	60.1	48.8	8.25
200	10	10	15	8	5	9.56	9.40	4.23	103.	103.	56.9	51.1	5.19
200	10	10	15	6	3	7.88	4.79	2.65	75.0	755.	61.4	48.6	8.65
150	10	5	23.2	8	5	8.73	7.05	3.51	68.6	68.8	70.3	58.9	7.41

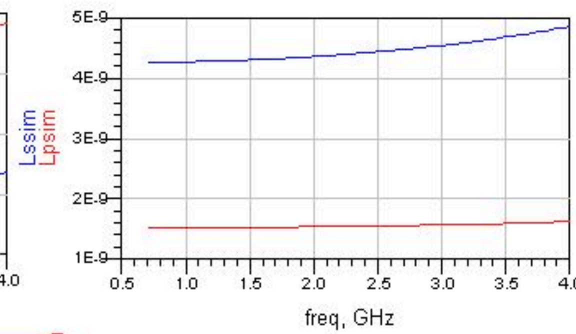
ADS setup

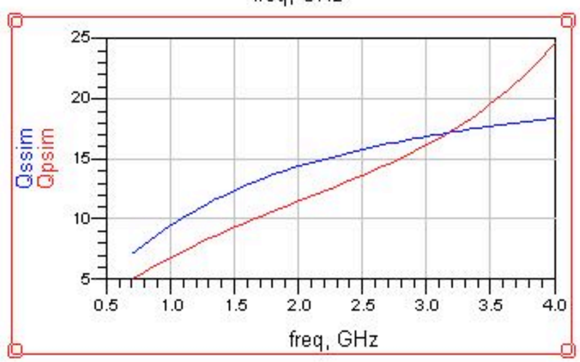
- Add source /usr/nikola/groups/vlsi/pkgs/ads/ads.cshrc (or ~robin/ads.cshrc) in .cshrc.local
- Start ADS command: ads
- Before use:
  - Create technology file
  - Create layout file

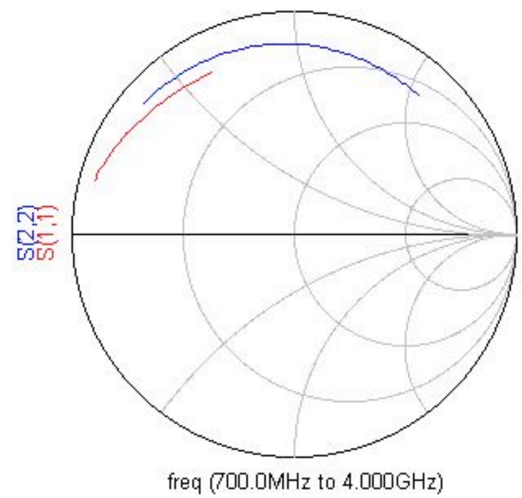
ADS sample results: concentric structure



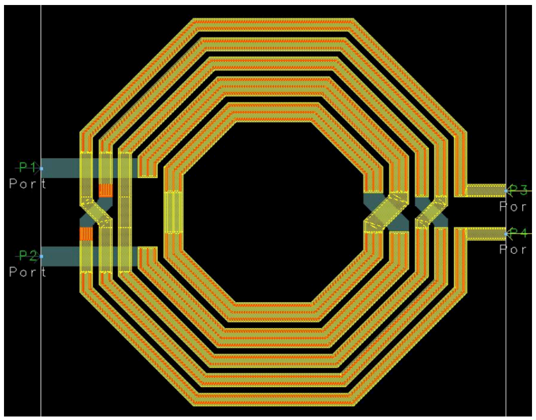


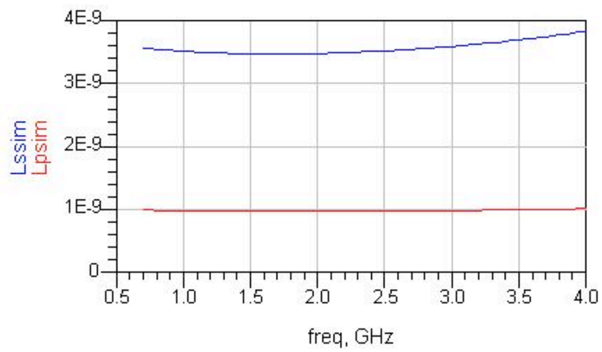


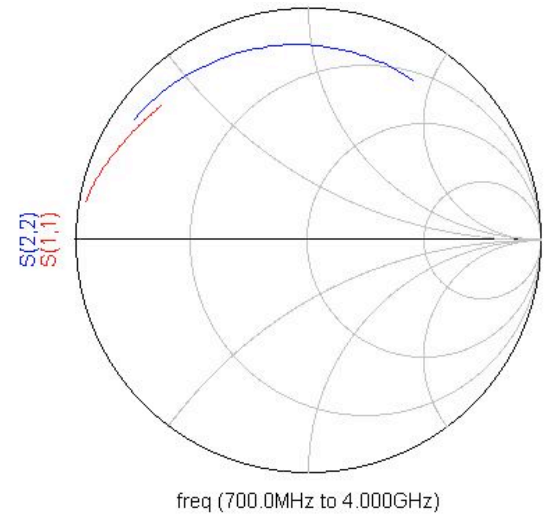


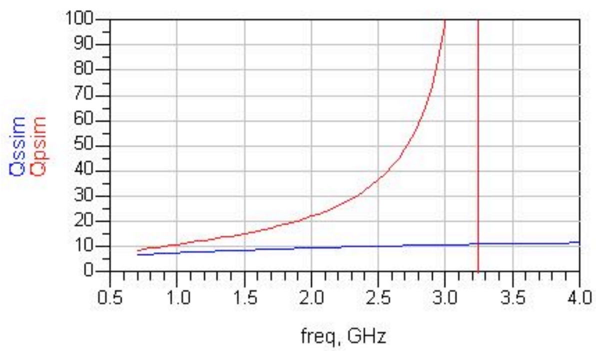


ADS sample results: Stack & Concentric Structure









Example: Low Noise Amplifier (LNA)

- Wide bandwidth (0.8 ~2.4GHz)
  - Multi-mode operation
- Differential
- High gain
- Low noise (noise figure <3dB)

Design Process

- Transformer: less number of capacitor array than Inductor
  - Less parasitic from capacitor array
- Reasonable values
  - Inductor: < 10nH
  - Capacitor: < 20pF
- 0.8GHz : ~4nH , ~10pF
- 2.4GHz : ~1nH , ~4pF

Design Process

- LC Network Q
  - usually dominated by the transformer
  - Bandwidth of the network ($Q=f_0/BW$)
- Gain
  - gm*Rout
  - $Rs(1+Q^2)$
- Noise
  - Proportional to K and Q

Design Process

- ASITIC
  - Estimate the dimension and Inductance
- Create layout in Cadence
- Simulate the circuit in ADS
  - Generate S-parameter results
- Compare layout result with model
  - Find the best fit model for the transformer

Challenges

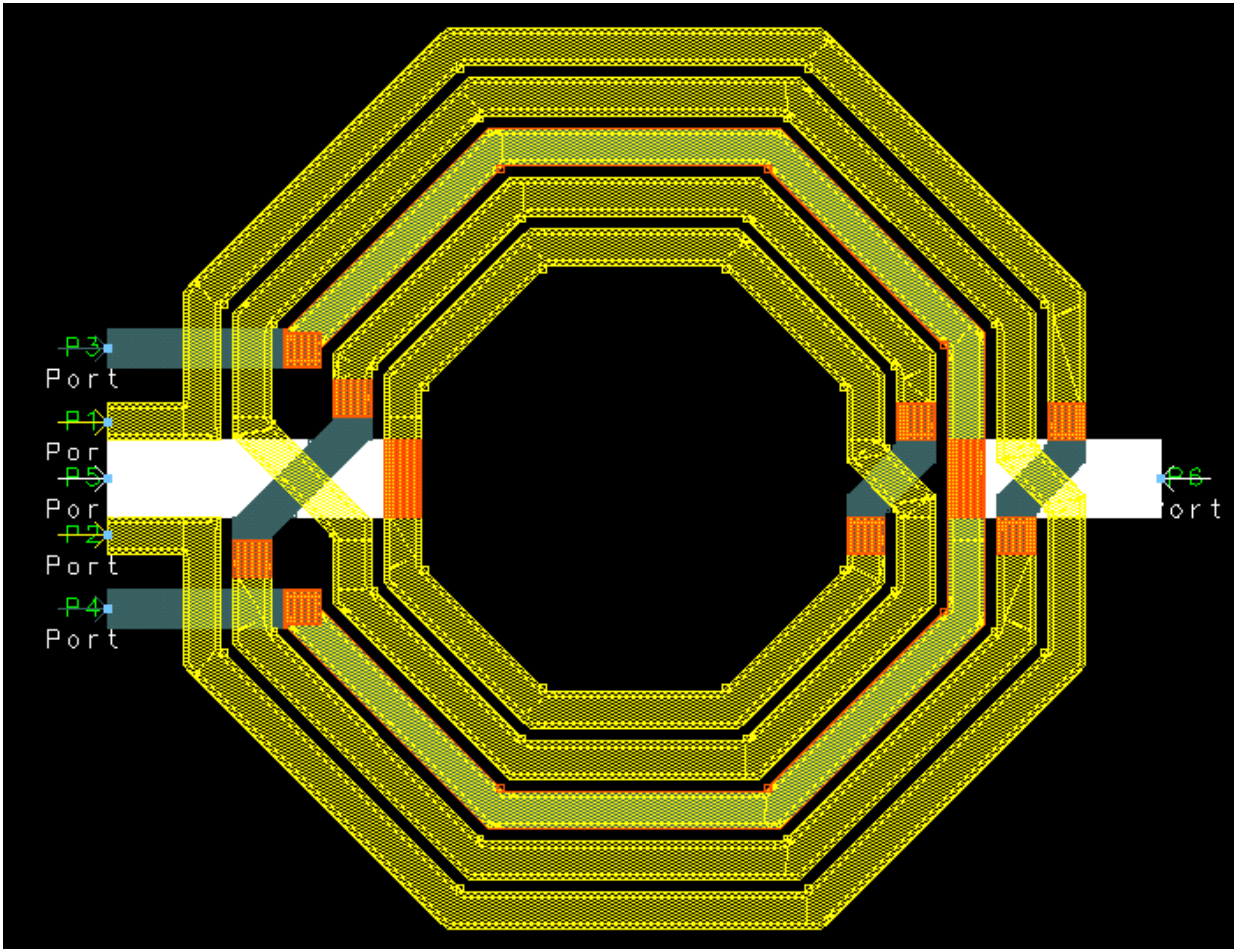
- Quality factor <10
  - Lower than 10 with small inductance value at low frequency
  - Negative resistance circuit
    - High power consumption
    - Positive feedback: reduce linearity
  - Increase inductance value (increase area and SRF)
- Coupling and Self resonant frequency
  - Usually require SRF 2 times higher than operation frequency
  - Overlay structure: SRF is too low for the required inductance
  - Nested Structure: both are medium

Transformer Summary

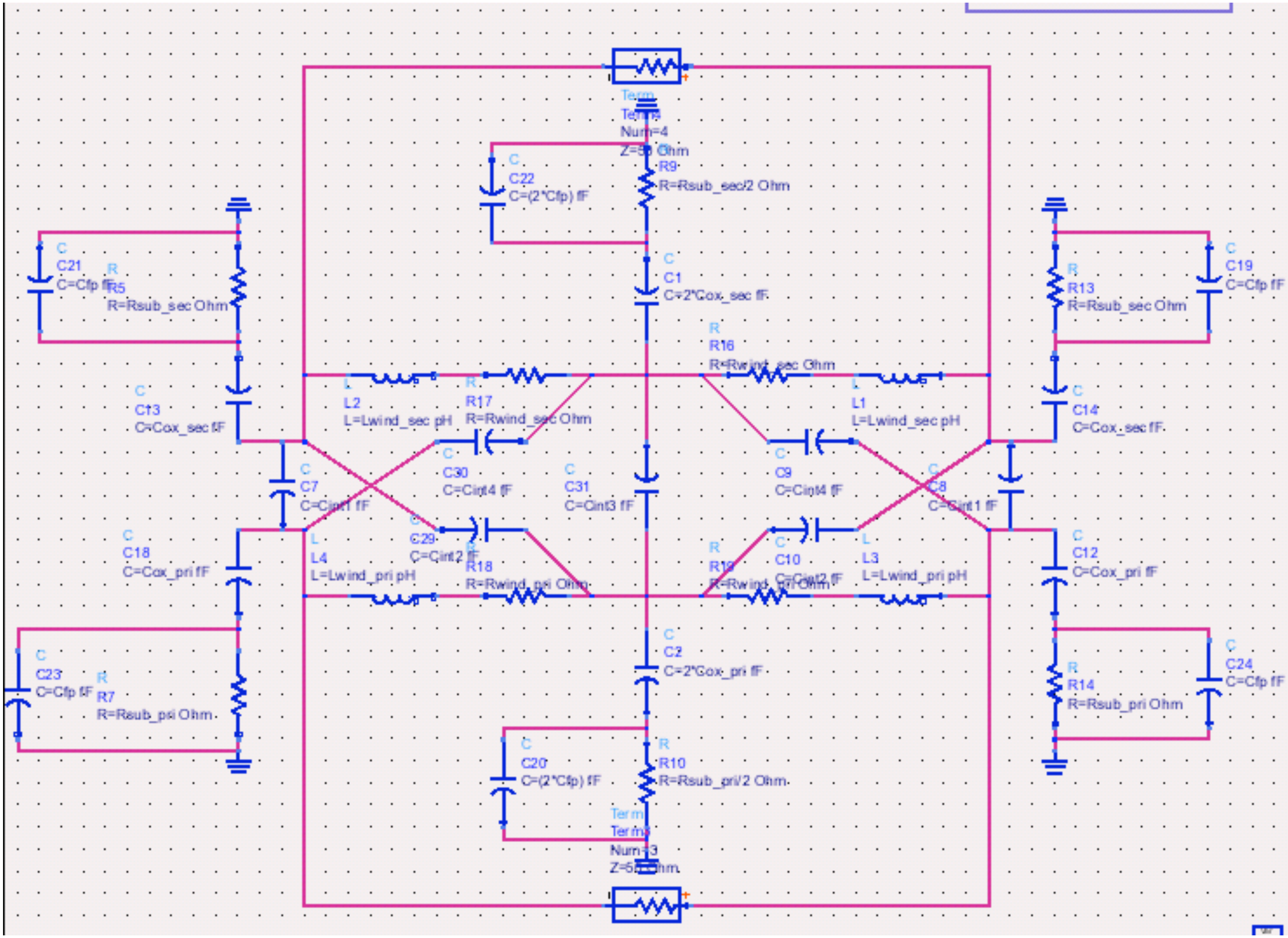
	concentric (inv)	Frlan (inv)	frlan (inv)
inductance (pri at 0.8GHz)	6.2nH	3.6nH	5.5nH
inductance (sec at 2.4GHz)	1nH	1.6nH	1nH
Q (pri at 0.8GHz)	9	7	7
Q (sec at 2.4GHz)	13.5	17	14
k (0.8 ~ 2.4GHz)	0.4~0.54	0.7~0.75	0.55~0.66
area (um x um)	360 x 360	375 x 360	360 x 360
Metal Width (um)	15	15	15
Number of Turns	4:2	4:2	4:2
Metal Space (um)	5	5	5

	frlan (non-inv)	frlan - stack (non-inv)
inductance (pri at 0.8GHz)	4nH	5nH
inductance (sec at 2.4GHz)	0.5nH	0.5nH
Q (pri at 0.8GHz)	7	9
Q (sec at 2.4GHz)	8	11.5
k (0.8 ~ 2.4GHz)	0.67~0.72	0.64~0.72
area (um x um)	320 x 320	360 x 360
Metal Width (um)	15	15
Number of Turns	4:1	4:1
Metal Space (um)	5	5

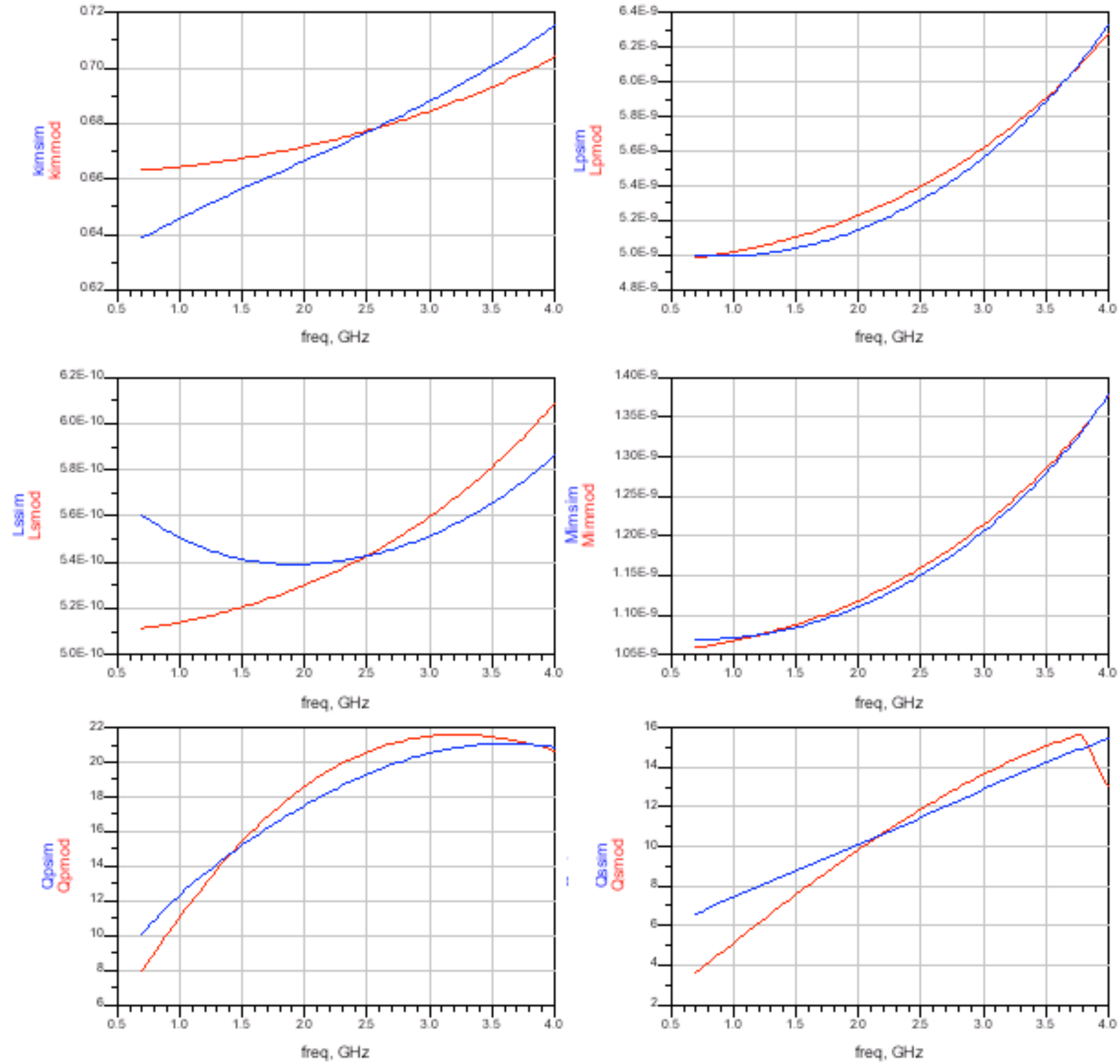
Layout in ADS



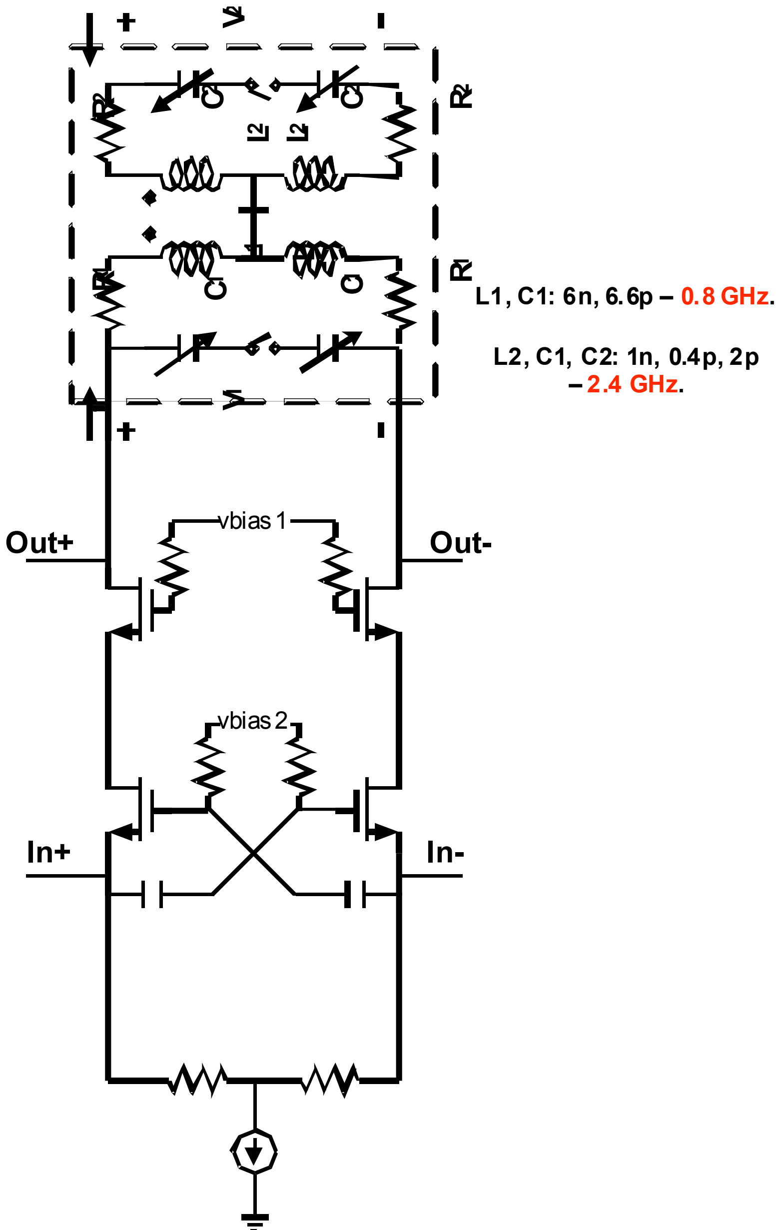
Transformer Model



Model VS S-parameter



LNA



- Wide - band input matching using common - gate LNA
- Tunable output load from 0.8GHz - 2.5GHz
- Primary inductance: ~5n
- Secondary inductance: ~0.5n

Resonator Corners @ 0.8

	Slow	Typ	Fast
S21 (dB)	19	25.0	32.4
Volt. Gain (dB)	22.5	28.5	36
S11 (dB)	< -15	<-15	<-12
NF (dB)	6.6	6.7	5.8
Power (mW)	(4.2+3.8) *1.2 =9.6	(4.8 + 5.6)*1.2 =12.5	(5.4+7.6)*1.2 = 15.6
Q (using neg. FB)	18	32	80
IIP3 (dBm)	-10.9	-16.32	-22.22

Corners @ 2.4 GHz **(No Q-enhancement)**

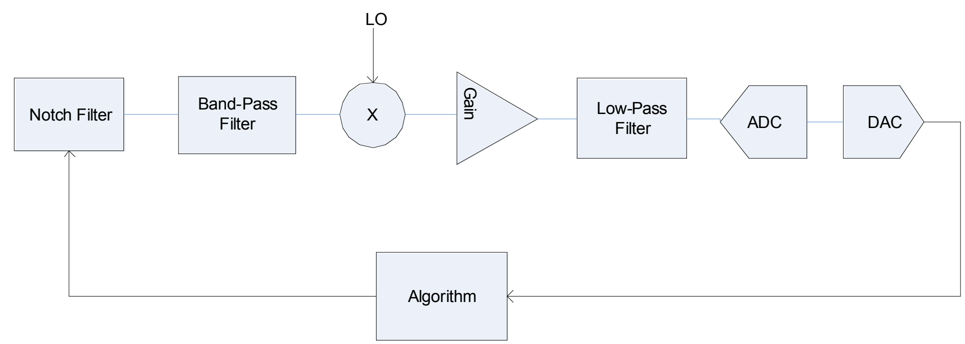
	Slow	Typ	Fast
S21 (dB)	19	20.75	21.75
Volt. Gain (dB)	22.5	24.35	25.5
S11 (dB)	< -15	<-15	<-15
NF (dB)	3.05	2.6	2.4
Power (mW)	(4.2) *1.2 =5	(4.8)*1.2 =5.76	(5.4)*1.2 = 6.5
Q	8	8	8
IIP3 (dBm)	-0.6	-2.78	-6.54

Future work

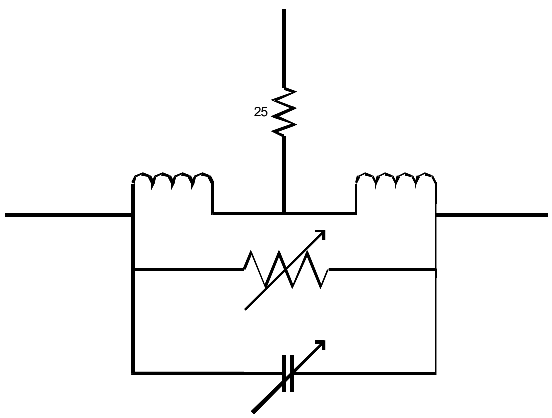
- Matlab program
  - Enter inductance and dimension
  - Output different structures with appropriate turns, metal width
  - Q plot of different structures
- Tunable matching network
  - Power amplifier

Tunable Notch Filter

Block Diagram:



Tunable Notch filter:



Filter results

- Notch Filter: 1.2GHz ~45dB
- Band-Pass: 1.2GHz ~0dB
- Mixer :1.2GHz
- Gain : 40dB
- LPF: 150MHz
- ADC: 4 bit -0.4~0.4 input range, 250MHz/sample
- Tuning range: 1.2 ~1.45GHz